EFFECTS OF RESERVOIR BOUNDARY ABSORPTION ON THE EARTHQUAKE RESPONSE OF ARCH DAMS

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ABSTRACT :

A procedure is developed for the earthquake response analysis of dam–reservoir-foundation system. The arch/gravity dam and a near filed foundation region are modeled with finite elements (FE), while the infinite fluid domain and the unbounded foundation are modeled with scaled boundary finite elements (SBFE). SBFE can be coupled seamlessly with FE and only the interface with FE needs to be discretized. The effects of water compressibility and reservoir boundary absorption on the earthquake response of an arch dam have been investigated for a wide range of wave reflection coefficient. It was found that reservoir boundary absorption introduces an added damping to the dam-reservoir-foundation system and reduces the hydrodynamic pressure on dam face considerably. Inclusion of water compressibility and reservoir boundary absorption is essential to predict the earthquake response of arch dams and to evaluate the earthquake safety of existing dams.

KEYWORDS: dam-reservoir-foundation interaction, reservoir boundary absorption, earthquake response, arch dam

1. INTRODUCTION

The hydrodynamic effects have been shown to be significant in the earthquake response of arch dams. Prof. Chopra and his co-workers led the pioneer research in this field (Hall and Chopra 1983, Fok and Chopra 1986, Tan and Chopra 1995). However, as the model is somewhat complicated and associates with large computational effort, its implementation in the engineering practice is difficult, which obstructs to get a clear understanding of the effects of reservoir boundary absorption on the earthquake response of arch dams. In this paper, based on the Scaled Boundary Finite Element (SBFE) method (Wolf and Song, 2000), a procedure is developed to analyze the earthquake response of arch dams. The effects of dam-reservoir interaction and dam-unbounded foundation interaction are considered. Emphasis is placed on the effects of water compressibility and reservoir boundary absorption on the earthquake response of concrete arch dams.

2. EARTHQUAKE RESPONSE OF DAM-RESERVOIR-FOUNDATION SYSTEM

The earthquake analysis of the dam-reservoir-foundation system is performed in the frequency domain, and the results are converted into time domain through Fast Fourier Transformation method. In the case of arch dams, the dam and a finite bounded foundation region adjacent to the dam (near field), as shown in the Fig.1 are idealized as finite element system. The surrounding unbounded foundation region is treated as a SBFE system. Coupling of SBFE with FE can be performed seamlessly. Because the canyon shape of arch dams is usually complicated in nature, applying SBFE to model the unbounded foundation straight forwardly associates with considerable difficulties. A cone model is developed to simulate the effect of unbounded foundation on the earthquake response of arch dams. It has been shown that very good agreement with results of rigorous solution can be achieved by adjusting the aspect ratio or the open angle of the truncated cone (Lin, Du and Hu, 2007A.).

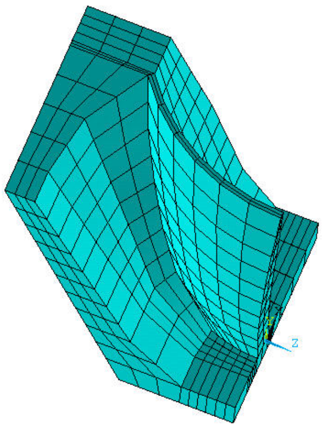
To assist in the solution of the earthquake response of dam-reservoir-foundation system, the total displacement vector $\{u^t\}$ is separated into a quasi-static vector $\{\hat{u}\}$ and a dynamic vector $\{\tilde{u}\}$ as follows:

$$\begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} \hat{u}_s \\ \hat{u}_b \end{Bmatrix} + \begin{Bmatrix} \tilde{u}_s \\ \tilde{u}_b \end{Bmatrix} \tag{2.1}$$

