LABORATORY AND PROTOTYPE TESTS FOR THE INVESTIGATION AND CORRECTION OF EXCESSIVE DOWNPULL FORCES OF LARGE CYLINDER GATES UNDER HIGH HEADS

by

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SUMMARY

The purpose of this series of investigations was to evaluate the hydraulic downpull forces which would likely act upon the cylinder gates in the power intake towers at Hoover Dam under emergency closure conditions. Analytical studies were first made and were followed by a hydraulic model study which indicated that excessive downpull forces on the gate suspensions would occur. An opportunity arose to perform downpull tests on one of the Hoover gates under selected conditions. The data acquired were analyzed in the light of the model studies and specifications were prepared for the modification of the gate bottom cross-section to alleviate the excessive hydraulic forces. After the gate was altered it was again given a test to determine the effect of the modification. The results corroborated the previous studies. Downpull forces were reduced by a factor of as much as 4-1/2 for heads approaching the maximum.

Techniques of performing the tests on the prototype gate are presented together with a discussion of the results in relation to the analytical and laboratory studies.

The Problem

The release of water from Lake Mead for irrigation and power purposes is through four intake towers connected to 30-foot diameter penstock headers which lead to the turbines in the power plant and to needle valves in the canyon wall and tunnel plug outlet works downstream from the dam. In each tower are two cylinder gates 32 feet in diameter, 11 feet high, and 14 inches thick, one at the base at elevation 895 and the other at elevation 1045 feet above sea level (Figure 1). The flow into a penstock must pass through these gates, and the closure of both the upper and lower gates permits the penstock and all of its appurtenances to be unwatered for inspection and maintenance. With the water surface in the reservoir at normal high water level, elevation 1229, the head on the lower gate is 334 feet.

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At the time the intakes were designed it was anticipated that the gates would be opened or closed under balanced conditions with no flow through the penstock. However, conditions may occur which would necessitate an emergency closure of the cylinder gates. A needle valve might jam in a wide open position or a section of the penstock might burst. During such an emergency closure the water surface inside the tower would drop and the unbalanced pressure would cause an inward radial thrust against the outside surface of the gate. The cylinder gates are sufficiently strong to withstand the inward radial thrust but water rushing underneath a gate and into a tower would cause a pressure reduction on the gate bottom resulting in a hydraulic downpull force on the gate. The 500,000-pound capacity hoist would be overloaded if the total hydraulic downpull force on the 330,000-pound gate exceeded 170,000 pounds.

On the basis of investigations on other types of closure gates it was conceivable that the hydraulic downpull force would greatly exceed this amount.1/ 2/ This possibility was not considered at the time the cylinder gates and hoists were designed for Hoover Dam. The possible occurrence of such large forces made it desirable to know their magnitude and to make a study of the capacity of the three hoist stems to determine whether they were strong enough to withstand emergency closure conditions. The stem pins were designed for forces up to 413,000 pounds per stem but it was possible that corrosion had weakened them. However, an inspection showed them to be in very good condition, so it was assumed they could withstand this force.

A mathematical study was first made of the forces acting on the gates for various openings, water levels, and penstock flows to ascertain what changes in the gate operating equipment might be needed.

Mathematical Study of Forces Acting on Gate

Computations were made to arrive at an approximate value of prospective forces on the gate suspension during an emergency closure. It was assumed that the lower gate was being closed, that the upper gate was shut, that the movement of the lower gate was so slow that the time factor could be neglected, and that the water surface in the reservoir was at elevation 1200. Discharges of 5,000, 10,000, 20,000, and 40,000 second-feet were considered.

The mathematical study included the use of momentum relationships and an examination of the shape of the flow passage under the gate

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1/ "Coaster Gate and Handling Equipment for River Outlet Conduits in Shasta Dam" by J. E. Warnock and H. J. Pound, Volume 68, Transactions, ASCE, 1946.

2/ "An Experimental Study of the Hydraulic Downpull on a Coaster Gate" by J. D. Cronin and W. Hansen, Journal, The Institution of Engineers, Australia, July-August 1949.

for different openings to arrive at an estimate of the pressure distribution on the gate bottom. The results of the study indicated that if an emergency closure were necessary with large discharges through the tower, the downpull forces might be as great as 600,000 to 900,000 pounds, depending on the gate opening. Forces of this magnitude were nearing the capacity of the gate stems. Since these downpull forces were based on the estimated pressure distribution on the bottom surface of the gate and the nature of the flow and thus the pressures in the gate flow passage are questionable, the values obtained could be considered only approximate.

Flow through a diverging passage, such as in a venturi meter, results in a reduced pressure in the narrow portion and an increase in pressure in the larger section downstream. The pressures in the passage may be computed as long as all are above the vapor pressure of the fluid. However, if the pressures are reduced to the vapor pressure this pressure may extend over various portions of the surface depending on the flow velocity. When vapor pressure is present and cavitation occurs, or if the flow boundaries diverge so sharply that separation of flow occurs at the boundary, it is uncertain what true pressure conditions exist in the diverging section. Cavitation pressures as well as separation of flow from the boundary were expected to occur in the passages under the Hoover gates. Both factors would change with the differential head on the gate and the gate opening. If a point of separation is near the upstream edge of the gate bottom, there may be only a relatively small downpull force. The force will increase if the point of separation is farther downstream.

Due to the fact that numerous variables and assumptions were necessary the results of the mathematical study were not conclusive so hydraulic model tests were made to determine the magnitude of the hydraulic forces to be handled by the gate suspension mechanism.

The Model Study

The model, built to a scale of 1:24, was nearly 18 feet tall and contained cylinder gates with walls 0.583-inch thick (Figures 2 and 3). It was the largest model which could be installed in the laboratory. While flow in the model was sufficiently turbulent to satisfy conditions of mechanical similarity in most respects, the nature of the boundary layer under the gate was critical in this problem at small gate openings where separation of the jet from the gate occurs. With a turbulent boundary layer, separation would occur farther downstream than with a laminar boundary layer, creating higher velocities in the constriction; consequently, lower pressures and greater downpull.

Computations were made to locate the point where the laminar layer becomes turbulent, assuming flow conditions as along a flat surface.

With a model head of 10 feet on the gate orifice the horizontal velocity V_x would be approximately 25.3 feet per second. It has been found that turbulent boundary layer will form when the Reynolds number R_x is 500,000.

$$R_x = \frac{V_x L}{\nu}$$

Where L is the distance from the leading edge, V_x is the velocity at the leading edge and ν is the kinematic viscosity of the fluid. Therefore,

$$L = \frac{500,000 \times 1.05 \times 10^{-5}}{25.3} = 0.208$$

This would indicate that the boundary layer would not form on the 0.0486-foot thick gate bottom; unless forced artificially. Moreover, it is doubtful that any reasonable size model would assure boundary flow which would compare favorably with the prototype. Hydraulic downpull forces for the prototype would therefore be greater than indicated by the model. It was realized that the model might serve only as a necessary step in obtaining a solution and that additional special tests might be required. The model was needed to ascertain the nature of the flow to be expected on the full-sized structure, to determine the operating conditions giving the maximum downpull force, to study the magnitude of the downpull forces, and to establish whether similarity between model and prototype did or did not exist. Moreover, there was a possibility that the model studies would provide a complete solution.

Provision was made on the model to measure the downpull forces with strain gages (Figure 2), but severe vibration of the model gates occurred at small openings where the maximum downpull force was indicated, so another method of evaluating them had to be used. Since the downpull force results from the difference in pressure on the top and bottom surfaces of the gate, the method used was that of integrating the pressure-distribution curves obtained from piezometer connections installed in the model gate. Tests were made for various heads, gate openings, and discharges, and the data expressed in prototype terms by hydraulic similitude relationships (Figure 4).

These data indicated that a maximum downpull force of 650,000 pounds would act on a lower gate for an opening of 6 inches; that separation of flow from the bottom surface of the gate would occur only when the gate was nearly closed, and that cavitation would occur on the bottom surface of the gate at normal reservoir levels for openings up to 1-1/2 feet under differential heads (reservoir water surface to water surface in tower) greater than 150 feet. Since cavitation and vapor pressure would be present on the prototype when the downpull is a maximum, the flow patterns of the model and full-sized structure will be dissimilar and the force indicated by the model would be too small.

