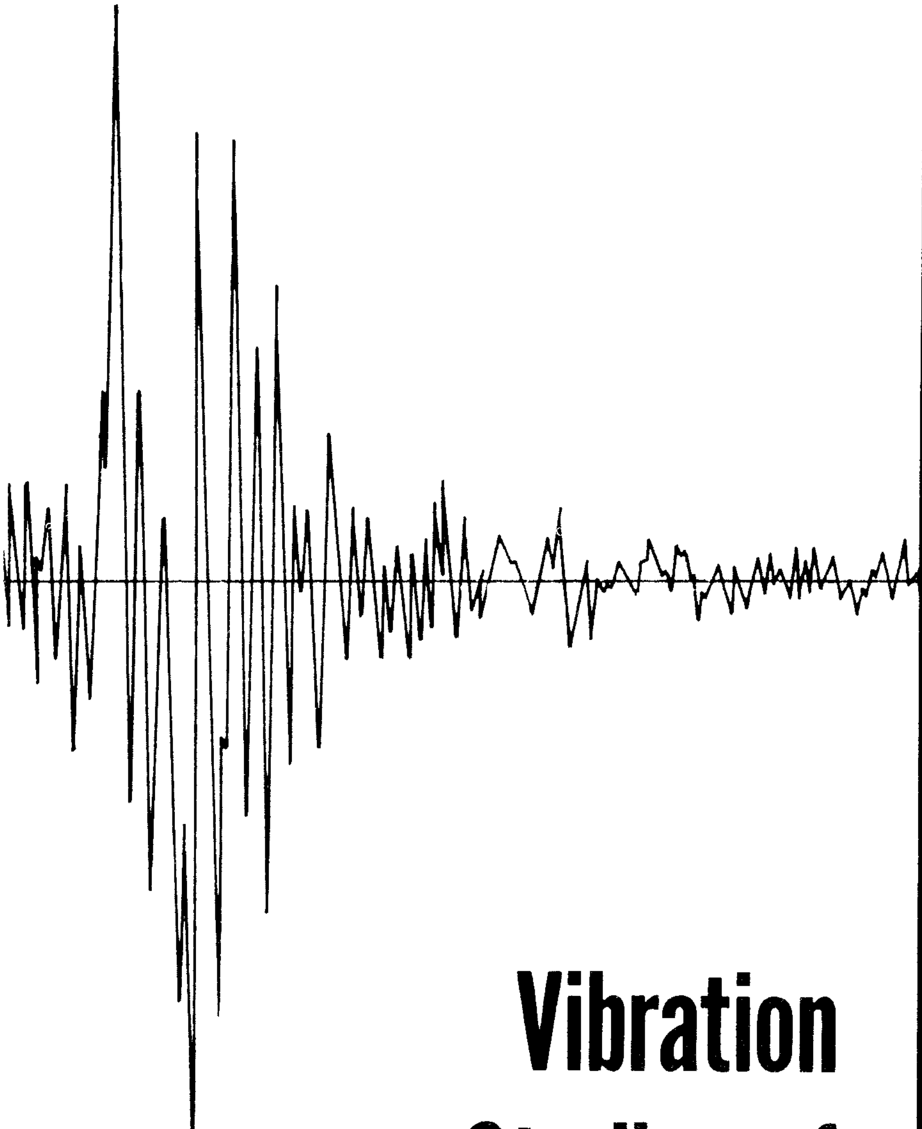

Vibration Studies of Monticello Dam

A Water Resources Technical Publication

RESEARCH REPORT NO. 9

United States Department of the
INTERIOR
Bureau of Reclamation

A WATER RESOURCES TECHNICAL PUBLICATION • Research Report No. 9

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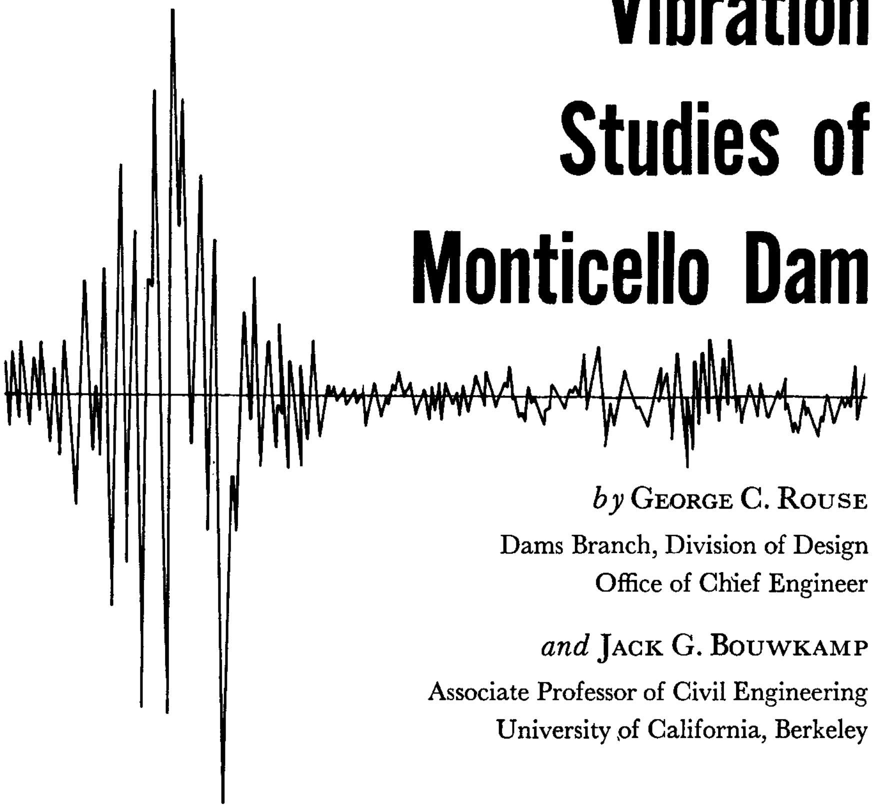

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UNITED STATES DEPARTMENT OF THE INTERIOR
Stewart L. Udall, *Secretary*

BUREAU OF RECLAMATION
Floyd E. Dominy, *Commissioner*

In its assigned function as the Nation's principal natural resource agency, the Department of the Interior bears a special obligation to assure that our expendable resources are conserved, that renewable resources are managed to produce optimum yields, and that all resources contribute their full measure to the progress, prosperity, and security of America, now and in the future.

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PREFACE

The effects of earthquakes on dams and other structures on Bureau of Reclamation water resources development projects in the Western United States are of continuing concern to the Bureau's engineers. The engineers have under particular study those areas that have sustained earthquakes which caused major damage to structures. They are also concerned with other areas in the Western States having lesser seismic activity where minor damage has occurred in the past but which could possibly have adverse effect on new structures of unusual height, magnitude, or design.

