

Modeling of dam-foundation interaction in analysis of arch dams

A. K. Chopra & H. Tan

University of California at Berkeley, Calif., USA

ABSTRACT: The limitations of "standard" earthquake analysis procedures for arch dams in modeling dam-foundation rock interaction effects are identified. Results from recently developed procedures demonstrate that the "standard" procedure fails to recognize the significant reduction in dam response arising from foundation material and radiation damping. The resulting overestimation of stresses in the dam may lead to overly conservative designs of new dams and to the erroneous conclusion that an existing dam is unsafe.

1 INTRODUCTION

Based on the substructure method, a procedure has been developed (Fok and Chopra 1986) to analyze the earthquake response of arch dams (Figure 1). Implemented in the computer program EACD-3D (Fok, Hall, and Chopra 1987), this analytical procedure considers the effects of dam-water interaction, water compressibility, and reservoir boundary absorption. These hydrodynamic effects have been shown to be significant in the earthquake response of arch dams.

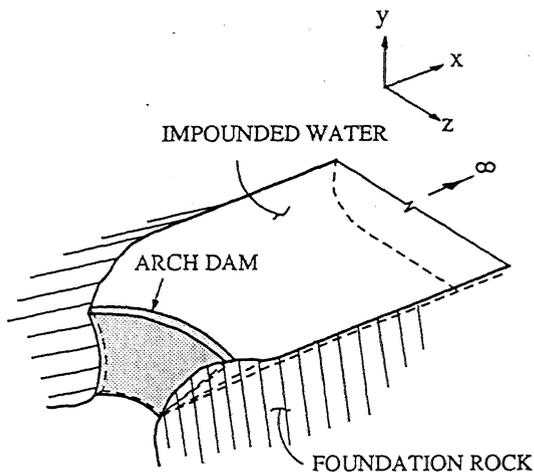


Figure 1. Arch dam-water-foundation rock system.

Required in the substructure method for earthquake analysis of concrete dams is the impedance matrix (or the frequency-dependent stiffness matrix) for the foundation rock region, defined at the finite element nodal points on the dam-foundation rock interface. Computation of this foundation impedance matrix for analysis of arch dams requires solution of a series of mixed boundary value problems governing the steady-state response of the canyon cut in a three-dimensional foundation rock region. Because such analyses are extremely complicated, usually only the foundation flexibility is considered in analysis of arch dams, i.e. material and radiation damping, as well as inertial effects of the foundation rock, are ignored. The objective of this work is to overcome these limitations and analyze the earthquake response of arch dams including dam-foundation rock interaction. Based on the results of such analyses, the significance of dam-foundation rock interaction effects in arch dam response is evaluated.

2 FOUNDATION IMPEDANCE MATRIX

The impedance matrix, $\underline{S}_f(\omega)$, where ω is the excitation frequency, relates the interaction forces $\underline{R}(t)$ at the dam-foundation rock interface, Γ_b , to the corresponding displacements, $\underline{r}(t)$, relative to the earthquake-induced displacements in the absence of the dam (Figure 2):

$$\underline{S}_f(\omega)\bar{\underline{r}}(\omega) = \bar{\underline{R}}(\omega) \quad (1)$$

where the overbar denotes a Fourier transform of the time functions. The square matrix, $\underline{S}_f(\omega)$, is of

the order equal to the number of degrees-of-freedom in the finite element idealization of the dam at the interface. The n^{th} column of this matrix multiplied by $e^{i\omega t}$ is the set of complex-valued forces required at the interface DOF to maintain a unit harmonic displacement, $e^{i\omega t}$, in the n^{th} DOF with zero displacements in all other DOF.

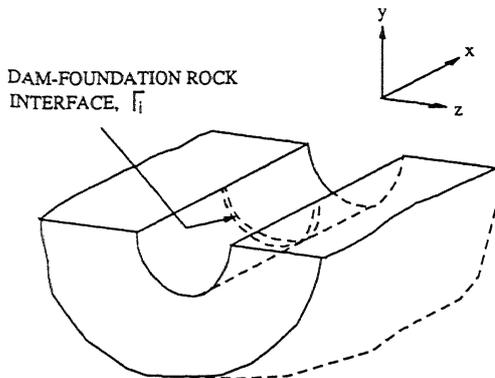


Figure 2. Infinitely-long canyon of arbitrary but uniform cross-section.

Evaluation of these forces requires solution of a series of mixed boundary value problems (BVP) with displacements prescribed at the interface, Γ_b , and tractions outside Γ_b --on the canyon wall and the half-space surface--are prescribed as zero. Instead of directly solving this mixed BVP, it is more convenient to solve a stress BVP in which non-zero tractions are specified at the interface, Γ_b , and the resulting displacements at Γ_i are determined. Assembled from these displacements, the dynamic flexibility influence matrix is inverted to determine the impedance matrix $\underline{S}_i(\omega)$.