Although it was not possible to determine the true magnitude of the hydraulic downpull forces with the model, it could be shown that the maximum values for the upper and lower gates would lie between certain limits. The limits for the lower gate would be 650,000 pounds indicated by the 1:24 model tests, and 1,250,000 pounds obtained by assuming vapor pressure on the entire sloping portion of the gate bottom.

An estimate of the adequacy of the suspension of the lower gates, considering that each of the three stems carries approximately one-third of the total gate weight plus downpull, indicated that the pins joining the lower stems would be stressed to about the yield strength in shear, with a total downward force of 1,240,000 pounds.

It was therefore concluded that further studies and tests be made to more accurately define the limits of possible downpull on the lower gates. The earlier studies had nearly exhausted the facilities of the laboratory at that time so the prototype structure was examined with a view of performing tests to determine the actual stem stresses for various operating conditions through the use of strain gages.

Tests on Prototype (Unmodified Gate)

Tests were performed on the lower gate of one intake tower. The tests were confined to a lower cylinder gate because hydraulic conditions for an emergency closure were more severe than for an upper gate and satisfactory operation of this gate would assure satisfactory operation of the upper gates. Moreover, the stem nuts of the lower gates were readily accessible while those of the upper gates were not. Strain gages of the SR-4 type were mounted on the stem nuts of the three operating stems of the lower gate in the upstream intake tower on the Arizona side of the canyon to measure the strain induced by the hydraulic downpull forces under emergency closure conditions. Two gages were placed on each nut, one diametrically opposite the other midway between the base and top of the nut, and connected in series electrically to operate as a unit. They were arranged in this manner to eliminate from the strain readings the effect of bending moments to which the nuts might be subjected during the test operation.

A set of two more gages mounted on a manganese-bronze block, similar to the stem nuts in composition, was provided at each stem to compensate for temperature changes. Each set of four gages was connected by electric wire leads to a Type K strain indicator which indicated the strain directly in millionths of an inch per inch.

The relation between the strain shown by the indicator and the total force applied to each stem nut was obtained by calibration. A crosshead beam was attached by long bolts to the gate hoist gear housing supporting the nut and this beam in turn supported a 300-ton capacity hydraulic jack which was used to apply known loads through a calibrated load cell to the stem screw. The calibration facilities are shown on Figures 5 and 6.

The calibrations were made without water flowing through the tower to eliminate the effect of hydraulic conditions which would add forces of unknown magnitude to the stem nuts. Calibration was confined between the hours of 11 p.m. and 2 a.m. on week days during periods of low power demand to permit power outages when the work was being done. These calibrations indicated that for stems 1 and 2 the force to produce 1 micro inch strain was 610 pounds while that for stem 3 was 625 pounds. Three strain indicators were used during the tests, one for each stem. This arrangement permitted taking readings on the three stem nuts individually and simultaneously. Indicator readings were recorded with the gate suspended on the stems and with the weight of the gate and stems released from the nuts, both during calibration of the stem nuts and prior to testing. This was done to determine the approximate weight of the gate and stems and to establish a datum from which hydraulic downpull forces could be measured. The 350,000 pounds weight obtained in this manner was considered approximate only because of the difficulty of determining the exact position of the gate hoist which would relieve the nuts of the weight of the gate and stems.

The actual downpull force due to the flow of water under the gate was obtained by multiplying the micro inches change in strain by the pounds force required to produce one micro inch strain in the particular nut.

A counterweighted float with the connecting cable threaded on pulleys, one of which turned one complete revolution for each foot of float travel, was used to determine the water-surface elevation within the tower. A counter was attached to the pulley in such a manner that it indicated the float travel and could be set to read the tower water surface directly in elevation above sea level.

During an emergency closure the water surface within the tower recedes as the gate is lowered and the amount of recession for a given gate opening depends on the flow being discharged from the penstock system. To represent this condition the upper gate was closed, the lower gate set at a given distance above the seat, and the water surface within the tower lowered by operating the 72-inch needle valves in the tunnel plug outlet. Observers were placed at several station to record and describe their observations. The time pieces of all men participating in the tests were synchronized each night before testing began. All data were recorded with respect to time or the elevation of the tower water surface which was recorded with respect to time.

As the valves were opened slowly to the positions predetermined from operating curves which were prepared as a guide for conducting the tests, the water surface in the tower receded. A strain reading on each stem nut was taken with the tower water surface at the elevation of the reservoir, 1168, and at elevation 1165 and at each 5-foot increment of change below elevation 1165.

Tests were first made with the gate set 3 inches above its seat because critical downpull forces were not expected at this setting. As the water surface within the tower approached elevation 1090 the noise of cavitation and slight vibration within the system was noted. An inspection of the penstock inside the 50-foot tunnel was made with the tower water surface at elevation 1058. The noise in the tunnel at the base of the tower was intense but there seemed to be no motion of the pipe other than slight cavitation shock. The noise and shock decreased rapidly toward the downstream end of the tunnel. From the inspection it was concluded that no serious conditions were present and the tests were resumed. Both noise and vibration increased as the water surface was drawn down until at elevation 1023 the test was stopped because of the severity of the conditions. At this point movement of the 1/2-inch thick floor plates in the parapet outside the tower could be seen. The total maximum hydraulic downpull on the gate of 540,000 pounds indicated by the strain gages on one stem was not considered excessive.

The needle valve outlets were closed, the cylinder gate set at a 6-inch opening and the same procedure followed as for the 3-inch setting. The downpull forces were only slightly greater than for the smaller opening and the noise and vibration appeared to be about the same.

Tests were made also at 15-, 12-, 10-1/2-, 9-, 8-, 7-, 5-, and 4-inch openings to determine the gate opening having the greatest hydraulic downpull. The tower water surface was lowered to an elevation sufficient to establish the maximum downpull for the 9-, 5-, and 3-inch openings, Figure 7A.

The gate opening was set under static conditions at the beginning of each test by measuring the height of the stem above the top of the stem nut. The gate operating mechanism was not disturbed during the test on any gate setting. Since the hydraulic downpull varied during each test, the elongation of the operating stems varied and thus the gate opening did not remain constant. With the physical properties of the stems known, it was possible to compute the elongation due to the hydraulic downpull forces. The curves of Figure 7B show the results after the corrections for the elongation of the stems were applied. These curves show that a maximum downpull force with the reservoir at elevation 1168 is 600,000 pounds and that this force occurs at a 4-inch actual gate opening with the tower water-surface elevation about 1020. Figure 9 shows the hydraulic downpull for both the upper and lower gates with the normal high reservoir elevation 1229.0.

The vibration and noise described previously was present at all openings tested. In general, the sound of flowing water in the tower became audible when the tower water surface approached elevation 1125, the noise of cavitation became audible as the water surface approached elevation 1100 and the intensity of the noise and vibration due to cavitation increased first slowly and then rapidly as the tower water surface receded to elevation 1040 and below. The elevation at which the noise of cavitation became audible seemed to vary slightly with gate opening. For the small gate openings, up to 6 inches, it seemed to start with the tower water surface at about elevation 1100; for medium openings, 6 inches through 8 inches, the tower water surface was about 1095; and for the larger openings the elevation was about 1080. This condition is to be expected since the divergence of the water passage under the gate increases as the gate opening decreases and the differential head causing cavitation to start in these passages would be less as the opening decreased.

In all cases the floor plates on the platform outside the tower were set in vibration when the tower water surface approached elevation 1040. However, there seemed to be a noticeable decrease in this vibration for the 15-inch opening. In all cases the downpull force became unsteady as cavitation was established. This unsteadiness increased as the water surface in the tower decreased. The nature of the unsteadiness in most cases was indicated by the continuous swinging of the strain indicator needle in short arcs. The fluctuation in downpull was small in these cases. At other times the needle would change position rather suddenly to another indicator reading and oscillate as described above. The maximum observed variation of this nature was 50,000 pounds per stem. This variation in force could be attributed only to a change in pressure on the gate bottom resulting from an unstable flow pattern under the gate. The maximum indicator reading was recorded in every case while the minimum was recorded only occasionally. Only the maximum force is shown on Figure 7.

