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Response of Concrete Gravity Dam with Finite Reservoir to Earthquake Ground Motion

T. A. Baumber[1] and A. Ghobarah[2]

ABSTRACT

The upstream reservoir is usually considered to be infinite in length in the analysis of dam-reservoir-foundation systems to earthquake ground motion. Many dams are situated such that the reservoir has a finite length. Dams may be situated very near a bend in a river or may be placed parallel to the rivers course. Sites for dams are typically chosen for the quality of the foundation materials rather than the upstream reservoir geometry. It was found, however, that the geometry of the upstream reservoir is important in completely defining the response of the system to earthquake ground motion. The dynamic tensile stresses in the dam monolith were found to increase with a decreasing reservoir length. The shape of the upstream reservoir was found to significantly affect the tensile stresses.

INTRODUCTION

In the analysis of dam-reservoir-foundation systems, the upstream reservoir is typically treated as an infinite length body of water in the direction perpendicular to the dam's crest. This assumption allows the equations of motion for the reservoir to be solved in a closed form. This model however does not satisfactorily represent the actual upstream reservoir impounded by the dam structure. Several large dams have been situated very near the bend in the river's course thus causing a finite reservoir to be created. The Lower Crystal Springs Dam in California is an example (National Academy Press, 1990). The assumption of a finite length reservoir may not be conservative in these cases. The objective of this study is to determine the effect of the geometry of the upstream reservoir on the dynamic tensile stresses induced into the dam monolith.

Limited research work has been conducted on the effect of a finite length reservoir. Hall and Chopra (1980) briefly examined this problem and found that additional response peaks occur in the frequency response functions. These additional peaks were caused by the change in the dynamic response of the finite length reservoir. Antes and Von Estorff (1987) found that the time histories of the system assuming a finite length reservoir had more frequency components than that for a system with an infinite length reservoir.

This paper discusses the effect of the geometry of the upstream reservoir on the dynamic tensile stresses created in the dam monolith during earthquake excitation. In particular, the effects of the ratio of the reservoir's length to the dam height (L/H) and the shape of the upstream reservoir are examined. A brief discussion of the analysis procedure used is presented.

[1] Structural Designer, DS-Lea Associates Ltd., North York, Toronto, Ontario, M2J 4R3.
[2] Professor, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, L8S 4L7.

ANALYSIS PROCEDURE

The dam-reservoir-foundation system is modelled using a substructuring technique. The dam monolith, the foundation underneath the monolith, and the upstream reservoir are each dealt with individually. The dam monolith is modelled as a two-dimensional elastic body. The interface between monoliths is assumed to be stress free thus allowing each monolith to vibrate independently. The monolith is therefore assumed to be in a condition of plane stress. The response of the monolith is assumed to be steady state with the transient part of the response being neglected. Hysteretic damping is assumed in the monolith substructure. The equations of motion governing the dynamic behaviour of this substructure, expressed in the frequency domain, is given by the standard equation of motion of an elastic solid. There is, however, an additional applied force term that is considered which accounts for the hydrodynamic forces applied to the dam monolith by the reservoir substructure (Hall and Chopra, 1980).

The foundation underneath the dam monolith is modelled as a two-dimensional visco-elastic half space. This analytical approach was originally developed by Dasgupta and Chopra (1977) and was later incorporated into the dam-reservoir-foundation analytical model by Chopra, Chakrabarti, and Gupta (1980). In this model, the foundation stiffness matrix is condensed to values that correspond only to those that occur at the monolith-foundation interface. In this substructure, the flexibility of the monolith's foundation can be considered in the analysis of the entire system.

The reservoir substructure models the motion of the upstream reservoir as irrotational, inviscid, and compressible. The equation of motion for the pressures developed in the reservoir is given by the two dimensional wave equation (Baumber, 1993). The solution of this equation is subject to four boundary conditions. The first boundary condition considers the pressure at the free surface is equal to zero. The second boundary condition represents the acceleration at the dam-reservoir interface. This boundary condition relates the accelerations of the dam monolith at the monolith-reservoir interface to the rate of change of the pressures at this location. The acceleration terms used in this boundary condition represent the acceleration of the dam monolith in its rigid body mode and its individual modes of vibration. This allows for each mode of vibration of the dam monolith to be considered individually in the solution of the reservoir's equation of motion. The last two boundary conditions represent the pressure gradients due to the absorptive capacity of the far boundary and the bottom of the reservoir. These two boundary conditions allow for the reservoir's energy to be dissipated by the reservoir's foundation. The boundary condition used in this study is the one-dimensional model developed by Hall and Chopra (1980).

