EARTHQUAKE RESPONSE OF CONCRETE GRAVITY DAMS AND ARCH DAM

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SUMMARY

Two procedures for analysis of the response of concrete dams in the event of earthquake ground motion including hydrodynamic and foundation interaction are presented here. One procedure concerns the two dimensional analysis of concrete gravity dams and the other procedure the three dimensional analysis of arch dams. The accuracy of these menthod is verified against existing results and a model test. From various case studies, the effects of interaction between dam, reservoir and foundation on the response of concrete dams to earthquakes are clarified.

INTRODUCTION

It is indicated in many reports that hydrodynamic and foundation interaction has significant effects on the earthquake response of concrete dams. Accordingly, it is desirable to obtain the earthquake response of dams including hydrodynamic and foundation interaction. In the past studies, however, only either dam-reservoir coupled vibration analysis or dam-foundation coupled vibration analysis, or combination of the two were conducted, in disregard of foundation and reservoir interaction at the bottom of reservoirs.

It is known that the pressure wave absorption at the reservoir bottom has significant effects on the dynamic water pressure, and the bottoms of the reservoir near dams tend to vibrate and produce dynamic water pressure due to the vibration of dams. It is also expected that the existance of a dam and a reservoir changes the input ground motion into them. These effects cannot be analysed without including foundation and reservoir interaction. Herein the coupled vibration analysis for the dam-reservoir-foundation system is developed for both gravity dams and arch dams, and the effcts of dam-reservoir, dam-foundation and reservoir-foundation interaction are studied.

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METHOD OF ANALYSIS FOR GRAVITY DAM

Finite element method is used to idealize the dam, and the nearby portion of reservoir water and foundation. A newly developed transmitting boundary for fluid-solid systems is utilized. At the bottom of the foundation rock, a viscous boundary absorbs vertically scattering waves.[Fig. 1] Brief description of transmitting boundary is given below.

The governing equation and boundary condition for reservoir water are assumed to be given as below

Governing equation
$$\frac{1}{C^2}\frac{\partial^2\phi}{\partial t^2}=\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2} \qquad \text{--(1)}$$

Boundary condition at water surface
$$\frac{1}{g}\frac{\partial^2\phi}{\partial t^2}+\frac{\partial\phi}{\partial y}=0 \qquad \text{--(2)}$$

Boundary condition at the interface of solid and water
$$\frac{\partial\phi}{\partial n}=\frac{\partial U_n}{\partial t} \qquad \text{--(3)}$$

$$P_d=-\rho_w\frac{\partial\phi}{\partial t} \qquad \text{--(4)}$$

, where ϕ, c, g, ρ_W, Pd, Un are velocity potential, sound velocity in water, acceleration of gravity, density of water, hydrodynamic pressure and the normal component of velocity of solid at the interface of water and solid.

It is assumed that the velocity potential ϕ is given by
$$\phi=\phi_0 e^{i(\omega t-ax)} \qquad \text{--(5)}$$

Reservoir water some distance away from dam is idealized by semi-infinite thin layer elements. ϕ is assumed to vary linearly in y direction within each layer. Applying Galerkin's method, we get the following equation for the ith layer.

$$\left.\begin{aligned}
&(\omega^2[M_{\phi e}]_i-[K_{\phi e}]_i-a^2[\lambda_{\phi e}]_i)\{\phi_{0e}\}_i+\{f_{\phi e}\}_i=0\\
&\{\phi_{0e}\}_i=\{\phi_{0,i},\ \phi_{0,i+1}\}^t\\
&\{f_e\}_i=\{\rho_\omega(\frac{\partial\phi_0}{\partial y})_{,i},\ -\rho_\omega(\frac{\partial\phi_0}{\partial y})_{,i+1}\}^t\\
&[M_{\phi e}]_i=\frac{\rho_\omega L_i}{C^2}\begin{bmatrix}1/3, & 1/6\\ 1/6, & 1/3\end{bmatrix}\\
&[K_{\phi e}]_i=\frac{\rho_\omega}{L_i}\begin{bmatrix}1, & -1\\ -1, & 1\end{bmatrix}\\
&[\lambda_{\phi e}]_i=\rho_\omega L_i\begin{bmatrix}1/3, & 1/6\\ 1/6, & 1/3\end{bmatrix}
\end{aligned}\right\} \qquad \text{--(6)}$$

, where Li is the depth of the layer and $\{\phi_{oe}\}_e$ is the values of ϕ_o at the boundary of the layer. At water surface and at boundary between water and foundation, following values are given.

