VIBRATIONS OF EARTH DAMS DURING EARTHQUAKES

by

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SYNOPSIS

Methods and results of field investigations on earth dam vibrations during weak earthquakes ($M<6$, Δ up to 250 km) are given. For this dam attempts were made to determine a dynamic model of an earth construction on the basis of investigation of amplitude spectra of dam and dam foot vibrations during earthquakes.

TERMS

$|F(f)|$ - Fourier's amplitude spectra;

$A(f)$ - conventional " spectra ";

f - frequency; $\omega = 2\pi f$ - circular frequency;

ρC - wave resistance, ρ - density and C - propagation velocity of seismic wave;

h_i - height of the block A_i with horizontal boundaries, z = 0 - free surface and $z = h_i$ - foot;

λ - wave length;

U - amplitude-frequency characteristic

INTRODICTION

Specific problems of seismic effects on dams were studied on a number of constructions. Construction of dams in seismic regions requires special seismic investigations directly on sites of their erection. First of all, these investigations are to be conducted to determine seismic hazards on the erection site, i.e. carrying out the detailed seismic zoning[1-4].

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The overall dimensions of large dams constructed from local fill materials, are of the some order of magnitude as the lengths of the seismic waves. Here, seismic effect is not uniform in plan and on height. Instrumental observations should be carried out on the existing dams to obtain physical description of the process and reveal its regularities.

Moreover, in designing a high dam from local fill materials, data on vibration frequencies at the foot of projecting construction are necessary.

OBSERVATIONS

Displacements on free surface of the dam and the foot were recorded simultaneously at several points. At the master stations three components were recorded: transverse (x), longitudinal (y) along the dam axis and vertical (z).

The ground observations cannot give complete data on wave fields formed in the dam body and on interaction of the dam with bedrocks. They should be carried out in combination with observations at the internal points of the medium. Due to absense of data on dam body vibrations, interpretation of ground observations data at separate stations (besides, on the dry surface only) should be considered as preliminary.

FREQUENCY ANALYSIS

During earthquakes, vibrations of the foundation and dam reaction are non-stationary processes (Fig.I) but in a known time interval and with approximation these processes can be considered as stationary ones. The vibration frequency composition may be considered as stationary one within the limits of the each such interval. This assumption permits to consider the recordings of vibrations as the sum of several stationary processes for which a special method has been designed.

To determine the resonance frequencies of the dam and spectrum features of disturbance and reaction for the given frequencies, Furier's amplitude spectra $|F(f)|$ were calculated of recording y(t) preset at time interval $t_1 \leq t \leq t_2 = t_1 + n\Delta t$ at the points $y (t_1 + k\Delta t)$ at $k = 0, I, 2 \ldots\ldots\ldots, n$ [5].

$$|F(f)| = \sqrt{[Re\,F(f)]^2 + [Im\,F(f)]^2}\,;$$

$$Re\,F(f) = \int_{t_1}^{t_2} y(t) \cos 2\pi f t\, dt\,; \quad Im\,F(f) = -\int_{t_1}^{t_2} y(t) \sin 2\pi f t\, dt$$

The dam was considered as a linear vibrating system stationary in the finite time interval $t_1 \le t \le t_2$. Outside this interval y(t) was supposed to be equal to zero.

Spectra of intervals with length from 7 to 2I sec were calculated. The spectrum sections were selected so as not to separate phases of similar waves. Basically those sections of recording were analysed which were formed by the shear and surface waves, as a rule, carrying on the maximum energy of the earthquake.

Apart from spectra $|F|$ conventional " spectra " A (Fig.2) were plotted and the last ones were calculated through statiatical treatment of amplitudesand periods visible on recording. Their plotting is based on the relationship:

$$|F(f,t)|_{f=f_0} = an\frac{T}{4}$$

for the current spectrum of sinusoid $y(t) = a \sin 2\pi f_0 t$ which at the frequency $f = f_0$ linearly depends on amplitude a, period $T = I/f$ and number n of the semicycles of the sinusoidal section under consideration.

THEORETICAL ASSUMPTIONS

Complex vibrations of " dam - underlying stratum " system have an interference nature (Fig.I). The interfering waves are produced due to superpositioning of waves which are multiply reflected inside the system.

