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SEISMIC RESPONSE OF ARCH DAMS TO WAVE SCATTERING AND SPATIAL VARIATION OF GROUND MOTIONS

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ABSTRACT

Stochastic response of arch dams to nonuniform multi-point excitation of SH or P (or SV) earthquake waves is studied. Scattering and diffraction of plane SH and P (or SV) waves by arbitrary dam canyon topography are determined through a weighted residual approach or a one cell cloning approach. The stochastic model of spatial variation of strong ground motions based on SMART-1 dense array observation data is developed. Input power spectral density function is formulated taking into consideration of the effects of wave scattering and spatial variation of ground motions. Numerical example of a 292 meter high arch dam is presented. It is found that the wave scattering and the spatial variation of ground motions have significant effects on the seismic response of arch dams. The stress distribution over the dam is extensively altered and high stresses are developed along the periphery of the dam due to nonuniform earthquake excitation.

KEYWORDS

Arch dam; seismic response; stochastic response; nonuniform seismic input; wave scattering; spatial variation of gound motions.

INTRODUCTION

As the dynamic analysis of arch dams is usually very complicated, for simplifying computation in the current engineering design practice of these structures in seismic active areas, the ground motions of the canyon are usually specified to be uniform. In fact, the earthquake input is far from uniform, especially for large arch dams, where the span of two abutments of the dam is comparable to the seismic wave length. Such evidence really exists, for example, at the Ambiesta dam (Castoldi, 1978) in Italy and at the Tonoyama dam (Okamoto *et al*, 1964) and Kurobe dam (Nose, 1970) in Japan, where records were obtained on both banks of the canyon, it revealed that the ground motions vary considerably over the base region of a dam. Therefore, to study the influence of this phenomenon on the stress distribution of arch dams has great significance, particularly in China, where safety evaluation of such dams against earthquake shocks is of great concern to the engineers, because a large number of arch dams rangd from 250 to 300 meters high have been built and will be built in seismic active zones.

In order to specify the earthquake input over the structure-foundation interface of arch dams in a more rational way, some investigations were carried out in recent years. In the former USSR, for the Toktogule dam the distribution of the ground motions along the canyon was studied on a plane model using ultra-sonic wave generating apparatus(Lyatkher *et al.*, 1977). In China, the free-field ground motions at the dam canyon for Er-tan and Long-Yang-Xia Arch dams were examined on three dimensional models with scales of 1:2000 and 1:600 and at the real dam sites using ambient vibration measurements as well. In USA, analysis of the effect of non-uniform seismic input due to wave scattering at the canyon topography on arch dam responses was conducted (Nowak, 1988).

The asynchronous in amplitude and in phase of earthquake excitations along the dam-foundation interface may be induced by several origins. First, wave scattering and diffaction are caused by canyon topography and geological irregularities. Second, phase differences due to travelling wave effects take place. Third, spatial variations of ground motions of random character were observed. However, the later has been received little attention in the literature. Ever since the begining of last decade of this century, closely spaced strong-motion seismograph arrays installed in highly seismic regions of the world have supplied essential information about the space-time variation of seismic ground motions. It revealed that, spatial as well as temporal variations of ground motions from points to points over relatively small distances took place. As a result, design of large span structures including arch dams should therefore considers both the effects of wave propagation and coherency decay of ground motions. The objective of this paper is to study in a quantitative way the influences of all the factors which affect the non-uniformities of seismic input on the dynamic response of arch dams.

WAVE SCATTERING AT DAM CANYON

To study the effect of wave scattering at arbitrary canyon topography on the distribution of ground motions along its periphery, the canyon shape is approximated as being prismatic, i. e., the canyon is assumed to be uniform in cross-section and to extend to infinite in the stream direction.

