DAM-RESERVOIR INTERACTION FOR A DAM WITH FLAT UPSTREAM FACE DURING EARTHQUAKES

by

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SYNOPSIS

The dam-reservoir seismic interaction problem is solved for dams with flat upstream faces. The compressibility of water and the effects of both horizontal and vertical components of the ground motion are taken into account. The influence of the foundation on the seismic response of the dam is included, so that the problem is treated as triple interaction one. The solution is based on the use of a combined finite-element-finite difference technique and on the FFT algorithm. Numerical results and conclusions are also given.

GLOSSARY OF TERMS

$a_h(t)$	horizontal component of the ground motion.
$a_v(t)$	vertical component of the ground motion.
$[C]$	damping matrix.
$\{D\}$	nodal displacement vector of the dam-foundation system.
$\{H(t)\}$	hydrodynamic interaction forces.
$[K]$	stiffness matrix.
$[M]$	lumped mass matrix.
$p(x,y,t)$	hydrodynamic pressure.
v_s	velocity of sound in water.
∇^2	Laplacian operator.
$\eta_i(t)$	generalized displacement in the i^{th} mode.
$\eta_i^c(\omega)$	complex frequency response.
$\{\Phi_i\}$	i^{th} mode shape vector for the dam-foundation system.

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INTRODUCTION

Previous studies have shown that the use of Westergaard solution for the hydrodynamic pressures on dams assumed to be rigid was quite good for design at that time; furthermore, many design codes in different countries still consider the hydrodynamic pressures on dams starting from this solution. In fact, some design methods using improvements and new developements /1,2/ (especially the consideration of both horizontal and vertical components of ground motion) have used Westergaard's solution as an useful tool in the aseismic design of dams quite a long period. However, the deformations which occur in the dam during the earthquake will modify the hydrodynamic pressure, consequently the problem has to be treated as an interaction one.

Another important effect is that of the foundatic deformability. All these impose the calculation of the earthquake response of the dam by solving a triple interaction problem (dam-foundation-reservoir). Chopra /3/ and Chakrabarti and Chopra /4/ have solved the dam-reservoir interaction problem for the case of dams with vertical upstream face. The influence of the vertical ground motion on the seismic response of dams with vertical upstream face was also analyzed /4,5/. The dam-foundation interaction problem was treated either by discretizing the foundation by the finite element technique or by considering it as a continuum /6,7/. The case of dam-reservoir interaction for dams with non-vertical upstream face was generally solved by discretizing the reservoir in finite elements /8/.

For dams with inclined upstream faces, the triple interaction problem is solved in this paper by considering the vertical component of the ground motion. The dam and the foundation are discretized by finite element method, the water being considered as an elastic, compressible continuum. The wave equation which governs its motion is solved by the finite difference method.

EQUATIONS OF MOTION

According to the substructure analysis used herein, the dam and the foundation (first substructure) are discretized in finite elements and the water (second substructure) is considered to be an elastic, compressible continuum (Fig.1).

Considering first only the horizontal component of the ground motion, the equations of motion of the dam-foundation system with hydrodynamic interaction forces included, are:

$$[M]\{\ddot{D}\} + [C]\{\dot{D}\} + [K]\{D\} = -[M]\{1\}a_h(t) + \{H(t)\} \qquad (1)$$

where:

$$\{1\}^T = [1\ 1\ 1\ \ldots]$$

The equations of motion are uncoupled by a transformation based on the modes of vibration of the dam-foundation-system. This aproximation simplifies the problem, only the first n modes of vibration being taken into account /4/:

$$\{D(t)\} = \sum_{i=1}^{n} \{\Phi_i\} \eta_i(t) \tag{2}$$

The standard uncoupling technique provides the equation for the generalized displacement in the i^{th} mode:

$$M_i^* \ddot{\eta}_i(t) + C_i^* \dot{\eta}_i(t) + K_i^* \eta_i(t) = F_i^*(t) \quad (i=1,2,\ldots n) \tag{3}$$

where M_i^*, C_i^*, K_i^* and F_i^* are the generalized quantities.

