CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

A DYNAMIC INVESTIGATION OF BOUQUET CANYON DAM

by

Willard O. Keightley

A report on research conducted under a
grant from the National Science Foundation

Pasadena, California

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Preface and Acknowledgment

The work reported herein is a part of a comprehensive study of the dynamic response of full-scale structures being conducted under research grant GP-934 of the National Science Foundation. Already reported under this program are dynamic measurements on a nine-story steel frame building and a five-story reinforced concrete building.* As a part of this same investigation, static and dynamic tests are under way on a steel frame structure loaded far into the plastic range, so that direct experimental evidence of the behavior of strongly nonlinear hysteretic systems will be available. These experimental studies are all accompanied by complete theoretical investigations with the object of attaining a true understanding of the relationships between analytical calculations and the actual behavior of real structures.

The studies of the Bouquet Canyon Dam, which are the subject of the present report, represent the cooperative effort of many groups and individuals. The Los Angeles Department of Water and Power, the owner of the dam, provided transportation, installation, and electric power for the vibration generators, and many other services. We much appreciate the interest and backing provided by Mr. S. B. Nelson, General Manager and Chief Engineer of the Department of Water and Power.

It was only through the personal interest and efforts of Mr. H. B. Hemborg, Principal Engineer of major project design and

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* Nielsen, N. N., Dynamic Response of Multistory Buildings, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, 1964.

inspection, Los Angeles Department of Water and Power, now retired, that the project was made possible. Mr. Hemborg also was chiefly responsible for planning and conducting the wave velocity measurement experiments, and special thanks are due him for major contributions to all aspects of the work. The assistance of Mr. Tom Marynick and Mr. Jack Berrier, who supervised various phases of the Department's activities in this investigation, is also appreciated.

The four vibration generators used to excite the dam were made available by the Division of Architecture of the State of California. Thanks are expressed to Mr. Jack Meehan of the Department of Architecture for arranging for the use of this equipment.

The equipment used to measure wave velocities through the dam was loaned by the DynaMetric Corporation of Pasadena, California. Mr. Dick Perley of DynaMetric and Mr. Joe Phelps, consultant to DynaMetric, advised and assisted with the wave velocity measurements.

Much of the field work and data reduction were carried out by Mr. Ilhan Gozaydin of the Highway Department of Turkey, now a graduate student in Mechanical Engineering at Stanford University. Mr. Gozaydin's careful and untiring efforts were an important contribution to the project. Dr. Sheldon Cherry, on leave from the University of British Columbia, and Mr. Geoffry Martin, a graduate student in Civil Engineering at the University of California, Berkeley, also helped with certain aspects of the field work. Mr. Raul Husid, on leave from the University of Chile, contributed to a portion of the data reduction.

Mr. Gerald Frazier, a graduate student in Civil Engineering at Montana State College, wrote the digital computer program for the

calculations of the natural frequencies and mode shapes of the dam. This digital computer analysis of the dam and a portion of the data analysis were carried out at Montana State College under a National Science Foundation grant to investigate the application of the Holzer technique for finding the natural frequencies of two-dimensional shear structures, under the direction of Professor W. O. Keightley. The ink tracings for the report, with the exception of Figures 7(a) and 7(b), were made under the supervision of Mr. Fred Sanford of Montana State College. Figures 7(a) and 7(b) were furnished by the Los Angeles Department of Water and Power.

The whole project was under the direction of Professor W. O. Keightley, of the Department of Civil Engineering and Mechanics, Montana State College, who carried out in person most of the field work, all of the analysis of the data, and the entire preparation of the report. We very much appreciate the careful and conscientious way in which Dr. Keightley has conducted this investigation, often under field conditions (including a forest fire!) that were far from ideal.

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Summary

An investigation was made of the dynamic properties of an earth dam 200 feet high, by 1200 feet long on the crest, by 1300 feet thick at the base. The dam was excited into steady-state vibrations over the frequency range 1-1/2 to 8 cycles per second by four synchronized rotating eccentric-mass vibration exciters operating on the crest in the upstream-downstream direction. Accelerations were measured on the crest and on the downstream face to indicate the natural frequencies of the dam and to estimate the shapes of the four lowest modes of vibration. The chief results of the investigation are summarized below.

1. At least 12 closely spaced resonances were detected in the frequency range 2 to 8 cps. The four lowest frequencies were almost uniformly spaced.
2. The lowest six resonant frequencies were predicted by the shear-wedge theory to be higher than the observed frequencies by amounts varying from 11% to 25%. The value of the shearing modulus which was used in the calculations was determined by measuring the velocities of shear waves through the dam.
3. The shapes of the lowest four modes predicted by the shear-wedge theory agreed well with the deflections observed on the crest of the dam. The predicted deflections at lower elevations on the dam, however, were several times greater than the observed deflections.
4. Equivalent viscous modal damping constants estimated from the widths of the resonance peaks varied from 3% critical to 6% critical. The close spacing of the resonances made precise determination of the damping constants difficult in some cases. Damping constants determined from several resonance peaks were surprisingly uniform at any one frequency.

5. No departure from linearity could be detected in the behavior of the dam as a whole. Third harmonic content in some of the acceleration records is believed to have resulted from nonlinear behavior of the soil in the immediate vicinity of the shaking machines.
6. The maximum shear stresses caused in the dam by the vibration exciters were computed by the shear-wedge theory to be only a few hundredths of one pound per square inch.
7. The local displacement response of the shaking machine mounting slab and of the soil adjacent to the slab always remained essentially in phase with the exciting force.
8. Measurements indicated that vibrations through the thickness of the dam were excited, that is the downstream face of the dam did not show the same response as the upstream face above the lowest few frequencies.
9. Abutment motions were as large as 7-1/2% of the maximum motion on the crest in the fourth mode.
10. Measurements of the phase of the response relative to the exciting force proved to be of value for making the best estimates of the mode shapes.

Introduction

Dams are a common feature of civilization today. The large population of the earth and the present scope of man's activities require the storage of large quantities of water, conveniently impounded by dams at high elevations. It is unlikely that any different means of performing this function will be devised in the forseeable future. As a result of the constantly increasing population and demand for water, more and more dams are being built, often close to densely populated areas, and on sites which are not ideally suited for dam construction. The increasing threat of catastrophe which can result from the rupture of a dam demands that a major effort be made to learn as much as possible about the safety of dams.

This investigation was undertaken to gather experimental information about the dynamic characteristics of an earth dam. The intention was to collect a detailed set of data from a reasonably simple structure, to serve as a basis for evaluating theoretical work on the dynamic properties of earth dams. When satisfactory agreement between theoretical prediction and observed experimental behavior has been reached, then some knowledge of the behavior of earth dams during earthquakes might be inferred. In addition, it is also possible that an experimental study of this kind might reveal some unexpected phenomenon in the behavior of the dam which could be used as an indicator of the strength of earth dams.

Experimental investigations of the dynamic properties of earth dams have been few. There has appeared to date only one published account of experimental work in which a full size earth dam was excited into steady-state vibrations so that resonance curves could be obtained.(1) This account described an investigation of Dry Canyon Dam, a 60-foot high combination of hydraulic fill and rolled earth fill in the Los Angeles water supply system. The instrumentation used was barely adequate for the investigation, and the dam itself was much more complex than desired in view of the existing state of theory. Nevertheless, three resonance curves were obtained, and the application of the simple shear-wedge theory to the problem suggested that with improved instrumentation and improved data analysis techniques, it might be possible to obtain more extensive and more reliable data from a less complex dam, thus permitting a thorough test of theory.

Several experimental studies of the dynamic properties of models of earth dams have been conducted, chiefly in Japan.(2), (3), (4) Models, of course, allow much more freedom in the conduct of the investigation, and in particular they permit the possibility of loading the model to a state of great deformation or to destruction. Uncertainties as to the relationship between the model and the prototype always exist, however, and it was felt that data from a full size earth dam was needed.

The chief problem in making a dynamic investigation of a full size earth dam is the application of a sufficiently large force, accurately known and preferably precisely controlled. Most conveniently the force should be sinusoidal in time, adjustable in amplitude, and variable in its point of application on the dam. The force should be sufficiently large so that its effect on the dam shows clearly above the background microseismic activity.

The experience at Dry Canyon Dam indicated that, with improved instrumentation, the rotating eccentric-mass vibration exciters used in that investigation would probably be satisfactory for an investigation of Bouquet Dam, approximately three times as high and two-and-one-half times as long. Although it would not be convenient to vary the position of the exciters on the dam, inasmuch as a concrete mounting slab would be required at each location, nevertheless the force produced by the exciters would be sinusoidal and accurately known, and could be precisely controlled. It was decided to utilize four machines operating synchronously to produce as large a force as possible, approximately 3,200 pounds amplitude at 1.0 cps, increasing with the square of the frequency to a maximum of 20,000 pounds. The use of four machines on the dam would also provide a good test of the synchronization abilities of the machines, which were at that time just emerging from the development stage.

Description of Bouquet Dam

Bouquet Dam, shown in Figures 1 and 2, was constructed in the period 1932-1934 to store water for the Los Angeles Department of Water and Power. Four articles describing R. R. Proctor's soil compaction philosophy and inspection techniques, newly developed at that time and put into practice at Bouquet Dam, appeared in Engineering News-Record in 1933.(5) An additional article describing the construction of the dam appeared in Civil Engineering in 1934.(6)

The dam is approximately 207 feet high at the centerline, 1260 feet thick at the base, and 1190 feet long on the crest, and it is set in a trapezoidal-shaped canyon opening in rock. The major part of the dam consists of a compacted fill of sandy clay. Cores taken in 1957 showed that at depths between 22 feet and 53 feet below the crest, the average dry density and the average moist density were respectively 122.6 and 136.8 pounds per cubic foot, with no apparent increase with depth. The maximum water level in the reservoir rises to 14 feet below the crest. At the time of construction the average dry and moist densities throughout the dam were reported respectively as 122.2 and 138.3 pounds per cubic foot, with very little variation from these averages. Based on the reported specific gravity of the sandy clay, 2.75, the 31 feet of fill below the maximum water level examined in 1957 contained about 6% air by volume, and was 80% saturated. During the period covered by this dynamic investigation in 1963, the water level in the reservoir was held at 25 feet below the crest.

On the downstream side, part of the embankment consists of two loose fills taken from the abutment and foundation excavation. The scant data available on pervious fill number one, the more impervious of the two, indicate a field dry density of 119.2 pounds per cubic foot. The absence of water in the drains under the loose fill suggests that the fill is not saturated. The specific gravity of pervious fill number one was reported as 2.70. No quantitative data are available for pervious fill number two, but it is known that it consists of the more pervious materials which were excavated at the same location as pervious fill number one.

Wave velocity measurements, which are described later, were made in order to determine the elastic moduli of the materials in the dam. The most reliable data were taken by measuring on a horizontal path through the dam, extending from the downstream face to a point 29 feet vertically below the upstream edge of the crest. Approximately 55% of the length of the path traversed by the waves consisted of compacted fill, and 45% consisted of pervious fill number two. The best estimates of the dilatational and shear wave velocities along this path were respectively 2090 and 1270 feet per second.

The rock in the west abutment of the dam was reported in the construction records as being schistose, whereas the rock in the east abutment is a diorite. The only quantitative data available for the rock is the value of the specific gravity, 2.70, reported for the pervious fill taken from the abutment excavation. The best estimate of the dilatational wave velocity through the rock is 4160 feet per second, measured in the west abutment. The measurements did not permit an estimate of the shear wave velocity to be made.

More accurate knowledge of the properties of the materials in the dam and in the abutments and foundation cannot be easily or inexpensively obtained at this time. Many holes would need to be drilled into the dam in order to accurately determine the properties of the three kinds of fill and to determine if these properties vary with depth. In view of the variable nature of the rock, no detailed investigation of rock properties can be conducted now that the dam is built. Wave velocity measurements made between holes drilled through the dam into the rock would seem to be the only reasonable method of investigation. Detailed measurements of rock properties, conducted at the time of construction of an earth dam when the overburden has been removed from the foundation, would be a worthwhile effort in a future dynamic investigation of a dam.

Vibration Exciting Equipment

The vibration exciters used on the dam are shown in Figures 3 and 4. Each exciter consists essentially of two eccentric masses which rotate in opposite directions about a vertical axis, producing a horizontal uniaxial force. The rotating masses are driven by a 1-1/2 horsepower direct-current motor, the speed of which is controlled by an amplidyne unit. Variations in the speed of the machines are held to within about 1/10 of 1% of the frequency of operation over the speed range 0 to 10 cps. It is possible to synchronize as many as four machines so that they all run in phase, under one master speed control.

Each machine produces a force of approximately 800 pounds amplitude at one cycle per second, the force increasing with the square of the frequency. Above 2-1/2 cycles per second the eccentric masses must be decreased by removing some of the lead slabs from the rotating baskets in order to limit the force to 5000 pounds per machine, an upper limit determined by the structural strength of the machines. Construction and operation of the machines are described in detail in two reports by Hudson.(7), (8) Several reports describing structural dynamic investigations in which the machines were used have been issued by the Earthquake Engineering Research Laboratory.(1), (9), (10) A more general summary article appeared recently in the Journal of the Engineering Mechanics Division of the American Society of Civil Engineers.(11)

The vibration exciters were connected to the dam by bolting them to a concrete slab 8' x 24' in plan, by 16" thick, cast into the earth on the crest. The slab contained one layer of 5/8" diameter steel rods placed at

18" on center in both directions. Six Rawl Company Multi-Calk expanding lead anchors for 1" diameter bolts anchored each machine to the concrete slab. The anchors tended to work loose under the reciprocating force, so that retightening of the bolts was often necessary. It is recommended for future tests that cast-in-place studs be used if they can be set at the time the slab is cast.

In an investigation of this kind it is desirable that the excitation applied to the structure be sinusoidal. Inasmuch as the force input to the dam is only that which can be transmitted through the sides and the bottom of the machine mounting slab, this means that the slab should not slide on the earth. In this instance a coefficient of friction of 0.5 would be necessary to prevent sliding. In a record of horizontal acceleration on the slab, shown in Figure 23(b), it is seen that a component of response at three times the forcing frequency is present. However, the measurements were not sufficiently detailed to ascribe this third harmonic component to sliding of the slab. Figure 16 shows that the displacement response of the slab, neglecting the harmonic content, was essentially in phase with the force of the shaking machines. The force applied through the slab to the dam, therefore, was essentially in phase with the force produced by the rotating eccentric masses, but it was larger in amplitude as a result of accelerations of the slab and the shaking machines. It was calculated that the actual force imposed on the dam was larger than the force produced by the machines by a maximum of 5% at 8 cps. The magnitude of this discrepancy would vary as the square of the frequency, and hence it was quite small at lower frequencies.

Electric power for the shaking machines and for the instruments was provided by an army surplus John Reiner Company gasoline engine-driven generator of 37.5 KVA capacity, loaned for the project by the Jet Propulsion Laboratory. The generator was mounted on a 1-1/2 ton truck on the west abutment about 50 feet south of the downstream edge of the crest. The truck is visible at the left hand edge of Figure 1. With this arrangement no significant amount of background vibration was noticed in the dam, even at the west abutment, due to operation of the generator. When the generator was operating properly it provided excellent frequency and voltage control so that proper synchronization of the shaking machines and quiet operation of the amplifiers were possible. A generator with poorer control had been tried previously, and it was found that good synchronization of the machines could not be maintained, and the oscillograph traces showed a greater than normal amount of noise. A variable autotransformer, with an expanded scale voltmeter reading from 110 to 120 volts, was used to maintain the voltage supplied to the amplifiers within a few volts variation. The expanded scale voltmeter provided a much more informative picture of voltage variations than was possible with a voltmeter reading from 0 to 250 volts.

Instrumentation

The response of the dam was measured with the instrumentation system shown in Figures 5 and 6. The system consisted of three strain gage accelerometers, three channels of amplification, and recording galvanometers. Sensitivity of the system was such that a sinusoidal acceleration of 10^{-6}g amplitude would produce an oscillogram trace of approximately 0.1" peak-to-peak amplitude in the range 0 - 10 cps, with a noise level varying from 0.03" to 0.07" peak-to-peak. Thus it was possible to effectively measure accelerations as low as 2 x 10^{-6}g.

Two of the accelerometers were model A4-0.25-350 unbonded strain gage accelerometers manufactured by the Statham Instruments Corporation of Los Angeles, California. Each accelerometer consisted essentially of a liquid-damped seismic mass suspended within a case by stretched wires which formed the four legs of a Wheatstone bridge. The bridge resistance was 350 ohms, damping was about 0.7 critical, and the undamped natural frequency was approximately 15 cycles per second. At the maximum allowable acceleration, 0.25g, the bridge produced 50 millivolts output at the maximum allowable excitation of 9 volts. These accelerometers, which could sense horizontal accelerations only, were fastened to steel base plates equipped with leveling screws as shown in Figure 5. The units were then simply carried from place to place on the dam, set down on a firm place or on a rock in the soil of the dam, leveled, covered with a cardboard box to reduce temperature fluctuations, and placed in operation.

The third accelerometer available was the Statham model A5-2-350, similar in operating principle to the two accelerometers previously described. This unit had a bridge resistance of 350 ohms, 0.7 critical damping, and an undamped natural frequency of approximately 100 cps. The maximum bridge output was 35 millivolts at 2g acceleration and 9 volts bridge excitation. This accelerometer was not sufficiently sensitive to be used near the abutments or on the lower portion of the dam.

One important advantage of the acceleration transducer is that static calibration is possible at the test site by simply rotating the unit through an angle in the earth's gravitational field. A calibration fixture consisting of two flat steel plates welded to form an angle of about 6° is shown in Figure 5. After the base of this fixture had been made level, an accelerometer was calibrated by first placing it flat on the horizontal plate, and then shifting it to the inclined plate, recording on the oscillogram a trace corresponding to each position. The operation was then repeated with the accelerometer reversed 180° about a vertical axis. Usually the accelerometers were calibrated at the start of each day and then again at the end of the day. The maximum variation observed in calibrations in any one day was 3%.

The carrier amplifiers, which supplied power to the strain gage bridges of the accelerometers and then amplified the accelerometer output voltages sufficiently to drive the recording galvanometers, were model C-3 amplifiers, approximately 15 years old, manufactured by the William Miller Company of Pasadena, California. The amplifiers supplied the accelerometer bridges with a 3 KC voltage, adjustable from 0 to 10 volts rms. Signal-to-noise ratio in these amplifiers was considerably larger than could be found in any carrier amplifiers of more recent manufacture. Unfortunately the William Miller Company has discontinued business, and it is no longer possible to purchase these amplifiers.

The recording galvanometers were model 7-351, mounted in a model 5-124 direct writing oscillograph manufactured by the Consolidated Electrodynamics Corporation of Pasadena, California. The galvanometers had natural frequencies of 20 cps and were electromagnetically damped to about 0.6 critical. The direct writing oscillograph used ultraviolet light to produce the three acceleration traces simultaneously on one piece of paper 7" wide. A convenient feature of this type of recording is that no development processing of the oscillogram is required. The record appears within a few seconds under ordinary room light or subdued sunlight, thus allowing the data to be scanned in the field. Exposure to full sunlight causes the records to disappear, hence it was necessary to cover the front of the oscillograph with a shield containing amber colored plastic material as shown in Figure 6.

In the investigation of a structure as large as Bouquet Dam it is often necessary to place the seismic pickup at a long distance from the amplifiers. In this investigation the cable between the accelerometer and the amplifier was sometimes as long as 900 feet. Balancing of the bridge in these instances was possible only when a cable with symmetrically placed wires was used. Belden Wire Company plastic covered, shielded, 22 gage, 4-wire cable, No. 8404, was found to be satisfactory when two opposite wires were used for the bridge supply, and the other two opposite wires were used for the bridge output. When a long 5-wire cable was tried, satisfactory balance could not be obtained.

In order to measure the phase relationship between the exciting force and the response of the dam, an inductive type pickup was attached to one of the shaking machines. When the exciting force reached its maximum, a small piece of iron attached to a rotating mass induced an electric pulse in the inductive pickup. This pulse was recorded on the oscillogram by a galvanometer of 3000 cps natural frequency. Phase determinations were then made by comparing the positions of the peaks of the acceleration traces with the positions of the pulses on the oscillogram as illustrated in Figure 21(b).

Wave Velocity Measurements

Values of the densities and the elastic moduli of the materials in the dam and in the foundation are parameters needed to correlate a theoretical analysis of the dam with the behavior observed in the field. It would be very desirable to be able to predict the dynamic properties of the dam from tests performed on laboratory sized samples of soil and rock. The rock at the site is not a homogeneous isotropic solid, but rather it contains a myriad of discontinuities and heterogeneities, is stratified on both the microscopic and the macroscopic scales, and the stratifications are often arranged in a chaotic manner. The rather random nature of the orientations and distributions of properties in the rock means that a great many small samples would need to be tested, and a statistical analysis would need to be made to determine the rock properties in gross. The problem of determining the effective in situ properties of the rock from tests on small samples would indeed be an interesting one.

The soil in the dam is much more uniform than the rock in the canyon, and it seems more likely that tests on small samples would correlate well with the observed properties of the dam as a whole. To measure the moduli of the soil at the very low stress levels attained in the resonance testing would be very difficult to accomplish by static tests, however, and probably wave velocity measurements or resonance tests of samples would be required, both of which present difficulties if the material is noncohesive.