Wave Scateering of Incident SH Waves

The problem is solved by discretization of boundary integral equations, for SH wave incidence it takes the form

$$\int_s u^* p ds = \int_s p^* u ds \tag{1}$$

where

$$p = G\frac{\partial u}{\partial n}, \quad p^* = G\frac{\partial u^*}{\partial n} \tag{2}$$

G is the shear modulus of the medium; n represents the outer normal direction and u^* is the general solution of wave equation

$$\nabla^2 u^* + k^2 u^* = 0 \tag{3}$$

where $k=\omega/c_s$ is the wave number; c_s is the shear wave velocity and ω is the circular frequency. Expressing the total displacement u as the sum of free-field component for half-space u^f and the scattered component u^s, we have

$$u^s = u - u^f \tag{4}$$

Substituting (4) into (1)

$$\int_s u^* (p - p^f) ds = \int_s p^* (u - u^f) ds \tag{5}$$

As at the canyon boundary and the free-field surface

$$p = 0 \qquad s \in s_1, s_2$$

eq. (5) reduces to

$$\int_s p^* u^f ds = \int_s u^* p^f ds \tag{6}$$

Expressing u^* by its complete system of solutions of wave equation, eq. (6) becomes

$$\int_s p_n^* u^f ds = \int_s u_n^* p^f ds \tag{7}$$

$$u_n^* = H_n^{(2)}(k_r)cos(n\theta) \qquad (n = 0,1,2,\cdots)$$

where $H_n^{(2)}(\cdots)$ represents the second kind of Hankel functions of n-th order. Eq. (7) is the basic equation for solving u^*, all the right hand side values are known.

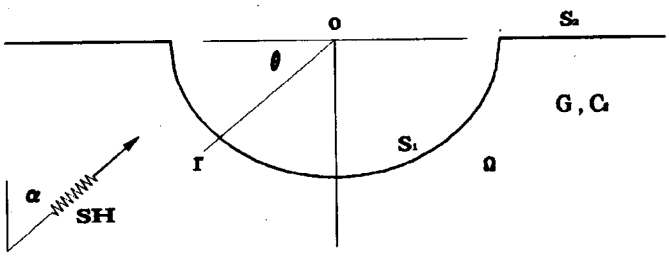
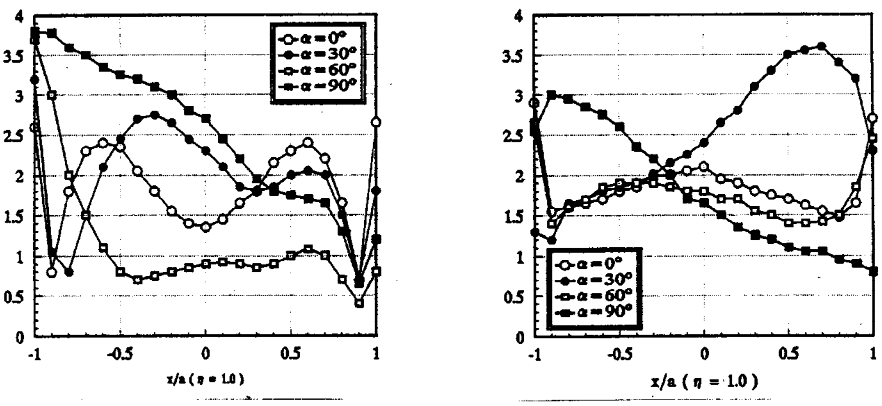


Fig. 1 Wave scattering at the canyon boundary

Fig. 2 illustrates the ground displacement distribution along a semi—circular canyon and a 292 m high arch dam canyon subjected to SH wave incidence with various impinge angle. For case (a), numerical (separated points) and analytical results(solid line) agree well with each other. Where η is the dimension ess frequency, $\eta=ka/\pi$, a is the radius of the canyon.



