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METHOD OF DETERMINING HYDRAULIC DOWNPULL FORCES ON HIGH HEAD GATES

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ABSTRACT

The paper discusses briefly model studies in the Bureau of Reclamation's Hydraulic Laboratory in which both the direct weighing method and the pressure-area computation method were used to determine hydraulic downpull on two high head gates. A detailed account is presented of one model study in which the pressure-area computation method alone was employed, also described are the methods used and results obtained in the field measurements of the prototype installations.

INTRODUCTION

The general design of a gate hoist provides for sufficient hoist capacity to open or close the gate under full operating head. The required capacity of the gate hoist is usually obtained by totaling the frictional resistance of the gate, the "dead" weight of the gate parts being moved, and the hydraulic forces tending to open or close the gate. The weight of the gate and other moving parts, either dry or submerged, is easily computed. The frictional resistance, which varies for different types of gates such as sliding, fixed wheel, or roller trains, may also be readily computed. However, the hydraulic force caused by the unbalanced water pressure above and below the gate leaf, particularly when the gate is in the throttling position, is far from simple to determine. A few of the possible methods of determining these hydraulic forces are presented here.

Water passing beneath a gate leaf creates a reduced pressure due to a change in the direction of flow and a change in energy from pressure head to velocity head. This reduced pressure acts on the bottom of the gate. There is a pressure on the top of the gate, water pressure if the leaf is submerged, and atmospheric pressure if it is above the free water surface. The downward hydraulic force on the gate is equal to the difference in pressure above and below the gate in pounds per square inch multiplied by the affected cross sectional area of the gate in square inches. By changing the shape of the bottom of the gate, or by altering the flow passage, a beneficial pressure change might be achieved which would reduce the hydraulic downpull. If the gate leaf is in a housing in the line, the pressure above the gate in the housing or bonnet can be partially controlled by carefully selecting the clearances between the leaf and the housing, both on the upstream and downstream sides of the gate.

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However, each new gate installation offers a new and specific problem in regard to hydraulic downpull, and each must be dealt with individually.

Shasta Dam Fixed-Wheel Gate

Laboratory studies have been made to determine the hydraulic downpull on several different types of gate installations. One of the Bureau of Reclamation's earliest model studies concerned an emergency bulkhead-type gate for Shasta Dam, designed to close the inlet to a conduit discharging under 323 feet of head. An attempt was made to "weigh" the model downpull forces by suspending the gate from a spring scales and taking continuous weight readings while the gate was being raised or lowered (Figure 1). However, the hydraulic downpull values were extremely difficult to determine because of excessive and variable frictional forces. Several piezometer taps were installed in the model gate and the downpull forces were computed by the pressure differential-area method. Results of the pressure measurements for various gate bottom designs are shown in Figure 2.

It was obvious that a large number of strategically placed piezometer taps on the gate surfaces would be necessary to determine the downpull forces accurately. As the weighing method appeared simpler, further attempts were made using this method. The roller chains were removed from the initial model gate and replaced with small flanged wheels resembling miniature railroad wheels. Under heads up to 10 feet, the apparatus seemed to operate satisfactorily, but for higher heads the wheels would stick momentarily and release suddenly, producing the same untenable conditions encountered with the roller chains. A new model gate was fabricated using wheels having a diameter equal to the thickness of the gate. These wheels turned on ball bearings to minimize the rolling and bearing friction. Nevertheless, the movements of the gate were still so jerky the forces were extremely difficult to record. It was found that the roller tracks had to be made glassy smooth before acceptable readings could be made.

From these tests, it appeared that the extreme precision required in fabricating this type of a model gate to be acceptable for weighing the downpull forces overshadowed the tedious recording and computations required in a pressure study.

The gate developed in the above studies was installed at Shasta Dam, and an opportunity arose to measure the downpull forces in the field installation. An SR-4 type strain gage was bonded to the gate hoisting stem as shown in Figure 3. The change in resistance of the strain gage was measured by a portable strain indicator, and the gate position was measured with an engineer's chain. As the test proceeded, the strain indicator, the engineer's chain, and a timing device were photographed by a motion picture camera operating at three frames per second. The timing device was included to correlate the gate opening and strain readings with a metering device. A chart showing the hydraulic downpull determined by a model study using the pressure-area method and by field measurements is shown in Figure 4. No attempt will be made here to justify the large discrepancy between model and prototype results at about 20 percent gate opening.

Hoover Dam Cylinder Gate

A laboratory study was made of the hydraulic downpull forces on the cylinder-type gate at Hoover Dam. Since the horizontal forces acted radially inward and were resisted internally by the gate, bearing and rolling friction were not a factor in the study. Force measurements by weighing appeared to be the simplest method of solution. The 1:24 scale model gate was suspended by a molybdenum bronze wire with the system so mounted that, as the total load varied, the elongation of the wire could be measured by a dial indicator (Figure 5) and the weight or load computed directly.

For gate openings greater than 18 inches (prototype) the system worked very well; however, the hydraulic downpull was quite small in this range. Below 18 inches small changes in gate opening were accompanied by large changes in hydraulic downpull. Any slight variation in opening from one side of the gate to the other, or any slight shift from side to side, would cause a large unbalance in hydraulic forces. As the gate attempted to follow the larger hydraulic force, the movement would be resisted by the suspending mechanism and guides. The distribution of forces would shift rapidly to a new location, and the entire model, although sturdily constructed of heavy-weight steel and brass, shook violently. No practical solution to the problem was found although many corrective measures were tried. For the final tests, the gate was removed, piezometers installed, and pressure-area studies were made with the gate wedged tightly in predetermined positions.

Prototype downpull was measured by means of strain gages on each of the three lifting nuts (Figure 6). Continuous oscillograph records of the change in resistance of each gage were made during the tests, and from these records the downpull was determined. The downpull curve determined by prototype measurements followed the trend of the model curve but produced values about 23 percent higher than those determined by model study (Figure 7).

Obviously the direct measurement of downpull forces on prototype gates is feasible. However, a model to be used for direct force measurements must be made with such extremely confining tolerances that the economy of this type of study is questionable.

Palisades Fixed-Wheel Gate

One of the preliminary plans for both the power tunnel and the outlet works tunnel at Palisades Dam considered the installation of a fixed-wheel-type gate covering a semi-bellmouth entrance, 20.0 feet wide and 39.3 feet high. A closed gate at this location, subjected to a head of 156 feet, would be required to withstand a hydrostatic force of 7,980 kips. In another plan, a beam was placed across the opening above the tunnel entrance to form the top part of the semi-bellmouth (Figure 8). This arrangement permitted the gate to be installed a short distance downstream from the tunnel entrance where the opening was 19.7 feet wide by 28.0 feet high. The hydrostatic force on the closed gate at this location would be 5,540 kips, or a load reduction of about 30 percent. The latter design was preferable from an economic standpoint, and a model study was instigated to determine the hydraulic characteristics of the installation, particularly the hydraulic downpull on the gate.

