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HYDRAULIC CHARACTERISTICS OF GATE SLOTS

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ABSTRACT

Turbulent flow conditions within gate slots, and cavitation damage just downstream from gate slots, occur when wheel (or roller) gates and slide gates are operated at small openings under heads in excess of about 35 feet. A discussion of these conditions is given together with a discussion of the investigation which led to a generally applicable, cavitation-free, gate slot design.

INTRODUCTION

There are many factors to be considered in designing gates of the wheel (roller) or slide type. One of the most important factors concerns the grooves or slots in which the ends of the gates are supported (Figure 1). This paper discusses the hydraulic characteristics of a wide variety of such slot shapes.

Unless gate slots are properly designed turbulence and cavitation will occur to cause the destruction of roller chains and wheels as well as costly damage to flow surfaces (Figure 2). More extensive damage than that shown in the illustration has occurred in several cases. Turbulent surging within the slots can be controlled by baffle plates attached to the bottoms of the gates, and, to some degree, by shaping the slots. It can also be eliminated by attaching extensions to the bottom corners of the gate leaves to fill the slots. Cavitation can be eliminated only by preventing the occurrence of vapor pressure in or near the slots. This may be quite difficult to accomplish in the high head installations encountered in present day designs. The difficulty of eliminating cavitation pressures therefore reduces the gate slot problem to principally a study of pressure intensity and distribution.

Damage to roller chains by violent turbulence and excessive cavitation erosion on flow surfaces of Bureau of Reclamation Stoney gate installations, led, in 1941, to studies of the causes and remedies for the trouble. An appraisal of existing structures, as well as structures under construction and in the design stages, disclosed the need for a four-phase investigation to obtain satisfactory and economical solutions for all the structures. The first phase was an inspection of existing structures to determine whether or not cavitation damage had occurred, and under what operating conditions. The second phase was to develop a means of correcting the trouble at existing structures with a minimum of alteration. The third phase was to evolve a satisfactory slot design that could be constructed

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within the confines of block-outs provided for second-stage concrete in spillways under construction. The fourth phase was to develop a design which would be generally applicable to future structures. This four-phase investigation concerned specific projects using wide slots for wheel or roller gates that operated under heads of about 50 feet. A discussion of the investigation results is given in subsequent sections of this paper.

More recent investigations of a more general nature have concerned both wheel and slide gates under much higher heads. Over the years following the tests mentioned above, many different types of outlet structures were built. During this time there was a constant trend toward higher heads and more severe operating conditions, particularly on slide gates, but it was not until inspections were made in recent years and severe damage was reported to slide gates that the problem was again high-lighted and the study of gate slots intensified. A typical example of damage to an older design high-pressure slide gate is illustrated in Figure 3.

TEST EQUIPMENT

The laboratory tests on slots of wheel gates were made on a relatively large-scale, sectional hydraulic model. A gate leaf controlled the flow, and thus the influence of the leaf at various positions was included. In this model, the heads and velocities were low and the discharges were within the capacity of the laboratory pumps. However, when higher heads were considered, the pump capacity was inadequate for complete hydraulic models of reasonable size, or for large scale sectional models that included a gate leaf and a slot of adequate size. Modified sectional models which contained a relatively large slot in one wall of a closed rectangular conduit were therefore used for most of the gate slot tests (Figures 4 and 5). Gate leaves were not used in these tests. Water was used as the flowing medium in the first tests, and air was used in the remainder. A cavitation testing facility that has recently become available in the Laboratory was used in one special test (Figure 6).

DISCUSSION OF TEST METHODS

The manner in which the gate leaf affects the flow in the slot, and the influence of this flow on the pressures in and near the slot, are important in the analysis of gate slot problems. The major portion of the tests discussed in this paper were made on hydraulic and aerodynamic models which represented the gate in the wide open position with the conduit downstream flowing full. At first thought, this method of testing would not seem to cover all the important conditions for the slot. However, an examination of flow conditions during the opening and closing cycles on a gate shows that this method will satisfy nearly all conditions of operation.

As the leaf of a wide open gate is moved toward the closed position, it deflects the flow downward and outward into the slots. This action becomes more pronounced as the leaf moves into the flow and it soon prevents aeration of the slot. This "sealing" point varies somewhat with the shape of the slot, but in all cases occurs at or near the wide open position. Tests made on a large hydraulic model illustrate this flow characteristic (Figures 7 and 8). The tests were conducted on a design in which the downstream corners were offset away from the flow, approximately 1/3 the slot depth, and the walls downstream from the slot corners diverged at a rate of 12:1.

The flow through this gate cleared the slots and the downstream walls when the leaf was wide open, and during closure of the gate until it reached about 97 percent open (Figure 7). At the 97 percent opening a small amount of water was deflected into the slot and it carried a great deal of air with it. This air-water mixture spiraled downward in the slot and flowed back into the stream at the bottom of the slot. As the leaf closed to 95 percent open, more water was directed into the top of the slot, but only the portion of the jet near the top stayed in contact with the walls. As the leaf closed to about 93 percent open, the slots filled quickly and the sides of the jet contacted and remained in contact with the walls for the full height of the jet (Figure 8). Some air was drawn into the slot at the corner near the gate leaf bottom at 93 percent open, but no air entered the slot at an opening of less than 92 percent. The gate opening at which the slots fill will vary with the slot design. On most gates filling of the slots will occur nearer full open than with the tested gate because the offsets in the tested gate were relatively large and the downstream walls diverged.

Because of the filling and sealing actions described above, it is believed that the data presented are generally applicable to the gate slot problem, particularly with the reference pressure taken at the downstream face of the leaf, and the reference velocity taken as the average flow velocity passing the slot. The data would not be applicable at large gate openings where the flow clears the downstream corners of the slots. This condition is not critical. The data would also not be applicable at very small openings with most slot shapes because at these openings the downstream edge of the slot becomes a control and a contraction occurs at the corner. This condition will be discussed in detail in a subsequent part of this paper.

In recent years model studies have been conducted on most of the gate slot types used by the Bureau of Reclamation. These studies were made to keep pace with more severe operating conditions, and because it was desirable to forestall inadequate operation wherever possible. The tests concerned slide gate slots in particular, but the results are applicable also to wheel gates since the main difference in the two types is size rather than shape.

CORRELATION PROBLEMS

It is important to note that the tests discussed in this paper were made over a period of years, that the facilities used were not always the same, and that many equipment and technique changes were made to obtain data which at first did not appear pertinent but later proved important. In light of these factors, the correlation between the results of the various water and air models was considered excellent. However, direct comparison of data presented in this paper must be made with care. One factor which makes comparison difficult is the relative location of piezometers. The steep pressure gradients in critical regions, such as in the slot at the downstream corner, and just below the downstream corner, make relative locations in different models quite important. This was not fully taken into consideration in the earlier tests. Where data are presented for design use, sufficient piezometer coverage was made to define accurately the pressure distribution. The curves present the low pressures in the critical areas using the relationship $\frac{h_x - h_o}{h_v}$; where h_x = pressure at any point, h_o = reference pressure at downstream face of gate leaf, and h_v = velocity head for average velocity past gate slot.

During the analysis of the test data, it was found that if h_x was assumed to be vapor pressure, the relationship, $\frac{h_x - h_o}{h_v}$, did not indicate the true head at which cavitation was known to occur in field installations. The relationship always indicated a much higher head would be needed to produce cavitation than actually existed in the field structures. A slot shape was therefore, placed in a cavitation test facility to determine what value of h_x would exist when incipient cavitation occurred at the slot (Figure 6). In this facility the ambient pressure and velocity could be varied to produce cavitation of different intensity.

TEST RESULTS

Early Tests for Wheel Gates

Inspection of Existing Structures

Several Bureau structures were examined in 1941 for signs of cavitation damage after the damage shown on Figure 2 was discovered. It was found that the structure shown in Figure 2 was the only one which had incurred serious damage. Two other structures had not operated sufficiently to be damaged, while another, which had operated for moderate periods, showed no damage. It is of interest to note that an inspection made on the latter structure in 1956, some 15 years later, revealed minor cavitation damage near the crest and just downstream from the gate slots.

Tests on Existing (Damaged) Design

A 1:24 sectional model was constructed of the gate design which had incurred damage. Tests showed that turbulent surging was present within the gate slots where the roller chains were located, and that this surging caused movement of loose parts of the chains. The destruction of the prototype roller chains was attributed to this action. Tests showed that the surging could be reduced to reasonable proportions by placing guard plates in the slots at the bottom corners of the leaf.

A number of gate slot shapes were tested in an attempt to eliminate the low pressures which caused the cavitation. The objective at the time was to eliminate all regions of subatmospheric pressure originating from the gate slots. Several treatments accomplished this, but all were not practicable. Some of the most promising designs for various stages of construction are shown in Figure 9.

Flow lines in the bottom of the slot and on nearby surfaces of the original design at a small gate opening were recorded by paint tests (Figure 10). The tests showed clearly the presence of a separation zone along the wall immediately downstream of the slot, and the presence of complex currents within the slot. A plot of the pressure distribution on the wall downstream from the slot showed severe subatmospheric pressures in the separation zone (A, Figure 9).

The treatment proposed for the damaged structure, that of placing a deflector at the upstream corner of the slot and a 90 degree circular arc at the downstream corner (B, Figure 9), was never used. The power units at the project were placed in operation shortly after specifications were prepared for the slot changes, and the requirement of the gates to release large quantities of water frequently was eliminated. Only repairs to the damaged surfaces were deemed necessary and this work was done.

Designs for Structures Under Construction

A slot with a deflector on the upstream corner, the downstream corner offset outwardly, and the downstream wall curved inwardly to connect to the previous, parallel-wall alinement, was developed for the under-construction case (C, Figure 9). This design has been used on a limited number of structures and there has been no report of damage.

Designs for Structures in Planning Stage

Variations of the design adopted for the under-construction case were considered for future projects. One slot shape was similar to that developed several years later for relatively narrow gate slots (D, Figure 9). In this case the offset of the downstream corner was about one-third of the slot depth, considerably more than the recent design. Paint tests showed the flow to be in contact with the wall with no evidence of separation to cause severe subatmospheric pressure (Figure 11). The pressure distribution in this case was entirely satisfactory, but the design was not pursued when it was decided to avoid the slot problem by using slot filler extensions on the bottom corners of the gate leaves.

The slot filler extended down into recesses within the spillway crest when the gate was closed, and rose with the leaf to fill the slot as the gate opened. The filler occupied the full slot section to form smooth flow boundaries on which no subatmospheric pressures or cavitation could occur.

The ideal design of this type would be one which filled the slots at all gate openings. This was considered impracticable, and a length of 6 feet was finally adopted for the one case on which the extensions were used because operation at larger openings would be rare. At this point the tests were interrupted by war requirements and work was suspended for several years.

European Experiences

Shortly after the test program was suspended, an article on European experiences was published. 2/ The article pointed out that the problem was not a new one, and stated that it was necessary to alter and repair structures built as early as 1885. Some of the solutions used were illustrated (Figure 12). There is a striking similarity between these and some of the shapes developed and used in more recent years. Actually the main difference is that present-day designs have been extended to include slide gates, and refined to handle much higher heads.

Tests for Slide Gates and Wheel Gates

Plans were made to use slide gates at higher heads than those at which damage had already occurred. A series of studies on the standard slide gate, Figure 13, showed that severe subatmospheric pressures existed just downstream from the slot. The pressures were so low that with high-velocity flows, cavitation damage would surely occur.

The early studies disclosed that low pressures could exist in as many as four locations in and near the slots, depending on the configuration of the slots. This was the case regardless of the type of leaf used.

The research on the water and air models concerned five distinct types of slots, and numerous variations of each type. The types will be referred to as:

1. Original slot with inline upstream and downstream walls
2. Slot with deflector on upstream corner
3. Slot with offset downstream corner and parallel downstream wall
4. Slot with offset downstream corner and divergent downstream wall
5. Slot with offset downstream corner and convergent downstream wall

Because tests have shown that a great amount of circulation occurs in slots, and that this circulation seems greater for wide slots than for narrow ones, it is believed that gate slots should be made as

2/ Engineering News Record, August 23, 1945 narrow as possible. However, in most of the tests made to obtain general data, the slot widths were varied to cover width-to-depth ratios from 0.5 to 2.5. In a few cases the width-to-depth ratio was increased to 5.0.

Standard Slide Gate

Pressure distribution curves for the slot with inline upstream and downstream walls, the shape referred to as the original design, showed a critical pressure area on the wall just downstream from the downstream slot corner. The pressure relationships for critical areas of the slot at various width-to-depth ratios are shown in Figure 14. The curve for the low pressure within the slot shows that pressures are about the same as the reference pressure, and that there is little change over a wide range of W/D ratios.

The pressures in the slot at the downstream corner are above the reference pressure and increase as W/D increases. The pressure at this point first increases rapidly, and then gradually, indicating that the flow spreads into the slot to cause a pressure build up as the slot widens. The leveling off of the pressure with the wider slots might be expected because the conditions are approaching those for a sudden contaction within a pipe.