Perhaps the most realistic method of determining the elastic moduli of the soil and the rock at the site is by measuring the velocities of waves through the materials in situ. If the theory of elastic wave propagation is assumed to apply, Young's modulus and the shear modulus are easily determined from the dilatational and the shear wave velocities, provided the density is known. This method averages the properties of the materials along the path traveled by the waves, at very low stress levels, probably of the order of those experienced in the resonance investigation. It would, however, be difficult to extract any information about damping from wave velocity measurements. Care must be taken to insure that the waves whose speed is being measured travel on a straight line from the excitation point to the pickup.

At Bouquet Dam an Electro-Tech geophone of 14 cps natural frequency, sensitive to motion along only one axis in the horizontal direction, was placed in a well 29 feet below the crest of the dam as shown in Figures 7(a) and 7(b). A sledge hammer, on which was attached a shock switch manufactured by the DynaMetric Corporation of Pasadena, California, was then struck against the downstream side of the dam opposite the position of the geophone. The signal from the shock switch started a DynaMetric model 117 seismic timer, which measured elapsed time in milliseconds until it was stopped by a signal from the geophone, indicating the arrival of the elastic waves through the dam. By orienting the sensitive axis of the geophone toward the hammer and then at 90° to this direction, two distinct travel times could be detected, suggesting that the velocities of dilatational and shear waves were being measured. Without additional information, such as travel times for intermediate distances, it is not possible to state with certainty that this was the case. Refractions from faces of discontinuity within the dam might possibly have resulted in the measurement of a phenomenon much more complex than the simple straight line passage of dilatational and shear waves from the hammer to the geophone. The velocities determined by assuming straight line wave propagation paths were 2090 and 1270 feet per second.

A later attempt was made to measure velocities in the dam and in a rock quarry at the west abutment by striking the surface of the ground and by mounting the geophone on the surface. It was found that travel time interval measurements could be repeated time after time, but the lengths of the intervals depended on the strength of the sledge hammer blows. Three distinct intervals were noted on the dam, and each could be obtained repeatedly by applying a sledge hammer blow of the proper strength. The harder the blow, the shorter the measured interval, and the greater the apparent velocity. This phenomenon was observed with the geophone oriented both toward the hammer and also perpendicular to this line. In the rock quarry two distinct intervals were noted, depending on the strength of the blow. The relationship between time interval and the strength of the sledge hammer blow was not noted in the measurements made through the thickness of the dam. In that instance the hammer was always struck with as much force as possible.

Without a more thorough investigation it is not possible to give much reliability to velocities measured in this manner. A portable two-channel seismograph which could produce records which could be viewed in the field would be a great improvement. Two geophones, separated by a measured distance, could be used to reduce the effect of the dynamic characteristics of the instruments. Visual examination in the field of the records of the two geophones, oriented both toward the hammer and at right angles to this line, should provide a much clearer picture of the traveling-wave phenomenon and should permit a more intelligent field operation. The recorder should have as high a speed as possible in order to allow measurements to be made over short distances, a necessary procedure when discontinuities are nearby.

Experimental Procedure

The data to be gathered from a resonance investigation of a structure are the frequencies at which the structure resonates, the deflected shapes of the structure at the resonant frequencies, the phase of the response relative to the excitation, the rates and the mechanisms of energy dissipation, the absolute values of the response of the structure to forces of specified frequency and magnitude at specified locations on the structure, and any observations of nonlinearity which may not be included in the preceding list.

The reliability and even the existence of these experimental observations depends, of course, on the amount and the quality of the apparatus available. Experimental observations are restricted to a great extent by the limited capabilities of structural vibration exciters which are available today. There does not at present exist structural vibration equipment which can cause any significant nonlinear behavior in structures containing as much deformation resisting material as is found in Bouquet Dam. Consequently, very little information concerning the behavior of the dam at large deformations can be gathered from tests on the dam itself, but rather such information must be deduced from tests on small samples of material. The localized nature of presently available excitation, in the form of machines operating at discrete points on a structure, cannot produce synchronous response at all points in the structure, hence the existence of modes in which all of the structure is moving in phase cannot be observed, but can be only surmised.

Instrumentation capability also limits the information which can be gained from a dynamic investigation. Instrumentation which is available today, for instance, does not permit the accurate determination of the actual mechanism of damping which operates in a continuous structure undergoing dynamic excitation. A method for determining the mechanism of energy dissipation from dynamic measurements in a lumped-mass structure was described and illustrated in Reference 1, but a continuous structure would present formidable difficulties for the method. Absolute amplitudes of response probably can be determined only within ± 5%, hence precise observations, such as small differences in the motions at two points, or slight departures from linearity cannot be reliably made. The limitations of the apparatus, therefore, primarily restricted the observations at Bouquet Dam to the more obvious aspects of the linear behavior of the structure.

The experimental procedure followed at Bouquet Dam was first to excite the dam into steady state vibrations at closely spaced intervals, usually 0.03 cps or less, over the frequency range 1-1/2 to 8 cps, and to measure the response at a number of points so that resonance curves could be plotted. Then the resonance curves were examined to find the most probable values of the resonant frequencies, and, while the excitation was held constant at each of these frequencies, the response was measured at closely spaced intervals over the surface of the dam in order to determine the mode shapes. The field work was conducted in 13 working days, for the most part by two men. Interspersed were days of reducing data and plotting resonance curves so that the resonant frequencies could be estimated. Because only one mounting slab was available for the shaking machines it was not possible to improve the purity of the resonances by more effectively distributing the exciting force. Figure 2 shows the locations of the resonance measurements on the dam.

Acceleration measurements were made at 100-foot intervals on the crest and on lines B and C on the downstream face, shown in Figure 2, in an attempt to determine the shapes of the four lowest modes of vibration. Because of the close spacing of the resonant frequencies and the localized nature of the excitation it was not possible to excite synchronous response at all points in the structure. Therefore the phase of the response at each point was measured, and what are considered to be improved estimates of the mode shapes were made by plotting the components of response which lagged the excitation by 90°.

Resonance measurements were made simultaneously at points on the downstream face and at corresponding points on the upstream face to determine if thickness modes of vibration were being excited. Unfortunately, because of the constant high water level in the reservoir, it was not possible to measure thickness vibrations very far below the crest, nor was it possible to determine the effect of the reservoir level on the behavior of the dam.

A major difficulty encountered in the field work was the maintenance of proper operation of the generator supplying electric power to the vibration exciters and to the instruments. It was amply demonstrated that when an investigation is to be conducted with the instrumentation and the vibration exciting equipment which were used at Bouquet Dam, reliable generating equipment is an absolute necessity.

At frequencies below two cycles per second, the acceleration response to the sinusoidal excitation became extremely small, of the same order as the background vibrations due to wind, traffic on the highway crossing the east abutment, and other causes. It was found that best results were obtained at these low frequencies by conducting the field work at night, when the background vibrations were at a minimum. During the period of least background disturbance more sensitive instrumentation would have been advantageous for measuring the response of the dam to the sinusoidal force. Under average daily working conditions, however, the sensitivity of the instrumentation was adequate.

Experimental Results

Resonance Curves.

The resonance curves of Bouquet Dam are shown in Figures 8 to 11. In addition to the amplitude of the displacement response, these figures also show the phase of the response relative to the force. The phase measurements may be compared among Figures 8 to 10. That is to say, all of the phase measurements around the frequency 4-1/2 cps, for example, in Figures 8 to 10 were made at the frequency 4.53 cps. It is possible, then, to determine the relative positions of several points on the dam at this frequency by referring to the plotted amplitudes and the phase measurements. In Figure 11, phase lags may be compared only between points on the downstream face and corresponding points on the upstream face.

The resonance curves are seen to contain many closely spaced peaks. In several instances the resonances overlap to the extent that the exact values of the resonant frequencies and estimates of the modal damping constants cannot be accurately made. Table 1 shows the frequencies of all of the maxima, determined by a visual analysis of the curves. In order to determine the most reliable values of the resonant frequencies, the frequencies were weighted by judging the degree to which the peaks are free from the influence of adjacent resonances. Asterisks in Table 1 indicate the most reliable values of the resonant frequencies. An attempt was made to group the frequencies of the maxima along horizontal lines so that all of the frequencies along one line pertained to one suspected resonant frequency of the dam. Above the first few frequencies, however, the grouping is often rather arbitrary, particularly in the case of frequencies observed at points below the crest.

Data pertaining to frequencies observed on the crest have been taken from Table 1, and are shown in Table 2. Although the data pertaining to the crest were taken by accelerometers placed on the downstream edge of the crest rather than on the axis, it is believed that these measurements were little influenced by thickness vibrations. The frequencies in Table 2, therefore, are assumed to represent primarily frequencies of the modes in which the plane through the axis of the dam is distorted, and in which all of the particles of the dam move antisymmetrically with respect to the axial plane. This is the type of distortion which is assumed in the simple shear-wedge theory which is briefly described later in the report. Resonances observed at lower elevations on the dam include, in addition to the antisymmetric modes, also those modes in which distortion is symmetric with respect to the axial plane. The resonance curves pertaining to points lower on the dam are thus more difficult to analyze.

It is seen in Table 2 that the lowest four resonant frequencies and a few of the higher ones appear to be rather reliably determined by three or more frequency determinations which lie within a narrow range. An interesting feature of the data is the almost constant value of the spacing of the lower resonant frequencies and the averages of the spacings of the of the higher frequencies. Although the data from Dry Canyon Dam were much less complete, the first seven frequencies were observed in that investigation to be rather uniformly spaced. The theory of the shear wedge applied to a dam which is long compared to its height, and which is set in a canyon of rectangular cross sectional shape, predicts that the spacing of the lower frequencies gradually increases with frequency, and becomes asymptotic to the value S/2L cps, where S is the shear wave velocity, and L is the length of the dam. Given later in this report are the results of a digital computer study of a shear-wedge representation of Bouquet Dam, set in a canyon of trapezoidal cross sectional shape. This study showed that the spacing of the resonant frequencies decreased significantly with increasing frequency. Obviously a more sophisticated representation of the dam will be needed to predict all of the resonant frequencies which were observed in Bouquet Dam. The development of a satisfactory representation of the dam will indeed be an interesting and a rewarding task.

With the exception of the frequency 5.93 cps pertaining to a maximum observed at Station 10 + 52 on line B, the frequencies of all of the maxima observed below the crest can be reasonably well associated with the frequencies observed on the crest. It might be assumed, then, that thickness vibrations of the dam had little influence on the resonance curves below the crest. In Figure 11, however, which shows the responses of corresponding points on opposite faces of the dam, it is seen that there are large differences between the amplitudes and the phases on the downstream face and the corresponding values observed on the upstream face. It was suspected at first that the earth fill of the dam might have settled away from the concrete slab on the upstream face in some places, and that resonances of the unsupported slab were responsible for the differences in the resonance curves. At Station 7 + 75, therefore, a 6" diameter hole was drilled through the slab, and accelerometers were mounted on the soil inside the hole and on the slab beside the hole. Over a range of frequencies the accelerations measured in the hole varied from 4% smaller to 6-1/2% larger than the accelerations measured on the surface of the slab, except at one particular frequency, 5.47 cps, at which the acceleration measured in the hole was 15% smaller. Data taken with the instrumentation system have proved to be normally consistent within ±5%, so it is possible that the 15% discrepancy resulted from separation of the slab from the earth fill. The plotted data pertaining to the upstream face at Station 7 + 75 in Figure 11 were taken with the accelerometer resting on the earth inside the hole. Another set of data was taken on a different day at Station 7 + 75, when the accelerometer on the upstream face was resting on the concrete slab rather than in the hole. The correspondence between the responses on the upstream and the downstream faces in this set of data, which is not shown here, agreed with that shown in the curves in Figure 11 in every detail, including the slightly smaller response on the downstream face at the fundamental frequency.

The reliability of the data pertaining to Station 10 + 00 in Figure 11 is suspect. A large brush fire in Bouquet Canyon threatened to sweep the downstream face of the dam and made necessary a hasty dismantling of all of the equipment. The operators, somewhat fatigued from loss of sleep due to the presence of the fire and of both ground and air fire-fighting equipment operating from the dam throughout the night, were probably not functioning with their usual efficiency. It is possible that after the equipment had been reassembled on the following day to make the measurements at Station 10 + 00, the two accelerometers were interchanged at the time of calibration. If this interchange did occur, then the data pertaining to the downstream face should be multiplied by 1.14 and the data pertaining to the upstream face should be multiplied by 0.87. These changes would bring the responses of the downstream and the upstream faces into close agreement at the low frequencies, and would in general increase their differences at higher frequencies. Unfortunately, only one calibration was made on that day and only one measurement was made with the two accelerometers side by side on the front face. This measurement would indicate a 13% difference between measurements made by the two instruments at one point if the scale factors mentioned above were applied. Measurements of thickness vibrations at Bouquet Dam were not as complete as desired. It is recommended that an investigation of thickness vibrations be conducted on an earth dam which has both faces accessible for the full depth of the dam, and which preferably is not faced with a rigid slab. One vibration exciter should be located on the upstream face of the dam, at some distance below the crest, and a second exciter should be located on the downstream face, opposite the first exciter. Thickness vibrations would then be best excited when the two exciters were operated in opposition, at 180° phase difference.

Mode Shape Measurements.

Figures 12 to 15 present the best estimates of the lowest four mode shapes of the dam. Because it was not possible to excite pure modal response (response characterized by all points in the dam moving at the same phase), the phase of the motion, in addition to the amplitude of the motion, was measured at each point. The total measured amplitude at each point was then resolved into two components, one in phase with the exciting force, and one at 90° phase to the exciting force. If the frequency of excitation matched exactly a natural frequency of the dam, and if the dam behaved as a linear structure, then all of the response of the mode undergoing resonance would appear in the component at 90° phase to the exciting force, and none would appear in the in-phase component of response. Of course, as a result of damping, all of the other modes of the dam would respond at angles other than 0° or 180° phase to the exciting force, and hence they would appear to some extent in the component of response at 90° phase, depending on the amount of damping, the spacing of the natural frequencies, and the location of the exciting force on the dam. For this reason and because the exact values of the natural frequencies of the dam were not known, the mode shapes in Figures 12 to 15 should not be considered to be pure mode shapes, but only the best estimates of mode shapes. More effective distribution of the excitation would have produced modes of greater purity.

The frequencies used to excite the modes differed slightly from the most probable values listed in Table 2 because all of the resonance data had not been analyzed at the time of the field measurements. It is believed that a more symmetrical fourth mode shape could have been produced by a better tuning of the frequency of excitation. These attempts to determine the best estimates of the mode shapes were based, of course, on the assumption of small damping in the modes, such that the frequencies of the observed resonances are very close to the frequencies at which the phase lag is 90°.

An interesting feature of the mode shapes are their "tails" at the abutments. The shapes are very definitely not the half-sine waves which at first thought might be predicted in view of the fact that primarily shearing distortion is expected. It is also interesting to observe the in-phase components of response which were excited at the several frequencies. It can be seen that at the frequencies of the first and the second modes there were also excited considerable amplitudes of the third mode. At the third frequency the fourth mode shape can be seen, and at the fourth frequency the fifth mode shape is evident at zero degrees phase to the exciting force. The results of this resolution of the response into in-phase and quadrature components are very informative and very satisfying to observe. Instrumentation which would permit more accurate and less laborious measurements of phase would be a welcome addition to the experimentalist's equipment.

Motions at the abutments are seen to be significant, as much as 7-1/2% of the maximum motion on the crest in the fourth mode. The "abutments" in Figures 12 to 15 locate what were judged in the field to be the junctions of the earth fill with the sides of the canyon. The distances between the abutments which were measured in the field are shorter than the distances indicated by the plans of the dam, possibly due to tapering of the canyon on the downstream side, or because the plans show the outline of excavation into the rock, which is no longer visible now that the dam is constructed. The amounts by which the measured abutment-to-abutment distances are shorter than the distances indicated by the plans are 40 feet, 35 feet, and 75 feet for the crest, line B, and line C respectively.

Unfortunately it was not possible to measure motions on the surface of the rock directly beneath the dam. Measurements of this kind would require holes to be bored through the dam to the rock. Because the motions on the rock would be very small, instrumentation more sensitive than the kind used on the surface of the dam would be required. Instrumentation of greater sensitivity which could be put into operation remotely at the bottom of a hole 200 feet deep cannot be easily obtained. The Lunar Seismometer, which was developed for sensing seismic motions on the moon, and is now being considered for commercial production by one or more instrument companies, possesses a self-leveling feature which would allow it to be placed into operation remotely. It is anticipated that this transducer, which can be housed in a case 6" long by 5" in diameter, when coupled with the United ElectroDynamics Corporation model EA-210 amplifier, with a differentiating amplifier at the output, will possess a sensitivity to acceleration approximately twice the sensitivity of the strain gage accelerometer-carrier amplifier system which was used in this investigation. A system of this kind might prove satisfactory for measuring motions on the rock beneath the dam.

Determination of Damping Constants.

The measurements did not permit the determination of the actual mechanism of energy dissipation in the dam. Some of the energy delivered to the dam by the shaking machines was dissipated by radiation into the canyon walls, but probably most of the energy was consumed by hysteretic stress-strain phenomena in the soil. The most convenient concept for attempting to measure the rate of energy dissipation is the concept of equivalent viscous modal damping. This concept utilizes hypothetical viscous dashpots attached to the structure to dissipate the same amount of energy per cycle as is actually dissipated in the structure by other means. The dashpots are arranged so that structural response consists of viscous damped uncoupled modes of vibration which have the same shapes as the modes of the undamped structure. In free vibration, each of the damped modes would decay exponentially in the same manner as a viscous damped single-degree-of-freedom oscillator. Strictly speaking, for this type of damping to exist, there would be required a viscous dashpot to connect each mass point in the structure to a fixed datum in space, or else there would be required, in the most general case, dashpots to connect each mass point in the structure with every other mass point in the structure. Such a situation does not exist in reality, of course, but nevertheless the concept of equivalent viscous modal damping is tractable and has proved in the past to be useful and to provide a good approximation of the damping in many structures.

If the damping is small, a modal damping constant can be determined by measuring the width of a resonance peak at a height of 0.707 times the peak amplitude, if a pure mode can be excited in the structure.* An examination of the resonance curves in Figures 8 to 10 shows that only the lowest mode was excited with any high degree of purity at several points on the structure. Damping constants which were estimated from measurements of the widths of the peaks of the first resonance as well as peaks of several of the higher resonances are shown in Table 3. In a few instances where the high portions of peaks were well defined, but where the response of adjacent modes superimposed to markedly alter the shapes of the peaks at lower amplitudes, the shapes of the lower portions of the peaks were estimated and sketched in to facilitate width measurements. The peaks which were sketched are noted in Table 3.

The consistency of the damping constants shown in Table 3 is surprising in view of the close spacing of the resonances. Because none of the peaks in the resonance curves represented the pure response of only one mode, the damping constants in Table 3 are not exact, but it is

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* The damping constant is determined by: $\zeta = \frac{1}{2} \cdot \frac{\Delta f}{f}$, where ζ is the fraction of critical damping, Δf is the width, in frequency units, of the resonance peak at a height of 0.707 times the peak amplitude, and f is the frequency at which the peak amplitude occurs.

believed that they are close to the values which would have been observed if pure modes could have been excited in the dam. The equivalent viscous modal damping constants are seen to vary from 3% to 6% of critical damping. It should be remembered that the maximum shearing stresses in the dam, computed by the shear-wedge theory, were only a few hundredths of one pound per square inch. The equivalent viscous modal damping constants of Dry Canyon Dam, which were determined in an entirely different manner from much fewer and less reliable data, were estimated to vary from 10% in the first mode to 2% in the ninth mode. The maximum shearing stresses experienced in Dry Canyon Dam were estimated to be a few ten thousandths of one pound per square inch.

Response of the Shaking Machine Mounting Slab.

The response of the slab on which the shaking machines were mounted and the response of the soil close to the slab indicate that locally the soil responded as a spring. As shown in Figure 16, the displacements of the slab and of the nearby soil always remained essentially in phase with the exciting force over the frequency range 2 to 6 cps. Superimposed on the local response of the soil was the response of the dam as a whole at the location of the machines. Except at the fundamental frequency, the response of the dam as a whole was very much smaller than the local response, and therefore it contributed only a small amount to the measured response.

In Figure 16, the upward trends of the curves were at first thought to indicate a softening nature of the soil, inasmuch as the exciting force increased with frequency. However, except on the lower curve at the frequency 3.83 cps, there are no sudden changes in the levels of unit response at the frequencies at which the eccentric-mass loadings in the machines, and hence the amplitudes of the exciting force, were changed. A possible explanation of the upward trends of the curves lies in the harmonic content of the acceleration records, samples of which are shown in Figure 23(b). When the amplitudes of these records were measured, contrary to the practice used to measure the amplitudes of all other records, the total peak-to-peak heights of the traces were measured, and no attempt was made to eliminate the effects of harmonics. It is possible that harmonic content which increased with frequency, and a rising characteristic of the accelerometer-galvanometer systems at frequencies close to their own natural frequencies, combined to result in what appeared to be a softening nature of the soil. A softening trend in the soil is, of course, to be expected, but the data do not indicate it sufficiently well to verify its existence.