In view of the previously mentioned studies, the weighing or force method of determining hydraulic downpull was not favorably considered for the Palisades model. Available data were analyzed to determine where critical pressure areas might occur on the gate so that an accurate pressure study might be made and the hydraulic downpull computed. Based on information thus obtained, 36 piezometer taps were placed in the 1:39 scale model gate. (Figure 9). The approach to the gate, the beam forming the top part of the semi-bellmouth entrance, and the transition downstream were formed of lightweight sheet metal (Figure 10); 24 piezometer taps were placed at critical points in the beam, entrance, gate slots, and transition. The entire apparatus was installed in a 36-inch-diameter pressure tank, and the 60 piezometer leads were carried through the wall of the tank and attached to a gage board as shown in Figure 11.

Preliminary testing concerned the general operation of the system to make certain the overall design would be hydraulically acceptable. When the gate was opened 80 percent or more and the discharge exceeded 18,000 cfs, the pressure on the downstream face of the gate exceeded that on the upstream face by a sufficient amount to force the gate away from the wheel tracks. This untenable situation was remedied by making a fairly large recess in the downstream face of the concrete beam (Figure 8), thereby keeping a balanced pressure on the upstream and downstream faces of the gate. All other configurations appeared to be acceptable.

The maximum emergency discharge which the wheel gate would be expected to throttle was 45,000 cfs. This discharge was computed assuming maximum reservoir elevation, the wheel gate fully opened, and a total separation of the 26-foot conduit near its exposed downstream end. Preliminary downpull tests disclosed that the forces prevailing with maximum discharge and the gate fully opened were about as expected and produced a hydraulic downpull of a little more than 700,000 pounds. However, a much larger downpull was encountered at about the midpoint of gate travel.

A plot of the pressure distribution on the gate bottom (Figure 12) disclosed that considerable variation in pressures occurred between adjacent piezometer taps. In computing the downpull, therefore, the small areas adjacent to each of the 15 taps were considered separately. The sum of these individual downward forces together with the downpull attributed to the upper and lower seals, constituted the total hydraulic downpull for any given condition of gate opening and discharge.

If the emergency discharge of 45,000 cfs existed with the gate 100 percent open, and the gate was then closed, the hydraulic downpull would vary as shown in Figure 13. The 707,000-pound hydraulic downpull with the fully opened gate would exist for any gate in this position; however, the maximum hydraulic downpull of 895,000 pounds at about 55 percent gate opening was peculiar to this particular gate bottom configuration. The downstream lip of the model gate was extended to create a higher pressure on the bottom web of the gate. The hydraulic downpull for various lip extensions is shown in Figure 13.

Structural considerations limited the permissible amount of lip extension. The maximum hydraulic downpull for a 29.5-inch lip extension was 895,000 pounds while that for a 68-1/2 inch extension was 670,000 pounds. However, the added cost of strengthening the 68-1/2 inch lip to withstand a thrust of 1,270,000 pounds was greater than the savings which would be realized using a smaller capacity hoisting cylinder. The designers, therefore, placed a limit of 550,000 pounds thrust on the extension, or a lip extension of about 30 inches.

Some reduction in downpull could be achieved by reducing the length of, and streamlining the upstream lip of the gate. The amount of streamlining or shortening was again a structural problem, so computations were made and the upstream lip changed accordingly. The configuration shown in Figure 14 was considered structurally sound and is the shape tested in the following study.

The fixed-wheel gate would be required to stop the flow caused by some random emergency such as a ruptured penstock, control valve or valves rendered inoperative in the opened position, etc.; 45,000 cfs is the maximum possible flow, and an air vent downstream from the gate limits the head here to 15 feet below atmospheric. The maximum reservoir elevation is 178.9 feet above the lower gate seat. Realizing these limitations, a calibration chart was made for the gate, plotting discharge against head drop from the reservoir to the air vent for various gate openings. Then the pressures on the gate were measured and the hydraulic downpull computed for several discharges for each 5 percent increment of gate opening. Next, by crossplotting, a downpull chart was drawn showing the hydraulic downpull which would be encountered as the gate was lowered from fully opened to closed, for any initial emergency discharge. As the gate was lowered into the stream, the discharge and the head at the air vent would decrease until the head at the air vent became negative 15 feet; then the gate would become the control. At this point, maximum downpull would prevail for each initial discharge.

In the downpull chart, Figure 15, the gate opening is based on a total travel of 29 feet; however, the bottom of the lower seal reaches the top of the tunnel after a travel of 27-2/3 feet. Therefore, the downpull is constant between 96 and 100 percent open since there is no change in the flow passage in this range.

The hydraulic downpull for maximum emergency discharge and the gate 100 percent open is 707,000 pounds, the same as for any other gate bottom design. The maximum hydraulic downpull is 813,000 pounds and occurs with the gate 57 percent open. The reduction in the upstream lip extension of 2-11/16 inches, comparable to extending the downstream lip this amount, would have produced a maximum downpull of 855,000 pounds. The 9-inch radius on the upstream lip evidently reduced the maximum downpull by 42,000 pounds.

As a result of the hydraulic downpull tests, the hoisting cylinder and connectors were made sufficiently rugged to lower (or hoist) a total of 1,300,000 pounds.

During field assembly of the fixed-wheel gate for the power penstock, it was noted that one of the wheels was cracked from hub to rim. Since a replacement wheel was not readily available, the damaged one was field repaired and the gate installed. A new wheel was acquired and stored to await installation at the first opportunity.

In order that work might be done on the gate, it must be raised to a work platform near the hoisting cylinder. The stem-handling equipment includes a catch on which the gate and stem rests while one 26-foot 4-inch stem section is removed and stored. Then the piston is returned and connected to the next stem and the assembly is again raised the full stroke of the piston. Although the hoisting cylinder is designed to hold 1,300,000 pounds, the catch in the handling equipment was designed to hold only the gate and stem plus 30 percent overload, or about 329,000 pounds. It was not anticipated that this catch might be required to hold against any hydraulic downpull. Before proceeding with removal of the gate it seemed advisable to measure the downpull forces existing with the power plant in operation. Consequently, a pressure gage was installed in the hoisting cylinder below the piston, and measurement made of the cylinder pressure while the gate was lowered 37 inches into the stream (gate 89.4 percent open) and raised again to full open. The discharge during the test was 6,000 cfs. The total force on the system did not exceed the safe limits for the stem catch. The gate was subsequently removed and repaired.

The results of these very limited field tests are shown in Figure 15. The trend follows the model results very closely; however, the actual field values are about double those determined from model study.

