Experimental study of dam-water-foundation interaction[1]

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ABSTRACT: This paper describes an experimental study of dam-water-foundation interaction that was conducted on Dongjiang Arch Dam in China. In the primary tests, the dam and its retained lake were excited by detonating explosive charges buried in the foundation rock. The system responses to the explosions were recorded by accelerometers, pressure transducers as well as by three-component seismographs. In the secondary test series, the system was excited by shock waves propagated in the lake from small suspended charges. In addition, two approaches based on the seismic refraction and reflection techniques were used to determine the reflection coefficient of the lake-bottom materials. The results obtained indicate that contain-ed explosive detonations appear to be the best means for exciting the dam-water-foundation system in order to predict the dynamic response of the combined system for validation of existing analytical procedures.

1 INTRODUCTION

This paper describes an experimental study of concrete arch dam-water-foundation interaction that was performed in September 1991 on Dong-jiang Dam -- a double curvature structure located in Zixing County, Hunan Province, China. This work was done as the most recent phase of a continuing cooperative research program funded under the U.S.-China Protocol on Earthquake Studies described by Clough et al. (1985). The two collaborating organizations in the present research are QUEST Structures of Emeryville, California and the Institute of Water Conservancy and Hydroelectric Research (IWHR) of Beijing, China. Dr. Yusof Ghanaat of QUEST Structures and Professor H-Q Chen of IWHR are co-principal investigators, while Professor Clough and Dr. C.G. Shen of IWHR have been designated as Project Advisers.

The objectives of the research were to develop new testing procedures for exciting the complete dam-water-foundation system, and to obtain measured data that can be used to validate the existing analytical procedures for predicting the earthquake response of arch dams. The basic concept in this experimental study was to excite the dynamic response of the dam and its retained lake by detonating explosive charges. In the principal program tests, large charges were fired in boreholes drilled into the solid foundation rock at a distance 800 m downstream of the dam; these were intended to excite the dam-water interaction by shock waves travelling through the foundation rock. In a secondary test series, the system was excited by shock waves propagated in the lake water from small explosive charges suspended in the retained lake. A major purpose of the tests was to determine the contribution to the dam-water interaction resulting from reflection and refraction of vibratory waves at the lake bottom, taking account of the sediment deposited there.

The primary instrumentation used in recording the dynamic interaction was a set of dynamic water pressure gages (hydrophones) and its recording system. This equipment was provided by the QUEST team, which was headed by Dr. Ghanaat and included Mr. Bruce Redpath who served as principal geophysicist, as well as Professor Clough. A second instrumentation system consisting of accelerometers and a computer based data acquisition unit was supplied by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) of Vicksburg, Mississippi under the direction of Dr. Robert Hall. The third major response recording system was a set of digital seismograph units together with a computer based data acquisition system; this was provided by IWHR and was under the general supervision of Professor H-Q Chen.

2 TEST STRUCTURE & INSTRUMENTATION

Dongjiang Dam, the highest double curvature arch dam presently in operation in China, is 157 m high

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and has a crest length of 438 m; it is 7 m and 35 m thick at the crest and base, respectively. The dam structure includes a powerhouse near the toe and four power penstocks; additionally there are three ski-jump spillways, one on the left and two on the right side. Figure 1 is a photograph of the dam taken from downstream.

Fig.1 Downstream view of Dongjiang Dam.

The hydrodynamic pressure recording system supplied by QUEST included a set of 20 Aquasense hydrophones having a cutoff frequency of 3 Hz and a sensitivity of 5.3 Volts/Bar. Each of these gages is encapsulated and provided with a waterproof lead wire; they proved to be completely free of water leakage problems during the entire test program. They were connected to a 24-channel EG&G Geometrics Model-2401 Seismograph, which is a computer based recorder including a 15 bit A/D converter, instantaneous floating point amplifiers, selective sampling ratios from 0.1 to 50 msec, various digital filters and built-in data storage capacity for 4096 data samples per record.

In the major tests of the dam, 9 of the 20 hydrophones were suspended in groups of three from locations at the dam crest; these measured the dynamic pressures at three different elevations at the dam face, as shown in Figure 2. Also shown are the two additional hydrophones suspended similarly that served to sense the dynamic pressures at locations near the abutments. Three additional strings of three sensors each were suspended from a support cable positioned on a vertical plane near the midsection of the dam and oriented normal to the dam face. These strings were attached at distances of 60 m, 110 m, and 210 m from the dam face (measured at the water surface); thus the 9 hydrophones were located on a rectangular grid as shown in Figure 3.