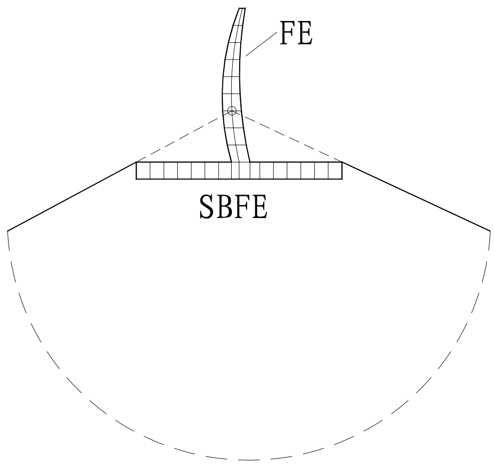
where the subscript b denotes the degree of freedom (DOF) at the interface of the near field and the unbounded far field of the foundation, and the subscript s the remaining DOF of the dam and the near field of the foundation. Then the governing equations of the dam-reservoir-foundation system can be expressed in the following form:

$$\begin{aligned} &\left(-\omega^2 \begin{bmatrix} [M_{ss}] & [M_{sb}] \\ [M_{bs}] & [M_{bb}] \end{bmatrix} + (1+i2\zeta) \begin{bmatrix} [K_{ss}] & [K_{sb}] \\ [K_{bs}] & [K_{bb}] \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & [S_b^\infty(\omega)] \end{bmatrix} - \omega^2 \begin{bmatrix} [Q_p(\omega)] \\ 0 \end{bmatrix} \right) \begin{Bmatrix} \tilde{u}_s(\infty) \\ \tilde{u}_b(\infty) \end{Bmatrix} \\ &= \omega^2 \begin{bmatrix} [M_{ss}] & [M_{sb}] \\ [M_{bs}] & [M_{bb}] \end{bmatrix} \begin{bmatrix} T_{Sb} \\ I \end{bmatrix} \{u_g(\omega)\} + \omega^2 \begin{Bmatrix} [Q_0] \\ 0 \end{Bmatrix} \{u_g(\omega)\} \end{aligned} \tag{2.2}$$

in which [M] and [K] are the mass and stiffness matrices for the finite element system of the dam and the near field of the foundation adjacent to the dam ; 2ζ is the hysteretic damping of the system, ζ is the viscous damping ratio, ζ=0.05; $[S_b^\infty]$ is the dynamic stiffness of the far field of the unbounded foundation, it is a function of the exciting frequency ω; $[Q_p]$ arises from the hydrodynamic pressure acting on the dam face due to motions of the dam relative to its base, which depends on the exciting frequency ω; $[Q_0]$ associates with the hydrodynamic pressures acting on the dam face due to ground acceleration while the dam is rigid, it also depends on the exciting frequency ω; $\{u_g(\omega)\}$ is the earthquake ground motion input in the frequency domain and $[T_{sb}] = -[K_{ss}]^{-1}[K_{sb}]$. As the purpose of this paper is to study the effects of reservoir boundary absorption on the earthquake response of arch dams, a uniform earthquake input is assumed to simplify the computation and it is specified along the boundary between the near field and the unbounded far field of the foundation. Few measurements of actual earthquake ground motion variations have been obtained at the real dam sites.



(a) FE discretization of the dam and the near field foundation



(b) Coupling of the dam and the near field foundation with the far field unbounded foundation

Fig.1 Idealization of the dam and the unbounded foundation

The earthquake input motion as well as the response displacements of the structure in the frequency domain and in the time domain form the Fourier transform pair

$$u(\omega)=\int_{-\infty}^{+\infty}u(t)\exp(-i\omega t)dt, \qquad u(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}u(\omega)\exp(i\omega t)d\omega \tag{2.3}$$

3. HYDRODYNAMIC ANALYSIS BASED ON SBFEM

Assuming the motion of water to be irrotational and neglecting the viscous effects, the hydrodynamic pressure *p*, generated in the reservoir in excess of the static pressure is governed by the Helmholtz equation (in the frequency domain) :

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}+\frac{\omega^2}{c^2}p=0 \tag{3.1}$$