Because of the large volumes of water impounded behind them, concrete dams in seismically active areas are a major engineering concern, and Bureau engineers have closely studied the effects of earthquakes on these structures. The latest of such studies is the series of vibration tests that were made during August-September 1965 at the Monticello Dam, a 304-foot-high concrete thin arch structure, on the Bureau's Solano project in California. The Bureau conducted the tests in cooperation with the University of California. The special equipment employed in the tests to induce vibrations, the instruments used to record and measure the effect of the vibrations on the dam, and the results obtained are described in this research report.

The tests conducted on Monticello Dam demonstrated the feasibility of determining dynamic properties of concrete dams by the measurement of accelerations of such structures when excited by vibration generators. Bureau design engineers are applying the knowledge acquired from the tests to develop analysis methods for determining seismic loadings for concrete dams.

Included in this publication is an informative abstract and list of descriptors, or keywords, and "identifiers." The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature of water resources development. The descriptors were selected from the "Thesaurus of Descriptors," which is the Bureau's standard for listings of keywords.

Other recently issued water resources technical publications are listed on the inside of the back cover.

ACKNOWLEDGMENTS

Dr. Dixon Rea and Mr. John Nadherny of the University of California, Berkeley, Calif., and Engineer Dewayne Misterek of the Bureau of Reclamation, Denver, Colo., assisted with the tests. Engineer Terry Polley of the Bureau of Reclamation, Sacramento, Calif., arranged for preparatory work necessary to perform the tests. Mr. Lawrence Fafek, caretaker of Monticello Dam, gave general assistance during the entire period of the field investigation. Engineer Louis Roehm of the Bureau of Reclamation at Denver assisted with the analysis of the vibration measurements. All work involved in the vibration studies of Monticello Dam was under the general direction of Mr. B. P. Bellport, Chief Engineer of the Bureau of Reclamation, at Denver.

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INTRODUCTION

Earthquakes result from instability of the earth's crust. Because of this instability, the crust is continually subjected to readjustments which may produce local stresses of sufficient magnitude to cause rupture (faulting). When rupture occurs, the strain energy which has been built up in the crust near the zone of rupture is released in a relatively short time. As a result, seismic (elastic) waves are generated which propagate throughout the earth's mass (*1*).* It is these waves which produce perceptible ground vibrations in the vicinity of an earthquake.

Ground vibrations generated by earthquakes are recorded by three types of instruments: Long-period, short-period, and strong-motion seismographs (*1, 2*). The first two types of instruments provide data required by seismologists for estimating the location and magnitude of distant earthquakes and for determining the relative seismicity of a particular area. The third type, strong-motion seismographs (accelerographs), which are triggered by an initial seismic pulse, provide data on ground accelerations in the vicinity of an earthquake. In addition, these instruments are often placed in buildings and other structures to record their dynamic response to seismic vibrations. Data recorded by strong-motion seismographs are used by engineers to develop earthquake design loadings for structures (*3, 4*).

Studies of strong-motion seismograph records indicate that:

1. At locations remote from the focus (hypocenter), the horizontal components of ground accelerations are about twice the vertical component (*5*).
2. For the same seismograph location, acceleration components for each earthquake recorded have different waveforms.
3. Predominant frequencies of seismic ground vibrations are usually less than 10 cycles per second. High-frequency components of these vibrations attenuate rapidly with increasing distance from the focus.
4. Recorded waveforms of ground vibrations generated by earthquakes indicate that these vibrations are random rather than harmonic.

When a structure is subjected to an earthquake, it oscillates in translational and torsional modes of vibration. The amplitudes of the transient displacements of a structure during an earthquake depend in part on the natural frequencies of the structure and on structural damping. If a structure is rigid, it will be subjected to the same accelerations as those imposed on it by seismic motion of its foundation. On the other hand, if a structure is flexible, the fundamental and higher natural frequencies of the structure may fall within the range of predominant frequencies for earthquake vibrations (less than 10 cycles per second). When this occurs, a quasi-resonant condition can be produced between the oscillations of the structure and the oscillations of the ground. A structure vibrating at or near resonance may be subjected to greater accelerations than those applied to it by seismic motion of its foundation. Based on the results of dynamic response tests similar to those described in this report, mass concrete arch dams may be classed as flexible structures (*6*).

At present, there is very little information available on the response of arch dams to seismic forces. The information that has been accumulated has been obtained by structural model tests (*7, 8*), vibration measurements on dams and abutments during earthquakes (*5*), and vibration measurements on dams subjected to exciting forces produced by proximity blasting and by vibration generators (*6, 7, 9*).

Some work has been done on the development of analytical methods for making dynamic response studies of arch dams for earthquake loadings (*10*). So that this work can progress, more basic information on the behavior of such dams during earthquakes is needed. In particular, information is required to determine the influence of the foundation, reservoir, vertical acceleration, and the amplitude of structural displacements on the dynamic response of concrete dams.

Seismic measurements of arch dams and their foundations made by the Japanese indicate that the

*Numbers designate literature cited in the references at the end of this report.

abutments may vibrate at higher frequencies than the rock mass near the base of the structure (*7*). The Japanese also found that the abutments may vibrate out of phase and with different displacement amplitudes. They attribute these anomalies to the shape of the damsite and the quality of the rock in the abutments. As a dam and its foundation behave dynamically as a coupled system, it is reasonable to assume that any nonuniformity in the dynamic response of the abutments during an earthquake will influence the dynamic response of the dam.

When a dam vibrates, the reservoir in the vicinity of the upstream face is also set into motion. The volume of water caused to oscillate with the dam produces: (1) A change of the mass of the coupled system, (2) transient pressures, and (3) some additional damping (*11*). Analytical methods which have been used for computing mass and transient pressure effects of the reservoir water are based on the assumptions that a dam is rigid and that water is incompressible. However, recent investigations made at the University of California indicate that these assumptions may not give results which are compatible with the actual conditions (*12*).

Near the epicenter of an earthquake, Okamoto found that vertical accelerations were greater than horizontal accelerations (*5*). If this is true, then arch dams, and in particular the double-curvature type located in seismically active regions, should be designed for vertical accelerations. At the present time, arch dams are usually designed only for the horizontal components of ground accelerations.

Damping factors for arch dams for small displacements have been determined for the most part from measurements on dams excited by vibration generators. These factors have been found to be relatively low—2 to 4 percent critical (*13*). Some investigators have concluded that damping factors increase with an increase in structural displacements (*14*). When subjected to large displacements, additional damping could be produced in concrete arch dams by relative movement in the plane of the contraction joints or at the abutment contacts. Because increased damping results in a decrease in the dynamic response of a dam, information on values of this quantity for relatively large displacements is needed before reasonable estimates of seismic loadings for these structures can be made. Also needed besides the data mentioned above is supplementary information on two other dynamic properties of arch dams: Natural frequencies and mode shapes. These are the basic data required in the development of methods for designing arch dams for seismic loadings.

