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EFFECT OF NONUNIFORM SEISMIC INPUT ON ARCH DAM RESPONSE

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SUMMARY

The response of Pacoima (arch) Dam to uniform and nonuniform ground motion is examined. The important effect of nonuniformities in the free-field motions, sometimes leading to a decrease in the dam response and sometimes to an increase, is quantified.

INTRODUCTION

Standard earthquake analyses of arch dams use uniform ground motions even though considerable variations in both amplitude and phase are known to occur along the foundation interface (Ref. 1). The few studies of this effect agree that nonuniformity in seismic input is important, but assessments vary from beneficial (Ref. 2) to detrimental (Refs. 3 and 4). Thus, seismic input for arch dams deserves further examination.

FORMULATION

Free-field motions at the surface of the canyon are computed by the Boundary Element Method for incident plane waves in a 2-D half space containing the canyon (Fig. 1). Thus, no variations occur in the stream direction. SH waves produce the stream component (S) of the excitation, and P and SV waves produce the perpendicular components, cross-stream (C) and vertical (V). The BEM solutions agree with others obtained by different methods (Ref. 5). Although the input mechanism is simplified compared to that of an earthquake, it is hoped that the resulting amplitude and phase variations are representative.

Given the free-field motions, the earthquake response of the dam (assumed linear) is computed by the finite element method. A pseudo-static component $\{U^S\}$ is obtained from

$$\begin{Bmatrix} U_d^S \\ U_i^S \end{Bmatrix} = \begin{Bmatrix} -K_{dd}^{-1}K_{di}\ U_i^{ff} \\ U_i^{ff} \end{Bmatrix} - \begin{bmatrix} K_{dd} & K_{di} \\ K_{di}^T & K_{ii}+\bar{K}_{ii} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ K_{ii} - K_{di}^T K_{dd}^{-1} K_{di} \end{bmatrix} \left\{U_i^{ff}\right\} \quad (1)$$

where degrees of freedom of the dam are partitioned into those off (subscript d) and on (subscript i) the foundation interface; $[K]$ = stiffness matrix of the dam; $[\bar{K}_{ii}]$ = stiffness matrix of the foundation condensed to the interface degrees of freedom (massless foundation assumed), and $\left\{U_i^{ff}\right\}$ contains the free-field displacements. The pseudo-static solution $\{U^S\}$ is the earthquake response of a massless dam with empty reservoir and foundation interaction included. During the earthquake, the external forces required for the dam to vibrate as $\{U^S\}$, considering the case of no viscous damping, are

$$\left\{\begin{matrix} F_d^S \\ F_i^S \end{matrix}\right\} = \begin{bmatrix} M_{dd} & M_{di} \\ M_{di}^T & M_{ii} \end{bmatrix} \left\{\begin{matrix} \ddot{U}_d^S \\ \ddot{U}_i^S \end{matrix}\right\} - \left\{\begin{matrix} R_d^S \\ R_i^S \end{matrix}\right\} - \left\{\begin{matrix} R_d^C \\ R_i^C \end{matrix}\right\} \tag{2}$$

where $[M]$ = mass matrix of the dam; $\left\{R^S\right\}$ = vector of water forces on the dam generated by the pseudo-static motions of the dam; and $\left\{R^C\right\}$ = similar vector generated by earthquake excitations at the reservoir floor and sides. Equation 2 requires that certain terms owing to interaction between the dam and water through the foundation be neglected (Ref. 6). Removal of the forces $\left\{F^S\right\}$ from the dam-water-foundation system produces the dynamic component $\left\{U^D\right\}$ of the dam response computed from

$$\begin{bmatrix} K_{dd} & K_{di} \\ K_{di}^T & K_{ii} + \bar{K}_{ii} \end{bmatrix} \left\{\begin{matrix} U_d^D \\ U_i^D \end{matrix}\right\} + \begin{bmatrix} M_{dd} + \hat{M}_{dd} & M_{di} + \hat{M}_{di} \\ M_{di}^T + \hat{M}_{di}^T & M_{ii} + \hat{M}_{ii} \end{bmatrix} \left\{\begin{matrix} \ddot{U}_d^D \\ \ddot{U}_i^D \end{matrix}\right\} = - \left\{\begin{matrix} F_d^S \\ F_i^S \end{matrix}\right\} \tag{3}$$