Since the severe vibration made it inadvisable to continue the lowering of the water surface in the tower to establish the downpull forces at the low elevations, and since it was considered essential to gain some idea of the conditions with a low tower water surface, particularly with only slight submergence of the gate, the gates were closed and the needle valve outlets opened to lower the tower water surface to elevation 915. The cylinder gate was then raised slowly and the needle valves opened slowly to hold the water surface constant at this elevation. There was noise from cavitation and the flowing water as the gate continued to open but no apparent vibration was present; however, the water surface within the tower began surging and caused the counterweighted float to be tossed about so violently that the float gage equipment was endangered. The gate was opened about 3/4-inch instead of the intended 3 inches. The test was discontinued because of the possibility of destroying and losing the float gage equipment. The downpull force for the 3/4-inch gate opening was measured with the tower water surface near elevation 920 and found to be about 50,000 pounds per stem.

In summary these tests, which represented an emergency closure, disclosed that excessive downpull forces and intense vibration of the tower, gate, and penstock would be present during such a closure. A proposal to remove a part of the gate bottom to reduce the downpull force and vibration was made as a result of these tests. The bottom of the lower gate in the upstream Arizona intake tower was modified as shown in Figure 8.

Tests on Prototype (Modified Gate)

Another series of tests was made in October 1953 to determine the effect of the change of the shape of the gate bottom on the downpull forces and vibration. The SR-4 type strain gages installed and left on the stem nuts of the lower cylinder gate in 1950 were inspected and the calibration checked before the downpull and vibration tests were begun. Additional SR-4 gages were attached to the stem nuts to obtain oscillograph records of force variations. Also, gages were mounted on bronze blocks, as in the 1950 tests, to compensate for temperature changes. A vibration meter was attached to the top of gate Stem No. 2 to record the vibration during the downpull tests. Type K strain indicators attached to wire leads of the SR-4 gages for each stem indicated strain directly in millionths of an inch per inch. The wire leads of the newly installed SR-4 gages were attached to galvanometer elements of an oscillograph, which indicated strain proportional to the movement of the lightbeam trace on sensitized paper. Movement at the vibration meter was also recorded by the oscillograph.

The relation between the total force applied to each stem and the strain shown by the indicators was obtained by calibrating the gages on the stem nut against those on a calibrated load cell mounted at the top of the stem. The relation between the force acting on a stem and the movement of the lightbeam on the oscillograph was obtained using the calibrated load cell. The calibration facilities were the same as those used for the tests described earlier and shown in Figures 5 and 6. The calibrations were made without the flow of water through the tower to eliminate any unknown hydraulic force on the stem nuts. The forces necessary to produce one micro inch per inch strain in the nut were 606, 615, and 638 pounds for nuts 1, 2, and 3, respectively. The tests were made when the reservoir level was at elevation 1155. With a 3-inch gate opening there was no noise in the tower until the water surface within the tower reached elevation 1100, when a rumble, associated with flowing turbulent water, was noted. This rumble increased gradually as the tower water surface decreased. At about elevation 1055 there was a sudden change in noise within the tower to that of water falling into a pool. This change occurred as the top of the upper cylinder gate became exposed and was attributed to leakage at the top seal of this gate. As the tower water surface receded to elevation 1000, the rumbling noise increased in intensity, movement was noted on the vibration pick-up record, and the floor plates in the parapet outside the tower began to vibrate. With the tower water near elevation 955, the noise was still intense but the vibration and rumble had decreased somewhat. With the tower water surface at elevation 940, the lowest for the test, the conditions were about as for the tower water surface at elevation 955. While the noise and vibration were considered severe, the intensity was substantially less than noted on the unmodified gate. Cavitation on the bottom surface of the gate had not been eliminated entirely by the modification.

The tower water surface was not lowered beyond elevation 940 because surging inside the tower increased rapidly as the water surface neared the gate. The maximum total hydraulic downpull on the gate measured during the test at this opening was 133,000 pounds with the tower water surface at elevation 1010. This force, which was the maximum obtained for the tests, was about 25 percent of that measured for a 5-inch setting on the unmodified gate. The downpull force increased as the tower water surface receded, reached a maximum, and then decreased, Figure 8.

The maximum hydraulic downpull force that might be expected with the reservoir at normal high level, elevation 1229, was determined to be about 200,000 pounds (Figure 9).

The strain indicators showed that changes in magnitude of the downpull force were occurring. Observation of the lightbeams on the viewer of the oscillograph showed the force on each stem was varying, at times slowly, as though the gate was wobbling, and occasionally rather suddenly, indicating a rapid change in the force being applied to the stem. A study of the oscillograms shows maximum variations in the slowly changing force to be about 65,000 pounds and in the rapid changes to be about 13,000 pounds. For example: at 3-inch gate opening these changes in downpull were 21,200 pounds in 12-1/2 seconds and 6,500 pounds in 2.2 seconds; at 5-inch gate opening the changes were 30,000 pounds in 4.0 seconds and 10,000 pounds in 0.2 second; at 9-inch gate opening the changes were 64,700 pounds in 7.8 seconds and 13,000 pounds in 0.1 second; and at 12-inch gate opening the changes were 51,000 pounds in 2.6 seconds and 10,000 pounds in 0.1 second.

A sample of the oscillograph record showing the fluctuation in downpull force and vibration of the gate stem is shown in Figure 10.

ACKNOWLEDGMENTS

This series of studies was carried out over a period of eight years by a number of investigators. The preliminary analysis preparatory to the model study was made by F. C. Lowe and D. Colgate who also conducted the model studies. The downpull tests on the prototype gates were conducted by James W. Ball, who was assisted by Val Jones, M. C. Henry, R. H. Kuemmich and several project workmen.

