11 WCEE

Paper No. 595. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC INTERACTION BETWEEN ARCH DAM AND ROCK CANYON

ZHANG CHUHAN JIN FENG and WANG GUANGLUN

Department of Hydraulic Engineering, Tsinghua University, Beijing, China 100084

ABSTRACT

Seismic response of a 250 m high arch dam is analyzed by coupling FE-BE-IBE time domain procedure previously presented. The complete interaction between the dam and the canyon, including radiation damping of the canyon and non-uniform input of the free-field motions, is taken into account in the analysis. Significant influences of the above-mentioned two factors on the dam response are verified. Safety evaluation of the dam against the design earthquake is described.

KEYWORDS

Seismic interaction; radiation damping; free-field motion; arch dam; rock canyon.

INTRODUCTION

The interaction between arch dams and rock canyon is an important topic that has not been fully investigated to date. Current procedures dealing with dynamic analysis of arch dams assume a truncated massless rock foundation and apply the design earthquake input at the rigid base beneath the truncated rock foundation. These assumptions neglect the interaction effects due to the radiation damping of the infinite mass rock and the non-uniform input motions along the canyon. Recent studies (Chopra et al., 1992, Dominguez et al., 1992, Zhang et al., 1988) reveal that these interaction effects are important and should be included in analysis. With this objective, a time domain procedure of coupling finite elements (FE), boundary elements (BE) and infinite boundary elements (IBE) developed by the authors (Zhang et al., 1993) is employed to quantify the interaction effects of the dam-canyon system under different earthquakes. Herein, first the main ideas of the procedure are briefly outlined. Second, the paper will focus on seismic analysis of the 250 m high arch dam-Laxiwa project to reveal the effects of radiation damping due to the infinite mass canyon and the non-uniform earthquake input along the dam canyon interface. Finally, the safety evaluation of the dam to resist the design earthquake is given.

PROCEDURE

As shown in Fig. 1, the arch dam is discretized by FEs while the canyon is meshed by normal BEs and IBEs. The substructure technique is employed to analyze the interaction of this system, which permits the rock canyon to be treated separately in determining its impedance matrix. Since the impedance matrix defined on the dam-canyon interface is frequency dependent, it is necessary to transform them into discrete parameters so that the entire system can be solved in the time domain. Applying the following relationship to each coefficient of the impedance matrix $S_{cc}(\omega)$, i.e.

$$S_{cc}(\omega) = -\omega^{2}\bar{m}_{cc} + i\omega\bar{c}_{cc} + \bar{k}_{cc} \tag{1}$$

yields the discrete parameters $\bar{m}_{cc}, \bar{c}_{cc}$ and $\bar{k}_{cc}$, which are frequency independent. Herein, by using a curve fitting the known coefficients $S_{cc}(\omega_1)$ and $S_{cc}(\omega_2)$ at the two boundary points within the frequency range of interest are used to obtain the discrete parameters $\bar{m}_{cc}, \bar{c}_{cc}$ and $\bar{k}_{cc}$. It is note worthy that since the impedance functions of the canyon behave in gradual monotonic fashion within the frequency range considered due to the normally high modulus of the canyon rock, the discrete parameter model has sufficient accuracy to match the frequency-dependent impedance functions. To analyze the coupling system even more efficiently, the mode synthesis technique is also employed to obtain the generalized coordinates for the dam. Earthquake input is defined as the free-field motions acting on the dam-canyon interface. With these simplifications and derivations, the system equations of motion for dam-canyon complete interaction are as follows.

