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Reduction of the Seismic Response of Concrete Gravity Dams using Hydrodynamic Isolation

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ABSTRACT

Due to the significance of the hydrodynamic pressure on the seismic response of a concrete gravity dam, the possibility of reducing the dynamic water pressure on the dam is investigated. An absorptive layer attached to the upstream face of the dam is considered. The resulting boundary value problem for the hydrodynamic pressure is solved for the cases of infinite and finite-length reservoirs. It was found that the response of an isolated dam is less than that of an unisolated dam. The effect of reservoir length to depth ratio on the extent of response reduction is also studied.

INTRODUCTION

Seismic response of a concrete dam is affected by the hydrodynamic pressure within the impounded water. The resulting stresses may lead to crack initiation and propagation inside the dam during a moderately strong seismic event. Because of this additional loading, there is merit in reducing the exerted hydrodynamic forces on the dam. The idea of hydrodynamic isolation has been regarded as a possible solution.

Lombardo et al. (1987) proposed the idea of an "air curtain" as an aseismic provision for concrete dams. Hall and El-Aidi (1989) examined the possibility of reducing dynamic pressures by considering two practical alternatives for providing the air curtain at the upstream face of the dam: a) anchored air balloons and b) injected gas bubbles. Neither of these two methods achieved the expected reduction in the dynamic response of the dam-reservoir system mainly due to the violation of the linear assumption on gas behaviour in addition to the excitation of extra modes associated with the oscillation of the gas domain. Furthermore, due to the required large volume of gas, the suggested isolation methods did not seem to be practical. Hall et al. (1992), studied the effect of a soft material attached to the upstream face of the concrete dam on the reduction of the dam response. However, the compressibility of the material was taken to be that of a perfect gas with a simplified one-dimensional behaviour. With this model for the soft layer, Hall et al. did not obtain significant reduction in the maximum developed stresses in the concrete dam.

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In this study, as an alternative to the air curtain concept, the possibility of reducing the hydrodynamic pressures on the concrete dam by using a "shield layer" made of wave-absorptive materials which covers the upstream face of the dam is examined.

ASSUMPTIONS AND GOVERNING EQUATIONS

The analysis is carried out in the frequency domain using a two dimensional model of a concrete dam. Reservoir models of both infinite and finite length are included in the analysis. The substructure method is applied using modal analysis for the dam structure together with a closed form solution for the reservoir continuum. Details of the analysis procedure can be found elsewhere (Fenves and Chopra 1984). The effect of the reservoir loading in the frequency domain is evaluated by solving the governing pressure wave equation together with the appropriate boundary conditions. With the assumption of linearly compressible and non-viscous water, the small amplitude irrotational vibration of the reservoir is governed by Helmholtz equation:

$$\frac{\partial^2 \bar{P}}{\partial x^2}+\frac{\partial^2 \bar{P}}{\partial y^2}+\frac{\omega^2}{C_w^2}\bar{P}=0 \qquad (1)$$

where $\bar{P}(x,y,\omega)$ is the complex-valued frequency response function for the hydrodynamic pressure, C_w is the travelling speed of pressure wave in water and ω is the frequency of excitation. The solution to equation (1) together with the appropriate boundary conditions are considered separately for the cases of infinite and finite-length reservoirs.