where $[\hat{M}]$ is the added mass matrix of the water, frequency dependent if water compressibility is considered. For this case, a frequency-domain solution of equations 1 to 3 is employed; hydrodynamic terms are computed as described in Ref. 6. Equation 3 is solved using dam-foundation eigenvectors as generalized coordinates which are assigned modal damping values to approximately represent viscous effects plus foundation radiation. The total earthquake response is obtained as

$$\{U\} = \left\{U^S\right\} + \left\{U^D\right\} . \tag{4}$$

From the frequency-domain solution, say for some response $r(\omega)$, the standard deviation of the response $r(t)$ over time (zero mean) is computed as

$$\sigma_r = \left(\int_{-\infty}^{\infty} \left|H_r(\omega)\right|^2 S(\omega)\, d\omega \right)^{1/2} \tag{4}$$

where $H_r(\omega)$ = transfer function, $S(\omega)$ is the power spectral density of the time history of the incident wave, and ω = frequency. To impart earthquake-like frequencies to the incident wave, $S(\omega)$ is taken proportional to the squared modulus of an average Fourier transform of horizontal ground motion on rock near a M = 7.5 earthquake (Ref. 7).

RESULTS

The system considered (Fig. 2) is the 111 m high Pacoima Dam with full reservoir: Young's modulus = 20,700 MPa (concrete) and 13,800 MPa (rock), specific gravity = 2.40 (concrete) and 2.64 (rock, for free-field computation only), 5% modal damping, and compressible water with a 0.85 reflection coefficient along the reservoir floor and sides (Ref. 6); the rock shear wave speed is 1475 m/sec. Six excitations are employed as specified in the following table. The last column gives the sum of incident and reflected amplitudes at a (horizontal) free surface; thus, the first three cases (stream excitation) are consistent and the last three cases (cross-vertical excitation) approximately so. Looking upstream, positive directions are forward (S), upward (V), right (C), and counter-clockwise from vertical (angle of incidence). Although the reservoir is modeled as infinite by a transmitting boundary, excitations to the water along the canyon (term $\{R_c\}$) are applied only within 180 m of the dam.

Case	Type	Wave	Angle of Incidence	Dir. of Motion	Amplitude of Uniform Excitation or Incident Wave	Surface Amplitude of Incident Wave with Reflection
U-S	uniform	—	—	S	1	—
SH0	incident	SH	0°	S	$\frac{1}{2}$	1
SH60	incident	SH	60°	S	$\frac{1}{2}$	1
U-CV	uniform	—	—	C,V	-1 (C), $\frac{1}{2}$ (V)	—
SVP0	incident	SV,P	0°	C,V	$-\frac{1}{2}$ (SV), $\frac{1}{4}$ (P)	-1 (C), $\frac{1}{2}$ (V)
P60	incident	P	60°	C,V	$\frac{1}{2}$	-0.93 (C), 0.45 (V)

Only a few results for arch stresses, which significantly exceed the cantilever stresses, are presented. These results include both the pseudo-static and dynamic components of the earthquake response, but no gravity stresses. Frequency-domain responses of the arch stress at the upstream side of the crest at the center (Fig. 3) reveal the importance of nonuniform seismic input. For stream excitation, the responses due to incident waves are less than those due to uniform ground motion, while for cross-vertical excitation, the responses due to uniform excitation lie between the two incident wave cases. The large increase with the P60 excitation is primarily in the fundamental *symmetric* mode and is produced by considerable bank-to-bank nonuniformity in the *cross-stream* component of this excitation, attributable to the nearly horizontal incidence and, thus, absent for cases U-CV and SVP0. Contours of the time-domain standard deviations of the arch stresses, the largest from the upstream and downstream faces, (Fig. 4) quantify the effect of nonuniform seismic input. Condensing the results, averages of these stresses along the crest expressed as a percent of the average for the uniform stream excitation are 100% U-S, 62% SH0, 73% SH60, 78% U-CV, 63% SVP0 and 122% P60. Incidently, similar figures for the case of empty reservoir are 89% U-S, 47% SH0, 66% SH60, 46% U-CV, 48% SVP0 and 62% P60.