CONCLUSIONS

Not all of the parameters controlling the hydraulic downpull forces on gates have been defined to a degree that will permit an accurate mathematical analysis of each individual problem. Scale model investigations are of primary importance to the engineer in the solution of these problems. The two most common procedures employed in a model study are the direct force, or "weighing" method, and the pressure-area computation method. For most applied studies, the pressure-area method is preferred because a simple and relatively inexpensive model will be adequate. The model may be either true scale or sectional.

The moving parts of a model gate to be used for direct force measurements must be fabricated to extremely close tolerances. This type of model can be quite useful for basic research.

Field investigations should be made whenever possible, and the results compared to those determined by model study. A sufficient number of such correlations on a gate type will enable the engineer to understand more clearly the function of each variable contributing to hydraulic downpull. Then, reliable charts and tables may be prepared from which the total of the hydraulic forces acting on this type gate may be computed.

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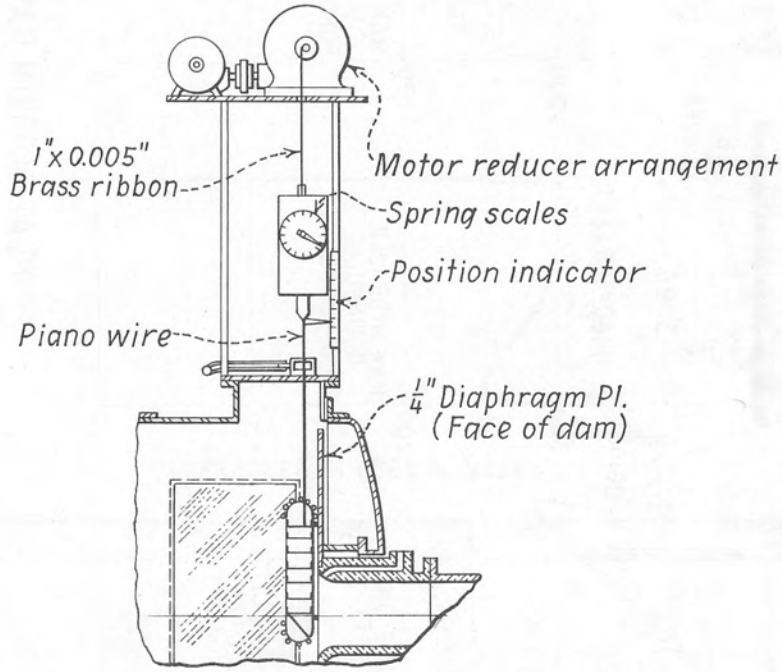
Figure 1



DETAIL OF MOTORIZED GATE LIFT

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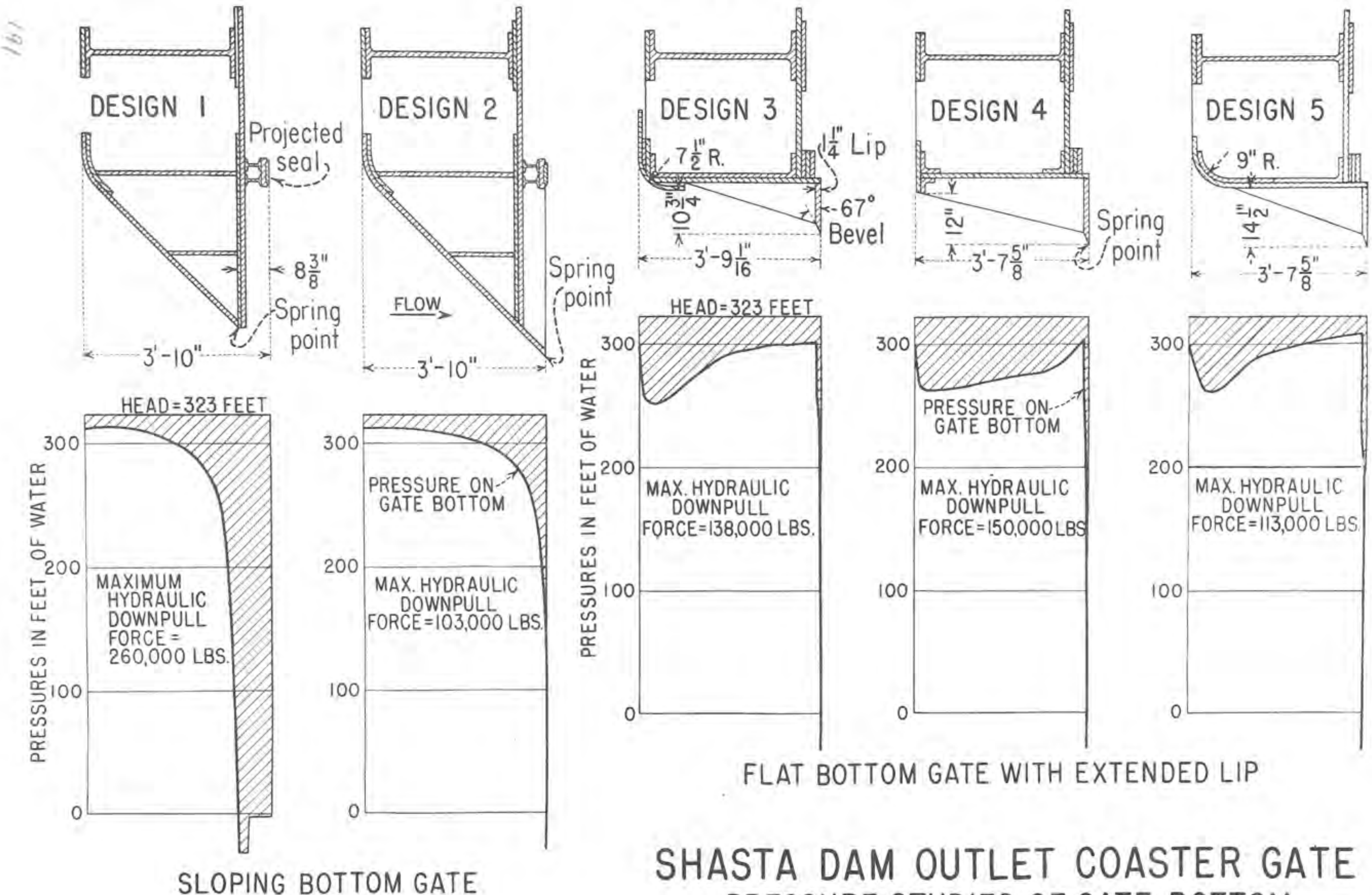