$$\begin{bmatrix} I & M^{*}_{lc} \\ M^{*}_{cl} & M^{*}_{cc} + \overline{M}_{cc} \end{bmatrix} \begin{Bmatrix} \ddot{q}_l \\ \ddot{u}_c \end{Bmatrix} + \begin{bmatrix} C^{*}_{ll} & C^{*}_{lc} \\ C^{*}_{cl} & C^{*}_{cc} + \overline{C}_{cc} \end{bmatrix} \begin{Bmatrix} \dot{q}_l \\ \dot{u}_c \end{Bmatrix} + \begin{bmatrix} \lambda_l & 0 \\ 0 & K^{*}_{cc} + \overline{K}_{cc} \end{bmatrix} \begin{Bmatrix} q_l \\ u_c \end{Bmatrix} = \begin{Bmatrix} -(M^{*}_{lc}\ddot{\bar{u}}_c + C^{*}_{lc}\dot{\bar{u}}_c + 0) \\ -(M^{*}_{cc}\ddot{\bar{u}}_c + C^{*}_{cc}\dot{\bar{u}}_c + K^{*}_{cc}\bar{u}_c) \end{Bmatrix} \tag{2}$$

where the submatrices with asterisks denote respectively the generalized mass, damping and stiffness of the dam with fix boundary; λ_l and q_l are respectively the retained eigenvalue matrix and the generalized coordinates of the dam with fix boundary; u_c, $\bar{u}_c$ are respectively the interaction and free-field motions at the interface; $\overline{M}_{cc}, \overline{C}_{cc}$ and $\overline{K}_{cc}$ are equivalent mass, damping and stiffness matrices assembled from $\bar{m}_{cc}, \bar{c}_{cc}$ and $\bar{k}_{cc}$. From equation (2), the q_l and u_c are solved given the free-field motion $\ddot{\bar{u}}_c$, $\dot{\bar{u}}_c$ and $\bar{u}_c$. Thus the total displacement field and resulting stresses can be obtained.

A computer program incorporating FE-BE-IBE coupling has been developed to take into account the complete interactions and non-uniform free-field input, both in time and frequency domains. Reservoir water is assumed to be incompressible for simplicity.

THE LAXIWA ARCH DAM AND THE DESIGN EARTHQUAKE

The Laxiwa hydro project includes a 250 m high, double-curvature arch dam and a power house with an installed capacity of 3720 MW. The width-to-height ratio of the canyon is 1.74 and the thickness-to-height ratio at the dam base is 0.18. The rock formation at the dam site is entirely solid granite with following parameters: Young's modulus E=3.5x10^4 MPa; mass density $\gamma = 2680$ kg/m^3; and Poisson's ratio $\nu = 0.23$. The corresponding properties for concrete are: E=3.5x10^4 MPa; $\gamma = 2400$ kg/m^3; and $\nu = 0.167$.

As shown in Fig. 1, the dam is discretized into a total of 56 shell elements. The canyon wall is divided into 8 layers with 48 normal BEs and 38 IBEs. The first 20 modes are included.

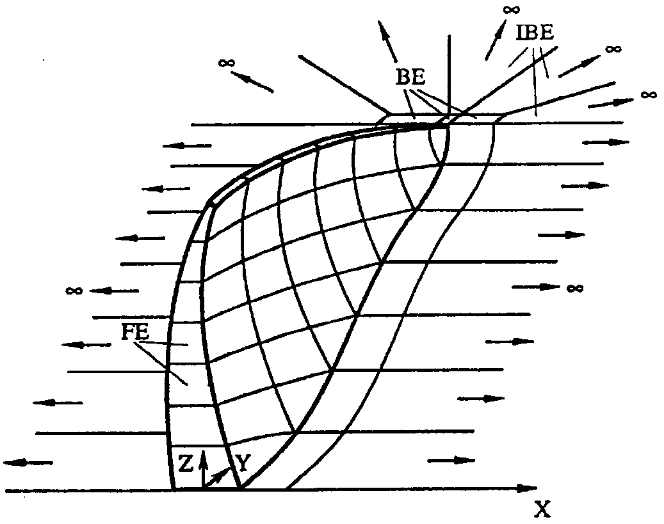


Fig. 1 FE-BE-IBE coupling for dam rock canyon

According to the seismic risk analysis, the design basis earthquake of 0.2 g for the dam is determined based on a probability of exceedance of 0.1 and a life period of 500 years. Several earthquakes are chosen to analyze the dam response: (1) an artificial earthquake produced from the given PVA and the design objective response spectrum; (2) Park Field June 27, 1966; (3) Koyna December 11, 1967. All time histories are proportionally scaled to the PVA of 0.2 g. Fig. 2 shows the response spectra for different earthquakes.

