VIBRATION BEHAVIOR OF XIANG HONG DIAN DAM

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SUMMARY

Results of a field measurement program on Xiang Hong Dian Dam in Anhui Province, PRC, are presented and correlated with finite element model analytical predictions. Forced vibration tests were carried out using 4 coupled rotating mass shakers newly developed in China, having an upper frequency limit of 25 Hz and force capacity of 4000 Kg per unit. Good correlation is indicated between calculated and measured mode shapes, frequencies, and hydrodynamic pressures, demonstrating the validity of the modeling of the dam and of its interaction with the reservoir, and the foundation.

INTRODUCTION

The effects of reservoir and foundation interaction on the dynamic behavior of arch dams is the subject of a three year research program presently being carried out under the U.S.-China Protocol for Scientific and Technical Cooperation in Earthquake Studies. The cooperating organizations are the Scientific Research Institute of Water Conservancy and Hydroelectric Power (SRIWCHP) Beijing, together with Tsinghua University and the Scientific Research Institute of Water Conservancy of Anhui Province (SRIWCAP) acting for China, and the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley, acting for the United States. The investigation is being carried out under the supervision of Professor K. T. Chang (Tsinghua University) and Professor R. W. Clough (EERC). The complete investigation will include making detailed measurements of the vibration properties of two arch dams in China (single curvature and double curvature) and comparing the results with predictions calculated using state of the art mathematical models. During later stages of the work, improved models will be formulated, based on indications from the test data.

Xiang Hong Dian (XHD) Dam in Anhui Province was selected as the subject of the first field measurement program. In August 1982 vibration tests were made and recorded mainly by teams of workers from SRIWCHP and SRIWCAP; supplementary

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measurements of hydrodynamic pressures and of foundation rock motions during the tests were obtained by the two co-authors from EERC. This paper reports partial results of the test on Xiang Hong Dian Dam; full details of the work will be published as a joint EERC-SRIWCHP report.

TEST PROGRAM

Description of the Dam

XHD Dam is located in the middle reach of the Pi river in Jinshai county of Anhui Province, China. It is a non-overflow gravity arch structure completed in 1958, 87.5 m high with a crest length of 361 m. The upstream face is a vertical cylindrical surface with 180 m radius; the thickness is 5 m at the crest and 39 m at the base. It is divided into 25 blocks of 14 m length between vertical contraction joints. Four horizontal walkways are located on the downstream face, as may be seen in Fig. 1.

Test Equipment

A system of four synchronized eccentric mass shakers, newly designed at SRIWCHP, was used to vibrate the dam. Principal features of the system are as follows: (1) the maximum force produced by each shaker is 4000 Kg; eccentric mass is provided by weights in rotating "baskets"; (2) frequency limits are 0.5 to 25 Hz in three ranges (0.5-5, 1-10, 2.5-25) with a maximum error in each range of 0.5%; (3) units can be set arbitrarily to act in phase or 180° out of phase with the master unit; control of phase is accurate to $\pm$ 5 degrees. Phase and frequency of each unit is indicated digitally. In this test the four exciters were deployed at the dam crest, located symmetrically at distances of approximately 47 m and 93 m from the centerline and oriented to apply forces in the radial direction.

The vibrations of the dam were sensed by two sets of velocity transducers provided by SRIWCHP and SRIWCAP, respectively; these generally were set in the integrating mode so as to indicate displacements directly. A total of 57 stations on the dam were established for these instruments: at the crest and along the four walkways, including some stations on the adjacent abutment rock. In addition, EERC established 14 stations for Ranger seismometers. These very sensitive instruments were used to measure motions of the foundation and abutment rock in order to study the foundation interaction mechanism; accordingly all but one of these stations were on rock, the other being at the dam crest to provide correlation with one of the SRIWCHP velocity meters. Because there were more recording stations for each type of instrument than there were instruments, it was necessary to repeat the tests with the transducers moved to new locations. Four repetitions were required to obtain all of the Ranger readings. Figure 2 shows the locations of the exciters and of the two types of instruments.

Experimental Procedure

Vibration properties were evaluated both from ambient vibration measurements as well as from the response to the coupled shear units, but only forced vibration results are discussed here. For the forced vibration tests, the frequency was varied gradually over the range from about 4 to 18 Hz, and the radial displacement amplitude was observed at several stations along the crest. In the frequency ranges near modal resonance, where the response varied rapidly with

frequency, the frequency increments were made very small (<0.05Hz) in order to identify the peak frequencies accurately. When all resonant frequencies had been identified, the exciters were operated successively at each frequency, and both radial and tangential response amplitudes were recorded for all transducer stations on the dam and foundation rock. In addition, readings of hydrodynamic pressure against the face of the dam were obtained at depths of 5, 15, and 25 m at three stations to the right of the centerline. Relative values of all readings were determined for each transducer to establish the vibration mode shapes.