SHASTA DAM OUTLET COASTER GATE
PRESSURE STUDIES OF GATE BOTTOM

Figure 3

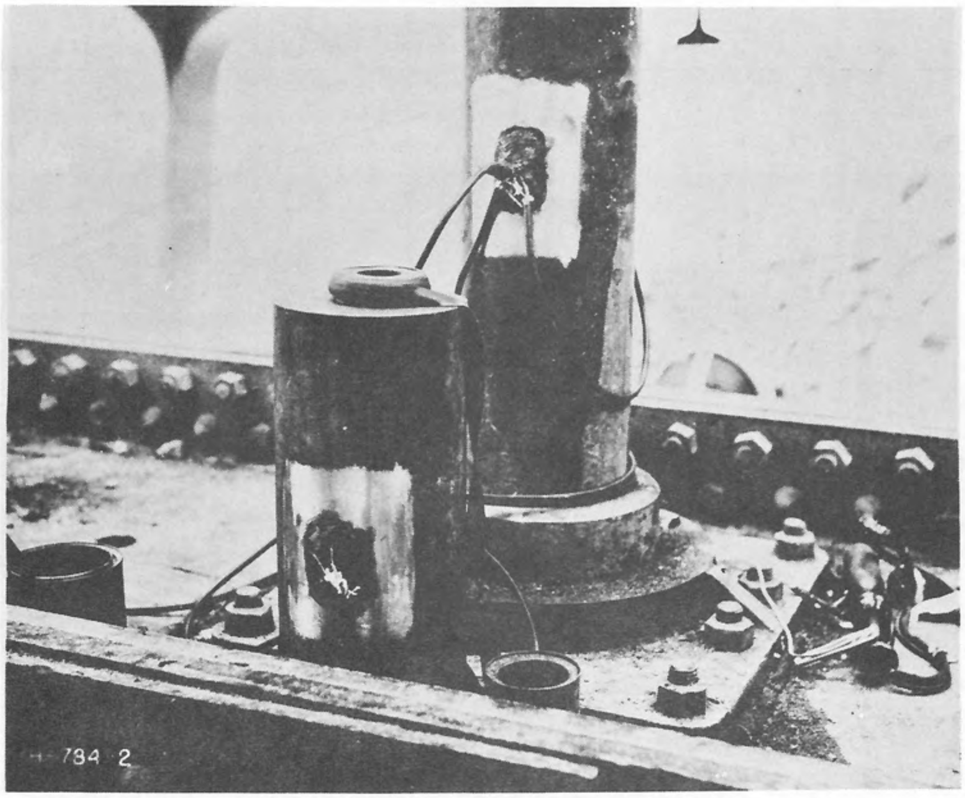

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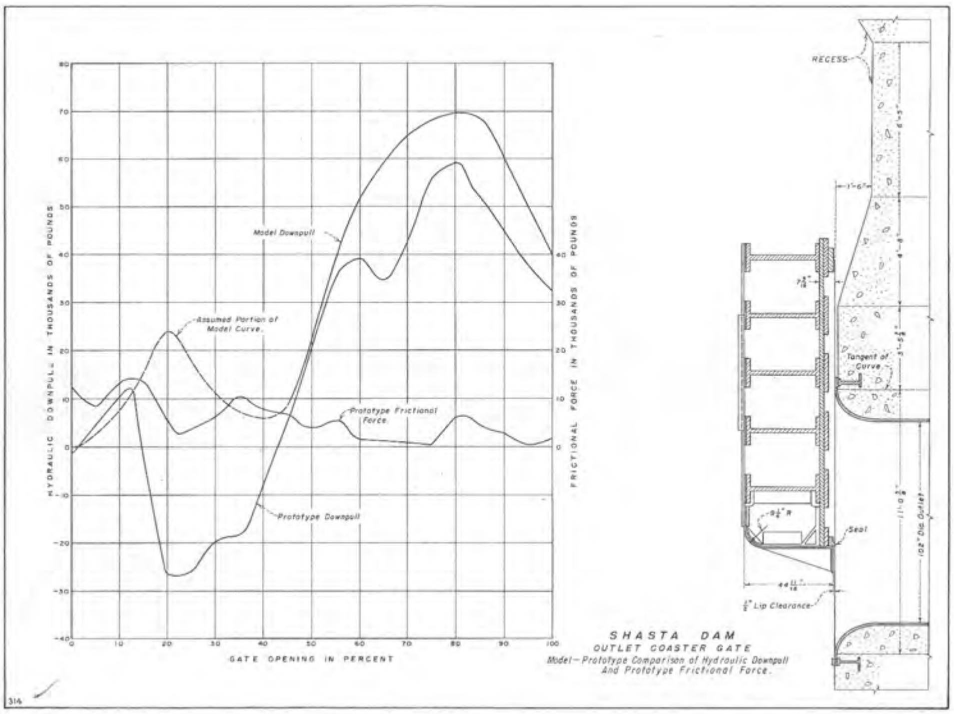
Figure 4



SHASTA DAM
OUTLET COASTER GATE
Model—Prototype Comparison of Hydraulic Downpull
And Prototype Frictional Force.

