SIMPLIFIED EARTHQUAKE ANALYSIS OF GRAVITY DAM-FOUNDATION SYSTEM

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SUMMARY

A method for approximating structure-foundation interaction effects has been developed and implemented into a simplified earthquake analysis of concrete gravity dams. This method is equivalent to a response spectrum analysis taking into account only the contributions of the fundamental mode. Both hydrodynamic and foundation interaction effects are included. Typical stiffness distributions are obtained and it is shown that these stiffness distributions can be used to model soil-structure interaction effects for general concrete gravity dams having a typical triangular cross section. With these implementations, the simplified earthquake analysis procedure provides an efficient and economic tool for preliminary design purposes.

INTRODUCTION

Traditionally concrete gravity dams have been analysed and designed by a procedure suggested by Westergaard (Ref. 1) in which the earthquake forces consisting of inertia and hydrodynamic forces are treated as static ones combined with hydrostatic water pressure, gravity loads, etc.

Up to date a considerable number of studies on the dynamic analysis of dams have been carried out using the finite element method. In some of these studies, hydrodynamic interaction taking into account the compressibility of water in the reservoir (Refs. 2,3,4), and structure-foundation interaction (Refs. 5,6) have been included in the dynamic analysis. From such studies, it has become apparent that a dynamic analysis must be used in the final design of large dams, especially in zones of high seismic activity, and that hydrodynamic interaction due to dam flexibility is significant and compressibility of water cannot be ignored. It has also been mentioned that a rational earthquake analysis of dams should include foundation interaction effects. However, while the whole dam-reservoir-foundation system is incorporated into a finite element mesh, such an analysis requires considerable computational effort because many unneccessary degrees of freedom have to be used in both reservoir and foundation for simulating various interaction effects.

Chopra (Refs. 5,7) used the substructure method to reduce the computational effort and showed that dam-reservoir interaction, dam-foundation interaction, and combined dam-reservoir-foundation interaction problems

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can be solved efficiently. In Chopra's studies, the gravity dam is treated as a two-dimensional finite element system; the reservoir is an infinite continuum in the up-stream direction with constant depth while the foundation is a finite element system or a viscoelastic halfspace. He employed the mode superposition technique considering only the first few modes of vibration. Chopra (Refs. 8,9) also proposed a simplified procedure which included only the fundamental vibration mode in calculating the design forces. This simplified method can be conveniently used in preliminary designs of large gravity dams or in the final designs of small dams. In this simplified method, the interaction effects between the flexible dam and reservoir have been included but dam-foundation interaction effects have been disregarded.

SYSTEM AND BASIC ASSUMPTIONS

The system consists of a concrete gravity dam supported by the horizontal surface of a viscoelastic half-plane with hysteretic damping and impounding a reservoir of constant depth, extending to the up-stream direction (Fig. 1). The system is analysed under the assumption of linear behaviour for the mass concrete and foundation rock, and compressible behaviour of water. The dam is idealized as a two-dimensional finite element system while the foundation and the reservoir of water are treated as continua. The reservoir may be assumed infinite in the up-stream direction, the bottom be horizontal, and the up-stream face of the dam be vertical. The interactions between dam-reservoir and dam-foundation are taken into account; however, reservoir-foundation interaction is neglected.

Since the vertical ground motion has less significant effect on the earthquake response of the dam than the horizontal one, only the horizontal ground motion is considered. In this study, only the dynamic effects are discussed. For the simplified earthquake analysis only the contributions of the fundamental mode of vibration are considered.

SIMPLIFIED ANALYSIS PROCEDURE

The maximum dynamic response of the dam including structure-foundation and hydrodynamic interaction effects may be approximated by a response spectrum analysis taking into account only the contribution of the fundamental mode of vibration. Subsequently a quasi-static earthquake analysis can be carried out. The concept of the simplification consists of three steps:

(i) idealization of the earthquake ground motion by a response spectrum;

(ii) formulation of inertia forces and hydrodynamic pressure by quasi-static loads based on standard mode shape; and

(iii) representation of structure-foundation interaction by using characteristic stiffness distribution corresponding to the fundamental mode of vibration at the structure-foundation interface; modelling of flexible base by independent horizontal and vertical springs (equivalent Winkler foundation).

Computational Steps of Simplified Method

The simplified analysis comprises of the following steps:

(1) Compute the fundamental natural circular frequency and period of vibration of the dam with empty reservoir and rigid foundation, by means of the empirical relations proposed by Chopra (Ref. 9).

$$T_s = 12H_s/\sqrt{E_c}$$

$$\omega_s = 2\pi/T_s$$

T_s : fundamental period, in s;

ω_s : fundamental circular frequency of dam on rigid base, in rad/s; and

E_c : modulus of elasticity of mass concrete of dam, in kPa.