The motion of the other substructure (reservoir) is governed , when the internal viscosity and surface waves are neglected, by the wave equation:

$$\nabla^2 p(x,y,t) = \frac{1}{v_s^2} \frac{\partial^2 p(x,y,t)}{\partial t^2} \tag{4}$$

RESPONSE TO HARMONIC EXCITATION

The response to a harmonic ground excitation $a_h(t)=e^{i\omega t}$ is also harmonic:

$$\ddot{\eta}_i(t) = \ddot{\eta}_i^c(\omega)\, e^{i\omega t} \tag{5}$$

$$p(x,y,t) = p^c(x,y,\omega)\, e^{i\omega t} \tag{6}$$

Using the equation (6), the wave equation becomes:

$$\nabla^2 p^c = - \frac{\omega^2}{v_s^2} p^c \tag{7}$$

This equation is solved by the finite difference method, on the mesh presented in figure 1, for the following boundary conditions:

a. At the free surface the hydrodynamic pressure vanishes:

$$p(x,y,\omega) = 0 \tag{8}$$

b. At the end of the reservoir, opposite to the dam the pressure vanishes:

$$p(x,y,\omega) = 0 \tag{9}$$

c. At the reservoir-dam interface the motion of the liquid equals the motion of the upstream face of the dam. The acceleration in the nodal points on the upstream face is the sum of the acceleration in the rigid structure determined by the ground motion and of the acceleration in the flexible srtucture, vibrating in the its modes of vibration, without motion at the base:

$$\{\ddot{D}^u(t)\} = \{1\}\, e^{i\omega t} + [\Phi^u]\{\ddot{\eta}(t)\} \qquad (10)$$

$[\Phi^u]$ is a matrix of modal ordinates corresponding to the nodes on the dam-reservoir interface. Explicitly, using Eq.(6), condition (c) becomes after some transformations:

$$-\frac{\partial p^c}{\partial x}\cos\alpha + \frac{\partial p^c}{\partial y}\sin\alpha = -\rho\left(\sum_{i=1}^{n}\ddot{\eta}_i^c(\omega)\,\varphi_i^u(x,y) + 1\right) \qquad (11)$$

where $\varphi_i^u(x,y)$ is the continuous form of the vector $\{\Phi_i^u\}$.

d. At the reservoir-foundation interface the boundary condition is similar to condition (c):

$$\frac{\partial p^c}{\partial y} = -\rho\left(\sum_{i=1}^{n}\ddot{\eta}_i^c(\omega)\,\varphi_i^b(x,y) + 1\right) \qquad (12)$$

Solving equation (7) for the boundary conditions (8), (9), (11) and (12) by the finite difference method, the hydrodynamic pressures $p^c(\omega)$ in the nodal points of the dam-reservoir interface and then the vector $\{H(\omega)\}_i$ are established. Introducing now the acceleration $a_h(t) = e^{i\omega t}$ and Eq.(5) in Eqs.(3), the complex frequency solution vector $\{\eta(\omega)\}$ is obtained. The response to a harmonic vertical excitation is computed by a a similar technique.

RESPONSE TO AN ARBITRARY EXCITATION

If the horizontal and the vertical components of the ground acceleration are $a_h(t)$ and $a_v(t)$ the generalized responses in time domain are obtained by the Fourier synthesis of the complex frequency responses. Then, for the total generalized response, Eq.(2) provides the nodal point displacements $\{D(t)\}$ and the stresses $\{\sigma(t)\}$ may be computed.

NUMERICAL RESULTS AND CONCLUSIONS

The rockfill dam presented in the Fig.1 was analyzed by using a computer program developed according to the method previously discussed. Results are given in the Fig.2 for H = 100.0 m, B = 200.0 m and two vibration modes considered.

The hydrodynamic interaction forces and the dam foundation interaction forces greatly modify the response of the dam; hydrodynamic forces, deflections and stresses are greater than in the case in which the dam is subjected to a hydrodynamic pressure obtained on a rigid dam.

The vertical component of the ground motion has a great influence on the seismic response of the dam in the case in which the problem is treated as a triple interaction one.

The compressibility of water cannot be neglected without an important loss in the accuracy of the response.

