MEASUREMENT OF DYNAMIC RESPONSE OF ARCH DAMS INCLUDING INTERACTION EFFECTS

Yusof GHANAAT[1], **Robert L HALL**[2] **And Bruce B REDPATH**[3]

SUMMARY

This paper describes an experimental study of dam-water-foundation interaction conducted at Longyangxia Dam in China. In the primary tests, the dam and its retained water were excited by detonating large explosive charges in shallow water upstream from the dam. The dam and water responses to the explosives were recorded by accelerometers, pressure sensors, and three-component seismographs. In secondary tests, the average reflection coefficient of the reservoir boundaries was measured using a newly developed procedure based on the acoustic reverberation concept. The results obtained indicate that explosive detonations appear to be the best means for exciting the dam-water-foundation system, and that an acoustic reverberation technique offers a practical procedure for measuring the overall reflection coefficient for the entire reservoir. Dam displacement and acceleration responses due to acceleration signals recorded at the base of the dam were computed using current analytical procedures. Generally good agreement between the measured and computed responses were obtained but the prediction could be improved if non-uniform input motion could be defined and used.

1. INTRODUCTION

This paper describes field measurements of dam-water-foundation interaction effects that were performed in October 1998 on Longyangxia Dam -- a gravity arch dam located in Gonghe County, Qinghai Province, China. This study was done as the most recent phase of a continuing cooperative research program funded by the US National Science Foundation under the US-China Protocol on Earthquake Studies with additional support from the US Army Corps of Engineers, Waterways Experiment Station (WES). The collaborating organizations in this research project are QUEST Structures of Orinda, California, Institute of Water Conservancy and Hydroelectric Research (IWHR) of Beijing, China, and Waterways Experiment Station, Vicksburg, Mississippi.

The objectives of the research were: 1) to develop new testing procedures for exciting dynamic response of the entire dam-water-foundation system, 2) to explore a new and improved procedure for in-situ measurement of the average reflection coefficient of the reservoir, and 3) to obtain measured data that would enable better validation of the current analytical procedures for predicting earthquake response of arch dams

The basic concept in the field measurements was to excite the dynamic response of the dam and its retained water by detonating explosive charges buried either in the foundation rock downstream from the dam or in shallow water upstream. The extremely narrow and steep gorge immediately downstream of the dam did not allow the use of explosives in bore holes as was done in a previous experiment at Dongjiang Dam in 1991. The explosive charges were, therefore, detonated in shallow water about 1.2 km upstream from the dam. In the primary program tests, large charges fired in water were intended to excite the dam-water interaction by blast-generated waves travelling through the foundation rock and water. In the secondary tests, the water interaction mechanism was excited by small explosive charges (blasting caps) suspended in the forebay. The major purpose of these tests was to determine the contribution to the dam-water interaction resulting from absorption of energy by the forebay bottom and sides, taking account of any sediment deposited at the bottom.

---

[1] *QUEST Structures, Orinda, California, yusofgh@msn.com*
[2] *US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi*
[3] *Redpath Geophysics, Murphys, California*

2. TEST STRUCTURE & INSTRUMENTATION

Longyangxia Dam is a 178 m-high concrete gravity arch dam completed in 1986. Longyangxia is the first dam in a cascade of seven dams planned for the upper reaches of Yellow River. As shown in Figure 1, the arch section of the dam is 396 m long at the crest level with a crest and base thickness of 15 m and 80 m, respectively. The dam also includes two 30 m high concrete gravity blocks at each end of the arch, beyond which auxiliary dams are provided on both banks. The total water front length of the dam structures is more than 1,223 meters. The dam includes an overflow spillway on the right abutment, two lower outlets on the right side near the base, and an intermediate outlet at mid-height near the left abutment.

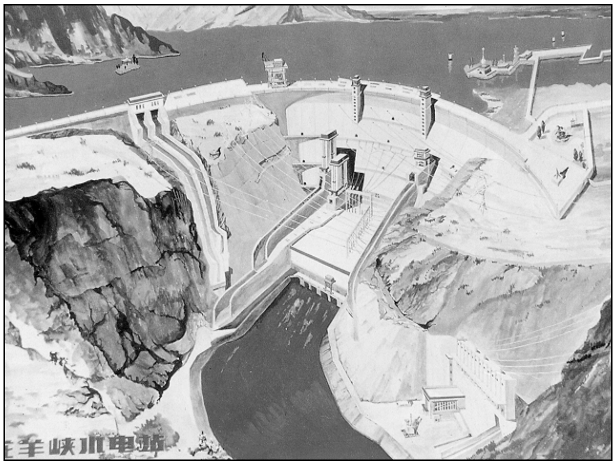


Fig. 1 Longyangxia Dam

The primary instrumentation used in recording the dynamic interaction were three sets of dynamic water pressure gages (hydrophones) installed on the face of the dam, within the forebay, and at the forebay entrance. A second instrumentation system consisting of accelerometers was employed to measure the dam response. The third response recording system included a set of digital seismograph units positioned in galleries near the dam-foundation interface. Each of these instrumentation systems is described next.