To obtain such data on natural frequencies and mode shapes, the Bureau of Reclamation in cooperation with the University of California, Berkeley, Calif., carried out during August–September 1965 dynamic response tests on Monticello Dam. Damping factors for small displacements were also determined for the modes investigated. Monticello Dam (fig. 1) is a 304-foot-high concrete arch structure which was built by the Bureau of Reclamation during 1953–57 (*15*). It is located on Putah Creek about 30 miles west of Sacramento, Calif.

This report describes the vibration tests on Monticello Dam and discusses the conclusions reached.

Figure 1.—**Downstream face of Monticello Dam.**

VIBRATION EQUIPMENT

To obtain information on the dynamic properties of Monticello Dam, the response of the dam was measured for steady-state forced vibrations. Natural frequencies and damping factors were found for the first five modes by measuring the response of the dam over a range of forced vibration frequencies extending from 2.5 to 8 cycles per second. Mode shapes for the crest and three cantilevers were then determined for the first four modes by measuring the response at predetermined locations on the dam while it was being subjected to forced vibrations having excitation frequencies corresponding to the natural frequencies. For example, to find the mode shapes for the first mode, measurements related to the deflections of the dam were recorded as a function of time while the crest of the dam was being subjected to known sinusoidally varying exciting forces applied at the resonant frequency found for the first mode.

Three types of equipment were needed to perform the dynamic response tests of Monticello Dam: (1) Vibration generators, also referred to as vibration exciters or shakers, (2) vibration pickups, and (3) vibration recorders. All this equipment was supplied by the University of California. The exciters (fig. 2) were developed and fabricated at the California Institute of Technology under the sponsorship of the State of California Department of General Services, Office of Architecture and Construction, through the Earthquake Engineering Research Institute.

Like several vibration generators built in past years, the exciters are of the two-mass, counter-rotating, eccentric-weight type (*16*). The weights rotate in horizontal planes about the same vertical shaft. By means of this equipment, sinusoidally varying forces can be applied to a structure along a predetermined axis. As baskets containing the weights rotate in opposite directions, maximum forces are attained twice each cycle when the baskets pass one another. When the baskets are 90° to the force axis, the centrifugal forces are opposed, and thus no resultant force is produced.

Each shaker was designed to generate a maximum force equal to 5 kips (5,000 pounds). However, during the tests, this load limit was only attained for six shaker speeds. At other speeds with the frequency range of 2.5 to 8 cycles per second, the applied forces varied between 3 and 5 kips, depending on the weights placed into the baskets (fig. 3).

When compared to similar vibration generators, the equipment used during the Monticello Dam vibration tests is unique:

1. The heaviest shaker component can be man-

Figure 2.—Vibration generator.

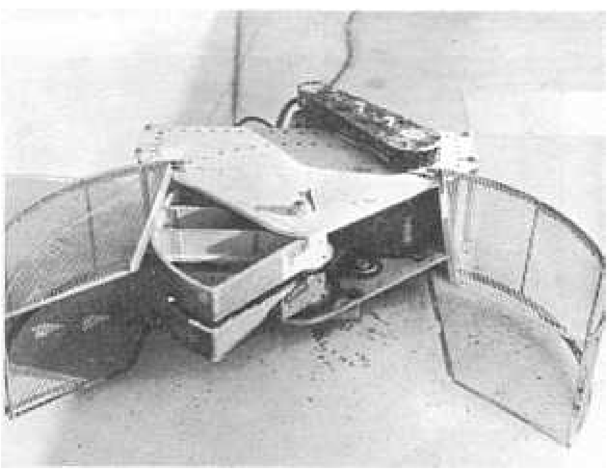
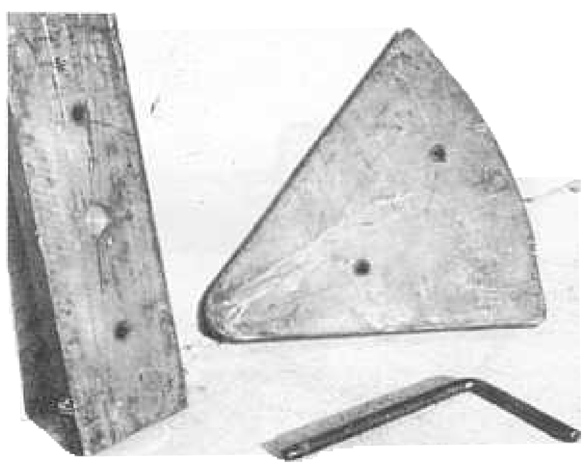


Figure 3.—Basket weights for vibration generator.



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handled at the test-site without the use of special equipment.

2. When more than one exciter is employed during a test, the additional units (called slave exciters) can be adjusted to generate forces which are in phase or 180° out of phase with those produced by the master exciter.

3. The rotational speeds of each shaker can be accurately controlled.

4. For the same rotational speed, the magnitude of the exciting forces can be increased up to the limit of 5 kips simply by placing the same type weight or combination of weights into each basket.

The baskets containing the weights are driven by a 1½-horsepower, direct-current electric motor. To control the basket speeds, a tachometer driven by the motor furnishes a signal which is proportional to the speed of rotation. This signal is compared with a reference signal which is proportional to the desired speed. The reference signal is generated when the operator adjusts the shaker speed control dial on the master control unit. If the speed of the shaker is different from the desired speed, an error signal equal to the difference between these two signals will result. This error signal controls the output of an amplidyne, which furnishes power for the shaker motor. Measurements of the actual speed of the shakers to the desired tolerance are made by an electronic counter, which provides 300 counts for each revolution of the eccentric weights. Input signals to the counter are generated by a second tachometer, driven by the exciter motor.

The accelerometers (fig. 4) employed throughout the Monticello Dam dynamic response tests for measuring vibrations of the dam were of the unbonded resistance-wire type, having ratings equal to either 0.20 g. or 0.25 g., and an undamped natural frequency of about 15 cycles per second. The accelerometers were oil damped, and had a damping ratio of 0.7 critical at approximately 80° F.

Basically, the transducer for this type of accelerometer converts changes in acceleration into proportional changes in ohmic resistance (*17*). It is made up of four coils of fine pretensioned wire, or filaments, and a mass supported at the center of a frame by cantilever springs. The springs permit unrestrained movement along one axis of the accelerometer. Two filaments are strung parallel to this axis from the mass to opposite sides of the frame. Each filament is wired to form one arm of a Wheatstone bridge circuit. When the instrument is subjected to a constant acceleration, for example gravity, two of the filaments will elongate and two will shorten. As a change in length of a filament is accompanied by a proportional change in its resistance, an electrical unbalance results, and current is caused to flow in the recorder instrument circuit. The response of this type of accelerometer is linear for sinusoidal inputs with frequencies less than one-half the natural frequency of the instrument.