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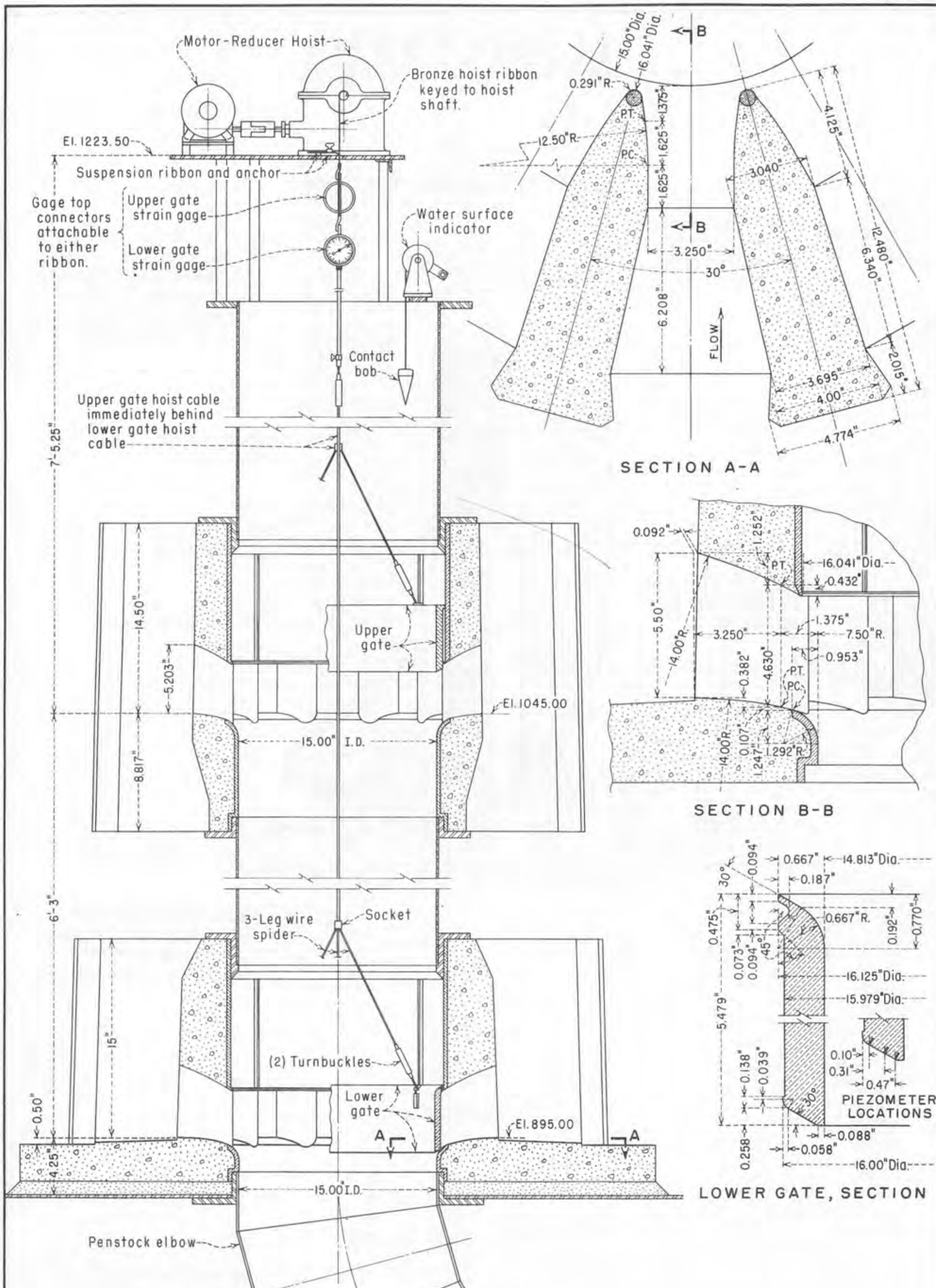
PAP-7

Figure 5



SECTION THROUGH MODEL ASSEMBLY
(WALLS OF TANK NOT SHOWN)

HOOVER DAM INTAKE TOWER - 1:24 SCALE MODEL

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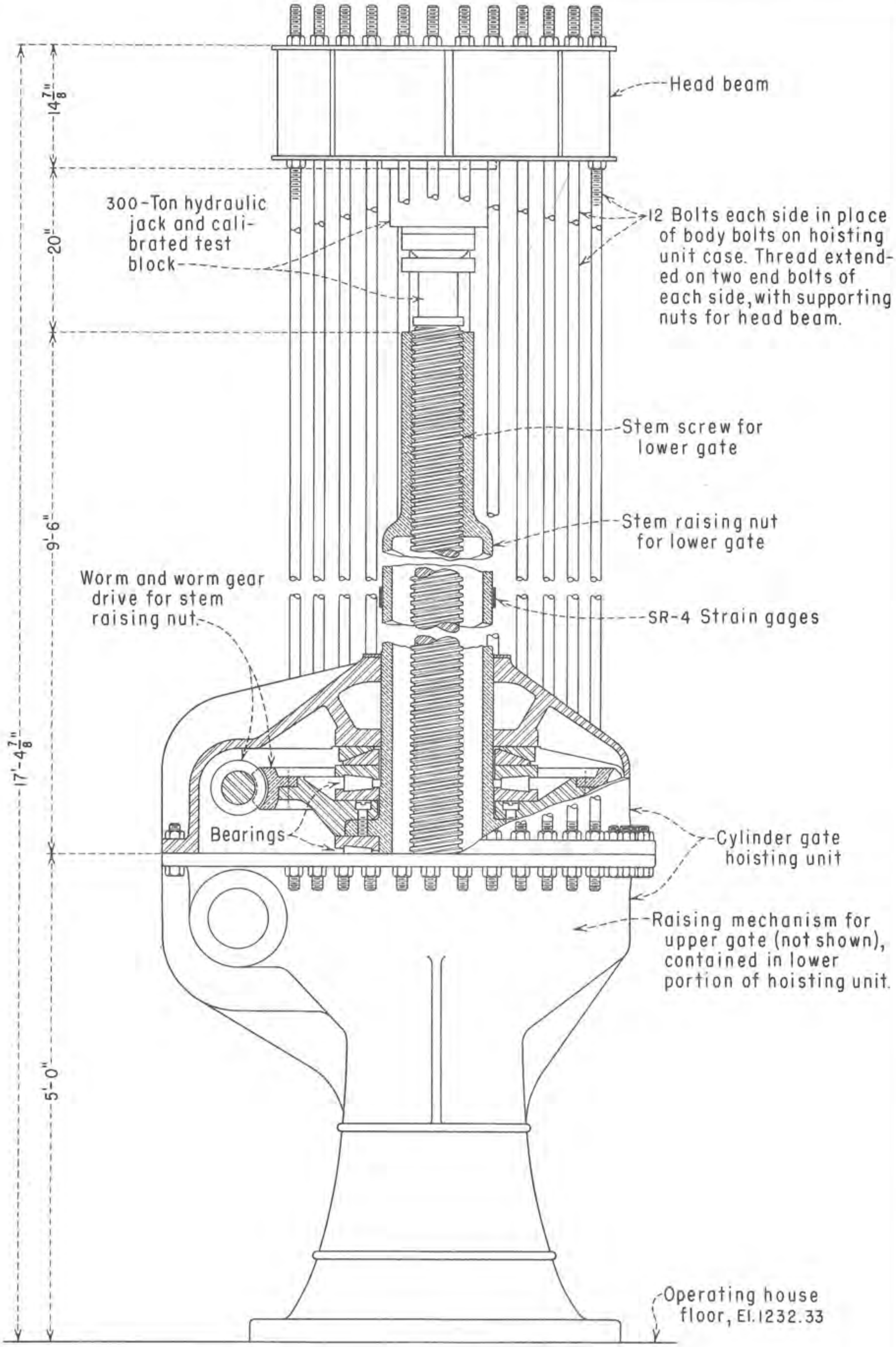
Figure 6