ANALYTICAL STUDIES

Computer Program

Analyses of the dam vibration properties were made using the finite element computer program ADAP (1). This program models the arch dam body by special "thick shell" or "3D shell" elements, and the foundation rock by 8 node "brick" elements. In addition, the program has been extended from its original form to model the reservoir by 16-node incompressible liquid elements (2), the "added mass" of the reservoir being added to the mass of the concrete in establishing the mathematical model. The program solves the undamped eigen-problem of the finite element model to obtain the vibration mode shapes and frequencies, and then uses mode superposition to calculate earthquake response. For the purposes of this investigation, the program also was modified to give the mode superposition response to a set of harmonic forces applied at the dam crest. Thus, it is possible to duplicate analytically the forced vibration tests.

Mathematical Model

In this study, the dam was modeled using 30 thickshell or 3D shell elements. The foundation rock was assumed to extend to a distance equal to the dam height in the upstream and downstream directions, as well as beneath the dam base; the total rock volume was represented by 80 massless brick elements. In initial calculations the elastic modulus of the concrete was taken to be 4×10^6 T/M^2, and parametric studies of foundation interaction were made using ratios of rock to concrete moduli equal to 1.3, 0.65, and 0.325. Then by comparison of the calculated vibration shapes at the rock-concrete interface with the measured shapes, it was determined that the ratio of 1.3 gave the best correlation. Thus, this ratio was adopted in subsequent analyses.

The reservoir was modeled by incompressible liquid 16-node elements having nodes matching the nodes at the concrete interface. In addition, liquid elements followed the topography of the reservoir bottom, and extended upstream to a rigid vertical plane at a distance of 300 meters from the dam face (4.2 times the reservoir depth); by numerical experiment it was demonstrated that the rigid boundary had no significant effect at this distance.

Types of Analyses

In addition to eigenvalue analyses of the reservoir-foundation-dam finite element model, the response of the model was evaluated when subjected to harmonic excitation simulating the input of the four shaking machines. The displacements of selected gage points on the dam and hydrodynamic pressures at

the pressure gage locations were determined at various modal frequencies; in addition frequency response curves were obtained by calculating the displacement amplitudes of selected gage points as the frequency was varied below and above resonance.

CORRELATION OF RESULTS

Vibration Frequencies

Because only a rough approximation of the dynamic modulus of the concrete could be obtained from test specimens, the first step in the correlation of analytical and experimental results was adjustment of the concrete modulus to obtain a least squares best fit of the frequencies. Only the first four modes were used in this adjustment because they are considered to be most reliable; the resulting concrete modulus was found to be 3.532×10^6 T/M^2 (4.945×10^6 psi). Values of the frequencies obtained analytically using this modulus are listed in Table 1, together with the corresponding experimental values. The designation S or AS associated with the measured frequencies indicates whether the shakers were operated in a symmetric or antisymmetric pattern during the test. The discrepancy between experimental and analytical values for the first four modes averages only 1.3 percent, which is well within the precision of the individual experimental results; even for the higher modes the agreement generally is remarkably good.

Mode Shapes

The first three vibration mode shapes, calculated and measured at the dam crest and at the upper two walkway levels, are plotted in Figs. 3-5. The analytical values have been normalized to the amplitude of displacement measured at one location in each mode. The apparent quality of correlation could have been improved in some modes by normalizing to a different location, but these figures clearly show that the mathematical model reproduces the essential behavior in the four modes. Although not shown for lack of space, the fourth and fifth mode shapes correlate equally well at these three levels, but the analytical results for Mode 5 show a phase reversal at the lower levels which is not evident in the measured results. However, it is believed that the sign change was overlooked in the experimental data because the readings were so small.

Frequency Response Curves

The experimental modal frequencies were determined by operating the shaker system at a sequence of closely spaced frequencies and plotting the resulting response amplitude measured at an appropriate point on the dam crest; similar analytical results were obtained by duplicating the procedure mathematically. The resulting frequency response curves for the first two modes obtained with symmetric excitation are shown in Fig. 6, and for the first two antisymmetrically excited modes in Fig. 7; experimental and analytical results are shown respectively by dashed and solid lines. The additional peak in the experimental response curve of Fig. 7 corresponds to the second peak in Fig. 6; this mode was excited by both symmetric and antisymmetric input patterns, but less strongly in the antisymmetric case.