The amplitudes of motion on the machine slab and on the soil adjacent to it were much larger than the general deformation picture of the dam would suggest. The small numbers written on the right hand sides of the oscillogram traces indicate, on the decibel scale, the factors by which the traces are attenuated. In Figure 23(b), which is a composite of records made with only one accelerometer, the decibel numbers give directly the ratios of the amplitudes in the vicinity of the shaking machines.* The amplitudes of motion on the slab were approximately three to four times

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* In all of the other oscillograms presented, in Figures 21(b), 22, and 23(a), three traces appear at each frequency. The top trace and the bottom trace in each group of three represent measurements made with accelerometers of ±1/4g range and of approximately equal sensitivity. The approximate relative amplitudes of acceleration represented by the top and bottom traces may be compared by simply taking the difference between the decibel numbers. The center trace in each group was measured with an accelerometer of ±2g range, and of approximately one tenth the sensitivity of the 1/4g accelerometers.

the amplitudes on the soil six inches away from the edge of the slab, measured in the upstream-downstream direction. This might suggest that the slab was sliding on the soil, but if no sliding occurred, an average strain of only 5×10^{-4} in./in. would be indicated. Such a strain is certainly possible in the soil. The nonsymmetric shapes of the traces of acceleration of the soil six inches behind the slab suggest a bilinear force-deformation relationship in the soil. From the decibel attenuation numbers in Figure 23(b) it can be seen that at the edges of the crest the amplitudes of the motions were approximately one eighth the amplitudes of motion of the machine slab, and were close to the values which would be predicted from mode shape measurements made at other points on the crest.

Linearity of Response.

All of the plotted data were reduced from accelerations, resulting from a force of varying amplitude, to displacements per unit force by simply dividing the acceleration response by the square of the circular frequency to obtain displacement, and then dividing again by the computed exciting force. The assumption was made, of course, that the structure responded linearly. In most instances, at points more than a few feet from the slab on which the shaking machines were mounted, the acceleration records were reasonably sinusoidal, justifying the reduction from acceleration to displacement. Harmonics were ignored as much as possible, and only the accelerations at the frequency of excitation were used in deriving displacement. Tracings of oscillograms showing sinusoidal accelerations, steady and unsteady harmonic content, and response modified by background accelerations are shown in Figures 21, 22, and 23.

Data to indicate the linearity of response with varying amplitude of force are shown in Figures 17 and 18, and in all of the resonance curves. Short horizontal lines are plotted above and below points on the resonance curves over short frequency ranges common to two different eccentric-mass loadings in the machines. Changes were made necessary in the eccentric mass-loadings because of the 5000 pound upper limitation on force permitted for each machine. The ratios of the force levels in the overlapping portions of the resonance curves were all approximately 2.5:1.0. A horizontal line plotted beneath a point in a resonance curve indicates that the eccentric mass loading in the machines was the heavier loading used in the lower frequency range. Similarly, a horizontal line plotted above a point refers to a smaller eccentric-mass loading used in the next higher frequency range. An examination of Figures 17 and 18 and Figures 8 to 11 shows that in some instances the response per unit force increased with an increase in exciting force, while in other instances the reverse was true, and in a few instances the unit response was the same for both force levels. These apparent inconsistencies in the behavior of the dam are in the range of expected errors in the measurements, hence no departures from linearity can be inferred.

The only observed phenomenon which would suggest nonlinearity in the behavior of the dam was the presence of harmonics in the acceleration records. At most stations on the dam a steady third harmonic was observed at one or more frequencies. The harmonic content was especially noticeable when the response at the frequency of excitation was very low. In a few instances the fifth harmonic of the exciting frequency was detected. Oscillograph records in Figure 22 illustrate a few of these observations.

It was thought that perhaps the response at three times the forcing frequency was the result of imperfect balance in the 1-1/2 horsepower direct current motors which powered the shaking machines, inasmuch as the frequency of the motors was three times the frequency of the rotating eccentric masses. In order to investigate this possibility the motors were operated alone, with the eccentric-mass driving belts disconnected. Except in the immediate vicinity of the slab on which the motors were operating, no response could be attributed to the operation of the motors only. On the slab and on the soil adjacent to it, the response due to operation of the motors was so small that it would not be apparent in the response due to normal operation of the shaking machines.

It is believed that the third harmonic in the acceleration records resulted from nonlinear behavior of the soil in the vicinity of the shaking machines. Figure 23(b) shows a typical record of horizontal acceleration on the machine slab. The product of (the mass of the slab plus the machines) times (the acceleration component at three times the forcing frequency), an inertia force imposed on the dam through the bottom of the slab, was only about 0.05% of the force produced by the eccentric masses. However, accelerations measured in the dam as a result of this force were relatively larger than the accelerations caused by the eccentric masses by the square of the frequency ratio, a factor of nine. Thus, it is entirely possible that accelerations at three times the frequency of excitation, particularly at third harmonic resonances, would be visible at the times when the response at the frequency of excitation was at a low level.

Only on one occasion was response at three times the forcing frequency noted when at the same time no third harmonic could be seen in the record of acceleration on the slab. In this instance, at a frequency of excitation of 8 cps, the component of response at 24 cps was detected with an accelerometer of 100 cps natural frequency, whereas an accelerometer of 15 cps natural frequency detected the response of the slab. It is believed that the frequency response characteristic of the accelerometer on the slab suppressed the component of acceleration at 24 cps so that it was not visible.

Accuracy of the Data

The results of several weeks of testing indicated that amplitude measurements could be repeated from day to day at a specific point on the dam within approximately ±5%. Figures 17 and 19 illustrate the consistency of the data. Several factors in addition to possibly changing characteristics of the dam might be responsible for these variations.

The amplitude of the exciting force probably did not vary from its assumed value by more than three or four percent. Frequencies were measured with a calibrated digital counter which counted 300 pulses per revolution of the eccentric masses. The stability of the count indicated that the accuracy of the frequency measurement was approximately 0. 1%. The moment of the eccentric masses about the center of rotation, determined at the time of construction of the machines, was probably within 2% of its assumed value. Variations among the individual masses were less than 1%.

Synchronization of the machines was indicated by meters on the amplidyne control units. Under normal operating conditions the low frequency meter movements occasionally might have indicated an intermittent phase error of 5° in one or more of the machines. An independent measurement of synchronization was made by utilizing inductive pickups simultaneously on two machines, and then comparing the positions of the two pulses produced on the oscillogram. When the machines were loaded with the largest eccentric mass possible, thus creating the most severe torque requirement, the maximum total range of phase variation observed was 16°.

In order to observe the effect of poor synchronization, one of the four machines was deliberately adjusted to go alternately in and out of phase relative to the other three machines. Under this condition the envelope of response of the dam was observed to vary by 3.2% on each side of a mean response, which itself was 6.5% smaller than the response due to all four machines operating in phase. When one machine was set to run steadily at 90° phase with the other three machines, the response of the dam was reduced by 9.8%. Theory would indicate that the reduction should be 21%. No explanation for the discrepancy is readily apparent. It is believed that at normal operating conditions imperfect synchronization resulted in variations in the exciting force of less than 1%.

The instrumentation which measured the response of the dam provided many possibilities for inaccuracies. It was known that a change in line voltage from 125 volts to 105 volts decreased the output of the amplifiers by approximately 5%. Consequently line voltage was constantly monitored, and a variable transformer was manually adjusted to keep variations within ± 3 volts. Other variations in amplifier gain, including variations due to temperature fluctuations, were of course possible. The attenuators in the amplifiers were rated at 1% accuracy, but no measurements were made to verify this rating.

Calibration of an accelerometer consisted of causing four static displacements of the inertial mass by rotating the accelerometer through a known angle in the earth's gravitational field. After the first two rotations, the accelerometer was reversed about the vertical axis so that the second two rotations displaced the inertial mass on the opposite side of the neutral position. In some instances the readings were biased towards one particular direction of displacement of the inertial mass. The maximum bias noted in any set of four displacements was 1½%. The bias was not constant in direction or in magnitude from day to day for any accelerometer, and very often could not be detected at all. This phenomenon could have been caused by static friction or looseness in the accelerometers or in the galvanometers, improper handling of the accelerometers during calibration, or by malfunctioning of the phase sensitive demodulator. The average of each set of four trace displacements was used for reducing the data of the response of the dam. The maximum variation noted between morning and evening calibrations, each the average of four readings, was 3%.

The frequency response characteristics of the low frequency accelerometer-galvanometer systems (15 cps and 20 cps natural frequency respectively) were investigated by placing the 1/4g accelerometers beside a 2g accelerometer (100 cps natural frequency), the output of which was recorded by a galvanometer of 100 cps natural frequency. This comparison was made on top of a concrete tower being vibrated in another study, where amplitudes were of the order ten times greater than those experienced at Bouquet Dam. The response of the 100 cps system, which had around 0.65 critical damping, was assumed flat in the range 0 to 8 cps, and phase lags were assumed to vary linearly with frequency.

Over the range 1-1/2 to 8 cps, one of the low frequency systems, channel No. 6, exhibited amplitudes ranging from 0.2% to 5% larger than the high frequency system, with no apparent relationship with frequency indicated. The other low frequency system, channel No. 3, exhibited amplitudes ranging from 4% smaller to 0.8% larger, with no apparent frequency dependence. These measurements, of course, were subject to all other sources of error such as unpredictable changes in amplifier gain, inaccuracies in calibration, improper orientation of the sensitive axes of the accelerometers, inaccurate attenuation ratios, recording errors due to variable trace amplitude and variable position of the trace on the oscillogram, and errors in reading the record. On the basis of this test, all of the plotted Bouquet Dam data which were measured with channel No. 6 have been multiplied by the factor 0.98, and all of the plotted data which were recorded with channel No. 3 have been multiplied by 1.02. The purpose of this scaling was to produce what are believed to be the most reliable values of the response of the dam. In some cases the use of these factors increased the agreement between recordings made at the same point on the dam, and in other cases the agreement was made poorer.

In another comparison between the response of channel No. 6 and the response of a 100 cps system, in the range 1.7 to 7.3 cps on the concrete tower, the response of channel No. 6 was greater by from 2% to 8%. In a third comparison on the tower, the response of channel No. 3

was smaller by from 5% to 12% than the response of a 100 cps system. It is believed that poor orientation or improper calibration of channel No. 3 was responsible for the large differences in this case.

On Bouquet Dam the responses of the two low frequency systems were compared when one accelerometer was resting on the loose fill on the downstream side of the dam, and the second accelerometer was beside the first, but resting on a lead slab which had been placed on the fill. The response of channel No. 6, on the lead slab, varied from 3% smaller to 7% larger than the response of channel No. 3, which was resting directly on the fill.

On the concrete slab covering the upstream face of the dam two methods were used to mount the accelerometers. In one case the accelerometers were placed directly on the concrete by extending the leveling screws sufficiently to level the instruments on the 3:1 slope. The response of channel No. 3 varied from 5% smaller to 0.3% larger than the response of channel No. 6, when the two accelerometers were placed side by side, mounted in this manner. In the other case, wedge-shaped wood blocks were placed on the concrete face of the dam, held only by friction, and the accelerometers were placed on the level top surfaces of these blocks. In a test at one frequency only, the response of the accelerometer on the wedge was found to be the same as the response of the accelerometer with extended leveling screws.

Under the best of field conditions, at Bouquet Dam and at other sites, it has been observed that occasionally individual points in resonance curves differ considerably from the values which would be indicated by adjacent points. The oscillograms from which the data for these points were taken do not appear unusual in any way, and it is certain that the frequency of the machines and the amplitude of the trace have been correctly measured. Although no study has been made to determine the reasons for these anomalies, it is believed that unpredictable changes in amplifier gain are probably responsible.

The accuracy of the phase measurements is in most cases probably within ± 15°. As mentioned previously, two machines showed relative phase variations over the range ± 8°. Phase measurements of the response of the dam were made relative to the pulse produced by only one machine. In most cases, each recorded phase angle represents the average of from four to eight phase measurements made on successive cycles. Figure 21(b) indicates the consistency among the measurements. Phase measurements were made relative to only the positive or the negative peak values of the oscillogram traces, not to both. If the traces had been unsymmetrical, different phase angles would have been obtained from opposite sides of the records. A few checks on the top and the bottom sides of smooth traces produced phase angles varying by only a few degrees. Where the records contained a considerable amount of harmonic content or noise, the traces were sketched in by eye, and amplitude and phase lag measurements were made from the sketches. All measurements were made with a scale divided 50 parts to the inch, tenths of divisions being estimated.

The data in Figure 20, which shows the phase lag characteristics of the two low frequency systems, were obtained by comparing the phase of the response of these systems with the phase of the response of a 100 cps system, when all of the instruments were mounted side by side on top of a conrete tower. The maximum deviation from the straight line in Figure 20 is 4°, giving some idea of the consistency of measurement on smooth records. Damping in the 100 cps system was not measured at this time, but it was known from previous experience with the equipment that the damping ratio was close to the value 0.65. It is seen in Figure 20 that the phase lag characteristic line, if extended, passes within 2° of the origin.

In spite of the comparisons of response indicated by different instruments, and in spite of the static calibrations of the accelerometers, the absolute accuracy of the measurements cannot be stated with certainty. All of the accelerometers used for the comparison measurements were similar in operating principle and were of the same manufacture, and the same amplifiers were used for all measurements. No other independently calibrated device of sufficient sensitivity was available for comparisons of amplitude and phase at the levels experienced at the dam.

Analytical Investigation of the Dam

An analytical investigation of the dam is being conducted at the present time. Because the work is not yet complete, the final report will not be issued until a later date, and only a brief summary of what has been accomplished so far is presented here. The investigation is being conducted by Mr. Gerald Frazier, a graduate student in Civil Engineering at Montana State College, as a part of his Master's Degree studies. The work is being financed by the National Science Foundation through a grant to investigate the application of the Holzer method for finding the natural frequencies of two-dimensional shear structures.

In the work which has been accomplished to date, the dam has been treated as a wedge of undamped elastic material which experiences only shearing distortions. No bending distortions and no distortions through the thickness of the dam have yet been considered. This simple model of the dam has been well presented by Ambraseys,(12), (13) and it was used later in Reference 1 in connection with the investigation of Dry Canyon Dam. The differential equation of motion of the shear wedge is of the second order in the space coordinates, and is similar to the equation describing vibrations of a membrane which tapers in thickness. Because of the irregularity of the cross sectional shape of the canyon, the problem is being treated numerically.

The numerical work which has been accomplished to date has been based on an application of the Holzer method to the case of two-dimensional shear structures, the principles for which appeared in Reference 1. It is planned later to solve the problem using the matrix approach, to make an analytical investigation of the thickness vibrations, and to consider bending as well as shearing distortions of the axial plane of the dam. Some early results of the analytical work are shown in Figure 24 and in Table 4. To obtain these results the dam was approximated by a grid, 18 spaces wide by 4 spaces high, of lumped masses connected by shear resistant springs. The shear wave velocity in the soil was assumed to be 1270 feet per second, and the walls of the canyon were assumed to be perfectly rigid.

The lowest four computed frequencies, shown in Table 4, are higher than the first four observed frequencies respectively by 11%, 16%, 19%, and 16%. It should be noted that the computed values of the frequencies are based on the value of the shear wave velocity which was measured, without any substantiation, at only one point in the dam. It is anticipated that the computed and the observed frequencies will be in closer agreement when the numerical work has been refined to account for the elasticity of the canyon walls.

The computed deformations of the crest in the lowest four mode shapes, shown in Figure 24, are seen to exhibit surprisingly good agreement with the mode shapes estimated from the field observations, shown in Figures 12 through 15. The good agreement is surprising in view of the facts that the exact values of the resonant frequencies were not known in the field, the resonant frequencies were closely spaced, and the excitation was concentrated at one point on the dam, making it impossible to excite mode shapes of a high degree of purity. A significant difference between the computed and the observed mode shapes occurs in the amplitudes of the lower portions of the dam relative to the amplitudes of the crest. The computed amplitudes on line C, relative to the amplitudes on the crest, are many times larger than the observed amplitudes. In the first mode the computed relative amplitudes on line C are three times larger, and in the second mode they are approximately 12 times larger than the observed values. Further investigation will be required to determine the reasons for these differences.

In Reference 1, an attempt was made to fit the theory of the shear wedge, with rigidly fixed rectangular boundaries, to the data which were obtained from the investigation of Dry Canyon Dam. Dry Canyon Dam consisted of a hydraulic fill with a compacted earth cap on the downstream face. It was founded on soil which extended for some 75 feet down to bedrock, and the abutments were not vertical faces of rock, but rather they were inclined, with layers of soil estimated from the plans to be about 12 feet thick on top of the rock. The dam did not taper uniformly in thickness from the base to the crest, but it was unsymmetrically stepped in cross section. The geometry and the boundary conditions of the dam were not well represented by the theoretical model, but at that time no more realistic analytical method was readily available. The dam was approximated for the analysis by a triangular wedge 65 feet high, with the top 5 feet removed, set in a rigid rectangular opening 485 feet long.

Two characteristics of the theory of the shear wedge in a rigid rectangular canyon indicated that the effective shear wave velocity in Dry Canyon Dam was between 300 and 350 feet per second. First, a value of 302 feet per second for the shear wave velocity resulted in the prediction of ten natural frequencies that showed surprisingly good agreement with the observed resonances. Second, the theory of the shear wedge with rectangular boundaries predicts that the spacing of the natural frequencies of a dam which is long compared to its height increases with frequency and eventually becomes almost uniform at higher frequencies. The spacing between the ninth and the tenth observed resonances of Dry Canyon Dam would indicate a shear wave velocity of 350 feet per second. The experimental data from Dry Canyon Dam were much fewer and of less reliability than the data which were obtained at Bouquet Dam, so a really critical examination of the agreement between the theory and the observations is not possible. It is believed, however, that a value of from 300 to 350 feet per second for the shear wave velocity is realistic.

It is informative to attempt to fit the theory of the shear wedge with rectangular boundaries to the data obtained from Bouquet Dam, although it is recognized that the canyon cross section is not rectangular, but rather it is strongly trapezoidal, almost triangular. Nevertheless, it is possible that if the canyon cross section is represented by a properly chosen equivalent rectangle, then a reasonably accurate value of the effective shear wave velocity might be obtained by fitting the shear-wedge theory to the lowest observed resonant frequency. This would mean that if the fundamental frequency and the density of an earth dam were known, a simple calculation might yield a reasonably accurate value of the shearing modulus.

If the length of an equivalent rectangle to approximate the canyon opening is assumed to be the average of the lengths of the crest and the base of the dam, 675 feet, and the height of the equivalent rectangle is assumed to be the full height of the central portion of the dam, 207 feet, then, referring to Reference 12, the lowest five frequencies predicted by the shear-wedge theory are 2.23 cps, 2.70 cps, 3.34 cps, 4.07 cps, and 4.80 cps, if the shear wave velocity is assumed to be 1155 feet per second. These frequencies are higher than the observed frequencies by 0%, 0.7%, 6.7%, 12.4%, and 24% respectively. On the other hand, if the results of the digital computer work, which recognized the trapezoidal nature of the canyon cross section, are reduced so that the computed fundamental frequency agrees with the observed fundamental frequency, a shear wave velocity of 1142 feet per second is indicated, and the lowest five frequencies are computed to be 2.23 cps, 2.81 cps, 3.34 cps, 3.77 cps, and 4.21 cps. These frequencies are greater than the observed frequencies by 0%, 4.9%, 6.7%, 4.1%, and 8.8% respectively.

Thus it is seen that although the simple rectangular approximation of the canyon yields results which are in slightly better agreement with the observations at the lowest frequencies and which are in considerably poorer agreement at the higher frequencies, than the results of the numerical work which recognized the trapezoidal shape of the canyon opening, both methods indicate essentially the same value for the shear wave velocity, around 1150 feet per second. Although the computed value of the shear wave velocity will change somewhat when foundation compliance and dilatational deformations are included, it is not expected that the change will be large. It appears that if the fundamental frequency of an earth dam is known, the effective shear wave velocity can be determined with fair accuracy by the simple rectangular approximation of the canyon cross section. The values of the shear wave velocities computed by this simple approximation for Dry Canyon Dam and for Bouquet Canyon Dam, 325 and 1150 feet per second respectively, indicate a very significant difference in the natures of the two fills.

Conclusions and Recommendations

The dynamic investigation of Bouquet Dam has added considerable evidence to the proposition that, at low stress levels, the general nature of the behavior of an earth dam is in agreement with the behavior which would be predicted for a viscous damped elastic solid of the same size and shape. The supposition of the existence of resonant frequencies, mode shapes, and modal viscous damping constants does not disagree in any major respect with the observations of the dam's behavior. It is reasonable to assume that some aspects of the response of the dam to the excitation of a small earthquake or to the accelerations in the initial portion of a large earthquake could be rather accurately predicted by the theory of linear vibrations, making use of the frequencies, the mode shapes, and the damping constants which were determined by the investigation. When theory has been refined to successfully predict the observed behavior of Bouquet Dam, presumably the same aspects of linear behavior of other earth dams could be predicted from a knowledge of their dimensions, densities, and elastic moduli.

Other properties of Bouquet Dam, which are of equal significance and which would be intimately related to the failure of an earth dam in a strong earthquake, were not observed in sufficient detail in the investigation. Very little was learned of thickness vibrations of the dam, which would influence slumping of the fill, and nothing was learned of the behavior of the dam at large stresses. Knowledge of both of these phenomena would be required to predict the behavior of the dam in a large earthquake.