The pressures immediately downstream from the downstream slot corner are the lowest and the most critical in this design. Cavitation will take place when these pressures are near the vapor pressure. Subatmospheric pressures occur at this point for all slot widths tested and become more severe as the slot width increases. The design is definitely not suitable for any but extremely low heads, possibly under about 35 feet.

It was noted that the pressure relationship, $\frac{h_x - h_o}{h_v}$, indicated that cavitation pressures would not occur at this location until a head in excess of 100 feet was reached. Field conditions show that severe cavitation will occur with this design for heads of 50 feet. This suggests that the pressure at this location does not have to reach vapor pressure for cavitation to occur at the slot. This slot shape with a W/D ratio of 1.0 was placed in a special test facility to determine the pressure that would exist just past the downstream slot corner when incipient cavitation occurs (Figure 6).

Tests were made at several velocities. At each velocity the ambient pressure was adjusted until cavitation could just be seen clearly at the downstream slot corner. The average value of $\frac{h_x - h_o}{h_v}$, for a piezometer located 0.06 inch from the corner was -0.14. For this case the values for h_x, h_o, and h_v, were -18.4, -10.0, and 60.0 feet of water respectively. Thus the pressure just downstream of the downstream slot corner need not be of vapor pressure magnitude for cavitation to occur at the slot.

From the cavitation tests on this shape it was concluded that there was a critical value of the ralationship $\frac{h_x - h_o}{h_v}$ for each slot shape and W/D ratio. However, this relationship is not an appropriate tool for predicting cavitation because it does not include the basic requirement for cavitation, that is, vapor pressure.

A better parameter for predicting cavitation at gate slots is the cavitation number, or index, $K = \frac{h_o - H_v}{h_v}$, where, h_o is the computed average pressure in feet of water in the flow passing the slot, H_v is the vapor pressure referred to atmosphere, and h_v is the velocity head corresponding to the average velocity of the flow passing the slot. The cavitation index for the tested shape was 0.28.

A program for determining the critical cavitation indexes for particular slot shapes is currently being pursued. Although the data presented in this paper do not provide this means of pin-pointing the cavitation characteristics of the various slot designs, it is extremely valuable for visualizing and comparing the cavitation potential and other hydraulic characteristics of the designs.

Contraction Upstream of Slot

In one gate design, a forced contraction was used to solve the slot problem (Figure 15). This large contraction directed the jet away from the slot and provided aeration of the jet as it issued from the gate. Model studies indicated satisfactory operation with free discharge, or with back pressure operation where aeration can occur. Several units of this design have been installed, and no trouble has been experienced after a number of years of operation. The capacity of the design is somewhat less than for the usual slide gate, the discharge coefficient being 0.80 based on the orifice diameter. This compares to about 0.94 for the slide gate.

Deflectors on Upstream Slot Corners

In tests made on a gate for a medium head installation which released flow directly into a stilling basin, the required uniformly distributed flow was obtained by adding small deflectors at the upstream edges of narrow slots, and by eliminating the convex curve on the upstream face of the gate (Figure 16). No pressures were measured in the vicinity of the slots. The deflectors decreased the capacity of the gate, the discharge coefficient being decreased to 0.84 from 0.94.

The design was used in moderate head installations, until the need arose for a higher capacity, higher head gate. An extensive investigation was then begun to develop a cavitation-free slot which would not adversely affect gate capacity. Two deflector heights for five different slot widths were tested. The deflectors varied from 0.025 to 0.25 times the slot width. In the first series, the downstream slot corner was in line with the upstream wall. The deflector caused a lowering of the pressure within the slot for all widths, but there was a gradual increase in this pressure as the slot widened (Figure 17). For different deflectors, the higher the deflector, using reasonably small sizes, the lower the pressure becomes within the slot. These trends apparently result from the ejector action induced by the deflected jet as it passes the slot. The lowest pressures within the slots were substantially below the reference pressure at the downstream face of the gate leaf. The pressures were severely subatmospheric in all cases, particularly so for slots with small width-to-depth ratios.

Similarly, the pressures within the slot at the downstream corner were severely subatmospheric, as were the pressures below the downstream corner, for large deflectors and small W/D ratios.

A second series of deflector tests was made with the downstream slot corner offset slightly outward. The results were not greatly different from those with no offset (Figure 18). No further tests were made using deflectors because they caused the pressures within the slots to go considerably below the reference pressure and appeared to be conducive to cavitation for all but very low heads. Furthermore, they restricted the flow passage and reduced the carrying capacity of the gates. Subsequent tests were directed toward developing a slot in which the downstream corners were offset outward from the flow. The amount of offset and the manner in which the surfaces just downstream from the corners were alined were of particular interest.

Offset Downstream Slot Corner and Parallel Downstream Walls

Offsetting the downstream corners outward and continuing the downstream walls parallel to the axis of the gate was considered. The typical pressure distribution curve for this design shows that critical conditions might exist at three locations (A, Figure 14). Pressures within the slots were substantially lower than the reference pressure. They would be severely subatmospheric with low back pressure on the gate at all width-to-depth ratios, and would become more severe with increases in W/D. The offset apparently causes an ejector action at the slot that lowers the pressure within the slot.

At small W/D ratios, the pressure within the slot at the downstream corner was severely subatmospheric for all offsets tested. The pressure increased gradually as W/D increased. Subatmospheric pressures would be most severe for the larger offsets, unless effective aeration could be provided.

Pressures immediately below the downstream corner of the slot may be positive or negative, depending upon the offset. Large offsets and wide slots give severe negative pressures.

This type of slot is similar to one on which cavitation damage occurred. Pressure relationships obtained from a model of the slot of the damaged structure are shown on Figure 14. These pressure relationships no doubt explain the cavitation damage experienced with the slot.

The pressure characteristics of the slot with an offset downstream corner and the parallel downstream wall indicate cavitation within the slot for all except very small offsets, thus the design was considered undesirable.

Offset Slot Corner and Diverging Downstream Walls

The effect of offsetting the downstream corners of slots and continuing the flow passage with divergent walls was investigated. A typical pressure curve for this design is shown on Figure 19. The pressures within the slot were much below the reference pressure and severely subatmospheric when there was little or no back pressure on the gate. The subatmospheric pressures became more severe as the offset increased. The pressure increased slightly as W/D increased.

Pressures in the slot at the downstream corner at small W/D ratios may be above or well below atmospheric, depending on the amount of offset. There was a pressure build up at this location for all offsets as W/D increased.

Pressures immediately below the downstream corner may be above or greatly below atmospheric pressure, depending on the amount of offset and the W/D ratio. Primarily the pressures were negative. Generally, the pressure decreased as W/D increased. The pressures became severely subatmospheric as the offset decreased.

The design with a large offset and diverging walls was similar to one on which cavitation damage was experienced. Pressure relationships obtained from a model approximating the prototype structure are shown in Figure 19. They indicate that low pressures within the slot were the source of damage. Local irregularities in the concrete, and at concrete-to-metal joints, may have been a contributing factor.

Offset Slot Corner and Converging Downstream Wall

Two distinct types of converging walls were studied. In one type the convergence rate was constant, such as 12:1 and 24:1. In the other type the rate varied, such as a circular arc extending from the offset corner to the point of tangency in line with the upstream wall.

The first tests were made using a hydraulic model. The tests were quite encouraging and one of the shapes was used successfully in two field installations. 3/. Later most of the shapes tested with water

3/ Hydraulic Laboratory Report 387 "Hydraulic Model Studies of the 7 foot 6 inch by 9 foot 0 inch Palisades Regulating Slide Gate"--Palisades Project--Idaho were reexamined in air, and then air tests were continued to develop cavitation-free designs.

12:1 Converging wall. One design in common use, having a 1-inch offset corner rounded on a 1-1/4-inch radius and a 12:1 converging downstream wall, was among the first examined by model studies. The test shape differed slightly from the prototype shape in that the upstream slot corner of the model was not rounded because it was reasoned that the rounding would cause the flow to expand into the slot rather than to continue past it. This expansion would worsen pressure conditions in the contraction at the downstream corner of the slot. The pressure curve (Figure 20) obtained with the test shape in a hydraulic model is similar to that previously reported. 4/ Negative pressures near the intersection of the 12:1 convergence and the straight wall were severe, more so than indicated in the previously reported tests. The Bureau tests indicated that the outwardly offset, 1-inch-rounded corner with a 12:1 convergence eliminated cavitation pressures near the downstream edge of the slot, but transferred them to the line of intersection of the converging and inline wall sections (Figure 20). Field experience shows cavitation below a slot with such a 12:1 convergence (Figure 21).

In tests which followed, the rounded downstream corner was replaced with a sharp one on the basis that earlier exploratory tests indicated no adverse effects. Various offsets of the downstream corner with the 12:1 convergence were investigated. The offsets varied from 0.03 to 0.15 times the slot width (Figure 22).

The lowest pressures within the slot were slightly less than the reference pressure at the downstream face of the leaf. These pressures approached the reference pressure as the W/D ratio increased. A rising pressure trend was noted within the slot at the downstream corner. The pressure immediately downstream from the corner was above the reference pressure at small W/D ratios and decreased to reach the reference pressure as W/D increased. The pressure immediately downstream from the intersection of the converging and parallel wall sections was below the reference pressure for all W/D ratios, and changed little with changes in this ratio.

24:1 Converging wall. The pressure distribution for a slot with the downstream corner offset a small amount and the wall immediately downstream converged at a 24:1 rate was similar to that for the same offset with a 12:1 convergence (Figures 22 and 23). The lowest pressure within the slot did not differ materially from that for the 12:1 convergence. This pressure was slightly below the reference pressure at the downstream face of the leaf, but approached the reference pressure as W/D increased. A comparison of data from the hydraulic and aerodynamic models for a 24:1 convergence shows excellent agreement (Figure 23).

4/ Symposium "Cavitation in Hydraulic Structures," Volume 112, page 1, 1947, ASCE Transactions

Pressures in the slot at the downstream corner were below the reference pressure at small W/D ratios and increased rapidly as W/D increased.

Although pressures immediately below the downstream corner decreased gradually as W/D increased, the pressures remained positive until the W/D ratio reached about 2.5.

Pressures downstream from the line of intersection of the converging walls are somewhat below the reference pressure. The pressure relationships are constant for all W/D ratios and are nearer the reference pressure than for the 12:1 convergence. The tests with water indicate slightly lower pressure than the test with air, (Figure 23). This is understandable because the surfaces upstream and downstream of the ~~plane~~ line of intersection were machined from metal on the hydraulic model, and were hand worked in wood on the air model. A much sharper intersection line resulted in the metal, and the pressures just past this line would be expected to be lower than for the slightly less sharp line in the wood.

In one series of tests, the slot depth was decreased to 1/2 the original depth (Figure 23). The pressure trends were similar to those for the deeper slot but occurred more gradually. It was concluded that the amount of offset was governed more by the slot width than the slot depth.

36:1 Converging walls. A more gradual convergence downstream from the offset corner changed the pressure conditions only slightly. The trend of the lowest pressure in the slot was about the same as for the more rapid convergence with the same corner offset (Figure 22). This was also true of the pressure within the slot at the downstream corner and the pressure immediately downstream from the offset corner. At W/D = 2.5, the latter pressure was quite low.

Pressures at the ~~plane~~ Line of intersection were slightly higher and, thus, nearer the reference pressure than for the more rapid convergences. However, the change was not sufficient to eliminate the need for rounding the corner at the line of intersection.

Offset Slot Corner and Curved Converging Downstream Wall

The low pressures just downstream from the line of intersection of the converging and parallel walls were cavitation potentials at high heads, and a means of preventing these low pressures was sought. Considerable improvement was obtained by rounding the intersection downstream from the 24:1 convergence, but the amount of rounding used did not eliminate the cavitation potential (Figures 23 and 24). It appeared that substantial rounding would be required to materially reduce this cavitation potential and it may be just as feasible to make the convergence a continuous curve.

Arc Convergence. Radii which varied from about 80 to 300 times the corner offset were tested. Pressure-wise this design proved superior to all others tested (Figure 25).

The low pressures within the slot were slightly below the reference pressures for all arcs when the downstream slot corner was offset. The pressures did not change as the W/D ratio was varied. When no offset was used the pressures were somewhat higher.

The pressures in the slot ~~of~~ at the downstream corner were slightly below the reference pressure at small W/D ratios and increased rapidly as W/D increased. Higher pressures occurred when there was no offset of the downstream slot corner.

The pressures downstream from the slot corner were generally above the reference pressures for all arcs used in combination with the offset downstream corner. When no offset was provided the pressures were substantially lower and were much lower than the reference pressure at a W/D of 2.5.

The lowest pressures occurring on the curved converging wall sections were slightly below the reference pressures and were about the same for all arcs, offsets and W/D ratios tested.

Elliptical convergence. In some recent installations where regulation was required under no back pressure or under a great deal of back pressure, use was made of a slot with parallel, outwardly offset downstream walls and with a plate on each downstream corner that extended into the passage the amount of the wall offset. The plate was intended to induce separation at the wall to permit circulation of flow to relieve low pressures adjacent to the wall. This design was considered for only those cases with free flow or with high back pressures and no model studies were made at the time.

