HYD 58

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC LABORATORY REPORT NO. 58

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REPORT ON VIBRATION STUDIES MADE AT BLACK CANYON DAM BOISE PROJECT.

By

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Denver, Colorado
July 26, 1939

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Denver, Colorado, July 26, 1939.

MEMORANDUM TO MR. K. B. KEENER
(R. E. Glover, T. F. Hammett, and C. W. Thomas)

Subject: Report on vibration studies made at Black Canyon Dam, Boise project, from March 20, 1939, through April 6, 1939.

References: Reference is made to the following memoranda and letters:

1. Letter to construction engineer, Boise project, March 4, 1939.

2. Memoranda to Mr. R. E. Glover from T. F. Hammett, dated November 14, 1938 and November 22, 1938.

3. Memorandum to the Chief Designing Engineer from Mr. Glover under date of March 14, 1939.

4. Memorandum to T. F. Hammett from Mr. R. E. Glover dated March 15, 1939.

1. Introduction. For sometime there has been a pronounced vibration set up at Black Canyon Dam caused by the flutter of the nappe of water flowing over the spillway gates when these were held at certain positions with respect to the lake elevation. While this vibration has caused no noticeable effect on the dam structure, it has caused the doors and windows of the power plant and some nearby buildings to shake.

It was the purpose of this trip to Black Canyon Dam to make as complete an investigation as possible of these vibrations, as to frequency, amplitude, the possible influence on the dam structure, and if possible to determine the cause and to find some means of preventing the flutter of the nappe.

It is commonly known that although the amplitude of an inducing sinusoidal force on a structure may be small, if the frequency of this force has a value close to the natural frequency of the structure, a condition of resonance may be obtained which may cause high dynamic stresses.

As the proposed designs of the spillways at both Shasta and Grand Coulee Dams are of the same type as that constructed at Black Canyon Dam, these studies may prove of some value in determining what allowance must be made to provide for this possibility in the design of these structures.

2. Apparatus used. The instruments used in this study were designed in this office and in most cases constructed in the Bureau's machine shop.

The following is a brief description of the instruments used in making these studies:

(a) Oscillograph.--The oscillograph, which is of the Duddell type, was designed for the purpose of obtaining a permanent record of the response of the instruments used in making the vibration studies. This instrument deflects a light spot by reflection from a mirror mounted on the moving element of a sensitive galvanometer, across the light sensitive surface of a moving film to produce the record. This oscillograph is provided with 6 elements ranging in sensitivity from about 3 to 6 milliamperes per inch deflection on the film, and each having a natural frequency of about 200 cycles per second with a high degree of damping.

(b) Accelerometers.--These instruments were designed to measure accelerations in the dam. Two sets of carbon piles were placed in each accelerometer unit in such a manner that the inertia forces set up by a relatively heavy mass under the action of some inducing force, acts upon the piles and the resulting change in resistance can be recorded by the oscillograph. These instruments have a natural frequency of about 20 cycles per second and are provided with oil damping. There were three accelerometer elements provided. These were arranged to measure vibration in three directions at right angles; namely, in the transverse direction of the dam (up and downstream), in the longitudinal direction (across stream), and in the vertical direction. These instruments were all calibrated by means of a shaking table in the manner described below.

(c) Pressure cells.--Two different types of pressure cells were designed to be used to measure the amplitude and frequency of the inducing force exerted on the dam by the flutter of the nappe.

(1) Carbon-pile pressure cell.--This pressure cell is referred to by this name because here again the principle of a change in resistance with change in pressure

on a pile of carbon disks is employed. The pile of carbon disks was placed beneath a diaphragm and connected electrically into a bridge circuit, using the oscillograph as a galvanometer, in such a manner that any change in pressure exerted on the diaphragm could automatically be recorded.

(2) Moving-coil pressure cell.--This instrument was designed using the principle that a voltage is induced in a coil which moves in a magnetic field. A coil was fastened rigidly to a diaphragm and arranged to move in a strong magnetic field set up by permanent magnets. Variation in pressure on the diaphragm causes the coil to move in this magnetic field. This coil is connected directly to an oscillograph element and the resulting current that flows can thus be automatically recorded. This instrument measures a variation in pressure which is a function of the frequency and amplitude of the inducing force.

All of these instruments were designed to be as portable as possible and at the same time sensitive enough to be operated simultaneously from a single 6-volt storage battery.

3. Calibration of instruments. Reference is made here to the memorandum to R. E. Glover of November 14, 1938, regarding the calibration of these instruments.

The following is a brief description of the procedure followed and the results obtained in calibrating the various instruments:

(a) Oscillograph.--The sensitivity of each element of the oscillograph was determined by measuring the amount of current passing through the element which would produce a one-inch deflection of the spot of light on the film.

(b) Accelerometer.--The three accelerometer units were calibrated by means of a shaking table designed in this office and shown in the pictures on the following pages. The shaking motion is imparted to the table by means of a rotating eccentric mass. This mass is fastened to the outer edge of a disk revolving at a known speed. The frame supporting this revolving disk is rigidly fastened to the platform of the table which is supported on rollers. The deflection of the table is determined by means of a scratch gage attached to one edge of the table and the amplitude of the scratch thus obtained being measured by means of a microscope. The accelerometer box is placed on the table and a record of the movement of the accelerometer unit is obtained on the oscillograph. Then, knowing the deflection of the table, the value of the eccentric weight plus the weight of the entire apparatus (including accelerometer box) and the speed of the disk carrying the eccentric weight, the acceleration produced can easily be calculated. Hence the deflection of the oscillograph element which represents an acceleration of 0.1 gravity can be found. As the shaking table oscillates in but one direction at a time, each accelerometer unit has to be calibrated separately. To calibrate the vertical element, one end of the table was suspended by means of a spring and the casters on the table blocked so that the only motion was in the vertical direction. With this set-up the same procedure was followed as for calibrating the horizontal units.

(c) Pressure cells.--(1) Carbon-pile pressure cell.--The calibration of this instrument involved simply submerging the instrument at various depths in water when the instrument was connected to an oscillograph element. Thus noting the deflection produced at various depths, a curve could be drawn to obtain the amount of deflection of the oscillograph element per foot of water.

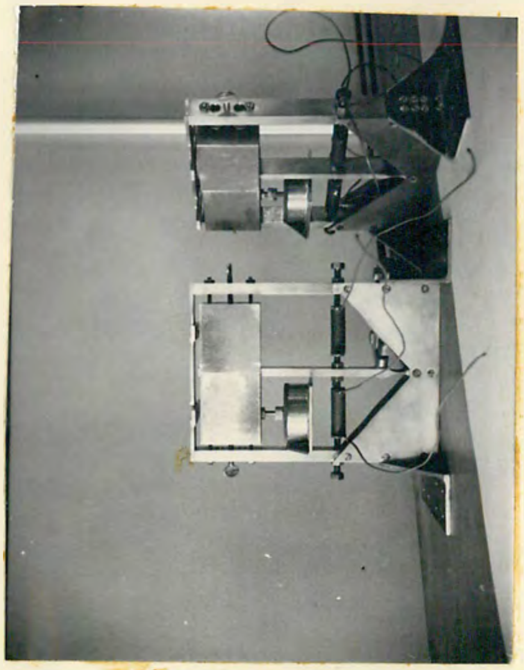
(2) The moving-coil pressure cell.--In order to calibrate this instrument a sinusoidal pressure whose amplitude and frequency are known must be applied to the disk. To apply this, the shaking table was suspended at one end by a spring just as for calibrating the vertical accelerometer unit. The moving-coil cell was placed on the table with a known weight resting at the center of the diaphragm. Hence when the table was in motion, the inertia of this weight would cause the diaphragm to deflect in and out, and the resulting sinusoidal current produced was recorded by means of the oscillograph. From the constants of the shaking table, the weight on the instrument and dimensions of the diaphragm, the deflection of this diaphragm could be computed. The equivalent water pressure necessary to produce this same deflection was calculated and hence the deflection of the oscillograph element per foot of water per cycle per second could be found.

(d) Summary of calibration.--The following is a table of the results of the calibration of the various instruments:

Instrument	Element No.	Calibration*
Oscillograph	1	5.80 milliamperes per 1" deflection
	2	4.00 " " " "
	3	2.70 " " " "
	4	2.93 " " " "
	5	3.17 " " " "
	6	3.80 " " " "
Accelerometer	1	1.0 inch per 0.1 gravity (osc. elem. No. 1)
	2	0.9 inch per 0.1 gravity (osc. elem. No. 2)
	3	1.6 inch per 0.1 gravity (osc. elem. No. 3)
Carbon-pile pressure cell	No. 1	1.71 inches per foot of water (osc. elem. No. 4)
Carbon-pile pressure cell	No. 2	0.60 inch per foot of water (osc. elem. No. 4)
Moving-coil pressure cell		0.22 inch per foot of water per cycle per second (osc. elem. No. 5)

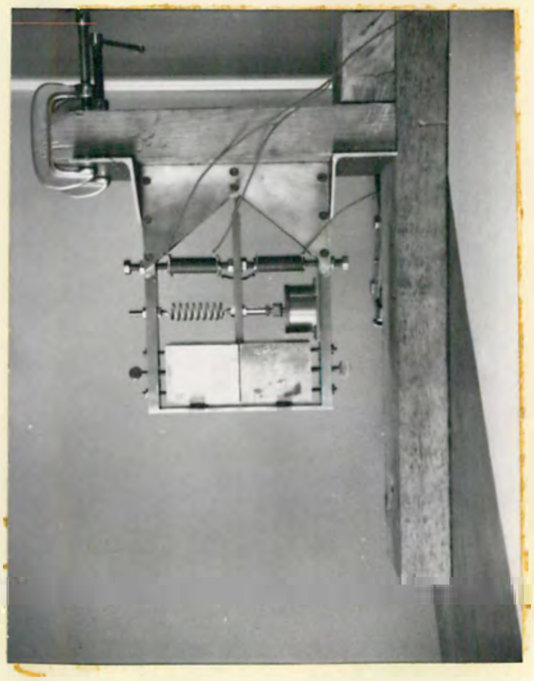
*All calibrations are given for maximum sensitivity of the instruments and oscillograph elements as they were adjusted at the time of calibration. The accelerometer units were calibrated at a battery voltage of 4 volts and the carbon-pile pressure cell at 2 volts.

VIBRATION STUDIES
BLACK CANYON DAM -- BOISE PROJECT, IDAHO

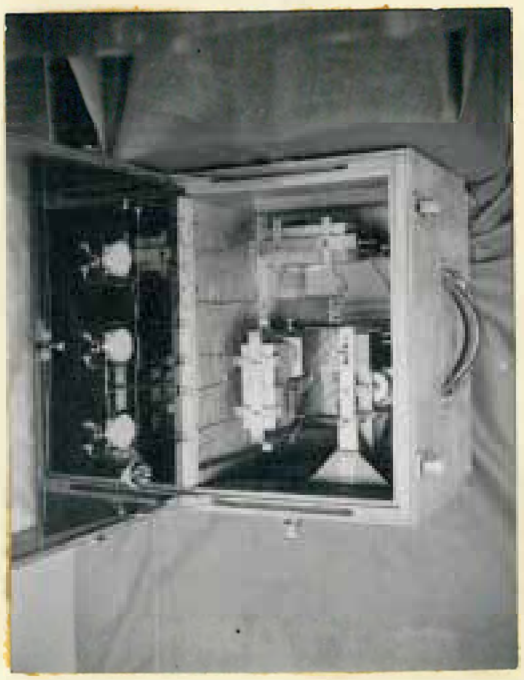


TWO HORIZONTAL ACCELEROMETER UNITS

OSCILLOGRAPH



VERTICAL ACCELEROMETER UNIT



THREE ACCELEROMETER UNITS ASSEMBLED
IN BOX WITH CONTROL PANEL

PRESSURE CELLS USED TO OBTAIN FREQUENCY AND AMPLITUDE OF FLUTTER-CARBON FILE PRESSURE CELL (LEFT) - MOVING - COIL PRESSURE CELL (RIGHT) - CONTROL BOX (CENTER)

VIEWS OF SHAKING TABLE USED TO CALIBRATE ACCELEROMETER UNITS

5. Arrangement of apparatus and method of procedure. The important data to be obtained at the Black Canyon Dam were:

(a) The frequency and amplitude of the flutter of the nappe.

(b) The acceleration of the dam when the nappe was fluttering.

(c) If possible the natural frequency of vibration of the dam in the transverse direction (up and downstream).