The chief contributions of this investigation have been the confirmation of elastic behavior of a huge mass of soil at low stress levels, the presentation of natural frequencies, mode shapes, and values of the damping constants at low stress levels in an earth fill, and the demonstration of equipment and procedures for conducting dynamic investigations of large structures. It is felt that the experimental evidence presented here is in sufficient detail and of sufficient reliability to make a contribution to the body of knowledge relating to earth dams, and to the art of making dynamic investigations of dams.

The report has been devoted primarily to the experimental aspects of the study of Bouquet Dam. Because the theoretical work has just been started, only a brief presentation was made to give some idea of what might be expected from theory. Some additional analysis of the experimental data remains yet to be accomplished, and a vigorous effort is now called for to develop a theory of the behavior of earth dams which will predict all of the frequencies and mode shapes which were observed in the field. Both of these activities are proceeding at the present time.

Much experimental work on earth dams remains yet to be carried out. A simple, economical, and reliable method of determining shear and dilatational wave velocities in earth fills needs to be developed. Thickness vibrations need to be studied on dams which have both faces accessible over the full height. Measurements of stresses and strains in dams undergoing dynamic excitation are called for, now that the general nature of the dynamic behavior of dams is known. These measurements will indeed be a challenge to the experimenter. Finally, the ultimate strength properties of earth dams must be investigated and theories must be developed to predict their behavior in the nonlinear range. The most likely avenues of approach to this difficult problem appear to be tests on small samples of soil at high stresses, detailed investigations of models of earth dams loaded to failure, and, hopefully, one or more tests of a full size dam or a large model of a dam located close to the epicenter of an underground atomic explosion.

Author's Acknowledgment

In addition to the persons and agencies acknowledged in the Preface, the author wishes to express his appreciation to Professors G. W. Housner and D. E. Hudson for their general guidance and many helpful consultations, and for providing the opportunity for the investigation to be conducted. It is also appropriate to call attention to the vital role played in the investigation by the vibration exciting equipment. Without the precise control and the excellent operating characteristics of the vibration exciters, the experimental observations could not have been made in such detail. The development of the vibration exciters has been a significant contribution to experimental structural dynamics. Appreciation is expressed to all of the persons who contributed to the design and the construction of the machines.

References

1. Keightley, W. O., "Vibration Tests of Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California, (July, 1963).

2. Yokoo, Y., Ishizaki, H., and Hatakayama, N., "Vibration Characteristics of Earth Dams," Trans. Japan Society of Civil Engr., no. 49, (1957).

3. Hatanaka, M., "Fundamental Considerations on the Earthquake Resistant Properties of the Earth Dam," Disaster Prevention Research Institute, Bulletin no. 11, Kyoto, Japan, (December, 1955).

4. Heiland, C. A., "Geophysical Investigations Concerning the Seismic Resistance of Earth Dams," Tech. Publ. 1054, American Institute of Mining and Metallurgical Engineers, (1939).

5. Proctor, R. R., "Fundamental Principles of Soil Compaction," Engineering News-Record, (August 31, 1933). Three companion articles followed in the issues of September 7, 21, and 28, 1933.

6. Van Norman, H. A., 'Bouquet Canyon Reservoir Dam," Civil Engineering, vol. 4, no. 8, (August, 1934), pp. 393-7.

7. Hudson, D. E., "A New Vibration Exciter for Dynamic Test of Full-Scale Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California, (September, 1961).

8. Hudson, D. E., "Synchronized Vibration Generators for Dynamic Tests of Full-Scale Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California, (November, 1962).

9. Keightley, W. O., Housner, G. W., and Hudson, D. E., "Vibration Tests of the Encino Dam Intake Tower," Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena California, (July, 1961).

10. Nielsen, N. N., "Dynamic Response of Multistory Buildings," Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California, (June, 1964).

11. Hudson, D. E., "Resonance Testing of Full-Scale Structures," Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, (June, 1964), pp. 1-19.

12. Ambraseys, N. N., "On the Shear Response of a Two-Dimensional Truncated Wedge Subjected to an Arbitrary Disturbance," Bulletin of the Seismological Society of America, (January, 1960), pp. 45-56.

13. Ambraseys, N. N., "The Seismic Stability of Earth Dams," Proceedings of the Second World Conference on Earthquake Engineering, Tokyo, Japan, (1960), pp. 1345-1363.

List of Tables

FREQUENCIES OF OBSERVED MAXIMA IN THE RESONANCE CURVES OF BOUQUET RESERVOIR DAM NO. 1

Sta	7+75 Crest	7+75 Line B	7+75 Line C	7+75 At Waterline	7+75 Opposite Waterline	4+05 Crest	10+52 Crest	10+52 Line B	10+52 Line C	10+00 At Waterline	10+00 Opposite Waterline	12+00 Crest	6+00 Crest	6+00 Line B
	2.22** cps	2.23**	2.25*	2.22**	2.23**	2.25*	2.23**	2.23**	2.23*			2.23**	2.25*	2.25*
						2.65*	2.68**	2.70*	2.72	2.68*	2.68*	2.70*	2.63*	2.60*
	3.13*	3.23		3.17*	3.18*	3.18*	3.13**	3.12*		3.10	3.10	3.13*	3.15*	3.17*
	3.43	3.53	3.53*	3.47		3.58*	3.63*	3.63*	3.53		3.67	3.62*		3.60*
	3.83			3.87						3.90		3.90		
	4.10			4.10				4.03*	4.03		3.97			
		4.63		4.47	4.43*	4.52**	4.53*	4.60		4.50*	4.50*	4.55*	4.48*	4.53*
		5.10	5.10	4.88			5.10*	5.13	4.93					5.03*
	5.33					5.35			5.27		5.28	5.25*		
	5.63*			5.70*	5.73*	5.73*					5.77	5.78*	5.57	5.50
								5.93						
	6.53*					6.53*								
	7.63													

** - most reliable data

* - less reliable

No asterisk - least reliable

TABLE 1

TABLE 2

FREQUENCIES OF RESONANCES OBSERVED ON THE CREST OF BOUQUET DAM

Lowest Value	Most Probable Value	Highest Value	Number of Observations	Difference Between Most Probable Values	
2.22 cps	2.23	2.25	5		
				0.45 cps	
2.63	2.68	2.70	4		
				0.45	
3.13	3.13	3.18	5		
				0.49	
3.43	3.62	3.63	4		
				0.25	
3.83	3.87	3.90	2		0.48
				0.23	
4.10	4.10	4.10	1		
				0.42	
4.48	4.52	4.55	4		0.50 average
				0.58	
5.10	5.10	5.10	1		
				0.20	
5.25	5.30	5.35	3		
				0.48	0.48 average
5.57	5.78	5.78	4		
				0.75	
6.53	6.53	6.53	2		
				1.10	
7.63	7.63	7.63	1		

Table 3

Modal Damping Constants Estimated From the Widths of Resonance Peaks

Bouquet Canyon Reservoir Dam No. 1

Frequency of Resonance	Station on Dam	Fraction of Critical Damping
2.23 cps	7 + 75, crest	0.043
	7 + 75, line B	0.041
	7 + 75, line C	0.043
	10 + 52, crest	0.040
	10 + 52, line B	0.040
	10 + 52, line C	0.043
	12 + 00, crest	0.042
2.68 cps	10 + 52, crest	0.035 (resonance peak sketched)
3.13 cps	7 + 75, crest	0.029
	10 + 52, crest	0.035 (resonance peak sketched)
	12 + 00, crest	0.031
	6 + 00, crest	0.032
	6 + 00, line B	0.031
3.62 cps	4 + 05, crest	0.034
	10 + 52, crest	0.028
4.52 cps	4 + 05, crest	0.047
	10 + 52, crest	0.045 (resonance peak sketched)
	12 + 00, crest	0.040
	6 + 00, crest	0.037
	6 + 00, line B	0.037
5.10 cps	10 + 52, crest	0.057 (resonance peak sketched)
5.30 cps	12 + 00, crest	0.059 (resonance peak sketched)
6.53 cps	7 + 75, crest	0.058
	4 + 05, crest	0.054

Table 4

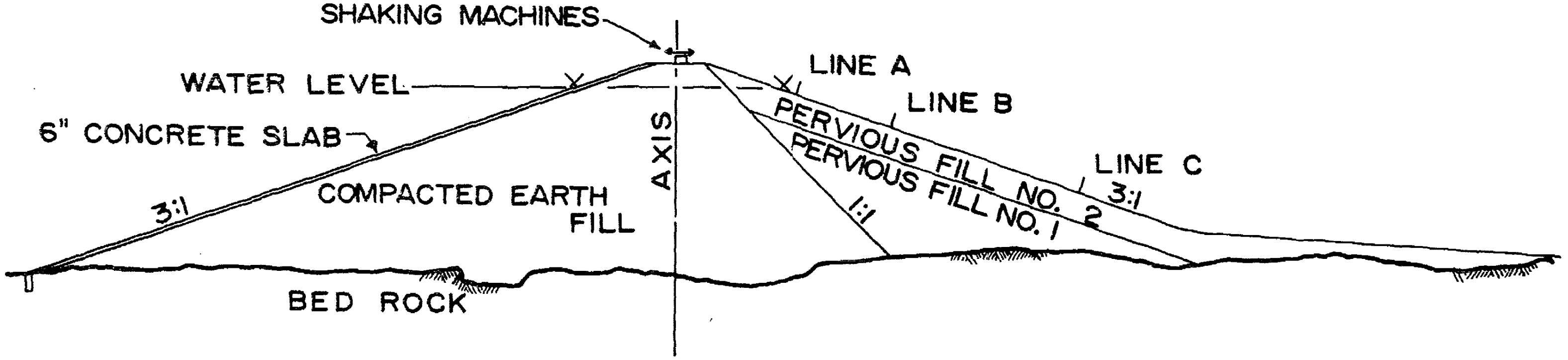
Observed and Computed Natural Frequencies of Bouquet Canyon Dam

Observed	Computed	Percent Error
2.23 cps	2.48	11%
2.68	3.12	16%
3.13	3.71	19%
3.62	4.19	16%
3.87	4.68	21%
4.10	5.12	25%

