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AIR MODEL STUDIES OF HYDRAULIC DOWNPULL ON LARGE GATES

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ABSTRACT

Air model studies were used to determine the hydraulic downpull forces on a large fixed-wheel gate and on a slide gate. The applicability of air tests for this work is discussed, and the method of applying the data is detailed. Data are presented that will be helpful in evaluating downpull forces on other similar gate structures.

INTRODUCTION

The use of air models for studying hydraulic problems has repeatedly proved to be a reliable and accurate expedient. The advantages of air tests in place of hydraulic tests have been thoroughly discussed by Hunter Rouse2/ and others, and many examples of the use of these air models are given by J. W. Ball and D. W. Appel.3/ Another unusual use of air models is presented in this paper, wherein studies of hydraulic downpull forces on a large fixed-wheel gate and on a high-pressure slide gate are discussed.

The downpull forces being considered here are those forces produced when flow occurs beneath the gate leaf, thereby reducing the pressures on the bottom of the leaf relative to the pressures on the top. This pressure difference, acting on the cross-sectional area of the leaf, produces a downpull force which must be considered in addition to frictional forces and the leaf weight in designing the stem and hoist. The method used for obtaining the downpull was to determine the unit pressures acting on the top and bottom surfaces of the gate leaves, and applying these pressures to appropriate areas to compute the downpull forces. No measurements of stem loads were made.

When the downpull studies were first considered, it was taken for granted that model studies would be made with water. But it was later recognized that air model studies would be equally satisfactory

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2/Rouse, Hunter, "Use of the Low Velocity Air Tunnel in Hydraulic Research," Bulletin No. 31, Studies of Engineering, State University of Iowa, Iowa City, Iowa, 1947 (Proceedings, Third Hydraulic Conference).

3/Ball, J. W., "Model Tests Using Low Velocity Air, with discussion by D. W. Appel. ASCE Paper No. 2517, Transactions, Volume 117, 1952.

and that they would be less expensive and time consuming. The method of testing with air would be identical to that for water because the air velocities would be maintained below about 250 feet per second, and incompressible flow equations could be used.[3/] The degree of error would not exceed about 5 percent at a velocity of 250 fps and would decrease rapidly with decreases in velocity. The velocities actually used were 64 fps or less, and the error was about 1 percent. Wetting would not be a problem in an air model and, therefore, untreated wood and metal surfaces could be used. The construction could be relatively lightweight because the density of air is low and the weight and pressure forces are small. The supply and exhaust systems posed no problems because the atmosphere served as both reservoir and receiver.

The argument in favor of hydraulic models was that by their use free water surfaces could be obtained. With air models discharging into the atmosphere no free surfaces are possible. With either of the two gates under consideration free surfaces will exist during free discharge operation.

This limitation was not as great a handicap for the air models as was first thought. In the case of the fixed-wheel gate, the maximum downpull occurs when there is no free surface and where back pressure or submerged conditions exist. Thus, only tests with submerged flow were required. These are accurately reproduced in an air model.

In the case of the slide gate, the downpull forces were desired at both free discharge and submerged conditions. After study of the leaf shape, it was found that the pressure acting on the leaf could be analyzed for either free discharge or submerged conditions by proper treatment of the data obtained from an air model. The treatment is discussed in detail later in this paper.

GATE STRUCTURES

The first gate studied was a fixed-wheel gate designed for the power conduit at Glendo Dam, Wyoming (Figure 1). This gate has a leaf 3.3 feet thick, 16.5 feet wide, and 21.0 feet high. It is located near the entrance of the 21-foot-diameter outlet and power tunnel and normally remains fully open. When a regular closure is required, it is made with no flow taking place and with the pressures upstream and downstream from the leaf balanced. Emergency closures with unbalanced pressures may also be made. Sustained operation with unbalanced pressures will occur during the tunnel filling period when the gate will be used as the flow regulator at openings of 3 to 6 inches.

The control point on this fixed-wheel gate is at the upstream bottom edge of the leaf. When the gate is controlling the flow, the pressures on the leaf bottom will be less than the pressures on the leaf top and less than in the tunnel just downstream. This occurs because as the flow passes beneath the leaf, the flow velocity--and hence the kinetic energy--becomes high. Simultaneously, and because the total energy in the water remains essentially constant, the piezometric pressures become low.

The pressures on the leaf bottom were of greatest interest during the tunnel filling period when the gate openings were very small. At these small openings, the ratio of opening height to gate thickness was small, so that in effect, the opening under the leaf approximated a "short tube," or more specifically, a "short slot." As the flow passed beneath the leaf, it experienced it's minimum cross section at the vena contracta, and then tended to expand and occupy most of the section between the conduit floor and the web of the bottom beam at the downstream face of the leaf. This action could prevent aeration between the leaf and the jet during free discharge operation, and would restrict the relief afforded by circulation of water during submerged operation. Thus, lower pressures than usual would occur on the entire leaf bottom at very small gate openings, and the downpull forces would be extremely large. When the gate opening increases, the jet contraction and subsequent expansion changes and more space is left between the jet and the downstream web. The fluid is readily able to move upstream through the space to relieve the low pressures on the gate bottom. When the gate reaches the full open position, the pressures beneath the leaf are about the same as those in the tunnel and on top of the leaf. At this point, the downpull is quite small.

The second gate studied was the slide gate design now being extensively used by the Bureau of Reclamation. This gate is a rectangular, downstream seal, high capacity slide gate designed for use as a regulator under high heads (Figure 2). The principal features of the gate are the small slots, the outwardly offset downstream slot corners followed by gradually converging side walls, and a leaf with a flat upstream face and a 45° sloping bottom. This gate was developed to meet the requirements of the outlet works at Palisades Dam where large flows of water at heads up to 240 feet are controlled. The gate has since been included in the designs of several outlet structures with heads as high as 373 feet.

The magnitude of the hydraulic downpull forces on the fixed-wheel gate and on the slide gate were desired so that adequate, but not excessive, hoists and handling equipment could be provided. Model studies were made on the gates to evaluate these downpull forces.

THE MODELS

Air was used as the flowing fluid in the models. A centrifugal blower drew air from the atmosphere and forced it through a 10-inch pipeline 6.4 diameters long, and then through the test section and back to the atmosphere (Figure 3). The rate of flow was measured by a flat plate orifice at the entrance of the 12-inch-diameter blower inlet line.

All of the parts for the models were of simple and inexpensive construction, and were fabricated in a short time.

The test section for the fixed-wheel gate consisted of a plywood conduit 16.67 inches high (Figure 4). The conduit was 8.25 inches wide upstream from the gate leaf, and 8.50 inches wide downstream from the leaf. The 2.82-inch-thick leaf was made of 12-gage sheet metal and contained 10 piezometers on the bottom along or near the conduit center line. Piezometers in the tunnel roof upstream and downstream from the leaf were used to obtain the pressure drop across the gate. The slots were simplified and represented the width but not the depth of the Glendo slots. The position of the gate leaf could be observed through transparent plastic windows that formed the outer slot walls.