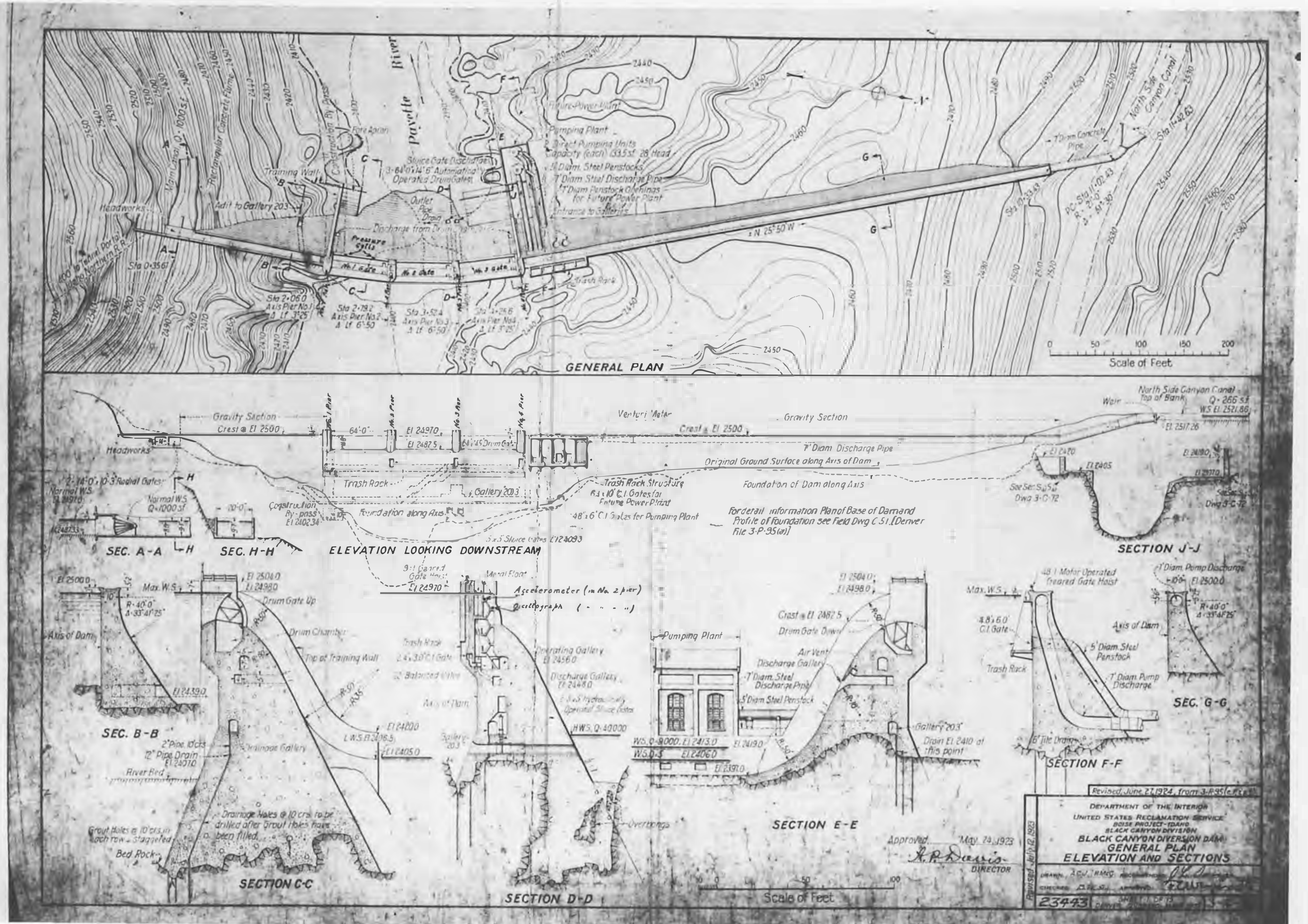
(d) Some method, if possible, of eliminating the flutter of the nappe.

Hence with these points in mind the instruments were set up in the following manner which was believed to be the best possible arrangement under the conditions met in the field.

The photostat shown on the following page indicates the position of the instruments as set up in the field and the method of identifying the various piers and gates by numbers. These numbers correspond to the method of identification used at the power plant.

Since all three gates in the spillway system are identical and for all practical purposes the flutter was similar on all gates, that gate which could be most easily operated and controlled was chosen to be used for making the studies of the flutter; namely, No. 1 gate. This was the only gate that could be operated electrically from both the switchboard in the power plant and by an electrical control located in the sixth landing from the top of the No. 2 pier stairway. The position of the crest of this gate could be read by means of a pointer coupled directly to the hinge pin of the drum gate which pointed to a scale of elevations marked in tenths of a foot on the wall of the pier stair well. The scale ran from 2482.50 feet, the lowest possible positition of the gate, to 2497.00 feet, the highest position of the gate.

The lake elevations were obtained from a lake gage located in pier No. 4. This gage was simply a flexible tube, one end of which was submerged in the reservoir at a certain elevation and the other end coming up into the pier and ending in a glass tube which was fastened to a scale marked in feet of elevation. The lake elevation could be checked by the electrical gage connected to the switchboard in the power plant. All lake elevations, however, given in the following pages are as read on the direct reading type gage set in pier No. 4. All elevations for the gate and the lake are given in feet above elevation 2400.00 feet.


GENERAL PLAN
Payette River
Headworks
Main Canal Q-1000 s.f.
Rectangular Concrete Flume
Construction By-Pass
Training Wall
Adit to Gallery 203
Sluice Gate Discharge
3-64'0"x14'6" Automatic Operated Drum Gates
Outlet Pipe Drain
Pressure Cells
No. 1 Gate
No. 2 Gate
No. 3 Gate
Future Power Plant
Pumping Plant
Direct Pumping Units Capacity (each) 133.5 s.f. 28' Head
5' Diam. Steel Penstocks
7' Diam. Steel Discharge Pipe
7' Diam. Penstock Openings for Future Power Plant
Entrance to Gallery
Trash Rack
N 25°50' W
7' Diam. Concrete Pipe
North Side Canyon Canal
Sta 11+42.63
Sta 0+35.67
Sta 2+06.0 Axis Pier No. 1 Δ Lf. 3°25'
Sta 2+19.2 Axis Pier No. 2 Δ Lf. 6°50'
Sta 3+52.4 Axis Pier No. 3 Δ Lf. 6°50'
Sta 4+26.6 Axis Pier No. 4 Δ Lf. 3°25'
Scale of Feet
ELEVATION LOOKING DOWNSTREAM
Gravity Section
Crest @ El. 2500
Venturi Meter
El. 2497.0
El. 2482.5
64'0"
64'x14'5" Drum Gate
7' Diam. Discharge Pipe
Original Ground Surface along Axis of Dam
Foundation of Dam along Axis
Trash Rack
Gallery 203
Trash Rack Structure
6-3x10' C.I. Gates for Future Power Plant
4-8'x6' C.I. Gates for Pumping Plant
Construction By-pass El. 2402.34
5'x5' Sluice Gates El. 2409.3
For detail information Plan of Base of Dam and Profile of Foundation see Field Dwg. C-51 [Denver File 3-P-95(a)]
North Side Canyon Canal Top of Bank
Weir
Q-266 s.f.
W.S. El. 2521.86
El. 2517.26
SEC. A-A
SEC. H-H
SECTION J-J
2-14'0"x10'3" Radial Gates
Normal W.S. Q-1000 s.f.
SEC. B-B
El. 2500.0
R-40'0"
Axis of Dam
El. 2439.0
SECTION C-C
El. 2504.0
El. 2498.0
Max. W.S.
Drum Gate Up
Drum Chamber
Top of Training Wall
El. 2400.0
L.W.S. El. 2406.5
El. 2405.0
2" Pipe 10' crs.
12" Pipe Drain El. 2401.0
Drainage Gallery
River Bed
Drainage Holes @ 10' crs. to be drilled after Grout Holes have been filled
Grout Holes @ 10' crs. in each row - staggered
Bed Rock
SECTION D-D
Metal Float
El. 2497.0
Accelerometer (in No. 2 pier)
Oscillograph
Trash Rack
Operating Gallery El. 2456.0
Discharge Gallery El. 2448.0
Axis of Dam
Gallery 203
Overhangs
H.W.S. Q-40000
SECTION E-E
Pumping Plant
Crest = El. 2482.5
Drum Gate Down
Air Vent
Discharge Gallery
7' Diam. Steel Discharge Pipe
5' Diam. Steel Penstock
Gallery 203
Drain El. 2410 at this point
W.S. Q-40000 El. 2413.0
W.S. Q-5 El. 2406.0
El. 2397.0
SECTION F-F
4-8'x6' Motor Operated Geared Gate Hoist
Max. W.S.
4-8'x6.0' C.I. Gate
Trash Rack
5' Diam. Steel Penstock
7' Diam. Pump Discharge
SEC. G-G
7' Diam. Pump Discharge
El. 2500.0
R-40'0"
Axis of Dam
Approved May 24, 1923
R. P. Davis
DIRECTOR
Scale of Feet
Revised June 27, 1924, from 3-R-95
DEPARTMENT OF THE INTERIOR
UNITED STATES RECLAMATION SERVICE
BOISE PROJECT-IDAHO
BLACK CANYON DIVISION
BLACK CANYON DIVERSION DAM
GENERAL PLAN
ELEVATION AND SECTIONS
23443

The carbon-pile pressure cell was rigidly fastened with screws to a holding plate designed to be bolted to the under side of the overhanging lip on the drum gate. This holding plate was then fastened by means of a bolt placed in an unused rivet hole in the skin plate forming the overhanging lip of No. 1 drum gate, about 16 feet from the No. 2 pier. The leads from the cell were brought along the under side of the lip of the gate and into the inside of the No. 2 pier to the oscillograph and control panel placed on the third landing (from the top) of the pier stairway.

The moving-coil pressure cell was fastened in a very similar manner to No. 1 drum gate about 16 feet in from pier No. 1.

The accelerometer box, containing the three accelerometer units, was placed inside of pier No. 2 on the second landing of the stairway. The box was leveled and solidly placed on blocks in such a position that No. 1 unit would measure any vertical vibrations, No. 2 element longitudinal (across stream) vibrations, and No. 3 element the transverse (up and downstream) vibrations. Leads from this were brought down to the third landing to the oscillograph box.

The photostat of the general plan of Black Canyon Dam and the following pictures show the position of the instruments as set up in the field.

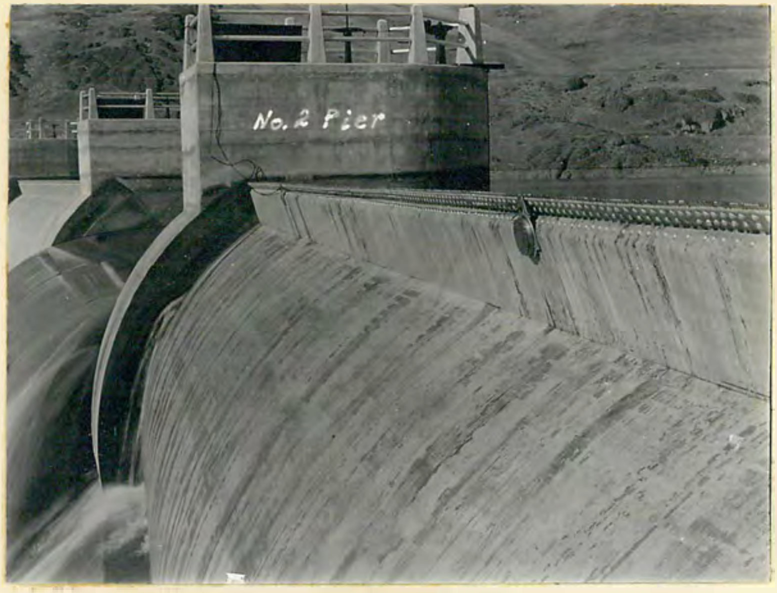
6. Method of procedure - Measurement of flutter and dam accelerations. Each instrument was connected to an oscillograph element in the following manner:

Osc. Elem. No.	Instrument
1	Accelerometer unit No. 1 (vertical)
2	Accelerometer unit No. 2 (longitudinal)
3	Timing wave 50.6 cycles/sec.
4	Accelerometer unit No. 3 (transverse)
5	Carbon-pile pressure cell No. 1
6	Moving-coil pressure cell

Hence No. 5 and No. 6 elements of the oscillograph recorded the amplitude and frequency of the flutter of the nappe over the gate, the Nos. 1, 2, and 4 elements recorded any vibrations in the dam, and the No. 3 element the output from a tuning fork used as a timing wave.

