11 WCEE

Published by Elsevier Science Ltd 1996
Paper No. 922. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

HIGH EARTH DAMS: SEISMIC LOADS, RELIABILITY AND DESIGN

V.M. LYATKHER and N.I. FROLOVA

Clean Energy Co.LTD, USA, P.O.Box 21361, Cleveland Hts, Ohio 44121, USA;
Research and Coordination Center for Seismology and Engineering,
Russian Acad. of Sci., Nikoloyamskaya str.51, Moscow, 109004, Russia

ABSTRACT

Two statistical approaches to seismic load assignment are presented. A procedure is proposed to estimate the real earthquake resistance of dams, to find economical ways of providing necessary reliability of dams under the conditions of seismological input data uncertainties. The proposed methods of estimation and control of earth dam reliability allow one to obtain the most economically effective design of dams, which is safe from extreme risk and unjustified reserve.

KEYWORDS

Seismic load assignment; earthquake resistance of earth dams.

INTRODUCTION

Development and application of the methods for assessing the earthquake resistance of high dams must rest on the knowledge about the seismic process, which is still not clearly understood and is rather complicated for investigations from the technical point of view. One special feature should be mentioned: however large an earthquake has been observed in the study area, it is always possible that a larger event may occur there. The crux of the matter is how often (with what probability) such events may occur and what structure should be designed in order to withstand such an event with minimal additional expenses and to provide safety of the pressure front in any form to avoid the breakdown wave causing the losses, which may by far exceed the cost of the hydroelectric power structure itself.

Another specific feature of the high dam earthquake resistance problem is the necessity to take into account the properties of real dams and to reveal the real reserve of bearing capacity of a structure when computing for a rare large seismic load.

It should be borne in mind that even the most advanced methods of computation of dam reliability and, in particurlar, their earthquake resistance, give rather uncertain results. This is due to the variability of seismic loads and dam material, and uncertainty of the static state of the dam before a large earthquake. Thus, the estimation of the dam earthquake resistance is in fact a problem in reliability theory. Besides, when the level of dam reliability (earthquake resistance) has been determined, another question arises before the engineer or project director, namely, what level of reliability should be taken, what probability of dam failure is acceptable and under what conditions. It is rather often that the correct decision (choice of optimal strategy) is based on intuition, although the methods of operations theory should be applied.

SEISMIC LOADS; CHOICE OF LOADS TAKING INTO ACCOUNT THE STRUCTURE FEATURES

Two statistical approaches for seismic load assignment are proposed. The first procedure requires that all available instrumental data should be classified according to:

- macroseismic intensity;
- soil conditions at the site; or
- earthquake magnitude;
- hypo- and epicentral distance;
- soil conditions at the site.

The classified data are statistically analyzed, the first two central and correlation moments are computed. When these data and that about the seismicity of the area are available, the problem of seismic load forecast is formulated as follows: find the load which is the most dangerous for the designed facility, and which corresponds to a definite probability of this load exceedance within a definite time interval. The general method for solving this problem was elaborated by the authors in (Lyatkher *et al.*, 1977, Lyatkher *et al.*, 1980, Frolova, 1980, Lyatkher *et al*, 1983). Here, an example is given of comparative seismic load assignment for similar dams located in the areas where earthquakes of the same intensity are possible, but with different repeat times T_I. We assume that the dam is not very high and its lower natural frequencies are higher than the predominant frequencies of the dangerous earthquake spectrum (greater than 5-10 Hz). In this case the seismic load may be characterized by one parameter - maximum acceleration of the dam base. In other cases several parameters, for instance, the Fourier spectra of possible ground motions or a set of possible accelerograms, velocigrams or seismograms, should be used.

It is shown (Lyatkher *et al,* 1980) that the probability that a parameter does not exceed for time interval T given value z is determined by the following approximate relation:

$$\int 1 - P(\zeta, T) \approx T \sum_{I=7}^{9} \frac{1 - F_I(\zeta)}{T_I} \tag{1}$$

where F_I is the distribution function of z for earthquakes with intensity I; T_I is the average time period between earthquakes with intensity I.