2.1 Water pressures

Water pressures on the face of the dam were measured using two strings of hydrophones lowered from the dam crest and positioned approximately at the 1/4 span locations. Two additional strings of hydrophones were suspended within the forebay from a support cable stretched along the river channel at the mid-point of the dam at distances 25 m and 67 m from the dam face. These four hydrophone strings were connected to the PC-based data acquisition system located on the crest of the dam.

A third array of hydrophones, discussed later, was stretched across the forebay entrance to measure blast-generated waves travelling toward the dam. This horizontal array included 12 hydrophones spaced at 3m intervals with a Geometrics R-24 digital seismograph as the recording unit.

2.2 Dam accelerations

Instrumentation system used to measure the dam response consisted of 17 accelerometers and a PC-based digital recording system. As shown in Figure 2, seven of these accelerometers (A1 to A7) were positioned along the crest of the dam and were oriented such that to sense the radial component of dam accelerations. The remaining 10 accelerometers were installed inside the galleries at four lower elevations, and were also oriented to measure the radial component of dam accelerations. The PC-based data acquisition system was placed in a room at the center of the dam crest.

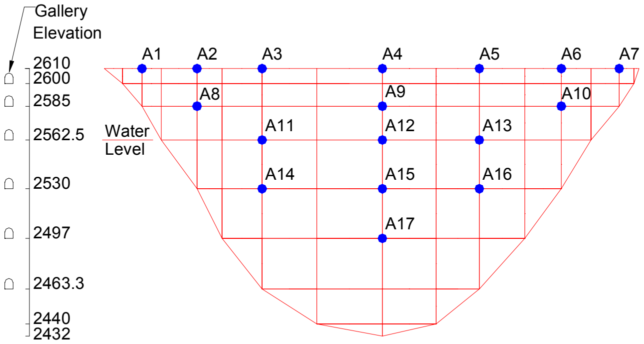


Figure 2. Accelerometers used to measure dam response

More than 12 digital three-component seismograph units were also employed: two strong motion seismographs were placed in the upper gallery near the dam crest, and the rest were positioned in galleries near the dam-foundation interface to provide some indication of the blast generated waves applied to the dam and foundation rock.

3. TEST PROGRAM

Blast-excitation tests were conducted by detonating four different explosive charges in shallow water. Initially, a 50-kg charge was detonated 2 km from the dam to calibrate the prediction of the resulting ground motion. The signals from this 50-kg calibration charge were much smaller than the ambient signals produced by turbine generators and other machinery. The main blast tests therefore consisted of a single 100-kg, a single 300-kg, and double 300-kg charges that were detonated at distance of 1.2 km from the dam. Figure 3 is a plan view showing the dam crest and water level contour lines, location of shots, hydrophone array at the forebay entrance, and the blasting caps employed in the reverberation tests. The large explosive charges for the main tests were lowered from a boat and detonated on the lake bottom in approximately 30 m of water.

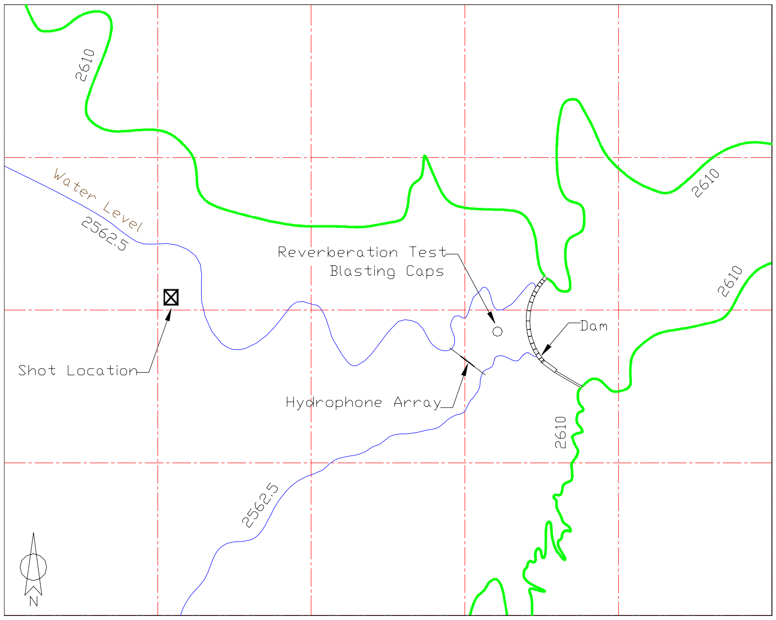


Figure 3. Plan view of Longyangxia Dam and its retained water

In the secondary tests the average acoustic reflection coefficient of the forebay at Longyangxia Dam was measured using a newly developed procedure based on the acoustic reverberation concept. Unlike our previous seismic reflection and seismic refraction techniques [Ghanaat et al., 1993; Ghanaat and Redpath, 1995] that measured reflection coefficients at a spot or within a small region, acoustic reverberation employed in this experiment was an exploratory attempt to obtain an overall reflection coefficient for the entire forebay. In acoustic reverberation tests, the water near the dam (forebay) was excited and brought to a steady state condition using an underwater energy source. The decaying response produced by turning off the source was then measured by hydrophones to obtain the reverberation time, from which the reflection coefficient for any surface or combination of surfaces could be determined.