The test section for the slide gate was 16.67 inches high and 8.25 inches wide (Figure 5). The 2.48-inch-thick leaf was made of heavy gage sheet metal and was supported in slots 0.64 inch wide. Three rows of eight piezometers were placed on the leaf bottom so the pressure distribution could be determined at distances of 0.18 and 1.10 inches from the sides of the leaf, and on the center line. An additional piezometer was placed on the bottom of one of the projections of the leaf that extends into the gate slots. The upstream pressure head was measured by a piezometer in the right wall 19 inches upstream from the leaf. A piezometer on the roof center line 1 inch upstream from the leaf gave the approximate bonnet pressure. No bonnet was included in the model, and there were no piezometers downstream from leaf.

All pressure measurements were made with water-filled U-tubes, and the readings were made in tenths of an inch and estimated to the nearest hundredth of an inch. The test procedure for each gate consisted of setting the leaf to the desired position, allowing a few minutes of operation for conditions to stabilize, and then taking the pressure readings. The leaf was then set to the next desired position and the procedure was repeated.

INVESTIGATIONS

The downpull forces on the gate leaves were determined by measuring the pressures acting on the top and bottom surfaces of the leaves, and not by measurement of stem loads by strain gages, spring scales, weights, or other devices. Previous experience at the Bureau of Reclamation has shown that the forces determined by pressure distribution may be more accurate than forces determined by stem load measurements because of the effects of frictional factors, vibration, and leaf movement. Proper clearances between parts are of particular importance, and it is often difficult to predict what these clearances will be, or to produce them in the model. When using the pressure-area method, care must be taken to insure getting pressure readings in all regions which can effect the downpull on the leaf, and to apply these pressures properly.

In the case of the Glendo fixed-wheel gate, the only condition where downpull will be an important factor is during submerged operation when gate openings are small relative to the leaf thickness. In this case the only pressure relief obtained beneath the leaf is that due to circulation of water between the leaf and the jet.

The pressures on top of the leaf can vary from essentially atmospheric when the backwater is insufficient to fill the tunnel, to high values when the downstream tunnel is flowing full.

When no backwater is present and the gate opening is appreciable, the jet will pass beneath the leaf and clear the downstream web enough to allow free aeration. Thus, the pressures under the leaf will be about atmospheric. The pressures above the leaf will also be about atmospheric because the gate seals are on the upstream face and the bottom surface is open to the tunnel pressure at the downstream face (Figure 1). There is little or no downpull under these conditions.

In the slide gate, downpull will be an important factor through a wide range of openings for both free discharge and submerged operation. The maximum downpull can occur with submerged operation because subatmospheric pressures can exist on the flat-bottomed portion of the leaf during this operation. In contrast to this, the lowest pressures on the flat-bottomed portion of the leaf during free discharge operation are about atmospheric. The bonnet pressures will be high at small gate openings for either free discharge or submerged operation because this type of gate seals on the downstream face of the leaf, and is open to the tunnel pressures at the upstream face (Figure 2). The high bonnet pressures are the main factor in the high downpull forces produced on these gates.

Fixed-Wheel Gate

In the simplified air model equivalent values of head differential that will occur across the full-size gate could not be set. But, as in a water model, the pressures on and across the leaf varied in accordance with the model heads and velocities. Thus, prototype pressures were obtained by multiplying model pressures by the ratio of the computed prototype head differential across the gate to the measured model differential. To compute the prototype head drop, it was assumed that the 21-foot-diameter tunnel was ruptured at the power bifurcation, and that the reservoir was at the maximum water surface elevation of 4669.0, producing a head of 178 feet. The head loss through the intake structure and tunnel with the gate 100 percent open limited the maximum flow to 21,500 cfs. As the gate closes to reduce the flow, the tunnel losses become smaller and the head drop across the gate becomes larger. At very small openings nearly the full shut-off head of 178 feet is acting on the gate. The relation of prototype head drop to gate opening is shown in Figure 6A.

The model was tested at a number of gate openings, and the pressure drop across the gate and the pressures on the bottom of the leaf were measured at each of the openings. These measured pressures are shown in Table 1. It is interesting to note that the pressure just above the lower seal (Piezometer No. 1) is almost the same as the pressure acting on the roof at the leaf, and hence on the upper seal. The upper seal has the same plan area as the lower one, and therefore the upward force on the upper seal is the same as the downward force on the lower seal. These forces balance one another; thus Piezometer No. 1 is not used in the downpull calculation. From these data, the prototype downpull forces were calculated as follows, using as an example a 3-inch prototype gate opening.

Model pressures in inches of water were:

Upstream head	Downstream head	Seal	Gate web (average)	D. S. lip
+8.07	-0.09	-1.25	-0.51	-0.52

Prototype head drop (from Figure 6A) = 178 feet

Factor for conversion = $\frac{178}{8.07 + 0.09} = 21.80$

Downstream head = -(0.09) (21.80) = -1.96 = head on top of leaf

Under the seal = -(1.25) (21.80) = -27.21

Under the web = -(0.51) (21.80) = -11.12

Under the DS lip = -(0.52) (21.80) = -11.34

If it is assumed that the pressure distribution at any section along the leaf is the same as the measured distribution at the center line section, the downpull may be found by multiplying the pressure difference between the gate top and bottom by the specific weight of water and by the area of the gate section (Figure 6B) on which the pressure difference acts.

Seal	= (27.21 - 1.96) (62.4) (16.5) (0.3802) =	9,900 pounds
Web	= (11.12 - 1.96) (62.4) (16.5) (2.9282) =	27,610
DS lip	= (11.34 - 1.96) (62.4) (16.5) (0.2240) =	2,160
	Total	39,670 pounds

A plot was made of the computed prototype downpull forces acting on the seal, under the lower web, and under the downstream lip for a wide range of gate openings (Figure 6B). The total downpull, which is the sum of the individual downpulls, is also shown.

This downpull information may be applied to other geometrically similar installations by the following method:

A. Find the downpull that would occur at the desired gate openings with the head drop for the proposed installation:

$$DP_2 = DP_1 \times \frac{H_n}{H_g}$$

where

DP_1 = Downpull, Figure 6B

DP_2 = Downpull with H_n

H_g = Head drop across Glendo gate, Figure 6A

H_n = Head drop for proposed installation

B. Obtain the desired downpull by multiplying DP_2 by the ratios of the areas under the two gates:

$$DP_3 = DP_2 \times \frac{A_n}{A_g}$$

where

DP_3 = downpull under the proposed gate with H_n

A_g = area under the tested gate

A_n = area under the proposed gate

It will be noted in the sample computation that the pressure beneath the bottom seal reached a dangerously low value of -27.21 feet of water. This is low enough to produce cavitation in installations at fairly high elevations. Even at elevations as low as sea level, pressure fluctuations of only moderate proportions would be enough to lower the pressures momentarily to where cavitation would occur. If the 178 foot head differential across the gate were increased to 200 feet, the seal pressure would become -30.60 feet and cavitation could extend over much of the seal. At a 250-foot head differential, cavitation pressures would exist for gate openings from about 2 to about 4 inches. For the conditions where cavitation is general, downpull on the seal is computed by applying cavitation pressures to the area under the seal.