Each acceleration trace was recorded on the same oscillograph chart by an ultraviolet light beam reflected from a galvanometer mirror onto paper sensitive to that type of light (fig. 5). Following exposure, about 10 seconds elapsed before the traces were completely visible. Before being transmitted to the galvanometer in the recorder, signals from the acceleration pickups were amplified by amplifiers having a low noise-to-signal ratio.

Two shakers were set up on the crest of the dam near the crown, 60 feet to the left and right of the centerline of block 11 (figs. 6, 7, and 8.). They were

Figure 4.—**Accelerometer and weight for holding it in place.**

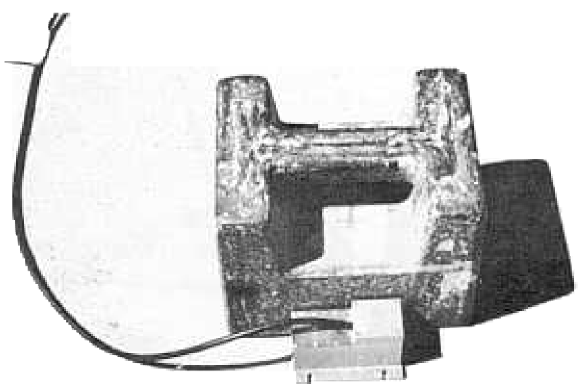
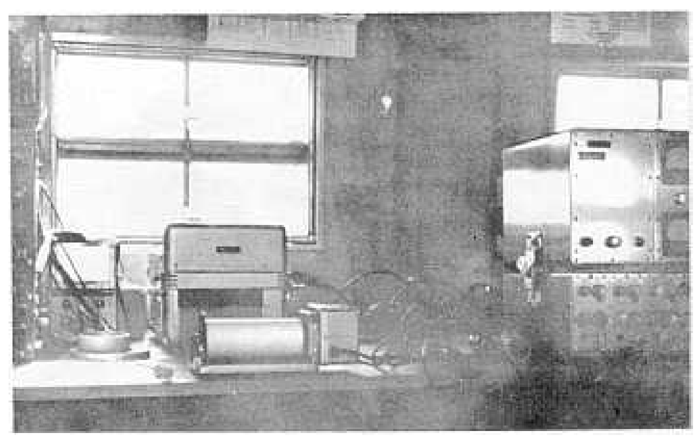


Figure 5.—**Direct-writing recorder set up in trailer.**



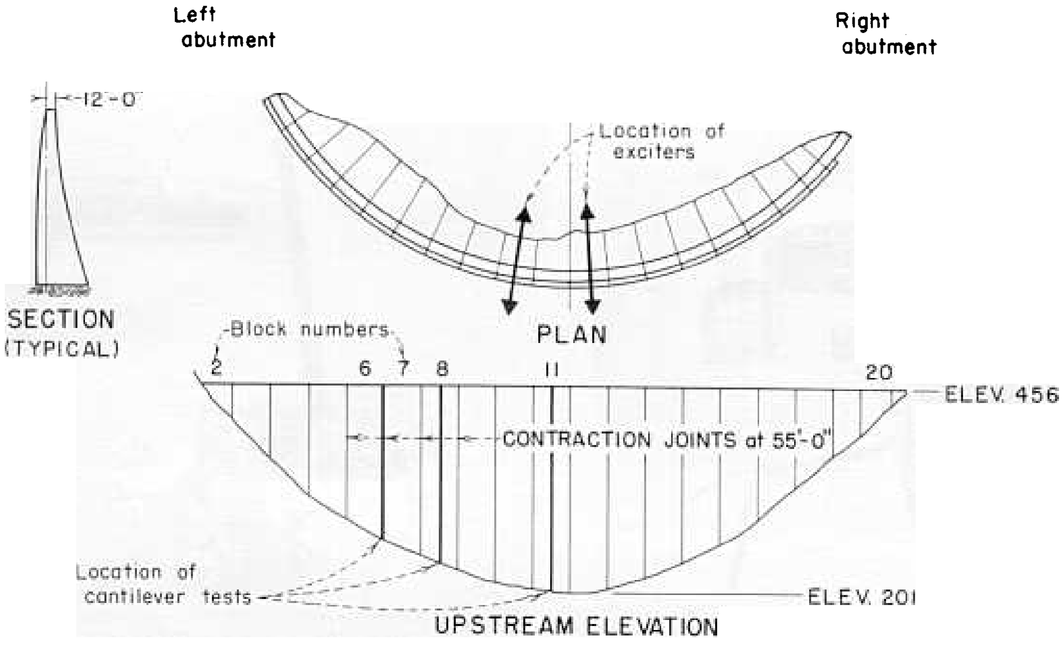


***Figure 6*.—Plan and elevation of Monticello Dam, showing location of exciters (arrows) and cantilevers on which vibration measurements were made.**

***Figure 7*.—Test equipment in place on dam; second shaker located beyond trailer.**

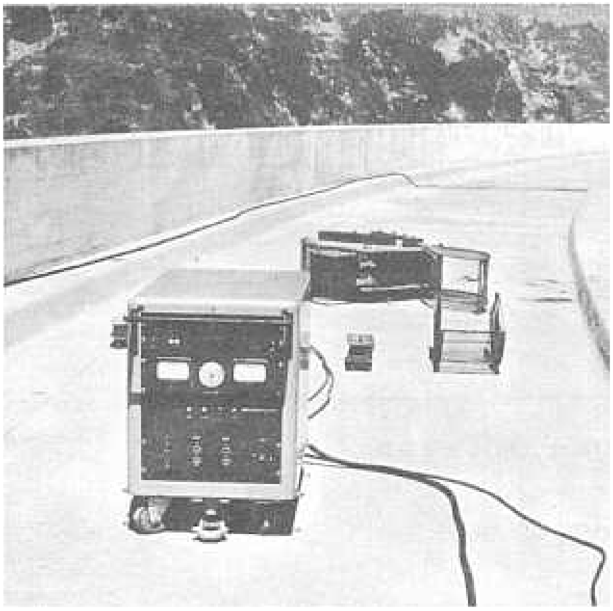


Figure 8.—Shaker and slave console 60 feet to left of crown cantilever.