STEM NUT CALIBRATING APPARATUS FOR CYLINDER GATE HOIST - HOOVER DAM INTAKE TOWER

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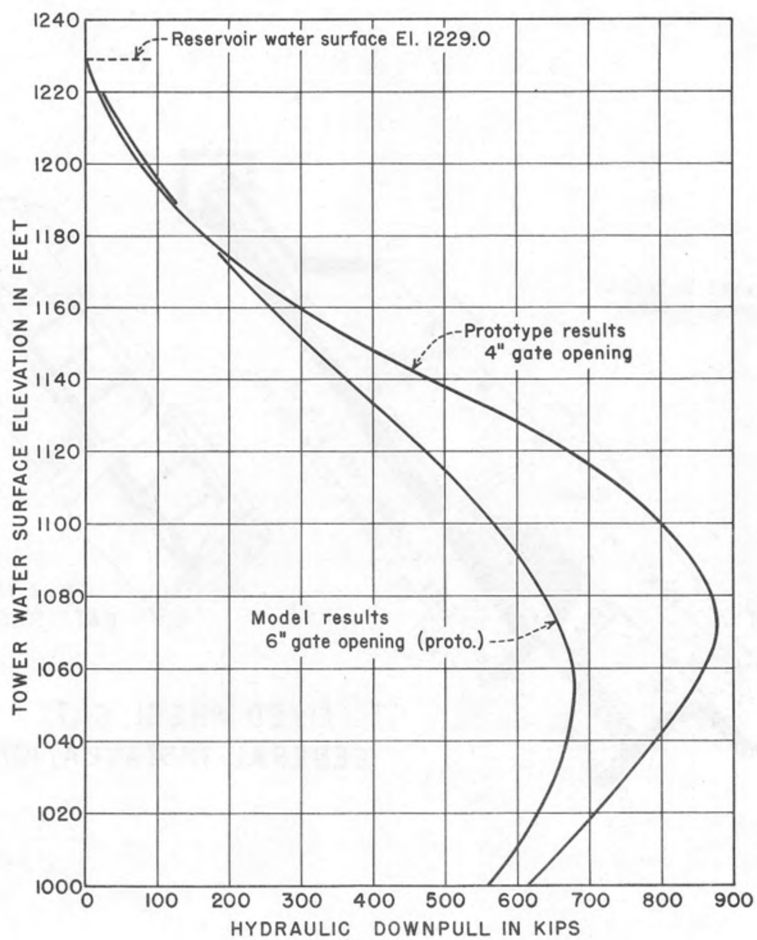

HOOVER DAM INTAKE TOWER

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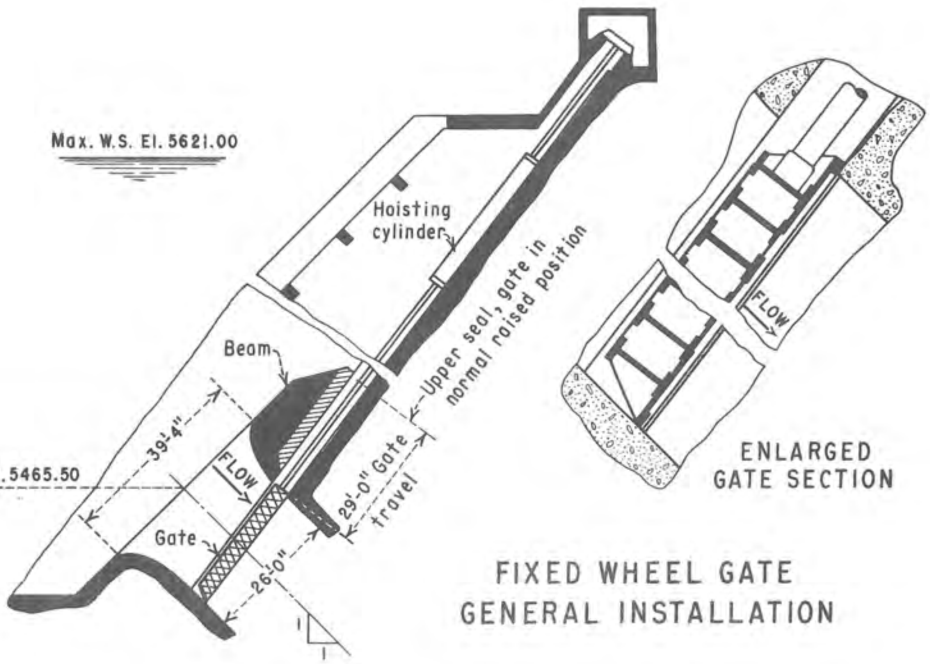
Figure 8



