Paper No. 1709. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

MODEL TEST AND COMPUTATION ANALYSIS FOR DYNAMIC BEHAVIOR OF ARCH DAM WITH CONTRACTION JOINTS

HOUQUN CHEN DEYU LI XIAO HU SHUNZAI HOU
China Institute of Water Resources and Hydropower Research,
Beijing(100044),P.R.China

ABSTRACT

This paper presents the results of a shaking table test of an arch dam model for conditions with and without contraction joints and the corresponding analytical computations. Both show that contraction joints open during earthquake and joint openings release tensile arch stresses and increase cantilever stresses. The experimental results and the analytical results are close to and verify each other.

KEYWORDS

Arch dam, contraction joint,shaking table, model test, nonlinear analysis,finite element

INTRODUCTION

Seismic response of arch dam is a major concern for both designers and researchers alike. The traditional linear analysis always produce very high tensile arch stresses in the upper portion of the dam, much higher than the strength of the concrete. Up to date,however,arch dam subject to strong earthquake showed little damage. This inconsistency is due to the fact that current practice of analysis is linear elastic while the dam response is nonlinear.

Arch dams are constructed in individual blocks seperated by vertical contraction joints. As the joints cannot develop the arch tensile stress, they would be expected to open when the seismic arch tensile stress exceeds corresponding arch compression due to static loads. Analytical studies (Kuo, 1982;Dowling, 1987) have been made to investigate the joint opening mechanism quantitatively. Recently, a computer program, ADAP–88(Fenves *et al.*, 1989), that models dynamic joint opening using nonlinear joint element and a step–by–step integration became available. There are also limited experimental works(Niwa and Clough,1980; Taskov and Jurukovski,1987) on simplified model to study this phenomenon with encouraging results.

This paper presents the results of an experimental study of the joints opening behavior and corresponding analytical work. The experimental research was carried out using a model of a double curvature arch dam with its reservoir and the triaxial earthquake simulation shaking table at the China Institute of Water Resources and Hydropower Research(IWHR) in Beijing, China. The analysis was made using the above program ADAP–88.

EXPERIMENTAL STUDY

Basic Considerations

Because of the dependence of the nonlinear dynamic response on the initial static stress, the dead weight of the dam and hydrostatic load of reservoir have to be considered in the test. In addition, the dynamic interaction between arch dam and reservoir water has significant effect on earthquake response of the dam. Therefore, a reservoir with a length of three times of dam height was included in the model.

The dam–foundation interaction is another complicated issue. In order to simplify the problem, it was decided to test the dam on a rigid foundation.

In order to study the effect of joints, the test was performed first with a monolithic dam model without joints and the same model but with three joints,located at the crown section and approximately the one–quarter points.Based on previous analytical study(Fenves *et al.*,1989), three joints in the model would be sufficient for reasonable results.

Earthquake Simulator Facility

The experimental study was performed on the triaxial earthquake simulation shaking table of IWHR. The performance specifications of the shaking table are listed below.

Size of table	5x5m
Maximum load weight	20t
Weight of table	23.5t
Frequency range	0.1～120Hz
Direction of excitation	2 horizontal and vertical simultaneously with 6 degree of freedom
Maximum displacement,horizontal	40mm
vertical	30mm

Maximum velocity,	horizontal	400mm / s
	vertical	300mm / s
Maximum acceleration,	horizontal	1.0g
	vertical	0.7g

A programmable data acquisition system of 100 channels and a custom developed PC based data processing software were used.

This shaking table is the most advanced facility in the world for dynamic model test of the dams(National Research Council,1990).

Scale model

For a realistic simulation of a prototype dam, the under designed Laxiwa arch dam located in the Yellow River of China was selected. Laxiwa, a 250m high logarithmic spiral double curvature arch dam, has a crest length of 501m,its thickness varies from 45m at the base to 10m at the crest.

Considering the shaking table performance characteristics and the properties of model materials, a geometrical scale of 1 / 300 was selected. By the principle of similitude theory the similitude constant C of the primary quantities must satisfy the following relationships:

Time	$C_t = C_l C_\rho^{1/2} C_E^{-1/2}$
Elastic deformation	$C_\delta = C_l^2 C_\rho C_E^{-1} C_a$
Strain	$C_\varepsilon = C_\delta C_l^{-1}$
Acceleration	$C_a = C_\delta C_E C_l^{-2} C_\rho^{-1}$
Unit weight of material	$C_\gamma = C_\rho C_g$
Possion's ratio	$C_\mu = 1$
Damping ratio	$C_\xi = 1$

Where C_l, C_ρ, C_E are the similitude constants of geometry,mass density of material, modules of elasticity of material, respectively. These are usually selected as basic similitude constants, and C_g is the similitude constant of gravity acceleration, which should definitely equal 1.0.