Water surface $$\rho_\omega \frac{\partial \phi_0}{\partial y} = \frac{\rho_\omega}{g} \omega^2 \phi_0 \qquad \text{--(7)}$$

Boundary between water and foundation $$-\rho_\omega \frac{\partial \phi_0}{\partial y} = -i\omega\rho_\omega u_{y0} \qquad \text{--(8)}$$

, where U_{yo} is the y component of complex velocity amplitude of foundation.

Superposing the matrices for all layers of water part and contributions from solid part, the equation of motion for the water-foundation system is given as follows.

$$\left(\omega^2 \begin{bmatrix} M_\phi', & O \\ O, & M_\delta \end{bmatrix} - \begin{bmatrix} K_\phi, & O \\ O, & K_\delta \end{bmatrix} - i a \begin{bmatrix} O, & O \\ O, & A_\delta \end{bmatrix} - i\omega \begin{bmatrix} O, & L^t \\ -L, & O \end{bmatrix} - a \begin{bmatrix} \lambda_\phi, & O \\ O, & \lambda_\delta \end{bmatrix} \right) \begin{Bmatrix} \phi_0^R \\ u_0^R \end{Bmatrix} + \begin{Bmatrix} O \\ f_0' \end{Bmatrix} = 0 \qquad \text{--(9)}$$

, where $M\phi$, $K\phi$, and $\lambda\phi$ are superposed matrices of $[M\phi]_e$, $[k\phi]_e$ and $[\lambda\phi]_e$ respectively, and M_s, $K\delta$, $A\delta$ and $\lambda\delta$ are contribution from solid part (Ref. 1), and L is a term to respresent the interaction between water and foundation given in eq. (3) and (4). From eq.(9) the transmitting boundary for fluid-solid system is obtained by the similar procedure described in Ref. 1.

METHOD OF ANALYSIS OF ARCH DAMS

Three dimensional finite elements are utilized to idealize dam, foundation and reservoir water close to the dam concerned. Reservoir water some distance away from the dam is idealized by finite prism method, so that a reservoir of any length can be analysed with ease. A damping term is included in the boundary condition along the reservoir side and bottom to approximately account for fluid-foundation interaction effects.(Fig. 2) Brief description of finite prism idealization is given below.

The velocity potential of water some distance away from dam is assumed to be given by

$$\phi = \phi_0 e^{i(\omega t + ay)} \qquad \text{--(10)}$$

The goerning equation and boundary condition are given as follows.

Governing equation $$-\frac{\omega^2}{c^2}\phi_0 = -a^2\phi_0 + \frac{\partial^2 \phi_0}{\partial x^2} + \frac{\partial^2 \phi_0}{\partial z^2} \qquad \text{--(11)}$$

Boundary condition at water surface $-\frac{\omega^2}{g}\phi_0 + \frac{\partial \phi_0}{\partial_z} = 0$ ---(12)

Boundary condition between water and solid

$$i\omega + C\beta\left(\frac{\partial\phi_0}{\partial_n} - U^*_{gn}\right) = 0 \quad \text{--(13)}$$

,where β is the impedance ratio of solid to water, and U_{gn}^* is the normal component of complex velocity amplitude of solid.

Applying Galerkin's method, we get the following equation for each prism.

$$\rho_w\left(a^2 - \frac{\omega^2}{c^2}\right)\left[\iint [N]^T[N]|J|d\xi\, d\eta\right]\{\phi_0\}_e$$

$$+ \rho_w\left[\iint [B]^T[B]|J|d\xi\, d\eta\right]\{\phi_0\}_e$$

Water surface $= +\frac{\rho_w \omega^2}{g}\cdot \int_s [N]^T[N]ds\{\phi_0\}_e$ --(14a)

Boundary between water and solid

$$= -\frac{i\omega\rho_w}{c\beta}\cdot\int_s [N]^T[N]ds\{\phi_0\}_e + \rho_w\int_s [N]^T[N]^* ds\{\dot{U}_g\} \quad \text{--(14b)}$$

, where [N] is the interpolation matrix, such that $\phi_0=[N]\{\phi_0\}e$, in which $\{\phi_0\}_e$ is the values of ϕ_0 at the nodal lines of the prism.