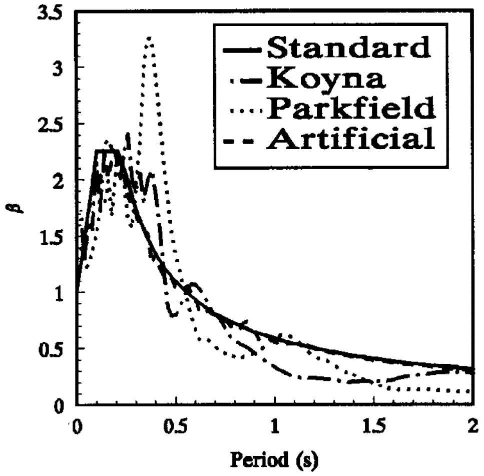
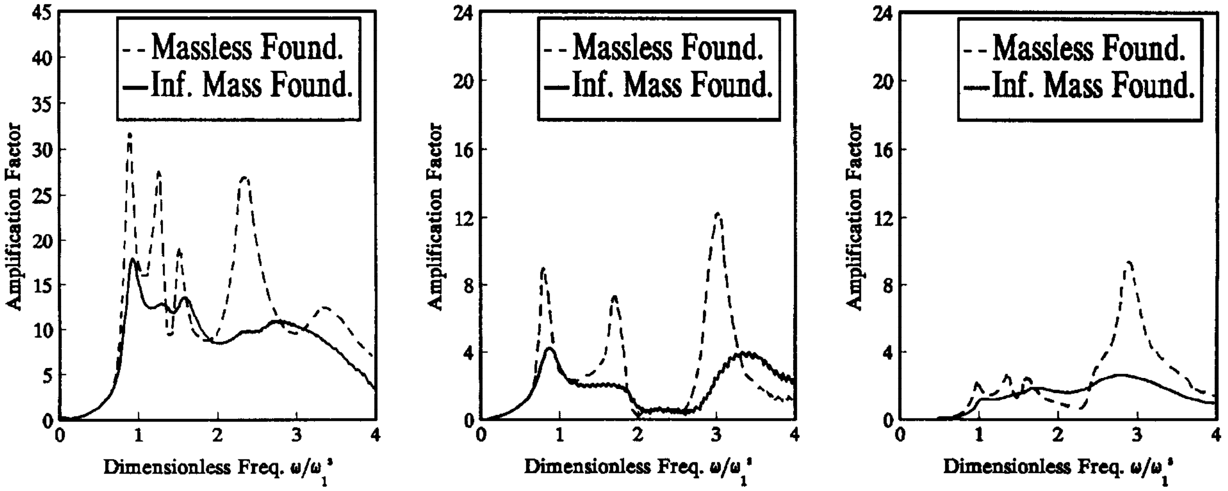


Fig. 2 Response spectra for analysis of the Laxiwa arch dam

EFFECTS OF RADIATION DAMPING

To examine the accuracy and efficiency of the procedure, response histories of the dam are obtained by having an impulse (approximately δ functions) uniformly act on the dam-canyon interface as the free-field input in equation (2). FFT is employed to gain the frequency response functions. Regular frequency domain method has also been used for comparison. From the results, the satisfactory accuracy and high efficiency are justified(Zhang et al., 1995).

The comparison of the response functions at the dam crest between the interaction model (i.e. infinite mass foundation) and the standard massless foundation is shown in Fig. 3. Significant reduction in the dam response in the entire frequency range for interaction model is observed. The comparison of maximum stresses of the dam between the two models under different earthquakes is shown in Table 1. It is concluded that the reductions in maximum stresses for the interaction model may range from 20-35% when compared with that of the massless foundation. A typical iso-stress envelop of the dam under the artificial design earthquake in stream direction is shown in Fig. 4. The patterns of the iso-stress envelop are similar in both cases, while vivid differences in stress level in whole structure can be seen, implying that the dam has a higher safety factors to resist the design earthquake when considering the interaction effects of the system.