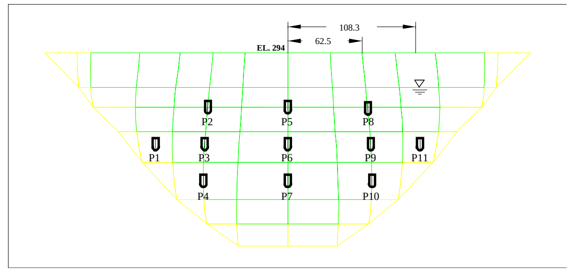

Fig.2 Location of pressure sensors on dam face.

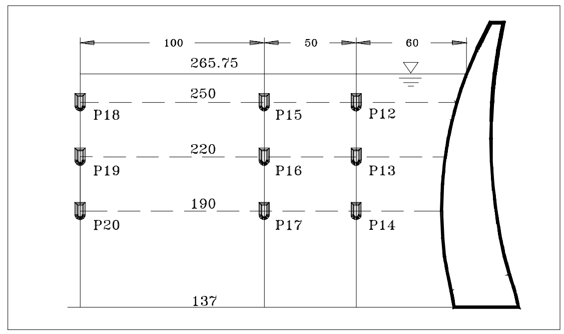

Fig.3 Location of pressure sensors inside lake.

The PC-based digital recording system supplied by WES included a set of 15 Wilcoxon accelerometers and served to record the response of the dam to either the explosive generated ground shock or the lake water shock wave. The accelerometers were positioned on the crest and within the galleries of the dam at the locations shown in Figure 4; all were oriented so as to sense the radial component of dam accelerations.

Also shown in Figure 4 are the positions where the 12 strong motion seismograph units supplied by IWHR were located. It will be noted that 7 of these were at the dam-rock interface, while the other 5 were equally spaced across the dam crest. The abutment positions were intended to give some indication of the shock wave applied to the dam by the foundation rock; of course, their records did not indicate "free-field" motions because of the influ-ence of the dynamic response of the dam. Comparison of the crest location response with that at the dam-rock interface gives an indication of the amplification caused by the dynamic response of the dam.

Two additional seismograph units were positioned along the river bank to record the free-field motions induced by the blasts. One was at the base of the bridge 100 m from the shot array, and the other was placed either at 445 m (S13a) or at 665 m (S13b) along the line between the shot holes and the dam base as shown in Figure 5. All of these seimographs as well as those on or adjacent to the dam were three component units with their axes oriented to record the acceleration along the main channel, across channel, and vertically.

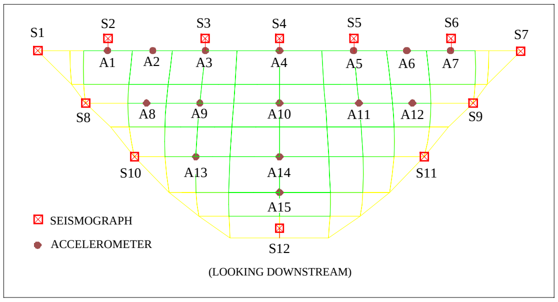

Fig.4 Location of accelerometers and seismo-graphs for measuring dam response.

3 EXPERIMENTAL PROGRAM

This experimental study included two types of explosion tests intended to demonstrate the dam's dynamic performance: those applied to the foundation rock and those detonated in the lake water. Other shock tests were done using small blasting cap charges to evaluate the reflection and refraction properties of the materials at the lake bottom. In addition, supplementary tests were performed to determine the vibration properties of the dam, and the topography of the lake bottom. Descriptions of each part of the test program follow.

3.1 *Blast tests*

A. Ground shock: For the ground shock phase of the testing, an array of 5 boreholes, 15 cm in diameter, were drilled to a depth of 40 m at a distance of 800 m from the dam base. As shown in Figure 5, this array was aligned approximately parallel to the dam axis so the shock wave propagating from simultaneous detonation of the charges would impinge nearly simultaneously along the entire base of the dam. Two preliminary shots of 40 kg each were detonated in hole no. 1 to calibrate the prediction of the resulting ground motion based on empirical equations. This calibration was needed to ensure that the larger charges used later would not damage the highway bridge located only 40 m away (see Figure 5). In addition these shots helped in setting gain ranges on the instrumentation and in establishing communication between recording and detonation sites that was needed for the firing count-down and for the firing impulse signal that gave a common time base for all recorders.

