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EARTHQUAKE INPUT MECHANISM AND ITS EFFECT ON DYNAMIC BEHAVIOR OF ARCH DAM

Houqun CHEN Shunzai HOU Jun WANG

Institute of Water Conservancy and Hydroelectric
Power Research (IWHR), PRC

SUMMARY

A deconvolution procedure is carried out to obtain the input to the base of deformable foundation beneath a dam canyon. The free-field motions at dam base are solved by convolution analysis by using finit element model with consistent lateral boundaries. A multiple-excitation technique is used to obtain the dynamic response of an arch dam. Results show that the free-field motions vary remarkably along the canyon wall. The conventional input scheme seems unreasonable, and, compared with the proposed procedure, might lead to an underestimation of the local stress response up to 100%.

INTRODUCTION

With the development of dynamic analysis of large dams, the importance of foundation interaction on the response of dams has long been recognized, but the earthquake input mechanism problem has received relatively little attention and remains rather primitive. Recently, more and more evidence from the records obtained at dam sits indicates that it was necessary to take the spatial variation of input ground motion for dams into account. For instance, at the Ambiesta Dam in Italy (Ref.1) and the Tonoyama, kuroba and Nagawado Dams in Japan (Ref. 2), where records were obtained on both banks, it is indicated that the ground motions vary considerably over the base region of a dam. For evaluating the canyon free-field motions, some investigations were carried out in recent years. In USSR for the Toctogule Dam the variance of the ground motions along the canyon was investigated on a plane model using ultrasonic wave propagating from the base beneath the dam foundation and also on a 1:4000 scale model simulating a region with an area of 6 6km arround the dam site and a depth of 4km in prototype (Ref. 3). In China the distribution of acceleration on the abutments of Longyangxia Arch Dam and Ertan Arch Dam under earthquake condition was studied by using the dynamic model test, the FEM calculation and the ambient vibration in-situ test (Ref. 4). The main conclusion drawn from these tests indicates also that the ground motion varies along the canyon. A more reliable procedure of determing three components of free-field motions of the infinite canyon as the input to the concrete-rock interface of an arch dam was investigated (Ref. 5). However, at present, in the standard earthquake input mechanism used in practice, it is assumed that a free-field earthquake accelerogram recorded at ground surface is applied identically to the rigid base rock of the massless deformable foudation. Obviously, it is not in the reality. Some preliminary investigation on the effect of seismic travelling wave on the dynamic behavior of an arch dam has been carried out (Ref. 6).

In this paper a complete study on the free-field input mechanism as well as the multiple-support excitation analysis of a dam-foundation-reservoir system is presented. In this case, a deconvolution procedure for 3 different recorded accelerograms is carried out to obtain the input to the base of deformable foundation beneath a dam canyon. The free-field motions at dam base are solved by convolution analysis by using finite element method with consistent lateral boundaries. Based on the obtained three components of free-field motions varying along the canyon wall, a multiple-excitation technique is used to obtain the dynamic response of an arch dam.

BASIC CONCEPT AND FORMULATION

Typically it is assumed that the original free-field motion was recorded at the surface of a horizontal stratified deformable foundation of infinite extent in the horizontal direction as shown in Fig.1. So three one-dimensional deconvolution analyses can be carried out for three components of recorded accelerogram separately. Essentially,such an analysis is nothing but an inverse application of the solving of the following one-dimensional wave propagation equation for horizontal component of the ground motion .

$$\rho\frac{\partial^2 u}{\partial t^2} = G\frac{\partial^2 u}{\partial z^2} + \eta\frac{\partial^3 u}{\partial z^2 \partial t} \tag{1}$$

where ρ, G, η. are mass density, shear modulus and viscous damping factor respectively.

Substituting E for G in equation (1), the simular equation and procedure can be used for vertical component.