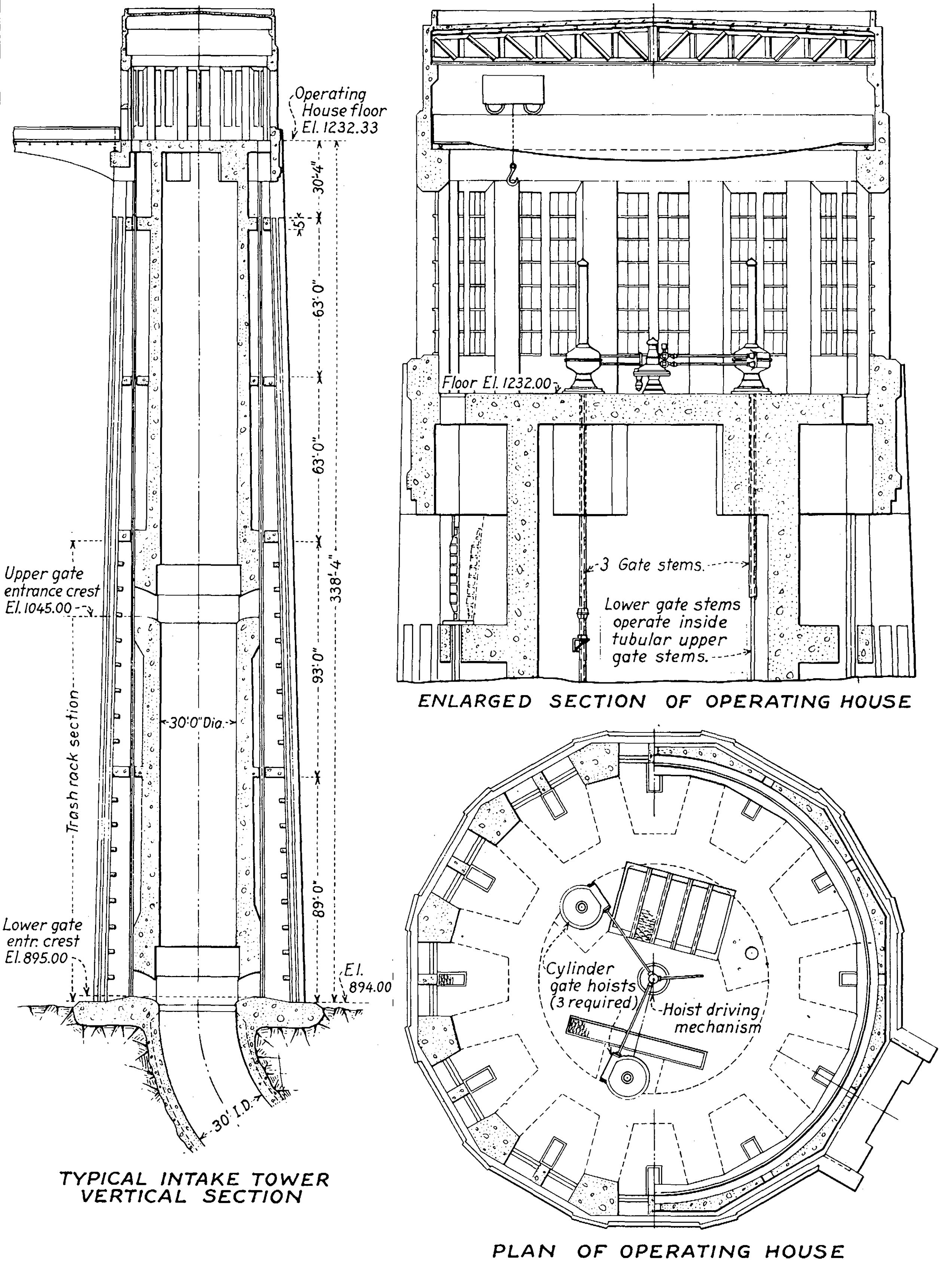


FIG. 1 - HOOVER DAM INTAKE TOWER

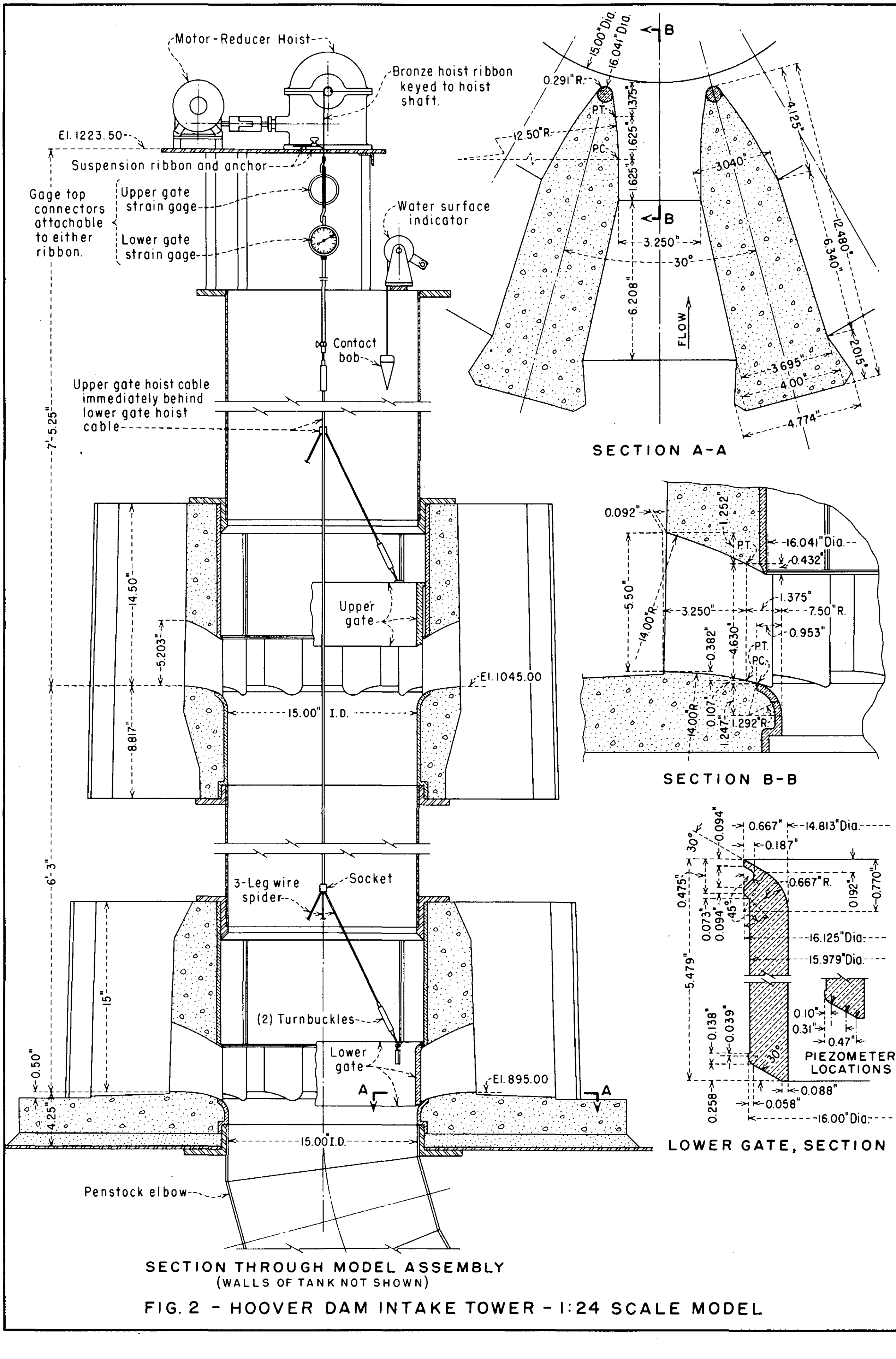
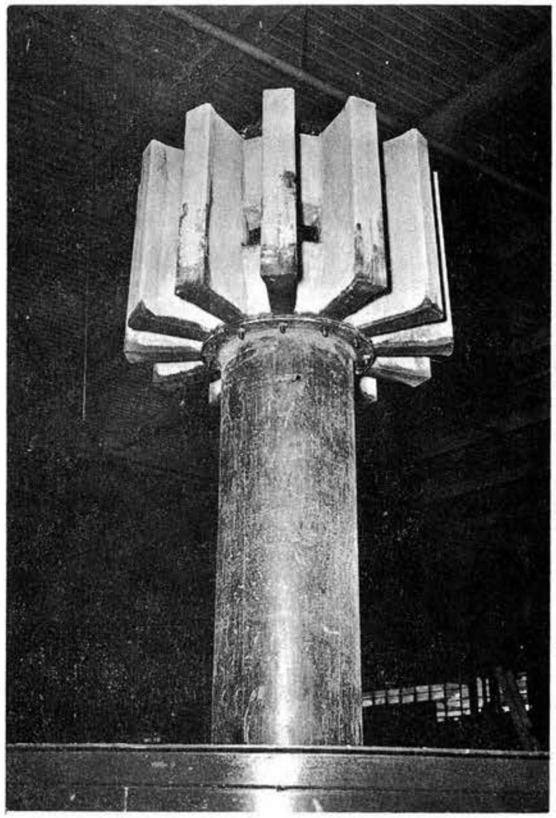
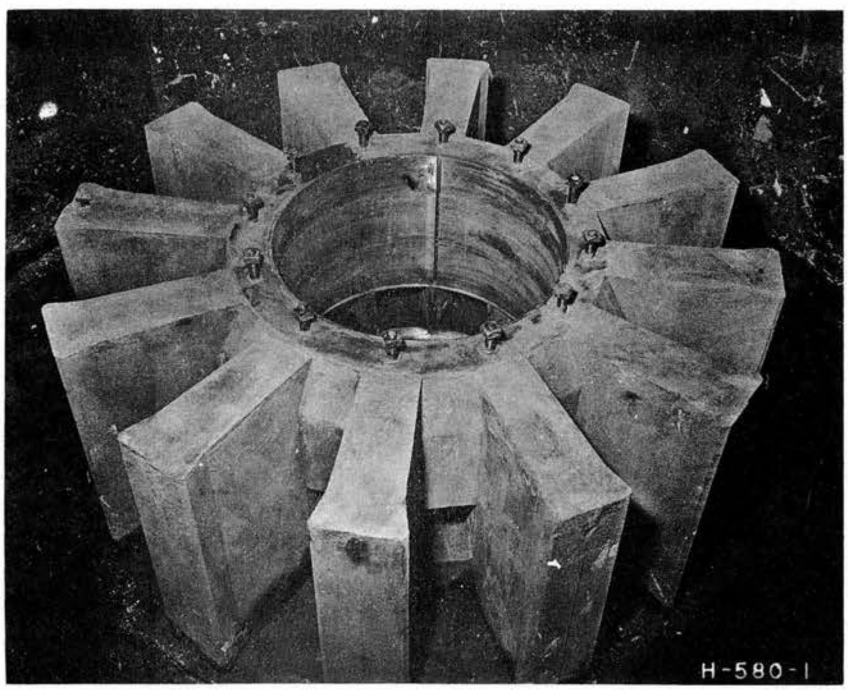