Infinite Length Reservoir

In past studies of the hydrodynamic pressure in the reservoir, the upstream surface of the concrete dam has been considered as completely reflective. However, it is possible to evaluate the equivalent wave reflection coefficient, α, of this boundary based on the physical properties of the concrete. For typical values of elastic modulus and specific density of concrete, E_d = 2.24x10^4 MPa and ρ_d = 2.48x10^3 kg/m^3 (subscript "d" represents the dam), the travelling speed of dilatational waves in concrete, C_d, is equal to $(E_d / \rho_d)^{1/2}$ = 3005 m/s. It is assumed that the specific density and the travelling speed of pressure waves in water are ρ_w=1000 kg/m^3 and C_w=1440 m/s, respectively. The relative acoustic impedance of the concrete with respect to that of water, β_d, can be obtained as: $\beta_d = \rho_d C_d / \rho_w C_w$ = 5.175. The wave reflection coefficient, α_d, which is defined as the relative amplitude of the reflected wave to the amplitude of the incidental wave normal to the interface, can be computed using the relative impedance, β_d, as: $\alpha_d=(\beta_d-1)/(\beta_d+1)$= 0.676. In studies of the effect of reservoir bottom sediments on the hydrodynamic pressures, the wave reflection coefficient is normally assigned values in the range of 0.8 - 0.9 (Fenves and Chopra, 1985). These values are higher than the equivalent wave reflection coefficient of the concrete dam face. In the present study, a soft layer is considered to be attached to the upstream face of the dam. This layer which partially absorbs the incident pressure waves from the reservoir is referred to as the "upstream layer". Due to the finite thickness of the concrete dam, the reflected waves from the downstream side of the dam and the dam-layer interface alter the equivalent value of the wave reflection coefficient. However, the effect of the upstream layer thickness and the geometry of the monolith cross section on the reflective waves to the reservoir are neglected. It is assumed that the reflected waves from the interface and downstream side of the dam are dissipated within the soft layer before entering the reservoir. With J Ritz vectors for the dam-foundation system, the boundary condition for the partially reflective surface of the dam is written as:

$$\frac{\partial \bar{P}}{\partial x}(0,y,\omega) = -\rho_w [1 - \omega^2 \bar{q}_{hd}(y,\omega) + \Sigma_{j=1}^{J} \psi_j(y)\ \bar{\ddot{Z}}_j(\omega)] \tag{2}$$

where $\psi_j(y)$ is a continuous function representing the jth mode shape of the dam

$\bar{\ddot{Z}}_j(\omega)$ is the complex frequency response function of the second derivative of the generalized coordinate $Z_j(t)$; and

$\bar{q}_{hd}(y,\omega)$ is the frequency response function for the horizontal displacement of the dam-reservoir interface due to the interaction between the impounded water and the soft layer on the upstream face of the dam

The reservoir-dam boundary is based on an analogy of the proposed model and that of Fenves and Chopra (1984) for the effects of reservoir bottom sediments and represents an approximate one-dimensional model for the absorption of water pressure waves at the surface of the dam. In this approximation, the dam is assumed to consist of hypothetically independent horizontal layers which receive the impinging pressure waves at right angles to the dam-reservoir interface. Brekhovskikh (1991) showed that a small angle of inclination for the incident waves does not introduce considerable errors in the results. The frequency response function $\bar{q}_{hd}(y,\omega)$ can be related to the hydrodynamic pressure at the upstream face of the dam through the compliance function $C_d(\omega)$:

$$\bar{q}_{hd}(y,\omega) = - C_d(\omega)\ .\ \bar{P}(0,y,\omega) \tag{3}$$

The function $C_d(\omega)$ is obtained from the solution of the wave equation in the upstream layer subjected to the appropriate boundary conditions:

$$C_d(\omega) = \frac{1}{\rho_d C_d \omega} i \tag{4}$$

where $i=\sqrt{-1}$ and C_d is the travelling speed of the dilatational waves within the upstream layer. By substituting equations (3) and (4) into equation (2) one obtains:

$$[\frac{\partial}{\partial x} + i\omega q_d]\,\bar{P}(0,y,\omega) = -\rho_w [1 + \Sigma_{j=1}^{J} \psi_j(y)\ \bar{\ddot{Z}}_j(\omega)] \tag{5}$$

where $q_d = \rho_w/\rho_d C_d$.

The frequency response function $\bar{P}(x,y,\omega)$ for the developing hydrodynamic pressure in the reservoir of depth H is the solution of equation (1) subject to the boundary condition (5), the boundary conditions at the reservoir bottom and reservoir free surface:

$$[\frac{\partial}{\partial y} - i\omega q]\,\bar{P}(x,0,\omega) = 0 \tag{6}$$

$$\bar{P}(x,H,\omega) = 0 \tag{7}$$

together with the radiation condition at the upstream of the reservoir. In equation (6), $q = \rho_w/\rho C$ where ρ and C are the specific density and the travelling speed of dilatational waves in the reservoir bottom materials, respectively. The frequency response function for the hydrodynamic pressure can be written as:

$$\bar{P}(x,y,\omega) = \bar{P}_o(x,y,\omega) + \Sigma^J_{j=1}\, \bar{Z}_j(\omega)\,.\, \bar{P}^f_j(x,y,\omega) \tag{8}$$