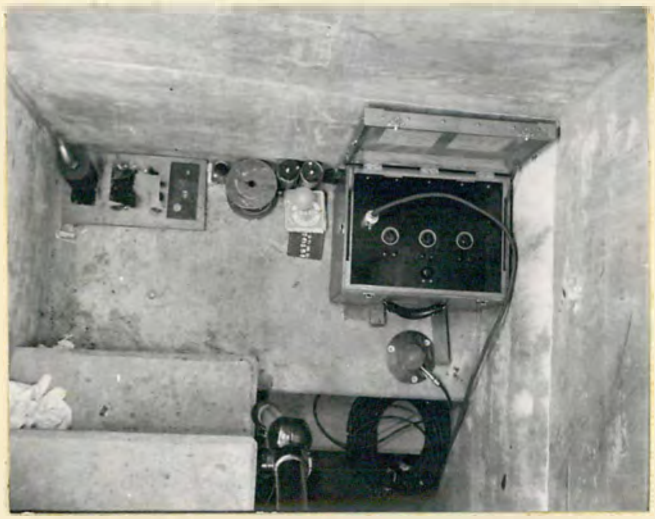
All instruments were first adjusted to zero by observing the light dots on the ground glass of the oscillograph. After these final adjustments were made, a run could be started. With

VIBRATION STUDIES - BLACK CANYON DAM -
BOISE PROJECT, IDAHO



PRESSURE CELLS ON LIP OF NO. 1 GATE
CARBON PILE PRESSURE CELL - LEFT
MOVING-COIL PRESSURE CELL - RIGHT

OSCILLOGRAPH SET-UP ON THIRD
LANDING OF NO. 2 PIER



ACCELEROMETER SET-UP ON SECOND
LANDING OF NO. 2 PIER

the lake previously set at some particular elevation, the No. 2 and No. 3 gates were set at positions to keep the lake at a fairly constant elevation for any one run.

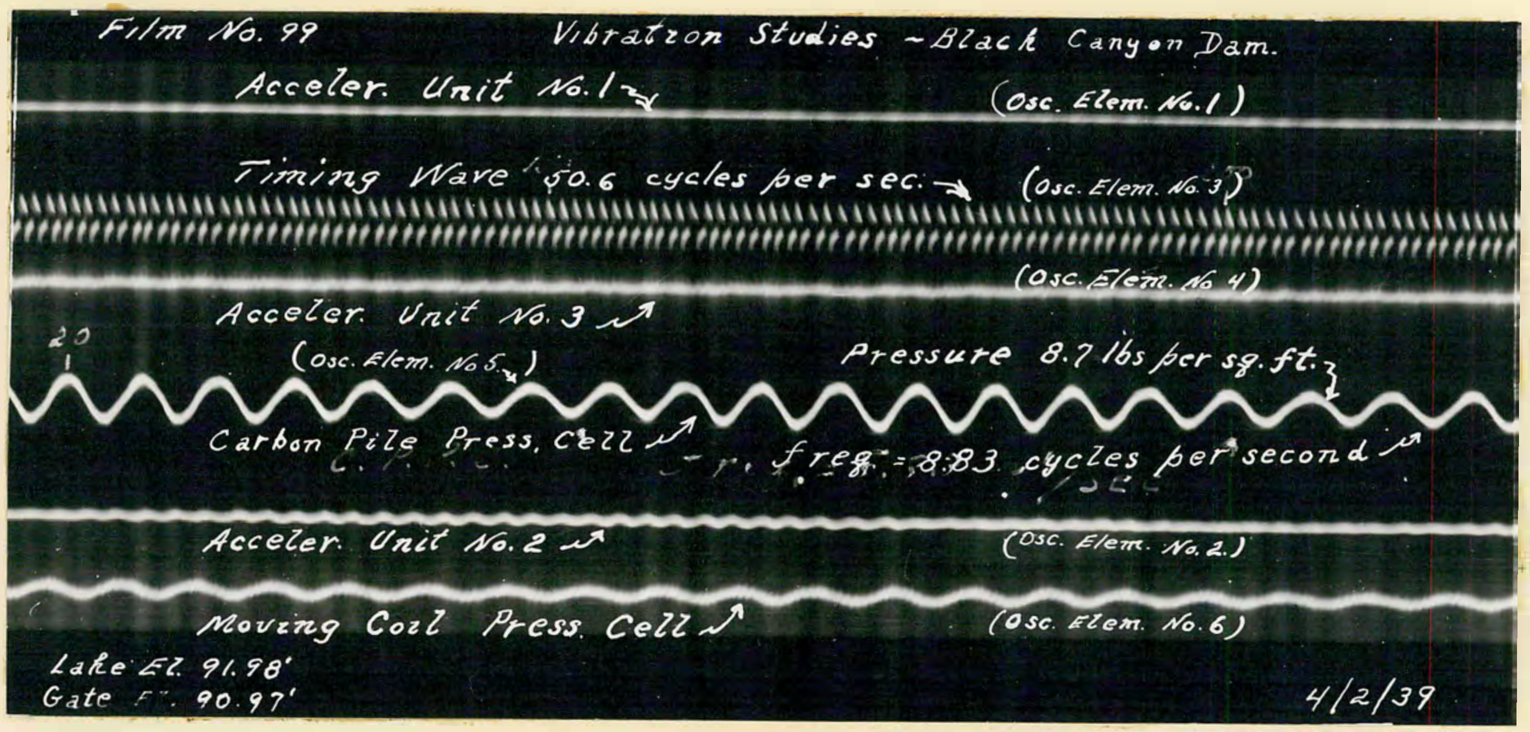
The No. 1 gate was then lowered and the lake elevation checked by the gate gage. When the crest of the gate was exactly at lake elevation, it was found that this elevation as read by the gate gage did not check the lake gage. It was also found that the gate gage did not read the same when the gate was being lowered as when it was being raised. Hence in order to get a check on this difference and in order to make a correction on the gate elevation, it was checked as closely as possible with the lake elevation as read by the lake gage for the gate going down and the gate coming up. In each case, the gate was lowered or raised sufficiently to take out any slack in the gage when the direction of the motion of the gate was changed.

Thus after obtaining the lake elevation by the crest of the gate, the gate was lowered slowly until the first flutter of the nappe was perceptible and could be seen on the ground glass of the oscillograph. This was determined by the two pressure cells located on the lip of the gate. As it was difficult to stop the gate exactly at this point, it was allowed to coast to a stop and a record taken. The gate elevation at the start of the flutter and at the points where a record was taken was recorded. After a record was taken of this first position the gate was lowered at about 0.2 of a foot intervals and records taken at each point until an elevation was reached at which the flutter ceased entirely. This end point was recorded and the gate was then lowered a couple of feet to make sure no further flutter would occur and also to take the slack out of the gate gage before reversing the direction of motion. With the gate coming up the elevations at the start and stop of the flutter were recorded as well as a few points in between in order to get some check on the readings obtained when the gate was being lowered. The gate was raised to the top and as it passed through the lake level, the gate gage was recorded in order to get another check of the gate gage versus the lake gage. At the end of each run, the lake gage was again recorded.

The accelerometer units were connected at all times during the run to the oscillograph in such a manner that any movements of these instruments would be recorded simultaneously along with the pressure cells.

The picture shown on the following page is a typical oscillogram obtained from one point in such a run.

7. <u>Some general remarks on the procedure followed and the performance of the instruments.</u> In general, the above proce-



Typical Oscillogram Obtained in Vibration Studies at Black Canyon Dam

VIBRATIONS STUDIES
BLACK CANYON DAM - BOISE PROJECT - IDAHO

dure was followed for each run. One run was made at each of the following lake elevations:

At lake elevation	89.03
" " "	90.12
" " "	91.11
" " "	91.72
" " "	91.80
" " "	92.60
" " "	93.65
" " "	93.69
" " "	94.50

It will be noted that some very nearly duplicate runs were made. This is because some runs were spoiled by such things as wave action on the lake, wind on the jet or because the slack in the gate was not taken care of properly. Hence some duplicate runs were made at approximately the same lake elevation in order to get a check at these points.

It was found necessary to increase the sensitivity of the instruments somewhat in order to get reasonable deflections of the oscillograph elements. This was done by increasing the battery voltage applied to the bridge circuit of the carbon-pile pressure cell and the accelerometer units. Hence the applied voltage to the carbon-pile pressure cell was increased to about 4 volts and to the accelerometer units to about 10 volts for all runs. The sensitivity of the moving-coil pressure cell could not be changed. All the oscillograph elements, except the timing element, were run on the most sensitive position of the control switch.

Due to the cool temperature of the air it was found that the accelerometer units were over-damped. That is, the viscosity of the oil in the damping pots was increased at these low temperatures to the extent that the units became very sluggish. Hence the adjustment on these damping pots was changed to give less damping. The natural damping of the instruments were recorded at frequent intervals by gently tapping the accelerometer box and obtaining the resulting vibration of the instruments on the oscillograph film.

Although the pressure cells seemed sensitive enough to get a good record of the amplitude and frequency of the flutter of the nappe, the accelerations in the dam were so slight that the accelerometer units indicated no noticeable movement in most cases. However, occasionally the units indicated a pronounced vibration that could not be felt physically by the observers. These vibrations apparently were not caused by the flutter of the nappe as they were not of the same frequency and often occurred when no flutter was present. Calculations, based on the calibration of these instruments, show that the maximum acceleration observed was not greater than 0.003 gravity.

Although runs were made over lake elevations ranging from about 89.00 to 94.00 this did not cover the entire range over which flutter apparently occurs. However, this range of lake elevations was limited by the water requirements of the powerhouse and irrigation system which had to operate as normally as possible. Although raising the lake to an elevation of 94.00 had little effect on the operation of the power plant and irrigation system, it was found unnecessary to go beyond this point as the readings indicated that the flutter would cease entirely at this point, regardless of the position of the gate.

At the lower lake elevation the readings still showed a slight range of lake elevations over which flutter would probably occur, but on extrapolating the curves it could be seen that the flutter would probably cease at a lake elevation of about 86.50 feet. Hence, it was felt that by obtaining the runs between 89.00 and 94.00, data could be obtained to give sufficient information about the flutter over the full range at which it occurs. Since a lake elevation of 89.00 interfered to some extent with normal operating conditions, it was decided not to go below this elevation.

8. Method of procedure in attempting to obtain the natural frequency and damping of the dam in the transverse direction. Although it is possible to make a rough calculation of the natural transverse frequency of a dam of this size and shape, the calculations become somewhat involved and might give somewhat uncertain results because of probable errors in assumptions. Hence, to obtain this figure, as well as the degree of damping, would prove of great value in determining the effect of the flutter on the dam structure as well as to check computations that might be made.

A method of striking the dam a blow and picking up the resulting natural oscillation was attempted. At first a few records were obtained of the movement of the accelerometer units caused by blasts of dynamite set off at the south abutment of the dam. These shots were being set off at frequent intervals by a crew of workmen constructing a fish screen for the Department of Fisheries at the headworks of the canal system, located at the south abutment of the dam. By cooperating with them at times when they were about to shoot, and employing a system of signals to time the shot so that it could be obtained on the oscillograph film, it was possible to obtain a few records which certainly indicated movement of the instruments. However, the results obtained were somewhat questionable; first, because the transverse frequency was desired and the shot followed the longitudinal axis of the dam, second, the frequencies obtained were so close to the natural frequency of the instruments themselves that it was difficult to tell whether or not the record indicated the frequency of the structure. As a good part of the force of these blasts traveled through the air, it is possible that the resulting concussion may have actually acted on the accelerometer box itself causing the instruments to give erroneous results rather than actually picking up vibrations through the dam. These blasts could be felt very distinctly and the panel of the oscillograph box could be seen to deflect slightly when the blast went off, indicating that possibly the accelerometer box was also affected by the air concussion.

Hence an attempt was made to eliminate any of these possible errors. Permission was obtained to shoot off some dynamite in the reservoir. This would strike a blow on the dam which would be in the right direction and still would not be allowed to travel through the air to give any erroneous results. In order to be more certain of striking the first mode of vibration of the dam, the blasts were set off about 800 feet upstream from the dam. Several attempts were necessary before a reasonable deflection of the accelerometer units could be obtained. As the accelerometer units were adjusted to give maximum sensitivity and the intensity of the blast was increased until the records showed a very small movement of the instruments, it was felt that no possible damage to the dam could result. Two records were finally obtained when it was found that 7 sticks of No. 30 powder placed at a depth of about 12 feet, 800 feet upstream from the dam gave a reasonable deflection.