It is appropriate to consider the cantilevers of the dam as linear elastic substructure in small deformation category. Hence, it is not necessary to satisfy the requirements $C_\delta = C_l$ and $C_E = C_l C_\rho$.

For practical reason only the natural water can be used as the reservoir water in the model, so it is necessary that $C_\gamma = 1.0$, $C_a = C_g = 1.0$. Thus $C_\rho = 1.0$, this means that the mass density of material for dam model must be the same as the concrete in the prototype dam.

Similitude law increases the model frequencies by a factor of 30. Preliminary computation showed that about 5–6 modes would be included within the frequency range of the shaking table.

Following the similitude requirements for material of model dam, a custom manufactured sulphurized heavy rubber was used. This homogeneous material is easy to be machined into complex forms and to be glued together by specially prepared natural rubber glue without changing its physical and mechanical properties. The density of the material is very close to that of concrete. The modulus of elasticity of the material is about 200 ~ 300MPa, depending on its temperature.

The dynamic modulus of elasticity E of the model material was determined first from the natural frequency of a cantilever beam of uniform rectangular cross section through an impact test. It was confirmed later using the dam model. The damping ratio was identified from the response curve of the beam specimen to impact load.

The dam model was made by gluing together 13 arch ribs at 14 elevations. An integral dam model was firstly made and rigidly attached to the supporting pedestal. Having finished all test cases for dam without joints, three joints were cut in the model using special prepared thin saw blade.

A custom designed steel supporting pedestal together with reservoir were fixed on the shaking table by anchor bolts.Resistance type strain gages and accelerometers were used as well as custom made relative–displacement transducers to measure the opening of joints.

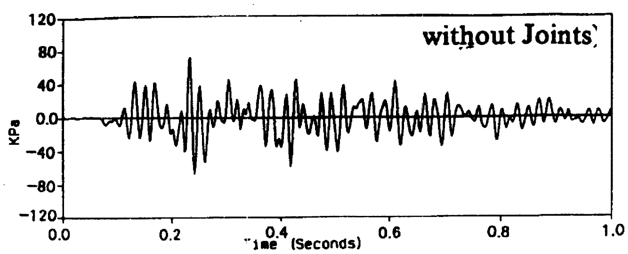
Test program

Two different earthquakes were used, an artificial earthquake based on the "Earthquake Resistance Design Code for Hydraulic Structure" in China and the well known Koyna earthquake. Tests were performed for different combinations of earthquake components from one component in the flow direction only to all three components with maximum ground acceleration varing from 0.2g to 0.6g. Tests were also made for different reservoir levels. This paper concentrated on one case, i.e. artificial earthquake with two horizontal components of 0.6g maximum ground acceleration and full reservoir.

Experimental results

The monolithic model was first tested for its natural frequency. The frequency of the first symmetrical mode was identified to be 56Hz. This results indicated an elastic modulus of 300MPa, a value used in the computation later.

Figure 1 shows the measured upstream arch stress at the crown of the top arch for the conditions without and with contraction joints. In this and other similar exhibits, tension is shown as negative stress. The clipped stress time history clearly shows the effect of joint opening. The joint opening time history at the crown of the top arch is shown in Fig.2.