where $\bar{P}_o(x,y,\omega)$ is the frequency response function due to the horizontal acceleration of a rigid dam and $\bar{P}^f_j(x,y,\omega)$ is the frequency response function due to the horizontal acceleration of the deflected dam associated with the jth Ritz vector. The solutions to the above boundary value problems for the hydrodynamic pressure due to rigid and flexible vibrations of the dam are:

$$\bar{P}_o(x,y,\omega) = -2\rho_w H \Sigma^{\infty}_{n=1} \frac{\mu^2_n(\omega)}{H[\mu^2_n(\omega)-(\omega q)^2]+i\omega q} . \frac{I_{on}(\omega)}{K_n + i\omega q_d} . e^{K_n x} . Y_n(y,\omega) \tag{9}$$

$$\bar{P}^f_j(x,y,\omega) = -2\rho H \Sigma^{\infty}_{n=1} \frac{\mu^2_n(\omega)}{H[\mu^2_n(\omega)-(\omega q)^2]+i\omega q} . \frac{I_{jn}(\omega)}{K_n + i\omega q_d} . e^{K_n x} . Y_n(y,\omega) \tag{10}$$

where K_n $= [\mu_n^2(\omega) - \omega^2/C_w^2]^{1/2}$

$\mu_n(\omega)$ is the nth eigenvalue of the impounded water

$Y_n(y,\omega)$ is the nth eigenfunction of the impounded water given by:

$$Y_n(y,\omega) = \frac{1}{2\mu_n(\omega)} \{[\mu_n(\omega)+\omega q]e^{i\mu_n(\omega)y} + [\mu_n(\omega)-\omega q]e^{-i\mu_n(\omega)y}\} \tag{11}$$

and $I_{0n}(\omega)$ and $I_{jn}(\omega)$ are defined as (Fenves and Chopra 1984):

$$I_{on}(\omega) = \frac{1}{H}\int_0^H Y_n(y,\omega)dy \tag{12}$$

$$I_{jn}(\omega)=\frac{1}{H}\int_0^H \psi_j(y)Y_n(y,\omega)dy \qquad (13)$$

Although equations (9) and (10) indicate the contribution of an infinite number of modes in the hydrodynamic response, in practical terms, the number of significant modes is limited by the highest frequency of excitation considered in the analysis.

Finite Length Reservoir

In the case of a reservoir with finite length, L, a partially absorptive boundary condition replaces the radiation condition of the infinite reservoir at the far side. The corresponding expression for the hydrodynamic pressure is obtained as:

$$\bar{P}_j^f(x,y,\omega)=-2\rho_w H\Sigma_{n=1}^{\infty}\frac{\mu_n^2(\omega)}{H[\mu_n^2(\omega)-(\omega q)^2]+i\omega q}\cdot\frac{I_{jn}(\omega)}{K_n-i\omega q_d}\cdot\frac{e^{K_n x}\frac{K_n+i\omega q_l}{K_n-i\omega q_l}e^{-2K_n L}+e^{-K_n x}}{\frac{K_n+i\omega q_d}{K_n-i\omega q_d}\cdot\frac{K_n+i\omega q_l}{K_n-i\omega q_l}-e^{-2K_n L}}\cdot Y_n(y,\omega) \qquad (14)$$

where $I_{0n}(\omega)$ is given by equation (12) for the rigid body case and when the effects of ground motion at far boundary are neglected. q_d , q , q_l are damping coefficients of dam upstream surface, reservoir bottom materials and reservoir far boundary, respectively.

For the case of an infinite-length reservoir ($L \rightarrow \infty$), equation (14) reduces to the expression for the hydrodynamic pressure given by equation (10). In the case of a finite-length reservoir confined within solid boundaries, it is expected that the response reduction due to the hydrodynamic isolation of dam monolith should be more significant than for the case of the reservoir of infinite length.

