UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDY TO REDUCE THE VIBRATION OF KEECHELUS DAM OUTLET WORKS--YAKIMA PROJECT, WASHINGTON

Hydraulic Laboratory Report No. Hyd-342

ENGINEERING LABORATORIES BRANCH

DESIGN AND CONSTRUCTION DIVISION
DENVER, COLORADO

November 23, 1953

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Laboratory Report No. Hyd-342
Hydraulic Laboratory Section
Written by: J. C Schuster
Checked and
reviewed by: W. C. Case
J. W. Ball

Subject: Hydraulic model study of the vibration of Keechelus Dam Outlet Works--Yakima Project, Washington

PURPOSE

Determine the cause of the severe vibration of the outlet gate structure (tower) during operation of the upper and lower cylinder gates and evolve a means of reducing or eliminating this vibration.

CONCLUSIONS

1. Extreme turbulence with rapid changes in pressure originating from the dissipation of energy within the tower structure causes vibration of the structure during operation of the cylinder gates at partial openings.

2. The vibration characteristics of the prototype structure could be evaluated only qualitatively by model studies, because it was infeasible to obtain similarity for the physical properties of the model and field structure.

3. The vibration intensity will vary depending on the manner in which the two cylinder gates and six inlet slide gates are used to control the outflow.

4. As the lower cylinder gate is opened, while the six inlet slide gates are open, the vibration intensity increases to a maximum as the discharge reaches about 2,500 cfs (Curve d, Figure 8). The intensity then decreases until at full gate opening it is about 40 percent of the maximum. With this method of operation vibration is indicated to be quite severe at 1,500 cfs discharge (Curve b, Figure 10).

5. The vibration is similar whether the cylinder gates are operated singly or simultaneously.

6. The maximum vibration as indicated in No. 4 above will be reduced approximately 3.3 times by leaving the lower cylinder gate open and regulating the outflow through equal openings of the six inlet slide gates. This operating procedure and the opening of the upper cylinder gate after the six slide gates are fully opened will permit releases to the tower capacity (about 3,950 cfs) without excessive vibration.

7. The placing of a control, such as a slide gate or butterfly valve at the downstream end of the outlet conduit, will reduce the vibration about 7.8 times over that for the condition where the discharge is controlled by the six inlet slide gates.

8. Rating curves for various combinations of the six inlet slide gates, with the lower cylinder gate open, are contained on Figure 12. The capacity of the outlet with the lower cylinder gate and the six slide gates fully opened is about 3,600 cfs. The 3,950 cfs maximum flow is obtained by opening the top cylinder gate after the lower cylinder gate and slide gates are fully open.

RECOMMENDATIONS

1. Control the outlet discharge with the six existing slide gates by operating the gates in a symmetrical pattern such as indicated by the rating curves of Figure 12.

2. Consider the installation of a slide or other suitable discharge control in the discharge conduit if the tower is ever rehabilitated.

ACKNOWLEDGMENT

Engineers from the Dams Branch and the Hydraulics Laboratory of the Engineering Laboratories Branch collaborated in this investigation.

INTRODUCTION

Keechelus Dam, completed in 1917, is located approximately 75 miles southeast of Seattle on the Yakima River near Easton, Washington (Figure 1). The reservoir behind this dam, with Kachess and Cle Elum Reservoirs nearby, is used for flood control and irrigation storage. Keechelus Dam is an earth-fill structure approximately 100 feet high above the stream bed and 6,500 feet long. An uncontrolled spillway with crest at elevation 2515 is located at the left abutment of the dam.

The outlet works is located approximately 1,800 feet to the right of the spillway. It consists of a gate tower 300 feet upstream from the axis of the dam and within the reservoir and approximately 450 feet of 11-foot 10-inch-high horseshoe-shaped conduit passing through the dam to a channel downstream (Figures 2, 3, and 4). The concrete gate tower structure contains two concrete cylinders, the outer being 1 foot eccentric with respect to the inner. The inner cylinder varies in inside diameter from 12 feet 3 inches at the bottom to 14 feet 9 inches at the top by steps in wall thickness which varies from 3 to 2 feet. The bottom of this cylinder is at elevation 2406 and the top at elevation 2525, 5 feet above the maximum reservoir elevation. Nine openings 4 feet high and approximately 3.2 feet wide at two levels, elevations 2415 and 2470, form water passages through the inner cylinder. They are controlled by two 12-foot-diameter cylinder gates operated from the gatehouse on top of the inner cylinder. There are nine pier flow guides at each elevation (Figure 4, Section D-D). Three of the flow guides are 120 degrees apart and extend as vertical separating walls between the inner and outer cylinders. One of the three walls is located on the outlet center line directly above the entrance of the outlet conduit and is the full height of the space between the inner and outer cylinder. The other two walls are not continuous but have 4-foot-high openings with bottom elevations of 2440 and 2448. The tops of these walls are at elevation 2474 and the bottoms at elevation 2430. A 27-foot 9-inch-inside-diameter outer cylinder extends from elevation 2415 to elevation 2474 and has a 3-foot-thick wall. The inlet to the gate tower contains six 7-foot-high by 3-foot-wide slide gates separated by piers. They are spaced on approximately 30 feet of the circumference of a 54.5-foot radius circle having its center on the outlet works center line 29.5 feet downstream of the inner cylinder center. Water is passed radially through a portion of the outer cylinder into the space between the two cylinders, then through the cylinder gate apertures into the inner cylinder and out through the outlet conduit. The invert of the conduit intersects the inner cylinder at elevation 2424.3. A vertical pier 2 feet thick and 11 feet long on the outlet center line divides the conduit entrance. A transition from the rectangular entrance to the horseshoe-shaped conduit is accomplished in a distance of 36 feet.

A paragraph included in a letter to the Regional Director from the Yakima Project dated March 6, 1950, subject: "Spillway repairs--Keechelus Dam--Yakima Project, Washington," stated the problem as follows:

> "Regarding vibration conditions in the outlet gate structure, experience has shown that vibration develops to an alarming extent when discharging about 1,500 cfs. The problem arises from rather explosive blasts of entrapped air which blow upward through the gatehouse with violent force. Simultaneous opening

of both lower and upper cylinder gates is never permitted because of severe vibration effect which develops when that is done."

Apparently the vibrations were transmitted throughout the gate structure since they were experienced from the gatehouse which is above the water surface. A flow condition transmitting pressure changes to component parts of the structure could cause the vibration as described from the "explosive blasts of entrapped air" and the "severe vibration effect" for simultaneous opening of both lower and upper cylinder gates. The laboratory constructed a scale model of the tower and outlet conduit to determine the cause of the vibration and to find ways of eliminating or reducing it.

OUTLET WORKS INVESTIGATION

The Model

The model used to investigate the vibration was a 1 to 15 scale, metal, wood, and plastic structure (Figure 5A). The model tower was attached to a reservoir head box with flanges which allowed the upstream half of the outer cylinder and the inlet structure to be contained within the head box. This arrangement gave sufficient space for water to circulate about the portion of the outside cylinder contained in the head box (Figure 5B) even though the prototype tower is completely surrounded by water. With the inlet to the tower located near the bottom of the structure, any effect on entrance-flow conditions due to submerging only half of the model tower was negligible. The downstream half of the tower cylinders, cylinder gates and apertures, and the exit conduit is visible from outside the head box. Six slide gates were made of 1/16-inch galvanized iron and placed in slots cut in the inlet piers (Figure 5B). The slide gate stems passed outside and between the head box and the upper part of the inner cylinder (Figure 5A). The cylinder gates were constructed and machined of brass to a scaled weight of approximately 7.5 pounds. A screw-lift bracket was mounted on a platform above the model and attached to the three gate stems of each cylinder gate. The 1/4-inch bronze gate stems were bolted to the gate-lift brackets. No stem guides were provided on the model gate structure. The rectangular and horseshoe-shaped parts of the exit conduit were of plastic with the transition formed from 20-gage galvanized iron. All piers and flow guides were constructed of wood. Water, supplied by a centrifugal pump and measured by Venturi meters, passed through an 8-inch gravel baffle to be evenly distributed as it entered the model reservoir. Reservoir elevations and pressure measurements were read from water manometers.