(a) semi-circular canyon (b) a real orch dam canyon

Fig. 2 Free-field ground displacements due to SH ware incidence with various impinge angle

Wave Scattering of Inplane Seismic Waves

In case of P and SV wave incidence, the wave scattering problems are solved as follows. First, the semi-infinite dynamic impedance $[S_i^\infty]$ of the canyon boundary is determined by cloning approach (Wolf *et al.*, 1994). Usually, a one-cell cloning approximation can give rather appropriate results. Then, the free-field ground displacements $\{u_g\}$ along the canyon boundary are found through the relationship of them with those of the half-plane without excavation of the canyon $\{u_f\}$.

$$[S_i^\infty]\{u_g\} = [S_f^\infty]\{u_f\} \tag{8}$$

$$[S_f^\infty] = [S_i^\infty] + [S_e]$$

where $[S_f^\infty]$ is the dynamic impedance of the half space along the boundary of the canyon, but without excavation of it; $[S_e]$ is the dynamic impedance of the excavated part of the canyon along the canyon boundary. Fig. 3 shows the ground displacements distribution of a 292 m high arch dam canyon due to SV wave incidence.

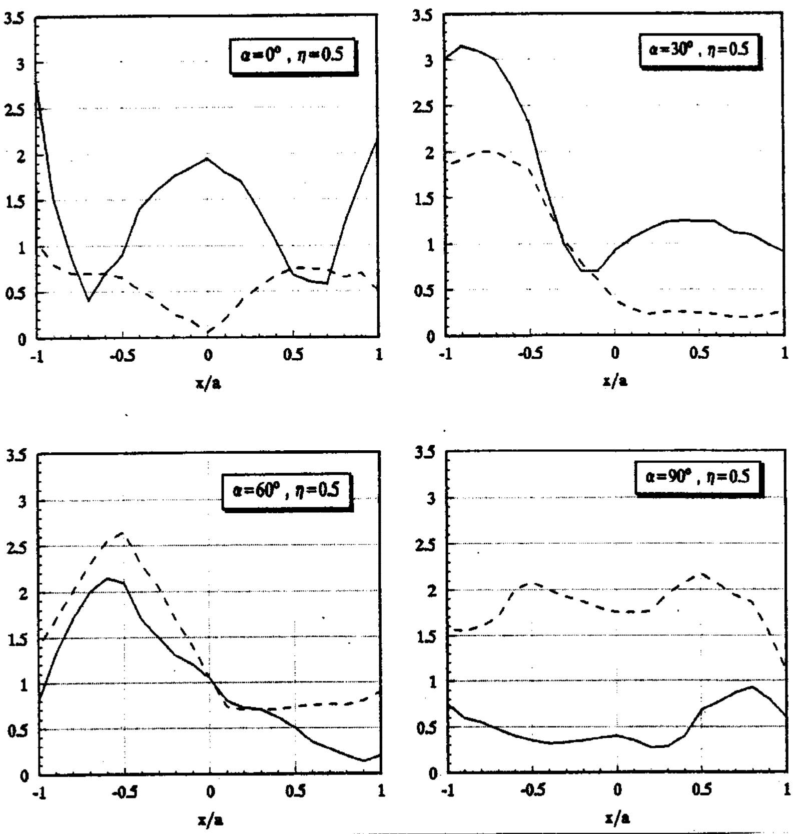


Fig. 3 Free-field ground displacements of a real arch dam canyon due to SV wave incidence

COMPUTATIONAL MODEL FOR SEISMIC INPUT

SMART-1, the first operational dense arranged strong-motion seismograph array established in Taiwan of China has collected a great number of useful observation data, which shared some light on the space-time variation of strong ground motions. Owing to the complexity of factors which affect the spatial variation of strong ground motions at different points at a site, stochastic models are usually employed by the researchers to describe such variation and to study the influences on the structural responses. In general, the space-time correlation model is expressed in the following form

$$\gamma(f,\Delta) = \rho(f,\Delta)exp[-i\omega\Delta/c_a(\omega)],\ f = \omega/2\pi \tag{9}$$

where $\gamma(f,\Delta)$ is the complex correlation factor; $\rho(f,\Delta)$ is the coherency function; Δ is the distance between the two points considered and $c_a(\omega)$ is the apparent velocity of earthquake waves.

