ISSN: 0974-5823 Vol. 7 No. 1 January, 2022

International Journal of Mechanical Engineering

Improvement of the Theory of Seismic Resistance of Dams as Hydro Elastic Systems

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Abstract. The article is devoted to improving the theory of earthquake resistance of dams as hydro elastic systems. Equations of motion of a planar deformed state of a hydro elastic system under consideration.

1. Introduction

When calculating the seismic effects of dams and other structures that perceive water pressure, in addition to seismic inertial forces, it is necessary to take into account the influence of the aquatic environment. The presence of an aqueous medium during the vibrations of the structure leads to the appearance of additional hydrodynamic pressure (with respect to hydrostatic) on the pressure faces of the structure and pore pressure in the body of the dam and the base, a change in the frequencies and forms of natural vibrations of the structure. This ultimately significantly affects the stable stress-strain state of construction. The question of taking into account the aquatic environment when calculating seismic resistance structures first arose in connection with the design of a number of high dams in seismically active areas of the earth.

2. Literature Review

The development of theoretical methods for calculating the seismic stability of dams, port structures, reservoirs - storage tanks for liquid fuel and other hydraulic and special structures has greatly stimulated the development of work on the study of the dynamic interaction of structures with liquid. Many of the major scientists (G. Westergard, T. Karman, L. S. Leibenzon, M. T. Urazbaev, and others), through their fundamental works, contributed to the progress in this field of mechanics. According to the static theory of earthquake resistance that prevailed until the mid 50-ies of the last century and to this day is quite widely used in calculations of hydraulic structures (especially in the preliminary stages of design), only the maximum value of the hydrodynamic pressure acting on the pressure face of the hard (non-deformable) structure, the base of which oscillates according to a given (usually harmonic) law. Stresses, deformations, etc. are then calculated as from an additional static load. The statement of the problem proposed by Westergard and the numerous works on determining the hydrodynamic pressure on rigid structures are obvious and consistent with this approach. Within the framework of static theory, it is easiest to give a rough estimate of the role of hydrodynamic pressure in the general complex of loads acting on a structure. For this purpose, we compare the magnitudes of the seismic and hydrostatic pressure of water within the framework of the simplest design scheme. According to the well-known Westergard solution for a rigid dam with a vertical pressure face located in a canyon of rectangular cross section and performing longitudinal harmonic oscillations with a frequency substantially less than the first natural frequency of the liquid volume, the seismic pressure of water is characterized by the following values: Maximum ordinate of the pressure plot (at the bottom of the dam) Pb = 0.74 Ks; The total pressure on the dam P = 0.54 Ks (1.1)