Initial Observations

The model was first operated at various reservoir elevations, discharges, and combinations of openings for the two cylinder gate controls. This was done to observe flow conditions which might be conducive to the forces which caused the prototype structure to vibrate. Rapid, violent, and irregular flow disturbances in the form of surges occurred within the inner cylinder. These surges were recorded on photographs, using an electronic flashlamp and camera. This method was used because illumination by flashlamp penetrated and defined the surge better than ordinary floodlighting. Typical surges were recorded at 50 percent cylinder gate opening for a discharge of 1,800 cfs and reservoir elevation 2467.5, and a discharge of 2,720 cfs and reservoir elevation 2520 (Figures 6 and 7).

Water flowed through the nine passages at the lower cylinder gate to the inner cylinder and formed large random eddies and surges. In general, the water flowed across the inner cylinder toward the exit conduit. Periodically, an unstable roller formed and rotated in a vertical plane back toward the upstream side within the inner cylinder. The instability of the roller and eddies affected the flow into the conduit entrance causing a fluctuation of the discharge. During the period that the outflow from the inner cylinder was retarded, the inflow under nearly constant head from the outer cylinder and reservoir was stored and increased the inner cylinder depth. With the increased depth in the cylinder, more of the inflow energy was absorbed, the eddies subsided, and the discharge again increased. This surging explained the statement "* * * rather explosive blasts of entrapped air which blow upward through the gatehouse with violent force" contained in the previously cited letter. The upward surging water which acted as a large piston compressed the air within the inner cylinder and forced it rapidly through the gatehouse. Although not specifically mentioned in the letter, a reversal of this process should occur with less noticeable force as the surge recedes and creates a low pressure within the tower. From observations and testing, the surges and the quantity of water concerned were sufficiently large to produce pressure forces which caused a vibration of the gate tower. If the surges had not been so rapid and the water surface within the tower not so turbulent, the forces acting on the tower would have been more equally distributed, and the vibration less noticeable. However, with the extremely turbulent conditions, the tower was subjected to unequal pressure distribution and rapidly changing dynamic forces.

Discharge Controlled by the Lower Cylinder Gate

The surging or fluctuating flow conditions which caused vibration of the structure were studied by comparing the rate at which the tower absorbed energy from the flow action. Since the surging indicated an unsteady condition of head loss through the cylinder gate apertures, this head loss was used in the equation--$P = \frac{Q\gamma h}{550}$, as a measure of energy dissipation within the tower. In this equation, P is horsepower, Q is the discharge in cubic feet per second, γ is water weight in pounds per cubic foot, h is the average head loss between outer and inner cylinders, and 550 is the number of foot pounds per second for one horsepower.

This analysis was applied to the lower cylinder gate (Figure 8A). Discharge and average head loss data from outer to inner cylinder were obtained for cylinder gate openings of 10 to 100 percent. From these data, the average horsepower dissipated in the prototype tower and the average horsepower dissipated per foot of inner cylinder depth from elevation 2406 were computed (Figure 8A, Curves c and d). A maximum average energy dissipation of approximately 13,800 horsepower, or 270 horsepower per foot of inner cylinder depth, occurred at about 52 percent gate opening for a discharge of approximately 2,700 cfs. At this discharge and opening, the maximum and minimum computed values were 15,200 and 9,900 horsepower.

Two schemes were tried in the model to reduce the vibration without a major revision of the tower. The first scheme was to regulate the flow with the six 7-foot-high by 3-foot-wide slide gates with the lower cylinder gate full open. The second scheme was to place a regulating gate in the discharge conduit with the slide gates and lower cylinder gate full open. The upper cylinder gate was kept closed for all tests on these two schemes.

Discharge Controlled by Six Slide Gates, Equally Opened

Discharge and head loss data for equal openings of the six slide gates were taken with the lower cylinder gate fully open. The head loss measured was that from the outer to the inner cylinder. Values on Curves c and d of Figure 8B show a maximum energy dissipation with the slide gates fully opened. This maximum of 7,400 horsepower for the slide gate control compares to the maximum of 13,800 horsepower for the cylinder gate control. A vibration reduction of approximately 3.3 times was indicated by the energy dissipation curves of the two control methods. The dissipation of energy is now confined to the water between the inner and outer cylinder. Vibration measurements at a discharge of 2,700 cfs were made on the model to check the tower movement with respect to the energy absorbed for the cylinder and slide gate controls.

Vibration Measurements

The flat surfaces of the sheet metal transition between the model tower and exit conduit (Figure 5A) were vibrated by the water surges so a vibration meter, which measured frequency and velocity of displacement, was fastened to the top surface of this transition a distance equivalent to 29.4 feet prototype downstream of the outer cylinder center. This vibration meter was a small alternating-current electricity generator in which the magnetic field of a permanent magnet was cut by a wire coil as the magnet moved at the frequency and velocity of the flat surface of the transition. The output voltage deflected a galvanometer in a recording oscillograph to produce an oscillogram trace whose amplitude was proportional to the velocity of displacement of the flat surface of the transition. The values of the vibration frequency and velocity of displacement of the model transition surface could only qualitatively represent the vibration characteristics of the prototype concrete transition because of the difference in physical properties of the two structures. Traces of approximately 30 seconds at a paper speed of 1.5 inches per second were made for each 10 percent opening of the cylinder gates and six slide gates for the same flow conditions used in the energy dissipation studies. Representative traces of the transition vibration for a 45 percent cylinder gate opening and 50 percent opening of the six slide gates for a discharge of 2,500 cfs are shown on Figures 9A and 9B.

Traces of pressure variation at the bottom of the transition 4 inches upstream of the vibration pick-up were also transmitted to the oscillogram by a reactance-type pressure cell connected to a piezometer (Figures 9A and 9B). The average trace amplitude (average velocity) was used to compare the slide gate control to the cylinder gate control. The percent indicated vibration for any gate opening is the average trace amplitude (velocity) for that opening divided by that for the full opening. The percent indicated vibration for any gate position was common to both schemes, since the conditions for full gate opening were the same in both cases.

Indicated vibration of the tower using the lower cylinder gate only reached a maximum at approximately 2,500 cfs (Curve a, Figure 10). The energy dissipation per foot of depth reached a maximum at approximately 2,700 cfs (Curve b, Figure 10). Both curves are of similar shape and indicate the tower will absorb maximum energy and have maximum vibration at approximately the same discharge and gate opening.

With the discharge controlled by the six slide gates equally opened, the energy dissipation per foot of depth and the indicated vibration of the tower were a maximum at 100 percent gate opening (Figure 10, Curves c and d). The indicated vibration with the cylinder gate control was found to be 4.8 times that for the slide gates at a discharge of 2,500 cfs (Figure 10). A reduction in tower vibration should result from controlling the discharge with the slide gates.

The project letter stated that vibration was severe with a discharge of 1,500 cfs controlled by the lower cylinder gate. No reservoir elevation or cylinder gate opening was given, but a reservoir elevation of approximately 2515 appears possible from the elevation of the debris on the lake banks (Figure 2). Based on the model results, the vibration for the slide gate control would be 23 percent of that for the cylinder gate control at this discharge and head (Figure 10). Some air movement within the gatehouse will be encountered, when the slide gates are used because of surging, but it should be less than for the cylinder gate control.