The boundary conditions to be satisfied are as follows:

along the dam-fluid interface $\quad p_{,n}=-\rho\ddot{u}_n \quad$ (3.2a)

along the reservoir bottom and sides $\quad p_{,n}=-\rho\ddot{v}_n+q\dot{p} \quad$ (3.2b)

at the free surface of water $\quad p=0 \quad$ (3.2c)

in which c is the velocity of compression waves in water; ρ is the mass density of water; $\ddot{u}_n$ and $\ddot{v}_n$ are the inward normal component of the acceleration of upstream dam face and of the reservoir boundary respectively. The last term in Eq. (3.2b) accounts for interaction between the fluid and the foundation medium. q is related to the wave reflection coefficient α by the following expression

$$q=\frac{1}{c}\frac{1-\alpha}{1+\alpha} \tag{3.3}$$

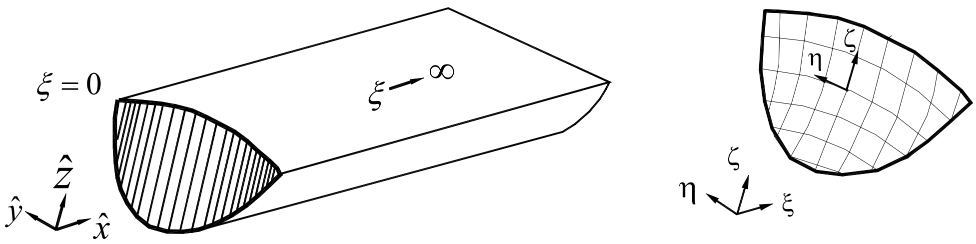


Fig. 2 Scaled boundary coordinates of the reservoir domain and its boundary

Based on the SBFE method with the scaled boundary coordinates chosen as shown in Fig.2 and the scaling center located at the negative infinity, Eqs.(3.1) and (3.2) are transformed into the following form (Lin, Du and Hu, 2007B.)

$$
\begin{aligned}
&[E^0]\{p(\xi,\omega)\}_{,\xi\xi}+([E^1]^T-[E^1])\{p(\xi,\omega)\}_{,\xi}+ \\
&(\omega^2[M^0]-i\omega q[C^0]-[E^2])\{p(\xi,\omega)\}-\rho[C^0]\{\ddot{v}_n\}=0
\end{aligned}
\tag{3.4}
$$

$$
([E^0]\{p(\xi,\omega)\}_{,\xi}+[E^1]^T\{p(\xi,\omega)\}-[M^1]\{\ddot{u}_n\})\Big|_{\xi=0}=0 \tag{3.5}
$$

The second-order ordinary differential equations (3.4) are the basic equations for evaluating the hydrodynamic pressures, while Eq.(3.5) is the boundary condition to be satisfied at the upstream dam surface ξ=0. In which the coefficient matrices $[E^0],[E^1],[E^2],[M^0],[C^0]$ and $[M^1]$ are determined as in the FEM. It is worth nothing that they are independent of ξ, which enables the integration to the performed only over the dam face. Eq.(3.4) is transformed into the first-order ordinary differential equations

$$
\{X(\xi,\omega)\}_{,\xi}=[Z]\{X(\xi,\omega)\}+\begin{Bmatrix}0\\ \{F\}\end{Bmatrix} \tag{3.6}
$$

by introducing the extended variables

$$
\{X(\xi,\omega)\}=\begin{Bmatrix}\{p(\xi,\omega)\}\\ \{R(\xi,\omega)\}\end{Bmatrix} \tag{3.7}
$$

with the coefficient matrices

$$
[Z]=\begin{bmatrix}-[E^0]^{-1}[E^1]^T & [E^0]^{-1}\\ [E^2]-[E^1][E^0]^{-1}[E^1]^T-\omega^2[M^0]+i\omega q[C^0] & [E^1][E^0]^{-1}\end{bmatrix} \tag{3.8}
$$

$$
\{F\}=\rho[C^0]\{\ddot{v}_n\} \tag{3.9}
$$

In Eq. (3.7) $\{R(\xi,\omega)\}$ is the nodal load resulting from the hydrodynamic pressure

$$
\{R(\xi,\omega)\}=[E^0]\{p(\xi,\omega)\}_{,\xi}+[E^1]^T\{p(\xi,\omega)\} \tag{3.10}
$$

The eigenvalue problem of [Z] is solved

$$
[Z][\Phi]=[\Phi][\Lambda] \tag{3.11}
$$

with the eigenvalues and eigenvectors partitioned as below

$$
[\Lambda]=\begin{bmatrix}-[\lambda_i] & 0\\ 0 & [\lambda_i]\end{bmatrix},[\Phi]=\begin{bmatrix}[\Phi_{11}] & [\Phi_{12}]\\ [\Phi_{21}] & [\Phi_{22}]\end{bmatrix} \tag{3.12}
$$