Slide Gate

It has been previously noted that a model that uses air as the flowing fluid and that discharges into the atmosphere is operating under submerged conditions. In the case of the slide gate, the flow patterns along the upstream face of the leaf and along the sloping bottom of the leaf will be the same for free discharge and for submerged operation.

Pressures measured on these components in an air model are therefore equally applicable to free discharge and submerged conditions. A distinct flow difference will exist, however, along the horizontal or flat portion of the leaf which lies downstream from the abrupt ending of the slope. During free discharge the flow will spring clear of this surface and the pressure on it, and on any seal extension, will be about atmospheric. During submerged operation an eddy of the flowing fluid will be in contact with the surface and the pressures will be a function of the head, the gate opening, and the effective back pressure on the gate. The lowest pressure that can occur on the surface when water is flowing is the vapor pressure of water, about -30 feet gage. The pressure under a seal extension, if one is used, will be affected in about the same manner.

Practical considerations dictate the width of the flat on the leaf bottom and on any seal extensions required. Therefore the geometry of the gate bottom may not be exactly similar for gates designed for different sized installations and heads. To make the data applicable to these variations in design the data was reduced to that applicable to the sloping portion of the leaf, and that applicable to the flat-bottom portion, including the slot projections and seal extensions (Figure 8A).

The method of determining the slide gate downpull was as follows: The model bonnet pressures, and hence the pressures acting downward on top of the leaf, were divided by the head differentials across the gate. This dimensionless ratio was plotted against percent gate opening in Figure 8B. Similarly, the pressures acting upward on the sloped portion of the leaf bottom were divided by the total heads producing flow. This ratio was also plotted in Figure 8B. The difference between these ratios, at any gate opening, multiplied by the prototype head producing flow, equals the prototype differential head acting downward on the cross-sectional area of the sloped portion of the leaf. This head difference, multiplied by the appropriate area, and by the density of water, results in the downpull force on this part of the leaf. To this force, the forces acting on the flat portion of the leaf and on the slot projections and seal extensions are added. This sum equals the total downpull force.

The pressures acting on the sloping portion of the leaf were investigated in detail. Three rows of piezometers were included on the leaf, one 0.18 inch from the leaf side, the second 1.10 inches from the leaf side, and the third in the leaf center line (Figure 5). The pressures for each row are plotted non-dimensionally in Figure 7 for gate openings of 10 through 80 percent. The pressure at any point on a similarly shaped leaf bottom can be determined by multiplying the appropriate dimensionless factor by the head producing flow (H_T-h_2) and subtracting this result from the total head upstream from the gate. For determining the downpull forces, the model pressures were replotted dimensionally with the forces being considered vertical.

Planimeter measurements were made of the areas within the pressure distribution envelopes for the sloping portions of the leaf. These areas were divided by the 2.23 inch thickness of the leaf above the sloped bottom to give an average pressure value at each piezometer row. The average pressures obtained for the row 0.18 inch from the leaf side were assumed to act from the leaf sides to stations 0.50 inch from the sides. The pressures for the row 1.10 inches from the side were assumed to act from the 0.50 inch stations to stations 2 inches from the sides. The pressures at the center line piezometers were assumed to act over the remaining width of the leaf. The products of these average pressures and appropriate areas were added together for each gate opening. These pressure-area summations were divided by the projected area of the sloping portion of the leaf to give the equivalent single pressure values that can be assumed to act over the sloped area of the leaf at each gate opening. These pressure values, divided by the total head producing flow, establish the curve plotted in Figure 8B. At zero opening, the average pressure acting upward on the plan area was the same as the total head. It decreased to a minimum at 70 percent open and increased again at 80 percent open. No tests were made at openings above 80 percent because the downpull would be small.

Free discharge conditions. In the full-sized slide gates the back of the leaf carries a seal that is in contact at all gate openings with a seal plate in the bonnet. There can be no flow or appreciable leakage between the back of the leaf and the bonnet, and only a little flow down the gate slots. Thus the bonnet pressure is about the same as the stagnation pressure just ahead of the leaf. The model pressure measurements, based on the piezometer in the top of the conduit 1 inch ahead of the leaf showed that without submergence the bonnet pressure was the same as the total head in the conduit at zero gate opening, and that it decreased with respect to the total head as the gate was opened (Figure 8B).

The difference between the bonnet pressure and the average pressure over the sloped bottom was a maximum at an opening of about 45 percent and the difference did not exceed about 53 percent of the total head (Figures 8B and C). The net downpull on the flat bottom, the slot projections, and any seal extensions can be determined from their areas and the difference between the bonnet pressures and atmospheric pressure. The total downpull will be the sum of the individual downpull forces acting on the various portions of the leaf.

A sample calculation of the downpull forces follows:

Assume: Free discharge conditions, gate leaf 6.0 feet wide, 2.0 feet thick, 3-inch flat on bottom, 6- by 6-inch slot projections, no seal extension (Figure 8D) Head H = 200 feet.

The net force acting downward on the plan area over the sloped part of the leaf bottom is:

(1)	Gate opening, %	10	30	40	50	60	80
(2)	Head diff / H_T %	23.3	47.1	52.9	52.9	51.4	25.1
(3)	(2) x H_T = head diff (feet, H_2O)	42.6	94.2	105.0	105.8	102.8	50.2
(4)	(3) x 62.4 = Press diff (psf)	2,658	5,878	6,522	6,602	6,414	3,132
(5)	(4) x area = downpull, lb (Area = 6.0 x 1.75 = 10.50)	27,909	61,719	68,796	69,321	67,347	32,886

The net force acting downward on the plan area of the flat bottom and the slot projections (no seal extension on standard gate) is:

(6)	Bonnet Pres / H_T %	99.5	96.0	92.2	86.3	78.0	50.1
(7)	(6) x H_T = Bonnet Pres = Head diff (ft, H_2O)	199.0	192.0	184.4	172.6	156.0	100.2
(8)	(7) x 62.4 = Pres diff (psf)	12,417	11,981	11,507	10,770	9,734	6,252
(9)	(8) x Area = Downpull; A = (0.25 x 6.0) + 2(0.5 x 0.5) = 2.00	24,834	23,962	23,014	21,540	19,468	12,504
(10)	(5) + (9) = Total downpull lb	52,743	85,681	91,810	90,861	86,815	45,390

(H_T = Total head upstream of gate.)

If it were assumed that the full total head acted over the entire sectional area of the leaf, the calculated downpull would be 200 x 62.4 x (10.5 + 2.0) = 156,000 pounds. The maximum downpull of 91,810 pounds obtained with the above test information is 59 percent of this value. This percentage will vary somewhat depending upon the width of the flat bottom of the leaf, the location of the leaf projections, and whether or not seal extensions are used.