Semi—empirical coherency functions $\rho(f,\Delta)$ have been proposed by some researchers, in this paper, a formula based on the SMART—1 observation data developed by one of the authors (Wang, 1993) is suggested.

$$\rho(f,\Delta) = exp[-(a + bf^2)\Delta] \tag{10}$$

where $$a = a_1 + a_2exp(-a_3\Delta),\quad b = b_1 + b_2exp(-b_3\Delta)$$

coefficients a_1, a_2, a_3 and b_1, b_2, b_3 are determined based on the data of strong motion events. Eq. (10) agrees well with the data of typical events E−39, E−43, E−45 etc. For the stochastic analysis of arch dam responses the power spectral density functions of seismic input $[S_{xx}]$ are constructed in the following manner. First, a free field displacement $u_0(\omega)$ of the ground surface in the vicinity of the canyon is chosen as a reference. The displacement at any point along the periphery of the canyon $u_i(\omega)$ is expressed through the coefficient of transmission $\beta_i(\omega)$

$$\beta_i(\omega) = u_i(\omega)/u_0(\omega) \tag{11}$$

values of $\beta_i(\omega)$ are determined by solving scattering problems described in the previous section. The autopower spectral density function of displacement at any point $S_{ii}(\omega)$ is related to that of the acceleration of the reference point $S_f(\omega)$ by the expression

$$S_{ii}(\omega) = \beta_i(\omega) S_f(\omega)/\omega^4 \tag{12}$$

In the literature, for determining $S_f(\omega)$ the Kanai-Tajimi formula is usually used. However, it does not satisfy continuously integrability conditions and cannot be used for multi-support response analysis. A modified formula proposed by Yu-Xian Hu is recommended here for evaluation of $S_f(\omega)$

$$S_f(\omega) = \frac{\omega_g^4 + 4\xi_g^2\omega_g^2\omega^2}{(\omega_g^2 - \omega^2)^2 + 4\xi_g^2\omega_g^2\omega^2} \cdot \frac{\omega^6}{\omega^6 + \omega_c^6} S_0 \tag{13}$$

where ω_g and ξ_g are the central frequency and the damping ratio respectively; ω_c is a low cut frequency and S_0 is a scale factor, corresponding to various level of seismic intensity.

The cross-power spectral density function of ground displacements of any two points i and j at the boundary of the canyon is expressed as

$$S_{ij}(\omega, \Delta_{ij}) = S_f(\omega)[\beta_i(\omega)\beta_j(\omega)]^{1/2}\rho(\omega, \Delta_{ij})exp(-i\omega\Delta_{ij}/c_a(\omega)]/\omega^4 \tag{14}$$

where $\beta_i(\omega)$, $\beta_j(\omega)$ and $\rho(\omega, \Delta_{ij})$ are given by eq. (11) and (10).

For stationary random process, the spectral density function of acceleration is related to that of displacement by the relation

$$\overline{S}_{ii}(\omega) = \omega^4 S_{ii}(\omega), \ \overline{S}_{ij}(\omega) = \omega^4 S_{ij}(\omega) \tag{15}$$

with the aid of eqs. (12) and (14), we get the earthquake input matrix of displacement as follows

$$[S_{xx}(\omega)] = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ & \cdots & \cdots & \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{bmatrix} \tag{16}$$

Where n is the number of multi-suppot excitation. In the similar way, we get the earthquake imput matrix of acceleration.

For typical event E-45 of SMART-1 array, corresponding parameters of power spectral density function are given in Table 1. The maximum horizontal and vertical acceleration are a_h=0. 251g and a_v=0. 110g respectively.

Table 1. Statistical parameters of Event E−45

ξ_g	ω_g	ω_c	S_0 (10^{-3})	a_1 (10^{-4})	a_2 (10^{-4})	a_3 (10^{-3})	b_1 (10^{-4})	b_2 (10^{-4})	b_3 (10^{-3})
0. 155	10. 30	1. 63	23. 54	3. 88	0. 0	−7. 16	0. 43	0. 43	1. 30

The power spectral density of the dam response $[S_{yy}]$ is related to that of the input $[S_{xx}]$ by the following expression

$$[S_{yy}] = [H][S_{xx}][H]^* \tag{17}$$

where $[H]$ is the matrix of complex frequency response and $[H]^*$ is its conjugate. $[H]$ is determined based on the dynamic analysis of the dam.