The real parts of all elements λ_i are negative. The solution of Eq. (3.6) is found to be

$$
\{X\}=\begin{Bmatrix}\{p(\xi)\}\\ \{R(\xi)\}\end{Bmatrix}=\begin{bmatrix}[\Phi_{11}] & [\Phi_{12}]\\ [\Phi_{21}] & [\Phi_{22}]\end{bmatrix}\begin{bmatrix}e^{-[\lambda_i]} & 0\\ 0 & e^{[\lambda_i]}\end{bmatrix}\begin{Bmatrix}\{c_1(\xi)\}\\ \{c_2(\xi)\}\end{Bmatrix} \tag{3.13}
$$

$\{c_1(\xi)\}$ and $\{c_2(\xi)\}$ are determined by boundary conditions. In case of earthquake wave exciting in the stream direction only $\{\ddot{v}_n\}=0$, we get the hydrodynamic pressure acting on the upstream face of the dam

$$\{p(\xi=0)\}=[\Phi_{12}][\Phi_{22}]^{-1}[M^1]\{\ddot{u}_n\} \tag{3.14}$$

The coupling between the fluid and the dam structure is accomplished at the interface by converting the hydrodynamic pressure into nodal force.

$$\{F\}=[L]^T[M^1]^T[\Phi_{12}][\Phi_{22}]^{-1}[M^1][L]\{\ddot{u}\}=[Q]\{\ddot{u}\} \tag{3.15}$$

$$[L]=\begin{bmatrix}[\lambda_1] & & & \\ & [\lambda_2] & & \\ & & \ddots & \\ & & & [\lambda_m]\end{bmatrix},[\lambda_i]=\begin{bmatrix}\lambda_{xi} & & \\ & \lambda_{yi} & \\ & & \lambda_{zi}\end{bmatrix}\ (i=1,2,\cdots m) \tag{3.16a}$$

$$\{u\}=[\{u_1\}\{u_2\}\cdots\{u_m\}]^T,\quad \{u_i\}=[u_{ix}\quad u_{iy}\quad u_{iz}]^T\quad (i=1,2,\ldots\ldots,m) \tag{3.16b}$$

where $\lambda_{xi},\lambda_{yi},\lambda_{zi}$ are the direction cosines of the inward normal at node i and m is the total number of nodes on the upstream dam face.

When earthquake wave excites in the cross-stream direction or in the vertical direction, the hydrodynamic pressure on the dam face becomes

$$\{p(\xi=0)\}=[\Phi_{12}][\Phi_{22}]^{-1}([M^1]\{\ddot{u}_n\}+\{B_1\})-\{B_2\} \tag{3.17}$$

$$\{B_1\}=([\Phi_{21}][\lambda_i]^{-1}[\mathrm{A}_{12}]-[\Phi_{22}][\lambda_i]^{-1}[\mathrm{A}_{22}])\rho[C^0]\{\ddot{v}_n\} \tag{3.18a}$$

$$\{B_2\}=([\Phi_{11}][\lambda_i]^{-1}[\mathrm{A}_{12}]-[\Phi_{12}][\lambda_i]^{-1}[\mathrm{A}_{22}])\rho[C^0]\{\ddot{v}_n\} \tag{3.18b}$$

where $[A]$ is the inverse of $[\Phi]$.

The effectiveness and accuracy of the proposed procedure were verified by comparison with the results of Fok and Chopra (1984) for the hydrodynamic force on the rigid face of Morrow Point Arch Dam. The total hydrodynamic forces acting on half of the dam due to upstream, vertical and cross-stream motion are shown in Fig.3, 5, 6 respectively. The hydrodynamic force is normalized with respect to the hydrostatic force $F_{st}=0.416\rho g H^3$, and the excitation frequency is normalized with respect to the first resonant frequency of the infinite reservoir with rigid boundary $\omega_{1r}=\pi c/2H$. Results of Fok and Chopra(1986A) for the case of earthquake wave excitation in the stream direction is shown in Fig.4. Curves of Fok and Chopra and those of ours agree well, however, the computational efforts in our case were saved considerably.