(2) Compute the fundamental frequency of vibration of the dam-foundation system ω_{sf} and determine the corresponding period of vibration:

$$\omega_{sf} = \omega_s \cdot R_o$$

$$T_{sf} = 2\pi/\omega_{sf}$$

R_o : ratio of fundamental frequencies of the dam on flexible and rigid foundation; R_o is a function of the relative foundation stiffness E_c/E_R and the frequency parameter a_o, (due to the small effect of a_o, the curve corresponding to $a_o = 0$ in Fig. 2, can be used) (Ref. 10);

where $a_o = \omega_s \cdot B / 2C_s$, B is the width of the gravity dam at the base and C_s is the shear wave velocity in the foundation, E_c and E_R are the moduli of elasticity of mass concrete and foundation rock, respectively.

ω_{sf} : fundamental circular frequency of vibration of dam-foundation system.

(3) Compute the fundamental period of the dam-reservoir-foundation system:

$$\tilde{T}_{sf} = R_1 T_{sf}$$

R_1 : ratio of fundamental periods of the dam with and without water in the reservoir; R_1 is a function of the relative reservoir depth H/H_s and the modulus of elasticity of mass concrete and can be obtained from the graphs in Fig. 3. (Ref. 9).

(4) Compute the ratio of the fundamental frequency of the dam-reservoir-foundation system and the infinite reservoir, in order to determine the hydrodynamic pressure on the dam:

$$R_2 = \frac{\tilde{\omega}_{sf}}{\omega_r} = \frac{1}{\tilde{T}_{sf}} \frac{4H}{C}$$

ω_r : fundamental circular frequency of infinite reservoir of constant depth; and

$\tilde{\omega}_{sf}$: fundamental circular frequency of dam-reservoir-foundation system.

(5) Compute the maximum lateral earthquake forces without hydrodynamic effects (first mode contribution):

$$f_s(y) = \alpha_1 S_a(T_{sf}) m(y) \psi(y)$$

$S_a(T_{sf})$: response spectrum of the absolute acceleration taken at period T_{sf};

$m(y)$: mass per unit height of dam;

$\psi(y)$: standard fundamental mode shape of vertical upstream face of triangular-shaped concrete gravity dam as proposed by Chopra (Ref. 9); and

α_1 : dynamic participation factor of fundamental mode (for conservative design a value of $\alpha_1 = 3$ is adopted).

(6) Compute the maximum lateral earthquake forces including hydrodynamic effects (first mode contribution):

$$\tilde{f}_s(y) = \alpha_2 S_a(\tilde{T}_{sf}) \left[m(y)\psi(y) + \bar{P}_1(y) \right]$$

$S_a(\tilde{T}_{sf})$: response spectrum of the absolute acceleration taken at period $\tilde{T}_{sf}$;

$\bar{P}_1(y)$: hydrodynamic pressure, as shown in Fig. 4; and

α_2 : dynamic participation factor of fundamental mode of dam-reservoir-foundation system (for conservative design a value of $\alpha_2 = 4$ is adopted).

(7) Evaluate the stiffnesses of horizontal and vertical springs at each nodal point of the dam-foundation interface. This can be

performed by using the graphs given in Fig. 5 (Ref. 10) for a visco-elastic half space with hysteretic damping constant of 0.1.

It is important to note that in the whole procedure structural damping is only reflected in the response spectrum S_a. Corresponding results of an example gravity dam are shown in Fig. 6 (Ref. 10) for full and empty reservoir condition respectively.

CONCLUSION

The proposed simplified earthquake analysis can easily be carried out by any finite element computer program for the static analysis of dams. No modifications of the program code are required, it is only necessary to calculate the load vector due to lateral forces, and the flexible base can be represented by simple horizontal and vertical springs located at each nodal point at the dam base.

This method provides an economic and efficient tool for mainly preliminary design purposes. The results are very satisfactory as long as an earthquake is mainly exciting the fundamental mode of vibration.

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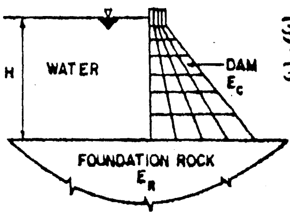

Fig. 1 Dam-reservoir-foundation system

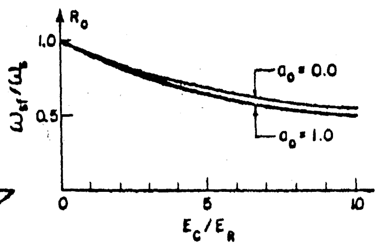

Fig. 2 Effect of foundation stiffness on fundamental frequency of dam-foundation system (Ref. 10)

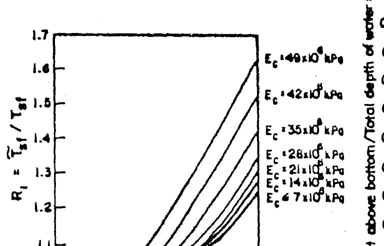

Fig. 3 Standard values for R_1, the ratio of fundamental vibration periods of dam with and without water, plotted against H/H_s, H = total depth of water and H_s = height of dam, for various values of E_c the modulus of elasticity of concrete

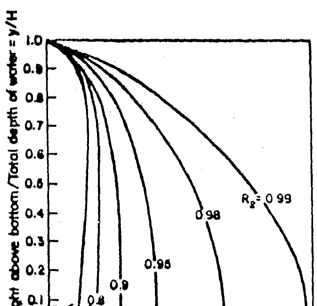

Fig. 4 Standard plots for variation of $\bar{p}$ over the depth of water for $H/H_s^1 = 1$ and various values of $R_2 = \tilde{\omega}_{sf}/\omega_r$, ρ_w = density of water