In a recent wheel gate installation it was necessary to regulate at various openings with moderate submergences. The slot design with the extended plate at the offset downstream corner was investigated.

Hydraulic model tests showed that the jet was unstable and shifted rapidly from side to side, indicating changes in pressure and flow pattern in the vicinity of the plates. Similar instability was shown in air model tests, and the pressures downstream from the plates were much below the reference pressure. It was reasoned that the instability, low pressures, and pressure fluctuations could be eliminated by better aeration and/or by filling the contraction areas just downstream from the plate with fillers of elliptical cross section (Figure 26). It was found that venting the region just downstream from the plates had little influence on the unstable flow. However, the tests for this specific installation showed that the elliptical shape eliminated the unstableness and raised the pressures until they were only 2 to 8 feet below atmospheric.

Some reduction in capacity will result for elliptical shapes protruding into the stream. In the structure for which the tests were made, the discharge was limited by a long unlined tunnel, and the capacity reduction was not important. This reduction might be of prime importance where capacity counts.

One of the most important advantages of the elliptical shape protruding into the stream is that cavitation will not be induced at any gate opening, including very small openings. Particular conditions encountered at very small openings are discussed in detail in a subsequent part of this paper.

Rounded Upstream Corners

The effect of rounding the upstream corner of slots was investigated by testing two degrees of rounding at several W/D ratios. The tests showed that a small amount of rounding had little effect on the pressures in and near the slot, but that more rounding produced a noticeable effect (Figure 27). The larger radius caused a pressure build up in the slot, increased the contraction, and lowered the pressures just below the downstream corner, as W/D increase. Thus, rounding of the upstream corner to any large degree would not seem desirable.

"Short Tube" Action at Small Gate Openings

Because of the finite seal surface width needed on the bottom of a gate leaf, there will be times during operation at very small gate openings when "short-tube" action will take place between the leaf seal surface and the body. When such operation is at high heads, cavitation will occur and there will be noise, vibration, and damage. Use of the gate at openings where short-tube action occurs is not recommended. For free discharge conditions, the opening is not critical until it is less than about one-half the width of the seal surface.

Small Gate Openings With and Without Back Pressure

Extensive pressure measurements disclosed severe subatmospheric pressures near the floor just downstream from the slot for small submergences at gate openings equivalent to about 5 inches on a 9-foot high gate. Apparently, the area for water to enter the slot becomes large with respect to the area under the gate, and the downstream edge of the slot just beyond the leaf bottom acts as the edge of an orifice. A contraction forms at the corner, and if the velocities are high and no aeration can occur, the pressures are low and cavitation will occur. With no back pressure on the gate aerations will occur and the pressures will be near atmospheric.

A number of tests were made in an attempt to relieve the negative pressures which occur for back pressure conditions. One series of tests concerned reducing the slot width near the floor, and another concerned moving the slot upstream relative to the downstream leaf face (Figures 28 and 29). No overall benefit was gained by narrowing the slot near the floor, and a local region of very severe negative pressure was created. The narrowed slot tests were therefore discontinued.

In pursuing the problem further, it was reasoned that the slot corner could not act as a control if the slot was moved upstream relative to the gate leaf. This design was tested, and proved entirely satisfactory hydraulically, but the arrangement was not ideal mechanically because of seal problems. A seal design which appeared satisfactory was suggested by the designers, but it has not been used to date. It should be noted that much less spray was created with the slot moved upstream, than with the regular slots or the slots made narrow at the floor.

Another solution may be found in the design where elliptical shapes that project into the stream are placed downstream from the slot corner. Preliminary studies show that these shapes can be cavitation-free at all gate openings and downstream submergences. Additional studies are needed to establish the design factors.

Notch in Deflector Upstream from Slot

In a test on a design which contained a notch in the corner of the deflector at the upstream edge of the slot, excessive subatmospheric pressures were noted (Figure 30). These low pressures occurred on the notch adjacent to the leaf bottom. The removal of the notch eliminated the severe negative pressures. It was concluded that if a deflector is used it must continue without change in shape until it reaches the upstream edge of the slot.

Treatment of Downstream Corner of Slot

The downstream corner was kept sharp in most of the tests to simplify the design. Tests show this to be satisfactory at all openings for the free flow condition. Also, it permitted the use of a gate with a shorter span. However, in some cases, a rounding might prove beneficial. This is particularly true in cases where relatively wide slots are required and where submerged flow is present. An elliptical shape, such as shown in Figure 26, is at present considered best for these conditions.

FIELD EXPERIENCE

Gate Having Offset Slot Corners and Converging Walls

The slot with an offset corner and a constant rate converging wall was used in the Palisades Dam outlet works. The design was developed in the early tests made on the water model, and the convergence used was 60 to 1. The offset of the downstream corner was 1/2 inch.

The gate bodies were made up of welded plates. The floor and lower portion of the walls of the downstream gate frame were made from a single plate. A 2-inch radius was used where the plate was turned upward to form the walls. The transition from this rounded corner of the gate frame to the sharp corner in the concrete flow passage downstream was made by a concrete fillet about 10 inches long (Figures 31 and 32). This fillet produced surfaces that receded from the flow on about a 10:1 slope.

Since the slide gate used at Palisades outlets was a new design, and it was known that severe damage had been experienced on other designs, close tolerances were specified for constructing and installing the gates, and frequent and thorough inspections were recommended during the operating seasons. Before the first two gates were placed in operation, it was noted that the concrete walls projected inward from the metal surface of the gate body as much as 1/2 inch. Grinding of these abrupt into-the-flow offsets was required of the contractor. However, the grinding was done on a rather sharp bevel, in some cases as steep as 4:1.

An inspection of the downstream flow passages, after considerable operation, showed evidence of cavitation at several locations. The cavitation at these locations was determined to be of a local nature produced by surface irregularities in the concrete. Pitted areas were found on the walls immediately below the gate frames at points where small into-the-flow offsets in the concrete walls had not been ground. Other areas were found downstream of the rather steep bevels formed by grinding larger offsets (Figure 31). Cavitation was also noted in joints in the concrete surfaces and on the surfaces of the fillets placed in the bottom corners downstream from the gate frames (Figure 32).

After subsequent operation at small openings for about 30 days at a head of about 190 feet, another examination was made. The cavitation damage at all locations had increased somewhat, but the damage on the corner fillets had become serious. The extent to which the damage had progressed on the fillets and adjacent surfaces is shown in Figure 33.

A close examination of the flow passages disclosed other interesting factors. Cavitation had occurred just downstream from an abrupt, into-the-flow, offset of about 1/8 inch (Figure 34). This is in agreement with laboratory tests made recently to determine the cavitation potential of abrupt offsets when subjected to high velocities and various pressures (Figure 35).

Cavitation damage was also noted in the concrete downstream from voids commonly known as "bug holes" (Figure 36). The damage was noticeable at the larger holes, and nonexistant at the small holes. The dividing point seemed to be about 1/2 inch.

There was no damage at the downstream end of the 60:1 converging wall, and there was no damage to any of the metal parts of the gate where installation had been made strictly in accordance with specifications.

From these observations, it is concluded that the cavitation downstream from the Palisades gates resulted from local surface irregularities, and not from the gate slot design. The damage is being repaired and the known cavitation-producing irregularities removed. Periodical inspections will be continued to ascertain the effectiveness of the corrective measures and to detect any other characteristics which could be responsible for cavitation damage.

CONCLUSIONS

Low pressures just downstream from the downstream corner of the original slot with parallel inline upstream and downstream walls make this design susceptible to cavitation. The pressures are much below the reference pressure at the downstream face of the leaf, and decrease as W/D increases. The design serves adequately for heads less than about 35 feet.

Deflectors at the upstream edges of slots produce an ejector action which lowers the pressures at the slot far below the reference pressure and will induce cavitation. There may be a small deflector design which would give satisfactory pressure conditions but it's size could be critical. A very large deflector which would cause a heavy contraction can be used successfully at a slot when aeration is provided.

Slots with offset corners and parallel downstream walls will have severe negative pressures within the slot and on the flow surfaces immediately downstream from the slots. The pressure within the slot will be lower for large offsets than for small ones, and the pressure downstream from the downstream corner will be lower for small offsets than for large ones. This design appears adequate for small offsets at moderate heads.

Slots with offset downstream corners and divergent walls have low pressures within the slot or immediately downstream from the downstream corner, depending on the amount of offset. The design is only satisfactory with large offsets at a limited range of slot widths, and small operating heads.

Slots with offset downstream corners and constant rate converging downstream walls have low pressures just downstream from the lines of intersection of the converging and parallel walls. The pressures decrease as the rate of convergence increases and the intersections may become cavitation potentials.

Slots with offset downstream corners and constant rate converging walls, with a rounded intersection will be free of cavitation at rather high heads. Further testing is required to determine the head limits. It is best to use rapid rates of convergence, insofar as the pressures within and just downstream from the slots are concerned, but the rate of convergence should not be rapid enough to cause difficulty in adequately rounding the line of intersection. A 24:1 rate of convergence with a 12-inch rounding is considered adequate for moderate heads but larger radius would be more desirable.

A slot design using offset corners and a variable rate of convergence is the most desirable from the hydraulic standpoint. Arcs used in this design should have radii in the range of about 100 to 250 times the offset of the downstream corner. Ellipses can also be used with excellent results.

The upstream corners of the gate slots should not be rounded or notched; both are detrimental to the pressure distribution.

The widening of slots permits more expansion of the jet into the slot, tending to increase the contraction at the downstream corner. However pressure conditions are acceptable for a wide range of W/D ratios in designs using offset corners with converging walls. This is particularly true for the 24:1 convergence and the long-radius curved convergence.

Sharp downstream corners of gate slots should always be offset away from the flow. The offset of the downstream corner of a gate slot should be small and related to the slot width. Within reasonable limits, this offset is not critical.

A cavitation-free slot for both free discharge and back pressure conditions, and small gate openings, has been developed. This design, which combines moving the slots upstream with a small offset at the downstream corner, is feasible. Some development work is needed to perfect a seal design, but this is considered practicable.

Sufficient field data have been obtained on a 7-1/2- by 9-foot free discharge gate to show that an offset of 1/2-inch followed by a 60:1 convergence is cavitation-free under a head of 200 feet.

Abrupt into-the-flow offsets and irregularities in flow surfaces are particularly troublesome. Offsets of less than 1/8-inch will cause damage. Also, cavitation may occur at offsets ground on steep bevels and at "bug holes." Thus, it is extremely important to provide smooth continuous surfaces downstream from gates operating under high heads.

Cavitation will occur where the bottom corners of the frame of a gate are rounded, the corners of the flow channel downstream are square, and short fillets are used to blend the rounded corner into the square one. Long fillets will decrease the cavitation potential.

Where there is a finite seal width across the bottom of the gate leaf, there will be a gate opening below which cavitation will occur between the leaf seal and the floor. This opening will be about one-half the seal width for free discharge. In cases where the flow is submerged, the critical opening may be somewhat larger.

ACKNOWLEDGEMENTS

Much credit is due W. P. Simmons, Jr. of the Bureau of Reclamation Hydraulic Laboratory staff for his part in conducting tests, analyzing data and preparing material used in this paper. Credit also goes to many foreign and rotation engineers in training with the Bureau who assisted in performing the numerous tests.

Appreciation is expressed by the author to the editors of Engineering News-Record for use of material on foreign installations contained in thier magazine, and to the Corps of Engineers for the use of a photograph showing cavitation damage below a stop-log slot at one of the Corps' structures.

Interior - Reclamation - Denver, Colo.