Moment resultant with respect to the sole M = 22Ks. At Ks = 0.2, the total hydrodynamic pressure on the dam (in relation to the Westergard design scheme under consideration) is 22% of the hydrostatic, which is already significant. Obviously, such a comparison, made within the framework of the static theory of earthquake resistance, is very conditional, since one should bear in mind the dynamic nature of the additional hydrodynamic pressure, as well as its possible increase with unsteady vibrations, acoustic resonance, vibrations of canyon sides and other circumstances not taken into account formula (1.1). A theoretical study of the dynamic interaction of structures with a fluid is based on a number of assumptions made to describe the motion of the fluid and the stress-strain state of the structure. In this case, the model of a continuous medium used (liquid, elastic, elastic-viscous, etc.) should describe the main features of the phenomenon and not be too complicated, since the complication of the model (usually easily achievable) can lead to significant mathematical difficulties with solving specific problems. A criterion for the correctness of certain assumptions is a comparison of theoretical and experimental results for a number of characteristic cases. An analysis of the work on the vibrations of structures in a liquid shows that different initial conditions are often used in different works, both in terms of describing the motion of a liquid and schematizing the construction. This circumstance is explained by a wide variety of technical problems, the solution of which requires a joint consideration of the equations of hydromechanics and the theory of elasticity. Even if we confine ourselves to the tasks of seismic resistance of hydraulic structures and close to them, then the systems of initial assumptions used in them turn out to be quite diverse. Obviously, solutions based on different initial assumptions have different areas of applicability, and comparing the results is therefore difficult. It should be noted that the development of computers and the widespread introduction of numerical methods in continuum mechanics allows us to reconsider the point of view on the need to introduce some assumptions. Many problems solved at one time by classical methods could be considered only after a substantial simplification of the physical and geometric aspects of the phenomenon. The use of numerical methods already makes it possible to abandon a number of simplifying assumptions and evaluate the role of factors, the inclusion of which was previously very difficult. In most problems considered in the theory of seismic resistance of hydraulic structures, the volume of fluid is limited by the free surface. This surface, if the liquid is in a constant and uniform gravitational zero, is flat. If a local disturbance is caused in any region of the free surface, then it will begin to propagate in all directions in the form of so-called gravitational plate-surface waves. The peculiarity of these waves is that they propagate mainly on the surface of the liquid, rapidly attenuating with increasing depth. The solution of the problem for the Westergard scheme (that is, with oscillations of a rigid wall) taking into account gravitational waves of small amplitude on a free surface was first given by N. Moponobe (1933), and then was considered in many works (see, for example, the works of S. Kotsubo, Chen-Zhen-Chen, T. Hatano and others. The solution of the more general hydrodynamic problem for the Westergard scheme, when an arbitrary velocity law of the oscillating wall is given, was given in the work of L. N. Grodko. Corresponding to the same scheme hydro elasticity problem, i.e. a system of joint oscillation equations s elastic wall and fluid motion with the surface waves, considered in L.I.Dyatlovitskogo, and V.N.Buyvola E.D.Lemberg. T. Hatano conducted special experiments in a steel tank filled with water, in which vibrations were excited using a piston. Based on the described field and model studies, T. Hatano concluded that if there is a layer of absorbing material at the bottom of the pool (for example, sand, silt, etc.), when determining the hydrodynamic pressure of water on a structure, one should proceed from the solution of the equation Laplace. That is, the compressibility of the water does not need to be taken into account, and therefore the possible increase in pressure with acoustic resonance should not be taken into account. In principle, any problem of the dynamic interaction of a structure with an aqueous medium should be solved on the basis of considering them as a single hydroelastic system. From the solution of coupled systems of equations of motion of an elastic body and a fluid under appropriate boundary and initial conditions, the stresses and displacements necessary for calculating the design (caused by both seismic inertial forces and hydrodynamic pressure) are determined. This way of solving the problem was first proposed, apparently, by L. S. Leibenzon and then developed in a number of works, for example, M. T. Urazbaev and his school [1-7]. The practical implementation of this approach, the most general from a theoretical point of view, is associated with very laborious calculations (especially for complex spatial systems such as arched and buttress dams, water intake towers, reservoirs, etc.). Therefore, in the applied theory of earthquake resistance of hydraulic structures, an approximate technique has been disseminated, based essentially on a separate consideration of these systems of equations. Unfortunately, the following fact should be noted.

3. Methodology

When calculating a gravitational dam with a height of 100 m, taking into account the attached mass of liquid according to Westergard, the decrease in the natural frequency of the dam was 34%. According to our methodology, where the real distribution of hydrodynamic pressure -8% was taken into account. This is due to the fact that according to our methodology, only the hydrodynamic pressure arising from the elastic part of the displacement affects the natural frequency. The pressure from the portable vibration of the structure acts as an external load. Therefore, the hydroelastic effect affects only the phase part of the stress, and the pressure arising from the figurative movement of the structure affects the formation of the stress state. The development of a method for calculating the seismic effects of lightweight and lightweight concrete dams of various designs as hydro elastic systems made it possible to discover the applicability limits of existing methods for their calculation using the Kirchhoff – Love hypothesis [2-6], and expand the range of applicability of the widely used Bubnov – Galerkin method by creating a common methods for constructing high-order approximating functions and modifying the method for differential equations with strongly variable coefficients, describing yuschimi in particular mathematical model of lightweight concrete dams. It is found that the physical meaning of the solution is satisfied when constructing approximating functions. For the first time, the use of the beam coordinate system made it possible to clarify the method for dynamically calculating concrete-gravity and arch dams in a narrow V-shaped gorge from longitudinal seismic impact and sections of buttress dams as triangular plates, experiencing mainly bending vibrations from the transverse component of the seismic. We also solved the problem of seismic resistance of hydro elastic systems in relation to soil dams. It is especially important for them to take into account the accumulation of plastic deformations. In addition, the saturation of a dam body with water affects its behaviour under load. The resulting pressure in the pore fluid, unloading the skeleton of the soil, can cause its progressive flow and destruction. It is known that when solving problems in a nonlinear formulation, a superposition of results for various loads is impossible. Therefore, solving the problem in a single statement, taking into account the real time of the action of the loads, will allow a more plausible result, since the soil is a purely nonlinearly deformable medium. We have solved the problems of determining the stress-strain state, pore pressure and the stability coefficient of soil dams of various designs on static and dynamic effects in a single formulation using a two-phase medium model.