A direct boundary element procedure has been developed to determine the impedance matrix associated with the nodal points at the base of a structure supported on a canyon cut in a homogeneous viscoelastic half-space (Zhang and Chopra 1991). The canyon is infinitely long and may be of arbitrary but uniform cross-section. The uniform cross-section of the canyon permits analytical integration along the canyon axis of the three-dimensional boundary integral equation. Thus, the original three-dimensional problem is reduced to an infinite series of two-dimensional problems, each of which corresponds to a particular wave number and involves Fourier transforms of full-space Green's functions. Appropriate superposition of the solutions of these

two dimensional boundary problems leads to a dynamic flexibility influence matrix which is inverted to determine the impedance matrix.

3 ANALYTICAL PROCEDURE

The computer program EACD-3D and our earlier results for earthquake response of arch dams were all for spatially-uniform ground motion at the dam-foundation rock interface and massless foundation rock. Analytical procedures have been developed and the computer program extended to use the dynamic stiffness matrix to model dam-foundation rock interaction. Based on the substructure method, this analytical procedure and computer program treats the dam as a finite element system; the fluid domain as a finite element system adjacent to the dam, with a wave-transmitting boundary at the upstream end of this region, and a partially wave-absorptive reservoir bottom to account for the effects of the foundation rock or overlying alluvium and sediments; and the foundation rock region as a homogeneous, viscoelastic half-space less the canyon--assumed as uniform--supporting the dam.

4 SYSTEM CONSIDERED

Numerical results are presented for the dynamic response of Morrow Point Dam, located on the Gunnison River in Colorado. It is a 465 ft. high, approximately symmetric, single-centered arch dam. For the purposes of dynamic analysis the dam is assumed to be symmetric about the x-y plane with the dimensions averaged from the two halves.

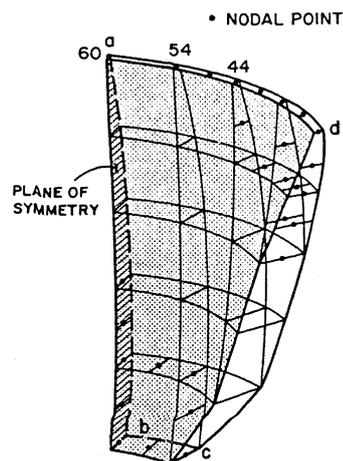


Figure 3. Finite element idealization of one-half of Morrow Point Dam.

The finite element idealization of one-half of the arch dam consists of 8 thick-shell finite elements in the main part of the dam and 8 transition elements in the part of the dam near its junction with the foundation rock, with a total of 61 nodal points (Figure 3). When dam-foundation interaction is considered, this idealization has approximately 300 degrees of freedom. The mass concrete of the dam is assumed to be homogeneous, isotropic, and linearly elastic with the following properties: Young's modulus = 4.0 million psi, unit weight = 155 pcf, and Poisson's ratio = 0.2. The constant hysteretic damping factor selected is 0.10, which corresponds to 5 percent damping in all natural vibration modes of the dam with an empty reservoir on rigid foundation rock.

The arch dam is supported in an infinitely-long canyon of uniform cross-section—defined by the geometry of the dam-foundation rock interface—cut in a homogeneous half-space. The properties of the rock are: Young's modulus = 1.0 million psi, unit weight = 165 pcf, Poisson's ratio = 0.2, and constant hysteretic damping factor = 0.10. The elastic modulus of the foundation rock has been chosen as a fraction of the modulus of dam concrete, an assumption that is appropriate in many practical situations because of joints in the foundation rock.

Because the objective of this paper is to investigate modeling of dam-foundation rock interaction and its effects, the water impounded behind the dam is not included in the system that is analyzed.

5 RESPONSE RESULTS

The dynamic response of the dam-foundation rock system described in the preceding section was analyzed for three conditions:

1. Dam on rigid foundation rock.
2. Dam-foundation rock system considering only foundation flexibility effects.
3. Dam-foundation rock system considering all interaction effects.

For each of these three cases, the complex frequency response functions were determined. These functions presented in Figures 4-6 are dimensionless response factors that represent the radial acceleration at one location at the dam crest due to unit, harmonic, free-field ground acceleration. The response of the dam to upstream or vertical ground motion is plotted at the crown location (nodal point 60 at the plane of symmetry in Figure 3). With the cross-section ground motion as the excitation, the response of the dam is presented at nodal point 54 on the dam crest (Figure 3) defined by $\theta = 13.25^\circ$ measured from the crown. The absolute value of the complex-valued frequency response function

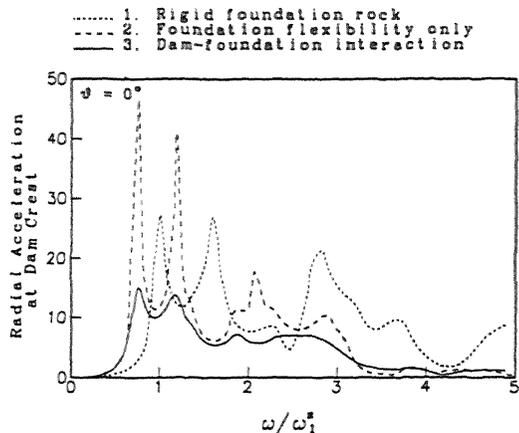


Figure 4. Response of dams to harmonic upstream ground motion for three foundation rock cases.