9. Procedure followed in an attempt to prevent flutter of nappe. From general observations of the flutter of this nappe it seemed that the logical cause of the flutter was a matter of air demand beneath the jet. Hence, an attempt was made to aerate this jet by splitting it into two parts, allowing air to enter at the center (that is at the center of the gate between piers) as well as at the ends.

A 6- by 8-inch log, 6 feet long was fastened to the middle of a rope slung between No. 1 and No. 2 piers. The log was lowered in such a manner that it would float up and downstream. The No. 1 gate was then lowered to a point where there was about 3 inches of water over the gate and a very pronounced flutter was present. Then the log was allowed to float out over the crest of the gate at the midpoint between piers and held on the crest in such a fashion that the jet was broken quite prominently at this point. The accompanying photographs on the following pages show the position of the log and the opening formed in the jet. Records of the pressure cells and the photographs of the

VIBRATION STUDIES
BLACK CANYON DAM - BOISE PROJECT, IDAHO

FLUTTER OF JET ON NO. 1 GATE BEFORE LOG WAS PUT IN PLACE
HEAD ON GATE 0.4 FT.

VIBRATION STUDIES
BLACK CANYON DAM - BOISE PROJECT, IDAHO

LOG ON ONE-THIRD POINT ON NO. 1 GATE
SHOWING FLUTTER OF TWO-THIRDS PORTION OF JET
HEAD ON GATE 0.4 FT.

LOG AT CENTER OF NO. 1 GATE - FLUTTER CEASED
HEAD ON GATE 0.4 FT.

jet were taken both before and after the log was put in place. As a second trial, the log was moved to a point about one-third of the distance between the two piers or about 20 feet from No. 2 pier. Here again records and photographs were taken to show the effect of aerating the jet.

10. Photographs and moving pictures taken. In the hopes of getting a clearer conception of the character of the flutter of the nappe and also to facilitate in making further studies of its action, several photographs and moving pictures were taken. The following is an outline of the pictures taken at Black Canyon Dam:

(a) General views of dam and power plant.
(b) Views of No. 1 and No. 2 gates while flutter is present.
(c) Views of all three gates fluttering; No. 1 and No. 2 gates only, fluttering; and No. 1 gate only, when fluttering.
(d) Views showing instruments as set up for measurements.
(e) View of log breaking jet on No. 1 gate at midpoint, and one-third point.

For all movie shots taken there was a duplicate set of still pictures taken at the same time and place. A record of these films may be found in the files of the Bureau's hydraulic laboratory.

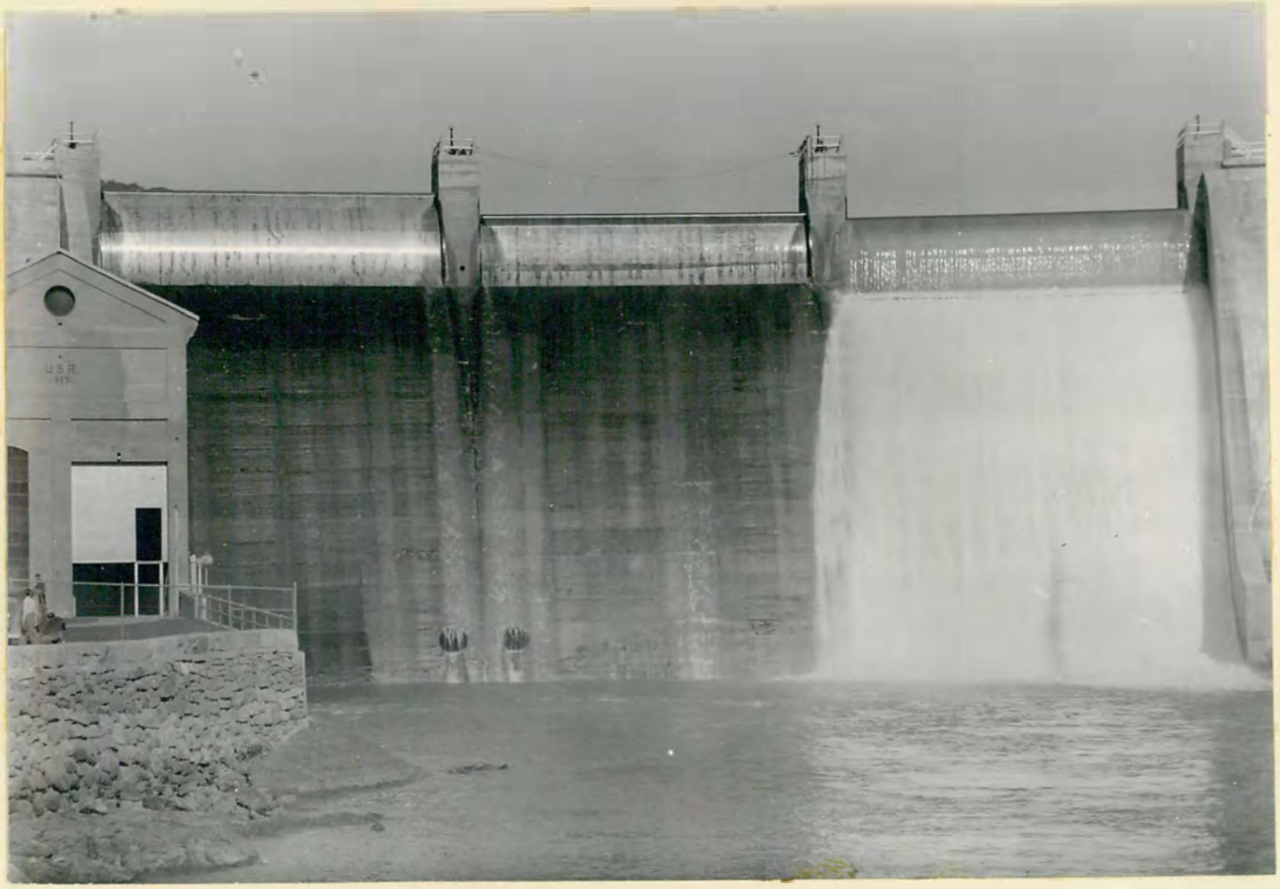
A few of the photographs are included at this point showing various interesting shots of the flutter of the nappe on different gates. Some of these show just what takes place when more than one gate is down and flutter is present on all the gates.

All oscillograms and data obtained in the field and computations made are filed in the analysis section files.

11. Analysis of data obtained. Before any accurate curves could be drawn, it was necessary to make a correction of the readings for the elevation of the crest of No. 1 drum gate. As pointed out before there was apparently a certain amount of slack in the gate gage and when this gage was checked against the lake gage the two did not agree. Also the direction of the motion of the gate whether up or down made a difference. However, by taking the average of all the gate readings taken to check the gate gage against the lake gage, two correction factors were found, one for the gate being lowered and one for the gate being raised. These correction factors seemed to check very satisfactorily and resulted in obtaining rather smooth curves.

VIBRATION STUDIES
BLACK CANYON DAM - BOISE PROJECT, IDAHO

GENERAL VIEW OF DAM - NO FLUTTER



OSCILLATION OF JET FROM NO. 1 GATE - GATE RAISED 7.6 FEET
HEAD ON GATE 1.15 FEET

VIBRATION STUDIES
BLACK CANYON DAM - BOISE PROJECT, IDAHO

OSCILLATION OF JETS FROM NO. 1 AND NO. 2 GATES - GATES RAISED 7.6 FEET - HEAD ON GATES 1.15 FEET

OSCILLATION OF JETS FROM ALL THREE GATES - GATES RAISED 7.6 FEET - HEAD ON GATES 1.15 FEET

In the following pages curves have been drawn to show the variations in the amplitude and frequency of the flutter for various gate and lake elevations.

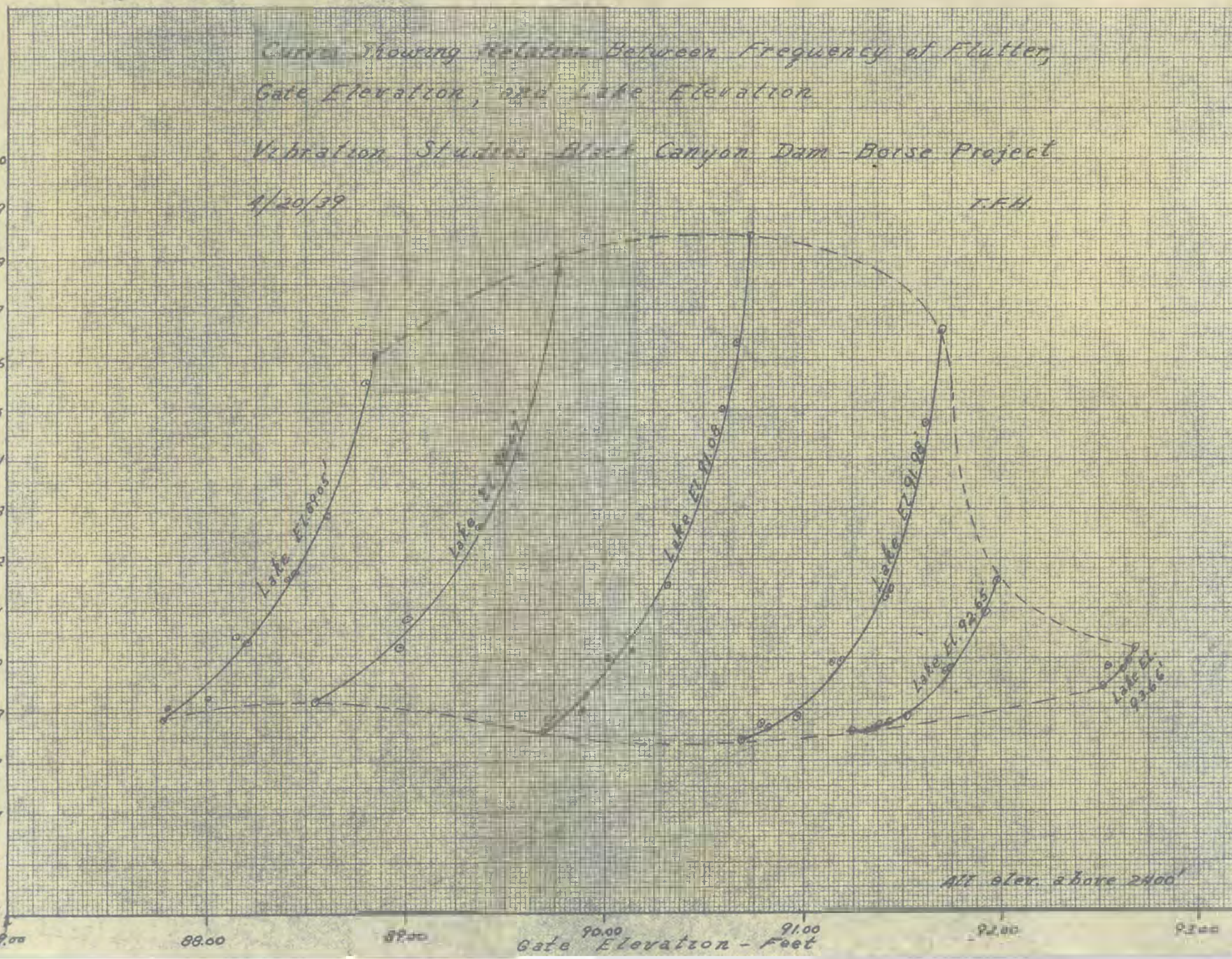
From these curves it can be seen that it is possible to obtain a flutter of the nappe from lake elevations ranging from about 87.00 feet to 94.00 feet. The frequency of the flutter over this range will vary from a minimum of about 7 cycles per second to 18.5 cycles per second. The lake elevation at which the maximum range of gate positions producing flutter is at about 91.00 feet.