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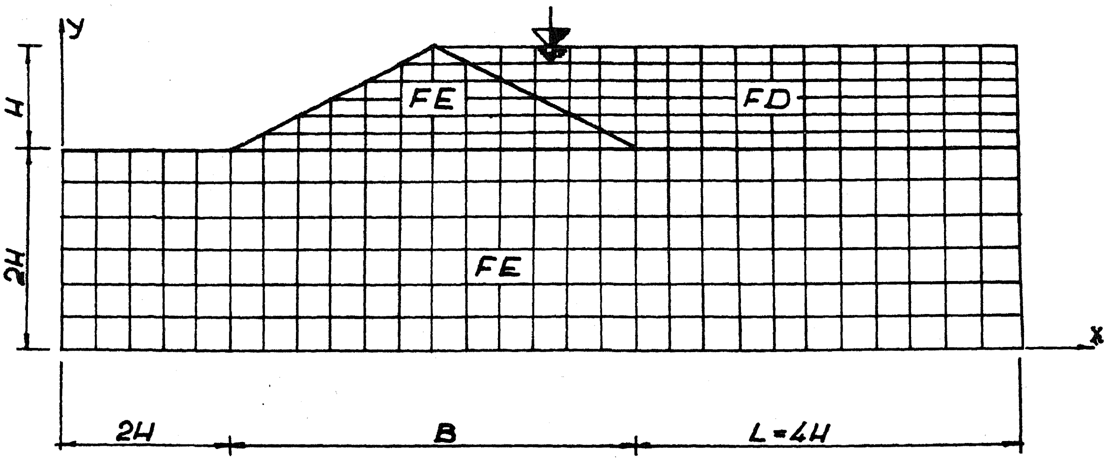

FD - Finite Difference Mesh;   FE - Finite Element Mesh

Fig.1 Dam-Foundation-Reservoir System

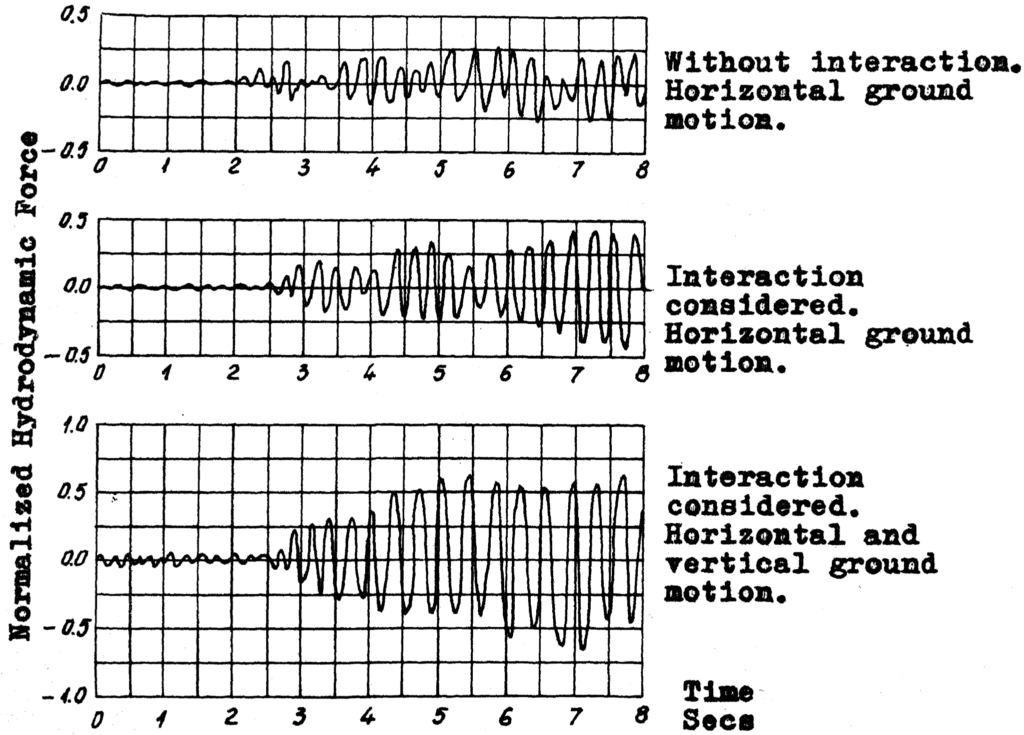

Fig.2 Hydrodynamic Force Response
Taft Earthquake, 1952
N-W Horizontal and Vertical Components