Submerged Conditions. If the tailwater elevation rises to submerge the gate or fill the downstream conduit, and the headwater elevation remains unchanged, the head differential across the gate, and hence the rate of flow, decreases. In spite of these changes, and provided that the Reynold's Number remains reasonably high, the flow pattern approaching and passing along the face and sloping portion of the leaf remains the same. And because the flow pattern is the same, the difference between the upstream conduit total head and the head at any point on these areas of the leaf, divided by the head differential across the gate, remains the same for any gate opening. Expressed mathematically, $\frac{H_T - h_x}{H_T - h_2} = K$, and the downpull force on the sloped portion of the leaf will be the same as for the free discharge condition with the same differential head. In the case where a gate can be placed more deeply or less deeply below the tailwater elevation, the effect of submergence change is merely to equally raise or lower the bonnet and leaf slope pressures. The head differential across the gate would remain constant, and so would the downpull forces (assuming no cavitation at the lower submergences).

When the discharge is into a pool, the head producing flow may be taken as the difference between the total head upstream from the gate and the pool depth downstream. When the discharge is into a filled conduit, the head producing flow may be taken as the difference between the total head upstream and the static head a distance of about 3 conduit heights downstream.

For submerged flow where conditions would permit vapor pressure under the flat on the leaf, the method of calculation would be the same as that in the free discharge example except that the downpull head differential in Item 7 would become the total bonnet pressure plus the numerical value of the vapor pressure, about 30 feet of water. This produces the greatest downpull possible, but it is unlikely that vapor pressure would ever occur over this whole area. Thus, this extreme downpull condition will probably never be reached. In the more likely cases where conduit failures or unexpectedly low tailwater will not be factors, and where the submergence will always be sufficient to hold the pressures on the leaf flat and on the seal above vapor pressure, the net downpull would be determined from the difference between the bonnet pressure and these surface pressures. Such surface pressures may be difficult to predict exactly, and would probably have to be determined experimentally if precise results were needed. But for ordinary work, the pressures can be obtained from the non-dimensional data presented in Figure 7.

SUMMARY

Air models are reliable tools for determining flow phenomena and pressure distribution in fluid flow passages. As such, they are readily adaptable to studies of downpull forces on gates, particularly where the gates operate submerged. They may also be used for downpull studies when the gates discharge freely, provided that care is taken in analyzing the flow conditions and resulting pressure distributions on the various portions of the gate leaves. Air models are less expensive to construct and test than hydraulic models, and they are accurate, convenient, and easy to work with.

The two gate types discussed in this paper are typical of installations being made throughout the country. The data are presented in a form usable for any sized gate, provided that the top and bottom of the leaves are generally geometrically similar to the test gates. The maximum downpull on the tested fixed-wheel gate occurred during submerged operation at about a 3-inch opening. The downpull rapidly decreased as the opening increased. On the slide gate, the maximum downpull force occurred at about a 45 percent gate opening. This calculation assumed that the total head remained constant at the gate regardless of gate opening. In the usual case, friction in the conduit ahead of the gate will cause a loss of head as the flow rate increases. The maximum downpull would be less than in the example, and would occur at a smaller gate opening. Bonnet pressures play a particularly important part in the case of the slide gate, and in designs where leakage from the bonnet is permitted or encouraged to decrease the bonnet pressures, downpull will be materially reduced. Of course, this drainage or leakage may create other complications, and cannot be regarded as an automatic solution to the downpull problem.

ACKNOWLEDGMENT

The studies discussed in this paper were conducted in the Hydraulic Laboratory of the Bureau of Reclamation, and the fixed-wheel gate studies were made by Donald Colgate, Hydraulic Engineer.

Table 1

MODEL PRESSURES (IN INCHES OF WATER) ON GLENDO FIXED-WHEEL GATE

	Piezometers											
Gate opening	1	2	3	4	5	6	7	8	9	10	U.S.	D.S.
0'-1.5"	8.08	-0.72	-0.27	-0.26	-0.28	-0.27	-0.27	-0.26	-0.26	-0.26	8.06	-0.04
0'-3"	8.06	-1.25	-0.50	-0.51	-0.53	-0.52	-0.52	-0.52	-0.49	-0.52	8.07	-0.09
0'-4.5"	8.46	-0.97	-0.51	-0.48	-0.47	-0.49	-0.54	-0.50	-0.50	-0.51	8.53	-0.07
0'-6"	8.38	-0.81	-0.53	-0.52	-0.56	-0.56	-0.58	-0.53	-0.50	-0.54	8.58	-0.10
0'-9"	7.57	-0.55	-0.47	-0.46	-0.49	-0.48	-0.49	-0.48	-0.45	-0.49	7.74	-0.11
1'-0"	7.14	-0.40	-0.34	-0.34	-0.35	-0.35	-0.37	-0.36	-0.33	-0.41	7.28	-0.03
1'-6"	8.90	-0.36	-0.34	-0.35	-0.37	-0.37	-0.35	-0.34	-0.34	-0.35	9.20	-0.05
2'-0"	8.97	-0.05	0.07	0.06	0.02	0.04	0.05	0.08	0.11	-0.01	9.36	0.15
3'-0"	8.65	-0.66	-0.55	-0.56	-0.60	-0.55	-0.55	-0.50	-0.47	-0.69	9.13	-0.49
5'-0"	6.95	-1.92	-0.79	-1.80	-1.87	-1.85	-1.86	-1.78	-1.72	-1.86	7.61	-1.79
6'-0"		-2.01		-1.94		-2.00		-1.97		-1.99	6.62	-1.86
10'-0"	5.56	2.19	2.28	2.21	2.23	2.24	2.25	2.25	2.25	2.25	5.60	2.33
15'-8"	1.75	1.66	1.63	1.67	1.64	1.64	1.64	1.67	1.65	1.62	1.75	1.63