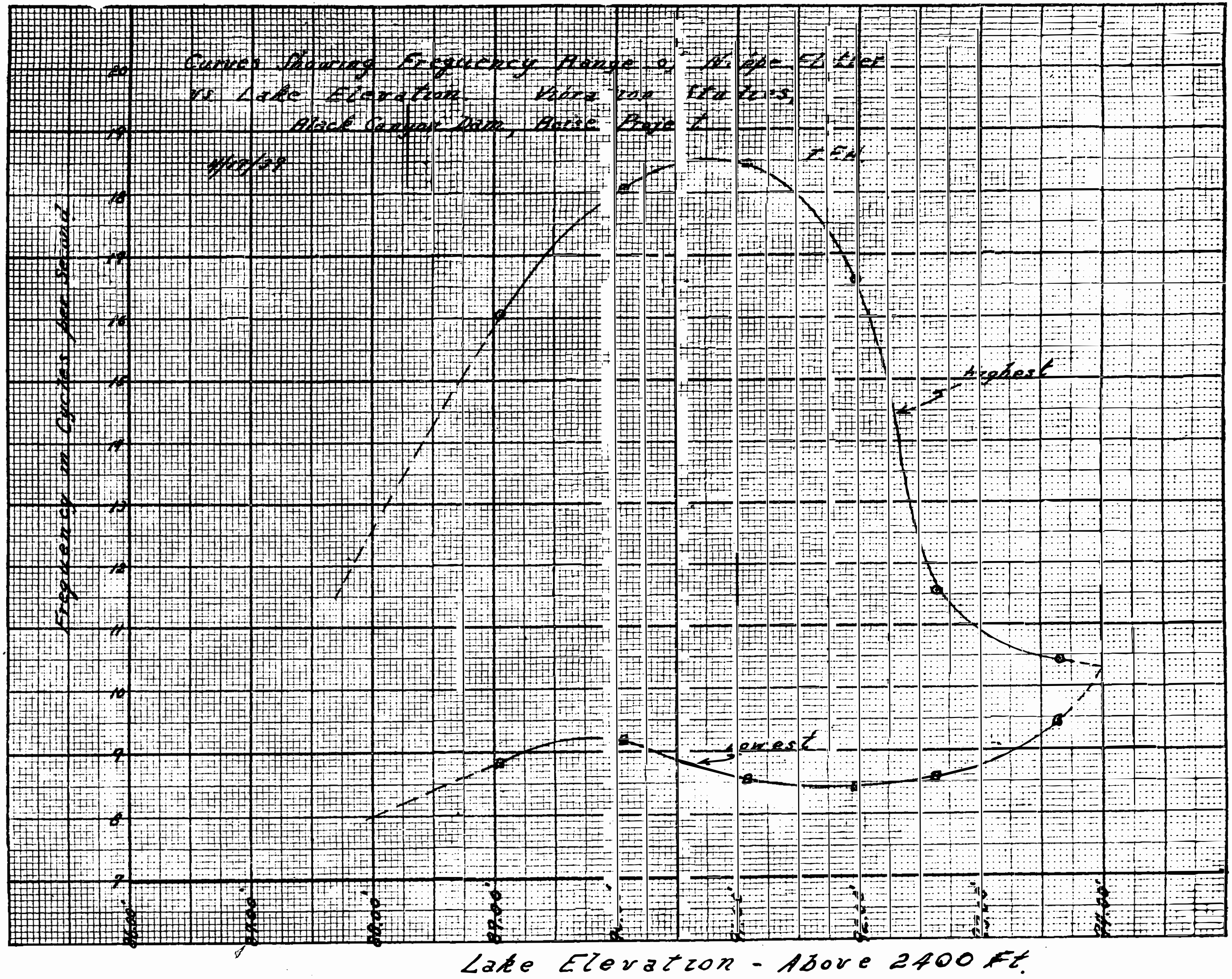
From the curves showing the gate positions at which the flutter started and stopped versus lake elevations, it can be seen that as the lake elevation decreases from about 94.00 feet, the range over which flutter occurs increases up to about 91.00 feet and then begins to decrease. Also these same curves show that the flow over the gate when the flutter starts decreases from high lake elevations until at 89.00 feet the flutter starts with a very thin jet of water over the gate.

The curve of pressure exerted by the flutter versus the lake elevation indicates that the maximum pressure occurs at about 92.00 feet lake elevation. This maximum is about 8.7 pounds per square foot. From the shape of the curve it seems quite certain that this is the maximum pressure that can be expected as the pressure drops off very rapidly as the lake elevations at which no flutter will occur are approached. Also it will be noticed that the curve showing the gate elevation at which maximum amplitude of the flutter occurs versus lake elevation is a straight line and almost exactly with one foot difference in elevation between the gate position and lake elevation.

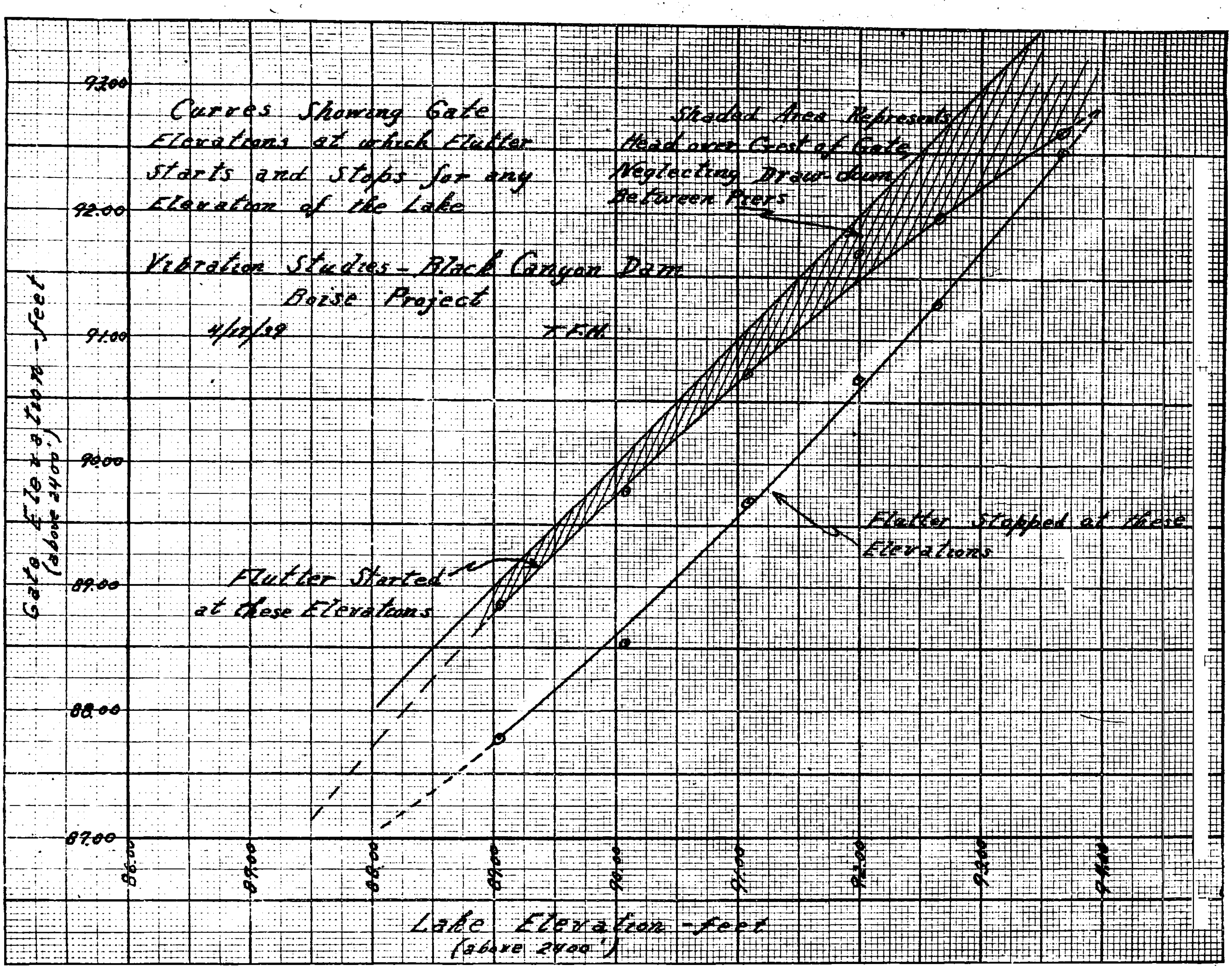
12. Results obtained in attempt to find the natural frequency of dam. Although the records obtained for determining the natural frequency of the dam show a distinct movement of the structure, there is some uncertainty as to just how the resulting records might be interpreted. Some of the records obtained indicate a frequency of approximately 25 cycles per second. However, as this figure is so close to the natural frequency of the accelerometer units, the record is somewhat confusing. Still another record seems to indicate that possibly, when the blast went off, the dam was simply deflected slightly downstrean and then settled back to its original position and failed to oscillate.

Some movements of the accelerometer units recorded during runs made to obtain the frequency and amplitude of the flutter of the jet show some extraneous vibrations present which seems to

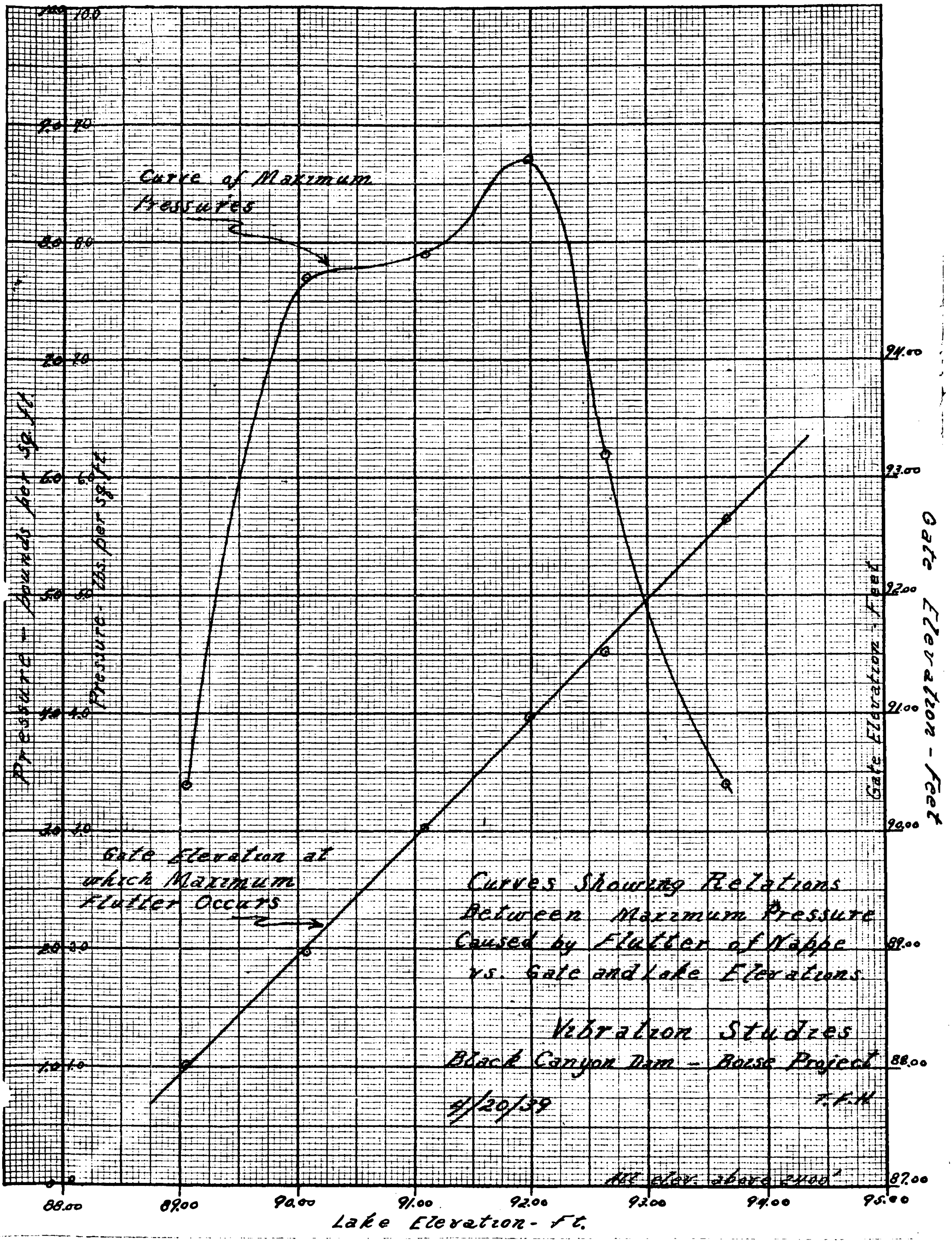

Curve Showing Relation Between Frequency of Flutter,
Gate Elevation, and Lake Elevation
Vibration Studies Black Canyon Dam - Boise Project
4/20/39
T.F.H.
Lake El 89.05'
Lake El 91.98'
Lake El. 92.65'
Lake El. 93.66'
All elev. above 2400'
Frequency - Cycles per Second
Gate Elevation - Feet
87.00
88.00
89.00
90.00
91.00
92.00
93.00
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20



Curves Showing Frequency Range of
vs Lake Elevation
Black Canyon Dam, Boise Project
Frequency in Cycles per Second
Highest
Lowest
Lake Elevation - Above 2400 Ft.