For the purpose of preliminary interpretation of the spectra , let us assume that the interfering waves are standing waves. This means that some or other part of the dam or the foot is replaced by an equivalent homogeneous and one dimensional ideally elastic model of height h with effective velocity of vertical (along z axis) propagation of disturbance c . The model has the upper boundary z = 0 is free of stresses and the lower boundary z = h is subjected to stresses ($\rho_1 c_1 \ll \rho_0 c_0$ where $\rho_1 c_1$ and $\rho_0 c_0$ are wave and embedment resistance respectively). Free vibrations of this model are described by the wave equation:

$$\frac{\partial^2 u}{\partial t^2} = c_1^2 \frac{\partial^2 u}{\partial z^2} \qquad \text{(I)}$$

and have a frequency

$$f_n = \frac{c_1}{4h} \quad (2n - I); \; n = I,2, \; \dots\dots\dots$$

In longitudinal waves: $c_1 = \sqrt{E/\rho}$ - longitudinal wave propagation velocity in the bar; it is less than a similar velocity in the plate $c_1 = \sqrt{E/\rho(I-\mu^2)}$ and

$c = \sqrt{E\,(I-\mu)\,/\rho\,(I+\mu)(I-2\mu)}$ in the unlimited medium, where ρ - density, E - Young's modulus, μ - Poisson's coefficient; $U = U_z$ - longitudinal displacement.

In torsional waves : $U = \varphi$ - twist angle, $c_1 = \sqrt{K/\rho I}$ - propagation velocity of torsional vibrations along the bar, K - torsional rigidity, $I = \int (x^2 + y^2)\, dS$ - moment of inertia of profile with respect to center of inertia, dS - profile element.

In shear waves[I]: $U = U_x$ (or U_y) - displacement along axis x (or y), $c_1 = \sqrt{\alpha G/\rho}$ - propagation velocity of shift vibrations along the bar ; α - coefficient of profile shape. For the shift vibrations in the block and in the plane of the plate $\alpha = I$.

Let us assume that the dam part is approximated by the said one dimensional model. For such a model formulas for shifts in S and P waves have been obtained, which sometimes carry the main energy of vibrations with an account of damping when the waves are incident obliquely and vertical propagation of waves take place [6]. The incident wave was taken as stationary and harmonic one, i.e. damping at the foot was not taken into account. Even in this simplest case, the formulas for the displacements of model are very complicated.

Simpler formulas were deduced for the case of vertical propagation of a flat harmonic wave P with a frequency ω and duration τ without damping effect [7]. For the purpose of comparison with other waves the amplitude of the incident wave is taken to be I. In multiple reflections of refracted waves from boundaries z = 0 and z = h, displacements U_z and deformations $\partial u_z / \partial z$ arise in the model which at a certain depth $0 \leq z \leq h$ can be expressed as follows

$$U_z = 2K_1 \frac{1 - K_0^n e^{-i2\omega n\tau}}{1 - K_0 e^{-i2\omega\tau}} \cos \omega \frac{z}{c_1} e^{i\omega(t-\tau)} \quad (2)$$

I) In seismic resistance theory shift deformations x and y along the main axes of inertia of construction are independent. Thus we can consider them separately. In field theory the shift wave is an elliptically polarized wave which may be considered as super positioning of two linearly polarized waves.

$$\frac{\partial U_z}{\partial z} = -\frac{2K_1\omega}{c_1}\sin\omega\frac{z}{c_1}\,\frac{1-K_0^n e^{-i2\omega n\tau}}{1-K_0 e^{-i2\omega\tau}}\,e^{i\omega(t-\tau)} \tag{3}$$

where $K_I = \dfrac{2\rho_0 c_0}{\rho_0 c_0 + \rho_1 c_1}$ and $K_0 = \dfrac{\rho_0 c_0 - \rho_1 c_1}{\rho_0 c_0 + \rho_1 c_1}$

are respectively refraction and reflection coefficients of incident wave at the boundary $z = h$.