When Ug=0, eq.14 is regarded as eigen value equation for a, and homogeneous component of ϕ_0 is given by the superposition of eigen vectors. The non-homogeneous component of ϕ is given by the following equations.

$$\phi^f = \phi_0^n e^{i\omega t + iay} + [V][e_i^*][\beta_i][V]^{-1}\left\{U_{gy}^{f*} - \left(\frac{a}{\omega} - \frac{1}{C\beta}\right)\phi_0^n e^{-ia(L_0+L)}\right\}e^{i\omega t} \quad \text{--(15)}$$

, where [V] is the matrix consists of eigen vector, [βi] and [e*i] are diagonal matrices whose components are $\frac{-C\beta\omega}{\omega + C\beta a_i}$ and e^{-ia_iL} respectively, in which ai is the ith eigen value.

The boundary conditions between finite element zone and finite prism zone is given by the similar procedures given in (Ref. 1).

Examples

At first the analytical results are compared with those of the dam-reservoir-foundation coupled vibration analysis conducted by Chopra, et al (Ref. 2) to find good agreement with each other.(Fig. 3) As the reservoir-foundation interactions were not considered in the analysis of Chopra, et al, the comparison is made with an analysis where the reservoir-foundation interaction are neglected. Next, various parameter surveys are made for gravity dam to obtain the following results;

(1) Due to the interactions with the reservoir, the dam's resonance frequency is lowered and the resonance amplitude is increased;

(2) The compressibility of the reservoir lowers the response magnification of the dam to earthquake motions;(Fig. 4)

(3) The smaller the modulus of elasticity of the foundation, the lower the dam's resonance frequency as well as the smaller the resonance amplitude;(Fig. 5)

(4) The reservoir-foundation interactions give considerable effects on the dam's response to vertical earthquake motions:(Fig. 6)

(5) The slope of the upstream face on the response of dam is significant.

Vibration tests are conducted on 1/200 model of the 105m high planned arch dam. The material properties of arch dam are given in table 1. The resonant frequencies and mode shapes are determined for both full and empty reservoir condition. Three dimensional analysis is made on the vibration test and the numerical results obtain satisfactory agreement with the expermental ones.(Fig. 7.8)

The response of the prototype arch dams to the horizontal component of the Kaihoku earthquake are computed, and the following results are obtained.(Fig.9)

(1) The displacements and stresses of the dam are significantly increased due to the hydrodynamic effects

(2) The dam acceleration depend somewhat on the reservoir shapes, fluid-foundation interaction(Fig. 10) and compressibility of water.

Conclusion

Procedures for the two-dimensional and three dimensional analyses of concrete dams to earthquake ground motion including dam-fluid, dam-foundation and fluid-foundation iteraction effects is presented. Their accuracy is verified against existing results and model test results. Using the procedure, the effects of dam-fluid, dam-foundation and fluid-foundation interactions are examined. It is shown that the fluid-foundation has significant effects on the earthquake response of dam.

References

1. Lysmer, J. and Drake, L.A., 1971. " A Finite Element Method for Seisology", Method of Computational Physics , Vol. II, Academic Press.

2. Chopra, A.K., Chakrabari, P. and Gupta, S.,1980. " Earthquake Response of Concrete Gravity Dams Including Hydrodynamic and Foundation interaction Effects", Rept. No. UCB/EERC-80/01, Univ. of California.