As each component of the acceleration time history can be converted into frequency domain by Fast Fourier Transform Technique, the displacement at the frequency can be expressed by

$$u(z,t)=U(z)\,e^{i\omega t} \tag{2}$$

where $U(z)= E\,e^{ikz}+ F\,e^{-ikz}$ (3)

Substitution of equations (2), (3) into boundary conditions of each layer leads to solving the transfer function between any two layers m and n.

$$A_{m.n}(\omega) = \frac{e_m(\omega)+f_m(\omega)}{e_n(\omega)+f_n(\omega)} \tag{4}$$

where $e_m(\omega) = E_m/E_1$, $f_m(\omega) = F_m/F_1$, $e_n(\omega) = E_n/E_1$, $f_n(\omega) = F_n/F_1$.

As $E_1=F_1$ can be solved from the boundary conditions at free surface, then all the three deconvolved motions $\{U_b\}$ at base rock can be obtained and applied simultaneously to the base rock of the foundation rock-dam system with consideration of actual topographic and geological features. The more reliable free-field motions at dam base can be solved by convolution analysis using finite element model. In this case a more efficient procedure with two two-dimensional convolution analyses would have to be done separately, one in-plane and the other out-of-plane. In these plane foundation models, two consistent lateral boundaries and a input base boundary were used (Ref. 7) as shown in Fig.2. After derivating the dynamic stiffness matrices of two consistent lateral boundaries [R] and [L], the frequency dependent matrix equation of motion $\{\tilde{V}\}$ can be written as follows:

$$(([K]_F + [R] + [L]) + i\omega[C] - \omega^2[M]_F)\{V\} = \omega^2[M]_F\{U_b\} \tag{5}$$

where $\{U_b\}$ is the harmonic component of the deconvolved input; $[M]_F$, $[C]_F$, $[K]_F$ are the properties of the foundation. The equation of dynamic response of the combined dam-foundation-reservoir system to the obtained free-field seismic input $\{\tilde{v}_g\}$ can be expressed as follows:

$$[M]\{\ddot{v}\} + [C]\{\dot{v}\} + [K]\{v\} = -([M][\psi] + [M_g])\{\ddot{\tilde{v}}_g\} \qquad (6)$$

where $[M]$, $[C]$, $[K]$ are the properties of the system; $[\psi]$ is the influence matrix defined as $[\psi]=[K]^{-1}[K_g]$; $[M_g]$, $[K_g]$ are the mass and stiffness contribution of the dam to the degrees of freedom in contact zone; $\{v\}$ is the vector of dynamic component of the added response resulting from putting the dam on the canyon.

The equation (6) can be more conveniently solved by mode superposition procedure and response spectrum analysis, provided that the modal participant coefficient vector is defined as

$$\{\gamma_j\} = \frac{\{\phi_j\}^T([M][\psi] + [M_g])}{\{\phi_j\}^T[M]\{\phi_j\}} \qquad (7)$$

in which $\{\phi_j\}$ is the jth modal shape vector.

The total response of dam can be expressed as the sum of the dynamic component $\{v\}$ and the pseudostatic component $\{v^s\} = [\psi]\{\tilde{v}_g\}$.

RESPONSE OF DONG JIANG ARCH DAM TO FREE-FIELD GROUND MOTION

The proposed free-field input mechanism and multiple-excitation analysis were applied to an actual double-curvature arch dam Dong Jiang with the maximum height of 157m. The first 12 natural frequencies are given in Table-1.

Table-1 Natural Frequencies of the Dam (HZ)

Mode	Foundation with Mass		Massless Foundation	
1	1.880	S	1.883	S
2	1.947	AS	1.951	AS
3	3.044	S	3.055	S
4	3.766	S	3.805	S
5	4.003	AS	4.023	AS
6	4.658	AS	4.781	AS
7	5.124	S	5.352	S
8	5.335	S	6.057	S
9	5.578	AS	6.132	AS
10	6.178	AS	6.432	S
10	6.178	AS	6.432	S
11	6.235	S	6.525	AS
12	6.451	AS	7.225	S

S - symmetric mode AS - antisymmetric mode

The accelerograms recorded at surfaces of three different rock foundations were selected to obtain the input motion of rigid base rock through deconvolution. They are: Song Pan (1976.8.16, China), Qian An(1976.8.9, China) and Koyna (1967.12.11, India). For being easy to be compared, the peak accelerations of all these records were scaled to 0.2 m/sec in horizontal directions, and 0.133m/sec in vertical direction.