FIG. 2 - HOOVER DAM INTAKE TOWER - 1:24 SCALE MODEL



A. Upper gate entrance, and tower below the upper gate.



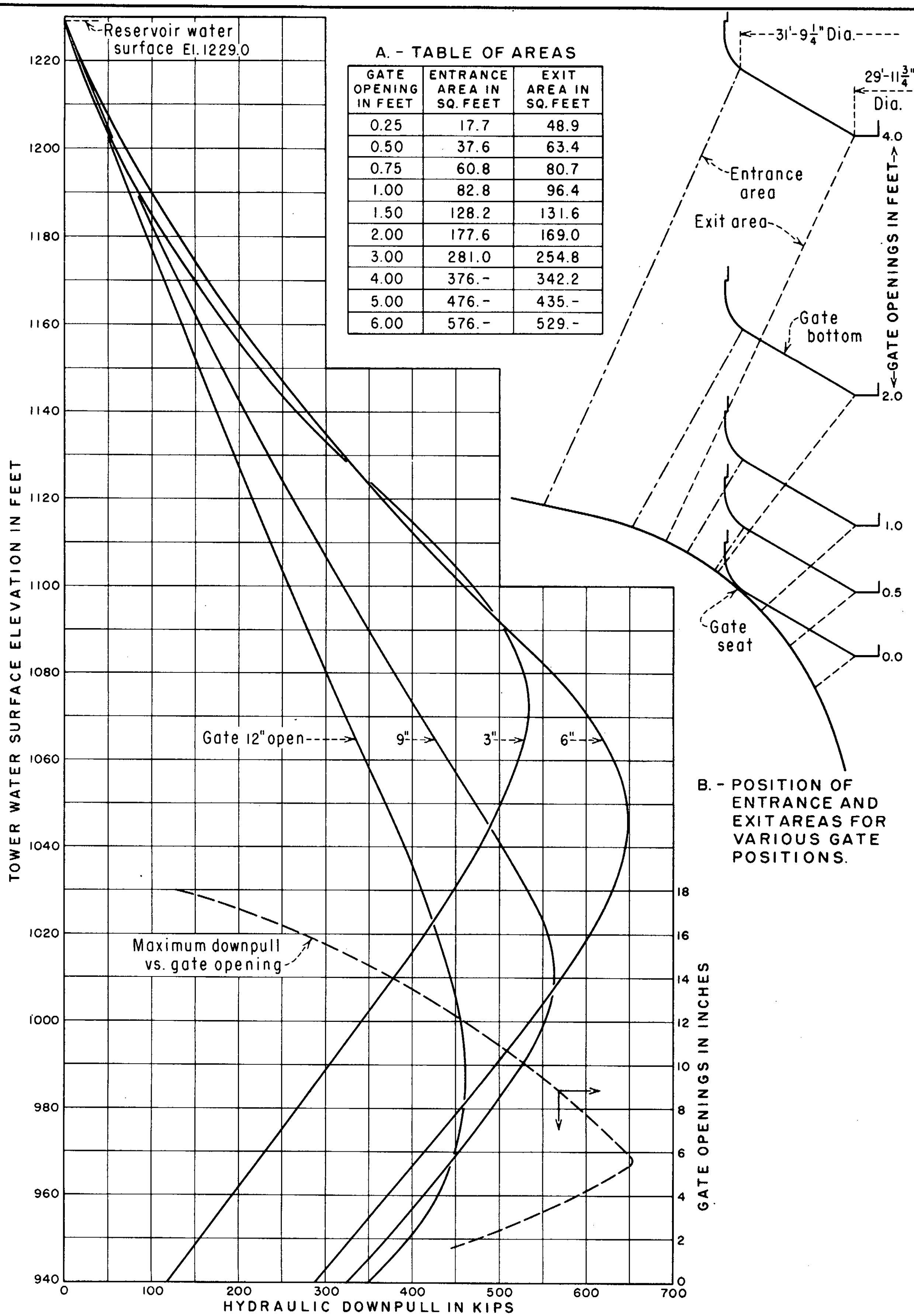
B. Lower gate liner and piers.

Fig. 3 Upper and Lower Gate Entrances

HOOVER DAM INTAKE TOWER--1:24 SCALE MODEL

A. - TABLE OF AREAS

GATE OPENING IN FEET	ENTRANCE AREA IN SQ. FEET	EXIT AREA IN SQ. FEET
0.25	17.7	48.9
0.50	37.6	63.4
0.75	60.8	80.7
1.00	82.8	96.4
1.50	128.2	131.6
2.00	177.6	169.0
3.00	281.0	254.8
4.00	376.-	342.2
5.00	476.-	435.-
6.00	576.-	529.-