Usually the earthquakes with one definite intensity I^* give the main contribution to the right-hand part of (1). The change of the average time interval between earthquakes with intensity I^* from T_1 to T_2 results in variation of the design value of maximum acceleration a from a_{1_I} to a_2 according to the law:

$$(a_1 / a_2) \approx (T_2 / T_1)^{1/\varphi} \tag{2}$$

here the parameter φ changes slightly when the probability P changes, while remaining within (5.0, 7.0).

In this method the correlation between various parameters, for instance, between Fourier amplitude spectra for different frequencies, is taken into account. It was shown (Lyatkher *et al*, 1977) that, if one of the parameters reaches a rare extreme value, the other parameters should have average values, but not their extreme ones. Fig. 1 shows how the design Fourier spectra should be chosen for the structures with a natural frequency of about 1Hz (line 1) and about 4 Hz (line 2) taking into account the data on correlation coefficients between Fourier spectra for different frequencies (fig. 2).

The other statistical approach to seismic load assignment is based on a simple physical model of the seismic source, which is represented as a dislocation propogating along a definite path with varying velocity. The dislocation releases the shear stress on plane areas which are oriented along its path, supposing a contrast in shear strain on these areas (finite displacements of dislocation sides relative to each other), and the normal strain and normal (compressive) stresses to be continuous on them. If the normal stresses prove to be tensile, then the dislocation is assumed to be opening, and the normal stress is taken to be equal to 0.

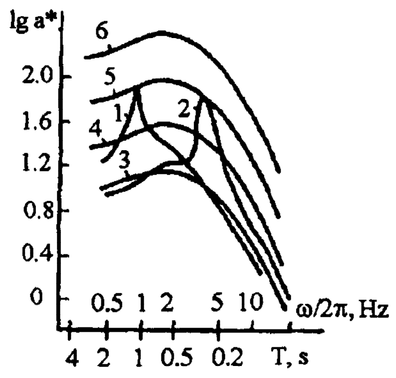

Fig. 1. Calculated spectra of intensity 7 seismic load with probability P=0.977 for structures with lower natural frequencies: 1 and 2 - 1 and 4 Hz; 3-6 - "envelope of spectra" with probability P=0.5; 0.84; 0.977; 0.999 respectively

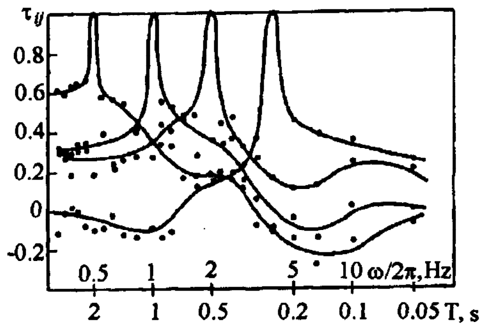

Fig. 2. Correlation between logarithms of Fourier spectra for different frequencies, averaged for earthquakes of various intensities

In this approach the parameters are the velocity of dislocation tip CD (a random function of time and coordinates), the stress released along the path of dislocation propagation, mechanical characteristics of the area of dislocation propagation and the whole area of propagation of seismic waves generated by the dislocation. Here it is important to take into account the inhomogeneities of the geological medium, and to make a proper choice of the scale for their averaging. A detailed geological description of the future earthquake source zone is important for the choice of the path of dislocation propagation and modelling of rupture velocity.

Based on these physical concepts, we obtained that the dislocation velocity is directly related to space inhomogeneities of the medium along the path of dislocation and average rupture velocity CD. Systematic computations were carried out according to this procedure (Lyatkher *et al.,* 1986). In particular, the relation between the average displacement of dislocation sides ΔU_0 and the value of released stress τ_0 was established:

$$\Delta U_0 = \xi \tau_0 L_0 / G \tag{3}$$

where L_0 is dislocation length, τ_0 is stress drop, G is shear modulus, ξ is a coefficient depending on dislocation orientation relative to the Earth's surface and ranging between 0.46 and 0.50. The calculated plots of the ground velocity variations versus time, as well as versus dislocation orientation relative to the Earth's surface, and the envelope of Fourier spectra of the design motion are very similar to the results of measurements during real large earthquakes. As an example, figure 3 shows the variations of ground motion velocities for the opposite sides of the dislocation (lines 1 and 2) and on the Earth's surface above the middle part of the seismic source at the depth of the source equal to its length and for horizontal propagation of the dislocation with constant velocity equal to CD at the source and zero outside the source.