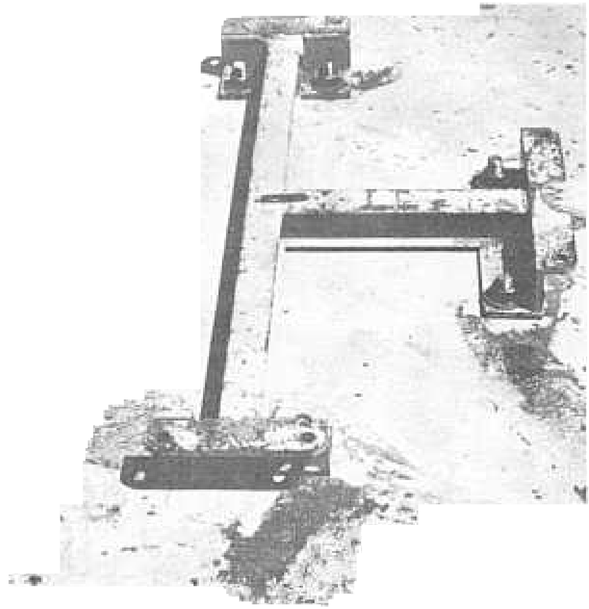
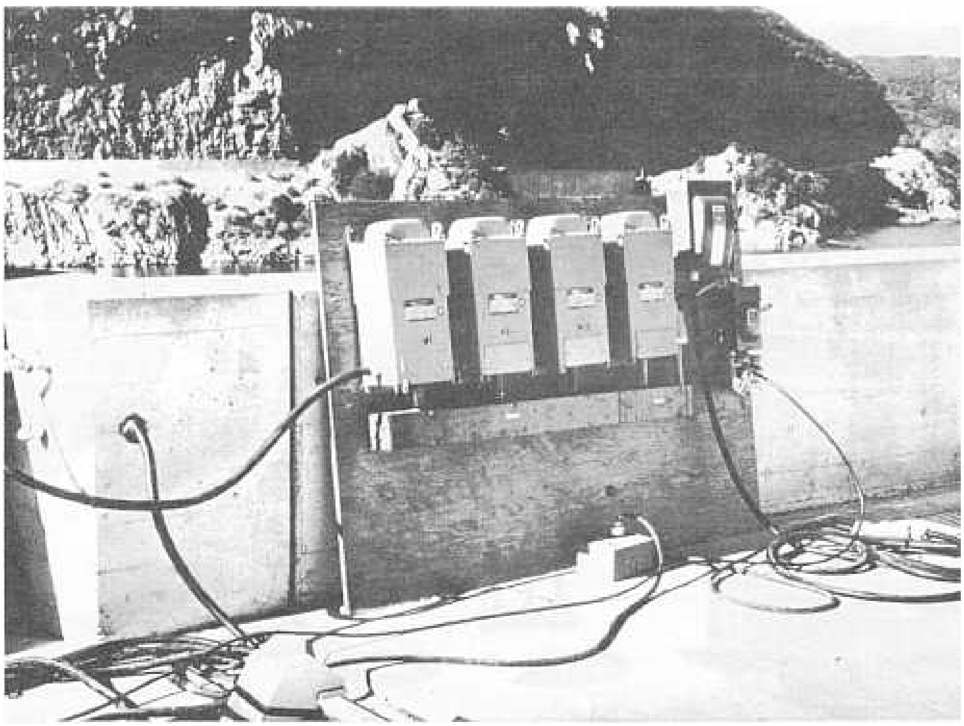


Figure 9.—Frame for mounting shaker on crest of dam.

Figure 10.—220-volt power supply for shakers.



so oriented that the directions of the exciting forces were radial.

Each shaker was bolted to a frame (fig. 9), which in turn was secured to the crest roadway by six 1-inch-diameter, 12-inch-long bolts. The bolts were grouted in place by epoxy mortar. Four 220-volt transformers supplied electrical power for the shakers (fig. 10).

VIBRATION TESTS

During the 10-day testing period, acceleration measurements were made on the crest and on the downstream face of the dam to obtain natural frequencies for the first five modes of vibration and the deflected shapes of the crest and of three cantilevers for the first four modes. Damping ratios for small displacements were determined from the frequency response curves.

Two series of tests were performed to obtain resonant frequencies of the dam, one before and the other after the mode shape tests. The purpose of the initial frequency response tests was to determine the first four resonant frequencies. Precise determinations of these frequencies were necessary before the mode shapes of the dam could be found. During the mode shape tests, the dam was excited at the resonant frequency corresponding to the mode being investigated. Data from the second series of tests were used to find the resonant frequency for the fifth mode and the damping ratios for all five modes.

Frequency response data were obtained by measuring accelerations for small increments of shaker speeds over the range of 2.5 to 8 cycles per second. Plots showing the variation of measured accelerations with change in frequency of the exciting forces were made as the tests progressed. Resonant frequencies were determined from the plots by noting the frequency for each peak amplitude of the curve. To define more accurately the shapes of the frequency response curves in the vicinity of resonance, incremental changes in the shaker speeds were reduced to about 0.02 cycle per second.

During the frequency response measurements for the symmetrical modes (1, 3, and 5), the shakers were synchronized. For the unsymmetrical modes (2 and 4), the shakers were set at 180° out of phase to produce a sinusoidally varying couple; that is, at the same instant of time, one shaker generated a radially-directed upstream component of force while the other generated a radially-directed downstream force component of the same magnitude. This type of loading proved to be very effective when investigating the unsymmetrical modes, not only for the frequency response tests but also for the mode shape tests.

During the second frequency response test, an accelerometer was located at each point on the crest where the maximum acceleration for each of the first four modes had been found. The respective positions chosen for these measurements were: The centerline of block 11 for modes 1, 3, and 5, the centerline of block 8 for mode 2, and the centerline of block 16 for mode 4.

Mode shapes of the crest and of the cantilever sections located in blocks 11 and 8 and near the contraction joint between blocks 6 and 7 were found for the first four modes. For the first mode, acceleration measurements to determine the deflected shapes of the crest were made in the radial and tangential directions at intervals of about 55 feet along the crest. For higher modes of vibration, accelerations were measured at intervals of about 27 feet to obtain better definition of the mode shape curves.

To determine the mode shapes of the three cantilevers, accelerometer supports and accelerometers were mounted on the downstream face (fig. 11). The supports were attached as the workmen moved up the face. After performance of the tests, the supports were removed as they moved down the face. While the cantilever mode shape tests were in progress, the two outlet valves at the toe of the dam were closed to reduce background noise.

Reference measurements were recorded during each mode shape test. The locations where these measurements were made are:

Structural element	Mode	Location of reference measurement [1]
Crest	1 and 3 . . .	Block 11.
Do	2	Block 14.
	4	Block 12.
Cantilever, block 11 . . .	1, 2, 3, and 4.	Block 11.
Cantilever, block 8 . . .	1, 2, 3, and 4.	Block 11 and block 8.
Cantilever, joint 6–7. . .	1, 2, 3, and 4.	Block 11 and joint 6–7.

[1] Centerline, radial direction on crest; lead-wire end of accelerometer toward left abutment for all radial measurements and downstream for all tangential measurements.