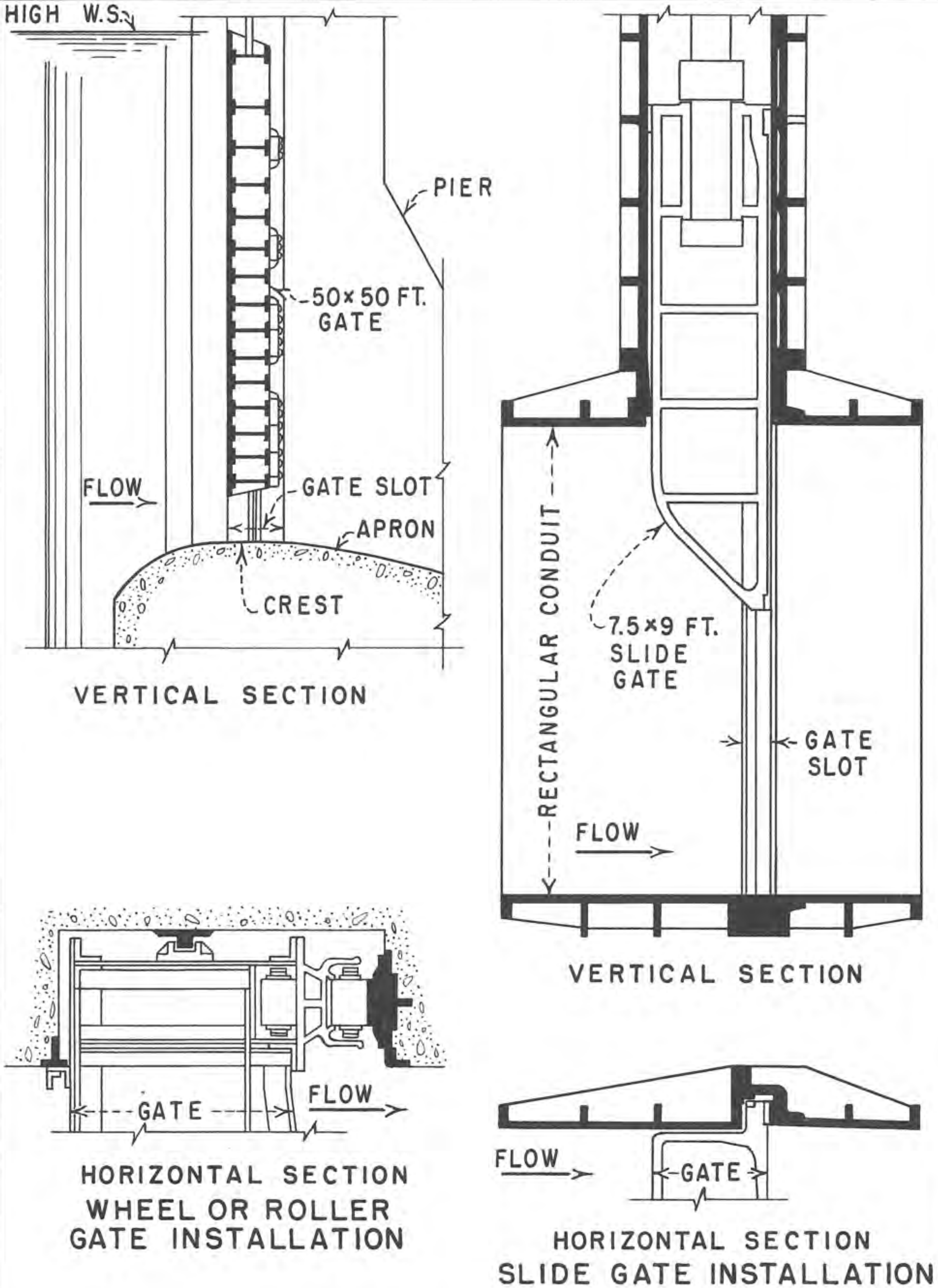

FIGURE I. TYPICAL GATE INSTALLATIONS

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Fig. 2. Cavitation-erosion downstream of gate slot. 50- x 50-foot stoney gate.

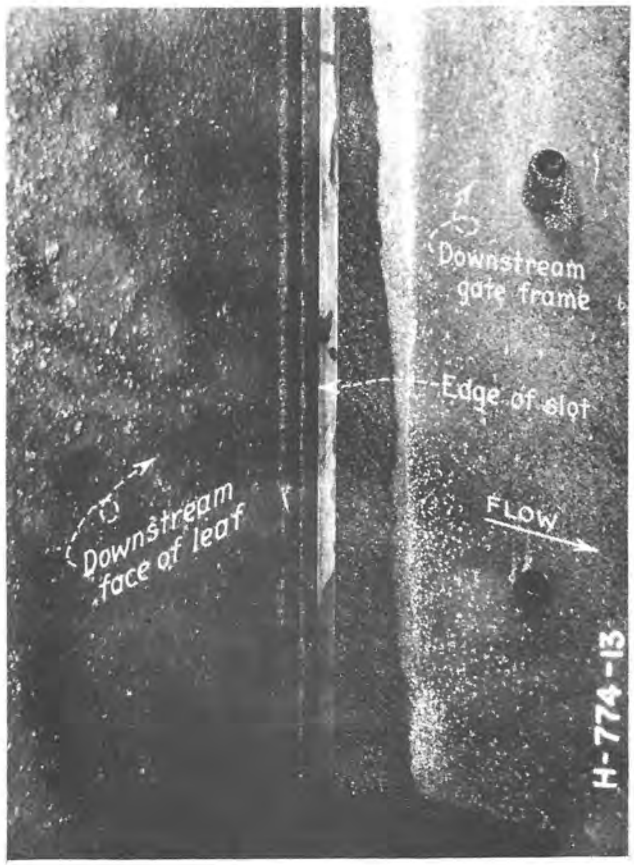

Fig. 3. Cavitation-erosion downstream of gate slot. Early high-pressure slide gate.

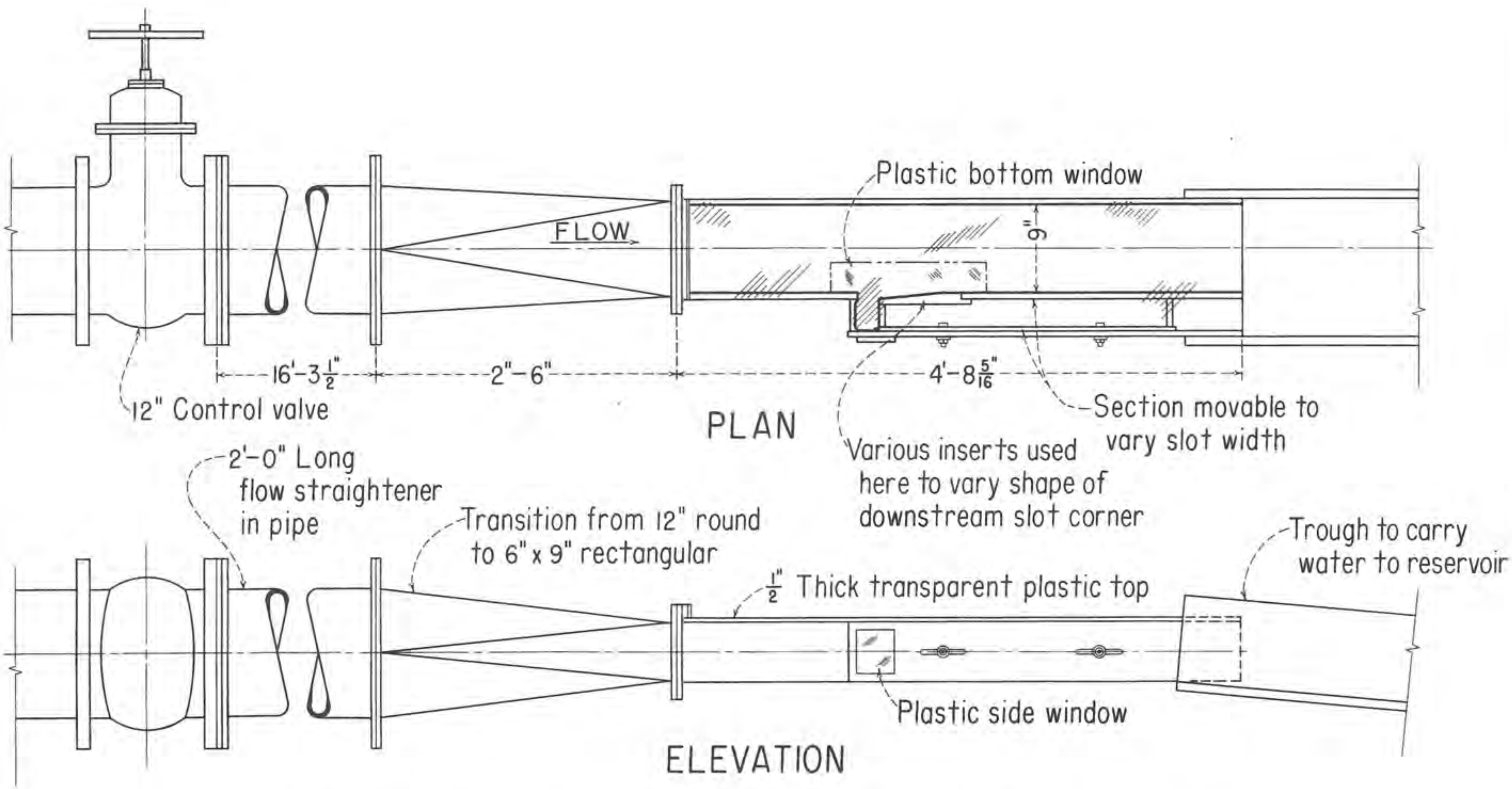

FIGURE 4. HYDRAULIC TEST FACILITY FOR GATE SLOTS

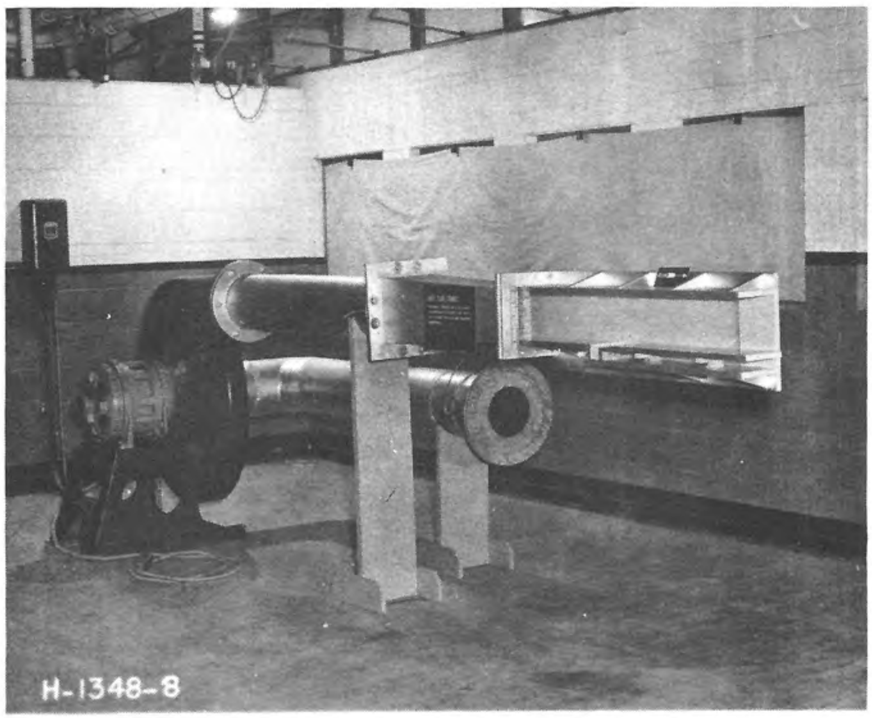

Fig. 5. Aerodynamic test facility for gate slots.