Curves Showing Gate
Elevations at which Flutter
Starts and Stops for any
Elevation of the Lake
Vibration Studies - Black Canyon Dam
Boise Project
4/10/29
K.F.H.
Shaded Area Represents
Head over Crest of Gate
Neglecting Draw-down
Between Piers
Flutter Started
at these Elevations
Flutter Stopped at these
Elevations
Gate Elevation - feet
(above 2400')
Lake Elevation - feet
(above 2400')
87.00
88.00
89.00
90.00
91.00
92.00
93.00
86.00
94.00


Curve of Maximum Pressures
Gate Elevation at which Maximum Flutter Occurs
Curves Showing Relations Between Maximum Pressure Caused by Flutter of Nappe vs. Gate and Lake Elevations
Vibration Studies
Black Canyon Dam - Boise Project
4/20/39
T.F.H.
All elev. above 2400'
Pressure - pounds per sq. ft.
Pressure - lbs. per sq. ft.
Gate Elevation - Feet
Lake Elevation - Ft.
88.00
89.00
90.00
91.00
92.00
93.00
94.00
95.00
87.00

indicate that these may be caused by the natural vibration of the dam. They definitely are not related to the flutter of the jet and some occurred while no flutter was present. But here again, the frequency of this vibration is around 25 cycles per second and close enough to the natural frequency of the instruments to be confusing. Some records show a marked beat note superimposed upon a fundamental vibration which seems to be the natural frequency of the instruments. Analysis of this beat note might be interpreted as a beat between the natural frequencies of the dam and instruments, if the dam were vibrating at its natural frequency. This interpretation would give a figure for the natural frequency of the dam of about 23.8 cycles per second. Some rough calculations were made for the natural frequency by assuming the cross section of the dam to be a wedge-shaped beam, cantilevered at the base. These calculations give a frequency of about 21 cycles per second. Hence, it might be concluded that the natural frequency of the dam is somewhere between 20 and 25 cycles per second.

13. Results of aerating the jet. When the jet is aerated at the midpoint between piers as described above and shown in the accompanying pictures, it becomes apparent from the oscillograms obtained of the action of the pressure cells and the pictures obtained that the flutter ceases almost entirely. In order to eliminate any possible doubt as to whether or not the aeration of the jet at this point did affect the flutter, the log was removed and the flutter returned with the same intensity as before the log was put in place. Upon replacing the log to break the jet, the flutter stopped. When the log was placed to break the jet at the one-third point a study of the pictures and oscillograms obtained shows that the two-thirds portion of the jet still continued to flutter while the one-third portion had stopped.

Hence it might be concluded that the cause of the flutter is probably a question of air demand beneath the jet and that proper aeration beneath the jet has a marked effect in reducing or eliminating the flutter.

14. Possible effect of jet flutter on stresses in the Grand Coulee and Shasta Dams. The following estimates were calculated by Mr. R. E. Glover and checked by J. Parmakian:

The maximum amplitude of the pressure variation observed beneath the overflowing jet at the Black Canyon diversion dam was 8.7 pounds per square foot. The stresses at the base of the dam due to this pressure applied as a static load on the vertical projection of the raised drum gate are as follows:

Grand Coulee Dam	0.0255	$\frac{\text{lb.}}{\text{in.}^2}$
Shasta Dam	0.0276	$\frac{\text{lb.}}{\text{in.}^2}$

The figure for the Grand Coulee Dam is for elevation 850 and is estimated on the basis of two 135- by 28-foot drum gates acting on a 300-foot length of dam. The Shasta drum gates are 110- by 28-feet but since the drum gate crest occupies only a relatively small part of the total crest length, the computations are based upon a unit length of dam and drum gate.

The stresses given above will be increased if the period of jet flutter happens to coincide with one of the natural frequencies of the dam. Under these conditions resonance will occur and the maximum amplitude will then depend upon the amount of natural damping present.

Data for the present computations were obtained from vibration measurements made by the U. S. Coast and Geodetic Survey on the Baker River Dam in Washington, the Morris Dam in California, and from vibration measurements made by the project personnel on the intake towers at the Boulder Dam. The interpretation of the data was made in this office in all cases. The analysis of the data yields the following results:

	Damping
Baker River Dam	1/16th critical
Morris Dam	1/9th critical
Boulder intake towers	1/100th critical

The factor to apply to the static load stresses to obtain the maximum stresses under dynamic conditions is given by the simple formula:

$$S_m = \frac{1}{2n} S_s$$

where

S_m represents the maximum stress under dynamic conditions

S_s represents the stress due to the maximum force applied as a static load

n represents the ratio of the actual to the critical damping.

The critical damping is the least amount of damping required to completely suppress the tendency of the structure to oscillate. The multipliers corresponding to the Baker River and Morris Dams and the Boulder intake tower damping rates are therefore 8.0, 4.5, and 50.0, respectively, and the corresponding stresses are:

	S_m
Grand Coulee Dam	0.115 to 1.27 lb./in.^{2}
Shasta Dam	0.124 to 1.38 lb./in.^{2}

The upper figure is regarded as being improbable.

In making the above estimate, the data obtained at the Black Canyon Dam were used without modification. It is probable, however, that the maximum pressure fluctuation under the jet will increase with an increase in the size of the gate. The Black Canyon drum gates are 64 feet long by 14.5 feet high and are, therefore, approximately half as high as the Grand Coulee and Shasta gates. Any reasonable allowance for this factor would, however, hardly be sufficient to make the vibration stresses assume importance from a structural or stability standpoint.

The relation between the maximum pressure and the height of the gate and the influence of the gate dimensions on the flutter frequency are, as yet, unknown and it would, therefore, add greatly to the value of the present data if measurements on gates of other dimensions could be obtained.

The estimated natural frequencies for the Grand Coulee, Shasta, and Black Canyon Dams are:

Dam	Natural Frequency
Grand Coulee	4.7 $\frac{\text{cycles}}{\text{sec.}}$
Shasta	4.1 $\frac{\text{cycles}}{\text{sec.}}$
Black Canyon	20.1 $\frac{\text{cycles}}{\text{sec.}}$

15. Some general remarks as to the probable cause of the jet flutter as concluded from observation made at Black Canyon Dam and various other similar structures:

Although vibration of the overfalling sheet of water from drum gates and weirs has been noted, little is known in regard to the mechanics of the phenomenon or the causes. Paucity of data concerning the subject forbids broad conclusions but certain deductions may be drawn from the observations that have been made: (1) The vibration is confined to the overfalling sheet of water. Only one instance of a structure vibrating as a result of the condition has been reported; (2) the vibration may occur with a number of combinations of drum-gate elevations and heads over the gate; (3) the vibration is caused by an insufficient air supply to the under side of the jet.

While tests were being conducted on a sectional model of the Grand Coulee crest and piers a vibration of the jet was noted at low flows when the gate was raised 86 percent of its total lift. It was concluded that the pressure fluctuation was due to the alternate sealing and breaking of the jets at the back of the pier. This conclusion was very probably influenced by the fact that the jet flowed over the backs of the piers when the gates were at high elevations and the reservoir level was normal, thus causing the region under the flow to be sealed from atmospheric pressure as can be noted in the following photograph. The overfalling water evacuated the air and the pressure under the jet was reduced to the extent that the flow was drawn back against the gate and the level of the water under the jet was raised. The model tests indicated that some provision should be made to admit air to the under side of the spillway jets when the gates operate in the upper region of their travel. Installation of air vents in the sides of the piers on the model eliminated the vibration and recommendations were made that such vents be installed in the prototype. (See memorandum to J. E. Warnock by J. W. Ball, dated July 7, 1938, "Model Studies Concerning the Aeration of the Grand Coulee Drum Gates").

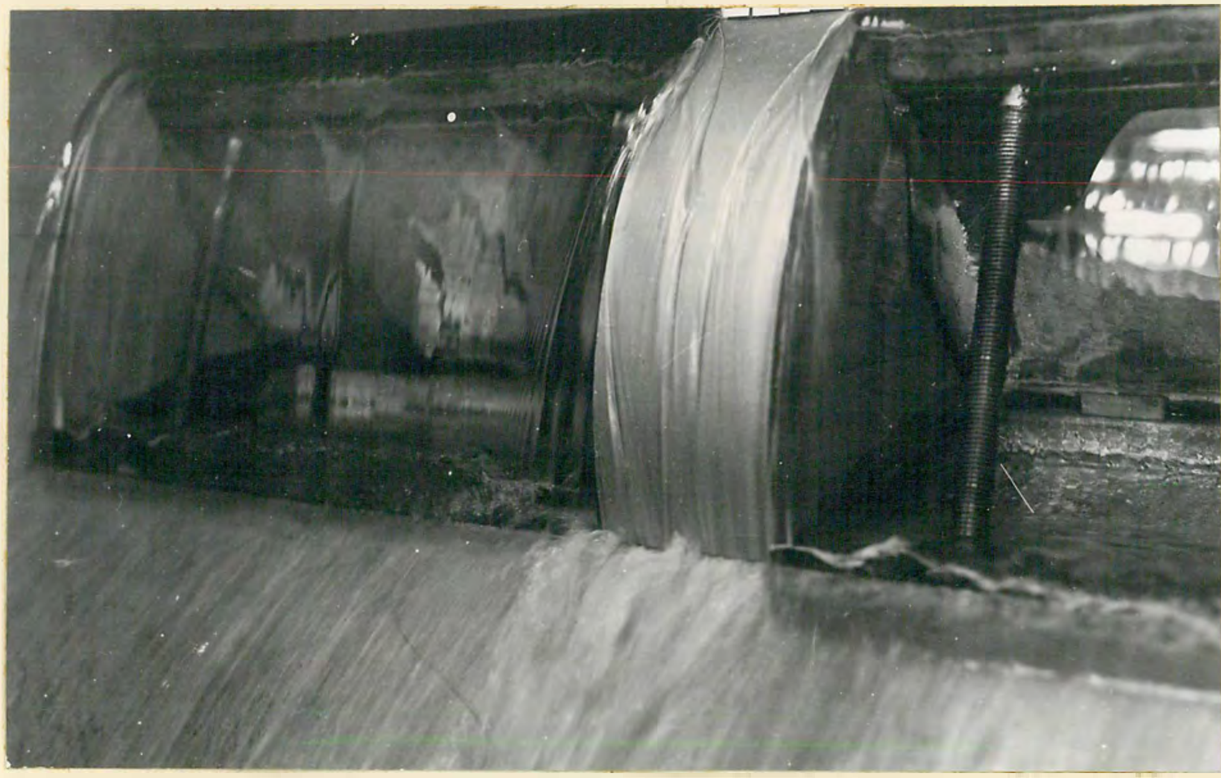
During the 1937 flood over the spillway at Norris Dam, vibration of the jets from all three drum gates was noted for several flow conditions. In the report "Performance of Norris Stilling Basin During 1937 Flood", Mr. G. H. Hickox states relative to the vibration "For small discharges up to 5,000 cubic feet per second, waves occurred on the face of the spillway ---. The waves appeared to be caused by vibration of the sheet of water falling over the gate. This vibration of the nappe does not show in the photographs but may be seen clearly in the motion pictures. It was thought the vibration might be due to an insufficient supply of air to the under side of the nappe. Figure 8 shows debris lodged on the crest of gate 1, causing a large opening in the nappe and allowing free access of air. The vibration of the nappe and the formation of waves was not prevented." Again in the Summary and Conclusions of the same report, Mr. Hickox states "At low discharges and with water flowing over the raised drum gates waves exist on the face of the spillway. They are caused by vibration of the nappe as it falls over the gate to the crest of the dam. The vibration of the nappe is apparently not due to a lack of air supply beneath it. The true cause is not known." The motion pictures referred to by Mr. Hickox were loaned to this office for review. The vibration of the jets over the drum gates was very noticeable for the low flows. The data contained in the report by Mr. Hickox show that the vibration occurred when the gates were from 50- to 70-percent raised and the head was between 1 and 3 feet. Flow conditions for the gate raised 62.1 percent and 1.7-foot head on the gate are shown on the following page.