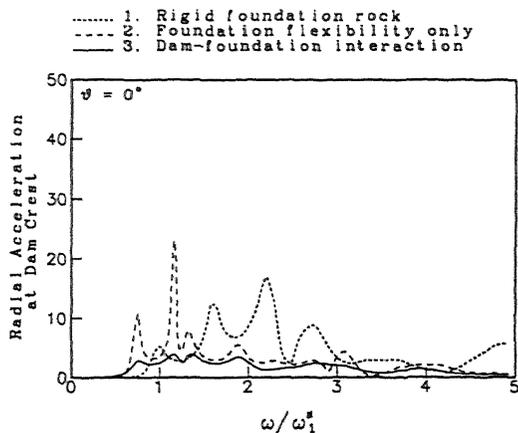


Figure 5. Response of dams to harmonic vertical ground motion for three foundation rock cases.

for acceleration is plotted in Figures 4-6 against the normalized excitation frequency parameter ω/ω_1 , where ω_1 is the fundamental natural vibration frequency of the dam without water on rigid foundation rock; ω_1^s is used as the normalizing factor for symmetric (upstream or vertical) ground motion, and ω_1^a is used for antisymmetric (cross-stream) ground motion.

The response of the dam supported on rigid foundation rock (Case 1) is characteristic of a multi-degree-of-freedom system with frequency-independent mass, stiffness, and damping matrices. In particular, the first resonance occurs at the fundamental natural vibration frequency of the dam: ω_1^s of the symmetric vibration mode in the case of upstream or vertical motion, or ω_1^a of the

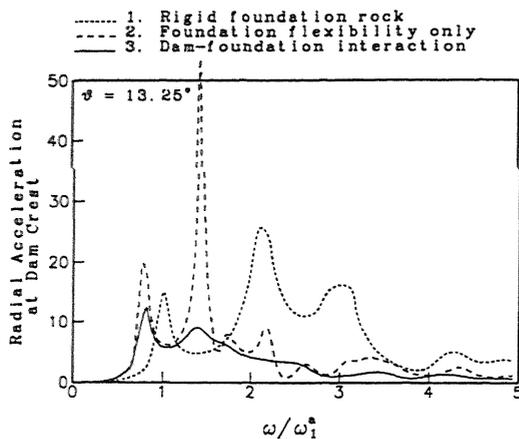


Figure 6. Response of dams to harmonic cross-stream ground motion for three foundation rock cases.

antisymmetric vibration mode in the case of cross-stream ground motion.

Because of foundation flexibility (Case 2), the fundamental resonant frequency of the dam decreases, the response at this frequency increases, and the frequency bandwidth at resonance decreases, implying a decrease in the apparent damping of the structure. The increase in response is, in part, due to the increase in the effective earthquake forces in individual vibration modes arising from modifications in the mode shape due to foundation flexibility. Similar but somewhat smaller effects of foundation flexibility are observed at higher resonant frequencies. These effects of foundation-rock flexibility are qualitatively similar in the response to the three components of ground motion.

When all aspects of dam-foundation rock interaction are considered (Case 3), the decrease in the fundamental resonant frequency is about the same as determined by considering foundation flexibility only. However, dam-foundation rock interaction reduces the amplitude of the fundamental resonant peak and increases the bandwidth at resonance because of material damping of foundation rock and radiation damping resulting from interaction. Similarly, dam-foundation interaction reduces the higher resonant frequencies—although to a lesser degree than the fundamental resonant frequency—and substantially reduces the amplitude of the higher resonant peaks. The above-mentioned effects of dam-foundation rock interaction are qualitatively similar in the response to the three components of ground motion.

6 CONCLUDING REMARKS

It is apparent from the limited response results presented that "standard" analyses of arch dams, wherein only the foundation flexibility is considered, are deficient in a major sense. In particular, the significant reduction in the dam response arising from foundation material and radiation damping is not recognized in the "standard" analyses. The resulting overestimation of stresses in the dam may lead to overconservative designs of new dams and to the erroneous conclusion that an existing dam is unsafe. Additional results showing the response of dams to realistic earthquake ground motion will be presented at the conference in order to quantify the significance of the above-mentioned limitation of "standard" analyses of arch dams.

ACKNOWLEDGEMENTS

This research investigation is supported by the National Science Foundation under Grant No. BCS-8719296. The authors are grateful for this support.

REFERENCES

- Fok, K-L. & A.K. Chopra 1986. Earthquake analysis of arch dams including dam-water interaction, reservoir boundary absorption and foundation flexibility. *Earthquake Engineering and Structural Dynamics* 14:155-184.
- Fok, K-L., J.F. Hall & A.K. Chopra 1986. *EACD-3D: A computer program for three-dimensional earthquake analysis of concrete dams*, Report No. UCB/EERC-86/09, Earthquake Engineering Research Center, University of California, Berkeley, July, 144 pages.
- Zhang, L-P. & A.K. Chopra 1991. Impedance functions for three-dimensional foundations supported on an infinitely long canyon of uniform cross-section in a homogeneous half-space. *Earthquake Engineering and Structural Dynamics* 20:1011-1028.