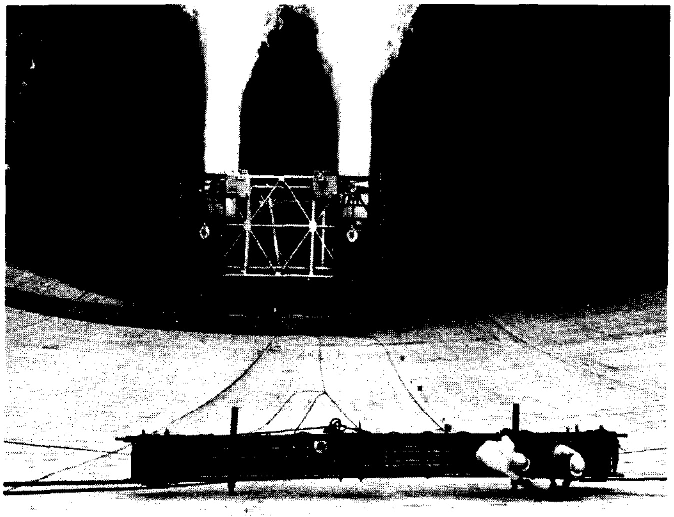


Figure 11.—**Workmen mounting accelerometers on downstream face.**

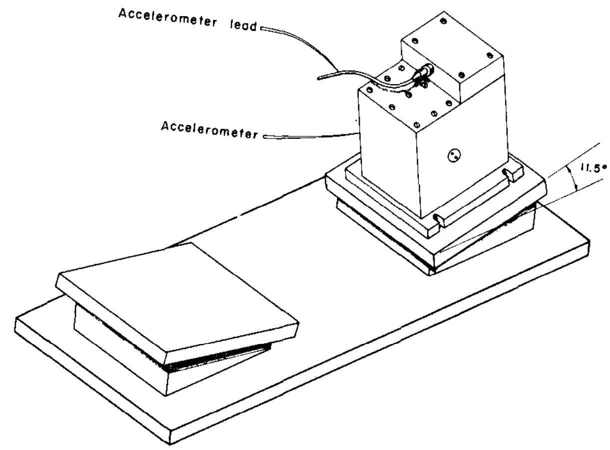


Figure 12.—**Device used for calibrating accelerometers.**

Comparisons of waveforms recorded during the mode shape tests of the crest showed that the maximum accelerations were either in phase or 180° out of phase with reference accelerations. (For example, all points on the f_1-curve (fig. 14) above the axis representing the developed centerline of the dam are in phase; those below this axis are 180° out of phase with the reference.) Similar comparisons were made of the acceleration waveforms recorded during the cantilever mode shape tests. These comparisons indicated, for the most part, that for each cantilever tested, acceleration waveforms recorded for points below the crest were in phase with those recorded on the crest. Acceleration traces which were not in phase with the reference have trace amplitudes less than 0.2 inch.

During the first series of tests on the dam, when a search was made for its natural frequencies, the phase angle at resonance between the time of application of the maximum exciting force and the time of maximum recorded accelerations was determined. To obtain this information, a small magnet was attached to the edge of the top basket and a flat copper wire coil was secured to the lower surface of the top frame plate for each shaker. The magnet was positioned beneath the coil with the baskets oriented as shown in figure 2. Coil leads were connected in series with a sensitive galvanometer in the recorder. Rotation of the baskets produced an electric pulse in the coil when the magnet passed beneath it. This pulse caused the galvanometer to deflect sufficiently to produce a sharp "pip" on the record. As the pip was recorded at the time of application of the maximum exciter force in the upstream direction, it was possible to determine from recorded data the phase angle between the time when this force occurred and the time of maximum acceleration or upstream displacement. (Maximum upstream displacement of the dam crest occurs at the same time as the maximum negative acceleration.) When the shakers were oscillating in phase at one of the natural frequencies of the dam, this phase angle was found to be $90° \pm 5°$ for accelerations measured on the crest at the centerline of block 10. This angle is in agreement with the theoretical angle for a viscously damped elastic system subjected to a harmonically oscillating shaking force, when the system is at resonance. Similar results were obtained when the shakers were operated 180° out of phase.

The accelerometers were calibrated statically at least twice each day for an input of 0.2 g. per 2 inches of amplitude on the chart. This was done by setting the accelerometers on an inclined plane having an angle of 11.5° with the horizontal (fig. 12). To increase the sensitivity to 0.001 g. per inch of chart amplitude, as required for the dynamic tests, the amplifier gain was increased to 100 times the gain used during static calibration. In addition to static calibration, the accelerometers were cross-calibrated three times each day so that an accurate determination of the mode shapes could be obtained. This was accomplished by setting the accelerometers on the centerline of block 11 and recording their response to the same radial accelerations.

EXPERIMENTAL RESULTS

The experimental results show, that within the range of vibration amplitudes tested, Monticello Dam behaved as a classical, linear, multidegree-of-freedom system with small damping. The modes of vibration of the dam were excited individually, and this enabled the resonant frequencies, mode shapes, and damping ratios to be determined accurately. It should be noted, however, that there was no interference between the first and second modes only because of the method of excitation, that is, running two machines in the positions described either in phase or 180° out-of-phase. If only one machine had been used, the first and second modes would have been excited in the range of 900 to 1,100 counts per second, and there would have been interference between the two resonance curves.

To convert measured data to the plotted data shown on figures 13 through 21, the recorded waveforms were assumed to be harmonic, and the magnitudes of the shaking forces were determined from data given on pages 6 through 8 (*16*). These data give values of the inertial forces in terms of shaker speed and combination of weights placed into the baskets. Displacement amplitudes were computed by the relation:

$$A= -\frac{a}{4\pi^2 f^2 F}$$

where

A = displacement amplitude (inch per kip, symmetrical modes, and inch per kip-feet, unsymmetrical modes)