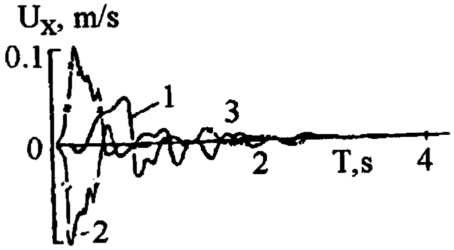

Fig. 3. Variations of ground motion velocities for sides of the dislocation: lines 1 and 2

This model of the seismic source allows one to generate the sets of seismic loads corresponding to fixed statistical characteristics of the medium structure, seismic wave propogation, peculiarities of the relief and geological structure of the area where the facility under investigation is located. These proposed procedures were used to calculate the seismic loads for the high Nurek dam with annual probability 10^{-4}.

With any procedure of seismic load assignment the obtained theoretical or analogue records of ground motion on the Earth's surface where the structure is located will be affected by the structure. The issue is analyzed in detail, and it is shown how the input data should be used when dealing with large or heavy structures (Lyatkher *et al.*, 1986, Lyatkher *et al.*, 1976). Only in the case of a rigid rock base and a small relative mass of the structure, we can practically disregard the seismic load distortion by the structure. In general, the procedure of seismic load assignment includes the choice of a theoretical surface which separates the structure and the massif of ground basement, within which a superposion of solutions may be assumed, and the identification of the stress drop and displacements on this surface, which are equal to their coseismic values in the case of no structure. If nonlinear processes (failure, plastic deformations) do not arise at the base, then it is advantageous to put the theoretical design surface on the boundary between the structure and the base. In this case the design stress drop is equal to zero.

EARTHQUAKE RESISTANCE OF DAMS

First of all it is necessary to find the dam outline after the earthquake, namely, to know the dam deformation during and after the earthquake in order to estimate the resistance of the structure. But this is not enough. It is important to know whether the dam can function properly (to keep water) for a long time as designed. In order to answer this question, the long-term deformations of the dam and changes in filtration through it should be forecast. Thus, the modern computations of earth dam resistance should include an analysis of this complex structure taking into account, at least, the following issues:

- non-linear relationship of load and deformation, which is seen, in particular, in the appearance of residual deformations after the disappearance of additional (seismic) loads;

-the presence of water-gas saturation of the dam material, filtration water variations in the dam;

- heterogeneity of the dam body due to its design (presence of anti-filtration elements, sighting galleries, steel reinforced members), as well as due to inevitable heterogeneity of the material stipulated by construction technology.

Methods and software for dam calculation that incorporate the above factors are available (Lyatkher *et al.*, 1976, Zaretskij *et al.*, 1983, Lyatkher *el al.*, 1986). The idea of these methods is simple: the dam material is represented as a two-phase continuum for which the combined equations, including the continuity equations (for each phase), the dynamic balance equations and equations of state for ground and water phases, are solved (numerically). The terms responsible for the phase interaction are naturally present in the equations of state. Models characterized by various levels of complexity differ mainly in the way of taking into account (or not taking into account) the convection and local inertia forces in the equations of state, in the form of equations of state for the material (here the distinctions may be essential), by representing the forces of phase interaction. In the more complete variant, the problem proves to be significantly non-linear, not allowing the superposition of solutions. In this case, in order to determine the stress-strain state of the dam it is necessary to compute all the processes starting from the stage of the dam construction taking into account the sequence, time period and technology of construction of its separate elements. The process of ground consolidation, depending on the above mentioned factors, affects the quasi-static state of the dam, which also depends on the regime of water level change in front of the dam. Thus, the uncertainty of seismic loads is emphasized by uncertainty of the dam state before the earthquake. The problem seems to be hopeless. The authors present the following proposal to solve the problem.