Assuming the base rock located at a depth of 3 times of the dam height beneath the surface, deconvolution analyses were carried out according to the actual geological condition of foundation at each record station. An area with a width of 5.4 times of the dam height has been taken for convolution analyses. As the dimension of finite element of rock medium is limited to be less then 1/5 of the minimum wave length transmitted through the medium, the convolution computation will be the extremely timeconsumming for the accelerogram with high frequency components. For this reason and also considering the fact that the maximum frequency of the 12th mode of Dong Jiang Dam is less then 8 HZ, the adopted accelerograms have been filtered with a cut-off frequency of 8 HZ.

The ratios of deconvolved peak acceleration to its original one for all three records are shown in table-2.

Table-2 Ratio of Deconvolved Acc to Original Acc

Record	X - dir	Y - dir	Z - dir
Song Pan	0.387	0.431	0.282
Qian An	0.472	0.591	0.384
Koyna	0.540	0.693	0.387

In general, the Fourier components near the natural frequencies of the foundations (f_f) are reduced remarkably after deconvolution as shown in Fig.3 for Qian An record (x-dir) with the fundamental f_f=1.14 HZ.

The free-field motions vary along the canyon remarkably both in amplitude and phase, but with less difference in shape of Fourier spectrum. The peak accelerations of free-field motions at canyon bottom decrease by (10-60)% as compared with their original ones, and the amplification factors from bottom to top of the canyon are 1.0-1.8 for different records in different direction as shown in Fig. 4.

In order to investigate the influence of the variance in phase and amplitude of the free-field motions on the response of the arch dam, a comparison has been made for the following 5 input schemes:

A. Conventional uniform input of recorded surface motions a(t) to the base rock of massless deformable foundation.

B. Uniform input of a(t) to the interface of dam as the free-field canyon motions.

C. Input of travelling recorded surface motions to the interface of dam as the free-field canyon motions, i.e., $\ddot{v}$ (t)=a(t - [illegible]) (where L_i is the distance of ith DOF at interface from the point at which the seismic wave first arrived along its propagation direction with the wave velocity (=3000m/s).

D. Input of a(t) to the interface of dam with an amplitude amplification factor of 2 linearly varied from the bottom to the top of canyon.

E.The proposed free-field canyon motions after deconvolution and convolution procedures.

The multiple-excitation analyses were carried out for all cases except case A.

In Fig.5 only the upstream arch stress responses at crest to 3 records for all 5 cases are illustrated. For comparision the analyses have been carried out both for original recorded motions and for their filtered motions with $f_{cut\ off}$ = 8 HZ in cases A, B and C. The results in Table-3 indicate that the influence of filtering on the responses of the dam is less than 3%.

Table-3 Response Ratio of Filtered Input to Original Input

Response	Δ			σ_a			σ_c		
Input case	A	B	C	A	B	C	A	B	C
Song Pan	0.96	1.03	1.02	0.95	1.02	1.02	1.02	1.02	1.02
Qian An	0.99	0.99	1.02	0.98	0.98	1.00	0.97	0.95	0.98
Koyna	0.99	0.97	0.96	0.99	0.97	0.96	1.03	0.99	0.97

Δ - Radial displacements at crest crown
σ_a - Upstream arch stresses at crest crown
σ_c - Upstream crown cantilever stresses at base

CONCLUSIONS

1. The free-field motions vary remarkably both in phase and amplitude along the canyon wall. The amplification factors of the accelerations are about 1.0-1.8 from the bottom to the top of the dam canyon.

2. The stress response of the dam in case (C) with travelling seismic wave is about (20-30)% higher than that in case (B) with uniform input.

3. The dynamic amplification of canyon input as in case (D) have significant influence on the dam response in the region adjacent to the abutment, which is mainly caused by the pseudostatic component.

4. The conventional input scheme of case (A) seems unreasonable, and, as compared with the proposed procedure in case (E), might lead to underestimation of the local stress response up to 100%, so it must be used with caution.