FIXED WHEEL GATE
GENERAL INSTALLATION

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Figure 9

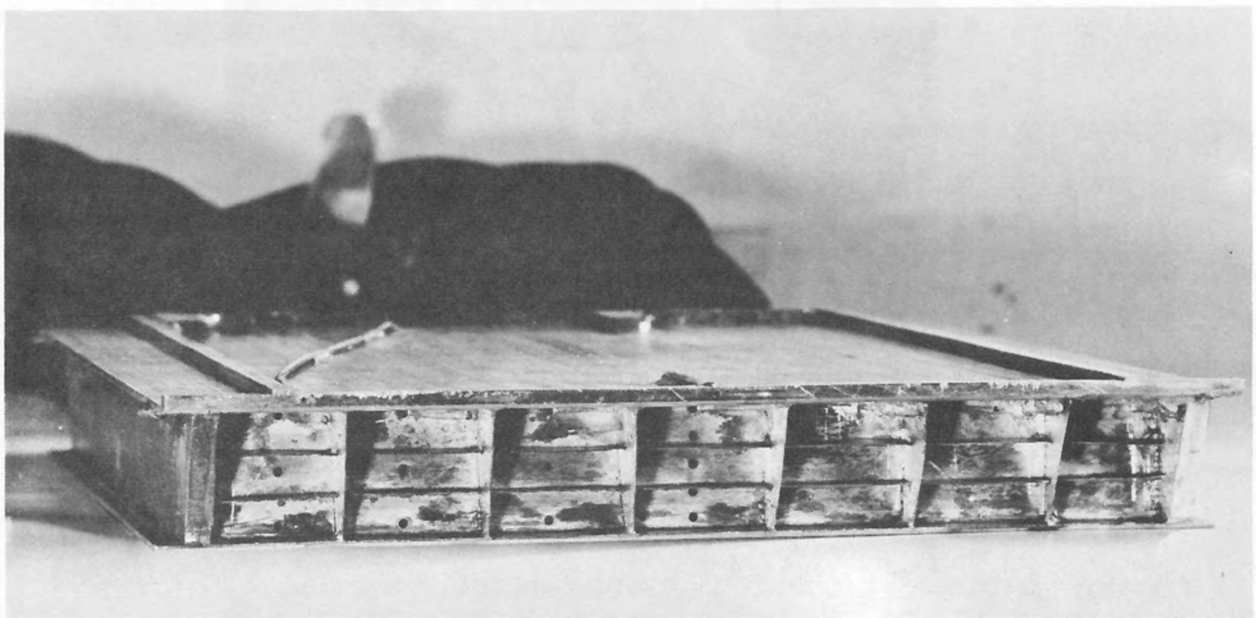


Figure 10

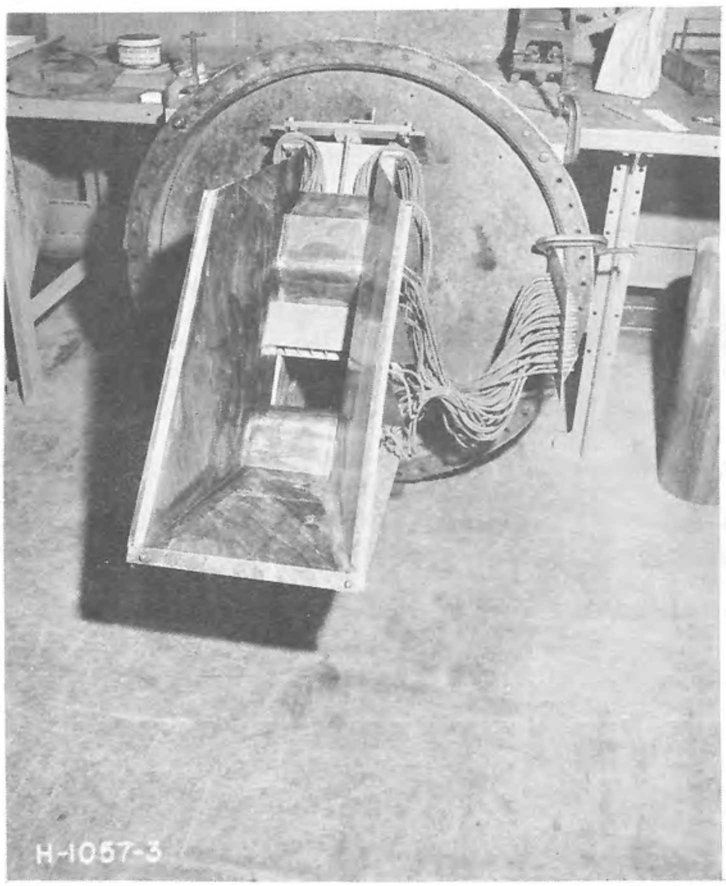


Figure 11

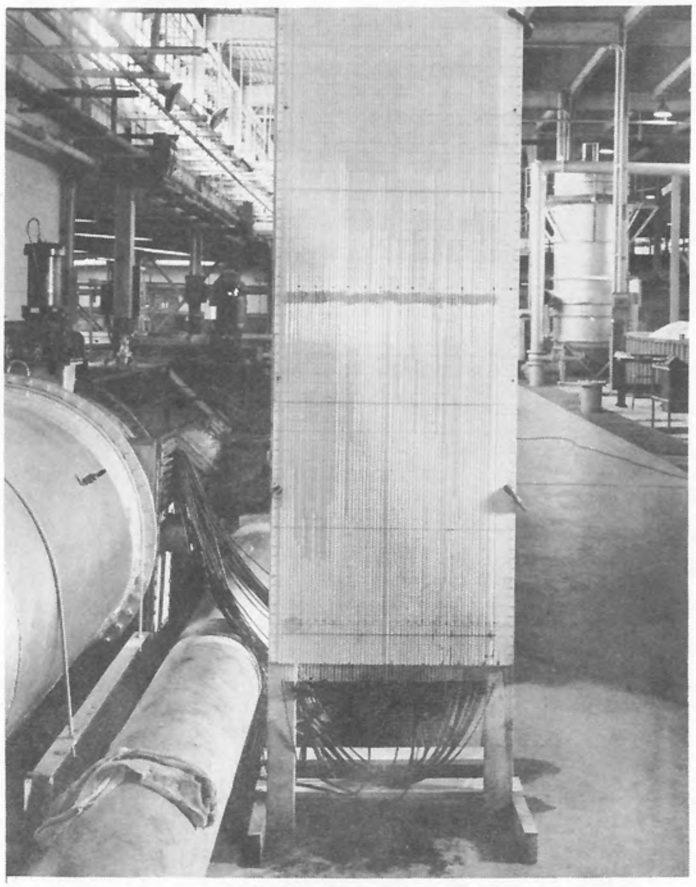
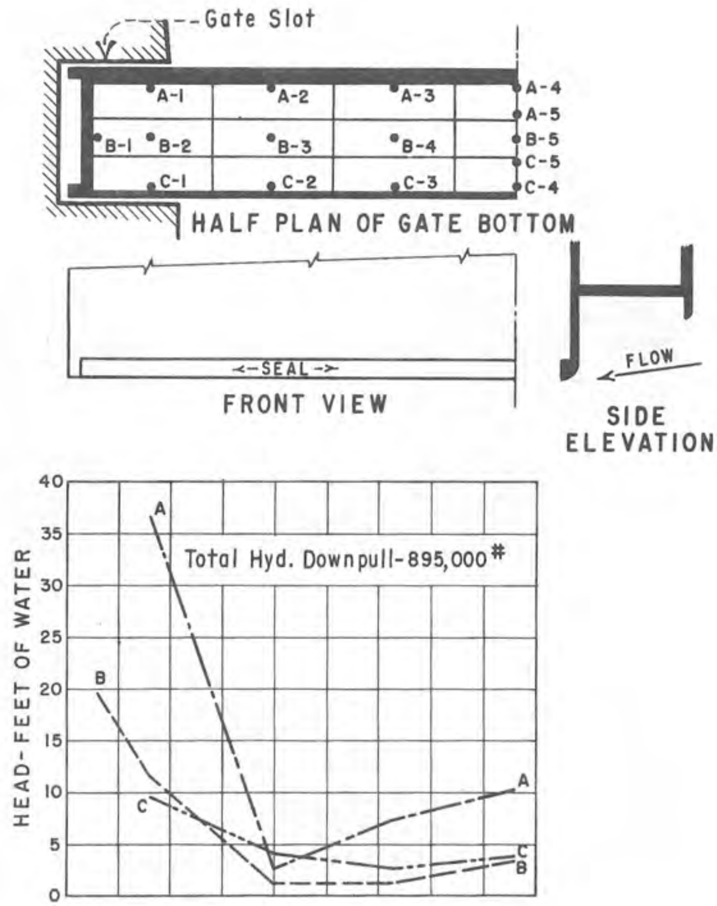