The pseudo-static contribution to the stresses in Fig. 4 is largest near the perimeter of the dam and reaches the 27% level (case SVP0), but is generally much smaller away from the perimeter.

CONCLUSIONS

Response of a typical large concrete arch dam is sensitive to the excitation mechanism. Results from the example studied suggest that incident waves produce largest responses when arriving at angles closer to horizontal. Stress levels generated by incident SH waves (used for excitation in the stream direction) may be only 60% to 70% those due to uniform ground motion; effects of incident P and SV waves (used for excitation perpendicular to the stream) are more variable with the potential for a significant increase. Additional work is needed to identify realistic patterns of incident waves for use in subsequent analyses.

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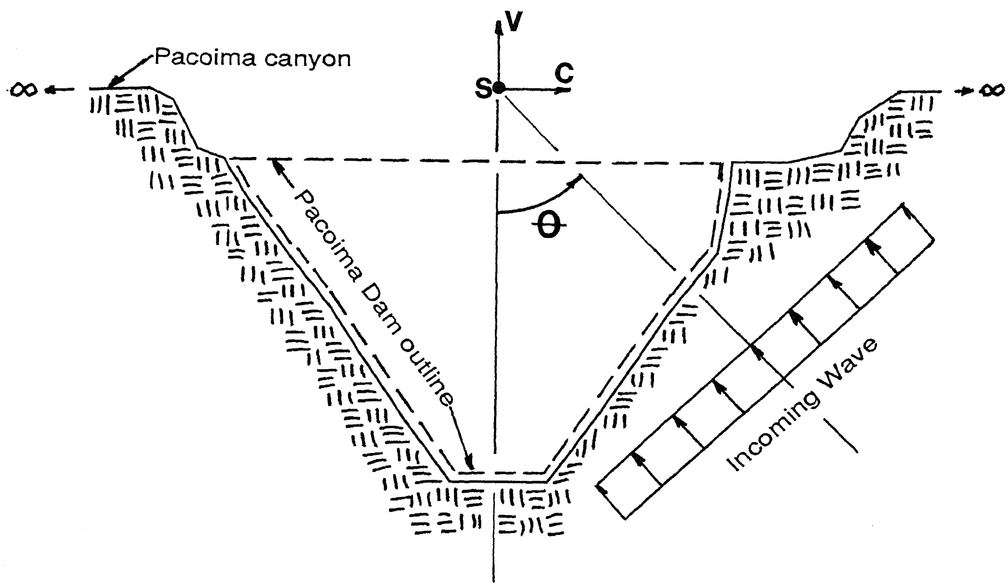