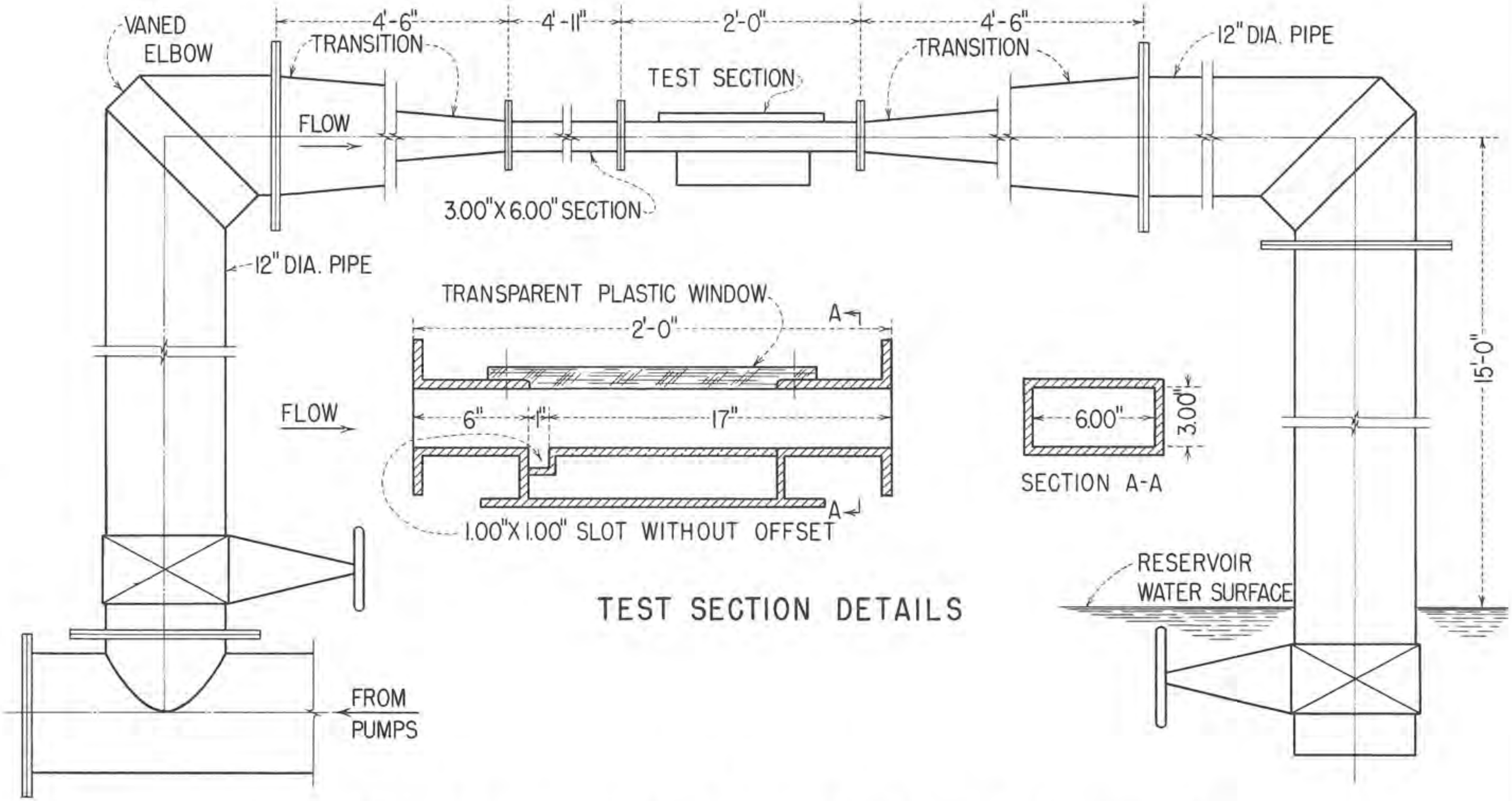

FIGURE 6. CAVITATION TEST FACILITY
WITH ORIGINAL GATE SLOT

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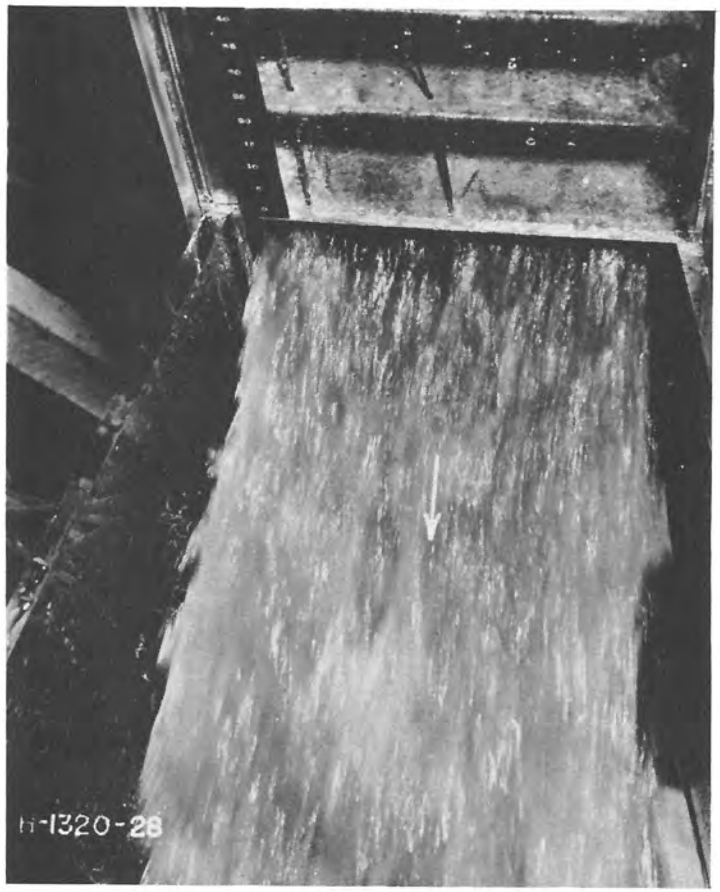

Fig. 7. Flow clears outwardly offset downstream corners and walls when leaf is fully opened.

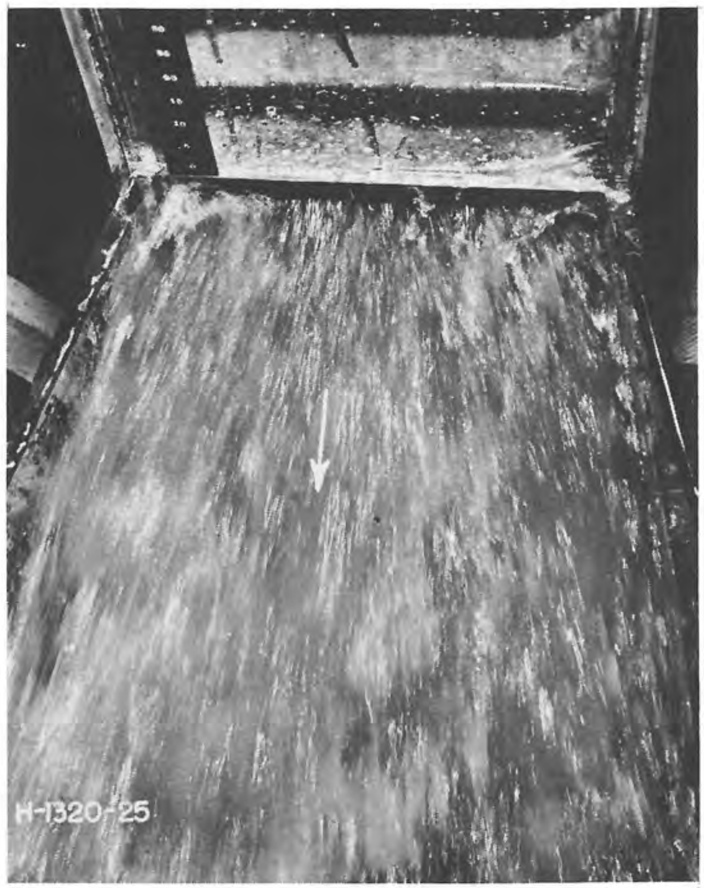

Fig. 8. Flow deflects to fill gate slots and remain in contact with downstream diverging walls when leaf is partially closed.

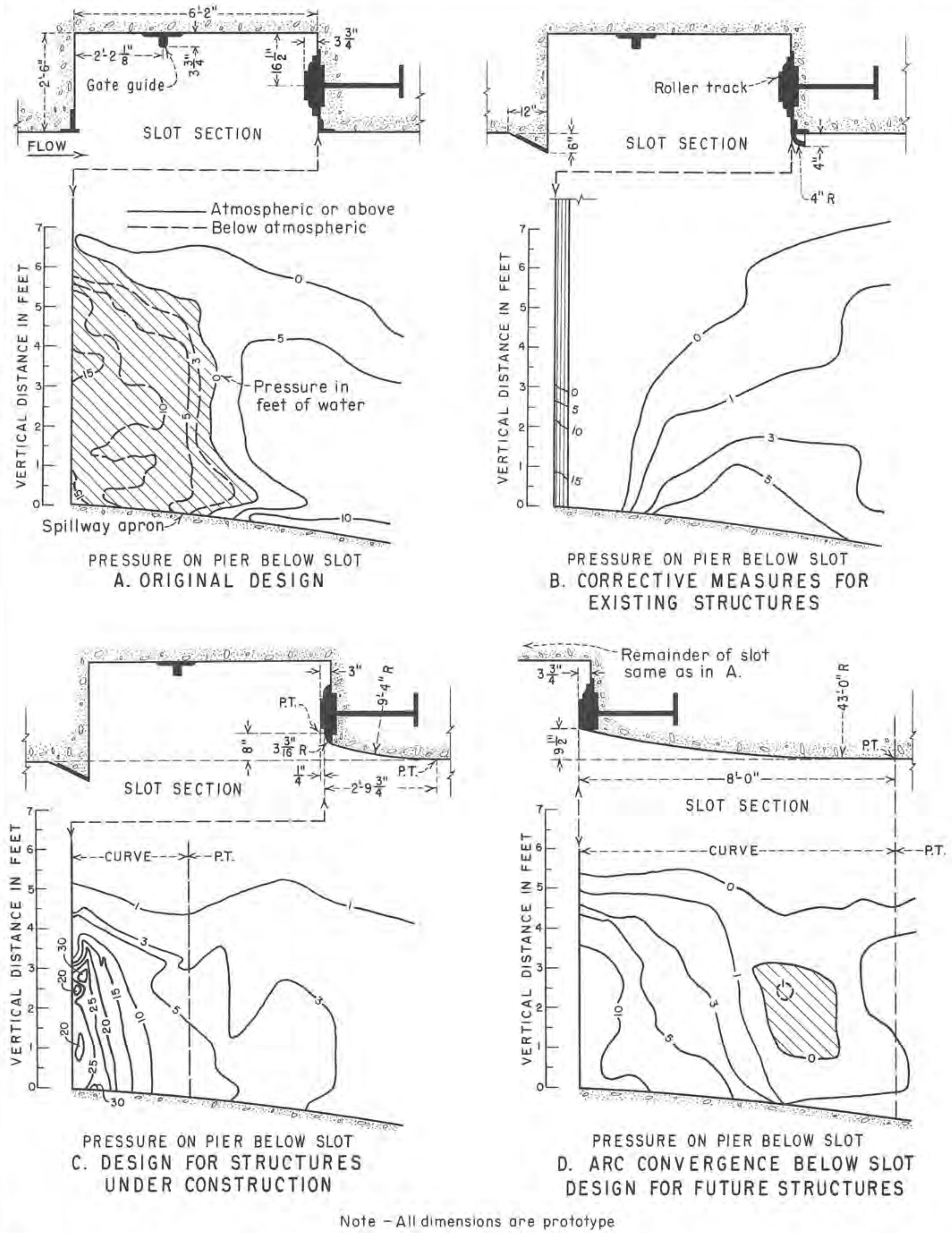

FIGURE 9. SLOT DESIGNS FOR FIXED-WHEEL GATES

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Fig. 10. Flow lines on bottom and nearby surfaces. Original slot with inline downstream wall.

Fig. 11. Flow lines on bottom and nearby surfaces. Slot with offset downstream corner and curved converging wall.