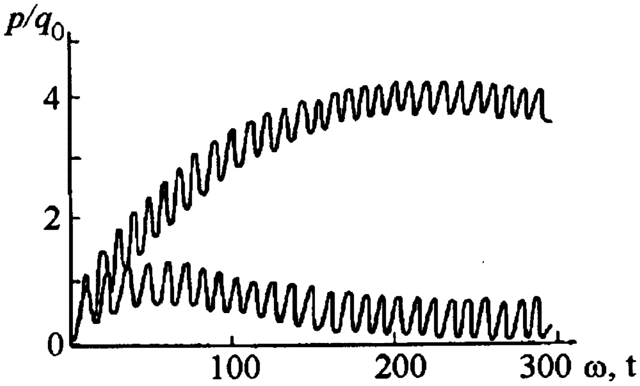

Fig. 4. Changes of excess pore pressure p with time under a periodic load with amplitude q_0 and frequency ω

1. Introduction of different time scales for the processes of quasi-static change of the dam and for rapid seismic processes. The expediency of such an approach is well illustrated by fig. 4, which shows the change of pore pressure in a water saturated soil layer affected by periodic loads with frequency ω on the top of the layer. The upper line corresponds to relatively high filtration resistance in the ground (the pore pressure does not have enough time to disperse and the process will definitely result in soil liquefaction), the lower line corresponds to the relative filtration coefficient 10 times as large. Liquefaction is hardly possible in such a material. Figure 5 shows the residual plastic deformations (a) of the Lower San Fernando dam and the process of pore pressure change (b) at the point A of this dam where the 1971 earthquake records were used

as seismic loads, computed with the authors' participation. The smooth change of average pressure due to seismic consolidation of soil and sharp peaks of pressure due to numerous transmissions of seismic waves is distinctly observed. The authors think that the failure of the real upper dam slope has been due not to peaks of "fast pressure", but to a smooth increase of vibroconsolidation and large plastic deformations. Division of time scales allows the dynamic (seismic) component of the process to be considered separately, solving a linearized problem with effective application of random process theory taking into account the seismic load variability.

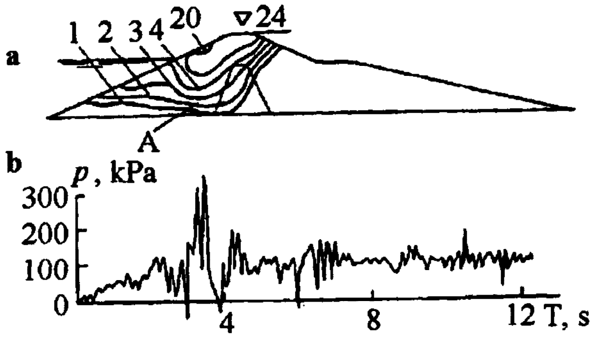

Fig. 5. Estimation of earthquake resistance of Lower San Fernando dam;
a - seismic residual deformations (%) b - dynamic pore pressures at the point A

2. Consideration of the fictitious (effective?) one-phase medium, whose movements agree well with the real situation everywhere, besides some "boundary" zones. These boundary zones reflect the real boundary conditions for the ground skeleton and pore liquid and may be rather diverse, but the equation for a one-phase medium requires their definite agreement. For instance, the load on the ground skeleton may act on the surface of a water saturated ground layer (line I in fig. 6) in the absence of loading on the liquid (drained layer), the movement of the ground skeleton may be given (lines II in fig. 6), either movement or pressure in liquid may be given (lines III). In boundary zones the conditions of ground skeleton movement and liquid movement agree, but in the main massif the processes take place as in an equilalent one-phase medium.

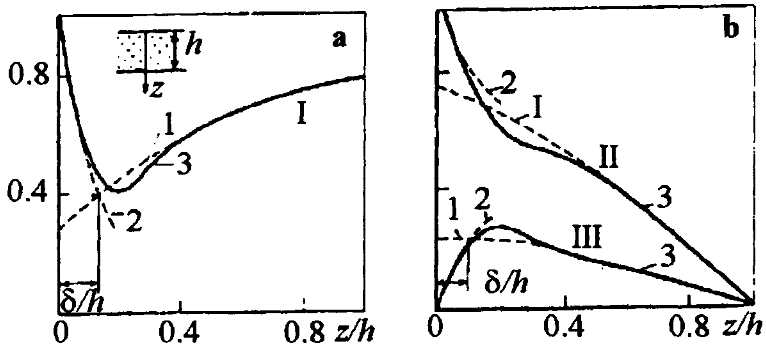

Fig. 6. Comparison of approximate and exact values of stresses (a) and velocities of movement of the water saturated ground skeleton (b)

3. When the residual deformations in dams after earthquakes are computed with the help of any method, the engineer should always answer the question: whether these deformations are dangerous or not. Here two criteria are possible:

- to estimate the permissible relative deformations in terms of the absolute value, by comparing with corresponding "critical" values; or

- to look for the situation where the slow movements in the dam do not become stable. For instance, fig. 5 shows that the slope in the failed dam is sliding along the surface with residual deformation of 5%. These conditions should be considered as inadmissible when checking the other dams.