Figure 12



PRESSURE DISTRIBUTION ON GATE BOTTOM

Gate opened 50% Q=19,500 cfs

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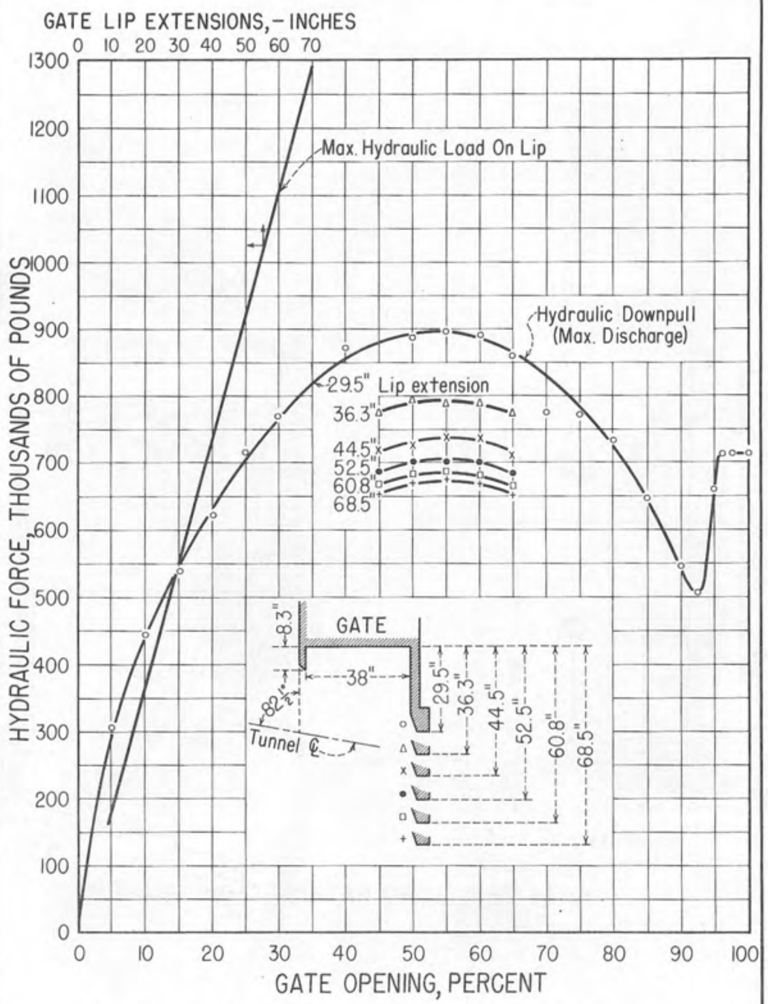

EFFECT OF LIP EXTENSION ON DOWNPULL

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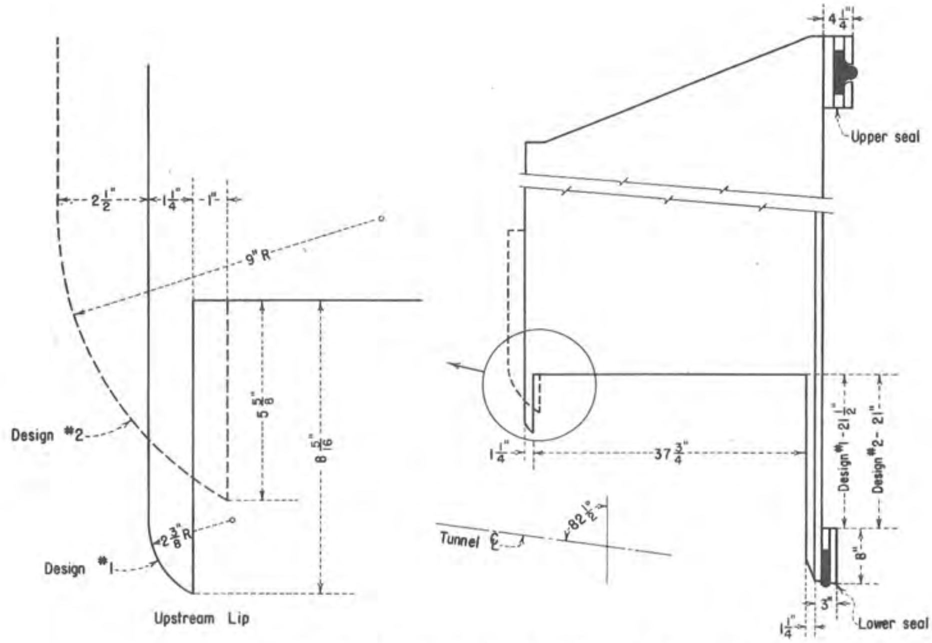
Figure 14



GATE SEALS AND GATE BOTTOM SHAPES

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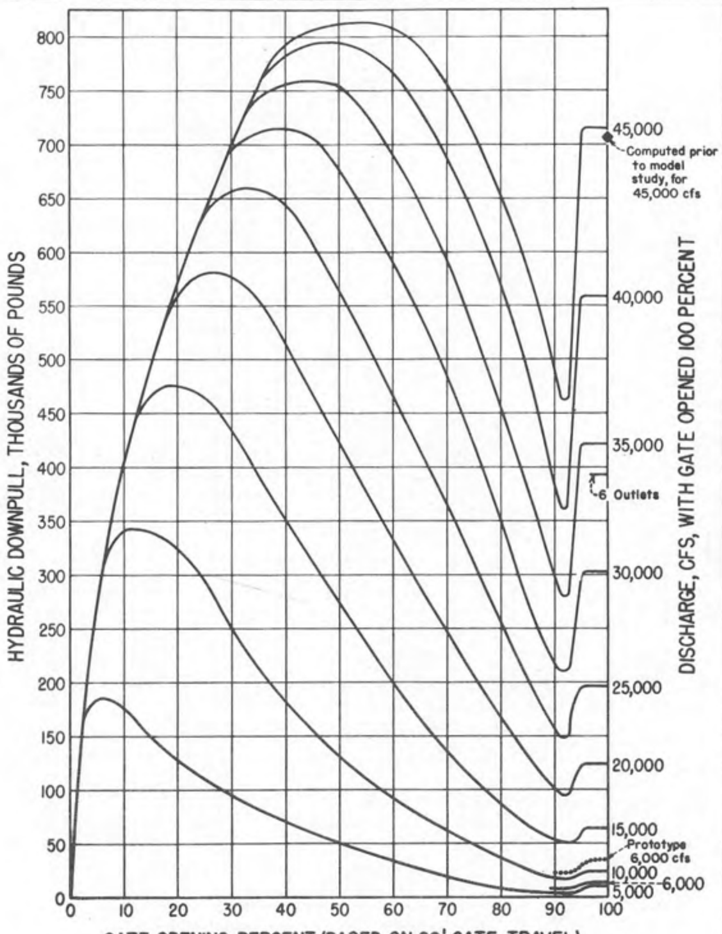
Figure 15



DESIGN No. 2 - RES. ELEV. 5621

PALISADES DAM - FIXED-WHEEL GATE

HYDRAULIC DOWNPULL TESTS

MODEL SCALE 1:39

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