B. - POSITION OF ENTRANCE AND EXIT AREAS FOR VARIOUS GATE POSITIONS.

C. - PROTOTYPE DOWNPULL FOR LOWER GATE COMPUTED FROM MODEL DATA

FIG. 4 - HYDRAULIC DOWNPULL AND FLOW AREAS - LOWER CYLINDER GATE - HOOVER DAM INTAKE TOWER

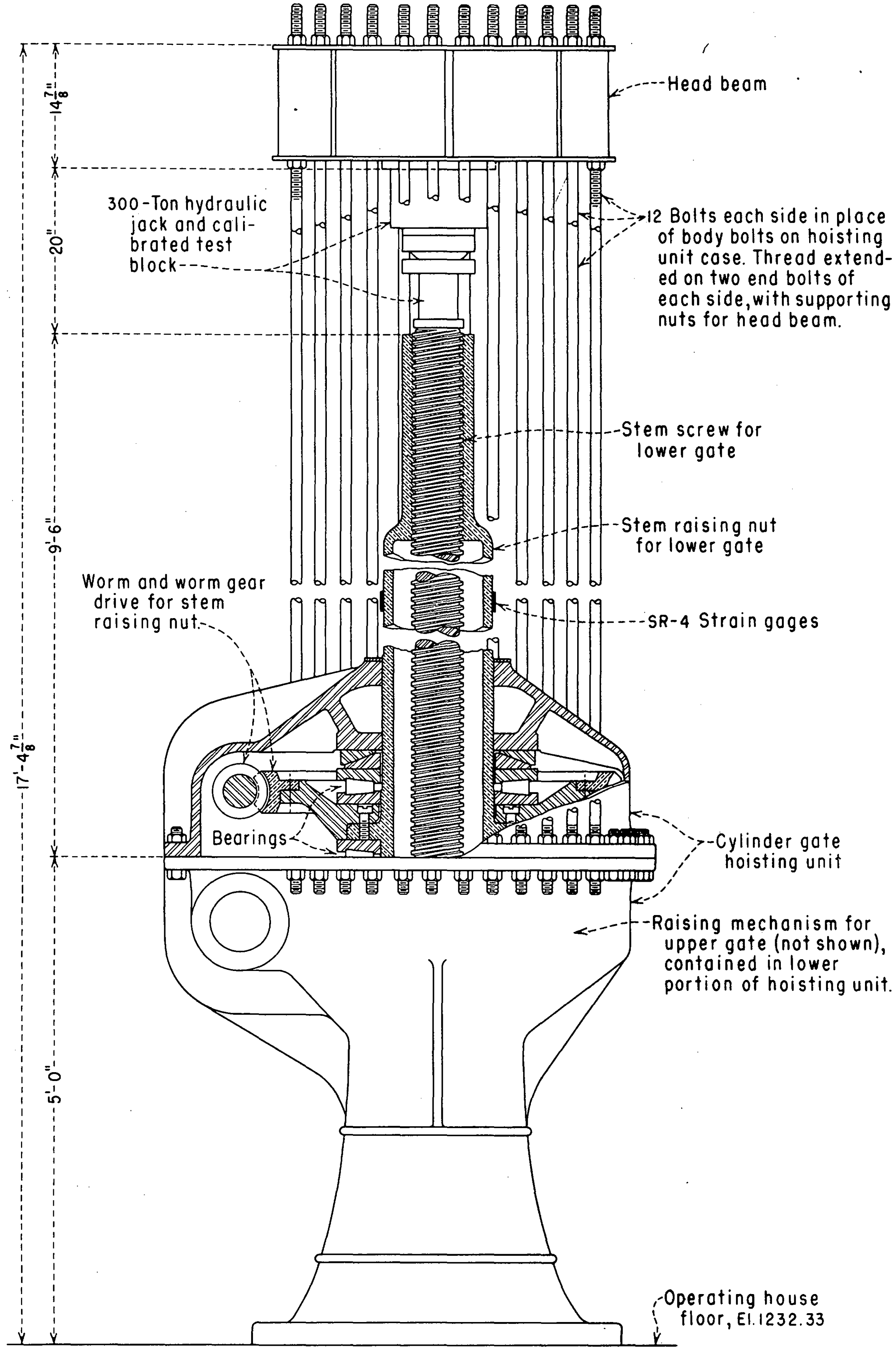
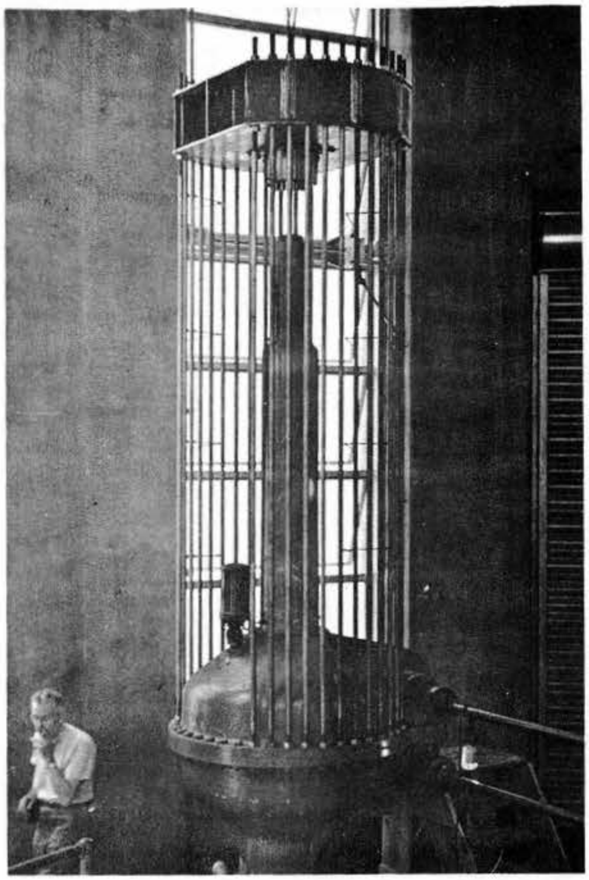
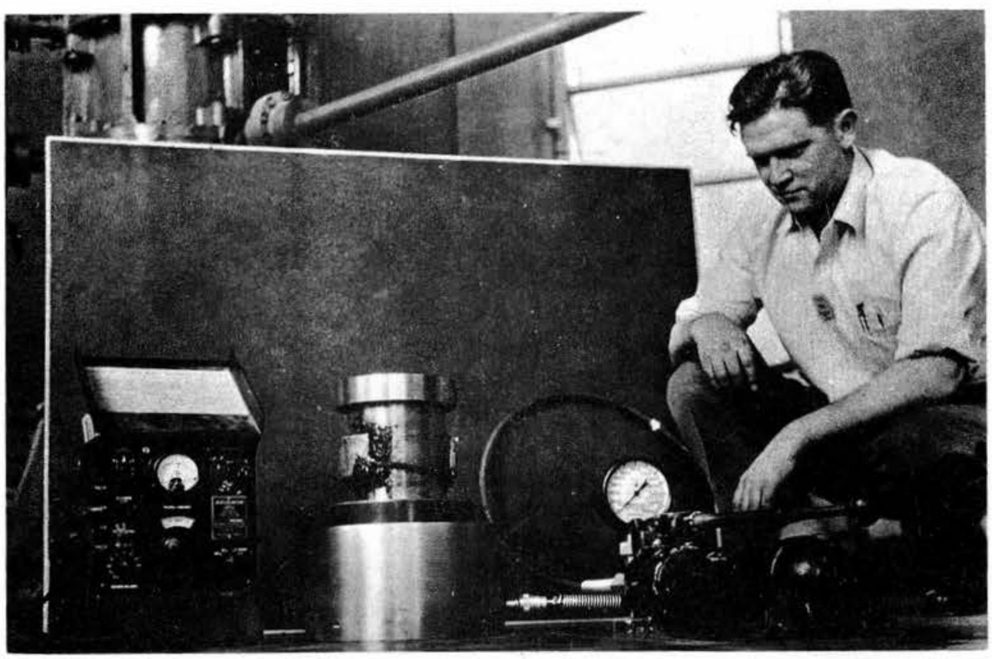


FIG. 5 - STEM NUT CALIBRATING APPARATUS FOR CYLINDER GATE HOIST - HOOVER DAM INTAKE TOWER



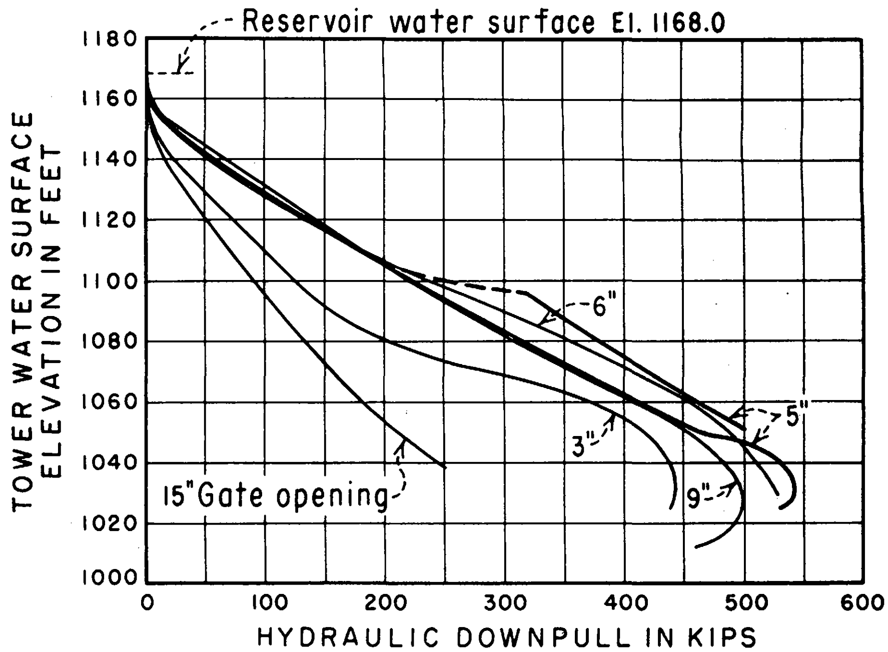
A. Stud-supported beam and hydraulic jack installed and ready for calibrating the the gate stem nuts.