Discharge Control in Exit Conduit

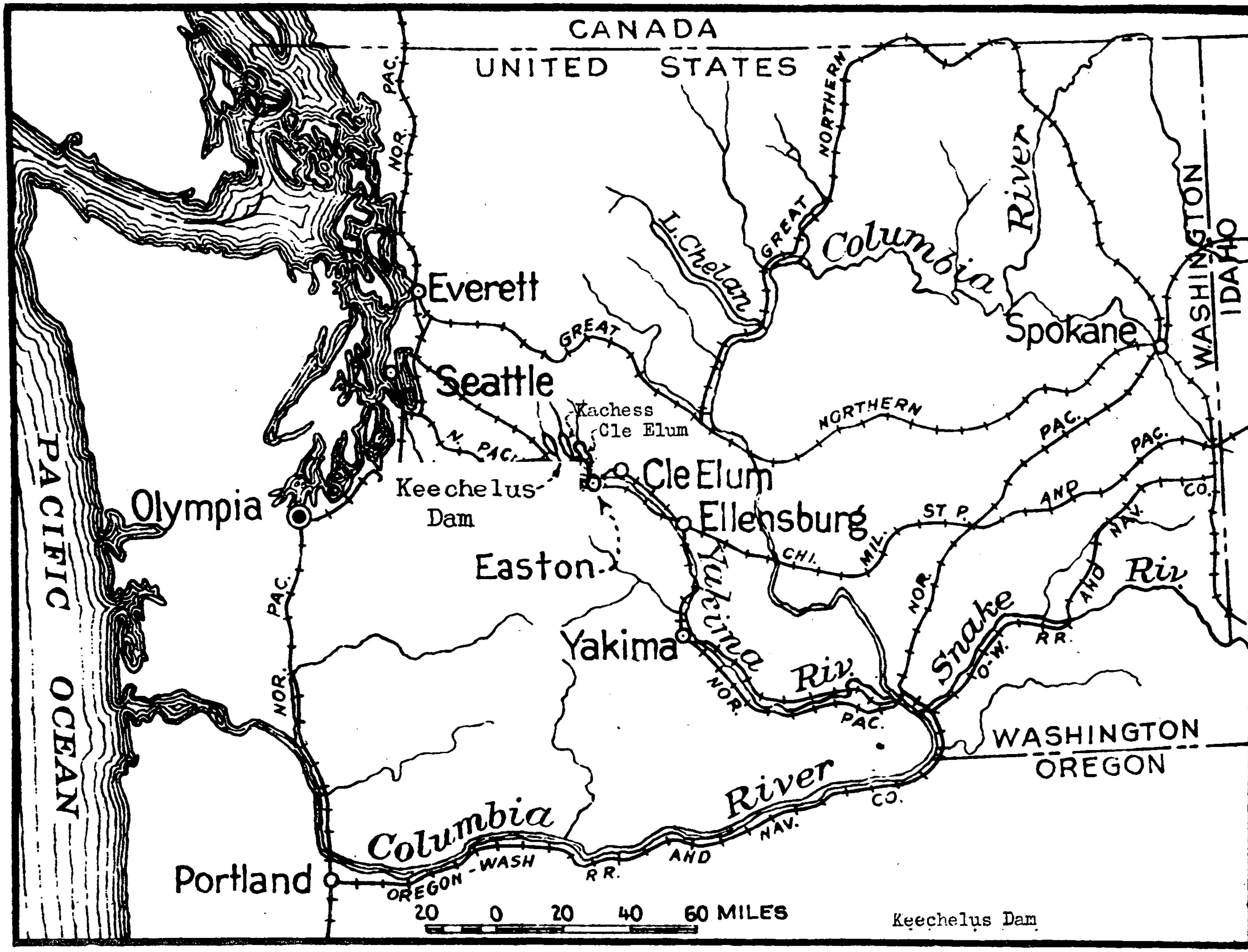
From the foregoing studies it was concluded that the vibration of the structure could be reduced and possibly eliminated by placing a control at the entrance or exit of the discharge conduit. If the conduit were unable to withstand reservoir head, this control would have to be located at the conduit entrance, otherwise it could be placed anywhere in the conduit.

A piece of 16-gage galvanized iron was cut to fit the shape of the discharge conduit and fastened to a shaft in a vertical position to represent a butterfly valve located 68 feet downstream of the outer cylinder center (Figure 5A). This position was selected because the cost of installing model gates or valves within the tower was prohibitive, and the plastic conduit and joints used in the model would not withstand the pressure when the valve was located at the exit. Moreover, conditions within the tower would be similar in both cases, so the location was not important. Satisfactory test results were obtained for comparison with the cylinder and slide gate data. With the slide gates and lower cylinder gate fully open and the discharge controlled by the butterfly valve, the tower head losses were a minimum. The major head loss occurred across the butterfly valve. With a valve located at the entrance or within the conduit, some means would have to be provided in the conduit to dissipate the energy of the discharged jet. With a valve at the exit of the conduit, a stilling basin would have to be provided.

Again, the indicated vibration curve was similar to the energy dissipation curve. For a discharge of 1,500 cfs using the energy curves of Figures 10 and 11, the energy dissipated per foot is 2 percent of that for the cylinder gate control and 13 percent of that for the slide gate control. The discharge and head loss curves pertain only to a butterfly valve in the setting tested. A discharge control located in the exit conduit will result in less tower vibration; thus, a control in the exit conduit should be considered if the outlet works structure is ever rehabilitated.

Outlet Works Capacity

The model slide gates were rated in various combinations of the six gates--each gate either fully opened or fully closed. They were rated in this manner because it was questionable if their condition, after 34 years of use, would permit operating them for extended periods at the more severe conditions for partial openings. With a reservoir elevation of 2520, the maximum discharge was 3,950 cfs for the outlet works tower with the slide gates and two cylinder gates fully open. With the upper cylinder gate closed, the discharge was reduced to 3,600 cfs (Figure 12). The value of 3,600 cfs, from Figure 12, is in disagreement by 4.4 percent with the value of Figures 8 and 11. This was attributed to the lower cylinder gate being wedged in a partially closed position during tests recorded on Figures 8 and 11. The effect of the partially closed gate on the vibration results is considered negligible.



Keechelus Dam

FIGURE I
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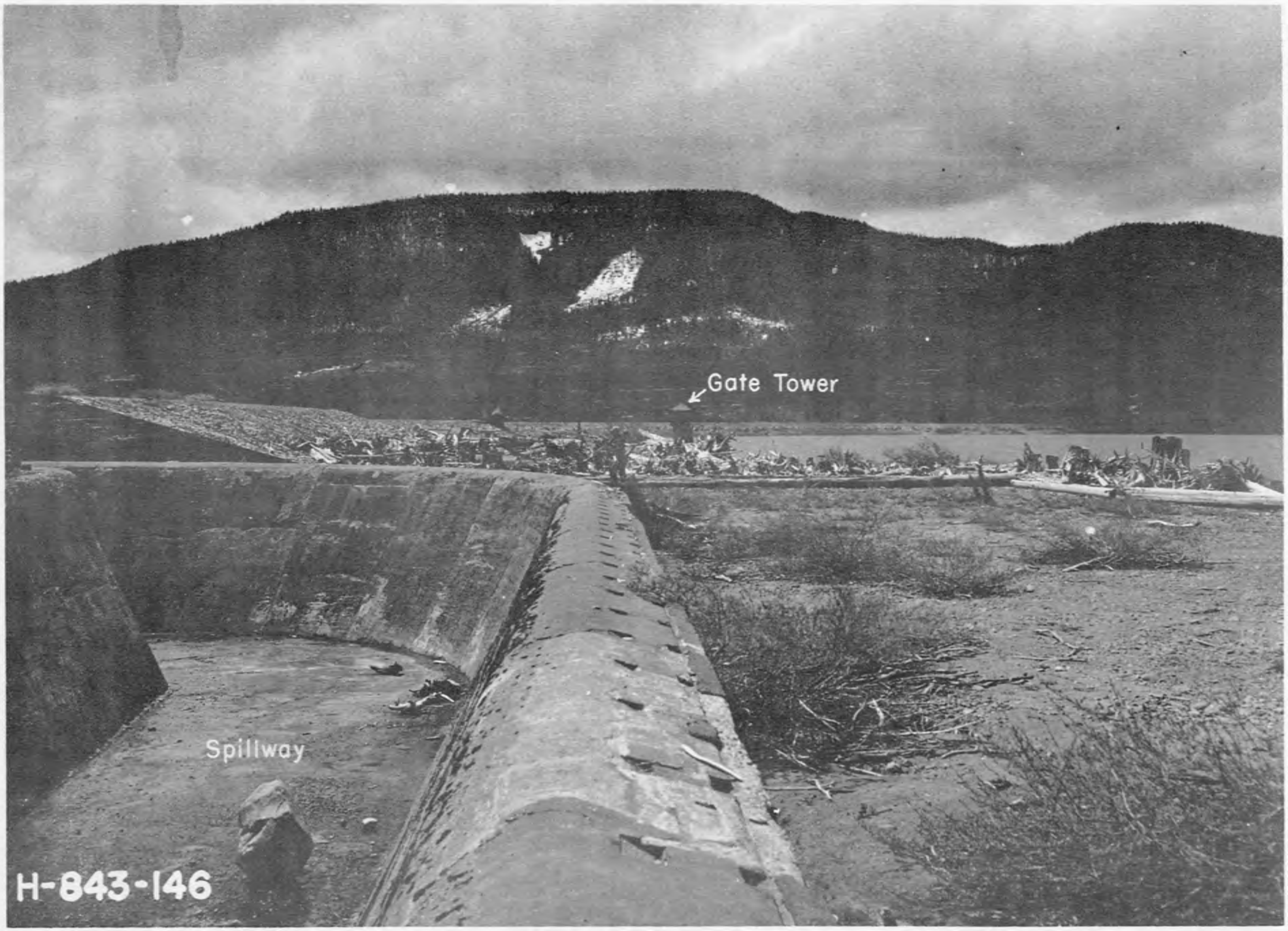