Using the other criterion of the dam resistance, the seismic load increases until the quasi-static problem can no longer be solved. For the Nurek dam it was realized at maximum acceleration of analogous accelerogram equal to 1.28g. If one or both criteria show that the dam is not resistant, then it is desirable (necessary?) to increase its resistance.

ENHANCING THE EARTHQUAKE RESISTANCE OF EARTH DAMS

The drastic ways to icrease the resistance of earth dams are: 1) construction of a flexible water-proof shield to exclude soil liquefaction and 2) reinforcement of dams.

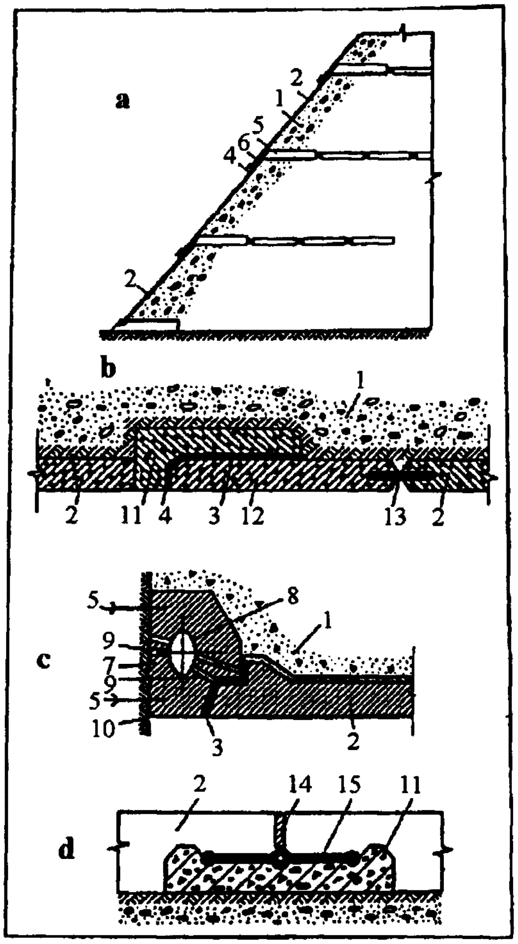

Fig. 7. Structural designs of dams with shields; a - suspended shield; b - deformation joint with compensator; c - scheme of bank support; d - scheme of inseparated plate of shield

The use of a flexible shield raises the problem of reliability of this shield, besides, impounding limitations appear. These demerits may be excluded by using a multisectional suspended shield (fig. 7a). The reliability of joints between the shield plates is increased by using linear and angular compensators (fig. 7b). Special attention is paid to junction of the shield and foundation, for instance, according to the scheme (fig. 7c), and its junction with sides (fig. 7d).

The principle of reinforcement of earth dams is known to the engineers for a long time. The first course of lectures on hydroelectric power structures, published in Russia by the general Neelov D.D. more than 100 years ago, includes a description of mill-ponds with flexible elements - fascines made of brushwoods, beams and so on. For the last 40 years this direction of investigation was regenerated with application of mainly fine armature grids, which are placed horizontally within small distances along height. A new step was made in this direction when constructing the high Nurek dam (fig. 8), where armoured antiseismic belts made of reinforced elements were put in upper 80 m of the dam. The upper tier of the antiseimic belt is placed along the whole width of the dam starting from the upper slope down to the lower one. Within the dam core the belt rises to the level of 295 m in order to keep the dam core 2.5 m higher than NHWL after the dam subsidence and exclude the overflow of water.