The equation of motion of dam-foundation system takes the form

$$\begin{pmatrix} M_{ss} & \\ & M_{bb} \end{pmatrix}\begin{Bmatrix} \ddot{u}_s^t \\ \ddot{u}_b^t \end{Bmatrix} + \begin{pmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{pmatrix}\begin{Bmatrix} \dot{u}_s^t \\ \dot{u}_b^t \end{Bmatrix} + \begin{pmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_{bb} \end{pmatrix}\begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ S_{bb}u_g \end{Bmatrix} \tag{18}$$

where $[M]$、$[C]$、$[K]$ are the mass, daming and stiffness Matrix respectively; $[S_{bb}]$ is the dynamic impedance of infinite half-space; $\{u^t\}$ the total displacement vector, $\{u_b^t\}$ refers to the degress of freedom at the dam-foundation interface, $\{u_s^t\}$ refers to the degrees of freedom not on the interface; $\{u_g\}$ is the free field ground displacements along the canyon boundary. Partitioning the total displacements into quasi-static and dynamic components

$$\{u^t\} = \begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} u_s \\ u_b \end{Bmatrix} + \begin{Bmatrix} u_d \\ u_f \end{Bmatrix} \tag{19}$$

It can be found that (Lin, 1996)

$$\{u_s\} = [R]\{u_b\}, \quad [R] = -[K_{ss}][K_{sb}] \tag{20}$$

$$\begin{pmatrix} M_{ss} & \\ & M_{bb} \end{pmatrix}\begin{Bmatrix} \ddot{u}_d \\ \ddot{u}_f \end{Bmatrix} + \begin{pmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{pmatrix}\begin{Bmatrix} \dot{u}_d \\ \dot{u}_f \end{Bmatrix} + \begin{pmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_{bb} \end{pmatrix}\begin{Bmatrix} u_d \\ u_f \end{Bmatrix} = -\begin{pmatrix} M_{ss}R & \\ & M_{bb} \end{pmatrix}\{\ddot{u}_b\} \tag{21}$$

in the frequency domain

$$\{u_d(\omega)\} = [Q]\{\ddot{u}_b(\omega)\} \tag{22}$$

$$[Q] = -([K_{ss}] + i\omega[C_{ss}] - \omega^2[M_{ss}])^{-1}[M_{ss}][R]$$

And

$$\{u_b\} = [T]\{u_g\} \tag{23}$$

$$[T] = ([K_{bs}][R] + [K_{bb}][S_{bb}])^{-1}[S_{bb}]$$

Where $[S_{bb}]$ may be approximated by (Lin, 1996)

$$[S_{bb}] = [S_{\infty}] - \omega^2[M_{\infty}] + i\omega[C_{\infty}] \tag{24}$$

Substituting (20)、(22) and (23) into (19)

$$\{u^t(\omega)\} = \begin{pmatrix} R \\ I \end{pmatrix}[T]\{u_g\} + \begin{pmatrix} Q \\ 0 \end{pmatrix}[T]\{\ddot{u}_g\} \tag{25}$$

From eq. (25), it is not difficult to find the complex frequency response matrix of nodel displacements and element stresses $[H(\omega)]$.

Based on eq. (17) we come to the standard deviation over time of the response, note that it has a zero mean.

$$\sigma_r = \left(\int_{-\infty}^{\infty} S_{yy}(\omega)d\omega\right)^{1/2} \tag{26}$$

NUMERICAL EXAMPLE

Stochastic stress responses of a 292 m high arch dam, which is planning to be built in south-west part of China, subjected to a vertical incident SH seismic wave are calculated and computed with those of uniform input. The seismic input parameters are taken from E-45 of SMART-1 (Table 1). It can be seen from Fig. 4 and Fig. 5 that taking into consideration effect of nonuniform seismic input the stress responses in the central part of the dam tend to reduce, however, along the perimeter of the upper part of the abutments high stresses are induced due to pseudo-static deformation.