VIBRATION STUDIES - KEECHELUS OUTLET WORKS
View of Keechelus Dam - 1949

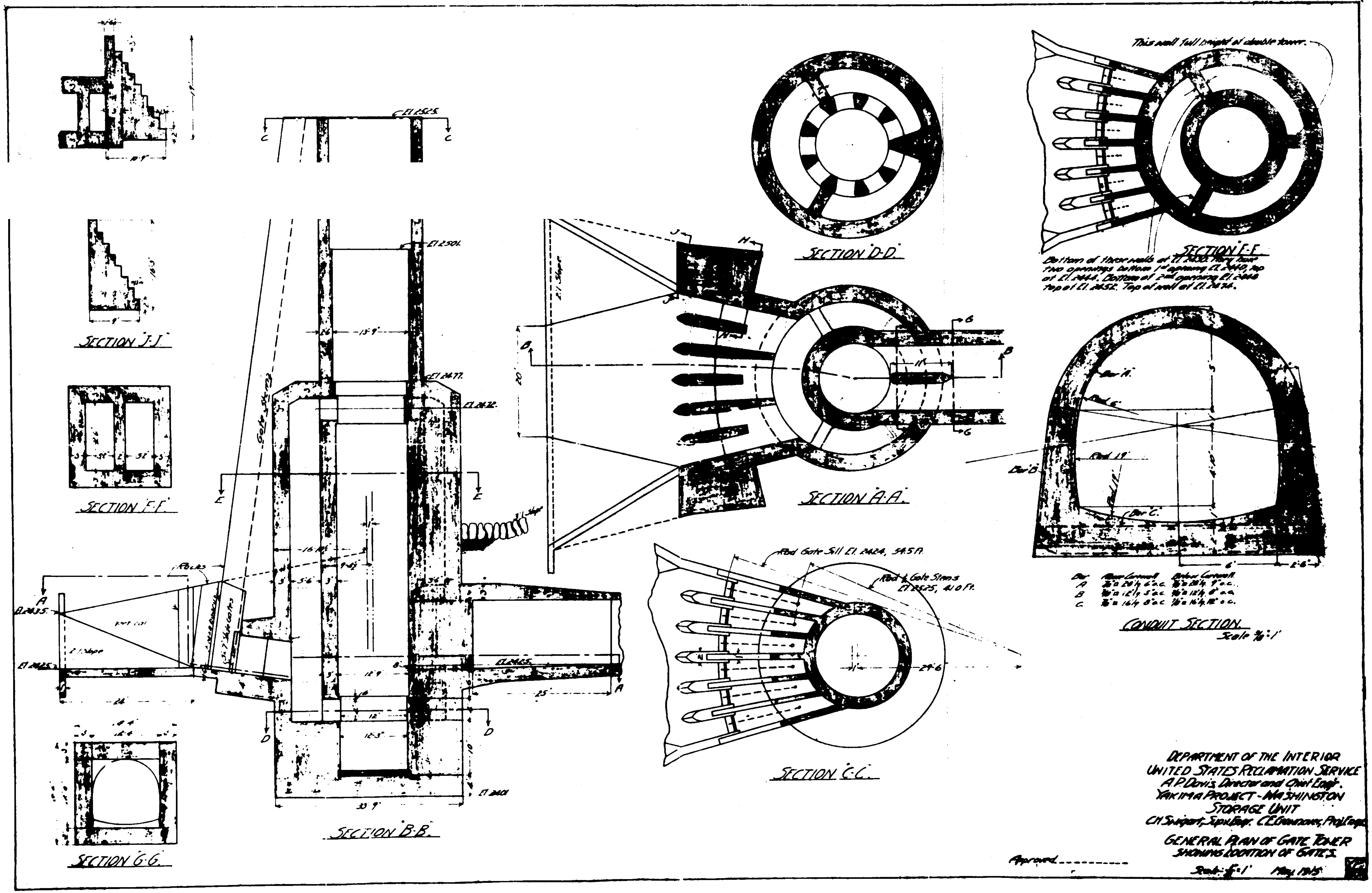
Figure 3
Report Hyd 342

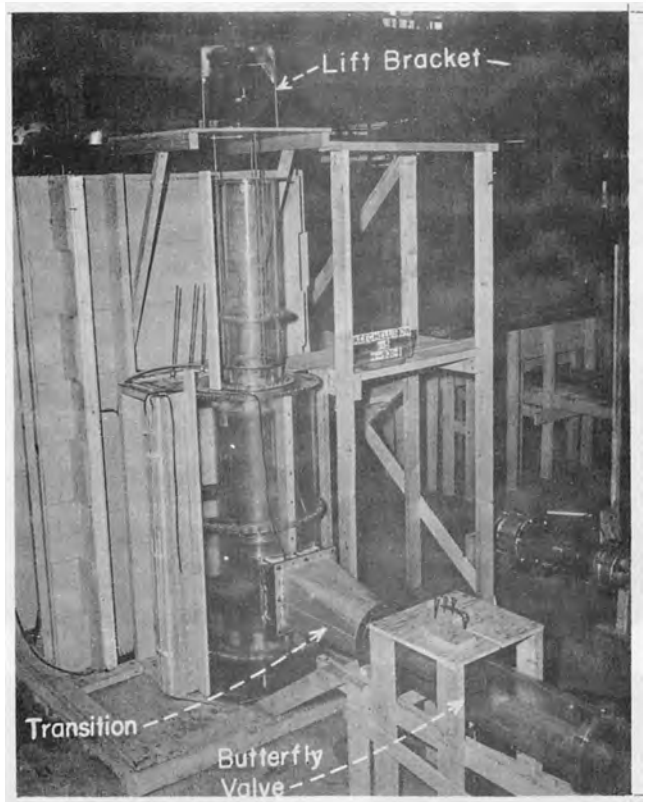
A. Exit channel of Keechelus Outlet Works

B. Exit of Keechelus Outlet Works conduit

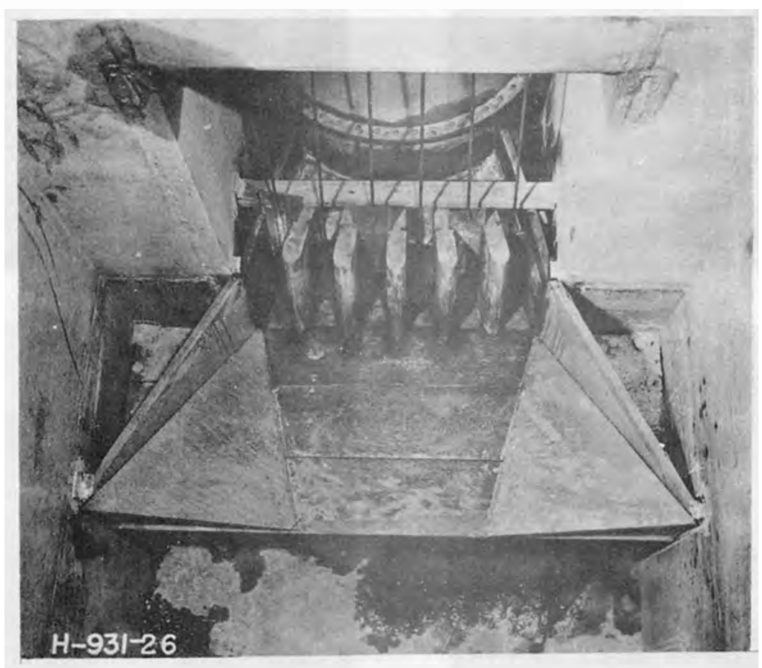
VIBRATION STUDIES - KEECHELUS OUTLET WORKS
View of Outlet Works Exit - 1949