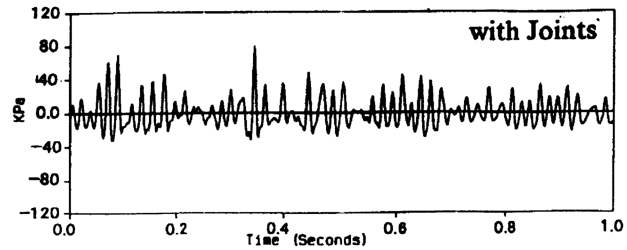


Fig.1 Measured Upstream Arch Stress at Crown of Top Arch

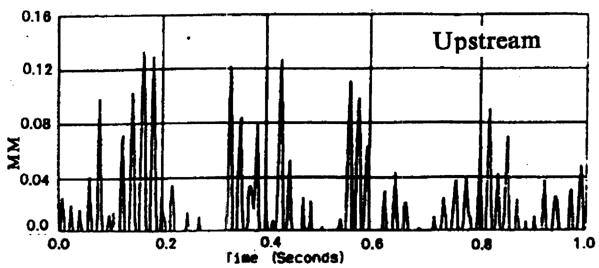


Fig.2 Measured Joint Opening at Crown of Top Arch

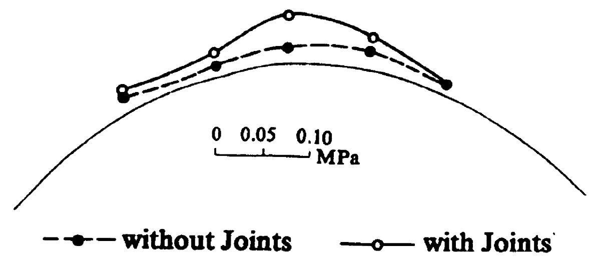


Fig.3 Measured Maximum Downstream Cantilever Stress at El. 70cm

Figure 3 illustrates the increase in cantilever stress due to the stress redistribution resulting from joint opening.

ANALYTICAL STUDY

The Sofiware

The computer program ADAP–88 (Fenves *et al.*,1989) was developed specifically for the analysis of arch dams allowing contraction joints to open during earthquake. The main feature and assumption involved are given below.

The contraction joints are modelled by joint elements with two coincident surfaces. The joint will open when its tensile strength is exceeded. It has stiffness under compression but does not have mass nor damping.

Three dimensional shell element and thick shell element are used modelling dam, and eight–node brick element modelling the transition zone near joints of dam and foundation rock. A substructure procedure condenses all DOF not related to the nodes on the joint element to reduce computational effort. A direct step–by–step integration analysis based on Newmark's average acceleration method is used to solve for the dynamic response. Equilibrium iteration is performed within each time step.

The hydrodynamic force is modelled by a diagonalized added mass matrix derived from fluid element assuming incompressible fluid. It is noted that for the scale model, the water is virtually incompressible. However, Previous study(Chen *et al.*,1989)showed that diagonalization of the added mass matrix tend to underestimate the natural frequencies.

Analytical Results

The finite element model of the dam includes 12 thick shell elements, 18 three dimensional shell elements, 324 brick elements and 48 nonlinear joint elements. The elastic modulus was 300MPa and damping ratio was 8% based on test results. The tensile strength of the joint was zero. The integration time step was 0.0004 seconds and the duration was 0.8 seconds corresponding to a prototype duration of 24 seconds.

Various conditions have been analyzed. As stated before, the main purpose of this paper is to investigate the effects of joint opening and to compare experimental and analytical results, so only the case with two horizontal components of artificial earthquake of 0.6g maximum acceleration and full reservoir is presented here.

Figure 4 shows the time history of upstream arch stress at the crown of the top arch for the dam without and with joints. Figure 5 presents the joint opening time histroy at the crown of the top arch. The increase of the cantilever stress due to joint opening is again demonstrated in Fig.6.