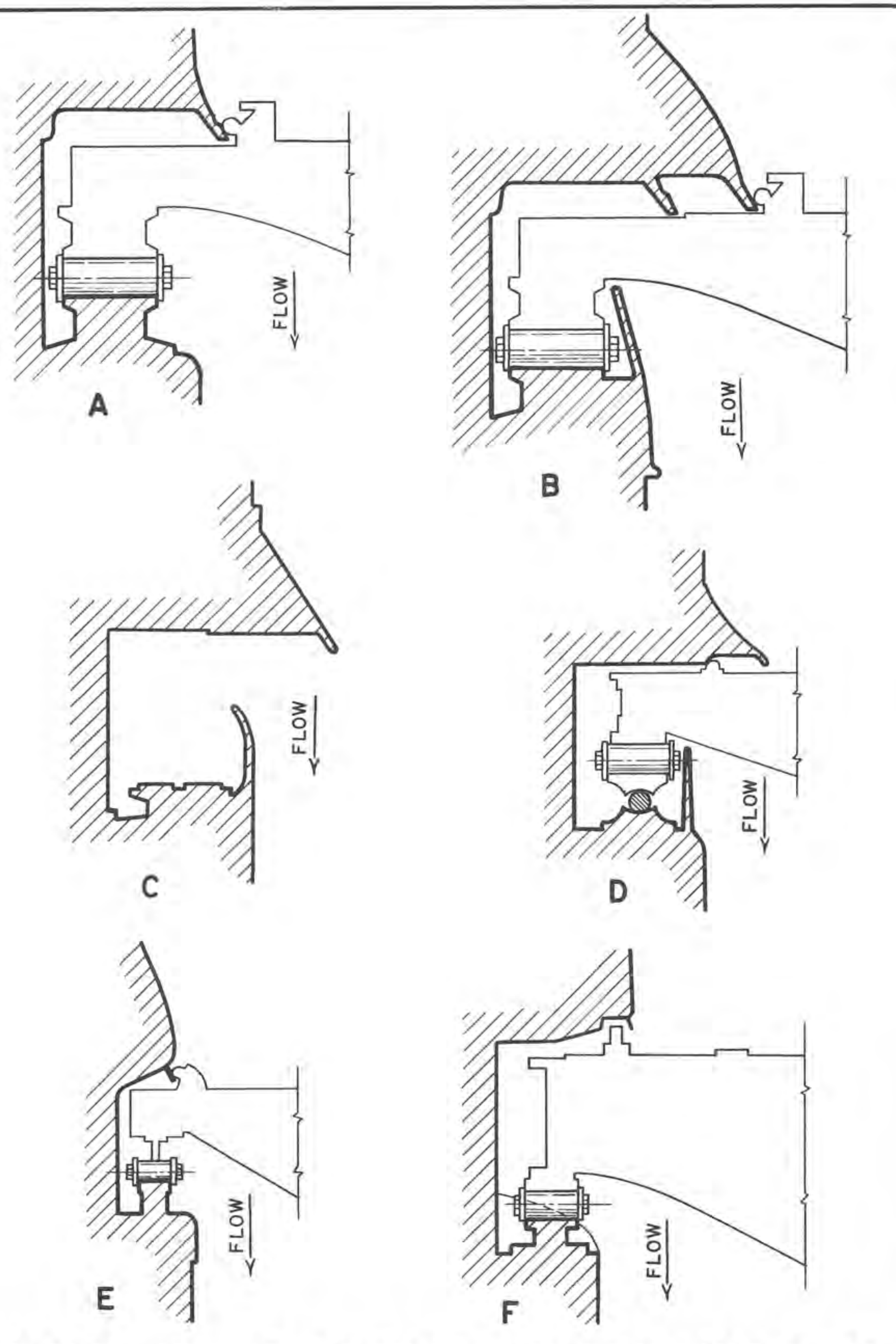

FIGURE 12. GATE SLOT DESIGNS USED TO ELIMINATE CAVITATION IN EARLY EUROPEAN INSTALLATIONS

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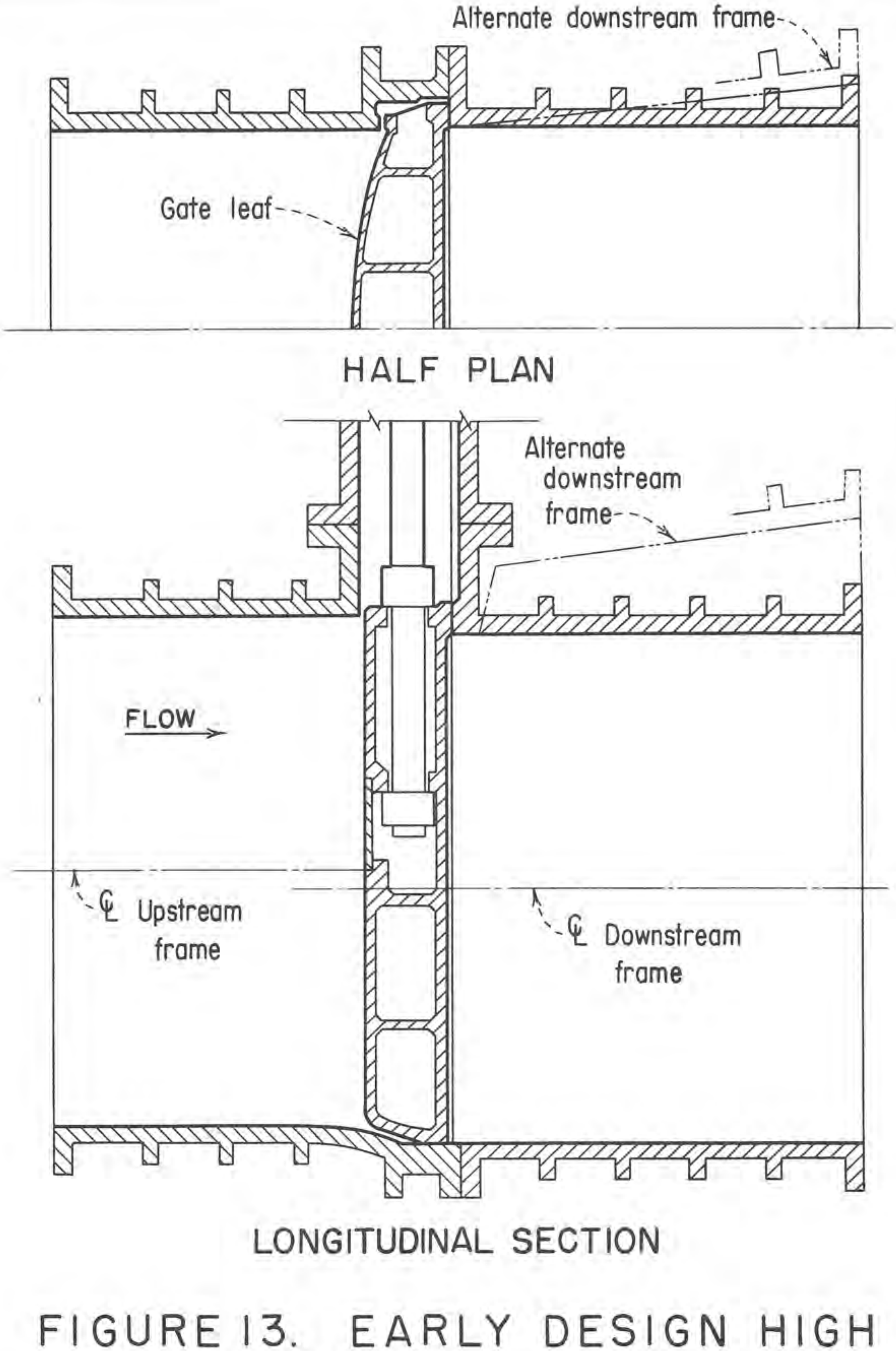

FIGURE 13. EARLY DESIGN HIGH PRESSURE SLIDE GATE

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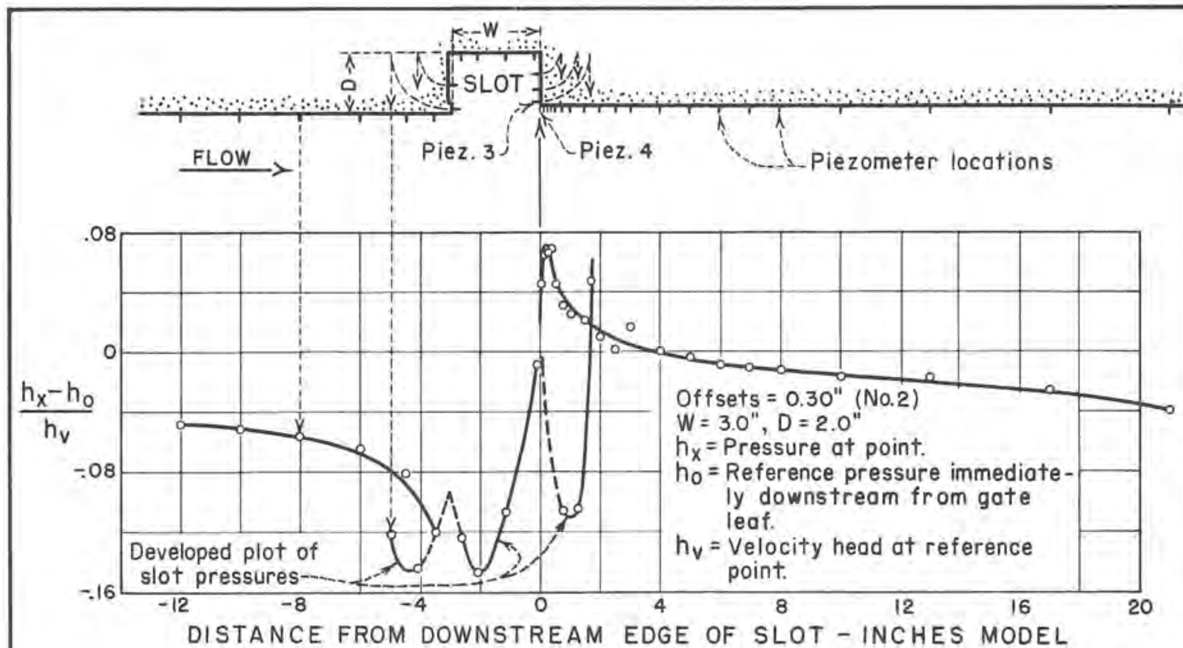
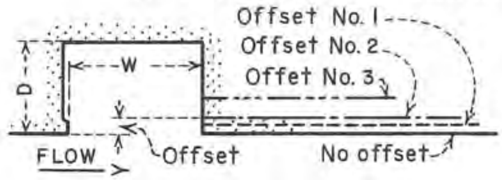


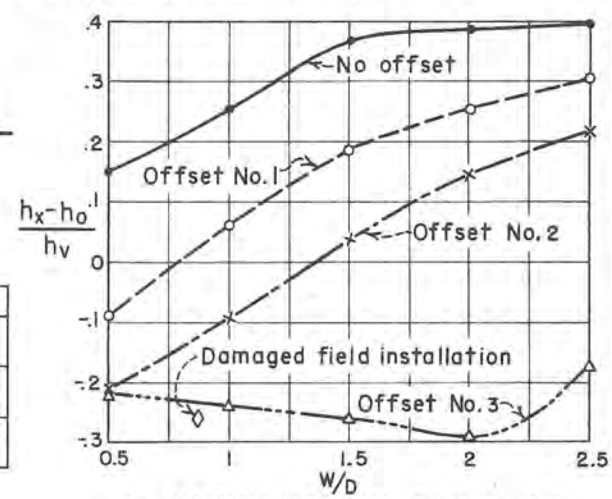
A. TYPICAL PRESSURE DISTRIBUTION CURVE



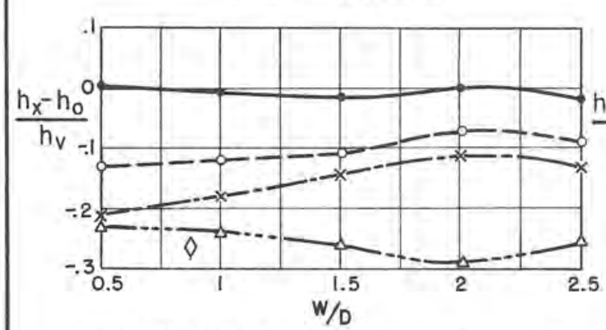
B. DIAGRAM OF SLOTS

W/D	0.50	1.00	1.50	2.00	2.50
OFFSET NO. 1	0.15W	0.075W	0.05W	0.037W	0.03W
OFFSET NO. 2	0.30W	0.15 W	0.10W	0.075W	0.06 W
OFFSET NO. 3	0.73 W	0.365W	0.243W	0.182W	0.146W

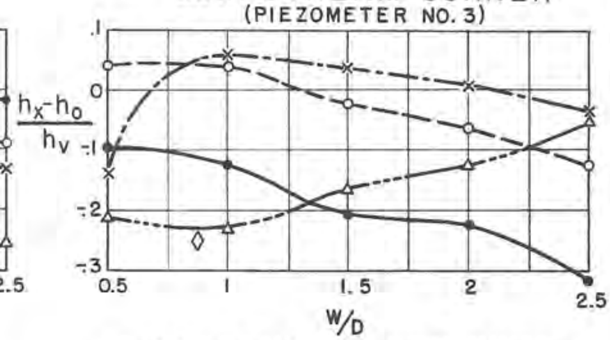
C. OFFSETS RELATIVE TO SLOT WIDTH



E. PRESSURE IN SLOT AT DOWNSTREAM CORNER (PIEZOMETER NO. 3)



D. LOWEST PRESSURE IN SLOT



F. PRESSURE BELOW DOWNSTREAM CORNER OF SLOT (PIEZOMETER NO. 4)

FIGURE 14. PRESSURE CHARACTERISTICS- SLOTS WITH OFFSET DOWNSTREAM CORNERS AND PARALLEL DOWNSTREAM WALLS

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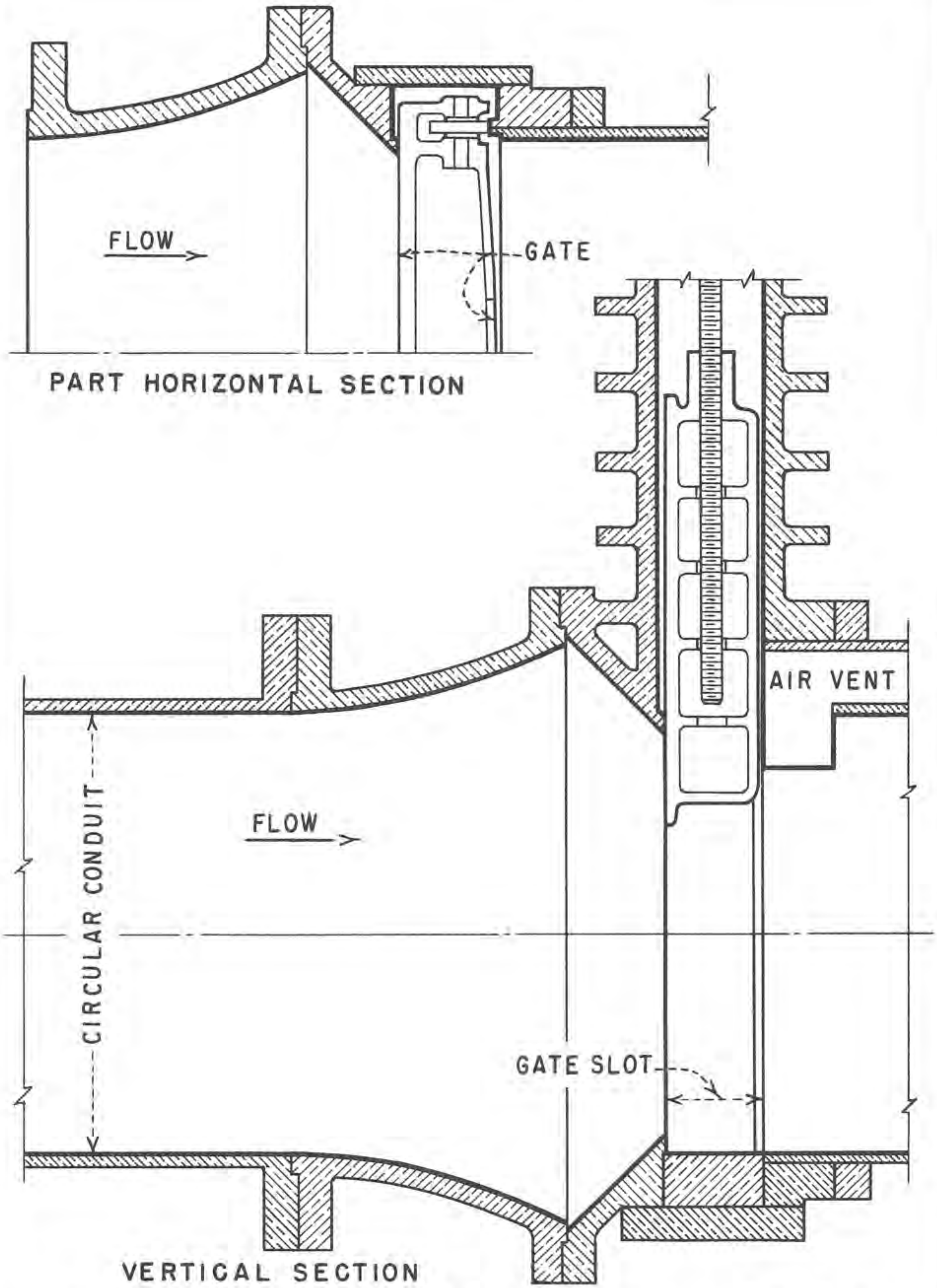