The reservoir's equation of motion can be solved using the four boundary conditions discussed above. The subsequent solution yields the pressures generated in the reservoir during the vibration of the dam monolith. Using the principle of virtual work, the hydrodynamic force terms can be determined. These hydrodynamic terms can then be substituted into the monolith's equation of motion and the modal response function for the system can be determined.

From the modal response function, the stresses at the centroid of each element can then be determined. The response function is combined with the fourier representation of the earthquake ground motion to determine the system's frequency domain response. The displacement time history of the system is then determined by performing an inverse fourier transform on the system's frequency domain response. The strains are then determined at the centroid and combined with the element's elasticity matrix. The maximum and minimum stresses are then determined from the calculated principal stresses.

Dam Monolith Geometry and Seismic Input

Figure 1 presents the physical dimensions and the finite element discretization of the dam monolith used in this study. The compressive strength of concrete is assumed to be 17 MPa with a modulus of elasticity of 20 685 MPa. The modulus of rupture is assumed to be 2.5 MPa.

Four earthquake ground motion records were used in the analysis. Two records with an intermediate a/v ratio (ratio of maximum ground acceleration to maximum ground velocity, g/(m/s)) and two records with a high a/v ratio were considered. Earthquake events with a low a/v ratio were deemed not to provide any new information. The records with an intermediate a/v ratio were the Imperial Valley (S00E; May 18, 1940; El Centro) and the Kern County (N21E; July 21, 1952; Taft Lincoln School Tunnel) events. These records have significant accelerations in the frequency range between 0 and 4 Hz and low accelerations at frequencies greater than 4 Hz.

The San Francisco (S80E; March 22, 1957; Golden Gate Park) and the Saguenay (Longitudinal component; Nov. 25, 1988; St-Ferreol) earthquake records were selected as the high a/v ratio events. These records have significant accelerations in the frequency range from 0 to 15 Hz. The recorded ground motion characteristics for all four selected records are listed in Table 1.

In this study, all records have been scaled such that their maximum ground velocity is equal to that of the Imperial Valley event. This was done to obtain a quantitative estimate of the effect of the frequency content of the earthquake ground motion on the monolith's response. It is of more interest to determine how the response of the system varies for each record as the physical characteristics of the dam-reservoir-foundation system are altered. The Kern County, San Francisco, and the Saguenay acceleration records were scaled by factors of 2.13, 7.26, and 12.32, respectively.

RESPONSE OF DAM-RESERVOIR-FOUNDATION SYSTEM

Effect of L/H Ratio

Figure 2 presents the dynamic tensile stress profiles for the dam monolith impounding a reservoir having an L/H ratio of 5.0 and infinity. In this figure, the monolith alone is excited by the Imperial Valley earthquake event and the far end boundary is assumed unaffected by the ground motion. The tensile stresses that are created in the dam monolith are virtually identical for the two cases when excited by this ground motion event. The Imperial Valley earthquake event has high input energy at excitation frequencies below 4 Hz. The fourier representation of the system's response in the frequency range of 0 to 4 Hz is virtually identical for the finite reservoir case considered and when the reservoir is assumed infinite (Baumber, 1993). The Imperial Valley earthquake event does not have significant input energy at frequencies greater than 4 Hz so the effect of the higher modes of vibration of the system with a finite reservoir length are not significant. Similar results were obtained when the other three ground motion records were used in the analysis. Table 2 presents the maximum value of the dynamic tensile stress experienced by the monolith during excitation. The results for a dam monolith having a reservoir with L/H ratios of 1.0, 2.5, 5.0, and infinity are presented in this table with the element number that this stress occurs at in parenthesis.

As the reservoir length decreases, the magnitude of the maximum dynamic tensile stress begins to differ from that of the infinite length reservoir case. This is true primarily for the earthquake events that have a high a/v ratio. Figure 3 presents the dynamic tensile stress profiles for the cases where the monolith is subjected to the Saguenay earthquake event and the reservoir has an L/H ratio of infinity and 1.0. As evident in this figure, the dynamic tensile stresses increase as the reservoir length decreases. The maximum value of the tensile stress for the infinite length reservoir case is 11.51 MPa. As the L/H ratio is decreased to a value of 1.0, the tensile stress value increases by 67.1% to 19.23 MPa. This increase in stress can be rationalized by examining the frequency response function for this case. The response peak that occurs near a frequency of 7.0 Hz is primarily responsible for the increase in stress. It is significantly increased in magnitude as compared to the infinite length reservoir case. The Saguenay earthquake record has significant energy near this frequency. This vibrational mode is therefore excited by this earthquake event when the reservoir has an L/H ratio of 1.0.