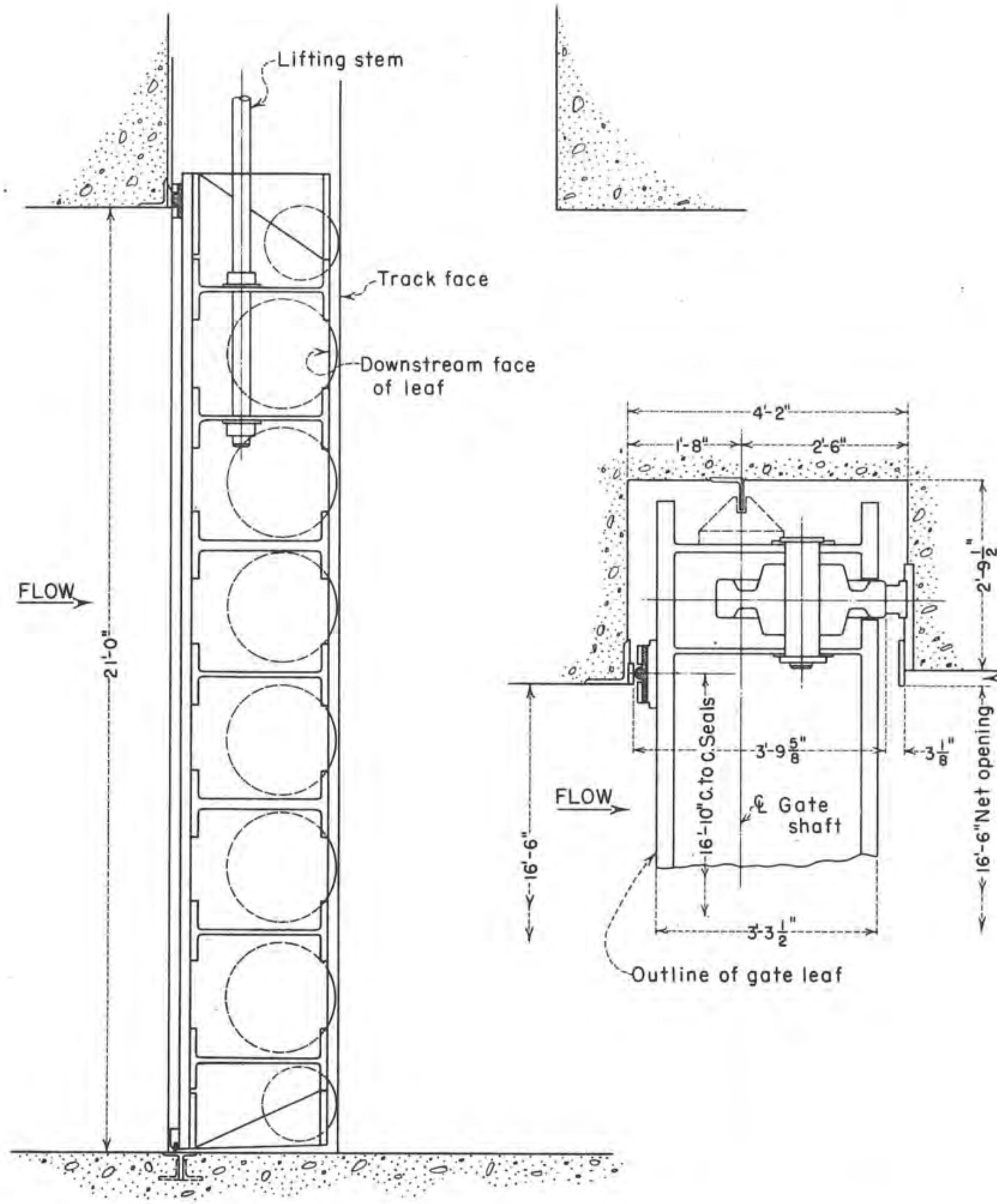

FIGURE 1 - 16.5' x 21' FIXED-WHEEL GATE
GLENDO DAM, WYOMING

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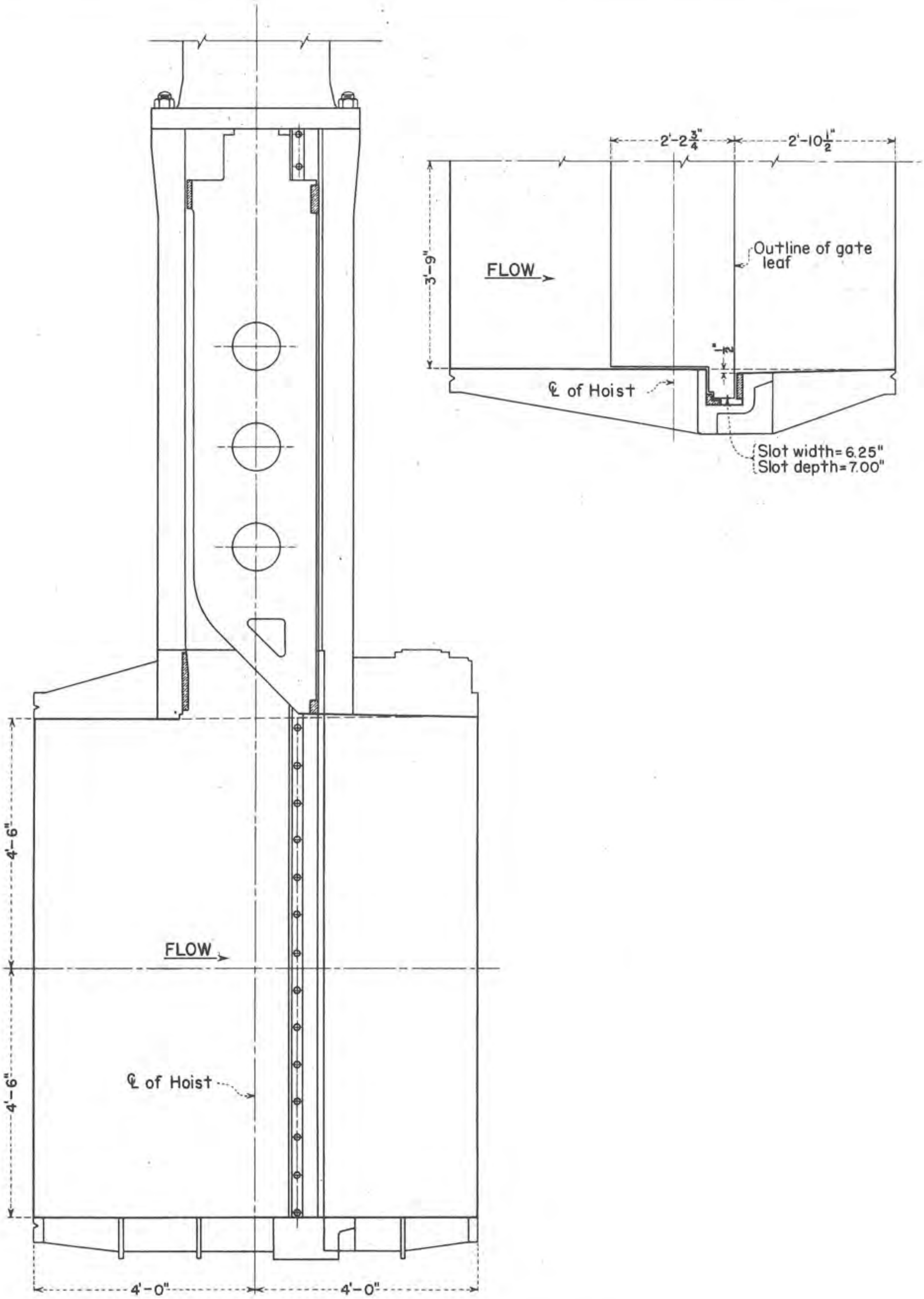