NUMERICAL EXAMPLE

To evaluate the effects of a partially absorptive dam-reservoir interface on the dam response, a numerical example is analyzed. A typical cross section of a 91.44 m high concrete dam with a downstream slope of 0.8 to 1 is considered. The modulus of elasticity of the dam concrete is assumed to be 21,500 MPa and Poisson ratio is equal to 0.2. Water is assumed compressible with the travelling speed of the acoustic wave C=1440 m/s. The ground motion considered in the analysis is the S69E component of Taft 1952 (Fig. 1). The dam foundation rock is assumed rigid and the reservoir bottom as completely reflective. In the case of the finite reservoir, the far boundary is assumed as totally reflective. Equations (9) and (10) were used to obtain the frequency response of the dam with a partially reflective upstream surface impounding a reservoir of infinite length. For the case of finite-length reservoir, equation (14) was used. In this case, a simplified procedure was applied using the first two mode shapes of the concrete dam in the analysis (Baumber, 1992). The accuracy of the procedure has been shown to be satisfactory provided the dominant frequencies of excitation are mainly smaller than the frequency of the second vibration mode of the dam monolith. Since this is usually the case for concrete gravity dams and the ground motion records that are normally considered, the results are valid for a wide range of practical applications.

In the case of an infinite-length reservoir, fundamental vibration mode of the dam-reservoir system shows the main contribution to the dam response (Fig. 3a). With the reflection coefficient $\alpha_d=2/3$ (which appears to be practically possible to obtain using an attached "soft" layer) a 41% reduction of response at the fundamental frequency of the system is obtained. In terms of stresses, figures 4a to 4c show about 20-30% reduction which brings the maximum developed stresses below the allowable tensile stress of concrete and reduces the risk of crack initiation and propagation inside the dam monolith.

The effect of partially absorptive interface in response reduction is even more appreciable for a reservoir of finite length. For a short reservoir length of $L/H=1$ with $\alpha_d=2/3$ for the absorptive layer, the reduction in response at the fundamental frequency of the dam-reservoir system is 57% (Figs. 2 and 3b). The amount of reduction decreases for higher values of L/H and remains nearly constant for $L/H>3$. According to figure 3c, for $L/H=3$, the corresponding value of response reduction is 49% which is virtually the same as the amount of reduction for $L/H=10$ (Fig. 3d). Figure 2 shows the relationship between the L/H ratio and the amount of response reduction at the fundamental frequency of the dam-reservoir system.

In a finite-length reservoir, higher modes of reservoir vibration are present (Figs. 3b to 3d); Hydrodynamic isolation reduces the response of the dam at higher frequencies considerably. As the ratio of L/H increases, the number of resonant peaks increases accordingly; yet, all the response peak amplitudes are reduced due to the absorption effect of the upstream layer.

CONCLUSIONS

Based on the results of this study, the following conclusions are reached:

1. The use of an absorptive layer attached to the upstream face of the dam, in the form of hydrodynamic isolation, provides an effective means of reducing seismic response of concrete gravity dams.
2. With an absorptive layer at the upstream side of the concrete dam, the developed stresses in the dam are reduced considerably. The scheme is even more effective when the reservoir is limited at the upstream end. In the case of a finite-length reservoir, the reservoir length effects are noticeable for $L/H<3$ with more response reduction for lower L/H values.
3. The absorptive layer does not possess a structural mode of vibration, the excitation of which would dominate the water pressure response and reduce the efficiency of the hydrodynamic isolation (Hall and El-Aidi (1989).

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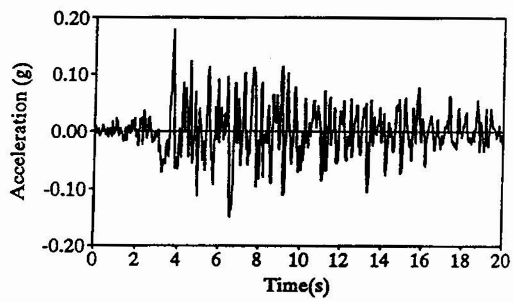

Fig. 1 Horizontal component of Taft ground motion, S69E, Kern County, CA, 21 July 1952.

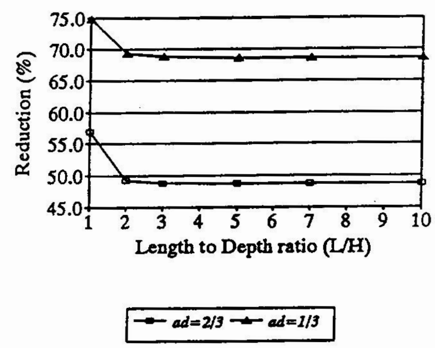

Fig. 2 Reduction of dam crest acceleration response in fundamental mode versus L/H ratio for different values of the wave reflection coefficient (α_d).