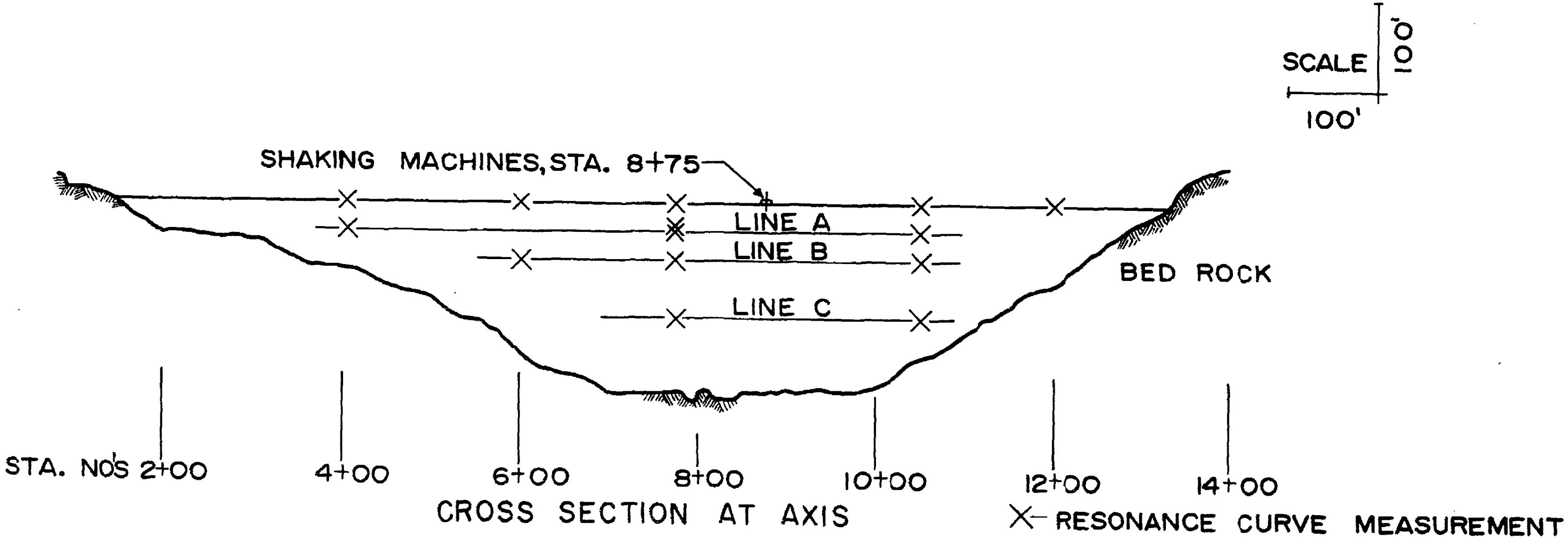
List of Illustrations

A GENERAL VIEW OF BOUQUET CANYON RESERVOIR DAM NO. 1

FIGURE 1



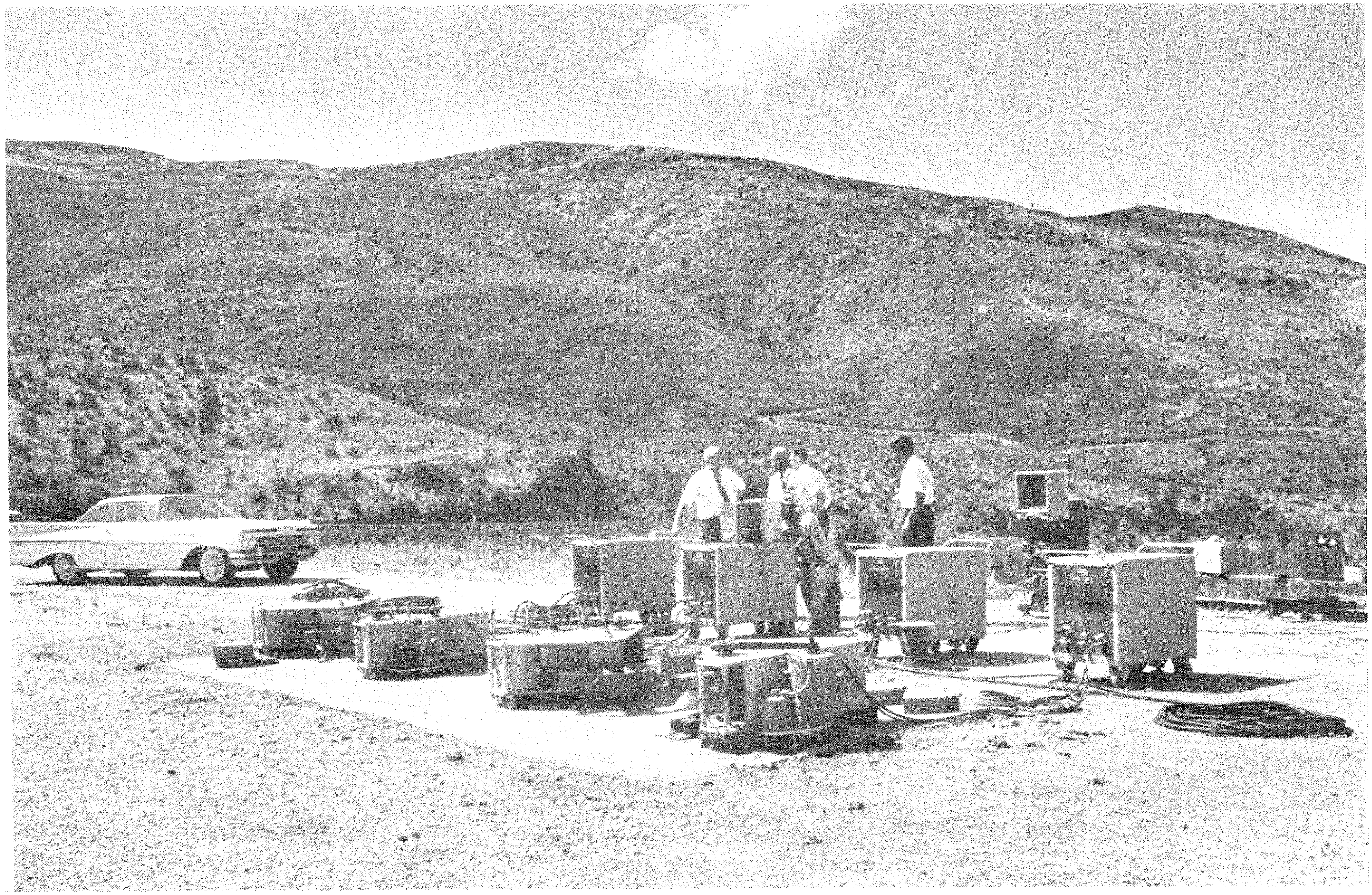
CROSS SECTION AT STA. 8+50



CROSS SECTION AT AXIS

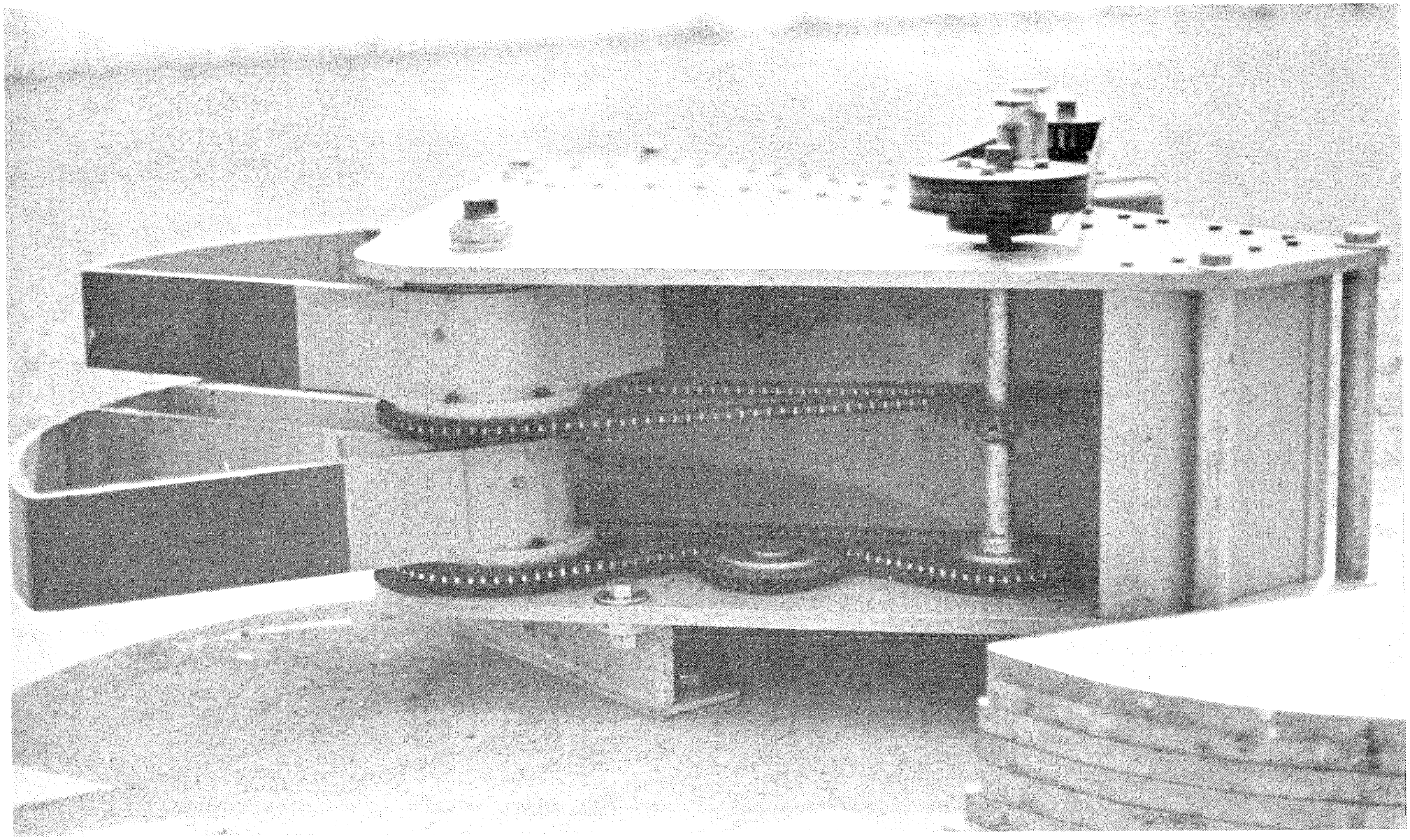
BOUQUET CANYON RESERVOIR DAM NO. 1

FIGURE 2



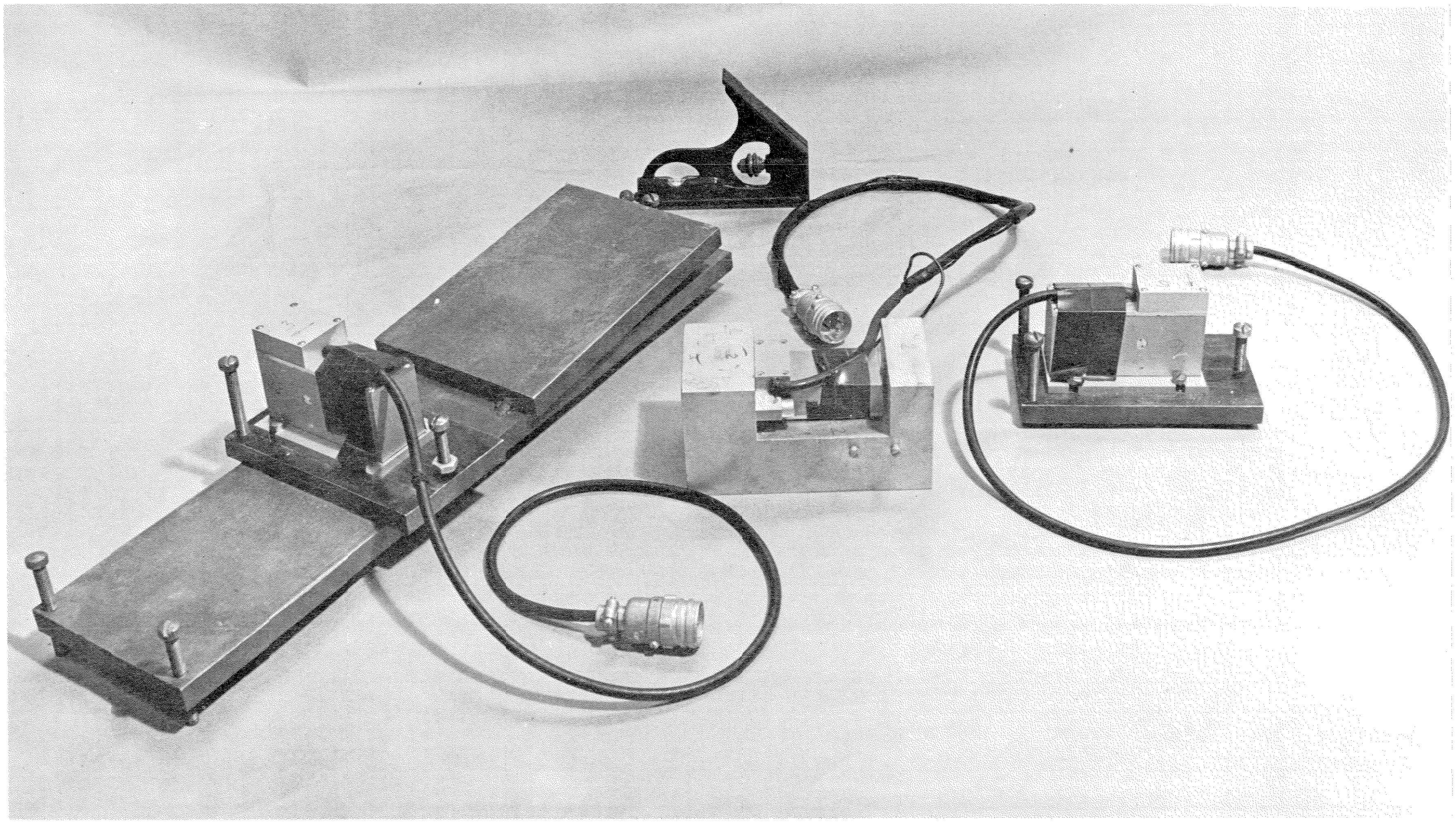
GENERAL VIEW OF THE VIBRATION EXCITERS ON BOUQUET DAM

FIGURE 3



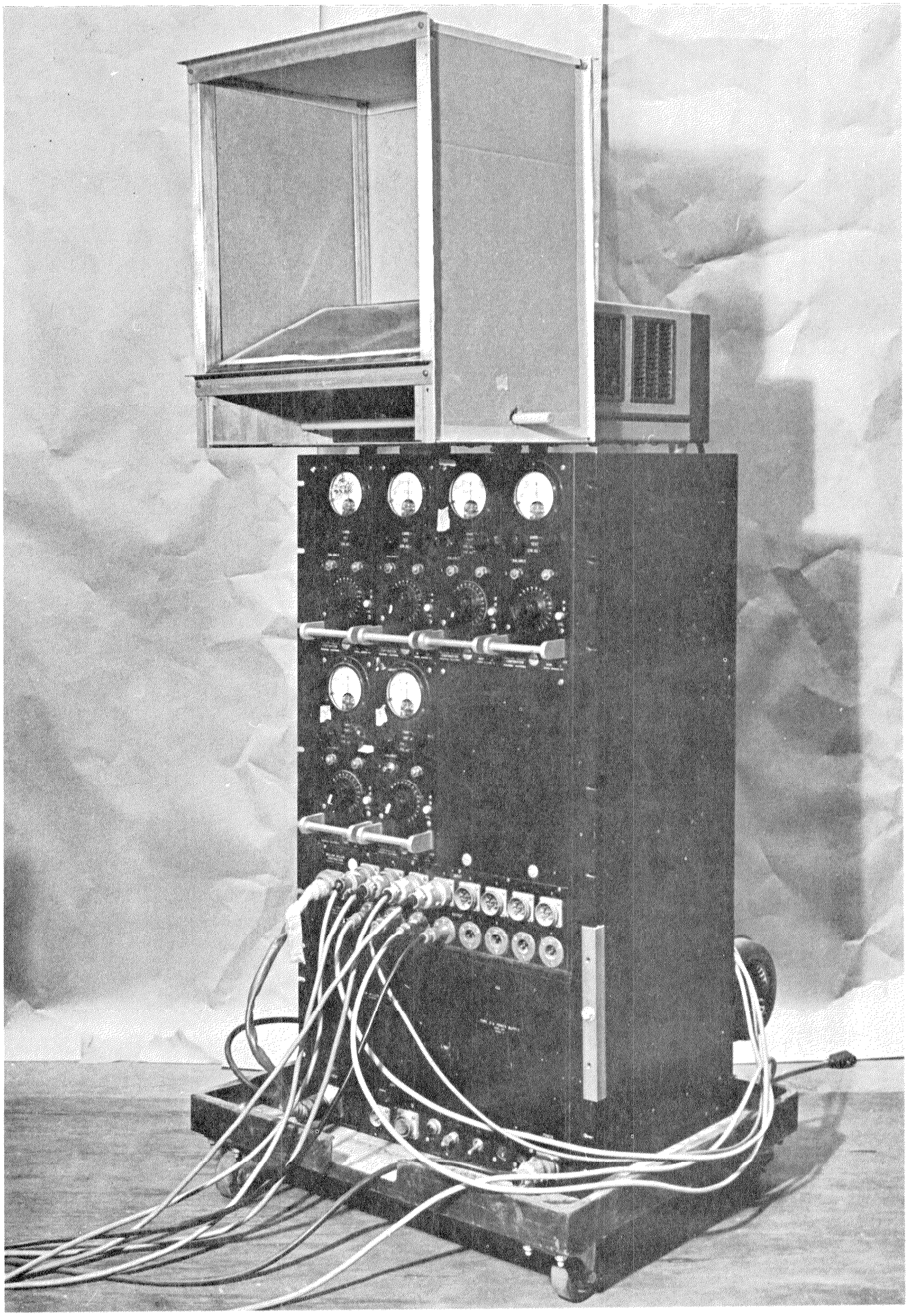
CLOSEUP VIEW OF A VIBRATION EXCITER

FIGURE 4



ACCELEROMETERS AND CALIBRATION FIXTURE

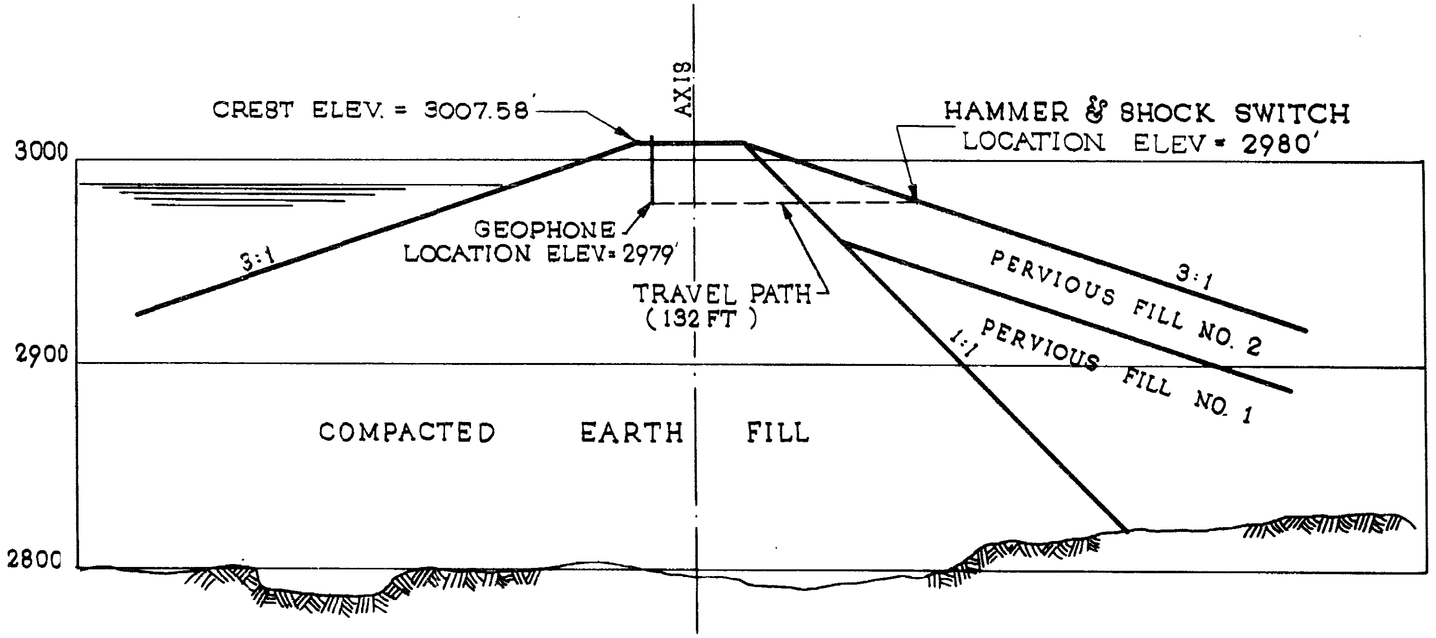
FIGURE 5



AMPLIFIERS AND OSCILLOGRAPH

FIGURE 6

BOUQUET CANYON RESERVOIR
DAM NO. 1
SEISMIC TIMER TESTS OF JUNE 28, 1963
P AND S WAVE VELOCITIES



CROSS-SECTION AT STA. 7+95

WAVE TYPE	TRAVEL TIME (MILLISEC.)	PATH LENGTH (FEET)	VELOCITY FEET/SEC.
P	63	132	2090
S	104	132	1270

FIGURE 7(a)

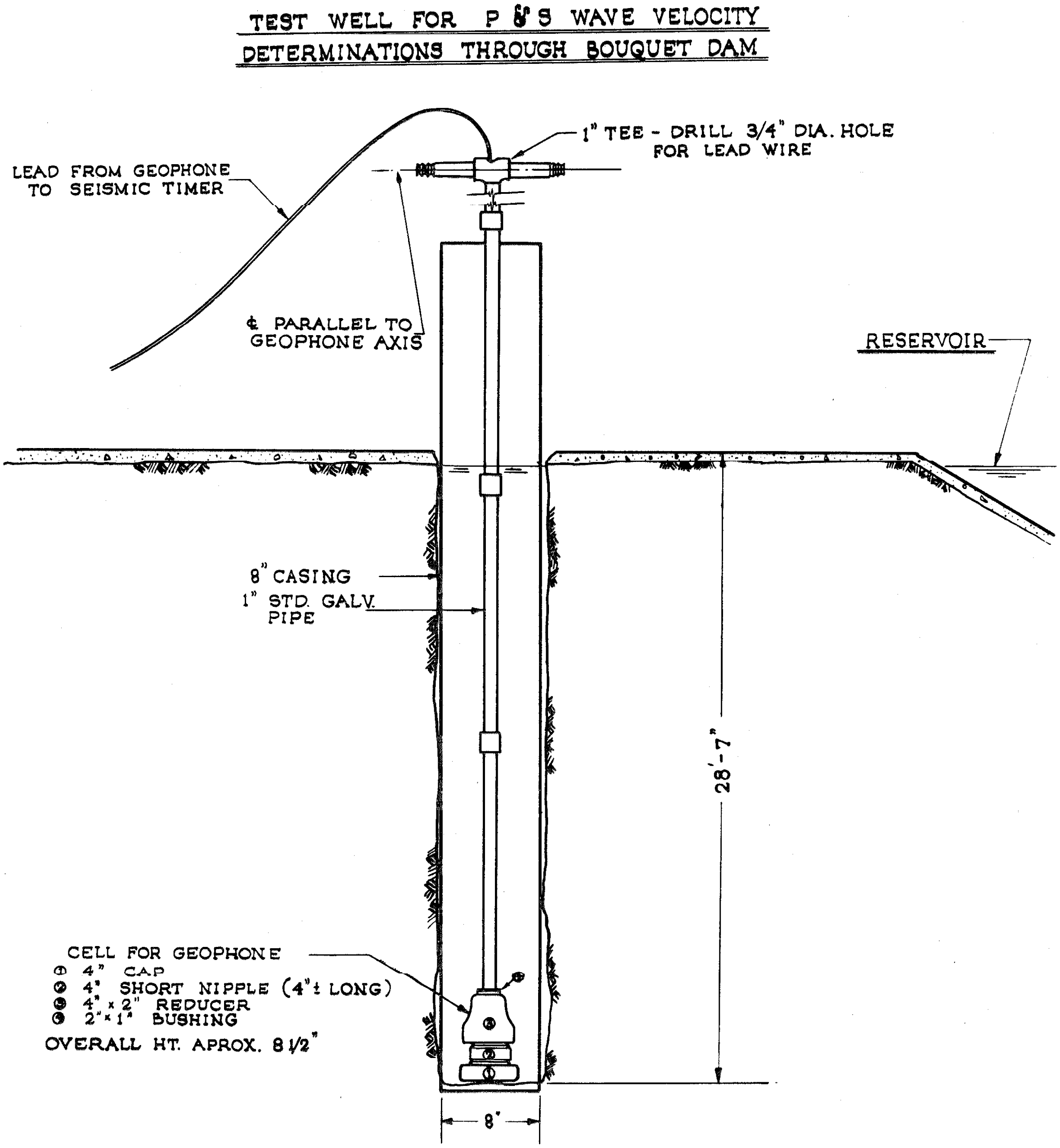

TEST WELL FOR P & S WAVE VELOCITY
DETERMINATIONS THROUGH BOUQUET DAM
LEAD FROM GEOPHONE TO SEISMIC TIMER
1" TEE - DRILL 3/4" DIA. HOLE FOR LEAD WIRE
℄ PARALLEL TO GEOPHONE AXIS
RESERVOIR
8" CASING
1" STD. GALV. PIPE
28'-7"
CELL FOR GEOPHONE
① 4" CAP
② 4" SHORT NIPPLE (4"± LONG)
③ 4" x 2" REDUCER
④ 2" x 1" BUSHING
OVERALL HT. APROX. 8 1/2"
①
②
③
④
8"

FIGURE 7(b)

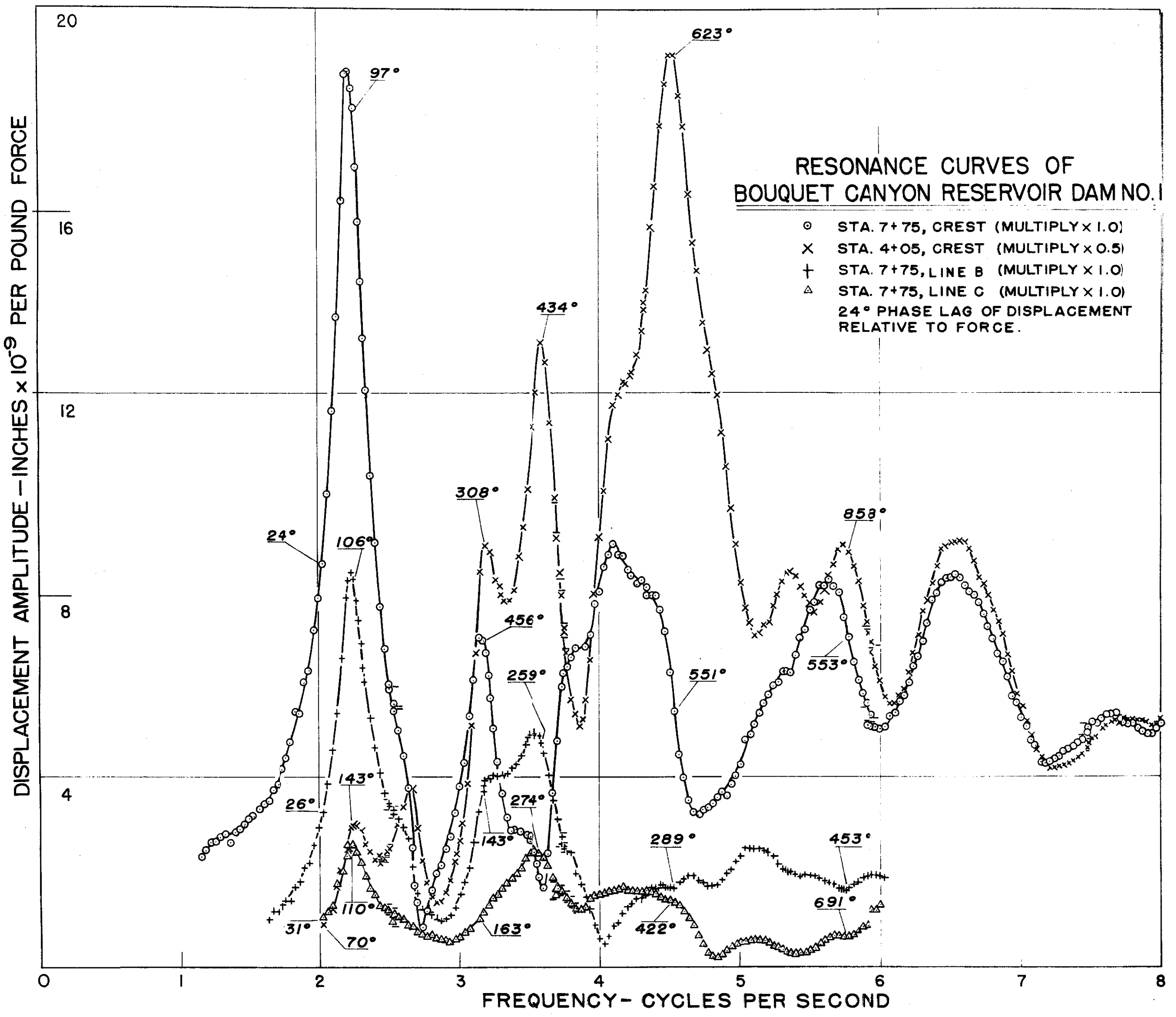

RESONANCE CURVES OF
BOUQUET CANYON RESERVOIR DAM NO. I
⊙ STA. 7+75, CREST (MULTIPLY × 1.0)
× STA. 4+05, CREST (MULTIPLY × 0.5)
+ STA. 7+75, LINE B (MULTIPLY × 1.0)
△ STA. 7+75, LINE C (MULTIPLY × 1.0)
24° PHASE LAG OF DISPLACEMENT RELATIVE TO FORCE.
DISPLACEMENT AMPLITUDE — INCHES × 10^{-9} PER POUND FORCE
FREQUENCY - CYCLES PER SECOND
0
1
2
3
4
5
6
7
8
4
8
12
16
20
97°
24°
106°
143°
26°
31°
110°
70°
308°
434°
456°
259°
274°
143°
163°
623°
551°
289°
422°
858°
553°
453°
691°