4. SUMMARY OF MEASURED DATA

This experiment has produced a complete set of measured data for the study of dam-water-foundation interaction effects. A total of 27 pressure gauges, 17 accelerations, and 33 components of strong motion seismograph records have been collected for each of the three explosion tests. A comprehensive analysis and interpretation of all recorded signals is in progress and will be documented in our final report to the U.S. National Science Foundation. Only a few representative measured data are presented and discussed in this paper.

4.1 Recorded water pressures

Figure 4 is an example of water pressure recorded at the forebay entrance. The recorded pressure signal suggests two explosions, even though only a single charge of 100 kg with no delay was used. Based on the time interval, water depth, and the weight of the charge, we believe that the second pulse starting at about 1 second is the result of gas-bubble collapse. The high-frequency low-amplitude pulses at about 1 second indicate an arrival through the water, whereas the accompanying low-frequency high-amplitude pulses represent signals propagating through the foundation rock. The computed power spectral density (PSD) of the pressure signal (lower graph of

Figure 4) indicates that dominant frequencies of the blast-generated motion are in the range of 5 to 8 Hz. Accordingly, lower modes of vibration of the dam below 10 Hz are expected to be excited satisfactorily.

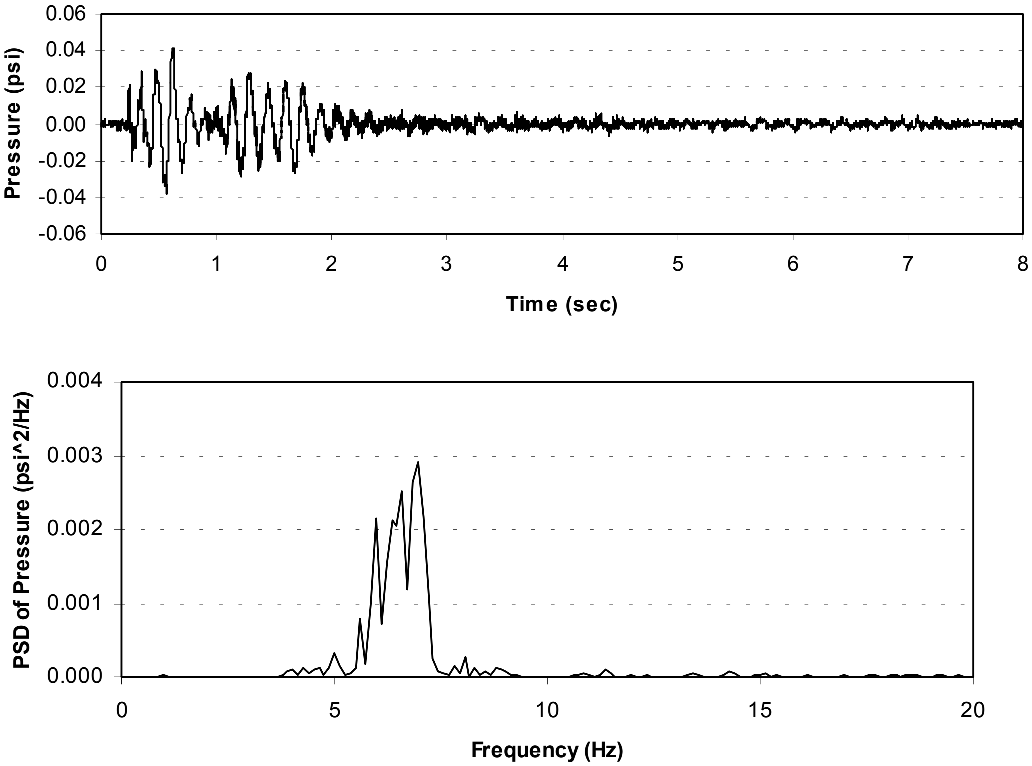


Figure 4. Recorded water pressure at forebay entrance with computed PSD due to single 100kg blast

Figure 5 shows an example of the recorded water pressure on the face of the dam induced by the single 100-kg blast. Despite the high-amplitude ambient signals present in the record, the blast-induced pressures are clearly visible in the 7.5 to 10 second time window. Also shown in Figure 5 is the PSD of the pressure record, indicating numerous resonant peaks, some of which have been identified as frequencies of the dam and the impounded water.