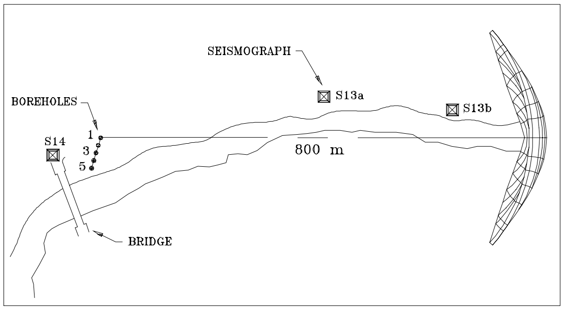

Fig. 5 Plan view showing dam, boreholes, free-field seismographs and highway bridge.

For the first multiple-hole ground shock blast, the five holes of the array were loaded with 120 kg of explosives each, making a total blast weight of 600 kg. The explosive used was a water-resistant ammonium nitrate based slurry supplied in cylinders 20 cm long and 13 cm in diameter; the charges were water stemmed. After the blast, the 4 holes located in competent rock (nos. 1, 2, 4, 5) were found to be undamaged and suitable for a second test. However, hole no. 3 had been drilled through fill material at the surface and thus was severely damaged. Hence for the second multiple blast only holes 1, 2, 4, and 5 could be used, but these were loaded with 150 kg each so the total blast weight again was 600 kg. In planning the test program it had been hoped to use sequential detonation with 100 to 200 ms delays; however such precise delay caps were not available to the project in China, so in both of the multiple blasts all charges were detonated simultaneously.

B. Lake water shock: Additional data on the dam-water interaction mechanism was obtained using as excitation the water shock waves induced by detonation of explosives in the lake. It was well-known from previous experience that such water shock tests could produce response in the dam as great as that caused by ground shock due to explosive charges two orders of magnitude larger; consequently it was important to learn how such water shock tests might be used in the study of dam-water interaction.

In these tests, 4 kg charges were suspended from a cable stretched across the lake parallel to the dam axis at a distance of 210 m from the dam face. The suspension point was about 30 m east of the dam midsection, and the charge was at a depth of 10 m. Three of these blast tests were performed with varying degrees of success, the variability being due mainly to difficulty in communication between the recording site at the crest of the dam and the detonation point on the lake. The first shot was totally unrecorded because it was detonated before the recorders were turned on; the timing of the second shot was well coordinated but the recording gain for the transducers below the water surface was too great so many transducer signals were saturated. In the third shot again good records were attained only for the accelerometers on the crest, even though the recording gains for the accelerometers in the galleries had been adjusted to measure up to 1g. No hydrophone records were obtained in this final shot.

C. *Refraction and reflection tests:* An additional series of water shock tests was done as a first attempt to develop procedures for measuring the reflection coefficient of the lake-bottom materials, the coefficient that had been used previously by Rosenblueth (1968) and by Hall and Chopra (1980). Two approaches were used, both utilizing a vertical 12-channel array of hydrophones and a blasting cap energy source as shown in Figure 6. In the first approach, the propagation velocity of the bottom materials was measured by means of novel technique described by Hunter and Pullan (1990). While refraction surveys are usually accomplished by recording the times of first arrival from a source of energy at the end of a linear string of detectors placed horizontally along the surface of interest, this is a difficult operation when 100 m of water overlies the surface. The method described by Hunter and Pullan that we employed requires only that a vertical array be suspended just above the bottom and that shots be detonated on the bottom at some horizontal distance away from the array. Knowing the propagation velocity and the density of the bottom sediments then allows a direct computation of the reflection coefficient based on the ratio of the acoustic impedances of the water and the underlying material.

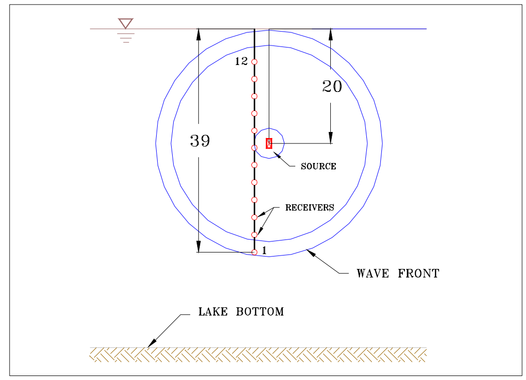

Fig.6 Test set-up for lake-bottom reflection tests

The second approach to obtaining the reflection coefficient was to attempt to measure the amplitude of incident and bottom-reflected pulses directly by recording these signals on the same array of vertical hydrophones as depicted in Figure 6. The array was suspended below the water surface and a cap was detonated few meters away from the center of the hydrophone array. Figure 7 shows a record obtained from one of these experiments. The incident and reflected (both surface and bottom-reflected) pulses are clearly visible on the record. The use of multi-channel array of sensors, as opposed to a single sensor, allows the events to be easily identified in the field simply by visual correlation across the record.