FIGURE 8

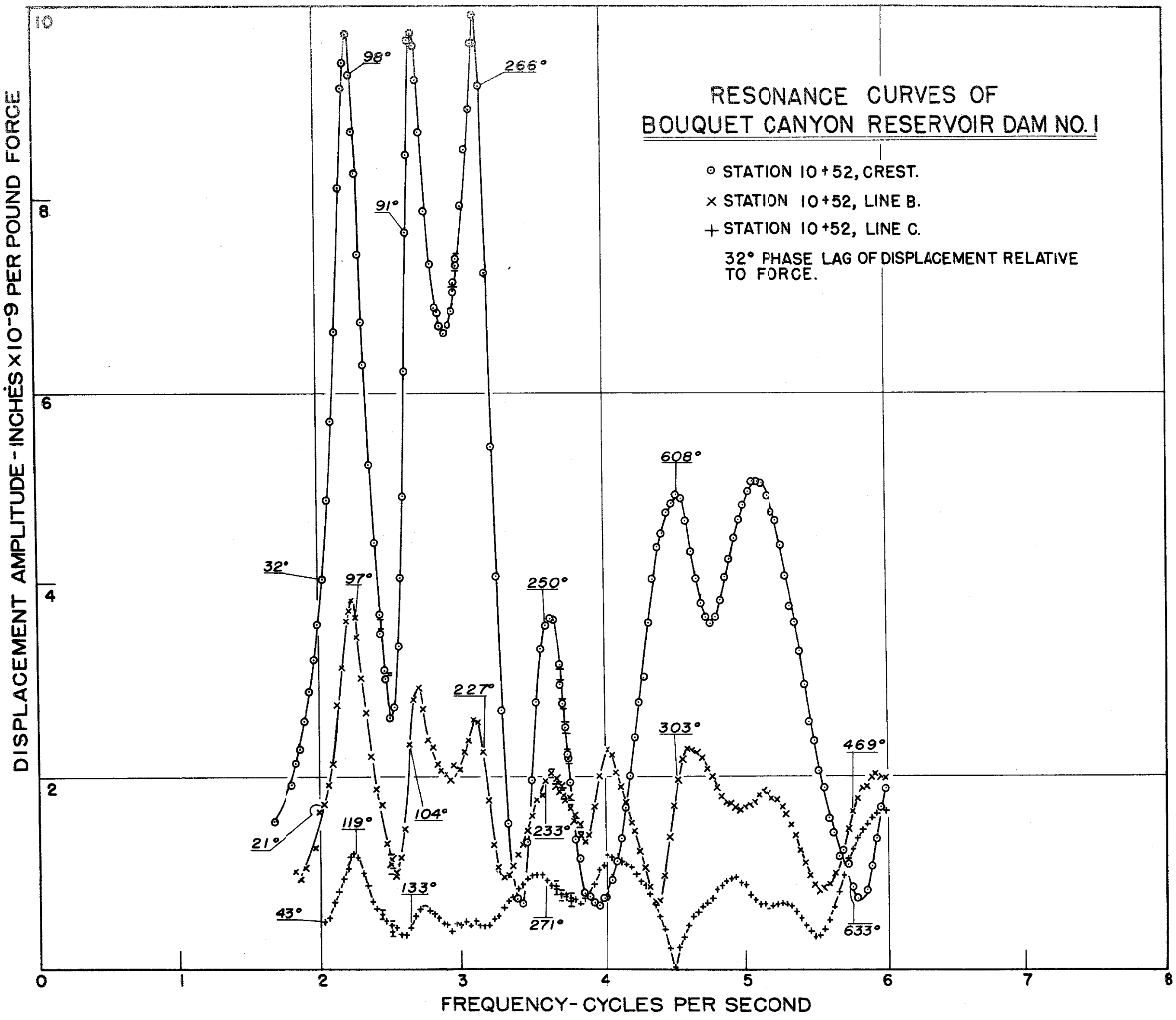

RESONANCE CURVES OF
BOUQUET CANYON RESERVOIR DAM NO. I
○ STATION 10+52, CREST.
× STATION 10+52, LINE B.
+ STATION 10+52, LINE C.
32° PHASE LAG OF DISPLACEMENT RELATIVE TO FORCE.
DISPLACEMENT AMPLITUDE - INCHES × 10⁻⁹ PER POUND FORCE
FREQUENCY - CYCLES PER SECOND
0
1
2
3
4
5
6
7
8
2
4
6
8
10
98°
91°
266°
32°
97°
21°
119°
43°
104°
133°
227°
250°
233°
271°
608°
303°
469°
633°

FIGURE 9

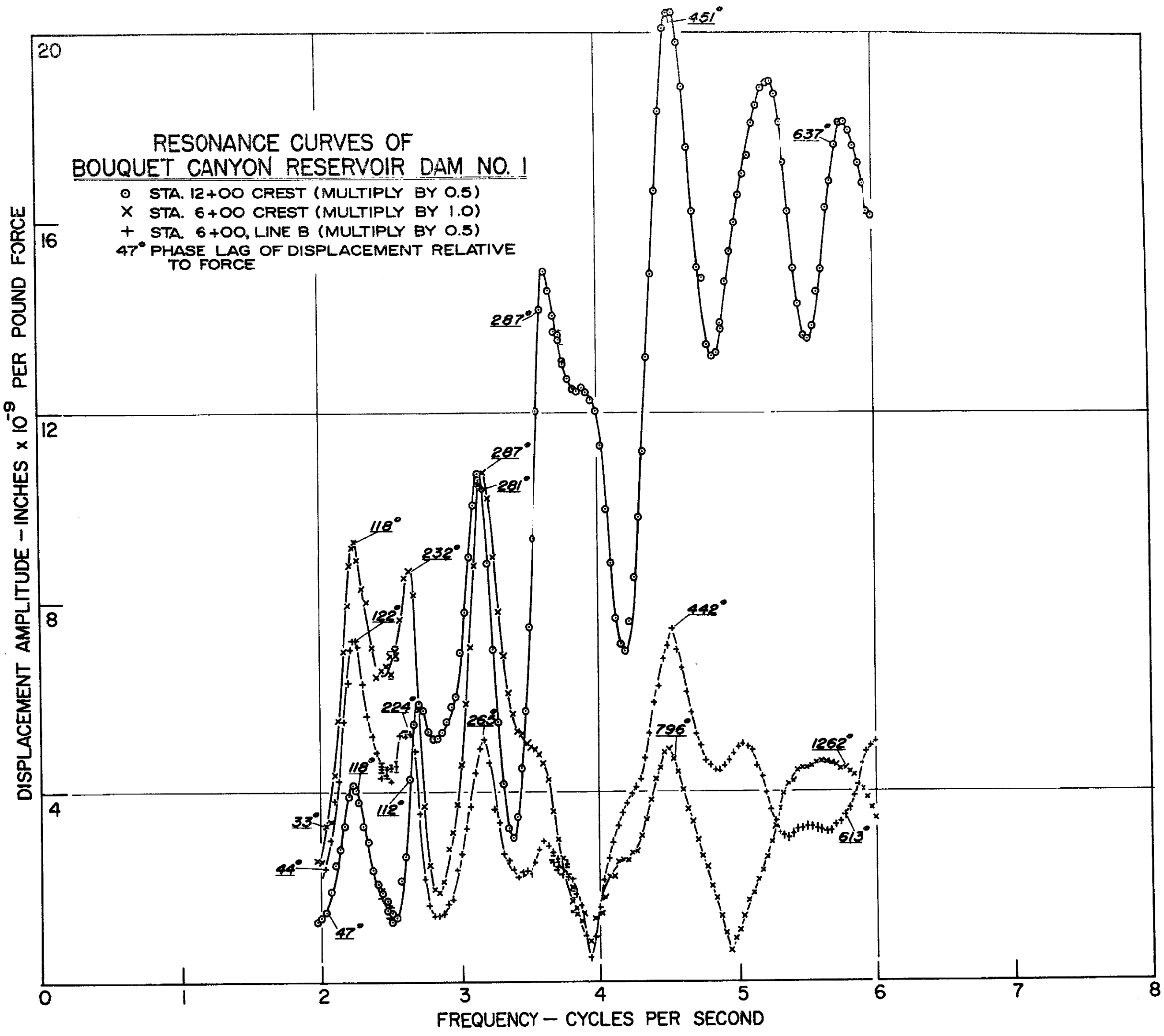

RESONANCE CURVES OF
BOUQUET CANYON RESERVOIR DAM NO. 1
○ STA. 12+00 CREST (MULTIPLY BY 0.5)
× STA. 6+00 CREST (MULTIPLY BY 1.0)
+ STA. 6+00, LINE B (MULTIPLY BY 0.5)
47° PHASE LAG OF DISPLACEMENT RELATIVE TO FORCE
DISPLACEMENT AMPLITUDE – INCHES x 10^{-9} PER POUND FORCE
FREQUENCY – CYCLES PER SECOND
0
1
2
3
4
5
6
7
8
4
8
12
16
20
451°
637°
287°
287°
281°
118°
232°
122°
224°
263°
118°
112°
33°
44°
47°
442°
796°
1262°
613°

FIGURE 10

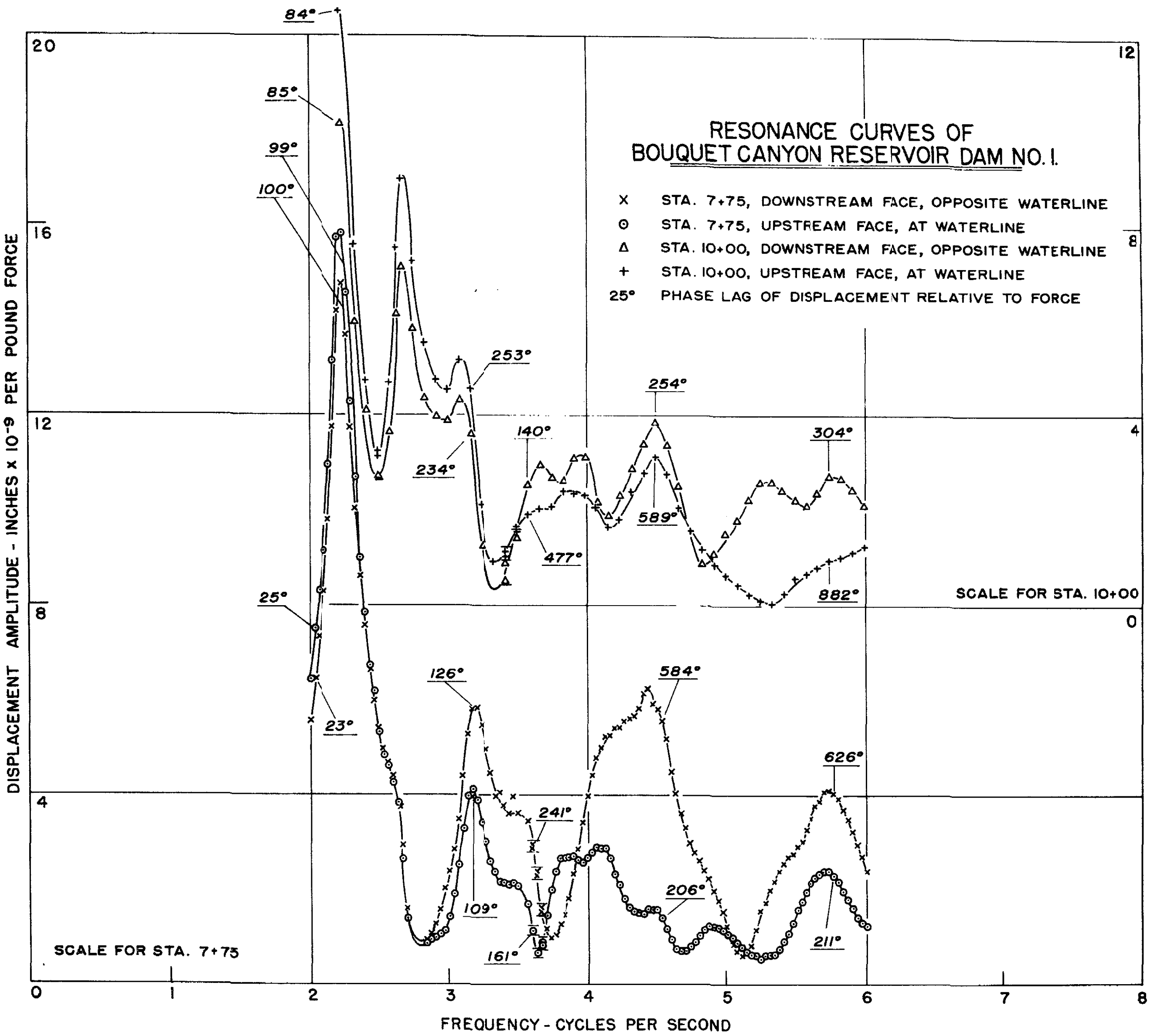
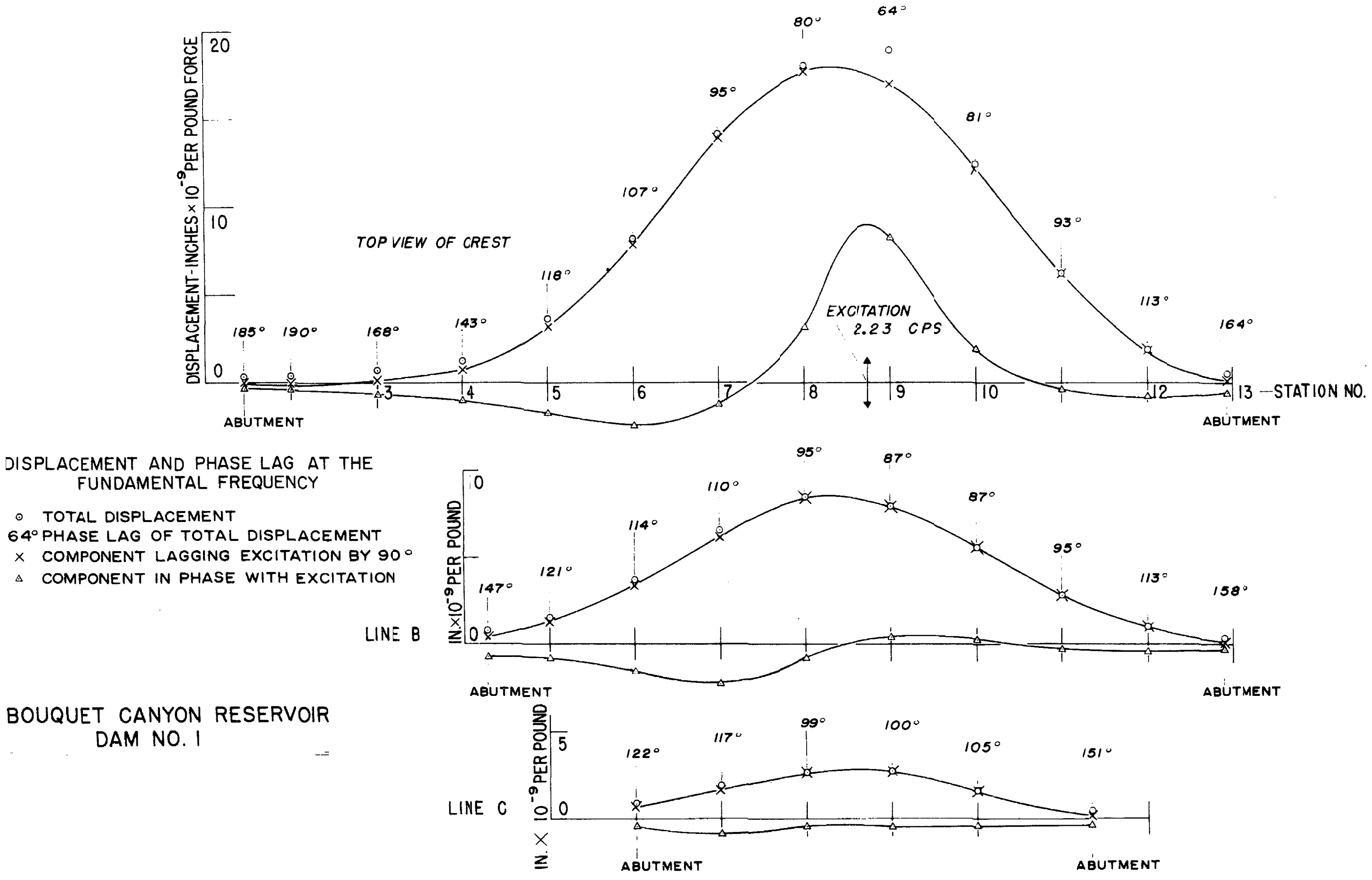

RESONANCE CURVES OF
BOUQUET CANYON RESERVOIR DAM NO. 1.
× STA. 7+75, DOWNSTREAM FACE, OPPOSITE WATERLINE
⊙ STA. 7+75, UPSTREAM FACE, AT WATERLINE
Δ STA. 10+00, DOWNSTREAM FACE, OPPOSITE WATERLINE
+ STA. 10+00, UPSTREAM FACE, AT WATERLINE
25° PHASE LAG OF DISPLACEMENT RELATIVE TO FORCE
84°
85°
99°
100°
25°
23°
253°
234°
140°
477°
254°
589°
304°
882°
126°
109°
241°
161°
584°
206°
626°
211°
SCALE FOR STA. 10+00
SCALE FOR STA. 7+75
DISPLACEMENT AMPLITUDE - INCHES x 10⁻⁹ PER POUND FORCE
FREQUENCY - CYCLES PER SECOND
20
16
12
8
4
0
12
8
4
0
1
2
3
4
5
6
7
8

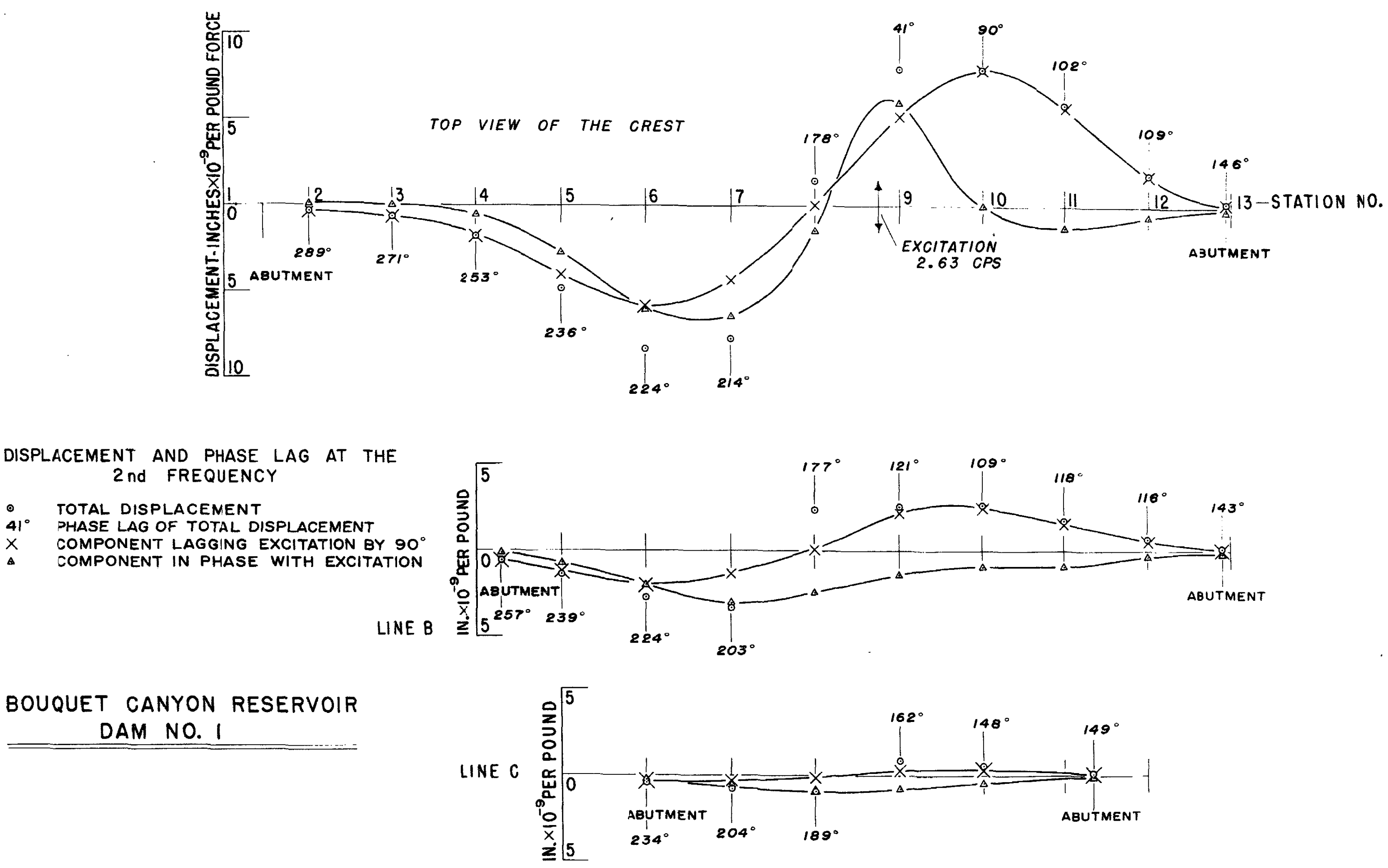
FIGURE 11



DISPLACEMENT AND PHASE LAG AT THE FUNDAMENTAL FREQUENCY

BOUQUET CANYON RESERVOIR
DAM NO. 1

FIGURE 12



DISPLACEMENT AND PHASE LAG AT THE
2nd FREQUENCY

⊙	TOTAL DISPLACEMENT
41°	PHASE LAG OF TOTAL DISPLACEMENT
×	COMPONENT LAGGING EXCITATION BY 90°
▲	COMPONENT IN PHASE WITH EXCITATION