FIGURE 4
REPORT HYD. 342





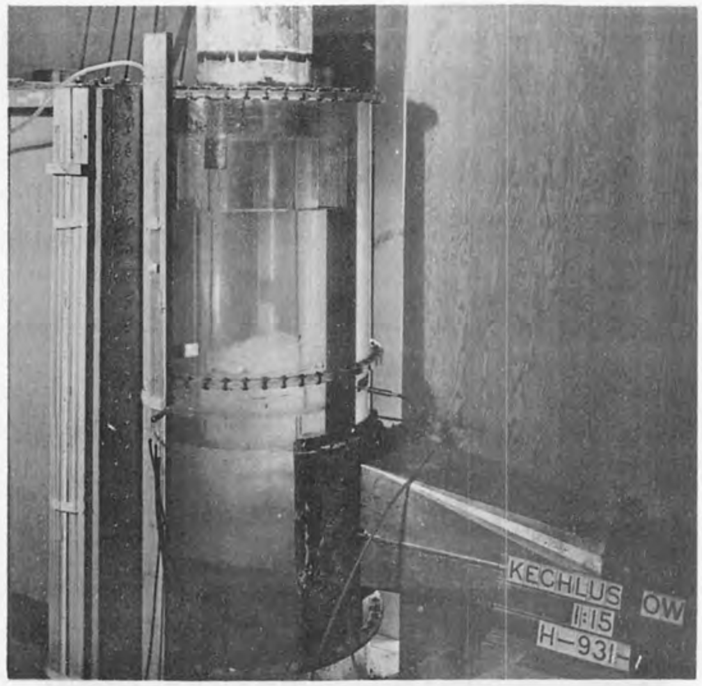
A. Gate tower and exit conduit

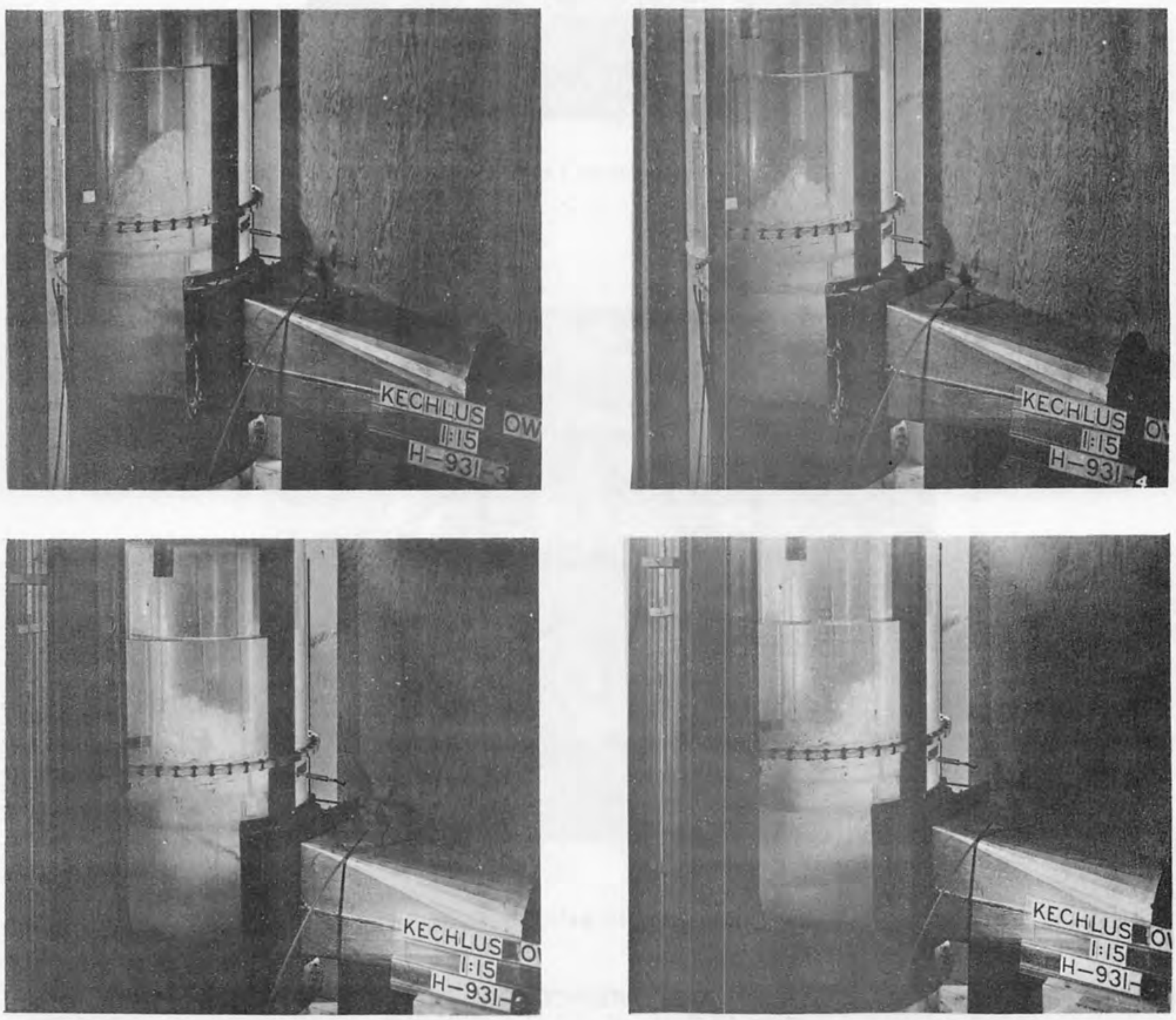


B. Inlet to gate tower

VIBRATION STUDIES - KEECHELUS OUTLET WORKS
1 to 15 Scale Model Outlet Works

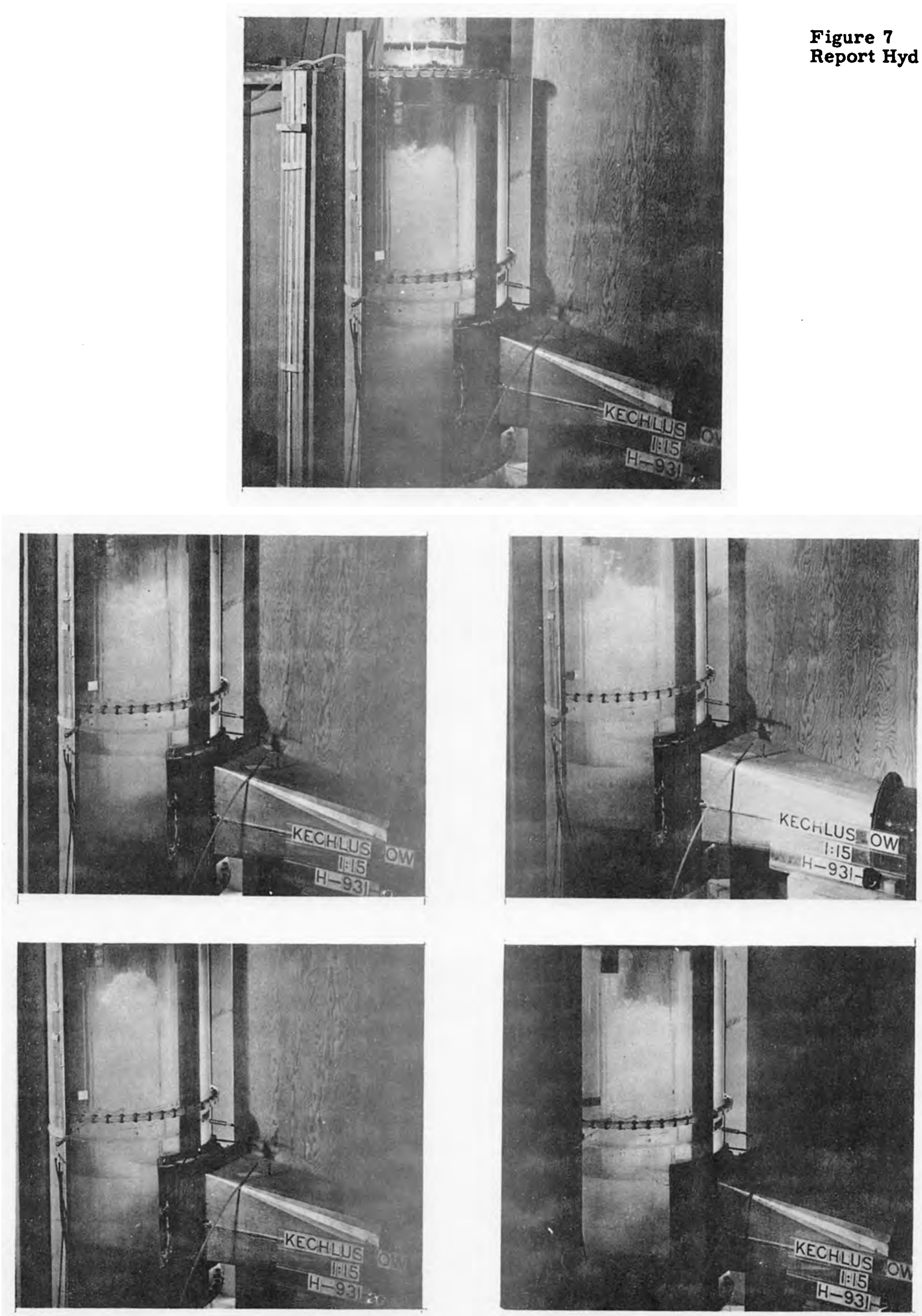
Figure 6
Report Hyd 342



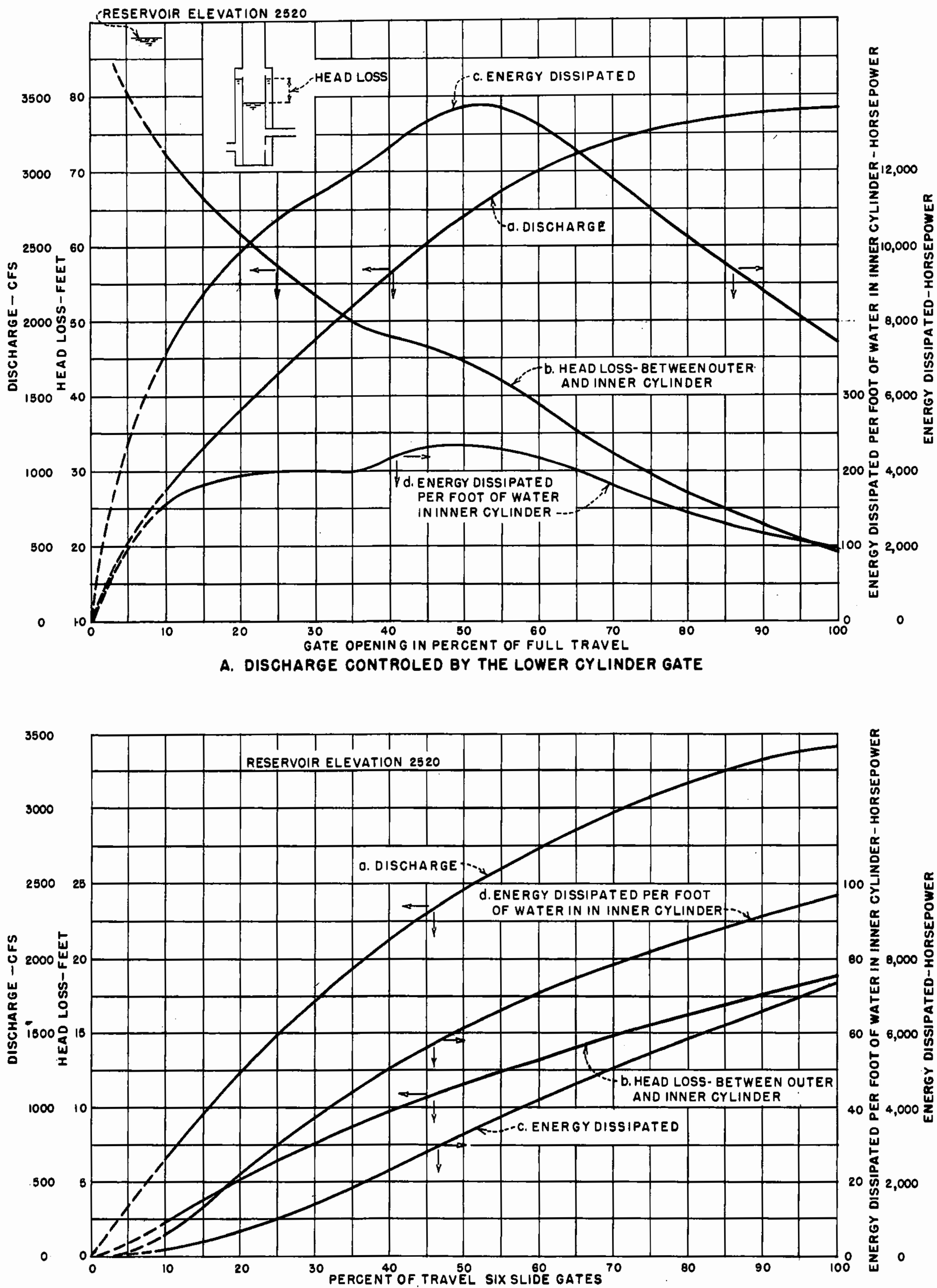


VIBRATION STUDIES - KEECHELUS OUTLET WORKS
Flow distrubance in model gate tower--Discharge 1800 cfs
Reservoir Elevation 2467.5--Lower ring gate 50 percent open

Figure 7
Report Hyd 342



VIBRATION STUDIES - KEECHELUS OUTLET WORKS
Flow disturbance in model gate tower--Discharge 2720 cfs
Reservoir Elevation 2520--Lower ring gate 50 percent open