As expected, the peaks of the analytical and experimental curves indicate the same frequency discrepancies shown in Table 1. The amplitudes of the

analytical curves were matched to the experimental data by iterative adjustment of the modal damping ratio. The "experimental" damping ratio was obtained from the experimental frequency response curves by the half-power method. The damping ratios listed on the two figures show excellent agreement between analysis and experiment.

Missing Mode

It will be noted in Table 1 that no experimental frequency is indicated for Mode 6. In order to determine why this mode was not observed experimentally,the frequency response curve in the vicinity of the 6th mode frequency was calculated by combining the responses to symmetric excitation of Modes 5, 6, and 7. The result (solid curve in Figure 8) clearly demonstrates that the contribution of mode 6 (which does have a peak at 7.62 Hz) is completely overwhelmed by that of mode 5; thus, the test data did not suggest the existence of mode 6. To study the problem further, the frequency response was calculated by combining Modes 4, 5, and 6. This standard analysis for Mode 5, shown by the dash-dot curve in Fig.8, may be compared with the experimentally determined (dashed line) response curve for mode 5. The reason for the obvious frequency discrepancy is not known, but the mode 5 damping value correlates well. The possible missing of a mode, as noted here for mode 6, is a basic difficulty of the forced vibration test procedure when frequencies are closely spaced. In this case, the analytical shape of mode 6 (not shown for lack of space) is nearly the same as mode 5 at the crest; the shapes differ in the vertical sections, but the crest measurements made in this test procedure offer no clue to the missing mode.

Correlation of Hydrodynamic Pressures

Hydrodynamic pressures measured at various points on the face of the dam during excitation at the first and second mode frequencies are plotted in Fig. 9; also shown are the analytically predicted pressure variations across the dam at these same levels. The agreement between the analysis and these few experimental values is remarkable. So far as is known, this is the first correlation that has been reported between measured modal hydrodynamic pressures and corresponding analytical results, and it certainly suggests that the incompressible reservoir model is valid, at least for the combinations of dimensions and frequency involved in these two modes.

CONCLUSIONS

The excellent agreement between analysis and experiment obtained in this study demonstrates the high quality of results that can be obtained using modern experimental equipment and refined mathematical models; however, the fact that several modes were not identified experimentally among the first twelve demonstrates a basic limitation of the forced vibration test procedure. On the other hand,the measurements of foundation rock motions and of hydrodynamic reservoir pressures indicate the potential of this experimental technique for studying reservoir and foundation interaction with concrete dams. A complete report on the results of such interaction studies will be presented in the final phase of the investigation after reduction of the data recorded on both dams.

REFERENCES

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2. Kuo,J.S.-H.,"Fluid-Structure Interaction-Added Mass Computations for Incompressible Fluids",University of California, Earthquake Engineering Research Center, Report No. UCB/EERC-82/09, 1982.

TABLE I: MODAL VIBRATION FREQUENCIES (Hz)
(Water Level = 126.9 m)

Mode No.	Measured	Calculated
1	4.1 S	3.977
2	4.3 AS	4.347
3	5.1 S	5.156
4	6.0 AS	5.996
5	7.0 S	7.501*
6	--	7.623*
7	8.2 AS	8.381*
8	--	9.100*
9	9.5 S	10.509
10	--	10.656
11	10.8 AS	10.967*
12	12.5 S	12.665*

*Analysis showed 2nd mode shape in cantilever direction; experiment did not show this shape.

System Properties

Rock: $E_r = 4.592 \times 10^6$ T/m^2 (6.531×10^6 psi)
$\gamma = 0$

Concrete: $E_c = 3.532 \times 10^6$ T/m^2 (5.024×10^6 psi)
$\gamma = 150$ pcf.