$$\left.\begin{aligned}&\rho_1(1-m_1)\ddot{u}_1=\frac{\partial\sigma_x}{\partial x}+\frac{\partial\tau}{\partial y}+\frac{\partial P}{\partial x}+\rho_2 g m_1\frac{(\dot{u}_2-\dot{u}_1)}{k_1}-\rho_1(1-m_1)(g+\ddot{w}(t))\\&\rho_1(1-m_1)\ddot{v}_1=\frac{\partial\sigma_y}{\partial y}+\frac{\partial\tau}{\partial x}+\frac{\partial P}{\partial y}+\rho_2 g m_1\frac{(\dot{v}_2-\dot{v}_1)}{k_2}-\rho_2(1-m_1)\ddot{u}_0(t);\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}&\rho_2 m_1\ddot{u}_2=\frac{\partial P}{\partial x}-\frac{\rho_2 g m_1}{k_1}(\dot{u}_2-\dot{u}_1)-\rho_2 g m_1;\\&\rho_2 m_1\ddot{v}_2=\frac{\partial P}{\partial y}-\frac{\rho_2 g m_1}{k_2}(\dot{v}_2-\dot{v}_1);\end{aligned}\right\} \quad (2)$$

$$\dot{P}=M_2\left[(1-m_1)\dot{\theta}+\left(\frac{\partial\dot{u}_2}{\partial x}+\frac{\partial\dot{v}_2}{\partial y}\right)m_1\right] \quad (3)$$

where σ_x, σ_y and τ - effective stresses associated with skeletal deformations by equations of state; $\dot{u}_1, \dot{v}_2$ - the speed of movement of the skeletal material in the direction of the axes x and y; P - first pressure;

m_1 - porosity; k_i - filter coefficient indirection; vertical and horizontal components of fluid velocity mineral particle density - fluid density

i -м filter coefficient in direction; vertical and horizontal components of fluid velocity mineral particle density - fluid density $\dot{u}_2, \dot{v}_1$ - filter coefficient in

direction; vertical and horizontal components of fluid velocity mineral particle density - fluid density; ρ_1 - filter coefficient in direction; vertical and horizontal components of fluid velocity mineral particle density – fluid density; ρ_2 filter coefficient in direction; vertical and horizontal components of fluid velocity mineral particle density - fluid density; $\dot{\theta}$ - volumetric strain rate $\dot{\theta}=\dot{\varepsilon}_x+\dot{\varepsilon}_y$; M_2 - fluid modulus; $\ddot{w}(t)$ and $\ddot{u}_0(t)$ - the vertical and horizontal components of the acceleration of the base during an earthquake.

As can be seen from system (1), in contrast to the single-phase theory, the selected element of the skeletal material is additionally affected by forces due to the pore pressure and interfacial interaction gradients, which are directly proportional to the difference in fluid and skeleton velocities, as well as inversely proportional to the filtration coefficients. The system of equations (1-3) is solved by the finite-difference method under the corresponding boundary and initial conditions both for the soil skeleton and for pore pressure.