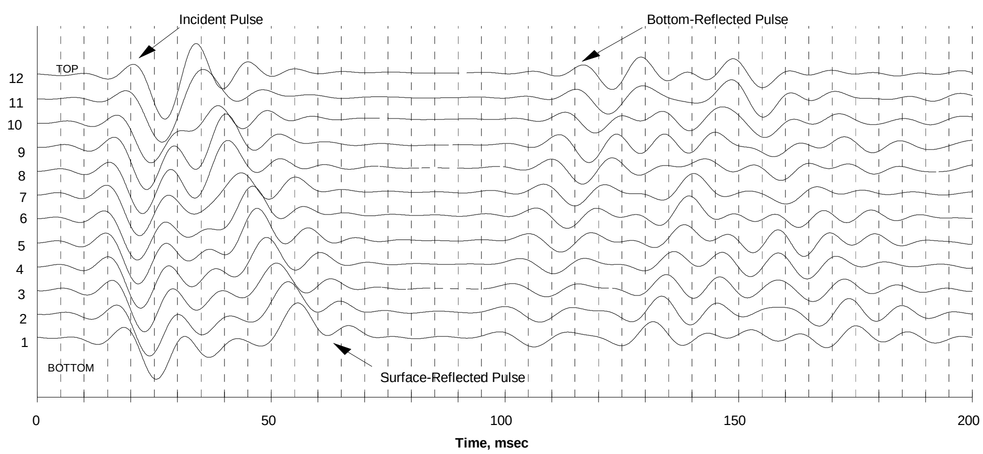

Fig. 7 Reflection record obtained from vertical array of hydrophones suspended in lake.

3.2 *Supplementary tests*

A. Ambient vibration tests: Although it was not a major purpose of this research program to study the vibration properties of Dongjiang Dam, it was considered important to use measured properties for validation of the mathematical model that was to be employed in subsequent phases of the research. For this reason, the response of hydro-phones and accelerometers in the dam to ambient noise were recorded, and these records were then used in evaluating the system vibration properties. To facilitate carrying out this research effort on dam-water interaction, the operators of the dam agreed to turn off the power turbines for a limited period of time so that the blast test data would be relatively pure. Thus it was possible to study the ambient excitation performance of the dam both with and without the turbines running, and it was found that the ambient noise signal was reduced by a factor of 6 when the turbines were turned off.

B. Bottom profile surveys: The lake geometry, especially near the dam, may have some influence on the dam-water interaction mechanism. The actual bottom profiles of dam-retained lakes needed for the dynamic response analysis usually differ from the original canyon topography due to the sediment accumulation and the overburden materials. Thus acoustic surveys were performed to establish the actual bottom profiles for the Dongjiang Lake. The measurements were conduct-ed from a boat moving steadily along three sections across the lake and along two additional sections in the channel direction. The equipment used consisted of a fathometer with both digital display of actual bottom depth at all times as well as a paper recorder, and an electronic compass for determining positions with respect to a fixed reference point. This procedure proved to be very effective and indicated some profile features that had not been noted in the construction drawings.

4 SUMMARY OF MEASURED DATA

This experiment has produced what is probably the most complete set of data now available for the study of dam-water-foundation interaction effects. A total of 20 pressures, 16 accelerations, and 42 components of strong motion seismograph records have been collected. In addition, each reflection and refraction test provided 12 additional pressure records for determining the bottom reflection coefficient. The comprehensive data analysis and interpretation of the recorded signals will take some time and will be presented in our final report to the National Science Foundation. Only a few examples of some of the measured data can be included in this paper mainly due to space limitation. The radial components of seismograph records S14 and S13b which were recorded at 100 m and 665 m distances, respectively, from the boreholes are shown in Figure 8. The most noticeable features in these traces are the reduction in amplitude and the elongation in duration of motions with distance from the energy source.

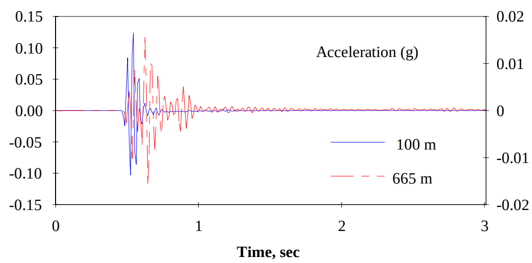

Fig. 8 Radial component of free-field records at 100 m and 665 m from energy source.