There was a very noticeable vibration of the nappe from the 12-foot measuring weir at the Montrose laboratory. Offsets in the sides of the flume downstream from the weir provided aeration of the jet at all flows. The vibration was apparent for heads from approximately one-tenth to two-tenths of a foot. For higher heads there was no apparent vibration. The movement was confined to the jet of water flowing over the weir and no surge in the approach channel or vibration of the vertical steel plate and angle forming the weir was noted. No measurements of amplitude or frequency are available.

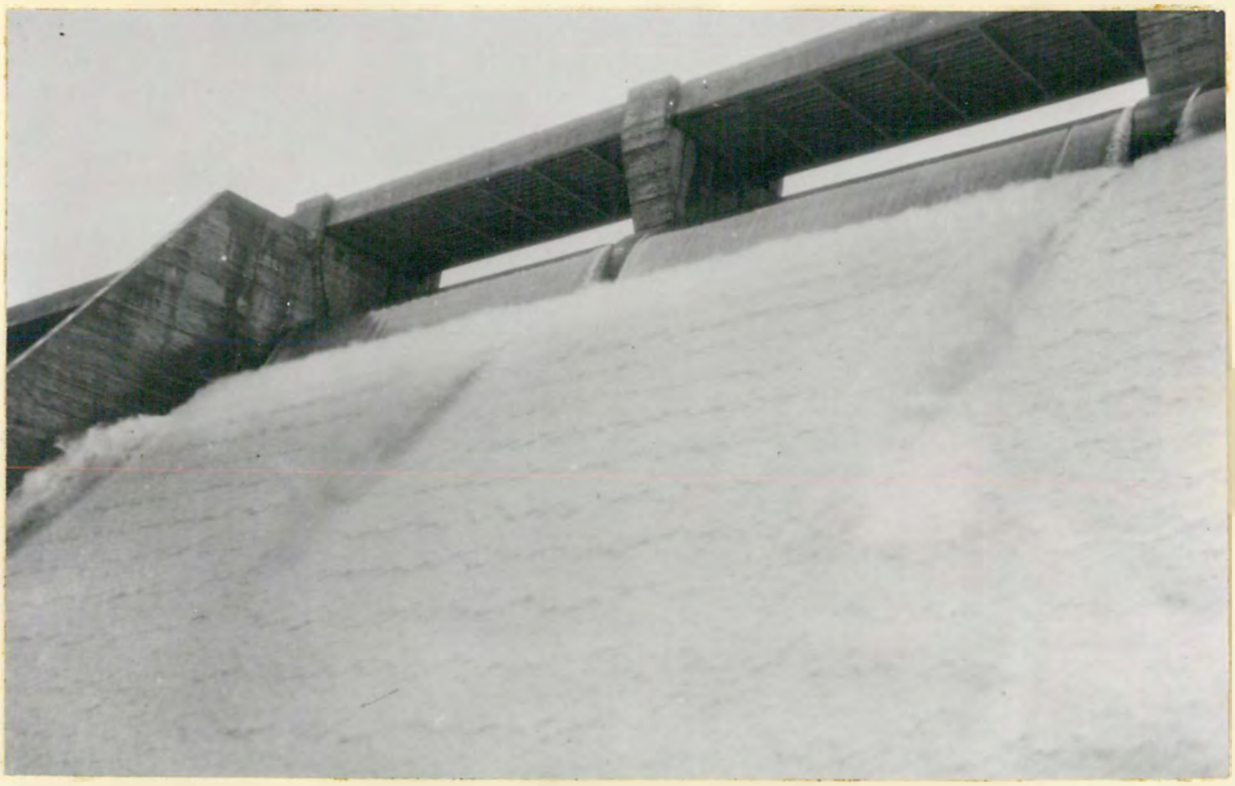
Engineer J. E. Warnock of this office reports observing vibration of the nappes from the movable weirs on the crest of a dam across Cedar River at Cedar Rapids, Iowa. The crests of these weirs were at different elevations. The frequency of the vibration was observed to be less for the weirs having the greater head. In some instances the jet over the weir was separated by debris lodged on the crest but vibration was present in some cases even with a very short length of free crest. Photographs of the vibration are shown on the following pages.

Mr. T. C. Butler, Jr., hydraulic engineer for Pamona Pump Company relates an incident regarding a movable crest dam. When this dam was put in operation the vibration of the nappe was severe, causing much noise and vibration of the structure. After completing plans for revision of the dam the trouble was eliminated by chaining logs to the crest to break the jet, thus allowing aeration of the under side of the nappe.

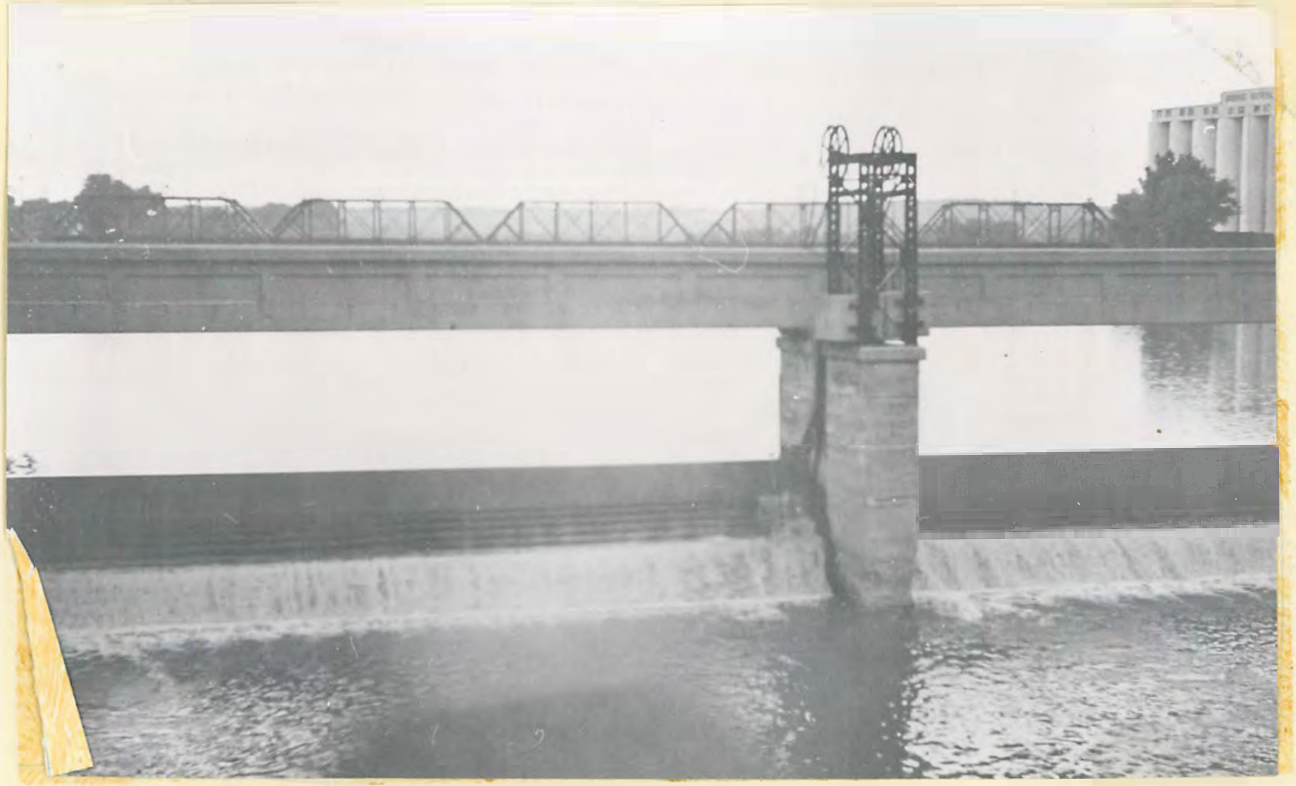
While vibration of the nappe has been observed on certain structures as discussed above, there have been several similar structures from which there has been no report of this phenomenon. The drum gates at Black Canyon Dam, Easton Dam, and Guernsey Dam are all 64 feet by 14.5 feet in slightly different settings. Vibration of the jets is evident at Black Canyon Dam for certain flows but at Easton and Guernsey Dams there is no report of vi-



FLOW OVER BACK OF PIER - 1:40 MODEL OF
GRAND COULEE SPILLWAY CREST



DISCHARGE OF 2,000 SECOND-FEET OVER NORRIS DAM SPILLWAY
RESERVOIR ELEVATION 1030.4 - GATE CREST ELEVATION 1028.7
FIXED SPILLWAY CREST ELEVATION 1020

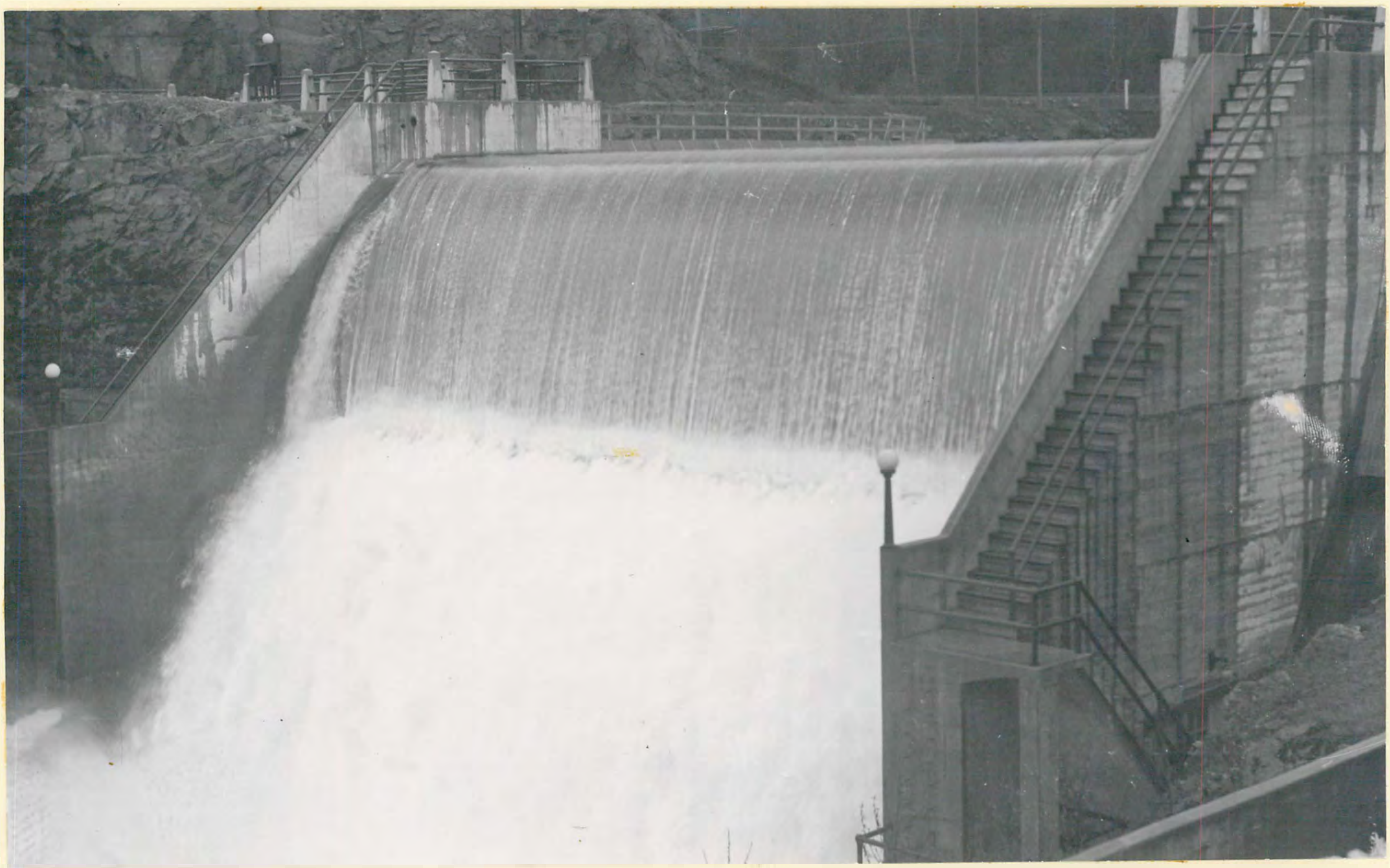


VIBRATION OF JET FROM WEIRS ON DAM IN CEDAR RIVER,
CEDAR RAPIDS, IOWA

bration at any time. At Easton Dam the under side of the jet is sealed from atmospheric pressure for low flows, with the gate completely raised, due to the spread of the jet over the backs of the end piers. This may be seen in the accompanying photograph. The fact that water is raised between the jet and the drum gate shows that a negative pressure exists in that region. The ribbed appearance of the upper surface of the jet is also indicative of a low pressure under the nappe. No vibration of the jet has been reported. Vibration might result if the gate were operated at the intermediate elevations with small heads over the crest. However, since Easton is a diversion dam, the reservoir is maintained at maximum elevation except during the winter months when the lake is drained. No vibration of the jets from the drum gates at Guernsey Dam has been reported. This may again be due to operating conditions but since the gates have been in operation for over ten years it seems logical that if vibration were present it would have been reported some time during that period.