Effect of Reservoir Geometry

The maximum dynamic tensile stresses that the monolith experiences when the reservoir geometry is idealized as triangular are listed in Table 3. A constant depth reservoir will be labelled as rectangular and the sloping reservoir bottom will be labelled as triangular reservoir. In this case, the ground motion is assumed to excite only the dam monolith while the far boundary is not affected by the earthquake. In comparing Tables 2 and 3, it is evident that the main effect of the triangular reservoir geometry is to increase the value of the maximum dynamic tensile stress. This again is a result of the contribution of the higher modes of vibration of the finite length reservoir system. The vibrational characteristics of the finite length reservoir result in the monolith having additional peaks in its frequency response function. The location and magnitude of these additional response peaks are altered as the geometry of the upstream reservoir is changed. The vibrational characteristics of this substructure are altered thus causing hydrodynamic pressures to be created at different excitation frequencies. This can be seen in Figure 4 which presents the frequency response function for a dam-reservoir-foundation system impounding reservoirs with both rectangular and triangular geometry and an L/H ratio of 5.0. It can be seen that the additional frequency response peaks that are created by the finite length geometry occur at different frequencies of excitation. These peaks tend to be greater in magnitude and closer to the fundamental frequency of the entire system than those for the rectangular geometry case. The response of the system to earthquake ground motion will be therefore larger for the triangular reservoir geometry case than for the rectangular geometry case.

CONCLUSIONS

In the dynamic analysis of dam-reservoir-foundation systems, the upstream reservoir is normally idealized as infinite in length. This has been done primarily to simplify the equations of motion of the overall system. This study examined the effects of the upstream reservoir geometry on the dynamic tensile stresses induced into the dam monolith. It was found that the physical characteristics of the upstream reservoir are very important in defining the response of the dam-reservoir-foundation system to earthquake ground motion. The ratio of the reservoir length to its height (L/H) and the geometry of the upstream reservoir have a significant influence on the system's response. The dynamic tensile stresses determined for the finite reservoir system were found to be significantly different from that of the case where the reservoir was assumed to be infinite. This was especially true for systems that were subjected to high a/v ratio earthquake ground motion. It was also found that the dynamic tensile stress distribution was significantly different for systems that had a small L/H ratio.

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Table 1 - Recorded Earthquake Ground motion characteristics

Earthquake Event	Magnitude	Epicentral Distance (km)	Maximum Accel. (g)	Maximum Vel. (m/s)	a/v (gs/m)
Imperial Valley (1940)	6.6	8	0.348	0.334	1.04
Kern County (1952)	7.6	56	0.156	0.157	0.99
San Francisco (1957)	5.25	11	0.105	0.046	2.28
Saguenay (1988)	5.7	114	0.121	0.027	4.46

Table 2 - Maximum Dynamic Tensile Stress (MPa), monolith excited only

	Earthquake record			
L/H	Imperial Valley	Kern County	San Francisco	Saguenay
∞	4.59(121)	5.97(121)	9.19(24)	11.51(24)
5.0	4.96(121)	6.05(24)	9.29(24)	12.86(24)
2.5	4.87(121)	6.81(24)	9.08(24)	14.34(24)
1.0	5.11(24)	5.81(121)	11.79(24)	19.23(24)

Table 3 - Maximum Dynamic Tensile Stress (MPa), triangular reservoir geometry

	Earthquake record			
L/H	Imperial Valley	Kern County	San Francisco	Saguenay
5.0	5.28(24)	6.97(24)	11.66(24)	12.97(24)
1.0	5.60(121)	7.36(24)	14.44(24)	16.56(24)