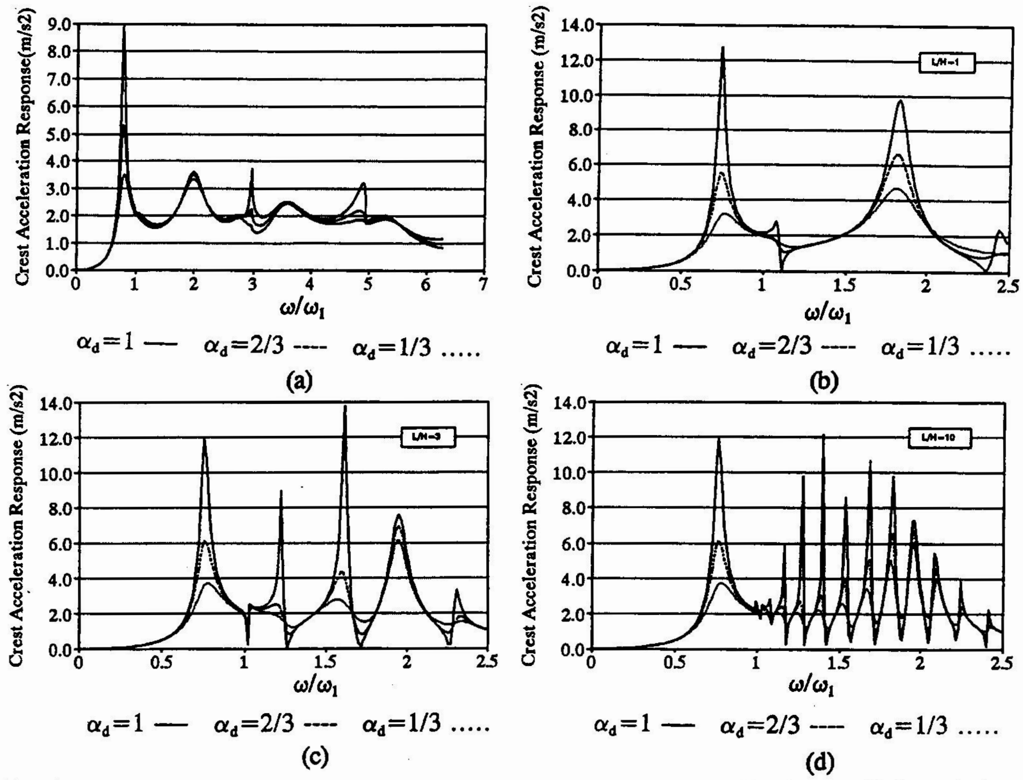

Fig. 3 Dam crest acceleration response for different values of wave reflection coefficient, (α_d), at the dam upstream face: a) reservoir of infinite length, b-d) finite-length reservoir with different length to depth ratios.

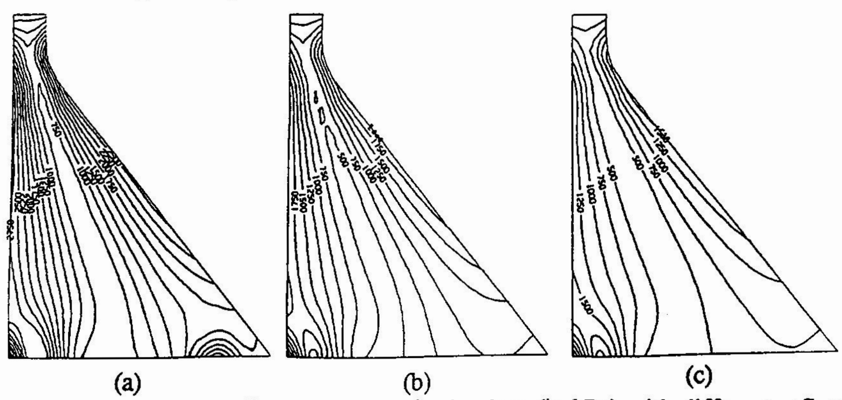

Fig. 4 Contours of maximum tensile stress values in the dam (in kPa) with different reflection coefficients,(α_d), at the upstream face: a) $\alpha_d=1.0$, b) $\alpha_d=2/3$, c) $\alpha_d=1/3$.