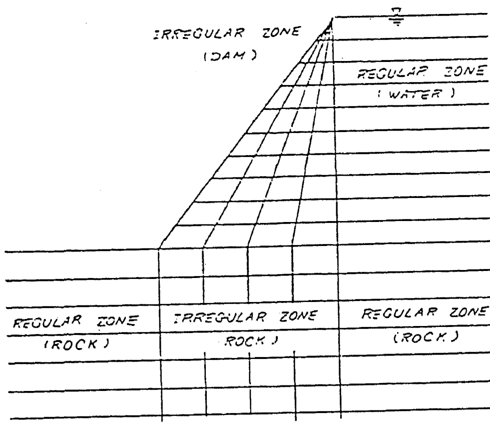

Fig. 1 MATHEMATICAL MODEL

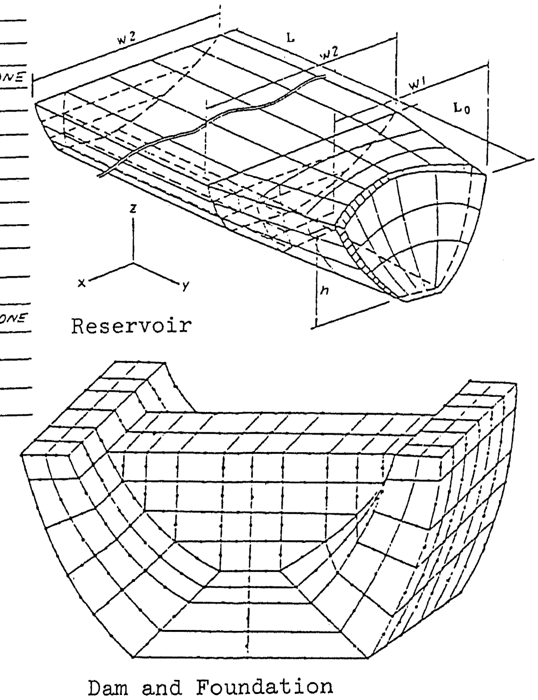

Fig. 2 MATHEMATICAL MODEL FOR ARCH DAM

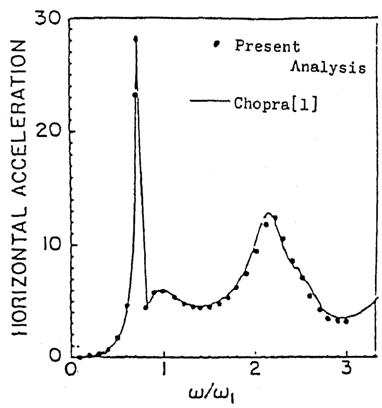

Fig. 3 RESPONSE OF DAM TO HARMONIC, HORIZONTAL GROUND MOTION (DAM-RESERVOIR SYSTEM)

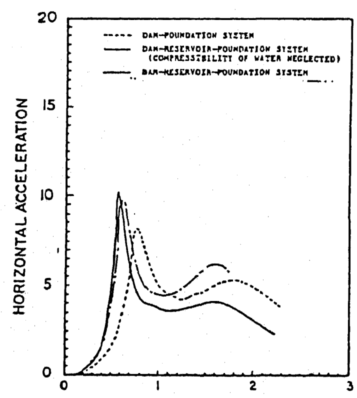

Fig. 4 INFLUENCE OF HYDRODYNAMIC EFFECTS IN THE RESPONCE OF DAMS TO HARMONIC HORIZONTAL GROUND MOTION ($E_f/E_d = 1$)

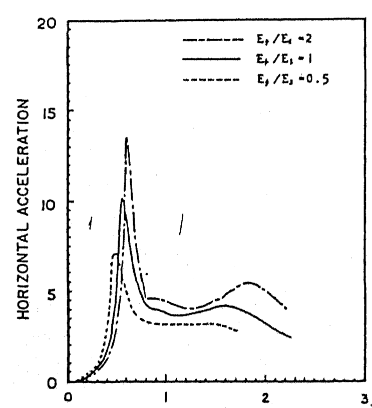

Fig. 5 INFLUENCE OF THE RATIO E_f/E_d ON RESPONCE OF DAMS TO HARMONIC GROUND ACCELERATION (E_d : YOUNG'S MODULUS OF DAM, E_f : YOUNG'S MODULUS OF FOUNDATION)