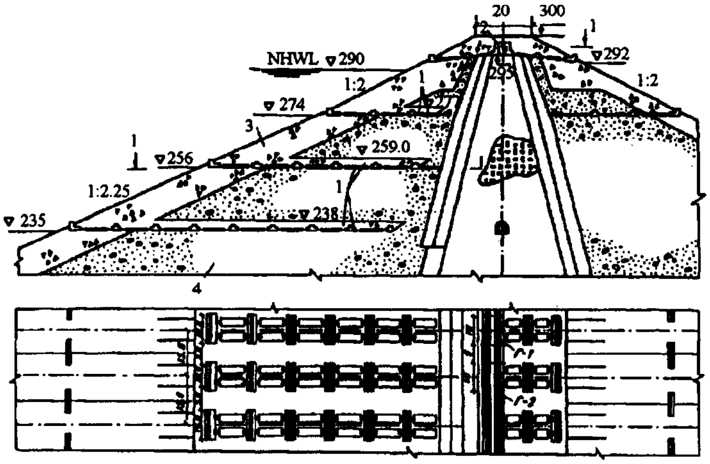

Fig. 8. Cross-section of the Nurek dam: 1 - antiseismic belts; 2 - sighting gallery for measurements; 3 - stone additional load of upper slope; 4 - support prism made of gravel soil

CONCLUSIONS

The efficiency of the armoured scheme adopted was confirmed by testing a physical model of scale 1:400 using centrifugal modelling, as well as by series of computations (fig. 9) and subsequent natural observations started in 1978 and continued up to now. The stress measurements in the reinforced elements of seismic belts showed that the main changes are connected with static deformations of large-fragment material of the dam prisms. The dam experienced several earthquakes with intensity up to 6 (MSK scale) during the period of observation. No stress changes were observed after these earthquakes.

Dam reinforcement with the help of seismic belts is particularly effective in combination with the shield use. Similar decisions applied to high dams may decrease the cost by 30% with simultanious increase of the dam reliability. The decrease of the dam sizes (in some cases by as much as 45%) may allow one to make shorter water-throw tunnels skirting the dam and to change significantly the esembling of the joint, thus obtaining a large economic effect.

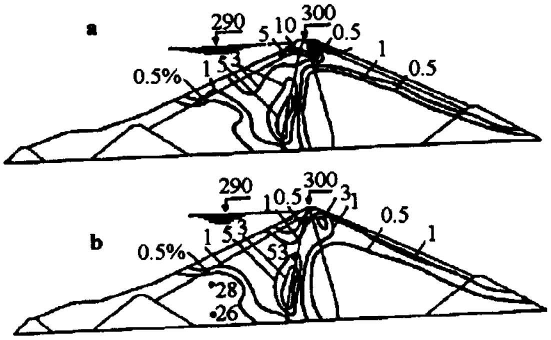

Fig. 9. Increase of residual ground deformations (%) in the Nurek dam: a - dam without strengthening b - dam with antiseismic belts

REFERENCES

Dynamics of continuous media in design of hydrotechnical structures (1976). (V.M. Lyatkher and Yu.S. Yakovlev, Ed.), Moscow, Energiya.

Frolova, N.I. (1980). Statistical characteristics of seismic effects. In: *Dynamics and earthquake resistance of buildings and structures* (Dushanbe, Donish), 113-128.

Lyatkher, V.M. and N.I. Frolova (1977). Statistical calculations of the spectra of seismic effects. *Izvestiya, Earth Physics,* vol.13, No.8, 543-553.

Lyatkher, V.M. and N.I. Frolova (1980). Probabilistic assignment of seismic loads. *Izvestiya, Earth Physics*, No.7, 35-47.

Lyatkher, V.M. and N.I. Frolova (1980). Statistical analysis of the response spectra of strong earthquakes and the forecast of seismic forces in complex systems. In: *Seismic forces acting on hydraulic and power structures* (Moscow, Nauka), 16-40.

Lyatkher, V.M. and N.I. Frolova (1983). Statistical prediction of seismic effects with the utilization of a shakeability map. *Izvestiya, Earth Physics,* vol.19, No.3, 231-236.

Lyatkher, V.M. and I.N. Ivazhenko (1986). Earthquake resistance of earth dams. Moscow, Nauka.

Seismic Zonation of the USSR territory (1980). (V.I.Bune and G.P.Gorshkov, Ed.), Moscow, Nauka.

Zaretskij, Yu.K. and V.N. Lombardo (1983). Statics and dynamics of earth dams. Moscow, Energoatomizdat.