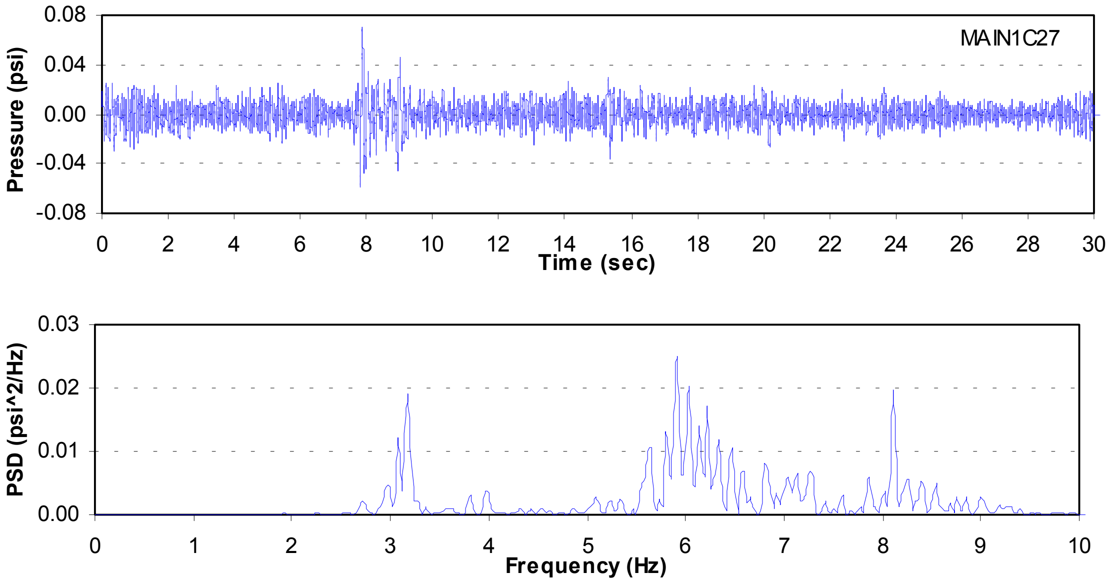


Figure 5. Recorded water pressure on dam surface with computed PSD due to single 100kg blast

4.2 Recorded dam accelerations

In addition to dam accelerations and water pressures the "*zero-time*" or firing pulse was also recorded so that the exact detonation time and, therefore, the travel times of signals through foundation rock and water could be determined. This pulse was transmitted by wire over a distance of 1.2 km to the recording center. An example of the recorded acceleration at the center of the dam crest is shown in Figure 6. The velocity and displacement histories were computed by successive integration of the recorded acceleration in the frequency domain. The results indicate that maximum dam accelerations of about 0.002 g and 0.008 g were obtained for the 100 kg and 300 kg shots, respectively.

The acceleration signal in Figure 6 exhibit three distinct parts. The first part between zero and about 7.5 seconds is the dam response to ambient noise caused by turbine generators and other machinery. The second part with high-amplitude pulses starting at about 7.5 seconds and lasting about 3 seconds is the response of the dam to the blast-generated ground motion. The remaining signal beyond 11 seconds is again the dam response to the ambient noise, except that the dam response is higher from 15 to 22 seconds due to vibration of the outlet-gate towers.

4.3 Dynamic characteristics of dam

In order to facilitate and improve the ability to identify dynamic properties of the dam, spectrograms of the measured dam accelerations were developed for all 17 acceleration response points. A spectrogram is a plot of PSD as a function of frequency and time, as shown in Figure 6. The top graph in this figure shows the measured dam acceleration signal and the bottom graph is the corresponding spectrogram exhibiting variation of PSD with time and frequency. Produced from the cross-section at 8 seconds, the second graph from the top exhibits frequency content of the measured acceleration signal at the time of 8 seconds. Whereas the second graph from the bottom obtained from the cross-section at 3.1 Hz, indicates spectral amplitude variations with time of a 3.1 Hz signal present in the recorded acceleration. Using such information the measured acceleration records were decomposed into dominant single-frequency records from which the dam response could be animated and its mode of vibration determined.