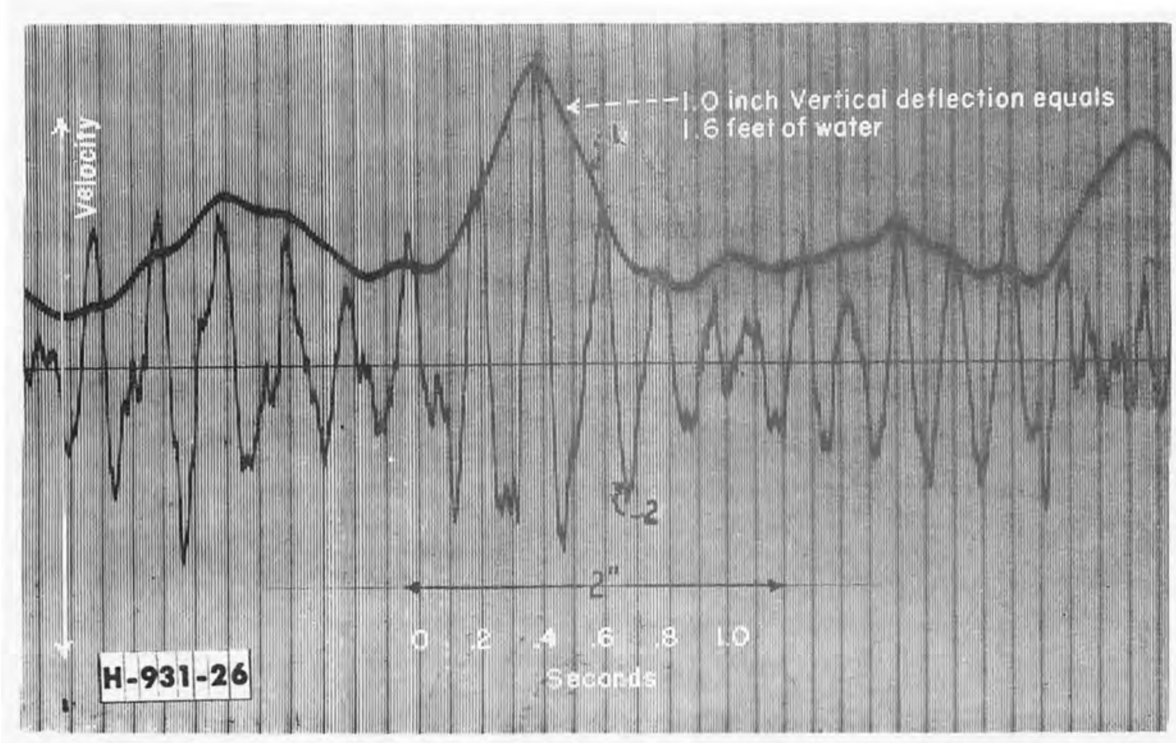


A. DISCHARGE CONTROLED BY THE LOWER CYLINDER GATE

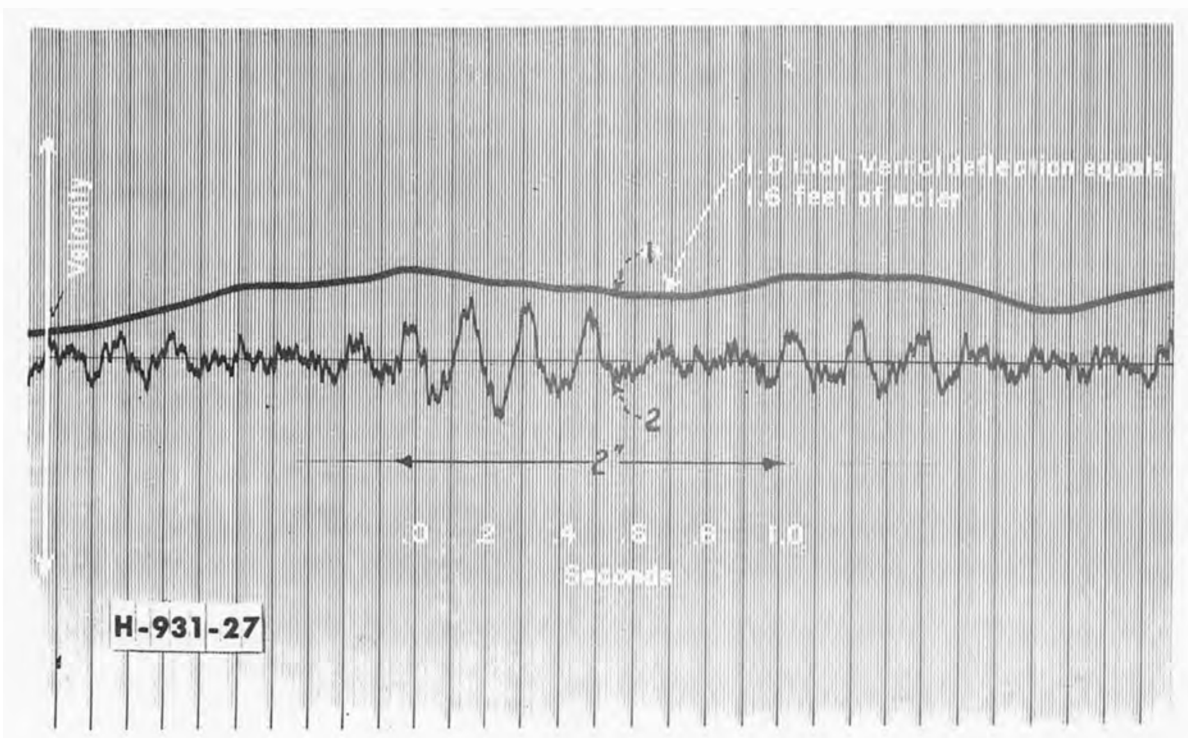
B. DISCHARGE CONTROLED BY SIX SLIDE GATES-EQUALLY OPENED

VIBRATION STUDIES-KEECHELUS OUTLET WORKS

Tower performance using two methods to control the outlet works discharge

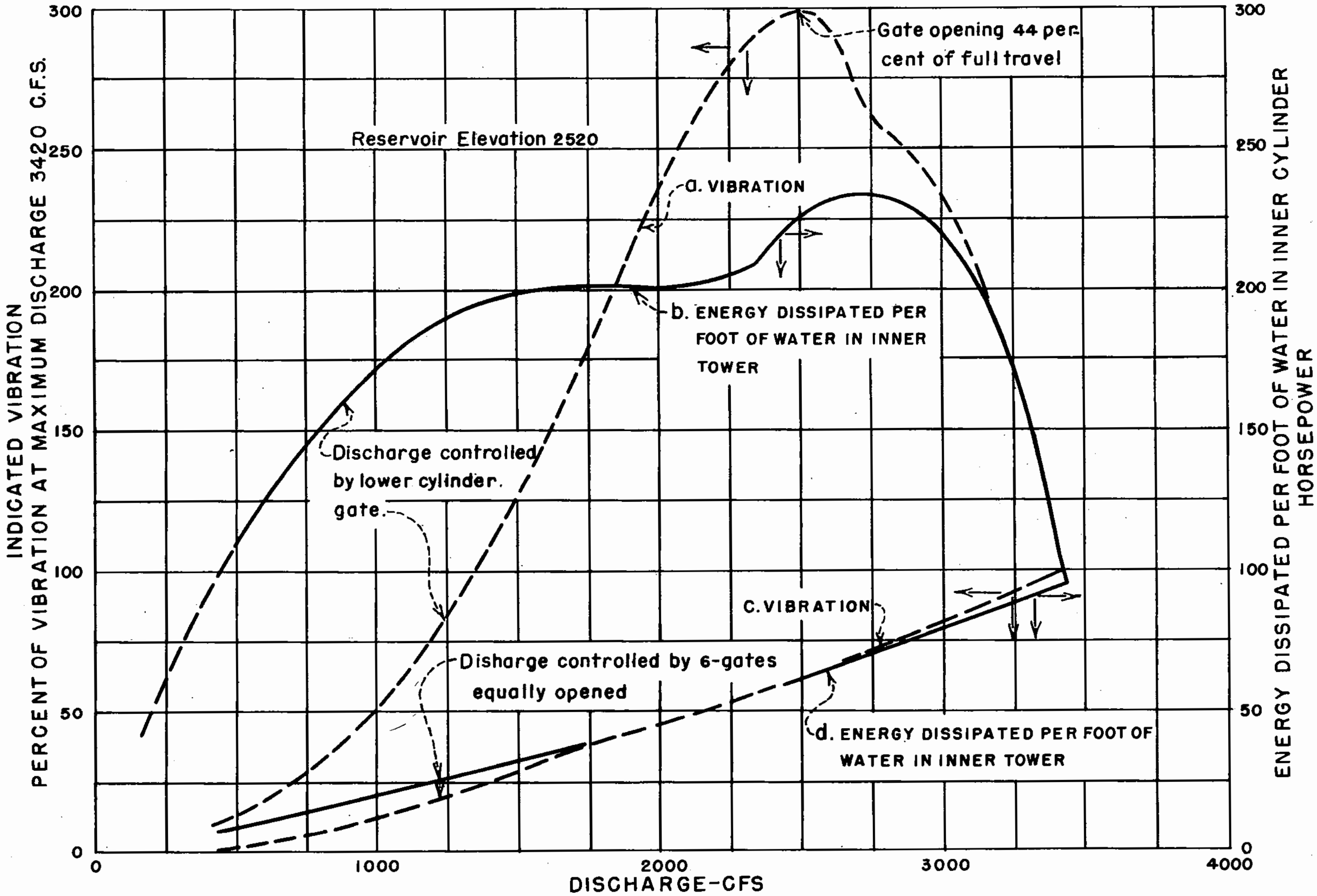


A. Trace from pressure cell (1) and vibration meter (2)--lower ring gate 45 percent open--discharge 2500 cfs, reservoir elevation 2520



B. Trace from pressure cell (1) and vibration meter (2)--6 slide gates 50 percent open--discharge 2500 cfs, reservoir elevation 2520