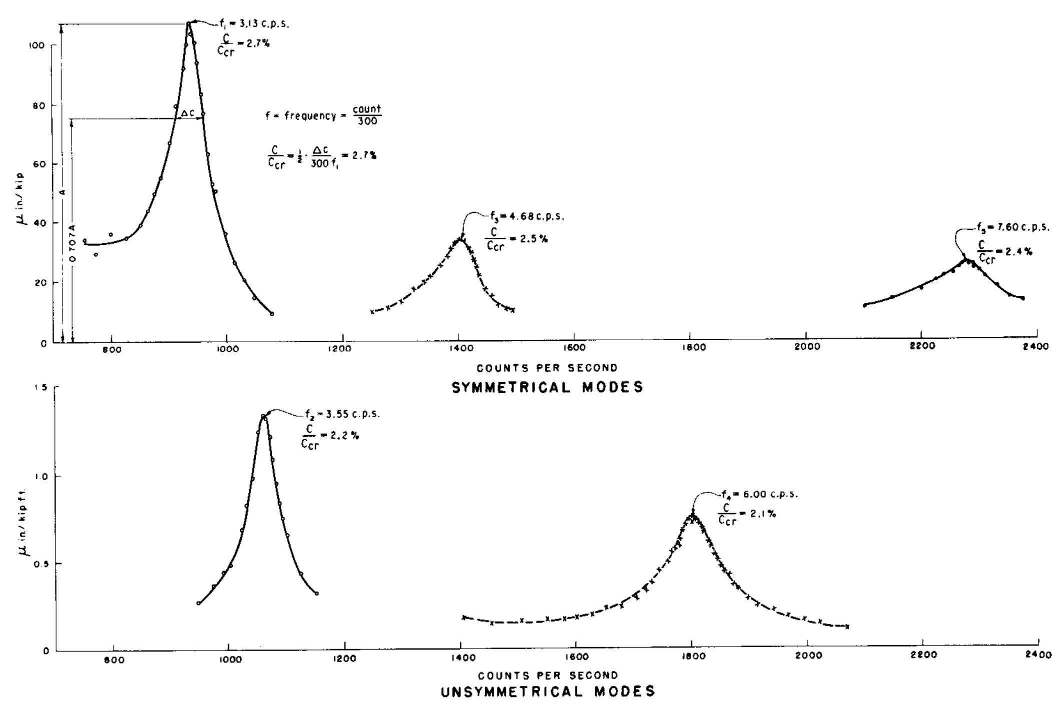
a = acceleration amplitude (inch per second [2])

f = frequency of vibration (cycles per second)

F = excitation force, symmetrical modes; or couple, unsymmetrical modes (kips or kip-feet)

Except for initial values for the f_1-curve, the shapes of the five frequency response curves (fig. 13) were obtained by drawing lines through the plotted points.