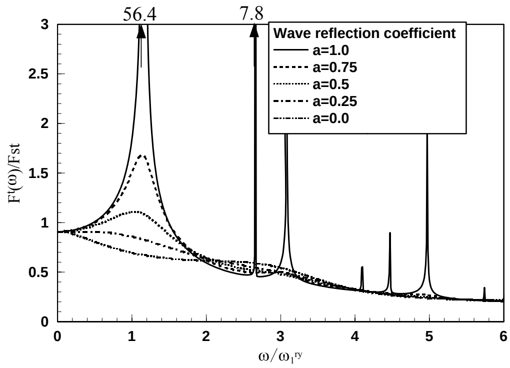


Fig.3 Hydrodynamic force on dam face due to excitation in the stream direction (present solution)

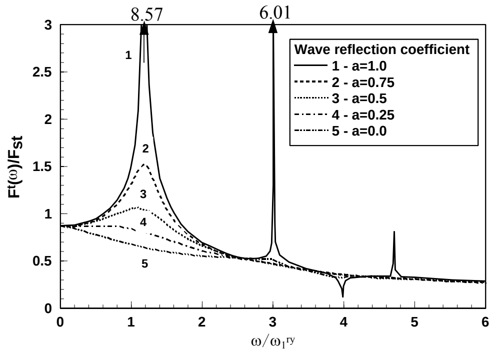


Fig.4 Hydrodynamic force on dam face due to excitation in the stream direction (Fok and Chopra,1986)

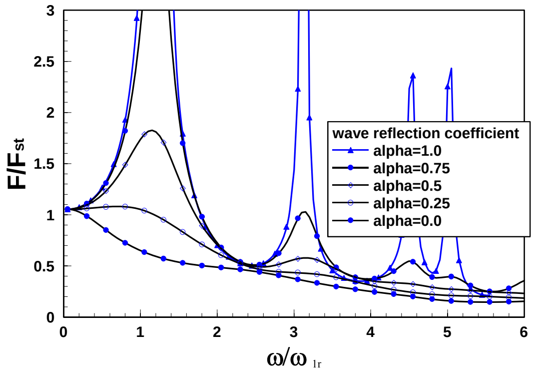


Fig.5 Hydrodynamic force on dam face due to excitation in the vertical direction

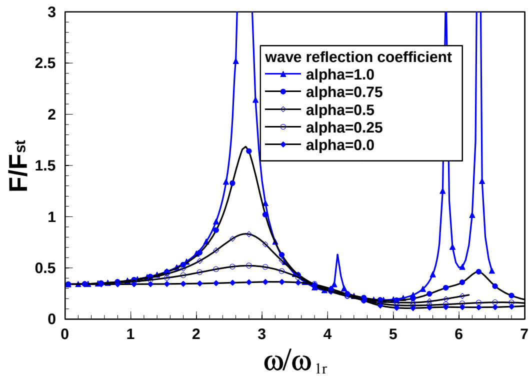


Fig.6 Hydrodynamic force on dam face due to excitation in the cross-stream direction

4. EFFECTS OF WATER COMPRESSIBILITY AND RESERVOIR BOUNDARY ABSORPTION

Effects of hydrodynamic pressure wave absorption at the reservoir boundary on the earthquake response of arch dam were studied for a wide range of wave reflection coefficient α, defined as the ratio of amplitudes of reflected hydrodynamic pressure wave to the amplitudes of a normally incident wave on the reservoir boundary.