FIGURE 15. GATE WITH LARGE CONTRACTION UPSTREAM FROM SLOT

552

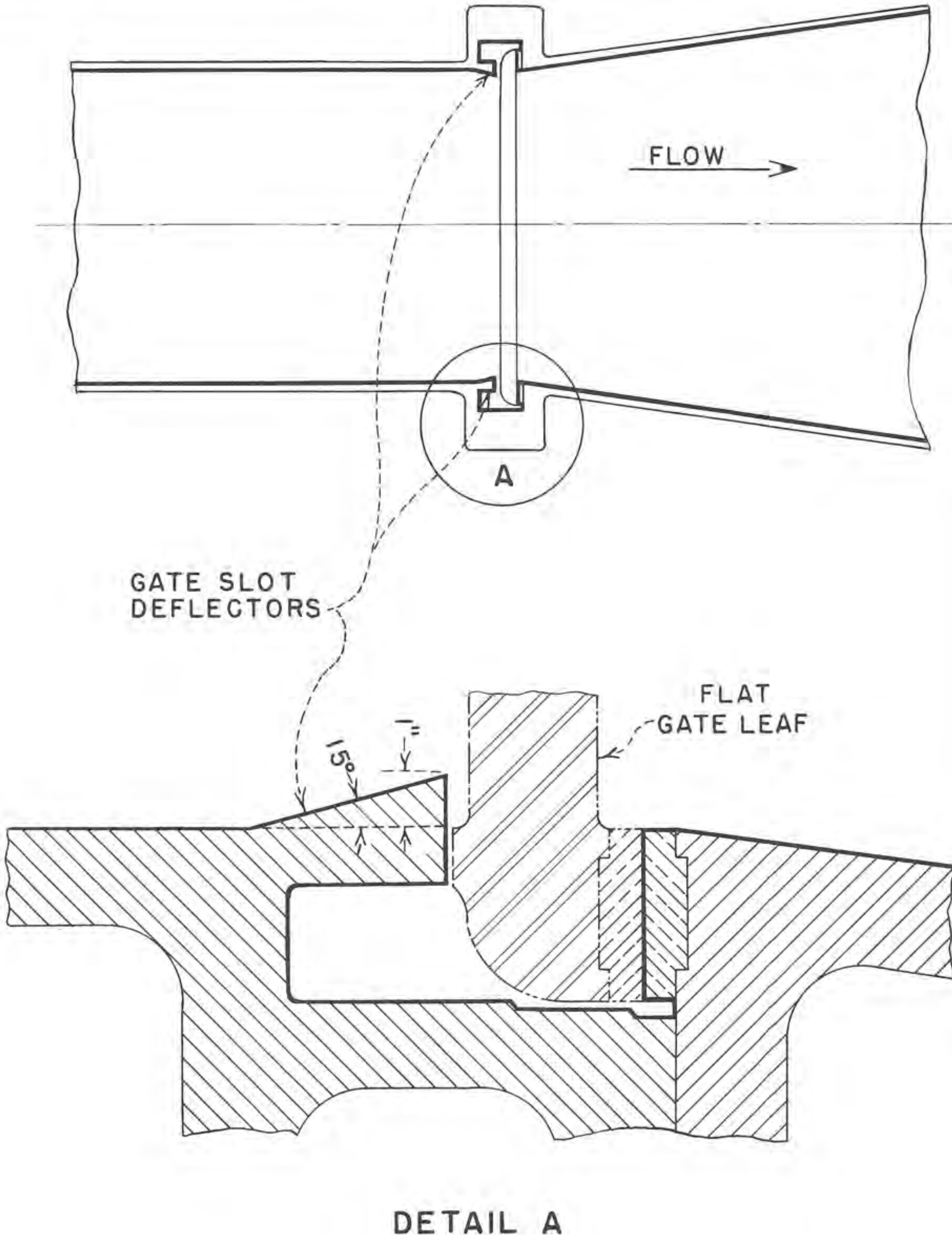

FIGURE 16. NARROW GATE SLOT
WITH SMALL DEFLECTOR
AT UPSTREAM CORNER

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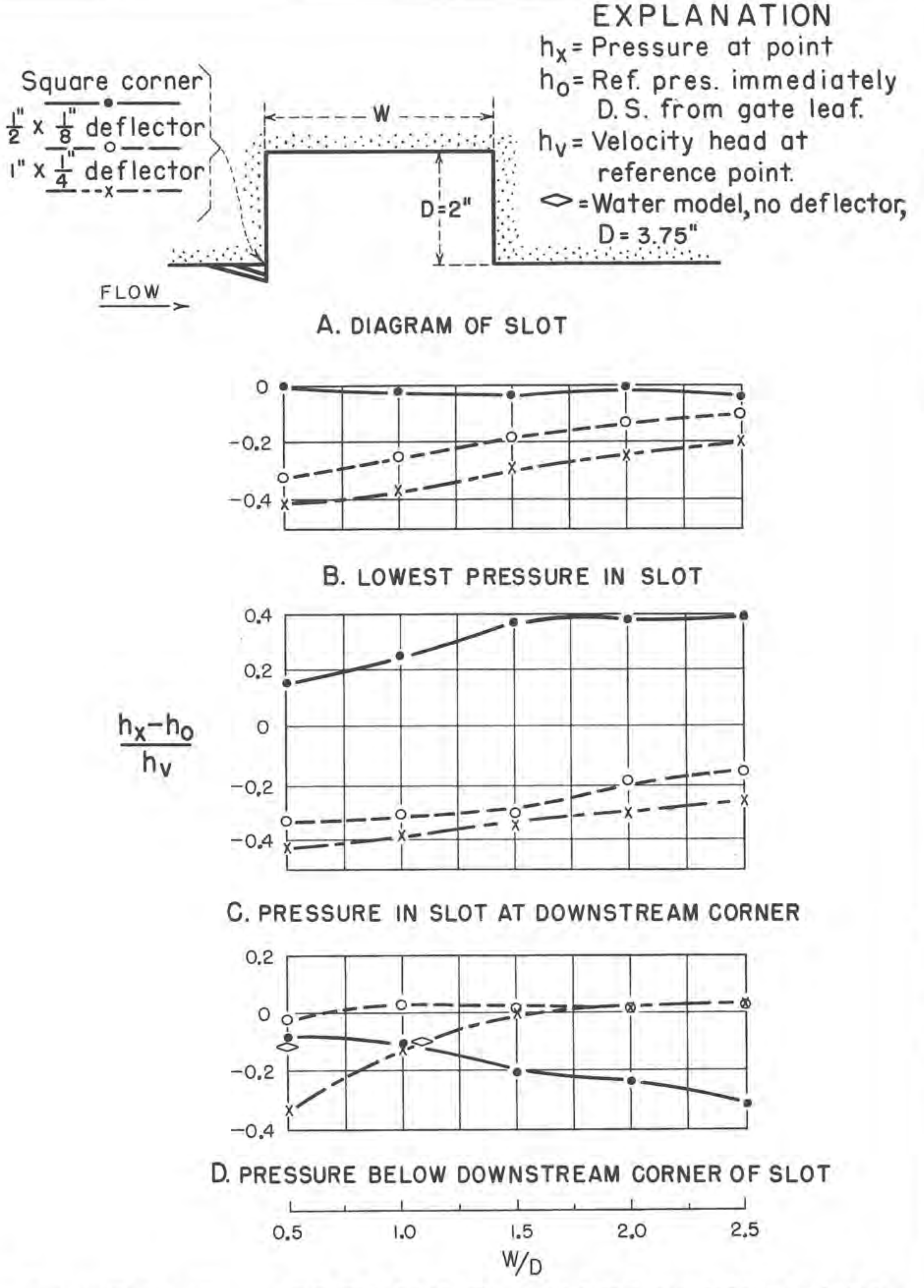