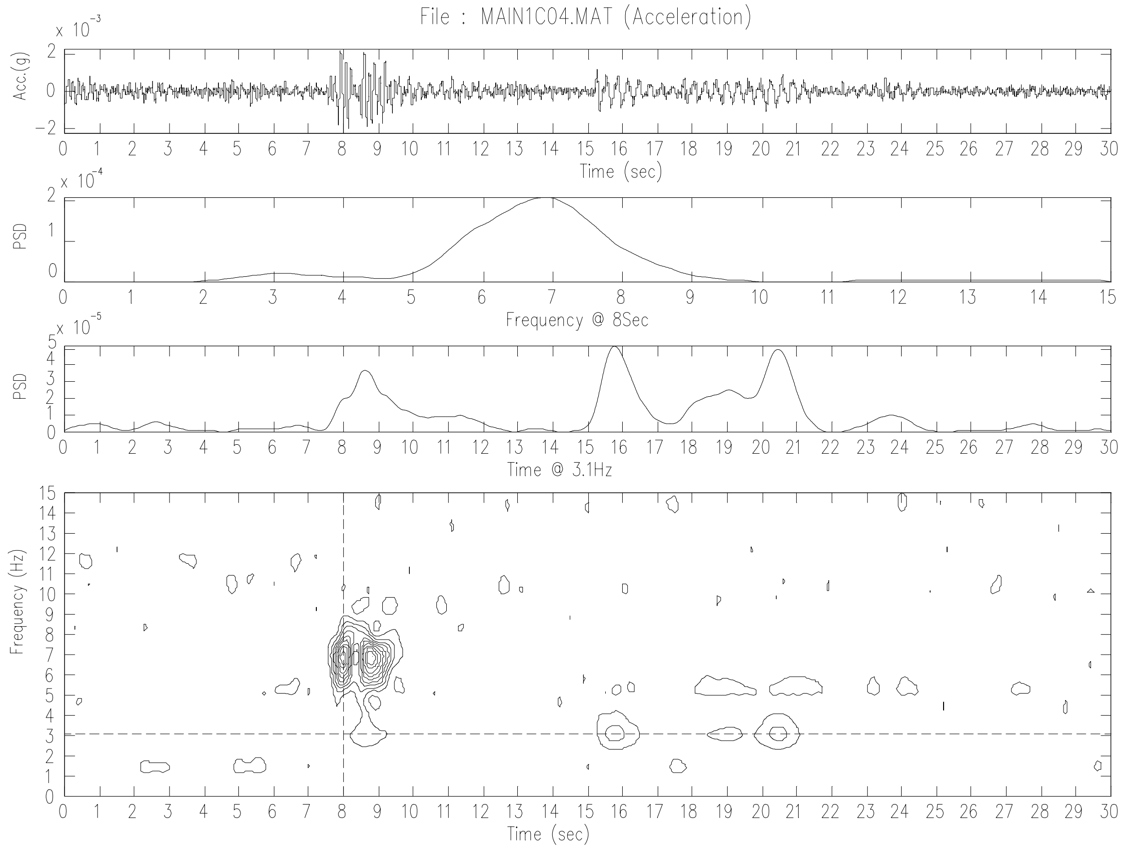
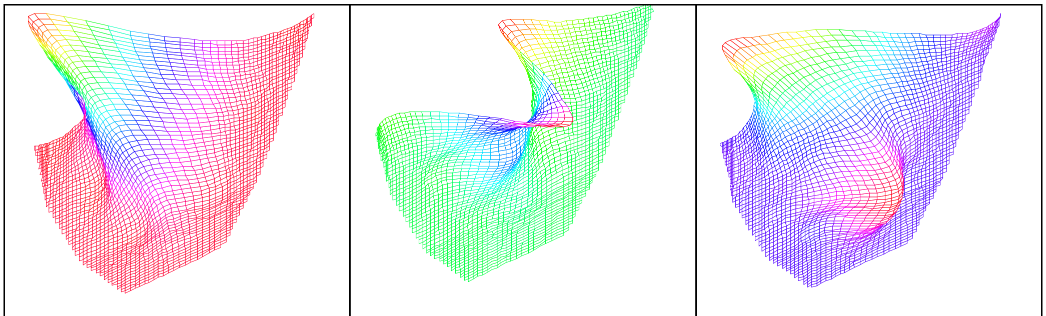


Figure 6. 2D Spectrogram of recorded dam acceleration

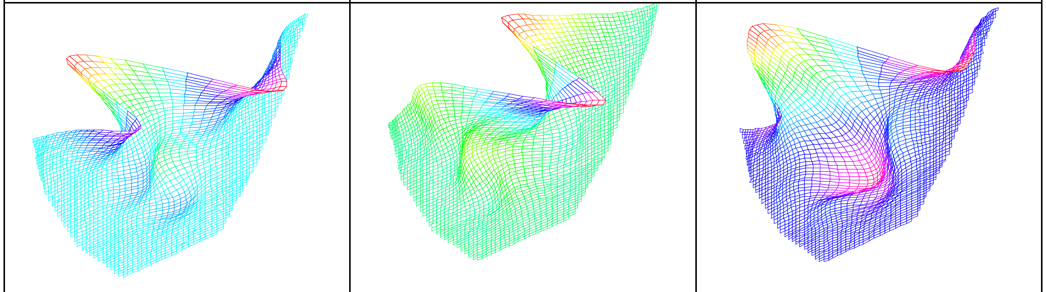
Following the above procedure, 10 modes of vibration were identified, six of which are displayed in Figure 7. Mode 1 at 3.17 Hz is the fundamental symmetric mode of the dam. Mode 2 with a frequency of 4.39 Hz represents the fundamental anti-symmetric mode of the dam. Mode 3 at 5.25 Hz is similar to the fundamental symmetric mode, except that it is accompanied by the second cantilever bending mode of the dam. Higher modes exhibit more complicated deflected shapes, but in general they consist of higher order bending of the arch sections combined with the second and higher cantilever bending modes. The measured modal damping ratios vary in the range of 0.51% to 1.85% of critical.