FIGURE 2 - 7.5' x 9.0' HIGH HEAD SLIDE GATES
PALISADES DAM, IDAHO

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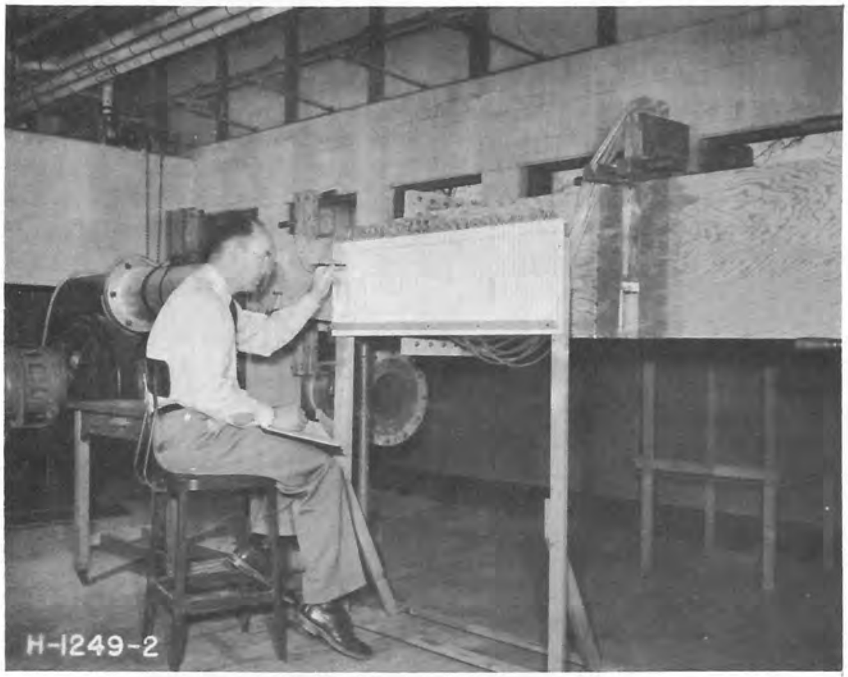
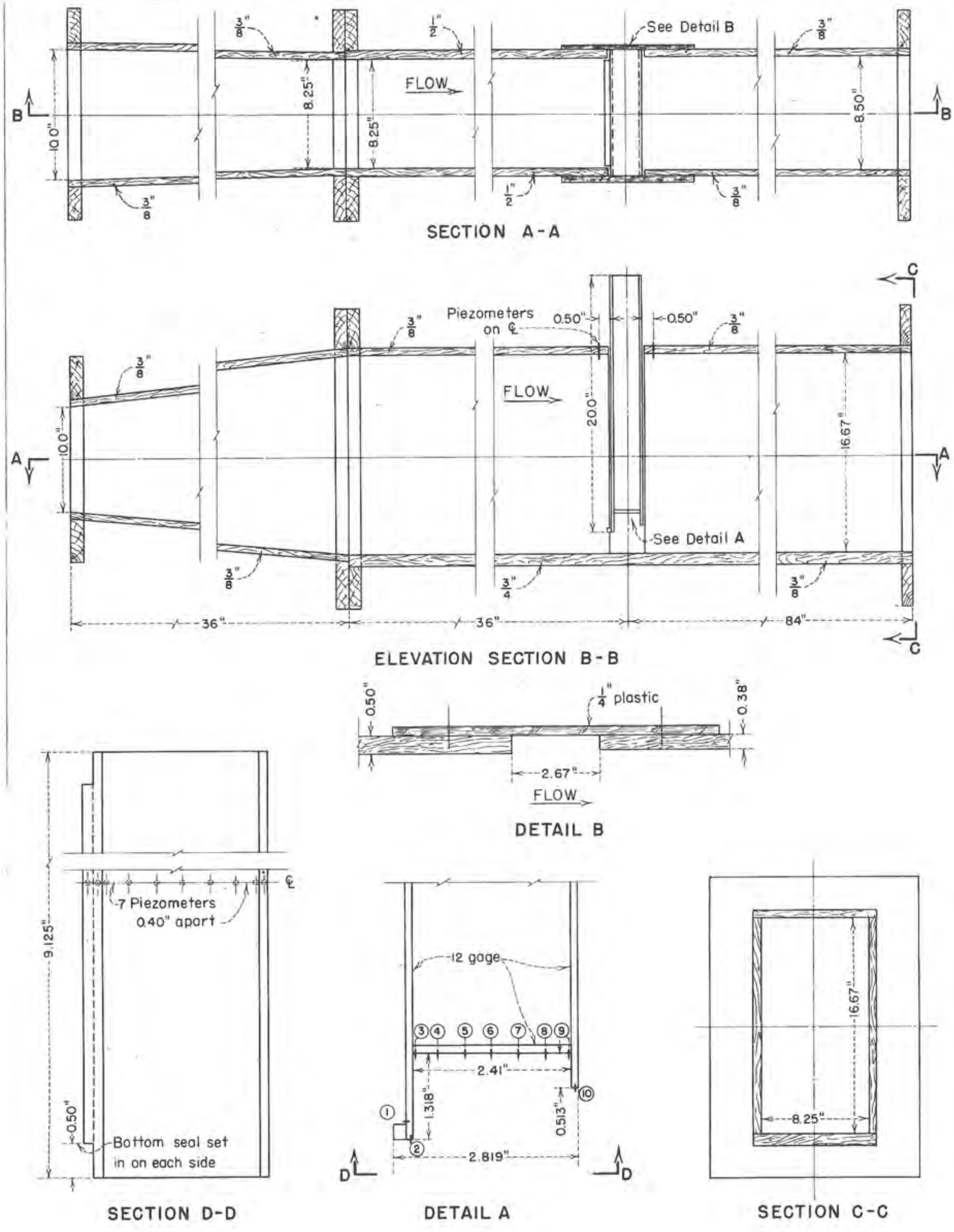


Air was drawn from the atmosphere into inlet orifice at center by centrifugal blower at left. Flow passed through a 10-inch-diameter pipe section, then the test section, and back into the atmosphere.