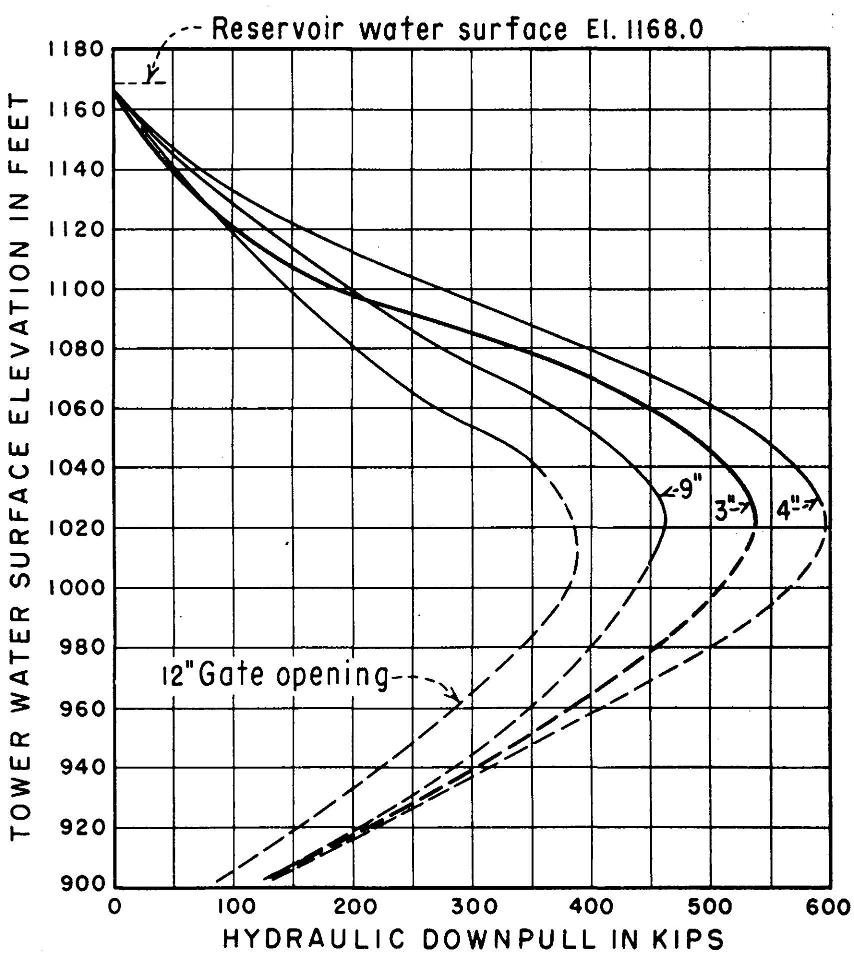
B. Type K strain indicator, hydraulic jack with calibrated load cell, and high pressure pump.

Fig. 6 Calibration Facilities for Hydraulic Downpull Tests

HOOVER DAM INTAKE TOWER

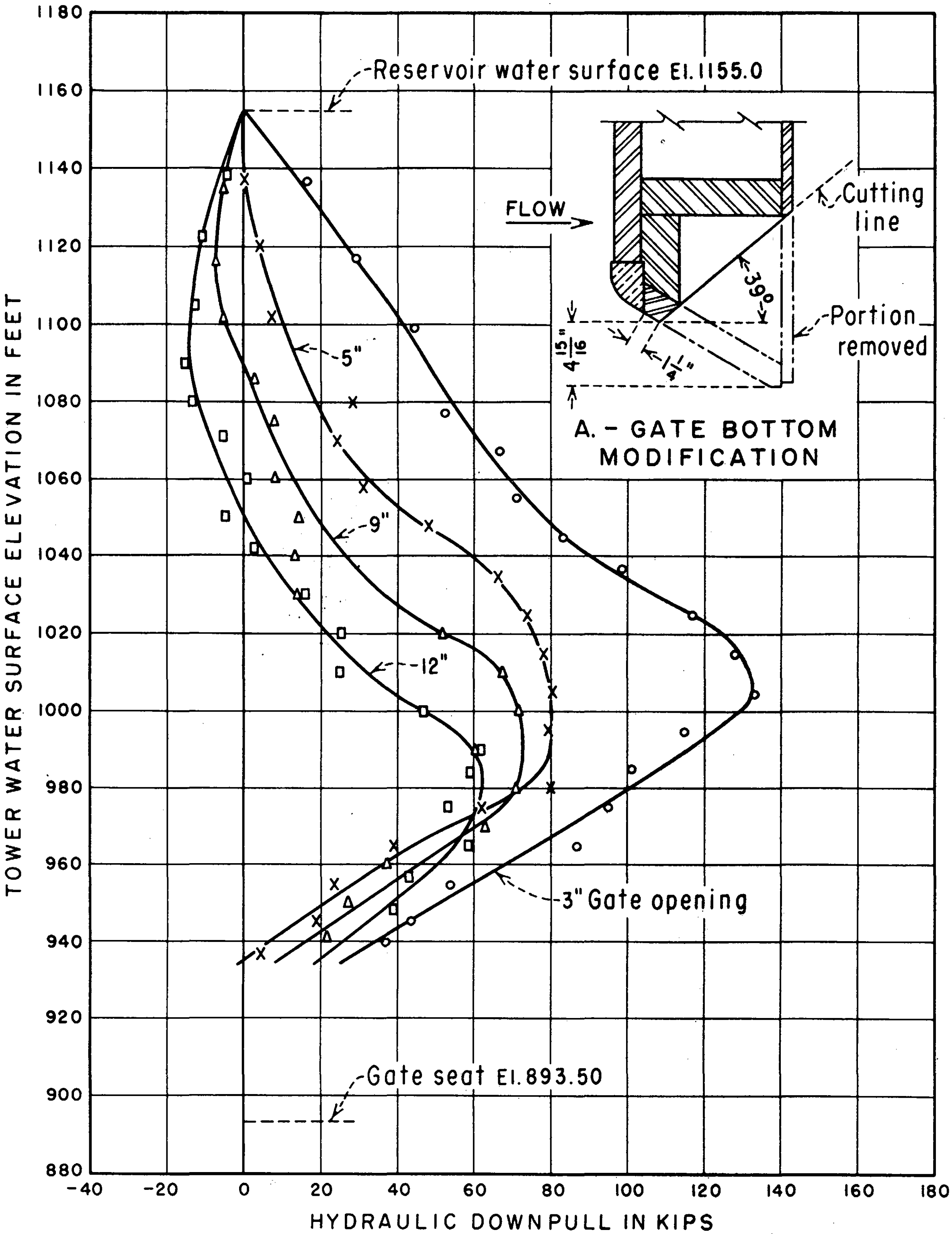


A. - HYDRAULIC DOWNPULL FOR RECORDED GATE OPENINGS



B. - HYDRAULIC DOWNPULL FOR GATE OPENINGS ADJUSTED FOR STEM ELONGATION

FIG. 7 - FIELD MEASUREMENTS - HYDRAULIC DOWNPULL FORCES - LOWER CYLINDER GATE - HOOVER DAM INTAKE TOWER



B. - HYDRAULIC DOWNPULL ON MODIFIED GATE

FIG. 8 - GATE MODIFICATIONS AND FIELD MEASUREMENTS OF HYDRAULIC DOWNPULL FORCES - MODIFIED LOWER CYLINDER GATE - HOOVER DAM INTAKE TOWER