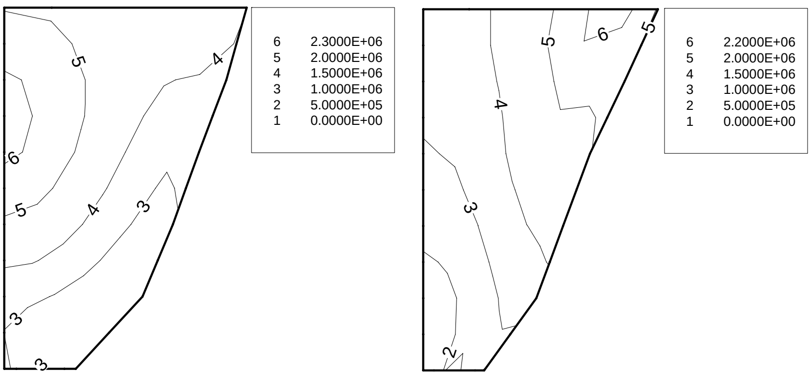
The arch dam selected for this study is the Morrow Point Dam. The dam is assumed symmetric, only half the dam, fluid domain and unbounded foundation domain need to be considered. The FE idealization of one-half of the arch dam and the near field foundation consist of 816 nodal points (2362DOF). The fluid domain and the far field unbounded foundation are modeled with SBFE, only the interface is discretized, 77 nodes and 274 nodes respectively were used. The material properties of the dam-reservoir-foundation system for this study are as follows. For the mass concrete of the dam, Young's modulus E_d=21GPa, unit mass ρ_d=2400kg/m^3, Poisson's ratio ν_d=0.17, and the constant hysteretic damping factor 0.1, which corresponds to a viscous damping ratio ζ=0.05. For the foundation rock, Young's modulus E_f=6.9GPa, unit mass ρ_f=2000kg/m^3, Poisson's ratio ν_f=0.2, and the constant hysteretic damping factor 0.1.

The Koyna earthquake record is used for the ground motion input, the peak acceleration is assigned as 0.2g. Because the objective of this research is to investigate the effects of absorption of the reservoir boundary on the dam response, the excitation of earthquake ground motion is assumed in the stream direction only, which makes a major contribution to the dam response in comparison with the vertical and cross-stream components of the ground motion.

Envelop values of maximum principal stresses (in Pa) of the dam-reservoir-foundation system of Morrow Point project for values of wave reflection coefficient α=0.25, 0.5, 0.75, 0.95 respectively are shown in Fig.7(a) to (d). For comparison, cases neglecting water compressibility were also studied. Under this circumstance, the hydrodynamic effect is equivalent to an added mass moving with the structure. Two approaches were used for the determination of added mass matrix [M_f]: a rigorous approach, [M_f] is evaluated by SBFE method, which is a full matrix and a simplified approach, [M_f] is approximated by a diagonal matrix and the diagonal terms are determined according to the Westergaard's classical formula.

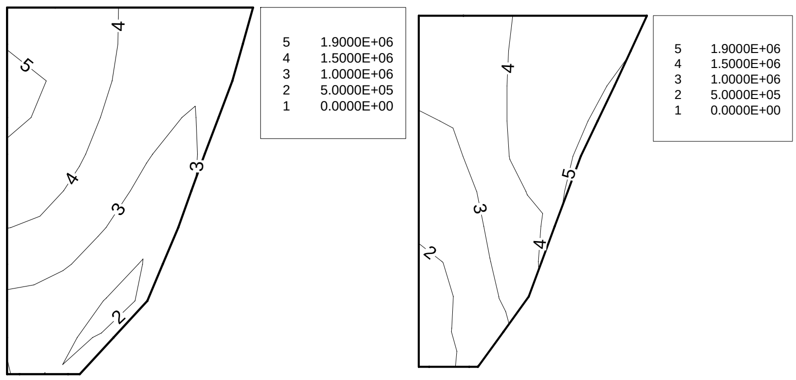
Envelope values of maximum principle stresses for incompressible water are also shown in Fig.7. In all cases, initial static stresses are excluded.

Results showing the cases of earthquake ground motion exciting in the vertical direction and in the cross-stream direction for wave reflection coefficient α=0.5 are depicted in Fig.8.