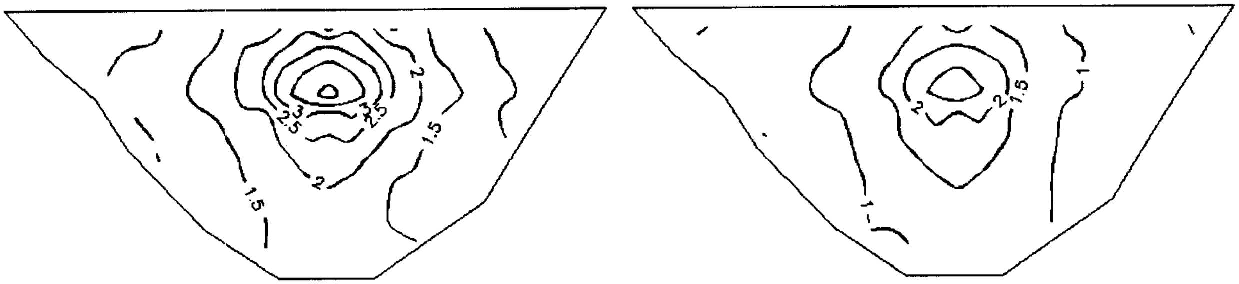


(a) Stream

(b) Cross-stream

(c) Vertical

Fig. 3 Comparison of response functions between the massless and infinite mass foundation



(a) Massless foundation

(b) Infinite mass foundation

Fig. 4 Comparison of upstream max. iso-stresses of Laxiwa arch dam between massless and infinite mass foundation under artificial earthquake (0.2g) in stream direction (MPa)

EFFECTS OF NON-UNIFORM FREE-FIELD INPUT

In order to evaluate the effects of non-uniform earthquake motions on dam response, it is necessary to set up a uniform input motion as the comparison basis. It is assumed that an identical earthquake wave is travelling through points A and B as shown in Fig. 5, the former located below the canyon and the latter underneath the half space. Two equivalent mechanisms for uniform and non-uniform input respectively are compared:(1) uniform free-field motions, obtained at the half space surface under the seismic wave incidence, but acting along the canyon interface uniformly; (2) non-uniform free-field motions obtained from the scattering effect of the canyon under the same seismic wave incidence. The 2-D BE-IBE coupling program is employed

Table 1 Comparison of max. stresses between interaction and massless model for Laxiwa dam (MPa)

Earthquakes	Model	Stream-wise motion		Cross stream motion		Vertical motion	
PVA=0.2 g		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Koyna	Massless	2.88	3.06	1.39	1.36	0.77	1.07
Dec.11, 1967	Interaction	2.10	2.16	0.96	1.04	0.55	0.67
	Reduction(%)	27	29	30	24	27	38
Park Field	Massless	5.52	4.79	2.29	2.02	1.75	1.92
June 27, 1966	Interaction	4.40	3.63	1.80	1.57	1.16	1.32
	Reduction(%)	16	24	22	23	34	31
Artificial	Massless	5.46	5.74	2.76	2.68	1.40	1.46
Design Earthq.	Interaction	3.70	3.23	2.31	2.06	0.76	0.80
	Reduction(%)	33	44	16	23	46	45