BOUQUET CANYON RESERVOIR
DAM NO. I

FIGURE 13

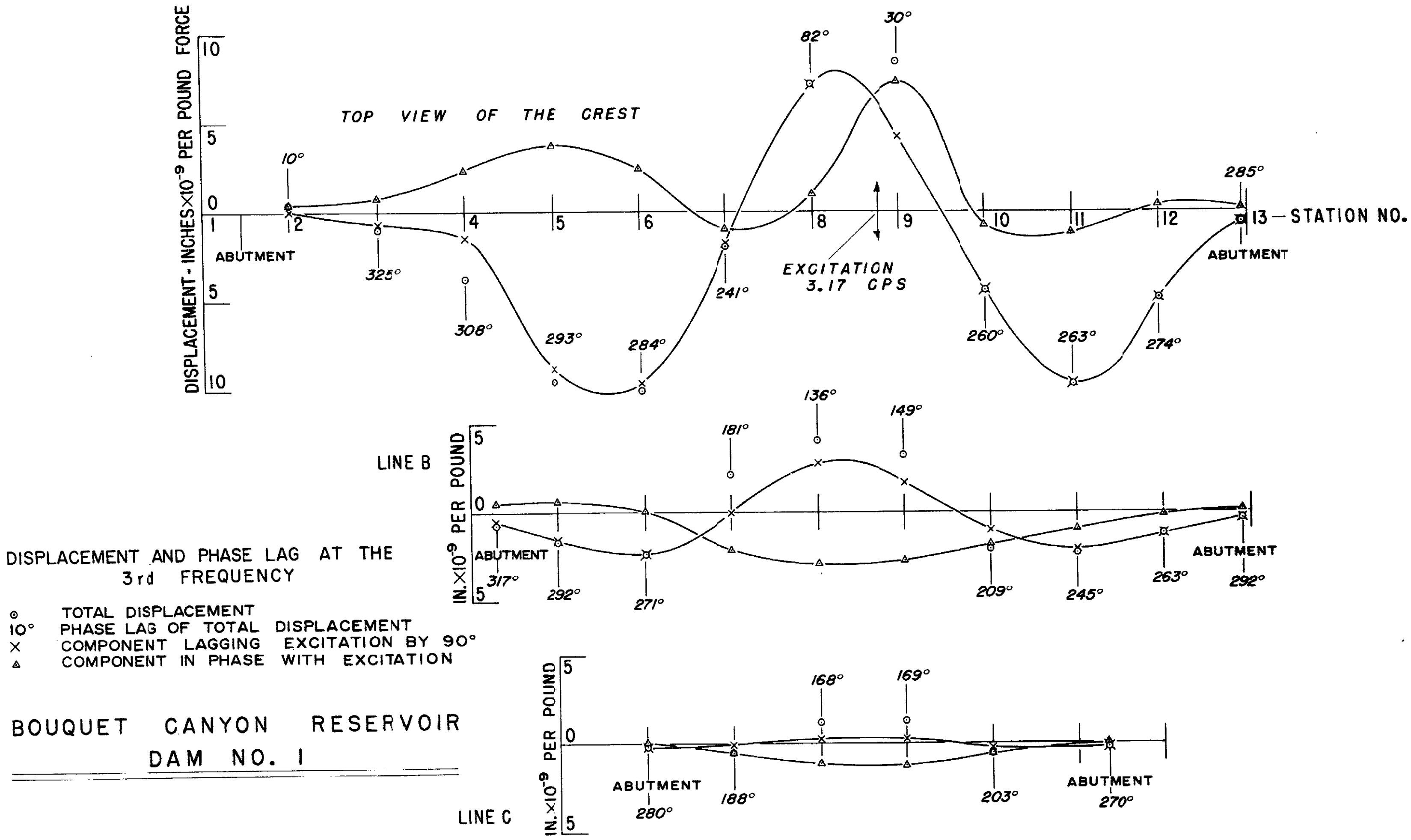
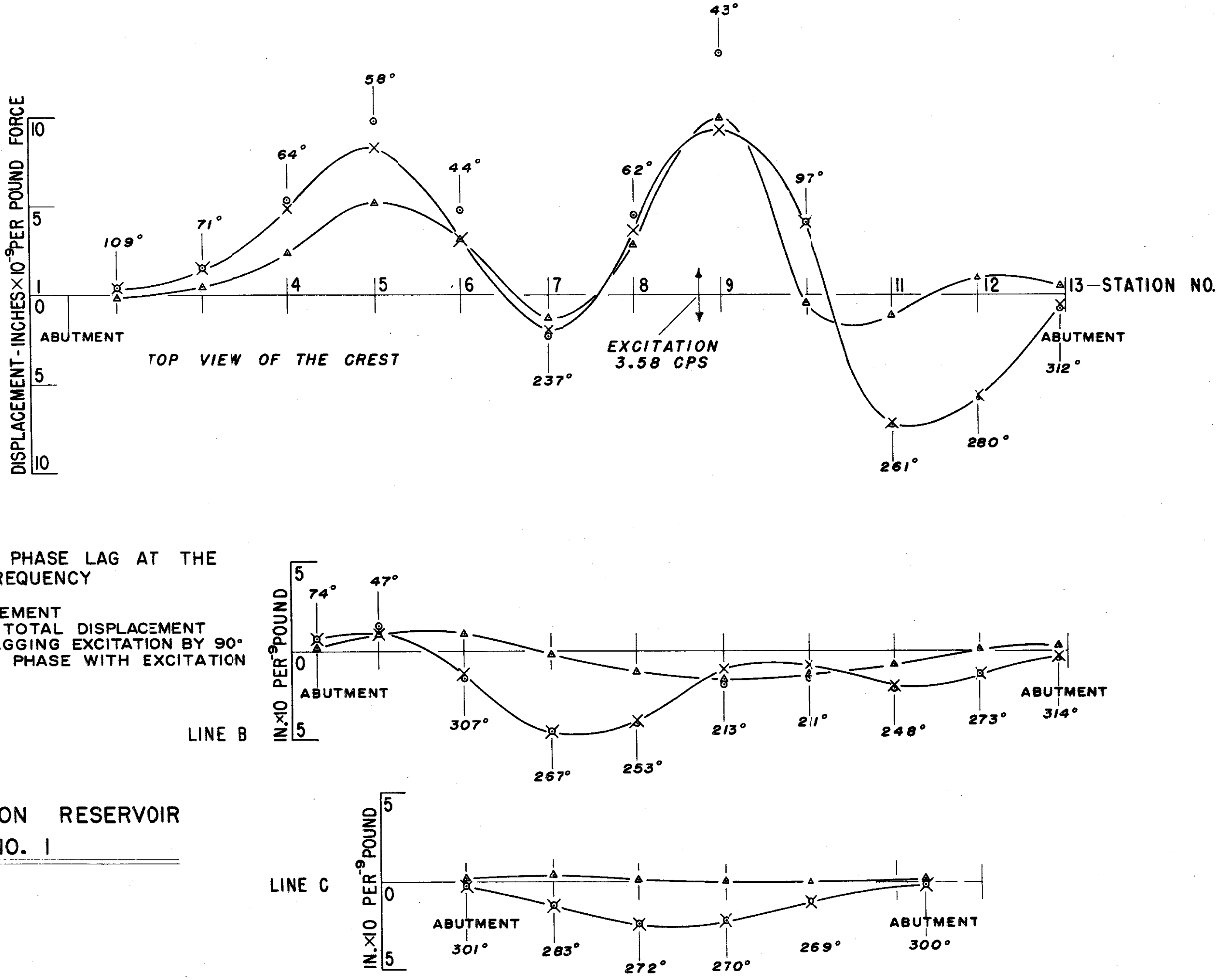

DISPLACEMENT - INCHES×10^-9 PER POUND FORCE
10
5
0
5
10
TOP VIEW OF THE CREST
1
2
4
5
6
8
9
10
11
12
13 — STATION NO.
ABUTMENT
ABUTMENT
10°
325°
308°
293°
284°
241°
82°
30°
260°
263°
274°
285°
EXCITATION
3.17 CPS
LINE B
IN.×10^-9 PER POUND
5
0
5
ABUTMENT
317°
292°
271°
181°
136°
149°
209°
245°
263°
ABUTMENT
292°
DISPLACEMENT AND PHASE LAG AT THE
3rd FREQUENCY
⊙ TOTAL DISPLACEMENT
10° PHASE LAG OF TOTAL DISPLACEMENT
× COMPONENT LAGGING EXCITATION BY 90°
▵ COMPONENT IN PHASE WITH EXCITATION
BOUQUET CANYON RESERVOIR
DAM NO. 1
LINE C
IN.×10^-9 PER POUND
5
0
5
ABUTMENT
280°
188°
168°
169°
203°
ABUTMENT
270°

FIGURE 14



DISPLACEMENT AND PHASE LAG AT THE
4 th FREQUENCY

⊙	TOTAL DISPLACEMENT
64°	PHASE LAG OF TOTAL DISPLACEMENT
×	COMPONENT LAGGING EXCITATION BY 90°
△	COMPONENT IN PHASE WITH EXCITATION

BOUQUET CANYON RESERVOIR
DAM NO. 1

FIGURE 15

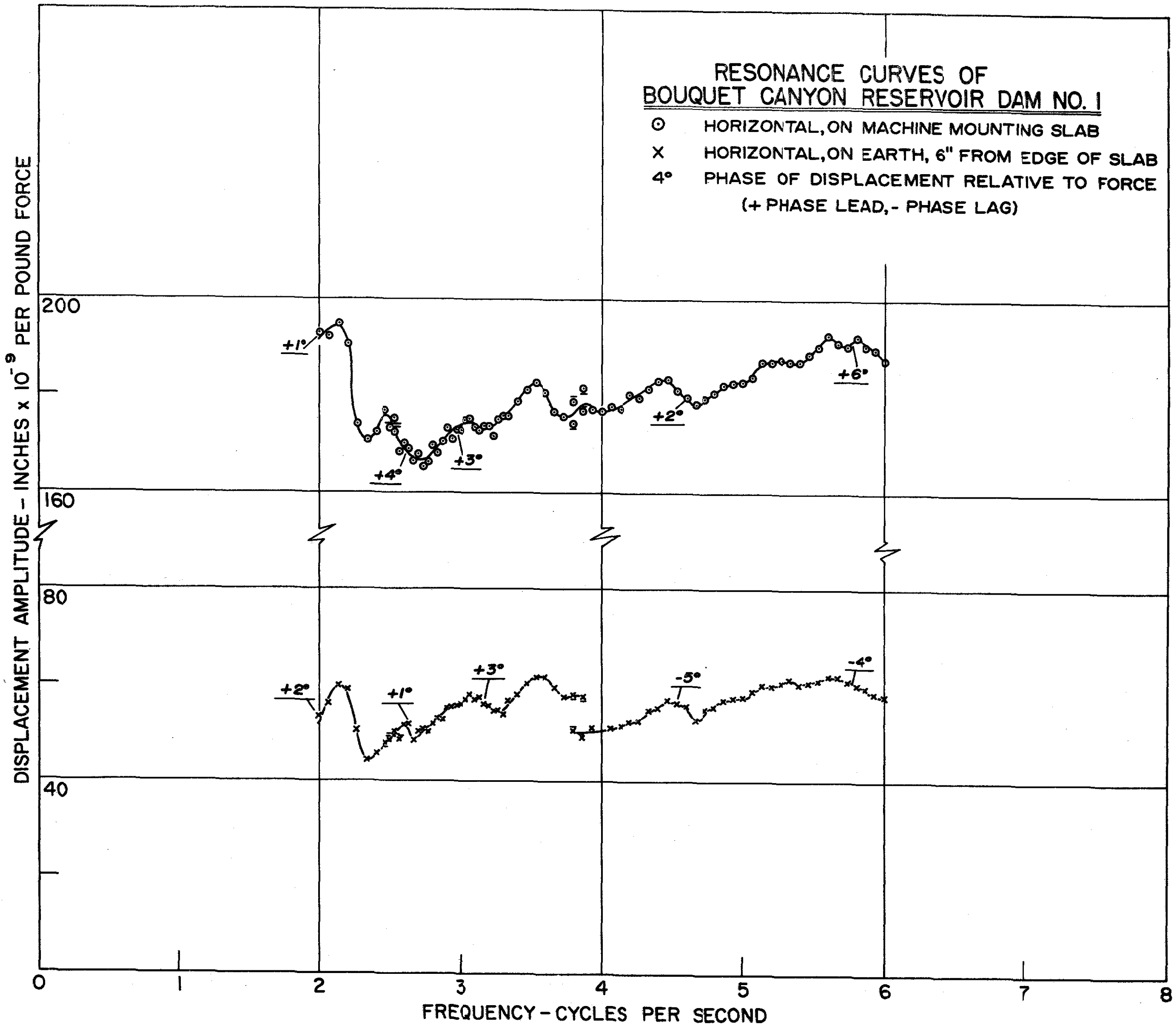

RESONANCE CURVES OF
BOUQUET CANYON RESERVOIR DAM NO. 1
⊙ HORIZONTAL, ON MACHINE MOUNTING SLAB
X HORIZONTAL, ON EARTH, 6" FROM EDGE OF SLAB
4° PHASE OF DISPLACEMENT RELATIVE TO FORCE
(+ PHASE LEAD, - PHASE LAG)
+1°
+4°
+3°
+2°
+6°
+2°
+1°
+3°
-5°
-4°
200
160
80
40
0
1
2
3
4
5
6
7
8
DISPLACEMENT AMPLITUDE - INCHES x 10^{-9} PER POUND FORCE
FREQUENCY - CYCLES PER SECOND

FIGURE 16

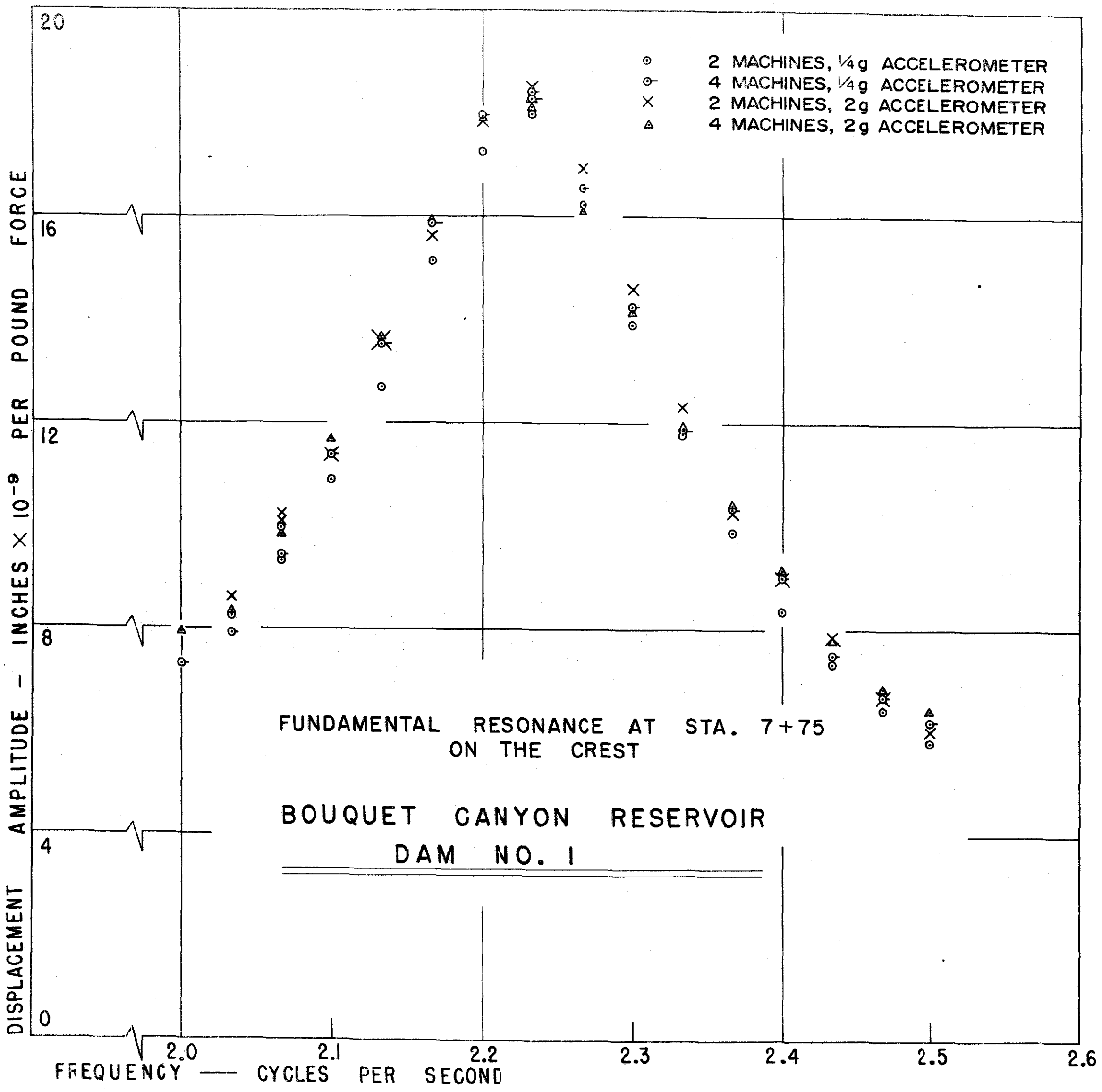
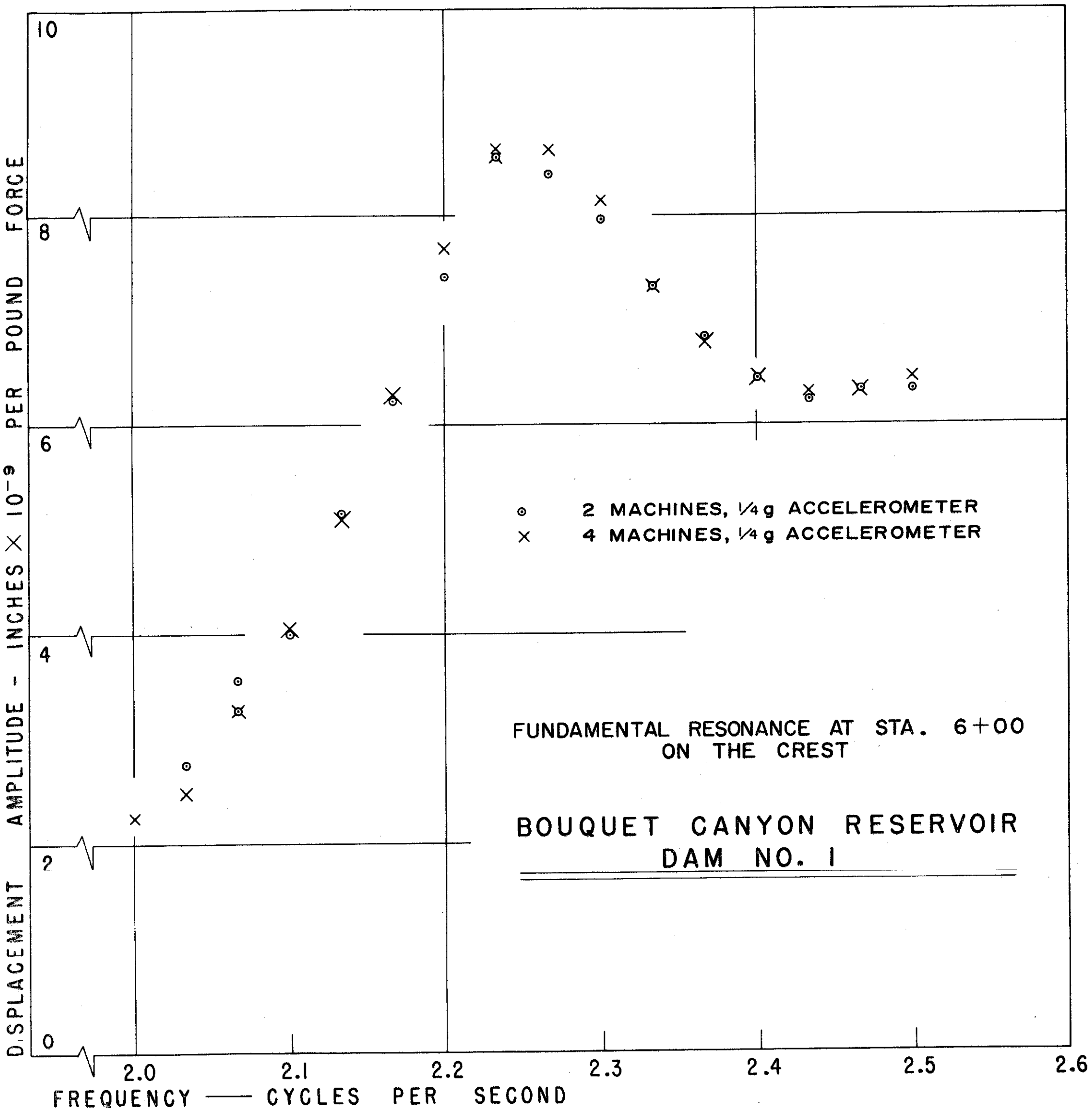