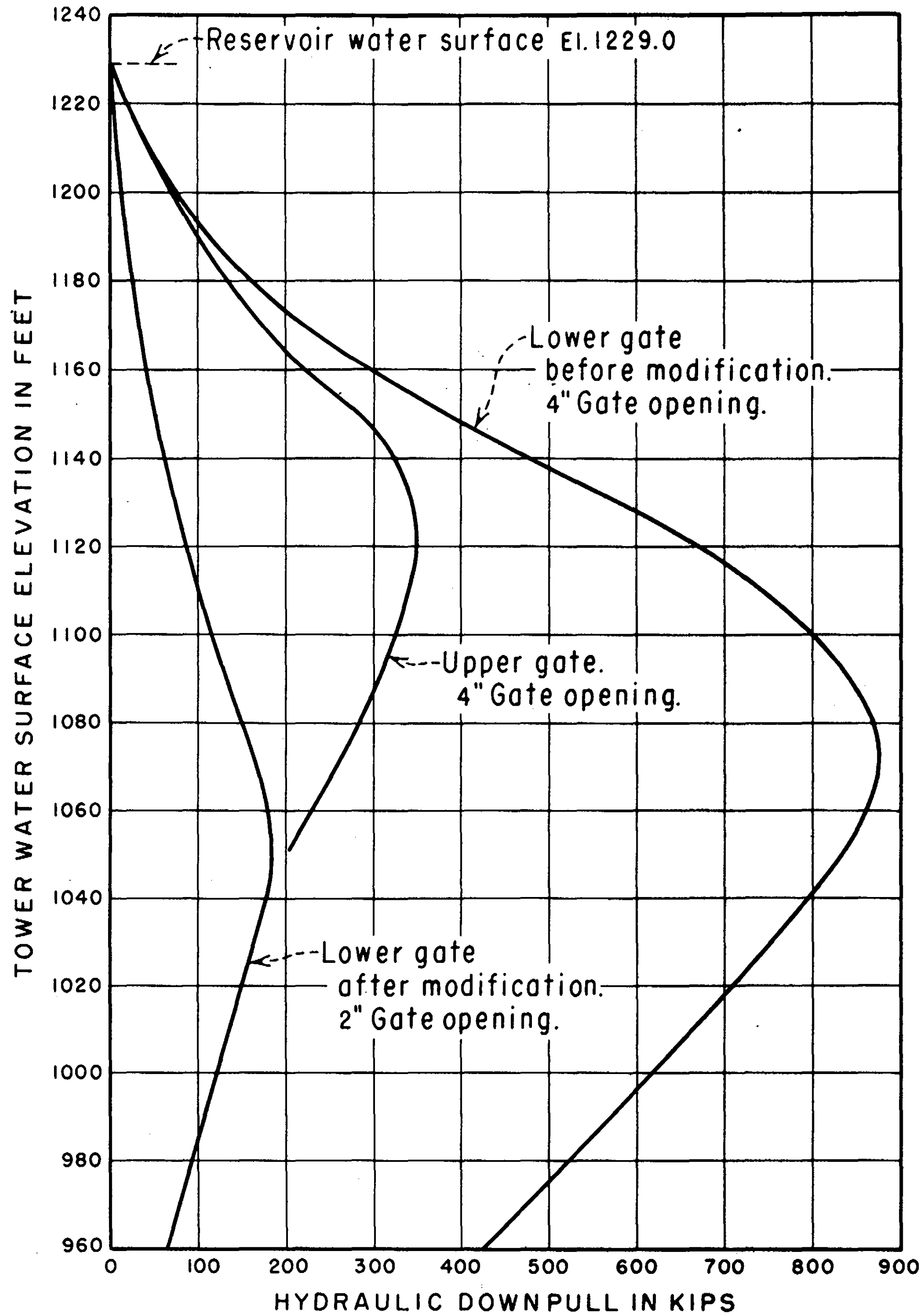
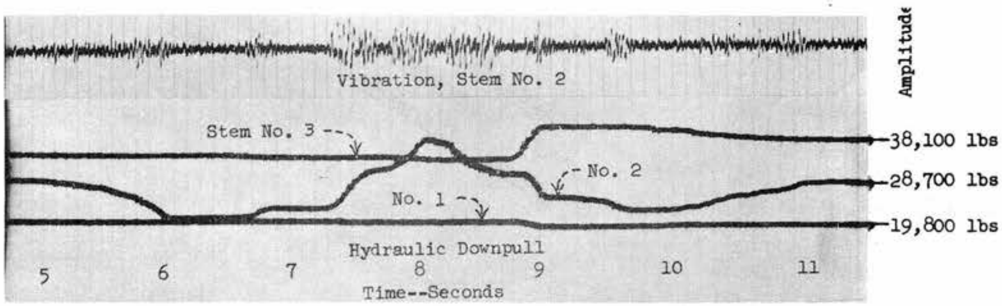
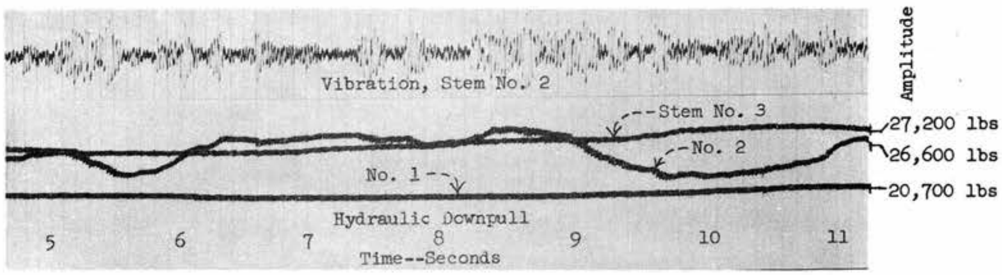


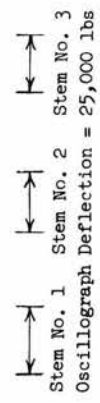
FIG. 9 - HYDRAULIC DOWNPULL FORCES BEFORE AND AFTER LOWER CYLINDER GATE MODIFICATION - HOOVER DAM INTAKE TOWER

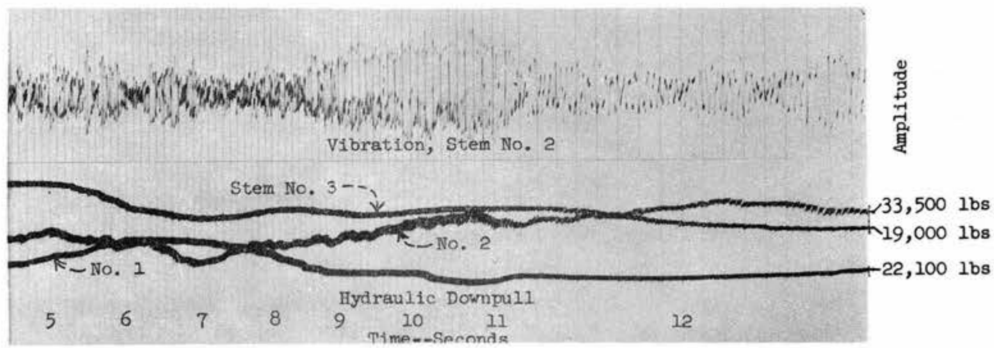


A. 12-inch Gate Opening, Tower W. S. 965

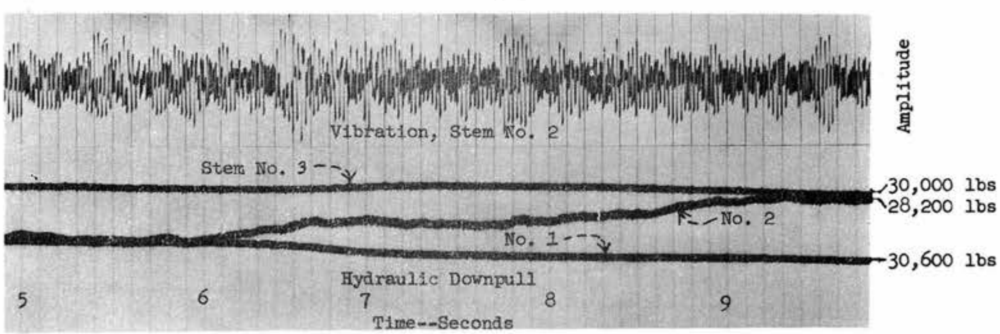


B. 9-inch Gate Opening, Tower W. S. 970





C. 5-inch Gate Opening, Tower W. S. 995



D. 3-inch Gate Opening, Tower W. S. 985

Figure 10--Sample Oscillograph Records--Hydraulic Downpull and Vibration--Modified Cylinder Gate