FIGURE 3 - AIR MODEL AND TEST FACILITIES

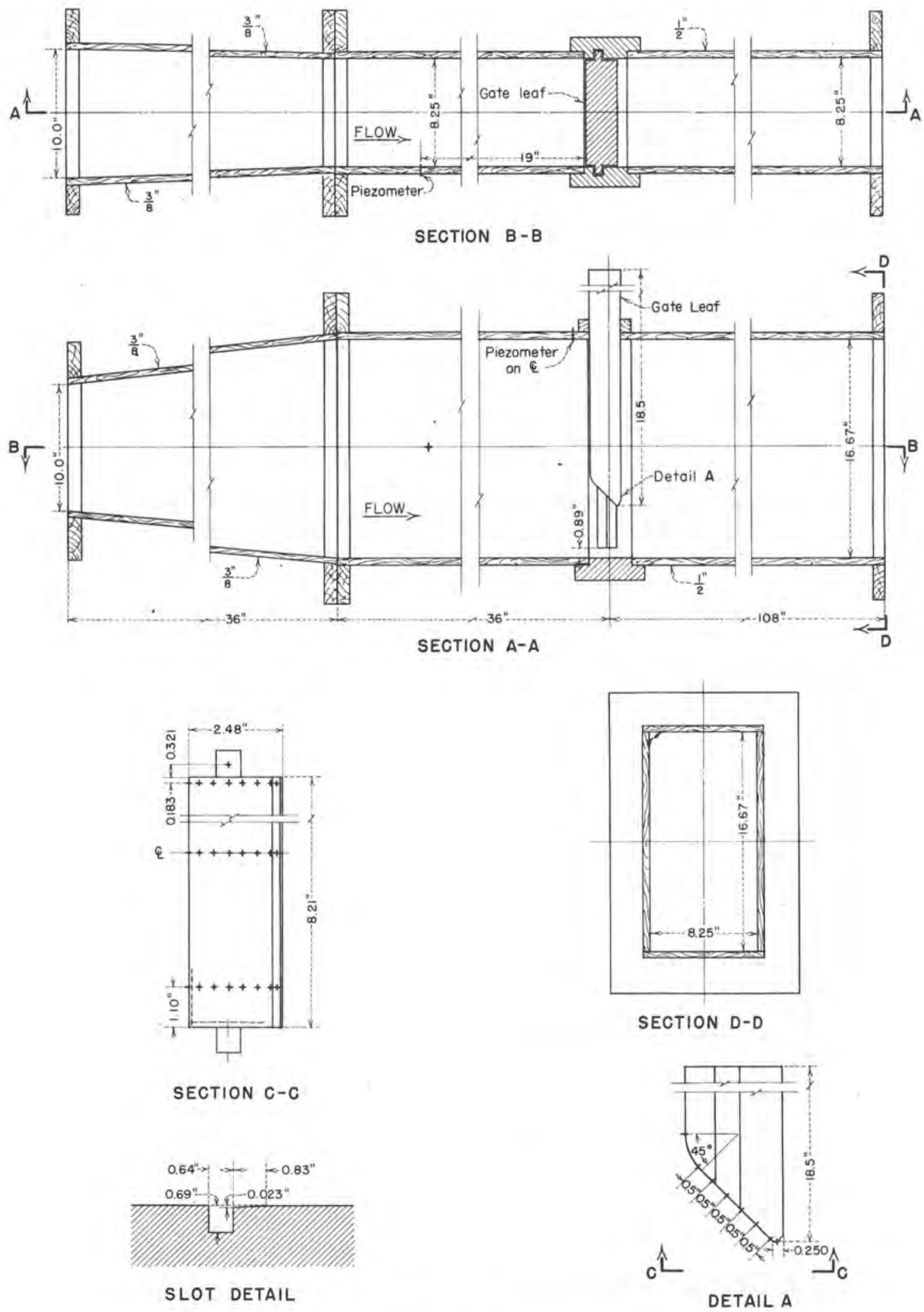


Material: Tunnel section, plywood. Gate leaf, sheet metal

FIGURE 4 - FIXED-WHEEL GATE TEST SECTION

AIR MODEL

607

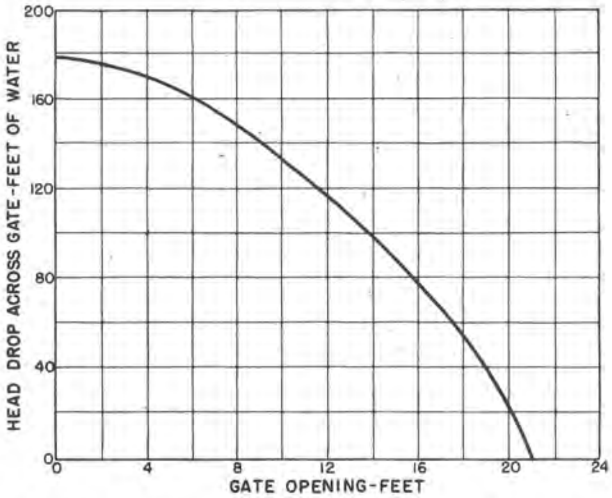


Material: Tunnel section, plywood. Gate leaf, sheet metal

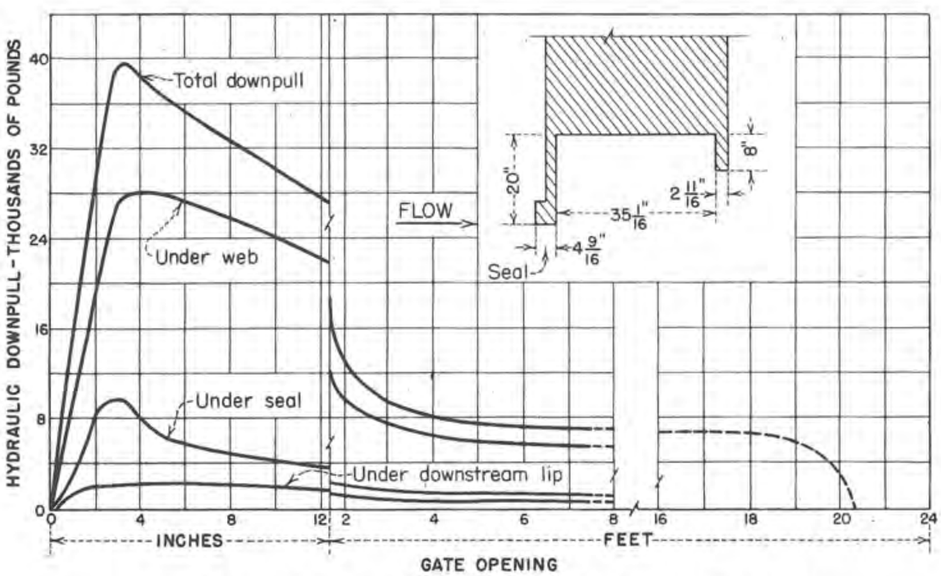
FIGURE 5 - SLIDE GATE TEST SECTION

AIR MODEL

607



A. HEAD DROP ACROSS GATE AS GATE IS CLOSED FOLLOWING A PENSTOCK BREAK 1865 FEET DOWNSTREAM. RESERVOIR ELEVATION 4669.0

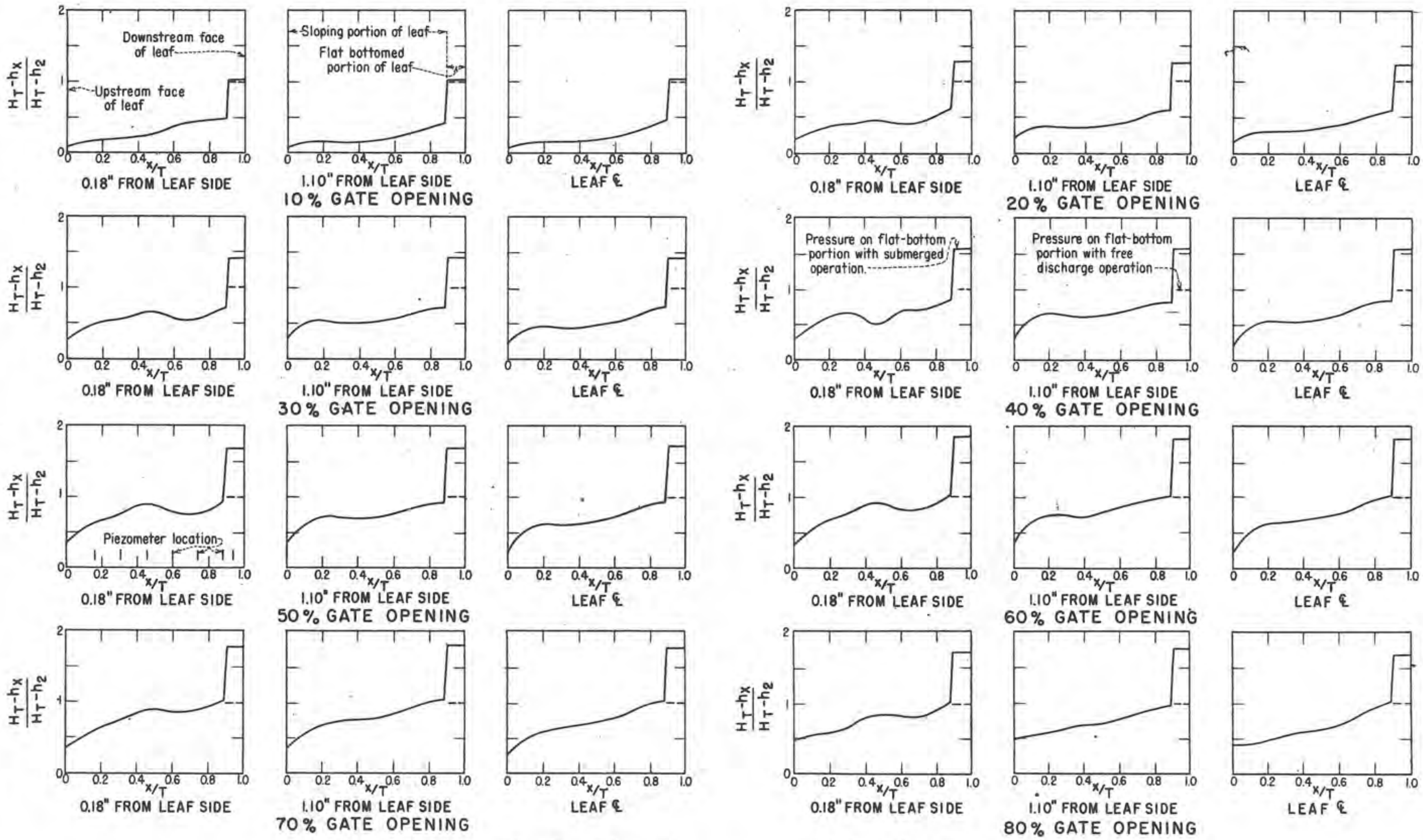