The formula (2) shows that an interfering wave in the one-dimensional and homogeneous ideally elastic medium is a standing wave with planes where the displacements reach extremal values and joint surfaces where displacements are equal to zero. Positions of these surfaces can be determined from the conditions

$$z = \frac{n\lambda_1}{2}\ ; \quad z = \frac{(2n+1)\lambda_1}{4}\ ; \quad n = 0, I, 2 \ldots\ldots \tag{4}$$

where $\lambda_1 = \dfrac{2\pi c_1}{\omega}$ - length of monochromatic plane wave.

For deformations maximum shift surfaces are considered as joint surfaces and visa versa. From (3) it is clear that in different soils velocity of deformations rate at depths for one and the same wave frequency depends on propagation velocity C_1. The lesser C_1 the quicker grows the deformation. Thus, at the same wave frequency in loose soils surfaces of maximum deformations are closer to the free surface than it is in solid grounds.

When $4h = (2n - I)\lambda$; $n = I, 2 \ldots\ldots$ (5)
the resonance amplitude at free surface $z = 0$ is equal to

$$\max U_z = 2K_1\frac{1-|K_0|^n}{1-K_0} \tag{6}$$

i.e. at the given n the higher is the resonance amplitude the closer $|K_0|$ is to I, but $|K_0| \longrightarrow I$, when $\rho_0 c_0 \gg \rho_1 c_1$. Thus, in some cases the resonance effect on the earth dam will be greater if the last is erected on the rocky grounds and lesser if it is built on layer of alluvium. This effect depends on soils selected for the foot and the dam, the dam height and thickness of the bedrock etc.

For the same one-dimensional ideally elastic model, displacement on the free surface z = 0 (amplitude of the incident wave is assumed as I) is equal to :

$$U = re^{i\nu}$$

where $r = 2\left[\cos^2\beta + \frac{m_1^2}{m_o^2}\sin^2\beta\right.$; $tg\nu = -\frac{m_1}{m_o} tg\beta$; (7)

$m_1 = \rho_1 c_{p1}$; $m_o = \rho_o c_{po}$; $\beta = \frac{\omega h}{c_{p1}} = 2\pi\frac{h}{\lambda_{p1}}$ for monochromatic wave P propagating vertically;

$m_1 = \rho_1 c_{s1} \sin e_1$, $m_o = \rho_o c_{so} \sin e_o$ and $\beta = 2\pi\frac{h}{\lambda_{s1}} \sin e_1$

for monochromatic direct wave SH incident at the foot z = h at angle e_o and refracted into the dam body at an angle e_1. Under conditions (5) of at β a multiple of $\pi/2$, r attains the maximum 2 m_o/m_1 while at β a multiple of π, or at $2h = n\lambda_1$, r = 2. In these cases the frequency of the model characteristics is a periodic function. As $\beta \to 0$ or $h/\lambda_1 \to 0$, $r \to 2$, i.e. the amplitude at the top of dam practically does not differ from the amplitude on the free surface of the foundation.

RESULTS AND DISCUSSION

The shape of frequency characteristics of the " dam - underlying stratum " system depends on geometric and physical parameters : height of that or another part of dam, gradient angle of dam slopes, dimensions of dam horizontal surfaces (the top of dam, berms), shape of canyon, water level in storage of water and, consequently, position of depression surface ; thickness of bedrocks; density of material used in the erection of the dam and foot; velocity of propagation and damping of seismic waves in the dam body and the bedrocks and their spacial distribution. For example, by the amplitude-frequency characteristic of the dam for travelling transverse waves $U_s(f)$ we mean the ratio of the amplitude spectrum $|F(f)|$ of wave SH recorded on the dam surface (outlet) to the amplitude spectrum $F_o(f)$ of wave SH recorded on the dam foot (inlet).

$$U_s(f) = \frac{|F(f)|}{|F_o(f)|} = \eta(f)\,\Psi(f)\,\xi(f)\frac{|S(f)|_{outleet}}{|S(f)|_{inleet}}$$

Where $\eta(f)$, $\psi(f)$, $\xi(f)$ - dam frequency characteristics for travelling waves SH, stimulated respectively by: heterogeneity (gradience, stratification) of velocity section $C_s(z)$ of the dam, absorption of waves in the dam; the effect of two strongly reflected boundaries (day surface and dam foot) which cause proper vibrations in the dam; $|S(f)|_{out}$ and $S(f)_{inpt}$ spectrum characteristics due to the contact of seismic detectors, located at the inlet and outlet of the dam, with the surroundings.