Mode - 1: f=3.17Hz, ξ=1.85%

Mode - 2: f=4.39Hz, ξ=1.28%

Mode - 3: f=5.25Hz, ξ=1.20%



Mode - 4: f=5.62Hz, ξ=1.15%

Mode - 5: f=5.98Hz, ξ=0.86%

Mode - 6: f=6.29Hz, ξ=0.88%

Figure 7. Measured mode shapes, frequencies, and modal damping ratios

4.4 Acoustic reverberation tests

The acoustic reverberation tests at Longyangxia Dam used a vertical array of 10 blasting caps as the excitation source and an array of 12 hydrophones as detectors. Assembled at intervals of 3 m, the blasting caps were suspended in water and, using a sequential blasting machine, were detonated from bottom to top using delays of 100 ms and 50 ms. The resulting water pressures were recorded by the array of 12 hydrophones stretched across the forebay entrance and connected to the Geomatrix R-24 digital seismograph (see Figure 3).

Reverberation time, the parameter of interest in the acoustic reverberation tests, refers to the amount of time required for the sound field in a space to decay 60 dB, or to one millionth of the original power. In simple terms this refers to the amount of time it takes for sound energy to bounce around a reservoir before being absorbed by the reservoir boundary materials. Closed spaces with highly reflective walls and boundaries have long reverberation times, and very absorbent spaces have short reverberation times. The top graph in Figure 8 shows a pressure signal recorded by one of the 12 hydrophones during the reverberation tests. This graph illustrates that the sequential detonation of 10 blasting caps did in fact produced a reasonably sustained signal, which then decayed at the conclusion of the detonation sequence. The bottom graph illustrates the procedure employed to determine the reverberation time. For this purpose the measured pressure signals were squared and averaged across all channels and then plotted in logarithmic scale. From the logarithmic graph it can be determined that an energy decay of 60 dB corresponds to a reverberation time of 1.6 seconds.

Knowing the reverberation time and the volume and total surface areas of the forebay, a reflection coefficient of 0.82 was obtained using the well-known Sabine equation, which can be found in any architectural acoustic textbook. This value is judged to be quite reasonable for a rock site with very little or no accumulated sediments.

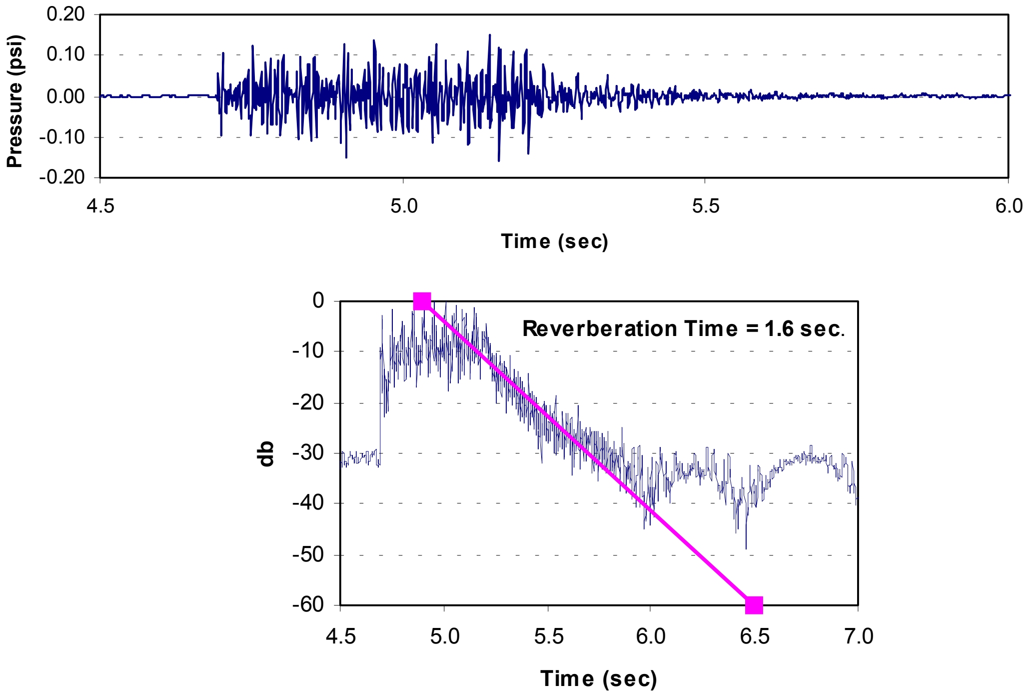


Figure 8. Measured reverberation time at Longyangxia Dam

5. SUMMARY OF CORRELATION STUDIES

Another objective of this study was to obtain measured data for validation of the current analytical procedures. For this purpose Longyangxia Dam, its foundation rock, and the impounded water were modeled using the GDAP [Ghanaat, 1993] and EACD-3D [Fok et al., 1986] programs. Both programs use the same finite-element models for the dam and foundation rock, except that GDAP employs incompressible water while EACD-3D considers water compressibility and reservoir boundary absorption effects to represent the impounded water.