Figures 9 and 10 show an example time-history and power spectrum of the dam response recorded at the center of the dam crest (A4 in Fig. 3). This power spectrum clearly indicates identifiable vibration modes that were excited; especially the measured 8 modes below 10 Hz are of particular interest in the response of the dam to earthquake ground motions. The power spectrum for one dy-namic pressure transducer (P3) shown in Figure 11 is another example pertinent to the study of dam-water interaction. Information related to the mode of vibrations similar to that identified from the acceleration record can be deduced from this pressure spectrum.

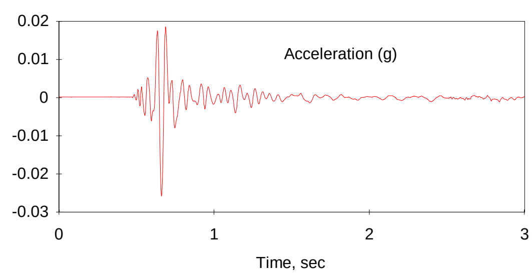

Fig.9 Time-history of dam radial acceleration A4.

The results of ambient measurements (not includ-ed in this paper) showed similar and some additional modes, even when the power turbines were off; in particular the hydrophones inside the lake at 210 m away from the dam could still record such ambient noise.

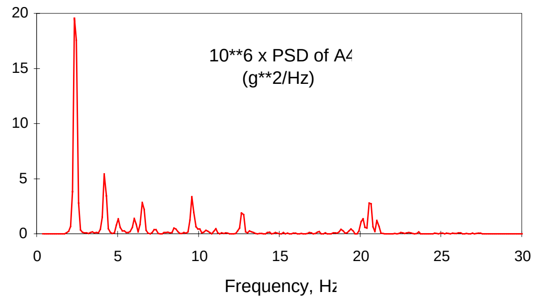

Fig. 10 Power spectrum of dam acceleration A4.

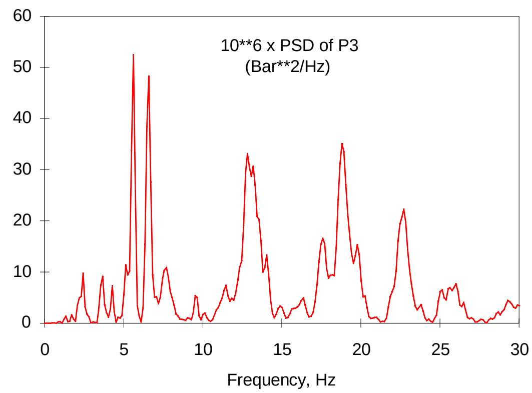

Fig. 11 Power spectrum of dynamic pressure P3.

5 CORRELATION STUDIES

In addition to the experimental aspects of the investigation described in this paper, the field measurements were preceded by several computer analyses of Dongjiang Dam in order to obtain a preliminary understanding of the expected dynamic response behavior. More refined computer analyses of the dam-water-foundation system, both including and ignoring the water compressibility and the lake-bottom absorption effects, are now underway and will be reported later. The main purpose of these analyses is to verify the accuracy of existing analytical procedures by comparing the calculated results with those measured in the field. For this purpose we will attempt to construct a transfer function between the measured dam response and the free-field ground motions. These transfer functions based on the measured accelerations and the dynamic ressures will then be compared with results calculated using the latest computer analysis procedures for the dam-water-foundation interaction.

6 CONCLUSION

This experiment has proved that concrete arch dams nd their retained lake can be successfully excited by detonating explosive charges buried in the foundation rock. It also demonstrated that good planning, execution, and appropriate instrumentation are essential for obtaining meaningful signals in the frequency range of interest. Similar to earthquake ground shaking, the complete system was excited by these blast shock waves travelling through the foundation rock; thus they produced more representative data on the dam-water-foundation interaction effects than are given by other test procedures. The seismic refraction and reflection approaches used here for the first time to measure the reflection coefficient of the lake-bottom materials were successful, and thus have provided two procedures for measuring this coefficient in the field.

The acquired data are specially unique because hey have provided a first opportunity to construct transfer functions between any measured dam point response and the ground motions measured in the free-field. This information in addition to expressing the measured vibration properties provides the basis for validating existing analytical procedures for predicting the earthquake response of arch dams.

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