Caculation of stress distribution of a 250 m high arch dam due to spatial variation of ground motions has also been carried out, and compared with the results of uniform earthquake input. It reveals that the stresses in the central part of the dam reduce to 90% of those of uniform input, and at the top abutment part of dam-foundation interface the stresses reach the level of 80% of the central part of the dam. If only the wave scattering effect is taken into consideration. while the random variation of ground motions is neglected, the stress concentration at the abutment part is relaxed to 65% of the original value.

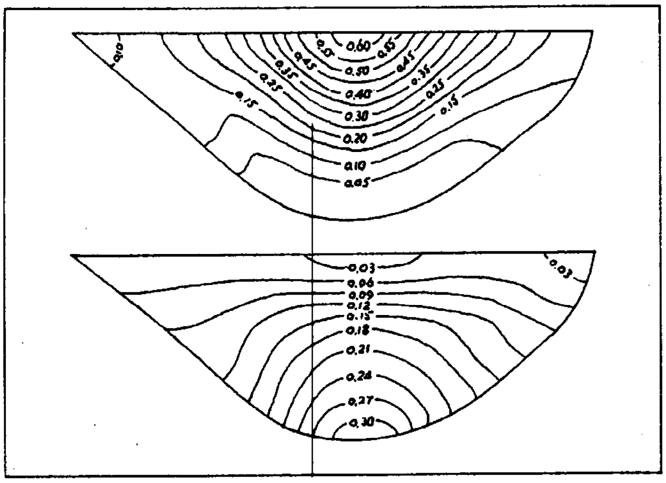


Fig. 4. Contours of upstream arch and cantilever stresses due to uniform input

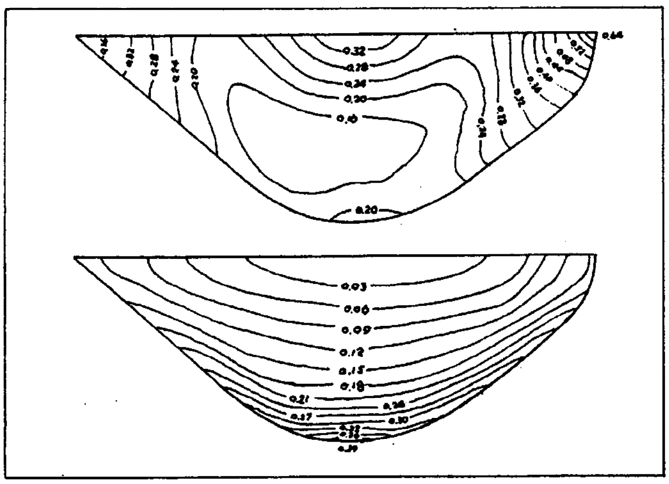


Fig. 5. Contours of upstream arch and cantilever stresses due to wave scattening and spatial variation of ground motions

From the above investigation, it can be concluded, that spatial variation of ground motions has significant influences on the seismic response of arch dams, but the influences are different for different dam conditions, which depend on the the height, the width height ratio of the canyon etc. In general, high stresses develop along the upper part of dam-foundation interface. The findings of this study provide some physical insights on the damage of Pacoima Dam from the Northridge Earthquake of January 17, 1994. During the earthquake, two wings of the top arch experienced extensive vibration and crack occured in both abutments(Technical Report NCEER, 1994).

CONCLUDING REMARKS

Our results strongly suggest that a ground motion input model taking into consideration of both wave scattering effect and the temporal spatial variation is very important for the seismic design of arch dams, because the traditional uniform input model ignores the high stress concentrations at two abutments of the dam.

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