Models for the dam and foundation rock were developed in accordance with the standard finite-element procedures using shell and solid elements. The impounded water was modeled using either incompressible or compressible fluid mesh constructed to match the measured bottom topography of the reservoir. A relatively close match between the measured and computed frequencies was obtained by increasing modulus of elasticity of the concrete and foundation rock by 40% (EACD-3D) and 63% (GDAP) beyond the static values. This increase of modulus is justified considering that the dynamic modulus is expected to be up to 50% higher than the static value. The GDAP mode shapes computed for the dam-water-foundation system provided good agreements with the measured mode shapes discussed earlier.

Dam displacement and acceleration responses were computed using acceleration signals recorded at the base of the dam as the input motion. The base motion consisted of radial, tangential, and vertical components that were applied uniformly in the stream, cross-stream, and vertical directions at the dam-foundation contact nodes. Various cases and conditions including fluid meshes constructed on the basis of a prismatic geometry and the measured reservoir topography were studied. Only displacement results for one case considering the reservoir topography, a measured reservoir boundary reflection coefficient of 0.82, and a measured average modal damping ratio of 2% are presented here. The results in the form of time histories of measured and computed radial, vertical, and tangential displacements at the center of the crest are displayed in Figure 9. Overall the GDAP model employing an incompressible water provides a satisfactory match with the measured results, especially for the vertical displacements. Despite more accurate representation of the dam-water interaction effects, EACD-3D gives a somewhat reasonable match mainly, because unlike the test results, some of the EACD-3D resonant peaks coincided with the peak of the input spectra. However, such comparison is problem specific and is applicable only to this dam and the input motion used and should not be generalized. The differences between the measured and computed radial and tangential displacements are believed to be related to the use of uniform input motion, as opposed to non-uniform input motions that vary both in amplitudes and phasing along the dam-foundation interface. It should be noted that the measured motions at the dam-foundation interface are not free-field motion and thus could not be used as the input.

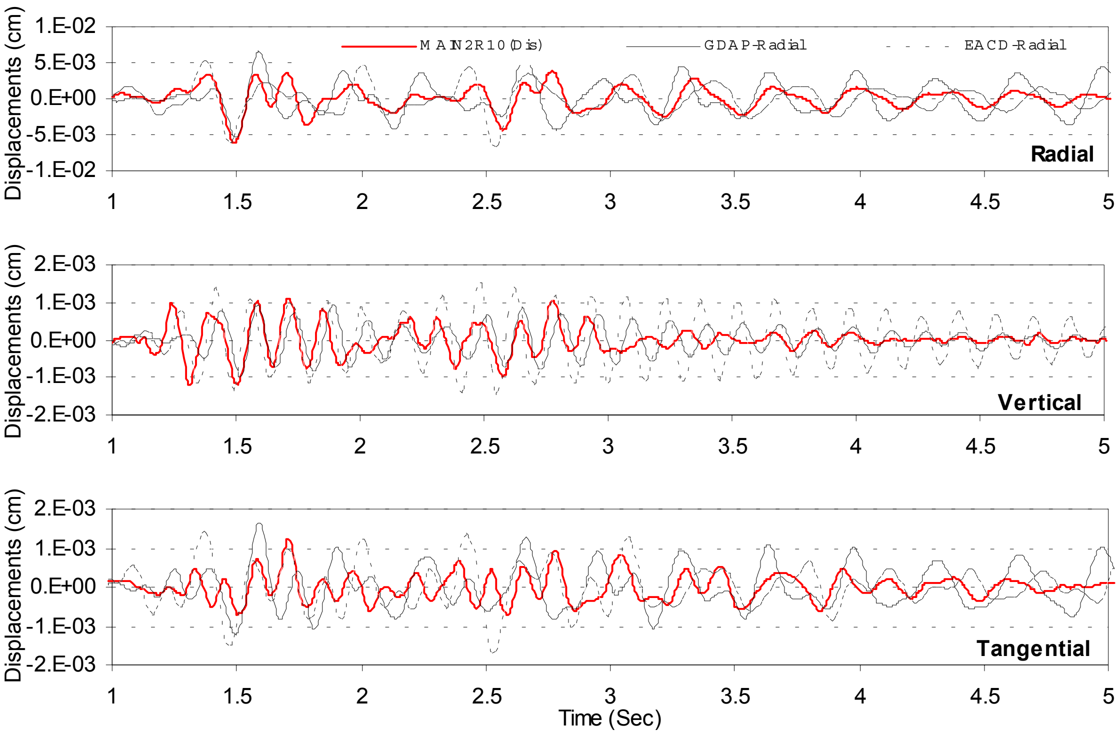


Figure 9. Comparison of measured and predicted crest displacements

6. CONCLUSIONS

Based on the analyses and correlation studies conducted so far the following conclusion can be drawn:

1. Detonating explosive charges in the water can successfully excite large arch dams and their retained lakes.

2. Dynamic properties of the dam can be obtained from such tests, provided that appropriate data processing techniques are employed.