The amplitude-frequency characteristic of the dam for travelling longitudinal waves $U_p(f)$ depends not only on similar parameters for that $U_s(f)$ but also on water level in the storage of water and the position of depression surface inside the dam. This surface is a strong boundary for longitudinal waves and a week one for transverse waves. Moreover, when the P and SV waves are obliquely incident exchange waves originate and the frequency characteristics of the dam complicate for oblique incidence of these waves as compared with waves SH which do not disperse their energy at any angle of incidence on the formation of exchange waves.

The dam characteristics U (f) for the travelling waves oscillate with an interval of oscillation:

$$f_n - f_{n-1} = \frac{\bar{c}_i}{2h_i}$$

where h_i - height of some block A (Fig.4) with plane-parallel reflecting boundaries (foot and free surface), $\bar{c}_i$ - effective velocity of the bodily wave in the block A.

During incidence of some or other waves the reaction of the block of dam (A) depends on relationship between the spectrum $|F_o(f)|$ of these waves and the frequency characteristic $U_i(f)$ of the block for the same waves. Depending on this relationship, the block A can serve both as the filter of lower or upper frequencies and as a resonance filter.

When passing through the dam body comparatively h.f. (short) waves with prevailing frequency $f_o > f_{1i}$ or with prevailing length $\lambda_i < 4h_i$ (where F_{1i} - the main frequency of natural vibrations of the block A) undergo maximum changes. In this case length of vibrations increases, new extrema appear, the maxima of h.f. wave spectra shifts into the low-frequency region, spectrum h.f. components are damped. For these waves the dam acts as a l.f. filter. If $f_o \to f_{1i}$ (or $\lambda_i \to 4h_i$) the incident waves passing through the dam body are intensified due to interference with multiple waves inside the dam. The duration of vibrations becomes greater, while frequency f does not change. For these waves the dam acts as a resonance filter. When low-frequency waves with $f_0 < f_{1i}$ (or $\lambda_i > 4h_i$) pass, the duration of vibrations becomes lesser while their prevailing frequeicies and spectrum maxima are shifted into higher frequency region. For these waves the dam acts as the filter of upper frequency.

Intensive increase in amplitude of vibrations at the crest (up to 7 times) in comparison with the amplitude at the foundation is not only due to the main standing wave , but also due to the increase in density of seismic energy of source caused by profile compression, reflection of waves from the free surface and the formation of difracted waves at zones of intersection of the planes.

On the block A in the group of intensive vibrations of the bedding course we observe both resonance vibrations of the block and the effect of other blocks or the foot on this block-forced vibrations of the block A_i (Fig.3). Theses vibrations alternate in time or occure simultaneously. In the latter case vibrations are superposed.

BIBLIOGRAPHY

I. Tischenko V.G., Lyamzina G.A. Vibrations of Stone-Ripraped Dams during Seismic Excitation. Proceedings Institute of Earths Physics, Academy of Sciences of the USSR, No.I7 (I84), I96I.

2. Lavrov I.M. Regularities of Vibrations of Earth Construction during Earthquake. " Vibrations of Earth Dams ", "Nauka", Moscow, I967.

3. Lyamzina G.A. Vibrations of Earth Dam During Explosions. "Vibrarions of Earth Dams"."Nauka", Moscow, I967.

4. Lavrov I.M. Spectral features of Vibrations of Earth Construction During Earthquakes. "Vibrations of Earth Dams"."Nauka", Moscow, I967.

5. Naimark B.M. et.al. Approximate Calculation of Spectra of Seismic Vibrations. 2Comruting Seismology". Vol.3, "Nauka", Moscow, I967.

6. Savarensky E.F. Elementary Estimation of Layer Effect on Vibrations of Earth Surface. Acc.Sci., USSR, Ser.Geophys., No.IO, I959.