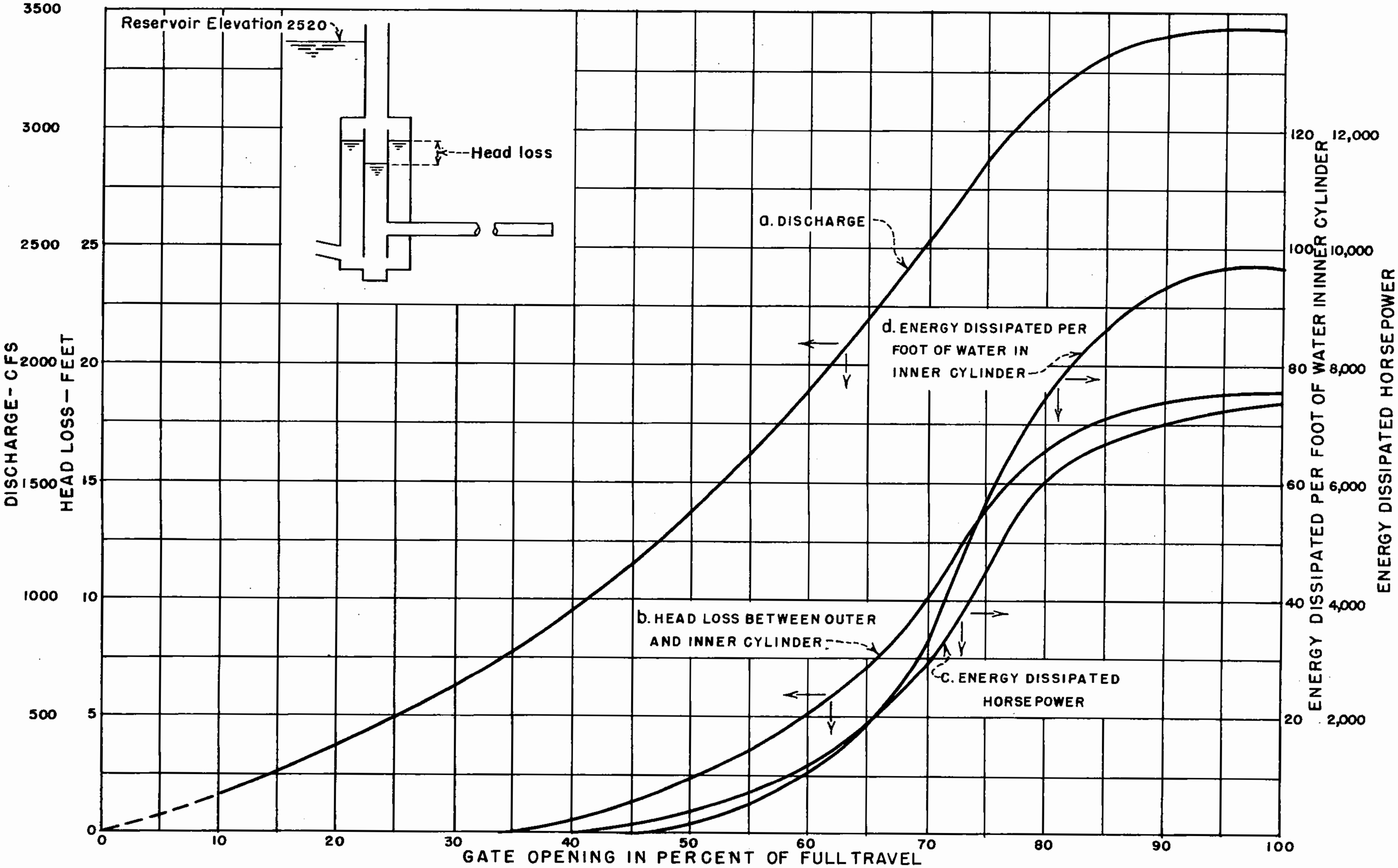
VIBRATION STUDIES - KEECHELUS OUTLET WORKS
Model Vibration Oscillograms



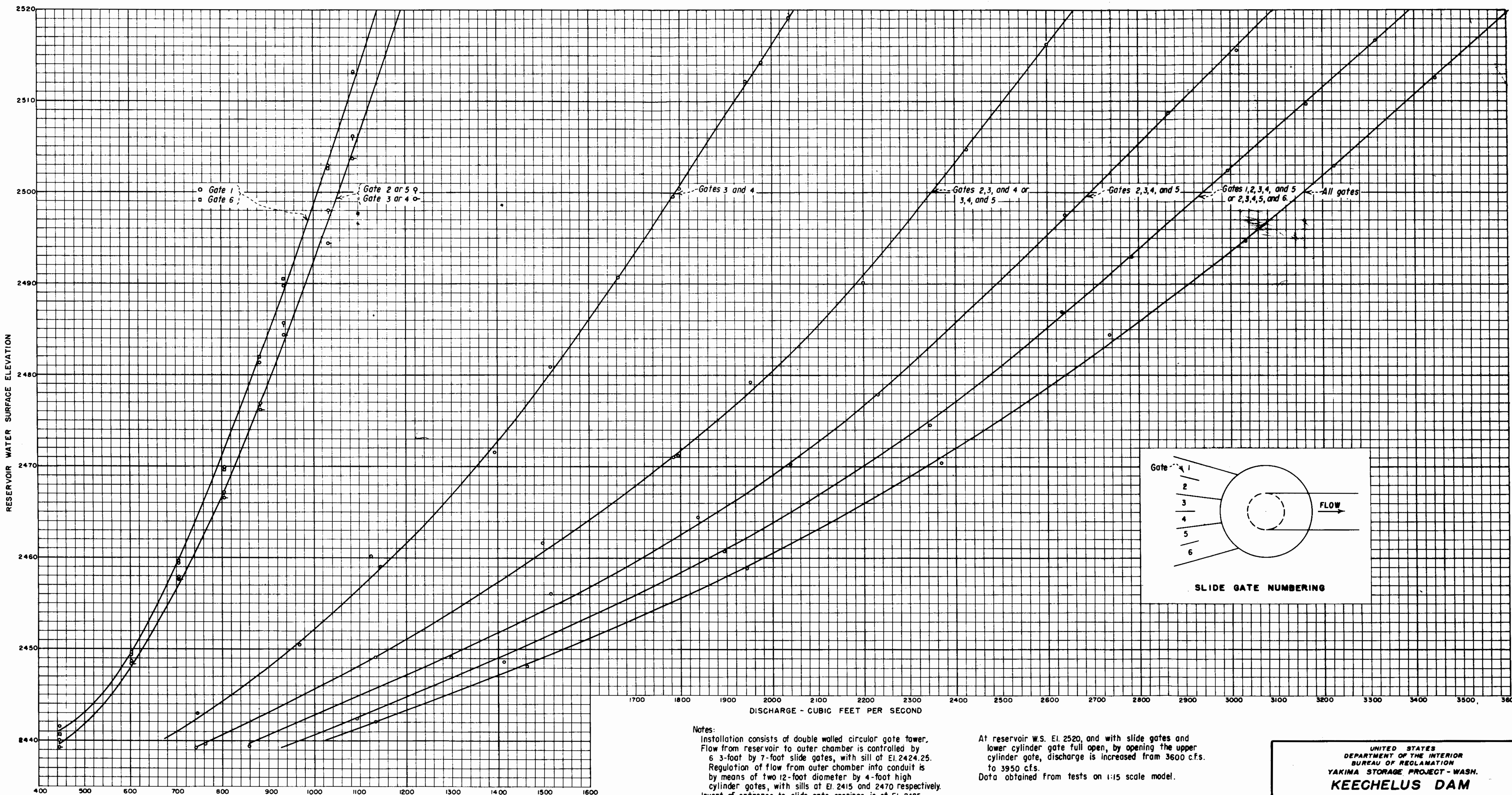
VIBRATION STUDIES—KEECHELUS OUTLET WORKS

Vibration studies using lower cylinder gate and
six slide gates to control discharge

FIGURE 10
REPORT HYD. 342



VIBRATION STUDIES— KEECHELUS OUTLET WORKS
Tower performance using a butterfly valve to control discharge



Notes:
Installation consists of double walled circular gate tower.
Flow from reservoir to outer chamber is controlled by 6 3-foot by 7-foot slide gates, with sill at El. 2424.25.
Regulation of flow from outer chamber into conduit is by means of two 12-foot diameter by 4-foot high cylinder gates, with sills at El. 2415 and 2470 respectively.
Invert of entrance to slide gate openings is at El. 2425.
Calibration based on following conditions:
- Slide gate or gates full open.
- Lower cylinder gate full open.
- Upper cylinder gate closed.

At reservoir W.S. El. 2520, and with slide gates and lower cylinder gate full open, by opening the upper cylinder gate, discharge is increased from 3600 c.f.s. to 3950 c.f.s.
Data obtained from tests on 1:15 scale model.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA STORAGE PROJECT - WASH.

KEECHELUS DAM
OUTLET WORKS
DISCHARGE CURVES

DRAWN J.C.B. SUBMITTED
TRACED J.F.M. RECOMMENDED
CHECKED C.J.H. APPROVED
ASST. CHIEF DESIGNING ENGINEER
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