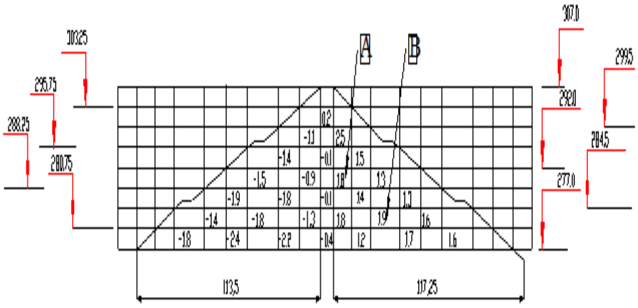
The boundary conditions on the pressure face in the case of taking into account the hydrostatic and hydrodynamic pressure of the liquid during seismic action are determined by the method proposed in [8]. In this paper, the relationship between stresses and deformations of the soil skeleton is taken into account according to the theory of an ideally elastoplastic body. The created methodology for calculating a soil dam as a two-phase medium, in contrast to the standard one, allows to take into account:

a) alternating change in the acceleration of the base, as a result of which the change in the response of the dam in the form of horizontal, vertical, tangential stresses, pore pressure, stability coefficient, vertical and horizontal displacements at each point of the dam at each time point of solving the problem;
b) the duration of the earthquake;
c) the ratio of the natural frequencies of oscillations of the dam and the base;
d) the phase difference of the skeleton of the soil and fluid;
e) the transition process, i.e. the ability to identify a resonant state;
f) the elastic properties of the soil skeleton in each zone of an inhomogeneous dam, elastic and changing at each moment of solving the problem.

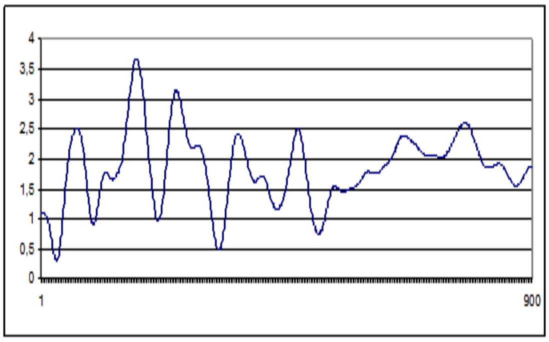
4. Conclusion

Fig. (1-3) shows the results of the calculation of tangential stresses in a soil dam. The seismic effect is given by the recording of the accelerogram of the Gazli earthquake lasting about 9 seconds. The results show that this dam does not fall into a resonant state with a given seismic effect, since already at 9 sec the dam assumed an almost stable state. This fact is the main assessment of the overall stability of the dam. Peak loads in the dam during an earthquake act for a short period of time, and if during this time the dam does not fall into a resonant state, then undamped oscillations do not occur. An assessment of the local stability of the slope points is checked on the basis of an analysis of the ratio of horizontal, vertical, tangential stresses and pore pressure of water.

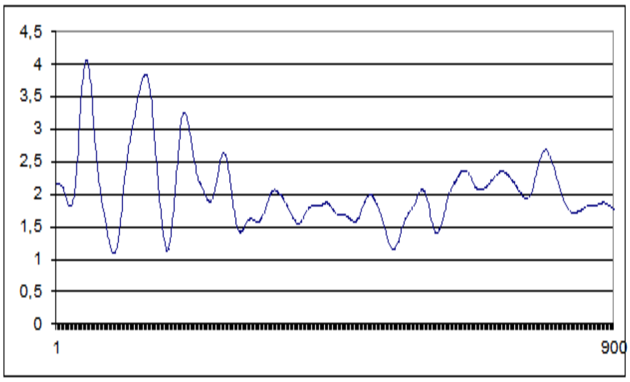
During an earthquake in the soil, an alternating change of the compaction and loosening process occurs. Soil is a self-healing material within certain load limits. The results show that already at 9 sec the dam assumed an almost stable state. Horizontal and vertical stresses over the entire cross section are compressive, while tangent stresses have small tensile stresses at the bottom face (stresses are given in t / m ^ 2). The program for calculating concrete dams was used to justify the dams of the Kurpsayskaya and Tashkumyrskaya HPPs on the Naryn River. The computer program for the soil dam was used to justify the dam projects in Ferghana, Syrdarya and Surkhandarya regions.



Pic. 1. Tangential stresses from static and dynamic effects at 9 sec.



Pic. 2. Time changes over 9 sec of shear stress at point A



Pic. 3. Changes in time over 9 seconds of shear stress at point V.

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