7. Kats A.Z. Estimate of Dynamic Effects on Soil Caused by Seismic Vibrations of Rigid Construction. Proceedings Institute of Earth Physics, Acc.Sci.USSR, No.22(I89), Moscow, I962.

8. Medvedev S.V., Lavrov I.M. Some Peculiarities of Vibrations of Earth Dams During Seismic Effects. "Construction and Architecture of Uzbekistan", No.IO, I966.

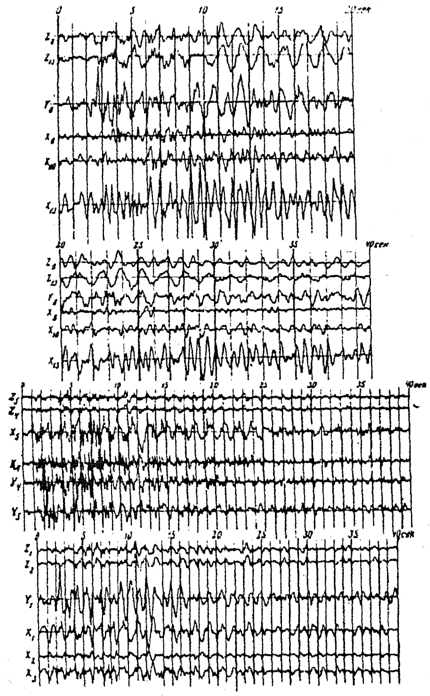

Fig.I. Recording components of Earthquake on the Dam and Foot; transverse (X) and longitudinally (Y) along the dam axis as well as vertically (Z) at different points (characteristics of channel are not identical). The lower index indicates for the observation point: I - observation point on sandstone; 8 - point on the bank; I3 - point on the dam crest; other points on the dam.

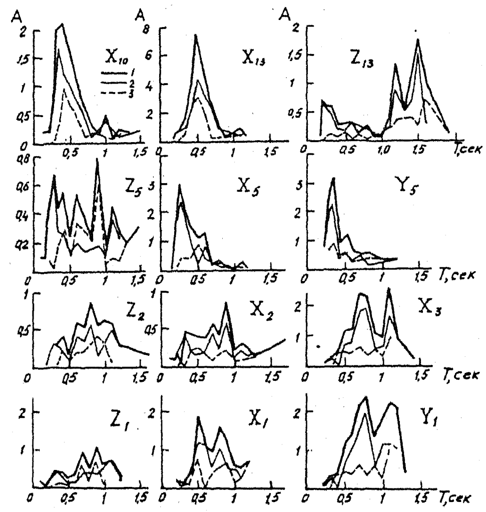

Fig.2. Spectra of Maximum Vibrations during Earthquake No.5 obtained by manual processing of seismograms - conventional spectra. I. - spectrum of the entire recording; 2 - spectrum of the first half of the recording;, 3 - spectrum of the second half of recording.

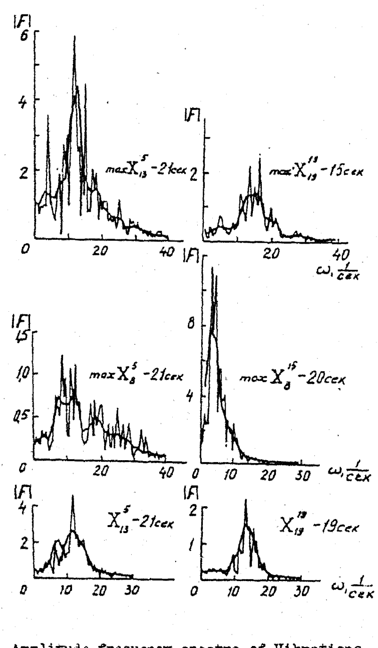

Fig.3. Amplitude-frequency spectra of Vibrations at different points of Earth Dam. The lower index indicates for the observation point, the upper one - for No. of earthquake, duration of the fragment of the recording is indicated in sec.

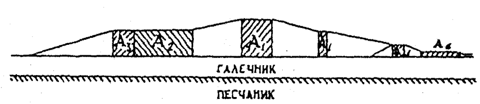

Fig.4. Dynamic Model of Earth Dam consisting of active (shaded) and passive (unshaded) blocks