Figure 1. Incident wave problem for Pacoima canyon

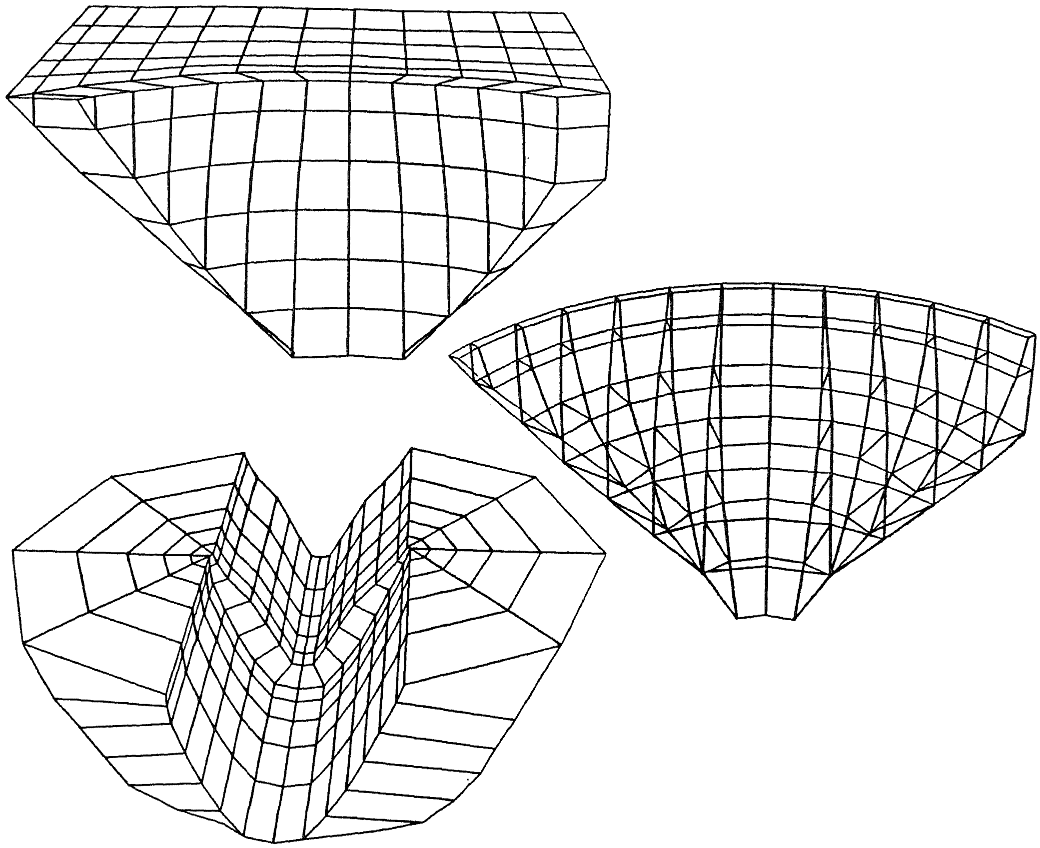

Figure 2. Finite element meshes of Pacoima Dam, water and foundation.

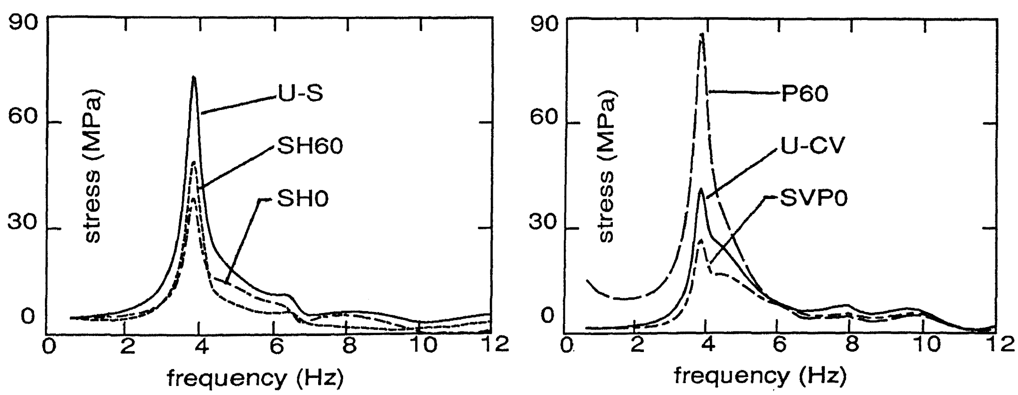

Figure 3. Frequency domain responses for the total (pseudo-static plus dynamic) arch stress on the upstream side of the crest at the center due to the excitations listed in the table (amplitudes times 1g).