***Figure 13.*—Frequency response curves.**



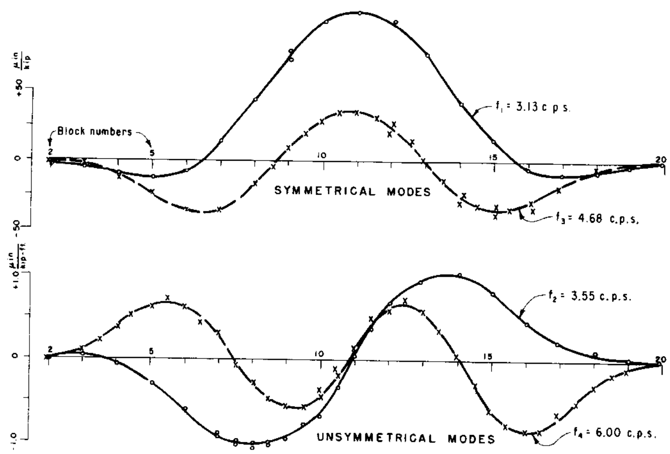


Figure 14.—**Radial deflections of crest.**

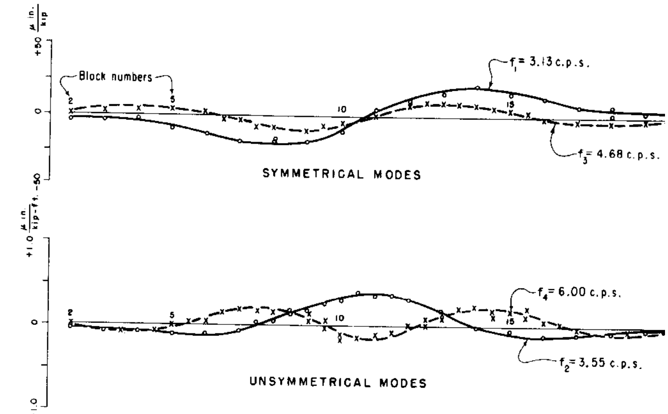


Figure 15.—**Tangential deflections of crest.**

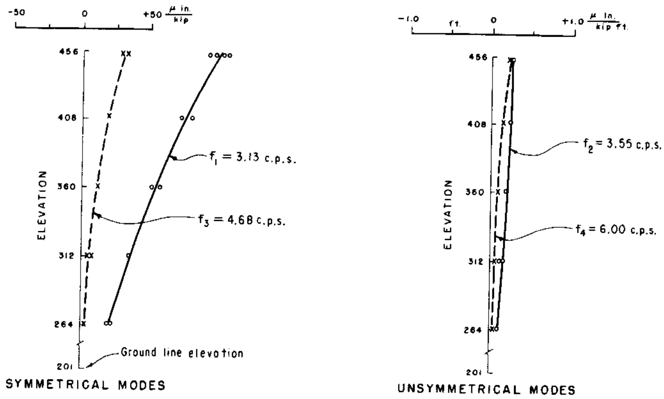


Figure 16.—**Radial deflections of cantilever, centerline of Block 11.**

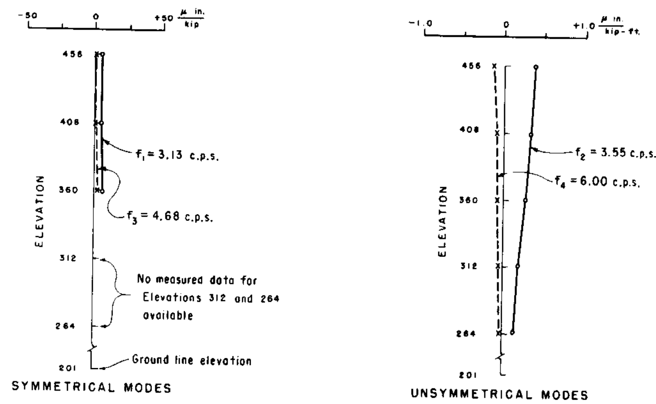


Figure 17.—**Tangential deflections of cantilever, centerline of Block 11.**

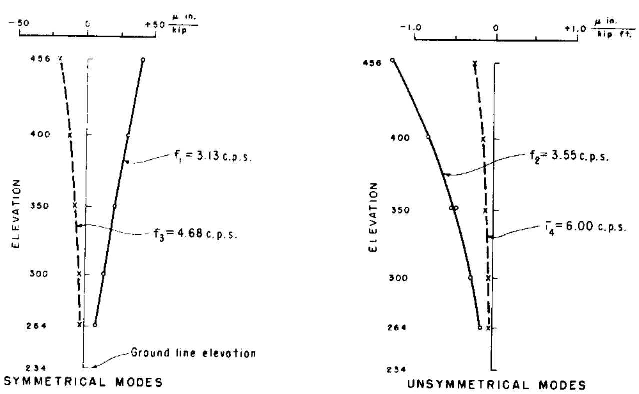


Figure 18.—**Radial deflections of cantilever, centerline of Block 8.**

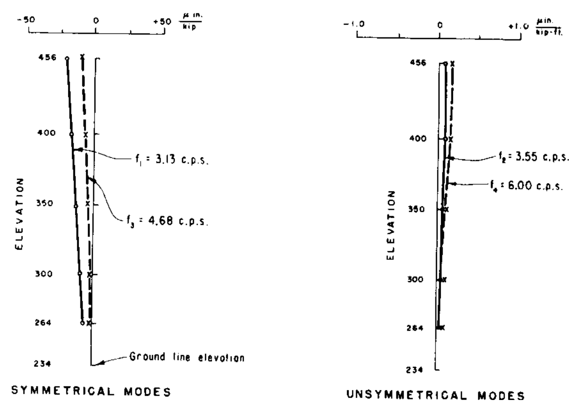


Figure 19.—**Tangential deflections of cantilever, centerline of Block 8.**

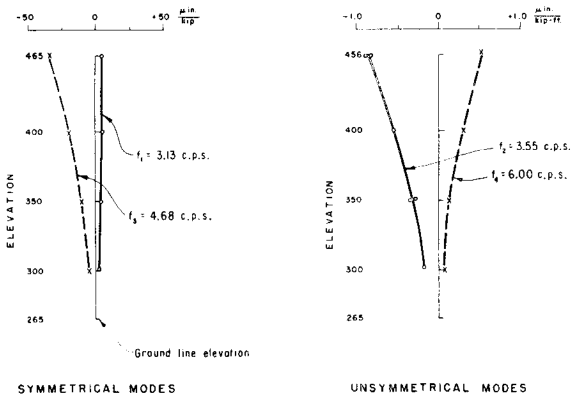


Figure 20.—**Radial deflections of cantilever, Joint 6–7.**

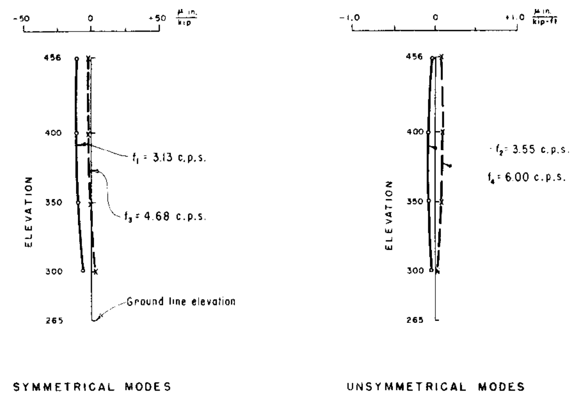


Figure 21.—**Tangential deflections of cantilever, Joint 6–7.**

Scatter of the three initial values for this curve resulted from the lack of satisfactory measured data. Acceleration records from which data for the three points were obtained have waveforms made up of two components, with the higher frequency component produced by background noise (accelerations) generated by water discharging from the outlets at the toe of the dam (fig. 11). Consequently, it was difficult to obtain satisfactory average acceleration amplitudes from the records. As the frequency of excitation was increased beyond 800 counts per second, the waveforms more closely approximate sine waves.

The peaks of the resonant curves are well defined because of the small amount of damping in the system. As a result, accurate determinations of the resonant frequencies were possible. The resonant frequencies for the first five modes are: 3.13, 3.55, 4.68, 6.00, and 7.60 cycles per second. Damping ratios for modes 1 through 5 were determined from the frequency response curves by the following relationship, which is based on the bandwidth method:

$$\frac{C}{C_{cr}}=\frac{\Delta f}{2f}$$

where $\frac{C}{C_{cr}}$ is the damping ratio, Δf the difference in frequency of the two points on a resonance curve with amplitudes 0.707 of the resonant amplitude, and f the resonant frequency. The damping ratios of the first five modes are 2.7, 2.2, 2.5, 2.1, and 2.4 percent of critical as shown in figure 13.

The mode shape curves for the crest and three cantilevers are shown in figures 14 through 21. Those for the crest are typical of the theoretical mode shapes for an end-restrained arch.

CONCLUSIONS

1. The tests conducted on Monticello Dam demonstrated the feasibility of determining the dynamic properties of a large dam by measuring accelerations of the structure when excited by vibration generators. The two vibration generators described were capable of exciting measurable responses in the dam's first five modes of vibration. In fact, it would have been possible to produce measurable accelerations of the dam by using only one shaker. A particular advantage of this type of vibration generator is that its heaviest component can be manhandled. Thus, no difficulty was encountered in setting the equipment in place on the dam.

2. The dynamic response of the dam was remarkably "clean," indicating negligible coupling between modes. This enabled the accurate determination of resonant frequencies, mode shapes, and damping ratios. The natural frequencies of the first five modes are: 3.13, 3.55, 4.68, 6.00, and 7.60 cycles per second. The range of the damping ratios is 2.1 to 2.7 percent of critical.

3. The test results indicate that no cantilever nodal points developed for the first four modes. It is doubtful whether this condition would have been found for higher modes of vibration.

4. Water discharging through two outlet valves at the toe of Monticello Dam produced background noise of sufficient intensity to be recorded on the acceleration traces. The effect of this noise was particularly noticeable on the acceleration traces recorded during the initial mode shape tests. As a consequence, to obtain satisfactory records for this series of tests, it was necessary to close the outlet valves while the tests were in progress. Whenever possible, dynamic response tests on mass concrete dams should be made during those periods when water releases from the reservoir are not required.

5. The method for securing each shaker to the dam permitted no relative movement between the shaker frame and the crest roadway.

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ABSTRACT

Tests conducted on Monticello Dam demonstrated the feasibility of determining dynamic properties of a concrete arch dam by measurement of the accelerations of the structure when excited by vibration generators. This research report includes a brief description of the vibration equipment and test procedures used and a discussion of some of the measured results. During the 10-day test period, acceleration measurements using unbonded resistance wire accelerometers were made on the crest and downstream face of the dam to obtain natural frequencies for the first five modes of vibration and the deflected shapes of the crest and of three cantilevers for the first four modes. Two test series were performed, before and after the mode shape tests, to obtain resonant frequencies of the dam. Frequency response data were obtained by measuring accelerations for small increments of shaker speed over the range of 2 to 8 cycles per second. Damping ratios for small displacements were determined from the frequency response curves. Vibration generators used were of the counter-rotating eccentric-weight type, with all components light enough to be manhandled on the dam. With this equipment, sinusoidally varying forces can be applied along any predetermined axis.

DESCRIPTORS—*concrete dams/arch dams/*structural behavior / *field tests // vibrators / mechanical // accelerometers / test procedures / frequency / *vibrations / dynamics / excitation / resonance / earthquakes / *seismic design / measuring instruments / instrumentation / calibrations / damping / portable / deflection / structural engineering / earth movements.

IDENTIFIERS—Vibration exciters / Monticello Dam, Calif. / California / vibration tests.

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