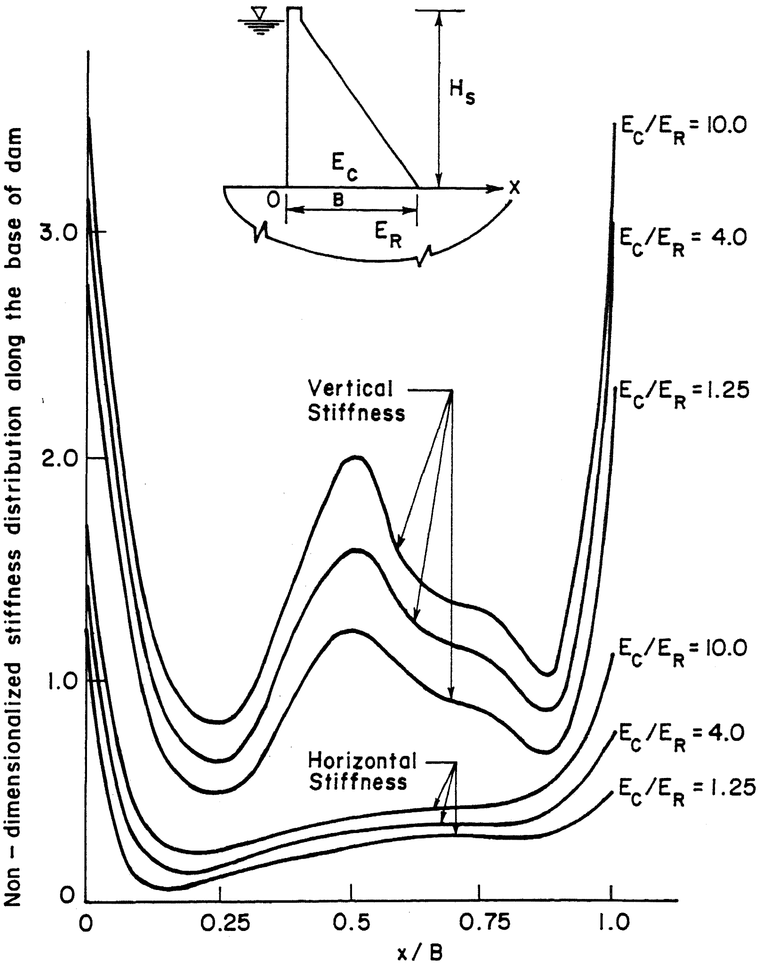

Fig. 5 Stiffness distribution along the structure foundation interface corresponding to fundamental mode of vibration (H_s = 120 m)

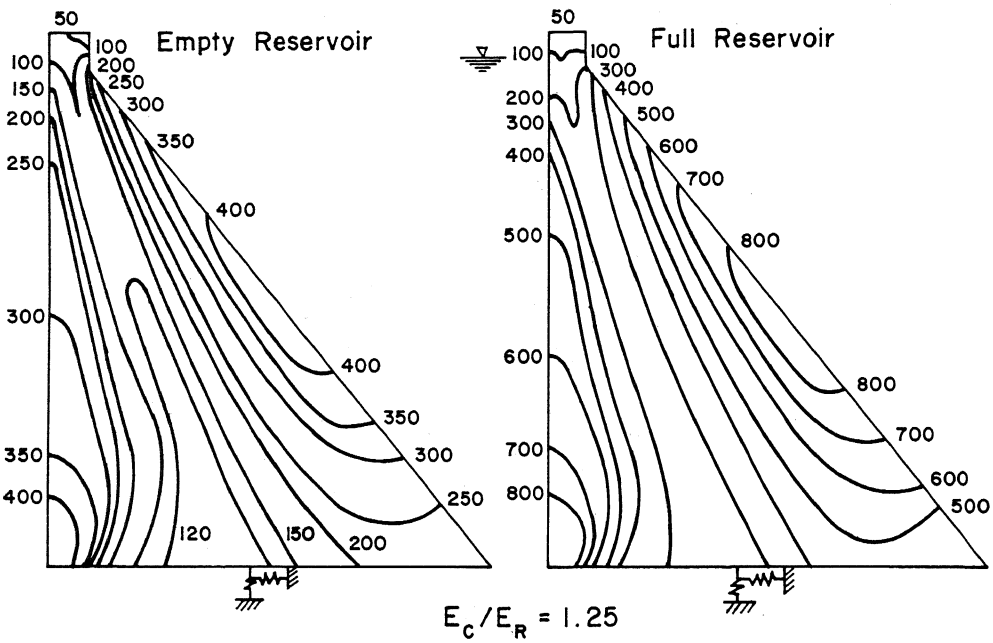

Fig. 6 Envelope values of maximum principal stresses (maximum tension) in kPa for a non-overflow monolith of Pine Flat Dam due to 0.1g horizontal earthquake load