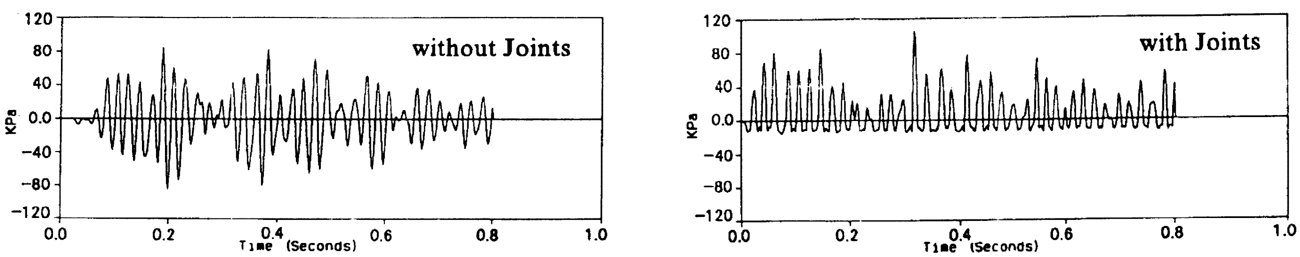


Fig.4 Caculated Upstream Arch Stress at Crown of Top Arch

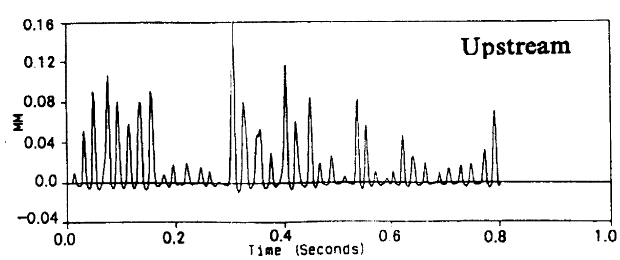


Fig.5 Caculated Joint Opening at Crown of Top Arch

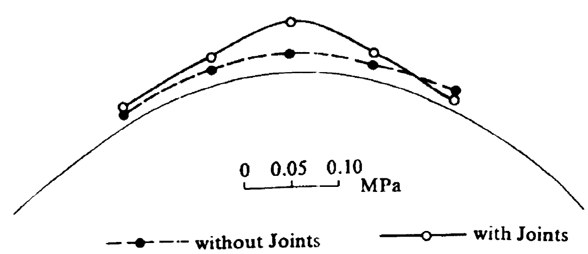
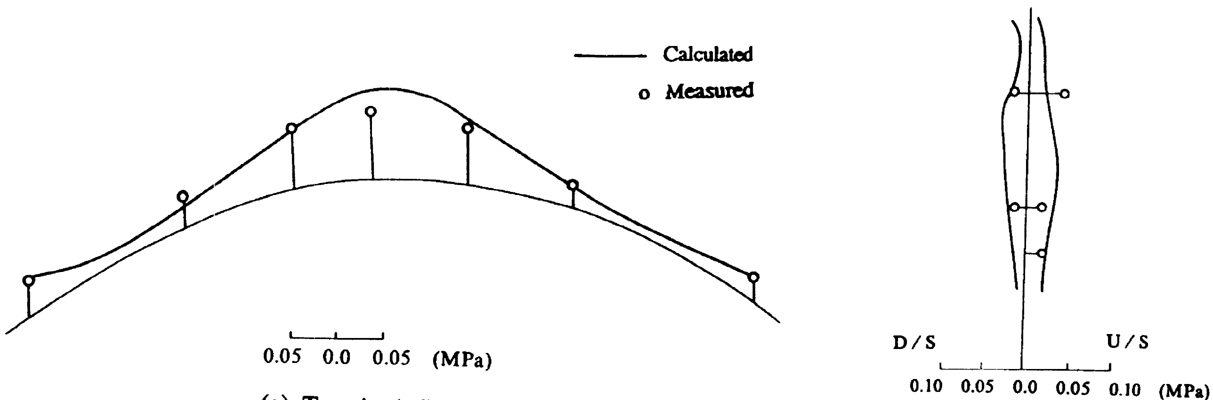


Fig.6 Caculated Maximum Downstream Cantilever Stress at El. 70cm

DISCUSSION AND CONCLUSION

Monolithic Dam

Tests of monolithic model with different level of ground accelerations showed that the seismic response was essentailly linear elastic for a maximum ground acceleration of up to 0.6g. The linear elastic seismic analysis of arch dams with rigid foundation and incompressible water is generally accepted as a well established practice. Its results are considered as satisfactory. In this sense, the analytical results can be used to confirm the accuracy of experimental results. Comparing Fig.1 and Fig.4, it is clear that both results are similar in magnitude and frequency contents. The very close results between tests and anlysis can also be observed in Fig.7.