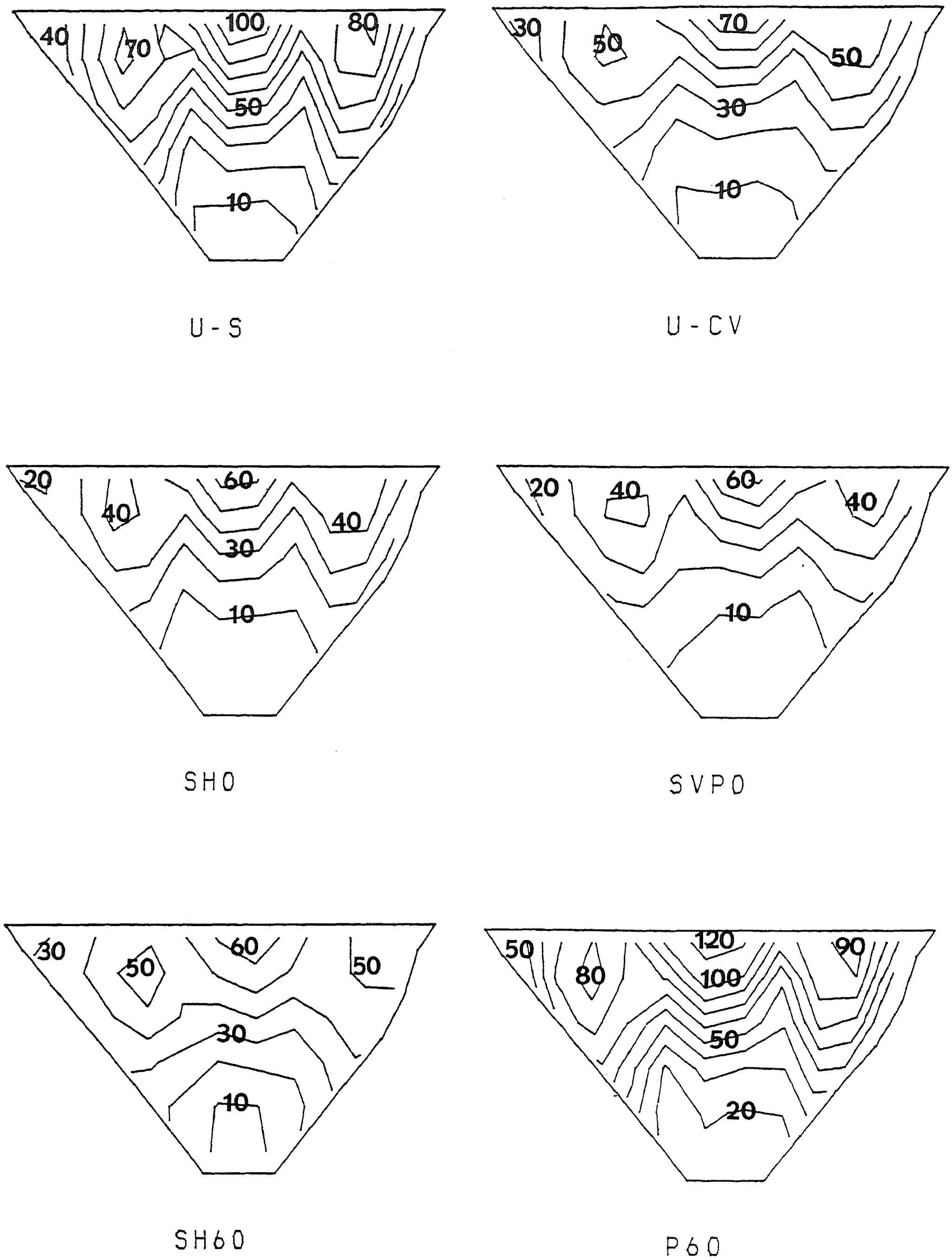

Figure 4. Contours of the standard deviations over time of the total (pseudo-static plus dynamic) arch stresses for a M = 7.5 earthquake normalized with the arch stress at the center crest for excitation U-S.