The drum gates at Norris Dam are 100- by 14 feet and the jets vibrate, while at Madden Dam no vibration has been reported on the 100- by 18-foot drum gates. Operating conditions at Madden Dam are such that the gates may not have been operated in the region where vibration would occur. A negative pressure under the jet at Madden Dam, amounting to 8 inches of mercury, occurred just as the gate was being raised from the seat on the crest. No other negative pressure was reported. No vibration of the jets from the 65- by 8-foot drum gates at Tieton Dam has been reported. The under side of the jet is sealed from atmospheric pressure at low flows with the gate completely raised as can be seen in the accompanying photograph. This condition causes the jets to strike the face of the spillway at the base of the gates resulting in a heavy spray. If the jets were aerated at the low flows the spray conditions would be relieved but vibration might result.

Further study is necessary to determine the mechanics of the vibration and its causes. The data collected to date indicate that the vibration is confined to the overflowing sheet of water and that there is no vibration of the drum gates. The major contributing cause is insufficient aeration of the jet. In regard to the mechanics of the vibration, there must be unbalanced forces acting on the jet to start the phenomenon. The region between the drum gate and the overfalling sheet of water is in a sense an air conduit. Air flowing into this conduit at the ends of the gate is absorbed by the jet. Since the absorption of air by the jet is not at a constant rate, fluctuations in the velocity of the air passing through the conduit result



GATE COMPLETELY RAISED - SMALL FLOW OVER CREST - EASTON DAM - YAKIMA PROJECT

65- BY 8-FOOT DRUM GATES ON TIETON DAM SPILLWAY
GATES COMPLETELY RAISED - SMALL HEAD OVER GATES

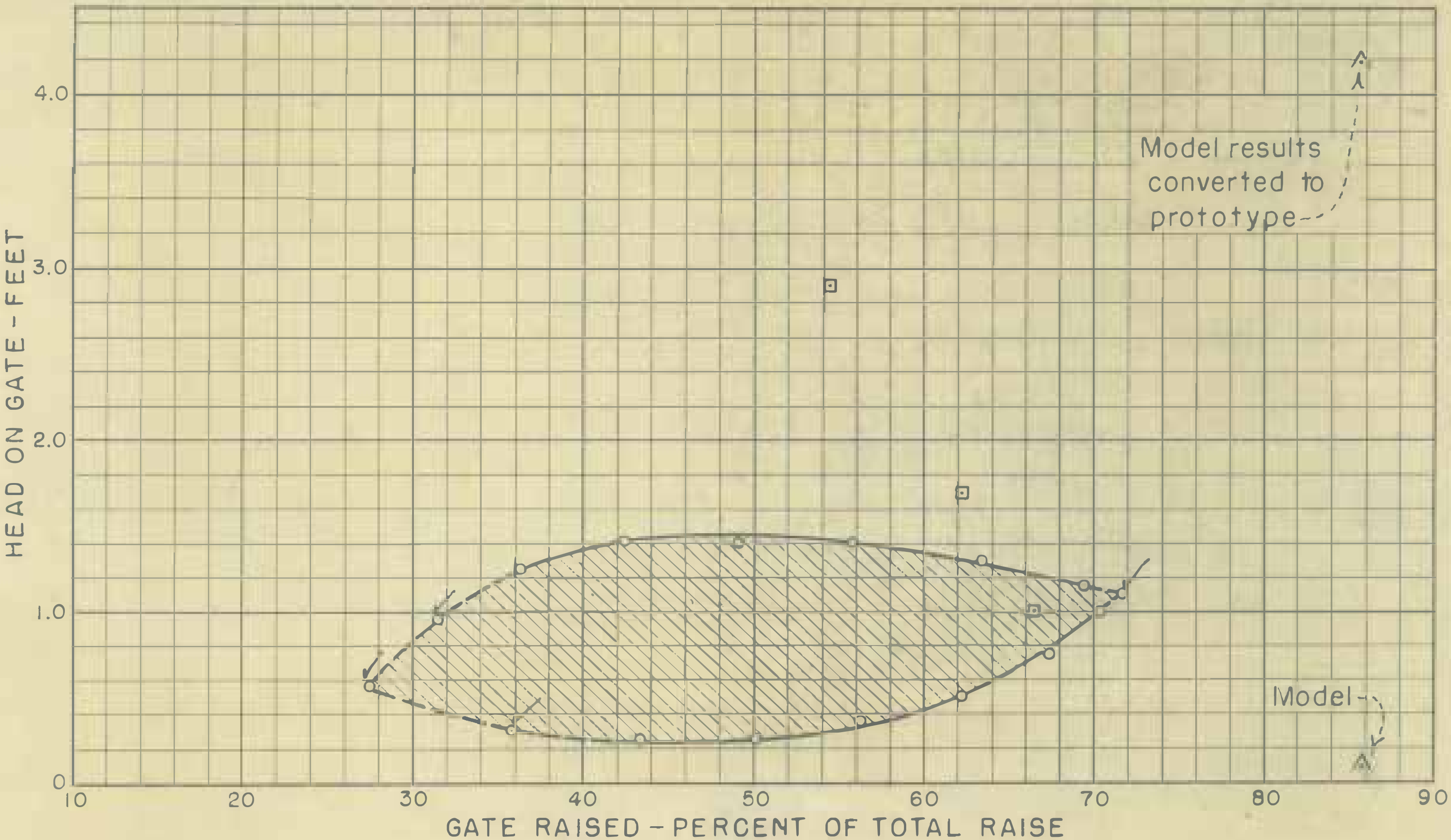
in changes in pressure. These changes in pressure unbalance the natural flow over the lip of the gate and an oscillation results. Once the oscillation has been started, small forces acting on the jet will maintain it in motion. In long gate installations a pressure below atmospheric must exist near the center of the gate in order that a flow of air from the ends of the gate may be maintained. The vibration may result from unbalanced forces caused by this low pressure on the under side of the jet near the center of the gate. Forces acting on the jet as it leaves the lip of the gate are: (1) A force due to the forward momentum of the water and, (2) gravitational force acting downward. The resultant of these forces is in an oblique direction downward. The forward momentum and the force of gravity both remain constant for given flow conditions. The water, due to its initial velocity in the forward direction, follows a parabolic path to the face of the dam. If the pressure under the jet is lowered, atmospheric pressure will act on the upper surface and bend the jet from its normal parabola toward the drum gate. The force added by the atmosphere will move the resultant force down. At the same time the decreased pressure under the nappe will result in a greater velocity of air entering at the ends of the gate and the additional quantity of entering air will then allow the jet to return to its normal position. The inertia of the jet probably carries it slightly above the normal parabola from whence it falls to its natural position and the cycle is repeated. This explanation is exemplified by the observation that the amplitude of the vibration is greatest near the center of the gate and lessens to the extent that it is very slight at the ends of the gate for some conditions of flow. A further check on this theory might be had by making pitot tube readings to obtain the velocity of the air as it enters at the ends of the gate and the decrease in velocity as the center of the gate is reached.

The conclusion that the vibration of the jet is caused by an insufficient air supply on the under side is contrary to Mr. Hickox's statement. However, the example cited by him shows the debris lodged approximately 20 feet from the right end of the gate. If the jet is considered to be well separated at this point there would be 80 feet of gate in one section and 20 feet in another. The 80-foot section would be of such a length that the openings at each end of the section would not be great enough to supply sufficient air to the under side and hence would not cease to vibrate. A similar circumstance was demonstrated during the Black Canyon tests as discussed in paragraph 13. Considering this incident, the length of the gate appears to be a factor contributing to the vibration. Another contributing factor appears to be the gate setting. It is logical to assume that the shape of the piers at the ends of the gate, the conformation of the gate, the downstream slope of the dam below the gate, and similar factors would govern the air supply to the under side of the nappe and hence would affect the vibration.

In considering means of aerating the jets from drum gates to eliminate the vibration, some of the previous conclusions should be reconsidered. According to more recent observations, the proposed vents in the piers for eliminating the vibration would not be effective for long gates and probably would not relieve the condition on medium-length gates.

Head over the drum gate plotted against the amount the gate was raised in percent of the total raise for Black Canyon Dam, Norris Dam, and the 1 to 40 model of Grand Coulee Dam is shown on the following page. The vibration of the jet at Black Canyon Dam occurred when the gates were raised from 25 percent to 75 percent of their total travel and the head was from 0.25 foot to 1.40 feet. There was no vibration of the jet when the gates were raised above 75 percent of their total lift. Extrapolation of the data shows that no vibration occurs when the gates are raised less than 25 percent of their total travel. Although the data from Norris Dam are few, the available points indicate that vibration occurs when the gates are raised from 50 percent to 70 percent of their total travel and the head is between 1.0 foot and 3.0 feet. The vibration of the jet on the Grand Coulee model occurred when the gate was raised 86 percent of its total travel and with a head over the gate of 0.1-foot model or 4.0-feet prototype. The prototype data indicate that the vibration of the jet occurs when the drum gates are within the middle one-half of their total travel, hence, vents provided to aerate the jet for the upper 30 percent of the gate travel as indicated by the model, would be only partially effective.

The problem should be recognized to exist and not be overlooked in the design of structures. The causes of the vibration should be further investigated. Test equipment should be an integral part of future drum-gate installations until sufficient data have been collected to analyze the conditions and enable the designer to introduce preventive measures. Should the vibration on existing structures become severe enough to damage the structure or cause vibration of surrounding pipes and windows, having a natural frequency the same as that of the vibrating jet, relief may be had by fastening small temporary piers to the lip of the drum gate to divide the jet and admit more air to the under side. In the case of Grand Coulee Dam, Shasta Dam, and other structures equipped with more than one drum gate, the desired quantity of water can probably be passed by manipulating



EXPLANATION

- ○ Black Canyon Dam.
- ○ Extrapolated from Black Canyon Dam Data.
- ⊡ Norris Dam.
- Λ Grand Coulee 1:40 Model.

NOTE

The shaded area represents conditions under which vibration occurs at Black Canyon Dam.

C. W. T. 6-27-39

the gates in such a manner that none of them will be operated in the range in which vibration of the jet will occur. Probably the most important matter to be observed in connection with the vibration is to inform the operators of drum-gate structures in regard to the nature of the problem, its effects, and the fact that the condition can be relieved by proper manipulation of the gates. If any vibration is observed it should be promptly reported.

16. Summary and conclusions. The results of this investigation may be summarized as follows:

A. The flutter of the nappe occurs over a definite range of lake elevations. In the case of Black Canyon Dam, this range is from 2486.50 to 2494.00 feet.

B. In this range of lake elevations mentioned above, flutter occurs over a definite range of gate positions. The range of gate positions over which flutter occurs depends on the lake elevation and was found to be a maximum of about 1.2 feet at a lake elevation of about 91.00 feet at Black Canyon Dam.

C. The frequencies found range from about 7 to 18.0 cycles per second.

D. The amplitude of the flutter measured as a pressure exerted on the dam reaches a maximum of about 8.7 pounds per square foot.

E. The maximum pressure was found to occur at all elevations of the lake, where flutter was present, when the difference in elevation between the lake and the crest of the gate was about one foot.

F. Proper aeration of the jet, such as allowing air to enter at the center of the spillway gate, has a marked effect in eliminating the flutter of the nappe.

G. The slight vibrations found in Black Canyon Dam were not caused by the flutter of the jet.

H. Although lack of sufficient information regarding the characteristics of the jet flutter that might be expected at Shasta and Grand Coulee Dams, prevents accurate calculations as to the stresses in these structures that might result, it seems quite probable, from present estimates, that these stresses will be of such magnitude as to assume little importance from a structural standpoint.

I. Observations made not only at Black Canyon Dam but on various other similar structures seem to indicate that the cause of the flutter is a question of air demand beneath the jet. However, further investigation of and reports on this subject are necessary before definite conclusions can be drawn as to its cause and prevention.

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