(a) Top Arch Stress

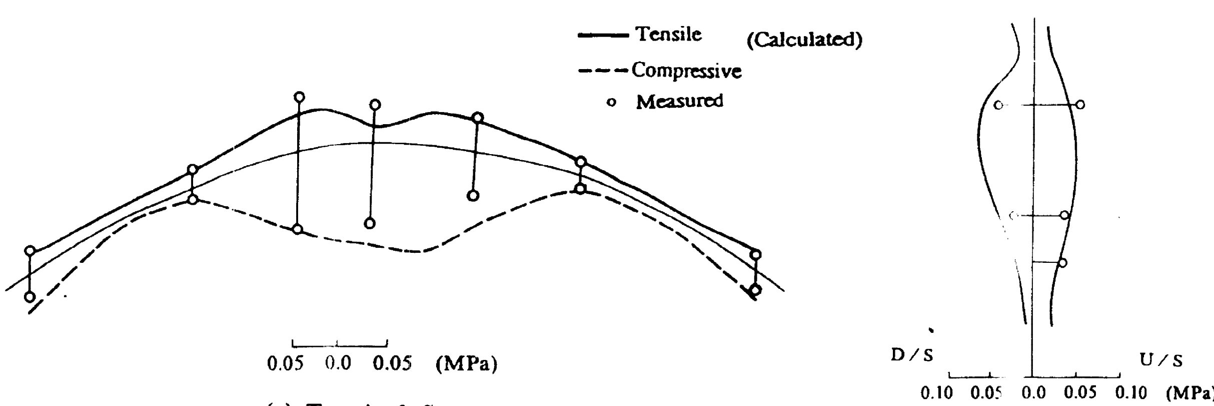
(b) Crown Cantilever Stress

Fig.7 Comparison of Maximum Stress(without Joints)

Dam with Joints

Both experimental results in Fig.1 and analytical results in Fig.4 clearly show the effect of the joint opening on arch stress. Tensile stresses are clipped. Both results are similar in magnitude and frequency contents. Time history plots of joint opening presented in Fig.2 and Fig.5 are remarkably close considering the complexity of the problem.

The good correlation of maximum stress envelopes between experimental and analytical results are demonstrated in Fig.8. Comapring Fig.7 and Fig.8, both experimental results and analytical results show a similar reduction in arch tensile stresses due to joint opening and a similar corresponding increase in cantilever stresses.



(a) Top Arch Stress

(b) Crown Cantilever Stress

Fig.8 Comparison of Maximum Stress(with Joints)

Conclusion

Based on the above presentation,the following conclusions can be drawn.

- Opening of contraction joints under seismic loading reduces high arch tensile stresses and increase cantilever stresses due to the significant stress redistribution.
- Both shaking table test and finite element analysis produce similar results on this phenomenon.

It has long been suggested that joint opening during earthquake is one of the explanations of observed seismic behavior of arch dams. This study demonstrated quantitively the behavior of this nonlinear mechanism. Further researches on this complex issue would provide important information for the design of arch dams as well as the evaluation of exsiting dams.

ACKNOWLEGEMENTS

The financial support from three U.S. organizations: Harza Consulting Engineers and Scientists, County of Los Angeles, Department of Public Works and Bureau of Reclamation is gratefully acknowledged. The authors wish to express their gratitude to Messrs C.H.Yeh, Shen Chonggang and V.J.Zipparro for their encouragement and help.

REFERENCES

James Shaw–Han Kuo(1982). Joint Opening Nonlinear Mechanism Interface Smeared Crack Model. University of California at Berkeley, Report No.UCB / EERC–82 / 10.

Michael J. Dowling (1987). Nonlinear Seismic Analysis of Arch Dams. California Institute of Technology, Report No. EERL 87–03.

Gregory L. Fenves, Soheil Mojtahedi, Richard B. Reimer (1989). ADAP–88: A Computer Program for Nonlinear Earthquake Analysis of Concrete Arch Dams. University of California at Berkeley, Report No. UCB / EERC–89 / 12.

A. Niwa and R.W.Clough(1980). Shaking Table Research on Concrete Dam Models. University of California at Berkeley, Report No. UCB / EERC–80 / 05.

Ljubomir Taskov and Dimitar Jurukovaski (1987). Shaking Table Tests of an Arch Dam Fragment. Proc. of China–U.S. Workshop on Earthquake Behavior of Arch Dams, Beijing, China.

Gregory L. Fenves, Soheil Mojtahedi, Richard B. Reimer (1992). Parameter Study of Joint Opening Effects on Earthquake Response of Arch Dams. University of California at Berkeley, Report No. UCB / EERC–92 / 05.

National Research Council et al.(1990). Earthquake Engineering for Concrete Dam's: Design, Performance, and Research Needs. National Academy Press. Washington, D.C.

H.Q.Chen, S.Z.Hou and D.W.Yang (1989). Study on Arch Dam–Reservoir Water Interaction Under Earthquake Condition. Journal of Hydraulic Enginerring, No.7.