B. DOWNPULL WHEN GATE CONTROLS FLOW AT RESERVOIR ELEVATION 4669.0

FIGURE 6 - HEAD DROP ACROSS, AND DOWNPULL FORCES ON GLENDO 16.5' x 21.0' FIXED-WHEEL GATE

DATA FROM AIR MODEL

607



H_T = Total head upstream from gate
h_x = Pressure head at leaf piezometers
h_2 = Pressure head downstream from gate

x = Distance from upstream face of leaf
T = Leaf thickness
Model leaf 8.21" wide x 2.48" thick

FIGURE 7-PRESSURES ON BOTTOM OF SLIDE GATE LEAF

DATA FROM AIR MODEL

607

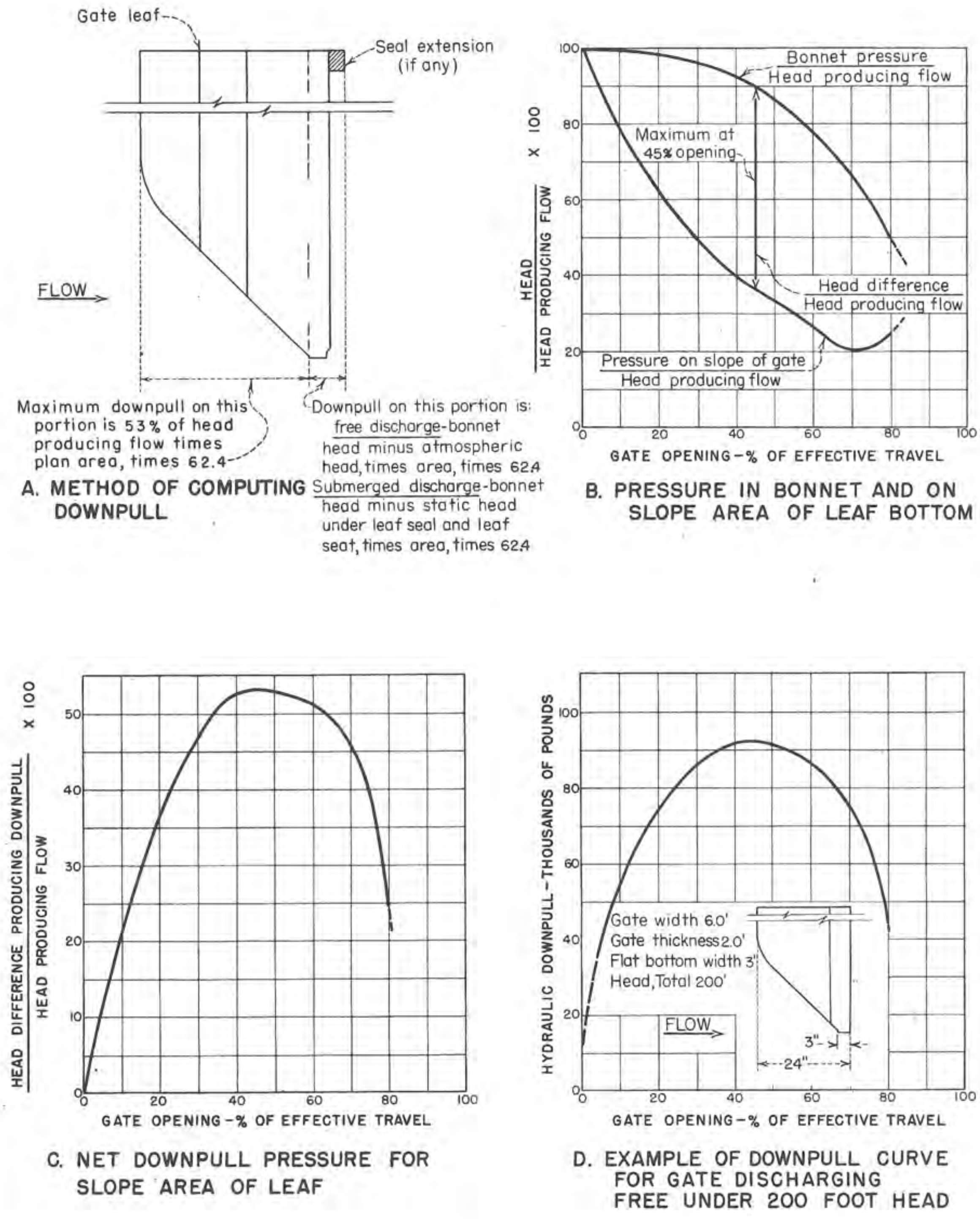


FIGURE 8 - PRESSURES IN BONNET AND ON LEAF, AND TYPICAL DOWNPULL CURVE FOR SLIDE GATE

DATA FROM AIR MODEL

607