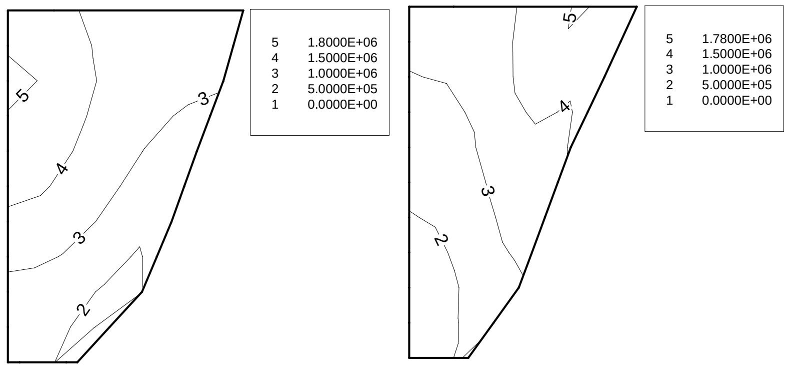
Upstream surface Downstream surface

(a) α=0.95



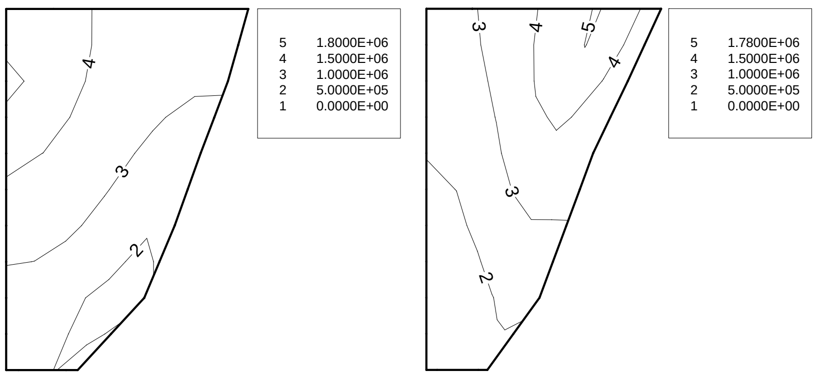
Upstream surface Downstream surface

(b) α=0.75



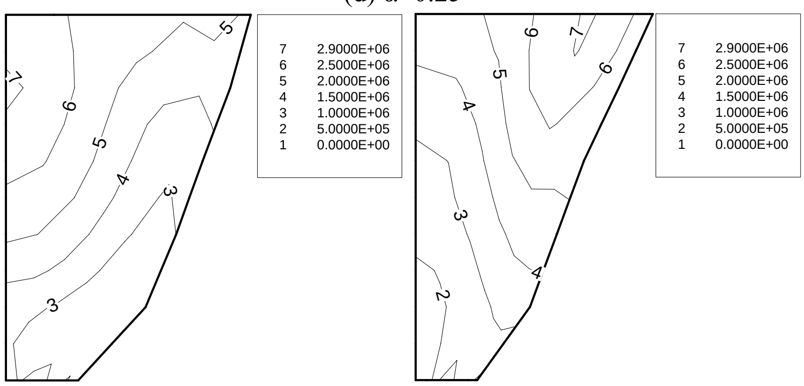
Upstream surface Downstream surface

(c) α=0. 5



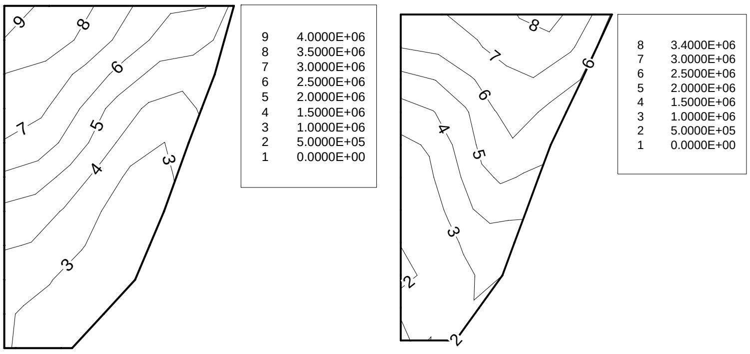
Upstream surface Downstream surface

(d) α=0.25



Upstream surface Downstream surface

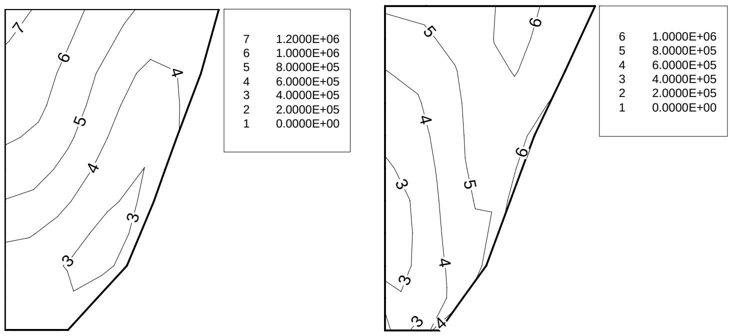
(e) incompressible water, rigorous added mass formulation