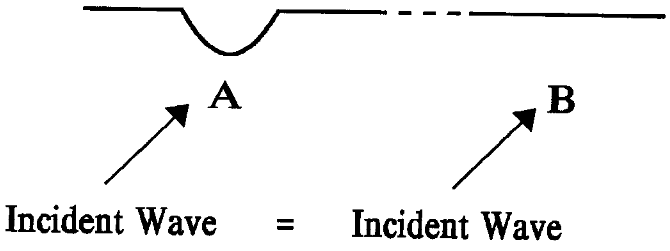
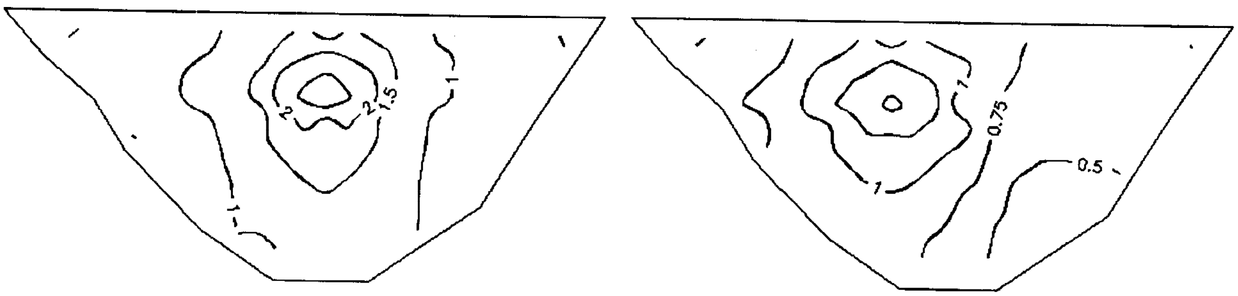


Fig. 5 Uniform and non-uniform earthquake wave input mechanism



(a) Uniform

(b) Non-uniform

Fig. 6 Comparison of upstream max. iso-stresses of Laxiwa arch dam between uniform and non-uniform artificial earthquake input in stream direction (MPa) to obtain the non-uniform free-field motions for SH, SV, P waves at different angles of incidence while the uniform free-field motions are computed by analytical solutions. Effects of radiation damping due to infinite mass canyon are included in this analysis. Since the tendency of responses for all earthquakes considered are similar, only the results of artificial design earthquake are given. Table 2 shows the input coefficients for different wave components and the results are summarized in Table 3. A typical iso-stress envelop for uniform and non-uniform input is shown in Figure 6.

Table 2 Input coefficients for uniform and non-uniform waves (multiplied by 0.2g)

Input wave type	Angle of incidence	Equivalent excitation	Non-uniform input	Uniform freefield
SH	0°	Stream-wise	0.5	1.0
	30°	Stream-wise	0.5	1.0
SV	30°	Cross-stream +Vertical	0.606	1.0 Cross-stream 0.634 Vertical
P	30°	Cross-stream +Vertical	0.596	0.686 Cross-stream 1.0 Vertical

Table 3. Comparison of max. stresses between uniform and non-uniform free-field motions for Laxiwa dam under artificial earthquake with PVA 0.2 g

Wave type	Free-field	Max. stresses (MPa)	
Angle of incidence	motions	Upstream	Downstream
SH/0°	Uniform	3.70	3.23
	Non-uniform	2.91	2.02
	Difference(%)	-21	-37
SH/30°	Uniform	3.70	3.23
	Non-uniform	2.24	1.79
	Difference(%)	-40	-45
SV/30°	Uniform	2.85	1.82
	Non-uniform	2.94	1.88
	Difference(%)	+3	+3
P/30°	Uniform	1.44	1.50
	Non-uniform	1.62	1.66
	Difference(%)	+12	+10

From the results, a significant decrease of the stresses is observed for the non-uniform input of SH waves. However, a noticeable increase of the stresses is also evident for inclined non-uniform input of SV and P waves. Different pattern of iso-stress envelop is also seen for non-uniform inclined wave input in Fig.6. The phenomenon of increase in stresses is likely to be due to opposite phase motions of the two abutments when inclined SV and P waves are travelling across the canyon. Nevertheless, the stream-wise excitations caused by SH waves are still the most important components in producing maximum stresses. Therefore, substantial reduction in maximum stresses of the dam can be expected due to the effects of both radiation damping and non-uniform free field motions .

SAFETY FACTORS OF THE DAM

Safety evaluation of the arch dam is related to unusual loading conditions which include normal hydrostatic, self-weight and temperature variation, as well as the design earthquake loads. For unusual loading conditions, the artificial design earthquake is selected and the stresses are added to the static counterparts. The following cases are considered in the analysis for comparison:

Case 1: Massless canyon and uniform free-field for stream-wise excitation
Case 2: Infinite mass canyon and non-uniform free-field for stream-wise excitation (SH/0°)
Case 3: Infinite mass canyon and uniform free-field for cross-stream and vertical excitations (SV/30°)
Case 4: Infinite mass canyon and non uniform free-field for cross-stream and vertical excitations (SV/30°)

The final results are listed in Table 4.