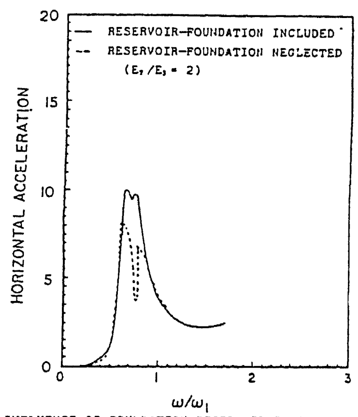

Fig. 6 INFLUENCE OF FOUNDATION-RESERVOIR INTERACTION ON RESPONCE OF A DAM TO VERTICAL HARMONIC GROUND MOTION

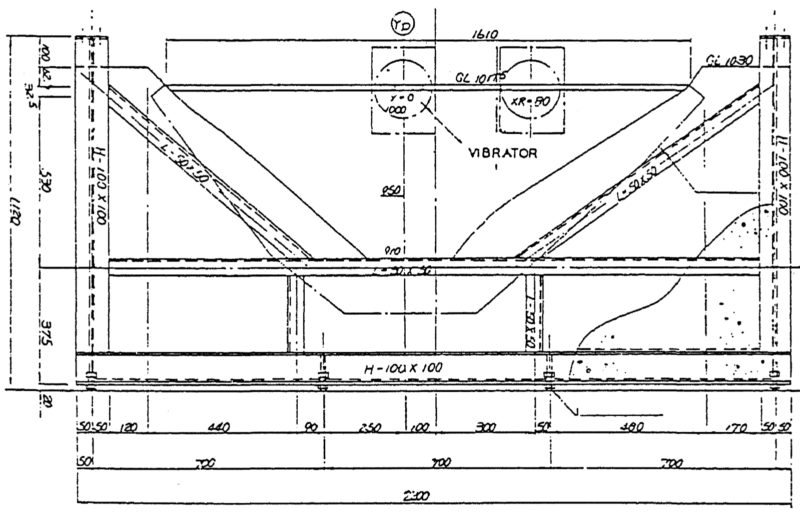

Fig. 7 VIBRATION MODEL

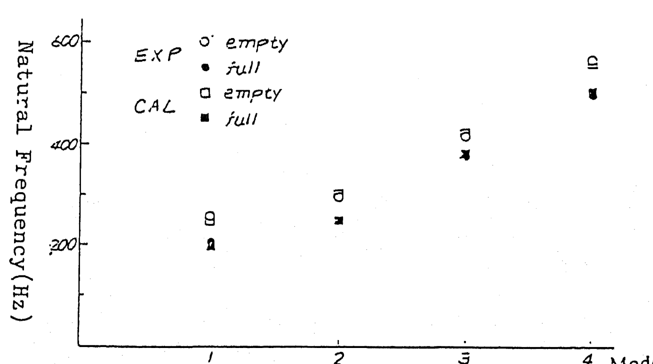

Fig. 8 NATURAL FREQUENCY OF DAM MODEL

Table 1. Material Properties of Model

	Density (t sec^2/m^4)	Young's modulus (t/m^2)	Poisson's ratio
Foundation	0.121	100000	0.4
Dam	0.234	500000	0.3

Table 2. Cases Analysed

Case Number	Water Level (m)	Normalized Seismic Wave (max. 100 gal)	Geometry of Reservoir		
			h_2/h_1	w_2/w_1	$L(L_0=h_1)$
1	105	Kaihoku Bridge	1	1	∞
2	105	"	1	3	∞
3	105	"	1	1	0
4	105	"	0	1	0
5	105	Golden Gate Bridge	1	1	∞
6	105	El Centro	1	1	∞
7	80	Kaihoku Bridge	1	1	∞
8	0	"	-	-	-

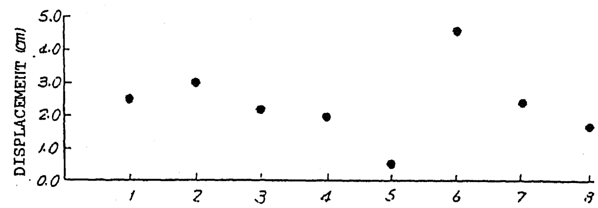

Fig. 9 MAXIMUM DISPLACEMENT OF DAM CREST DUE TO EARTHQUAKE

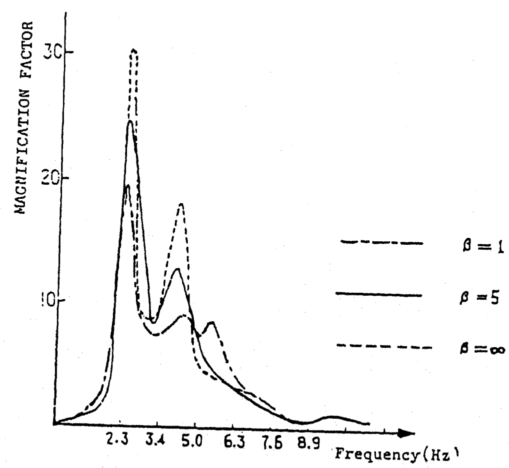

Fig.10 MAGNIFICATION FACTOR OF ACCELERATION AT DAM CREST OF ARCH DAM