Upstream surface Downstream surface

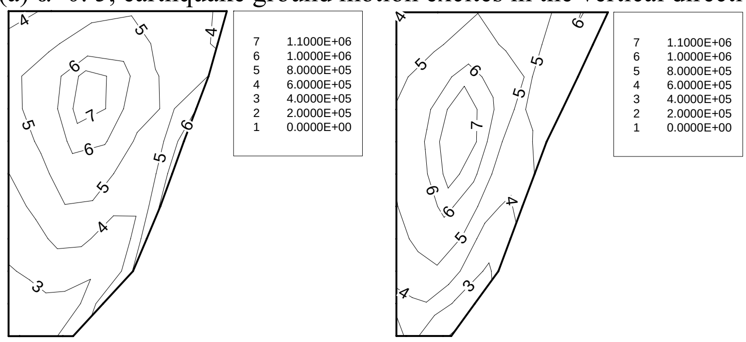
(f) incompressible water, simplified added mass formulation

Fig.7 Envelope values of maximum principal stresses of Morrow Point Dam due to upstream component of earthquake ground motion



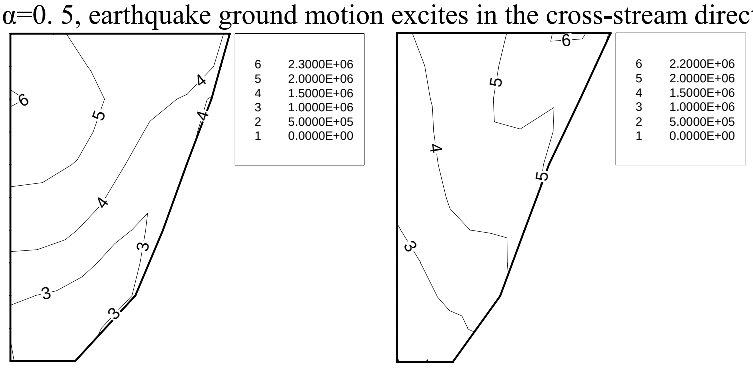
Upstream surface Downstream surface

(a) α=0. 5, earthquake ground motion excites in the vertical direction



Upstream surface Downstream surface

(b) α=0. 5, earthquake ground motion excites in the cross-stream direction



(c) α=0. 5, earthquake ground motion excites in all three directions simultaneously

Fig.8 Envelope values of maximum principal stresses of Morrow Point dam due to earthquake ground motion excites in the vertical direction, in the cross-stream direction separately and in all three directions simultaneously

Phase difference exists between the dynamic response of the dam to each of the three components of ground motion independently. When they act simultaneously, a reasonable estimate of the maximum response is the square root of the sum of the squares (SRSS) of the maximum component response. Results are also shown in Fig.8.

Similar results were obtained for gravity dam. However, it is not pronounced as that of the arch dam. Due to the limited space, the results are not presented here.

5. CONCLUSIONS

An absorptive reservoir boundary that reflects the energy dissipation due to alluvium and sediments overlaying the river bed gives a more realistic estimate of the earthquake response of concrete arch dams as well as concrete gravity dams. The proposed approach based on the SBFE method is computationally quite economical to carry out dam-reservoir interaction analysis. Morrow Point Dam is selected for this study. A wide range of wave reflection coefficient α has been considered. Numerical results lead to the following conclusions.

1. Reservoir boundary absorption introduces added damping to the dam-reservoir-foundation system, which reduces in general the hydrodynamic force on the dam face and results in decreasing the earthquake response of the dam. With increasing absorption of the reservoir boundary materials from α=0.75 to 0.25, the stress response of the dam decrease slightly with little change in the stress distribution pattern. While the value of α increase from 0.75 to 0.95, the stress response increase somewhat noticeably.

2. The added mass approach neglecting water compressibility substantially overestimate the significance of hydrodynamic effect, which results in an increase of the stress response of the dam, especially when the simplified added mass matrix is used.

Though the effects of reservoir boundary absorption on earthquake response of the dam in detail depend, in part, on the particular dam, the general trend helps a better understanding of the problem.

ACKNOWLEDGEMENTS

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