3. An acoustic reverberation technique to determine the effective overall reflection coefficient for the reservoir boundary appears to work and provides a most plausible value.

4. Water compressibility and reservoir topography appear to be important for this dam, even at low water level

5. Good agreement between the measured and computed dam responses were obtained but the prediction could be improved if non-uniform input motion could be defined and used.

REFERENCES

Fok, K.-L., Hall, J.F., and Chopra, A.K. (1986). *EACD-3D, A computer program for three-dimensional analysis of concrete dams*, Eq. Eng. Research Center, University of Calif., Berkeley, Report No. UCB/EERC-86/09.

Ghanaat, Y. (1993). *GDAP, Graphics-based Dam Analysis Program*, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Ghanaat, Y., Chen, H.-Q., Redpath, B.B., and Clough, R.W. (1993). *Experimental Study of Dongjiang Dam for Dam-Water-Foundation Interaction*, QUEST Report No. QS93-03 submitted to the US National Science Foundation.

Ghanaat, Y. and Redpath, B.B. (1995). *Measurements of reservoir-bottom reflection coefficient at seven concrete dam sites*, QUEST Report No. QS95-01 issued to the US Army Corps of Engineers, Waterways Experiment Station and US Bureau of Reclamation.

12WCEE
2000

ABSTRACT

The paper describes an experimental study of dam-water-foundation interaction conducted at Longyangxia Dam, a 178-m high concrete gravity arch dam in China. The basic concept in the field measurements was to excite the dynamic response of the dam and its retained water by detonating large explosive charges in shallow water upstream. In the primary tests, the dam and its retained water were excited by detonating a single 100-kg, a single 300-kg, and double 300-kg charges in shallow water about 1.2 km upstream from the dam. The dam and water responses to the explosives were recorded by 17 accelerometers and 27 pressure sensors (hydrophones) connected to a PC-based data recording system. Seven accelerometers were positioned along the crest of the dam and the remaining 10 were installed inside the galleries at four lower elevations. Two strings of hydrophones were positioned on the face of the dam, two suspended within the forebay, and a fifth string was stretched across the forebay entrance. More than 12 digital three-component seismograph units were also positioned in galleries near the dam-foundation interface to provide some indication of the blast generated waves applied to the dam and foundation rock. Samples of the recorded acceleration and pressure signals are presented and discussed. Dynamic properties of the dam including resonant frequencies, mode shapes, and damping determined using spectrograms of the recorded accelerations are also presented.

In secondary tests, the average reflection coefficient of the reservoir boundaries was measured using a newly developed procedure based on the acoustic reverberation concept. The acoustic reverberation tests at Longyangxia Dam used a vertical array of 10 blasting caps as the excitation source and an array of 12 hydrophones as detectors. Assembled at intervals of 3 m, the blasting caps were suspended in water and, using a sequential blasting machine, were detonated from bottom to top using delays of 100 ms and 50 ms. The recorded pressures indicate that the sequential detonation of 10 blasting caps produced a reasonably sustained signal, which then decayed at the conclusion of the detonation sequence. The decaying response of the measured pressures was used to obtain the reverberation time, which is defined as the amount of time required for the pressures to decay 60 dB, or to one millionth of the original power. Knowing the reverberation time and the volume and total surface areas of the forebay, a reflection coefficient of 0.82 was obtained using the well-known Sabine equation.

Finite-element models of the dam and foundation rock were developed to predict dam responses using acceleration signals recorded at the base of the dam as the input motion. The impounded water was modeled using either incompressible or compressible fluid mesh constructed in accordance with the measured bottom topography of the forebay. The computed mode shapes and frequencies for the dam-water-foundation system provided good agreements with the measured values. Dam displacement and acceleration responses computed using the measured reflection coefficient and modal damping gave a satisfactory match with the measured results.

Overall the results obtained indicate that explosive detonations appear to be the best means for exciting the dam-water-foundation system, and that an acoustic reverberation technique offers a practical procedure for measuring the overall reflection coefficient for the entire reservoir. Water compressibility and reservoir topography appears to be important for Longyangxia Dam, even at the low water level the dam was tested. Generally good agreement between the measured and computed responses were obtained but the prediction could be improved if non-uniform input motions could be defined and used.

EARTHQUAKE ENGINEERING IN PRACTICE:Dams, *Absorption, Acceleration records, Dam Arch, Dam-reservoir-foundation interaction, Experimental research., Explosives, Modelling, Modes of vibration, Reflection coefficient, Reverberation*