Table 4. Max. stresses and safety factors under unusual loading conditions for Laxiwa dam

Case	Max tensile stresses (MPa) Safety factors		Max. compression stresses (MPa) Safety factors	
	Upstream	Downstream	Upstream	Downstream
1	5.1 0.9	4.0 1.15	−13.2 3.4	−10.6 4.3
2	4.0 1.15	0.9 3.88	−10.5 4.3	−9.2 5.0
3	4.0 1.15	1.4 4.0	−11.0 4.1	−8.8 5.2
4	4.1 1.14	1.4 4.0	−11.2 4.0	−9.1 5.0

In the project design, the cubic strength of 35 MPa is selected for Laxiwa arch dam. The tensile strength is taken to be 1/10 of the cubic strength, i.e. 3.5 MPa. Assuming the dynamic strengths of the concrete for unusual loading conditions are increased by 30%, the resulting strengths for compression and tension are 45.5 MPa and 4.55 MPa respectively.

Comparing the max. stresses listed in Table 4 with the dynamic strength index, the safety factor for upstream tension becomes 0.9 (unsafe) for case 1 which is equivalent to the current standard procedure for dam analysis. However, the safety factor reaches 1.15(safe) for case 2 in which the radiation damping and non-uniform free-field are included. The increase of the safety factors for compression is also significant for case 2. For cross-stream+vertical excitations, the safety factors change insignificantly from case 3 to case 4, and they all satisfy the design criteria against the design earthquake.

CONCLUSION

The procedure of coupling FE-BE-IBE in time domain previously presented is employed for seismic interaction analysis of a 250 m high Laxiwa arch dam and the rock canyon. Several earthquakes are expressed as free-field input acting on the dam canyon interface. The procedure has the capability of incorporating both the radiation effects of an infinite canyon and the effects of non-uniform seismic input into the analysis of structural response which current method usually ignore. Analysis of the Laxiwa arch dam has drawn the following conclusions:

1. Effects of canyon radiation on structural response substantially reduce the dam stresses regardless of the different earthquake events and different direction of excitation. The amount of the reduction for the specific dam analyzed is approximately 20-35%.

2. Effects of non-uniform input are summarized into two categories: There appears a further decrease in response for non-uniform input in stream-wise excitation. However, there is a noticeable increase in cross-stram+vertical excitations.

3. The study on the Laxiwa arch dam by the presented procedure shows that the dam satisfies the safety criterion to resist the design earthquake if the canyon radiation and non-uniform input are taken into account.

ACKNOWLEDGMENT

This research is supported by the National Scientific and Technology Committee of China under National Climbing Plan (B). Appreciation is also expressed to Professor O. Pekau of Concordia University, Montreal, Canada for his valuable discussions and suggestions.

REFERENCES

Chopra, A.K. and Tan, H. (1992). Modeling of dam-foundation interaction in analysis of arch dams. *Proc. 10th world conf. earthquake eng.* Madrid 8, 4623-4626.

Dominguez, J. and Maeso, O.(1992). Model for the seismic analysis of arch dams including interaction effects. *Proc. 10th world conf. earthquake eng.* Madrid 8, 4601-4606.

Zhang Chuhan, Wang Guanglun and Zhao Chongbin (1988). Seismic wave propagation effects on arch dam response. *Proc. 9th world conf. earthquake eng.* Tokyo-Kyoto XI 367-372.

Zhang Chuhan, Jin Feng and Wang Guanglun (1993). A method of FE-BE-IBE coupling for seismic interaction of arch dam-canyons. *Boundary Element Methods, Proc. 5th Japan-China symposium on boundary element methods*. Elsevier, Amsterdam, 293-302.

Zhang Chuhan, Jin Feng and Pekau, O. A. (1995). Time domain procedure of FE-BE-IBE coupling for seismic interaction of arch dams and canyons. *Earthquake eng. struct. dyn.* 24. (to appear in December)