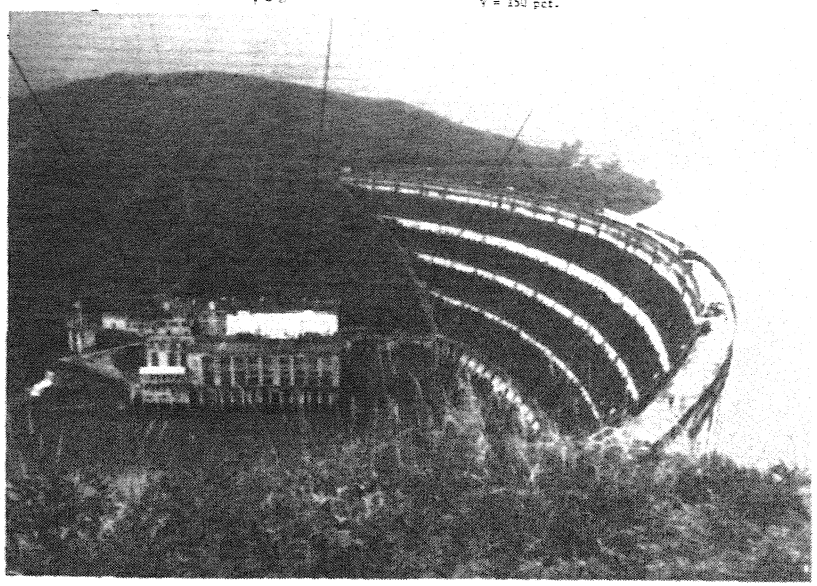
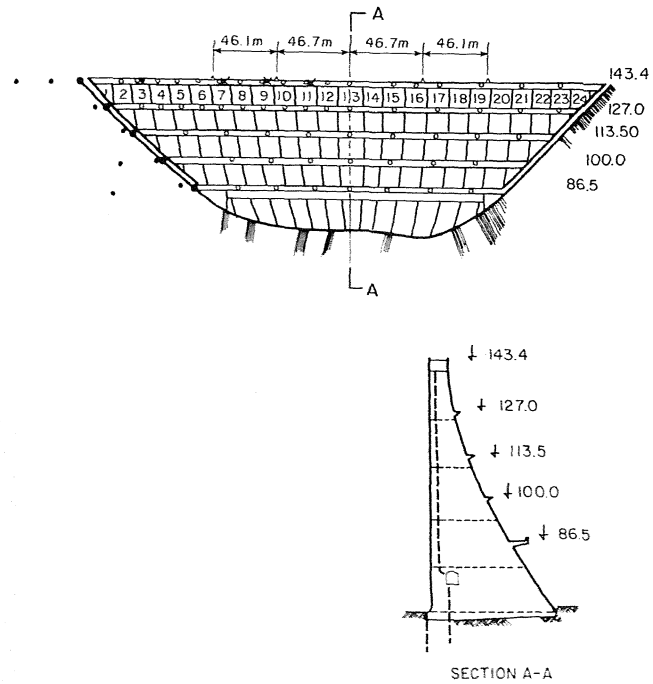