5. The proposed free-field input mechanism together with the multiple-excitation technique appears to be a more reliable approach for earthquake resistant analysis of an arch dam at present, through it still stands in need of further improvement.

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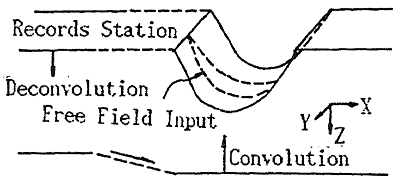


Fig.1 Model of Earthquake Input Mechanism

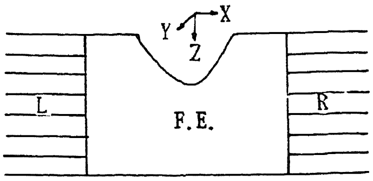
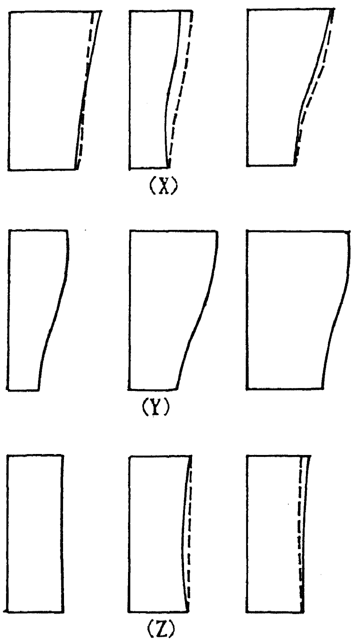


Fig.2 Mode of Consistent Boundaries



SongPan QianAn Koyna
Fig.4 Distribution of Free Field Acc along Canyon
----Left ----Right

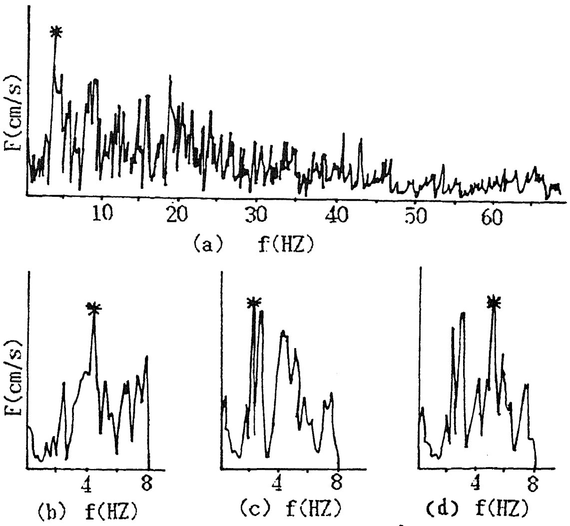


Fig.3 Spectra of Qian An Accelerogram
(a) Original (b) Deconvolved
(c) (d) Convolved on Left Bank and Bottom

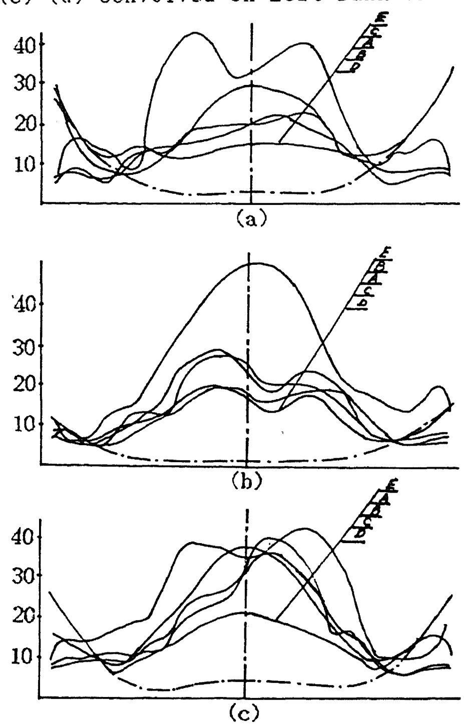


Fig.5 Comparison of Arch Stress Response at Crest (A)(B)(C)(D)(E) Input Scheme
(a) Song Pan (b) Qian An (c) Koyna