FIGURE 17 - ILLUSTRATING LINEARITY OF RESPONSE AND CONSISTENCY OF MEASUREMENTS



ILLUSTRATING LINEARITY OF RESPONSE

FIGURE 18

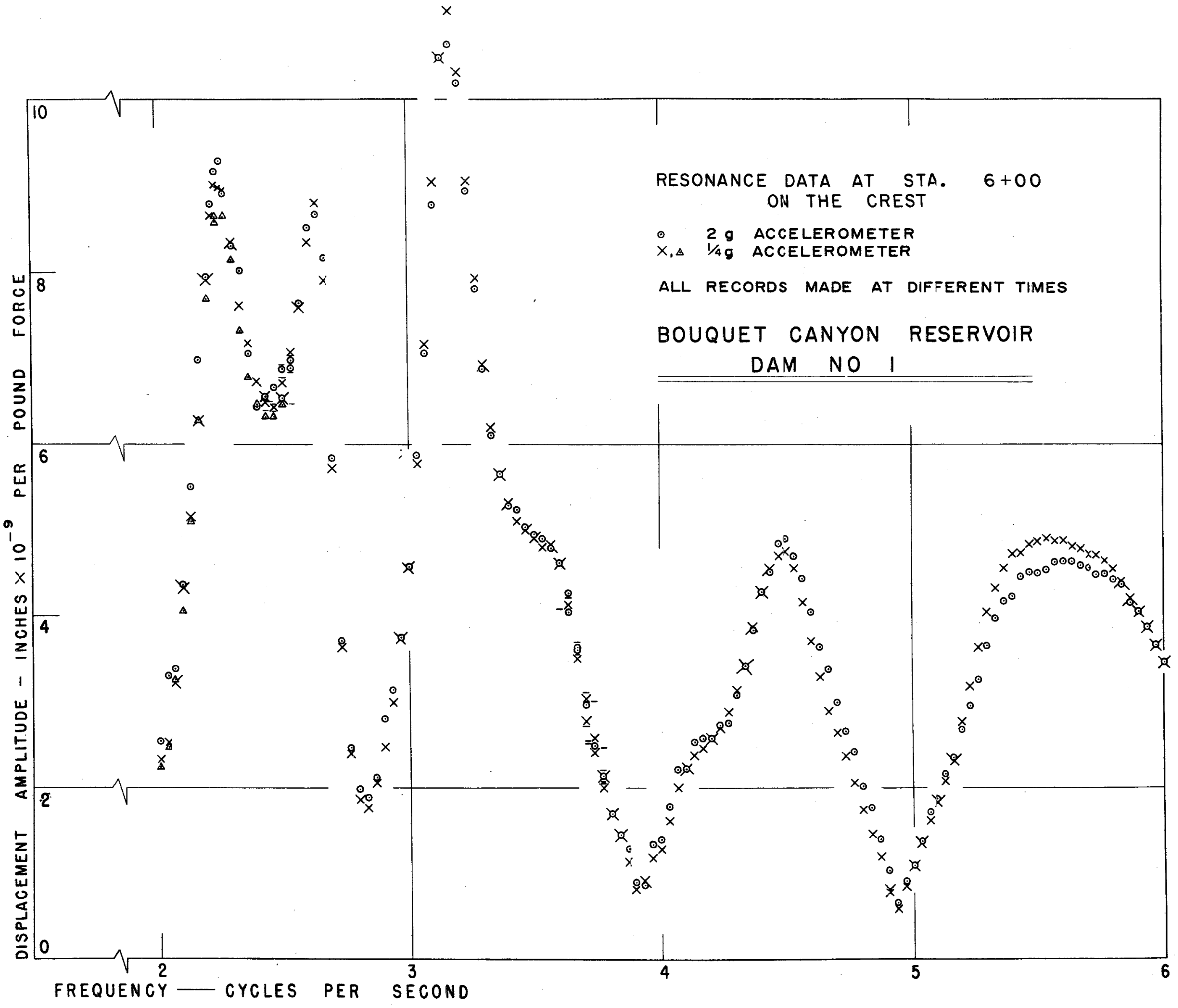


FIGURE 19 - ILLUSTRATING THE CONSISTENCY OF THE MEASUREMENTS

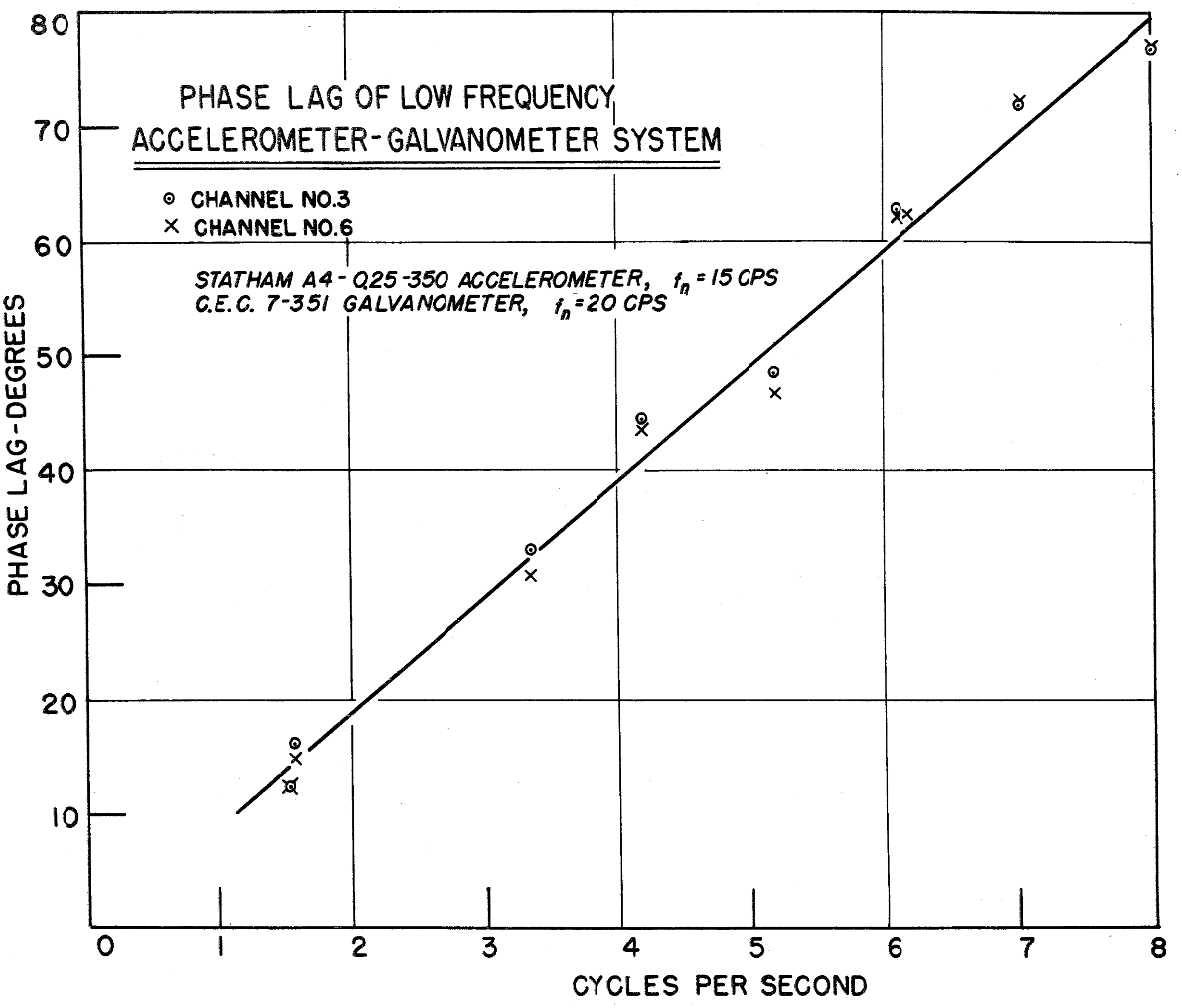
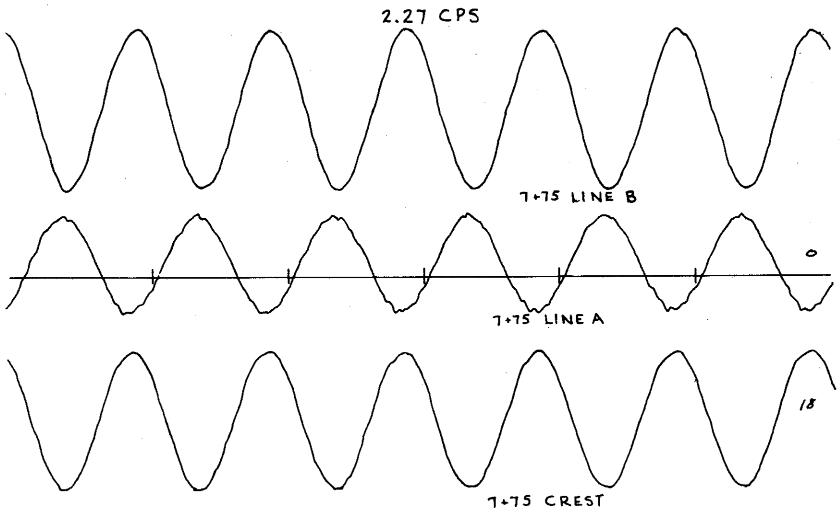
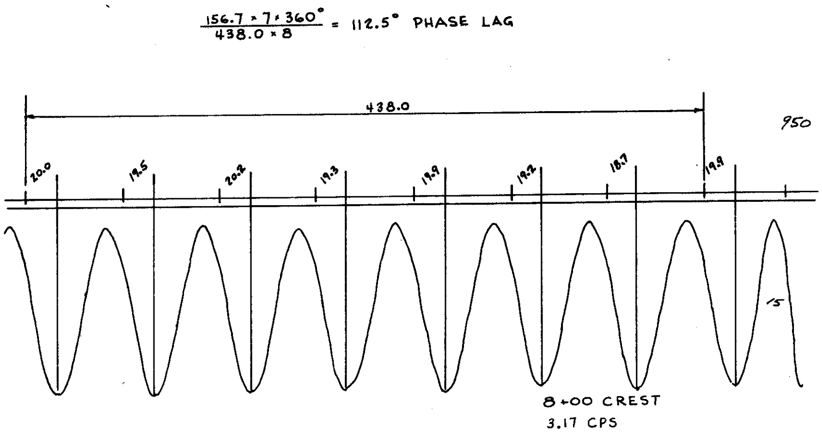

PHASE LAG OF LOW FREQUENCY
ACCELEROMETER-GALVANOMETER SYSTEM
⊙ CHANNEL NO.3
× CHANNEL NO.6
STATHAM A4 - 0.25-350 ACCELEROMETER, f_n = 15 CPS
C.E.C. 7-351 GALVANOMETER, f_n = 20 CPS
80
70
60
50
40
30
20
10
PHASE LAG-DEGREES
0
1
2
3
4
5
6
7
8
CYCLES PER SECOND

FIGURE 20



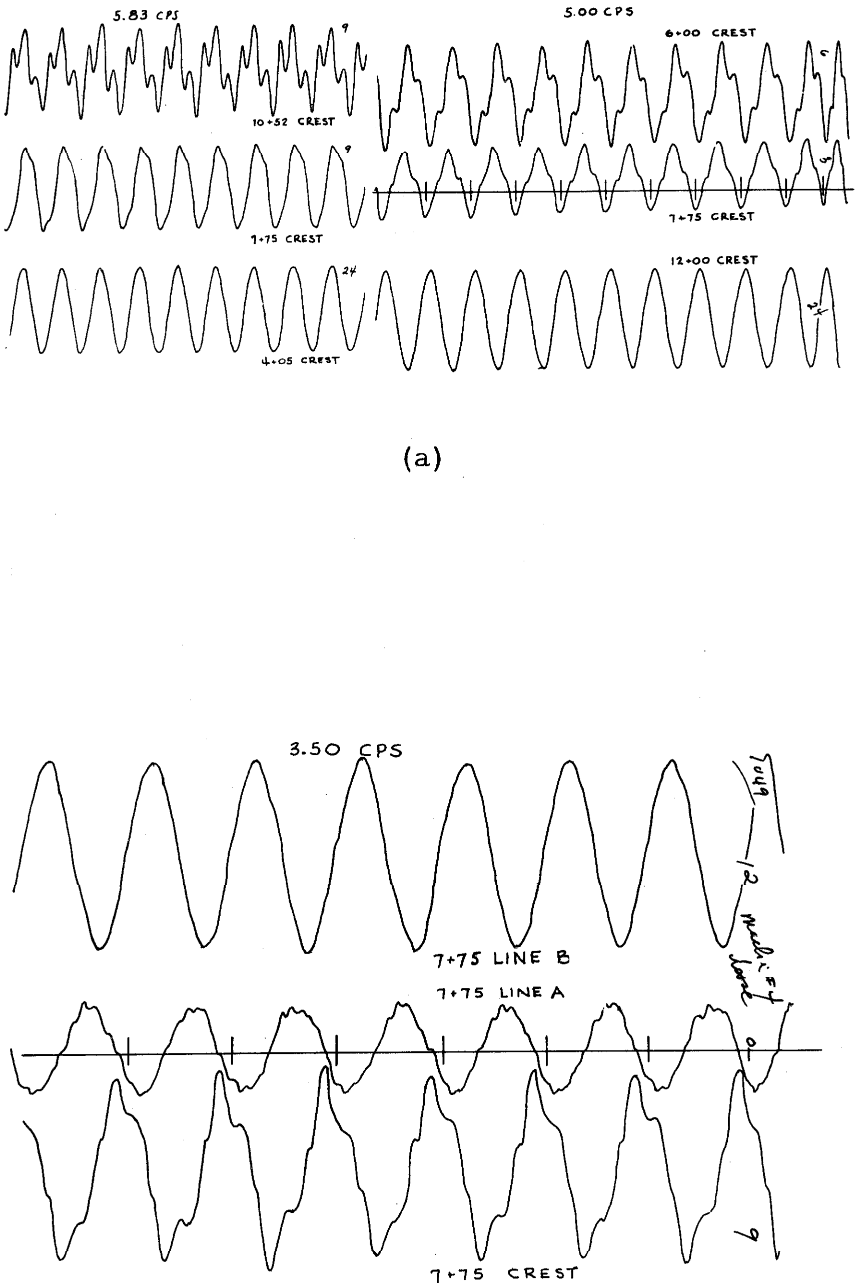
(a) Illustrating Smooth Traces



(b) Illustrating Phase Measurement

TRACINGS OF OSCILLOGRAPH RECORDS

FIGURE 21

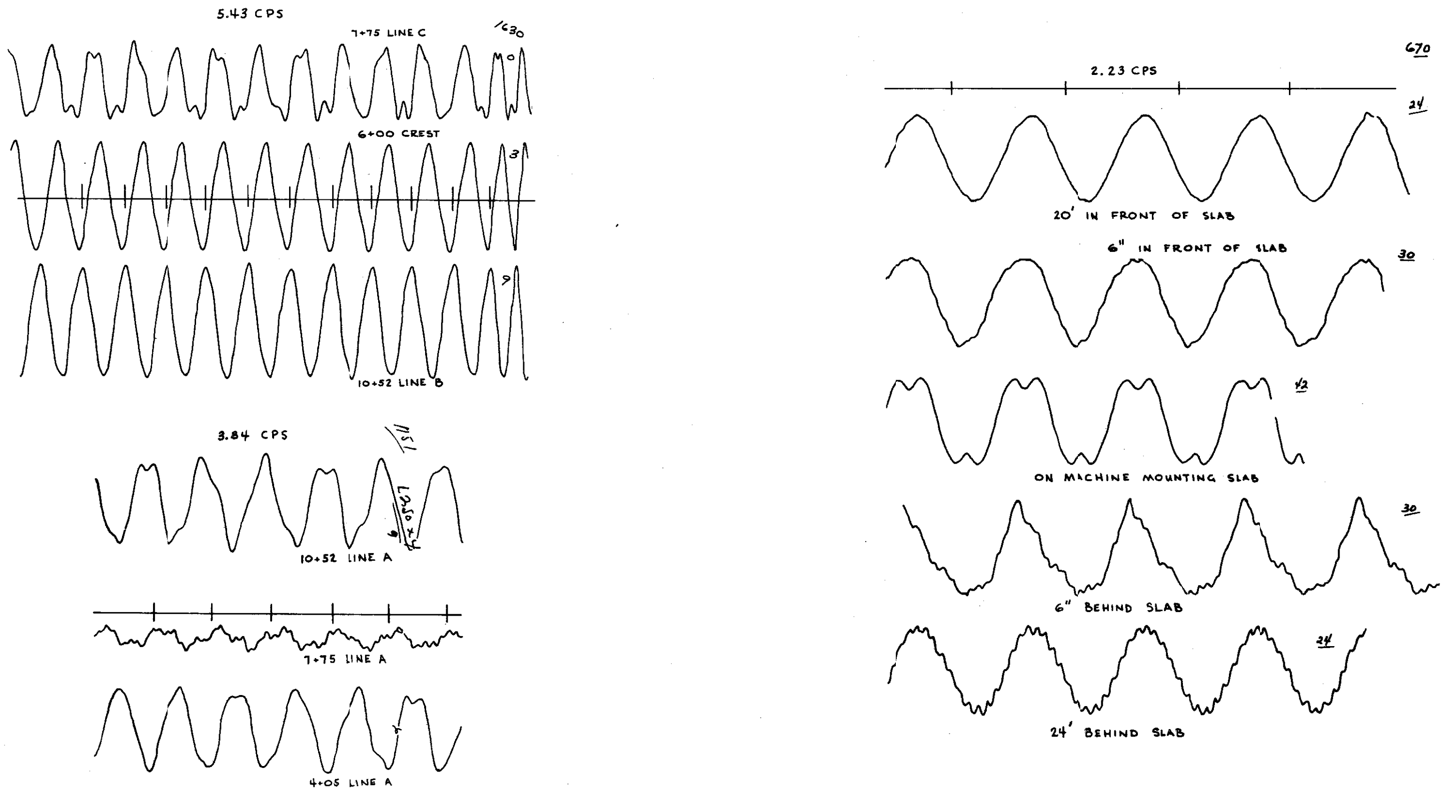


(a)

(b)

TRACINGS OF OSCILLOGRAPH RECORDS
ILLUSTRATING ULTRAHARMONIC RESPONSE

FIGURE 22

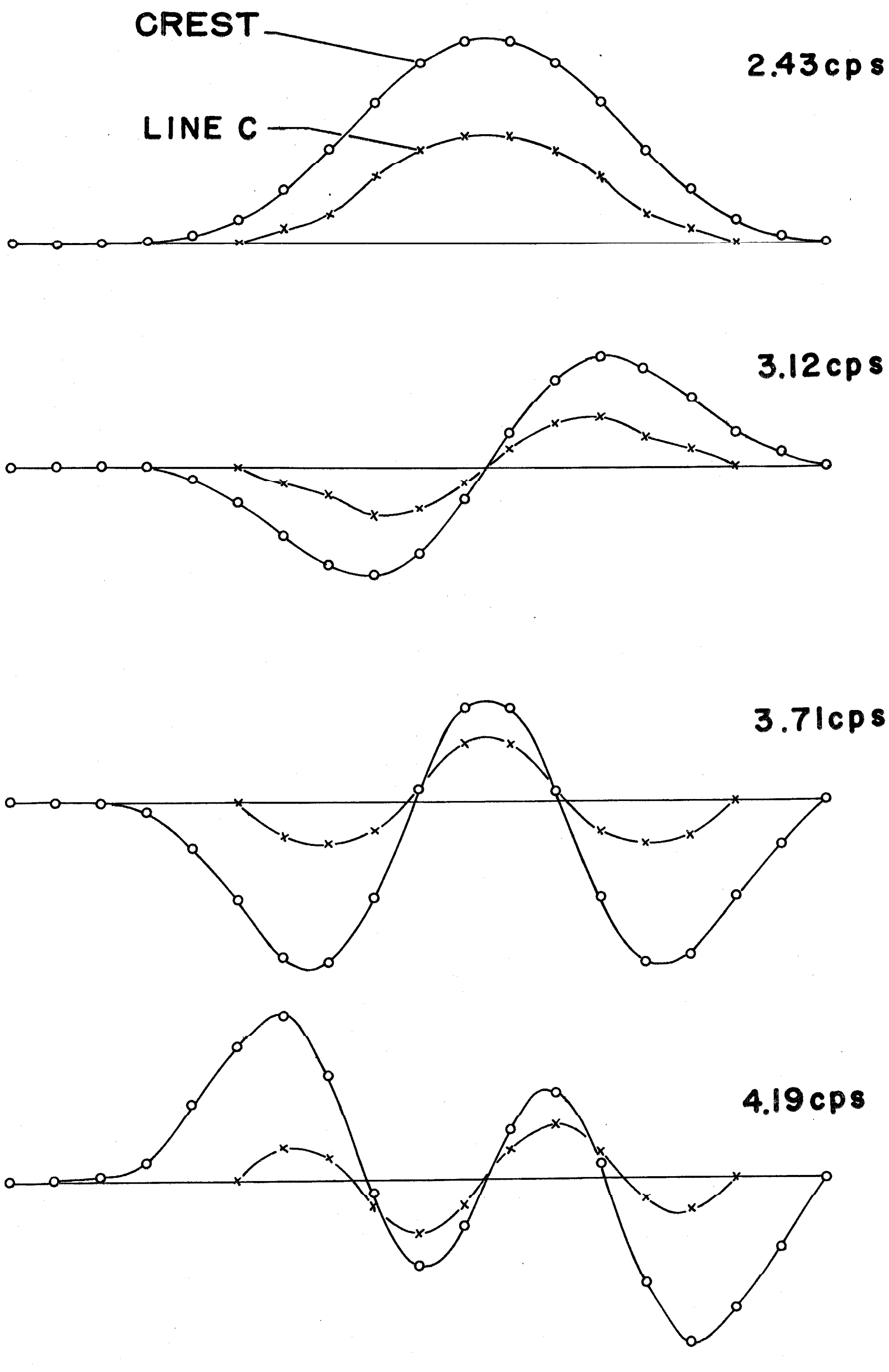


Illustrating Nonsteady
Response

Response in the Vicinity
of the Vibration Exciters

TRACINGS OF OSCILLOGRAPH RECORDS

FIGURE 23



COMPUTED MODE SHAPES

FIGURE 24