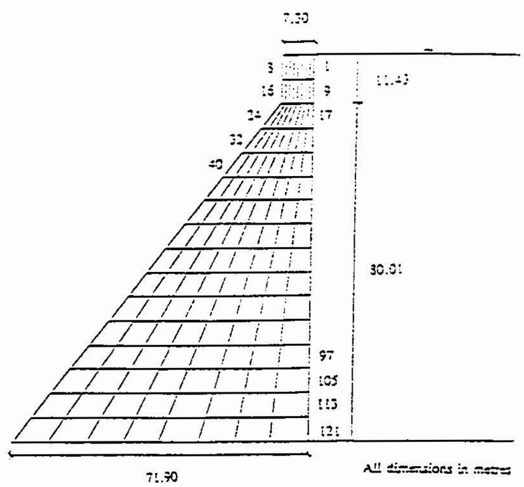

Figure 1 - Dam Monolith Considered

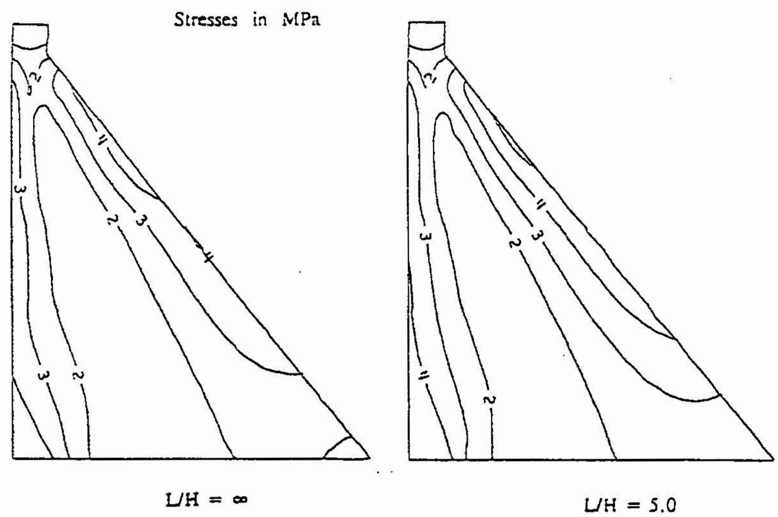

Figure 2 - Dynamic Tensile Stress Profile, Imperial Valley Earthquake Record

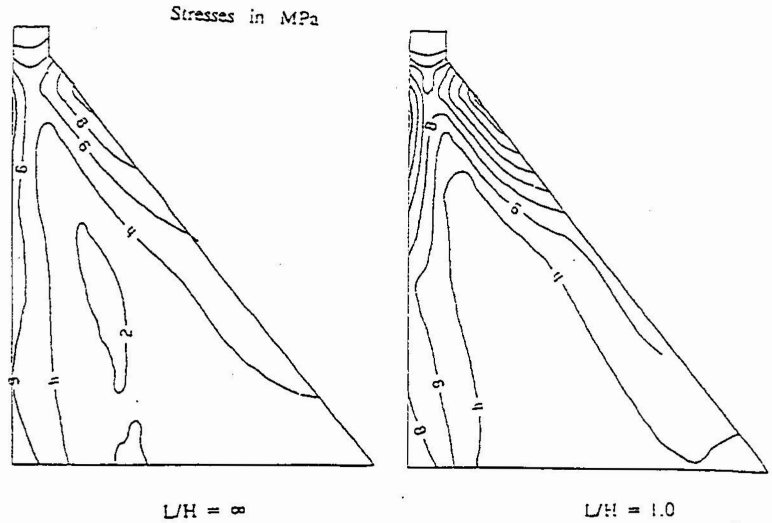

Figure 3 - Dynamic Tensile Stress Profile, Saguenay Earthquake Record

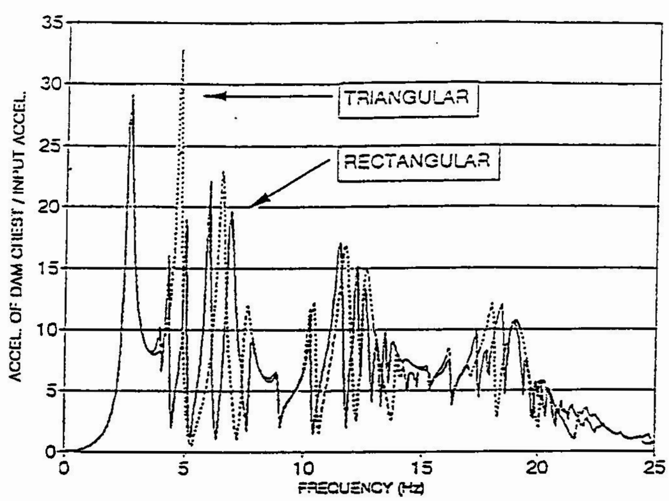

Figure 4 - Fourier Representation of monolith's response for
a rectangular and triangular reservoir geometry