FIG. 1 XIANG HONG DIAN DAM



△ ROTATING MASS SHAKER

○ SRIWCHP AND SRIWCAP STATION

● PERC STATION FOR DISPLACEMENT

⊠ PERC STATION FOR HYDRODYNAMIC PRESSURE

FIG. 2 DAM GEOMETRY AND INSTRUMENT LOCATIONS

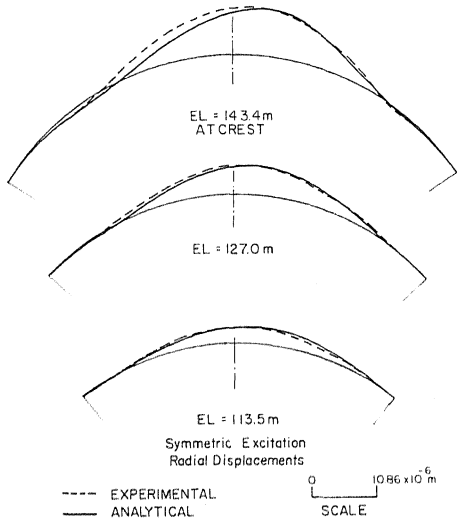


FIG. 3 FIRST MODE SHAPE,
f = 4.14 Hz

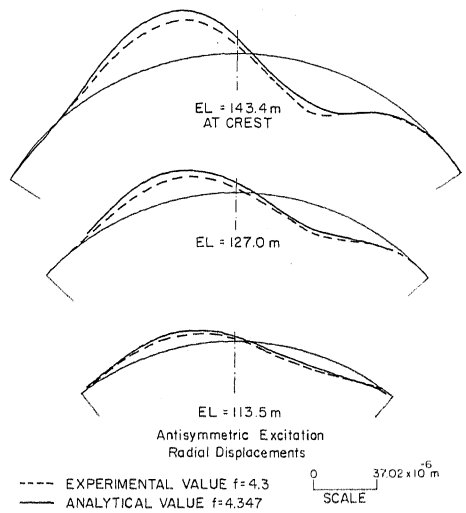


FIG. 4 SECOND MODE SHAPE,
f = 4.3 Hz

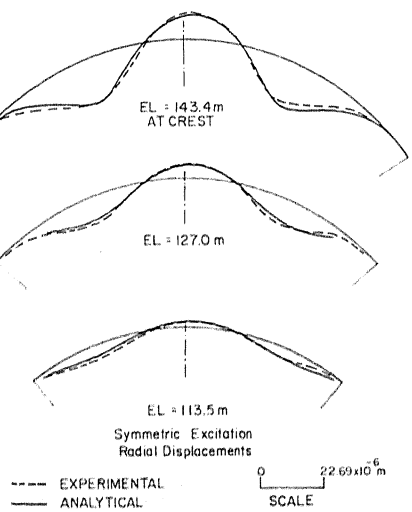
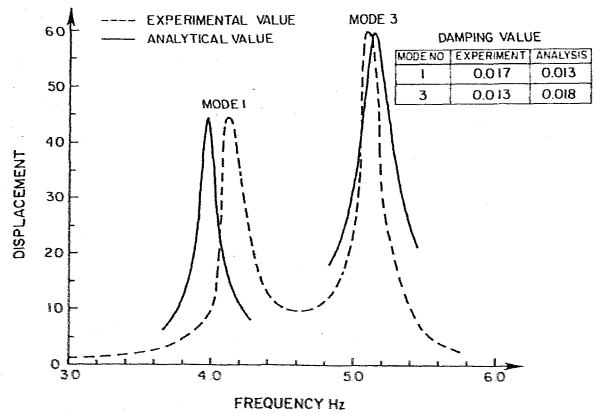
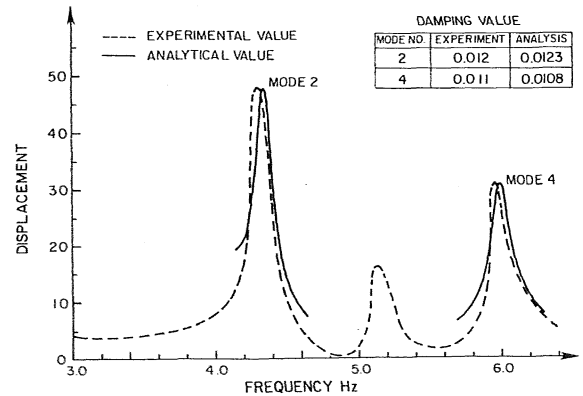


FIG. 5 THIRD MODE SHAPE,
f = 5.1 Hz



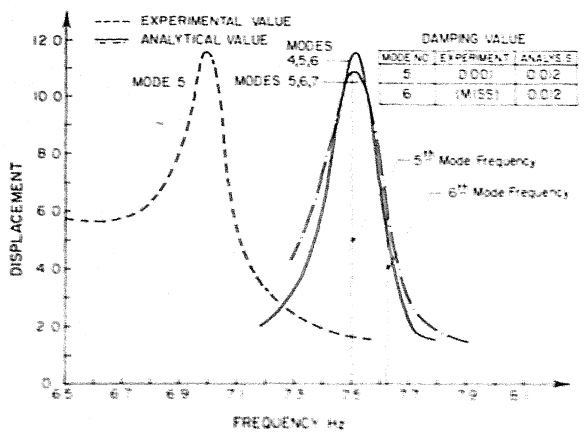
MODE NO	EXPERIMENT	ANALYSIS
1	0.017	0.013
3	0.013	0.018

FIG. 6 FREQUENCY RESPONSE CURVES FROM SYMMETRIC EXCITATION



MODE NO.	EXPERIMENT	ANALYSIS
2	0.012	0.0123
4	0.011	0.0108

FIG. 7 FREQUENCY RESPONSE CURVES FROM ANTISYMMETRIC EXCITATION



MODE NO	EXPERIMENT	ANALYSIS
5	0.001	0.012
6	(MISS)	0.012

FIG. 8 SYMMETRIC EXCITATION RESPONSE NEAR 6th MODE

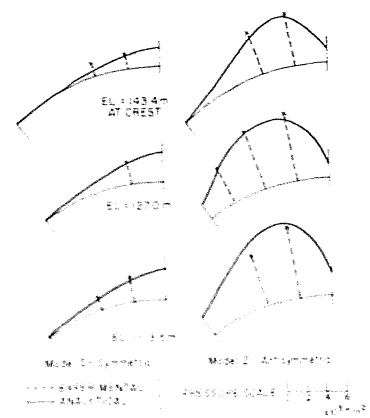


FIG. 9 HYDRODYNAMIC PRESSURES AT DAM FACE