FIGURE 17. PRESSURE CHARACTERISTICS-SLOTS WITH DEFLECTORS AT UPSTREAM CORNERS AND INLINE DOWNSTREAM WALLS

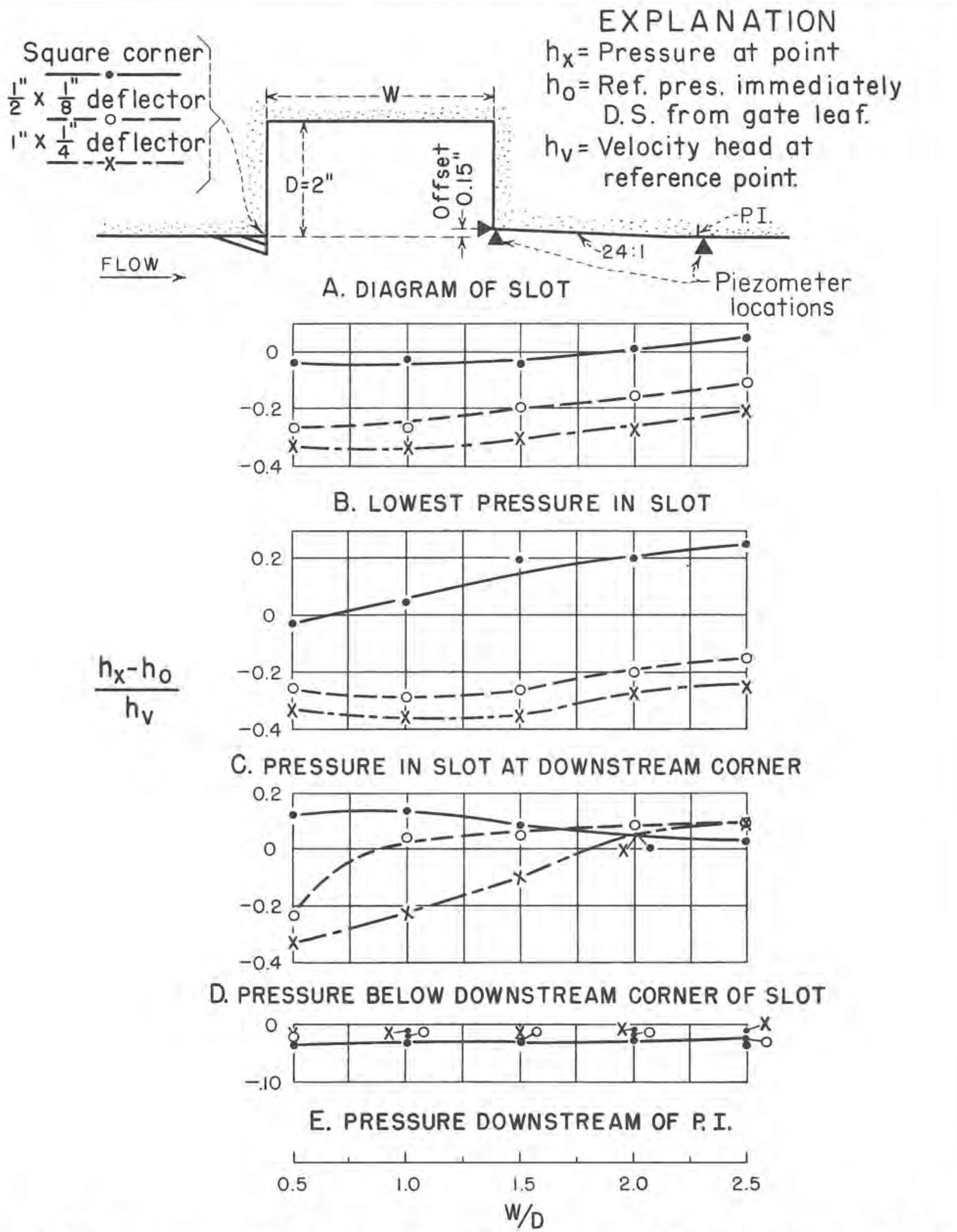
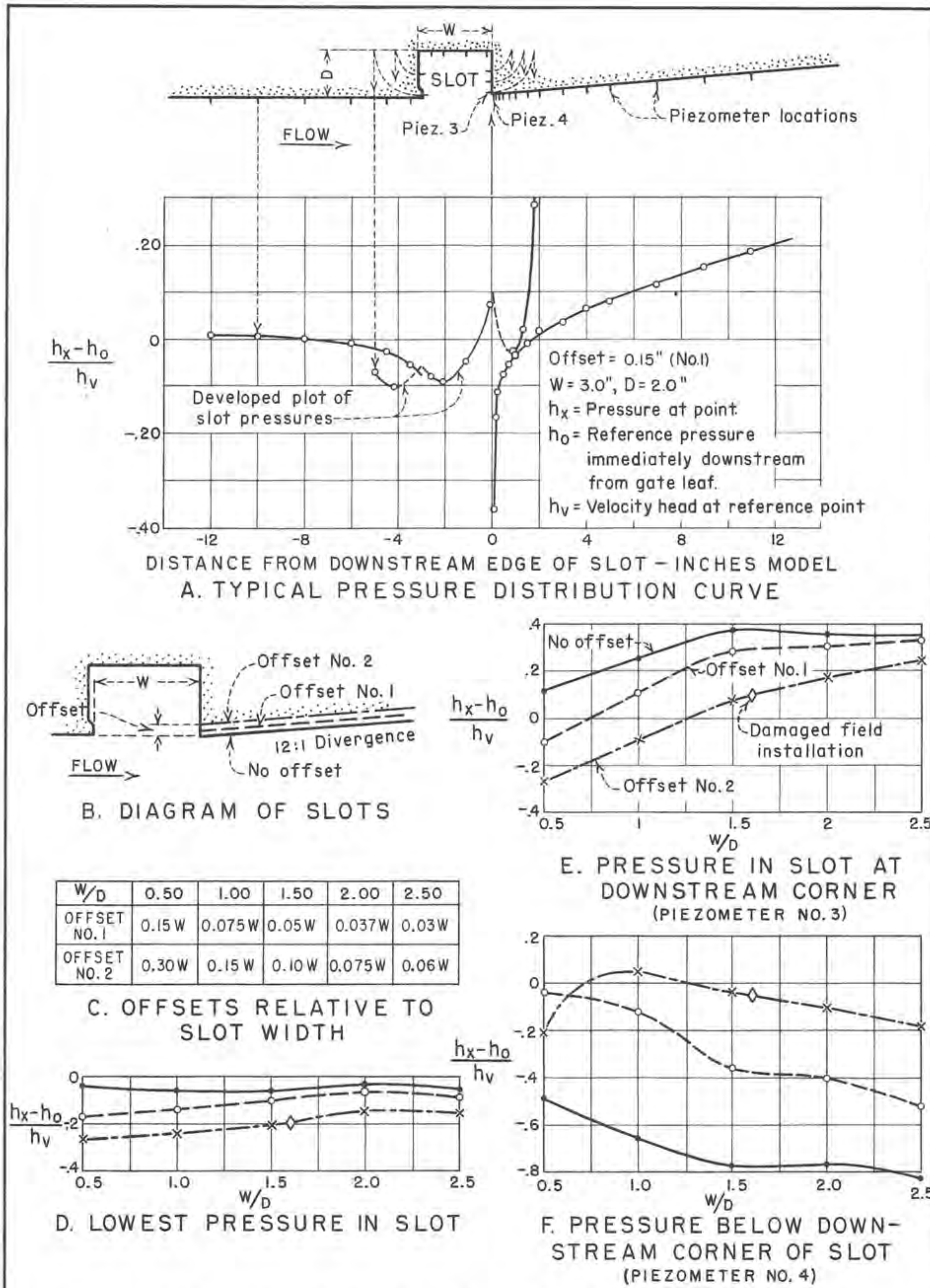


FIGURE 18. PRESSURE CHARACTERISTICS—SLOTS WITH DEFLECTORS AT UPSTREAM CORNERS AND WITH OFFSET DOWNSTREAM CORNERS AND 24:1 CONVERGING DOWNSTREAM WALLS



W/D	0.50	1.00	1.50	2.00	2.50
OFFSET NO. 1	0.15 W	0.075 W	0.05 W	0.037 W	0.03 W
OFFSET NO. 2	0.30 W	0.15 W	0.10 W	0.075 W	0.06 W

C. OFFSETS RELATIVE TO SLOT WIDTH

FIGURE 19. PRESSURE CHARACTERISTICS-SLOTS WITH OFFSET DOWNSTREAM CORNERS AND 24:1 DIVERGING DOWNSTREAM WALLS

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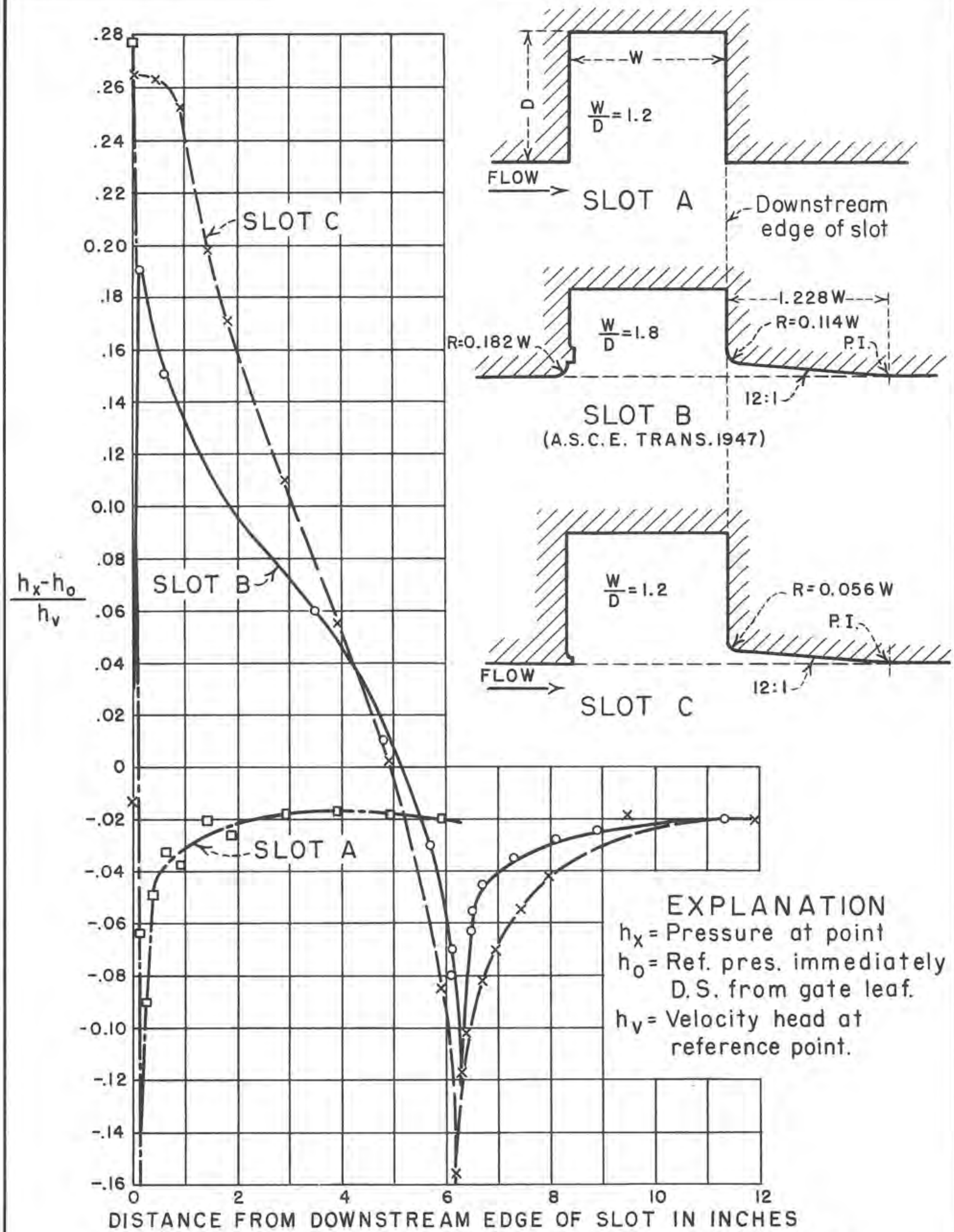

FIGURE 20. PRESSURE DISTRIBUTION-COMPARISON OF SLOT DESIGNS

HYDRAULIC MODEL

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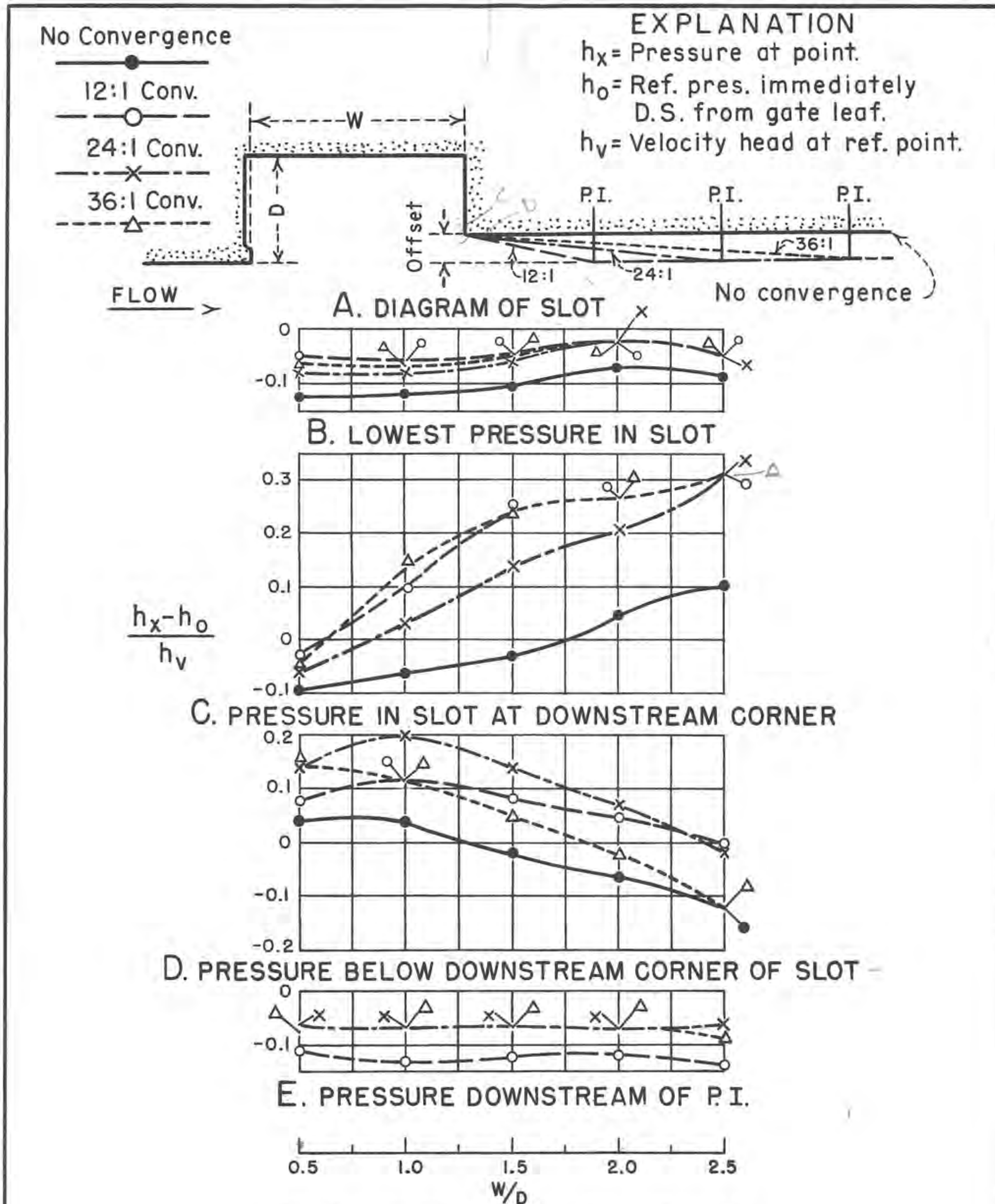
Fig. 21. Cavitation-erosion below stop-log slot with rounded, offset, downstream corner and 12:1 converging downstream wall.



W/D	0.50	1.00	1.50	2.00	2.50
OFFSET	0.15 W	0.075 W	0.05 W	0.037 W	0.03 W

FIGURE 22. PRESSURE CHARACTERISTICS-SLOT WITH OFFSET DOWNSTREAM CORNERS AND CONSTANT-RATE CONVERGING DOWNSTREAM WALLS

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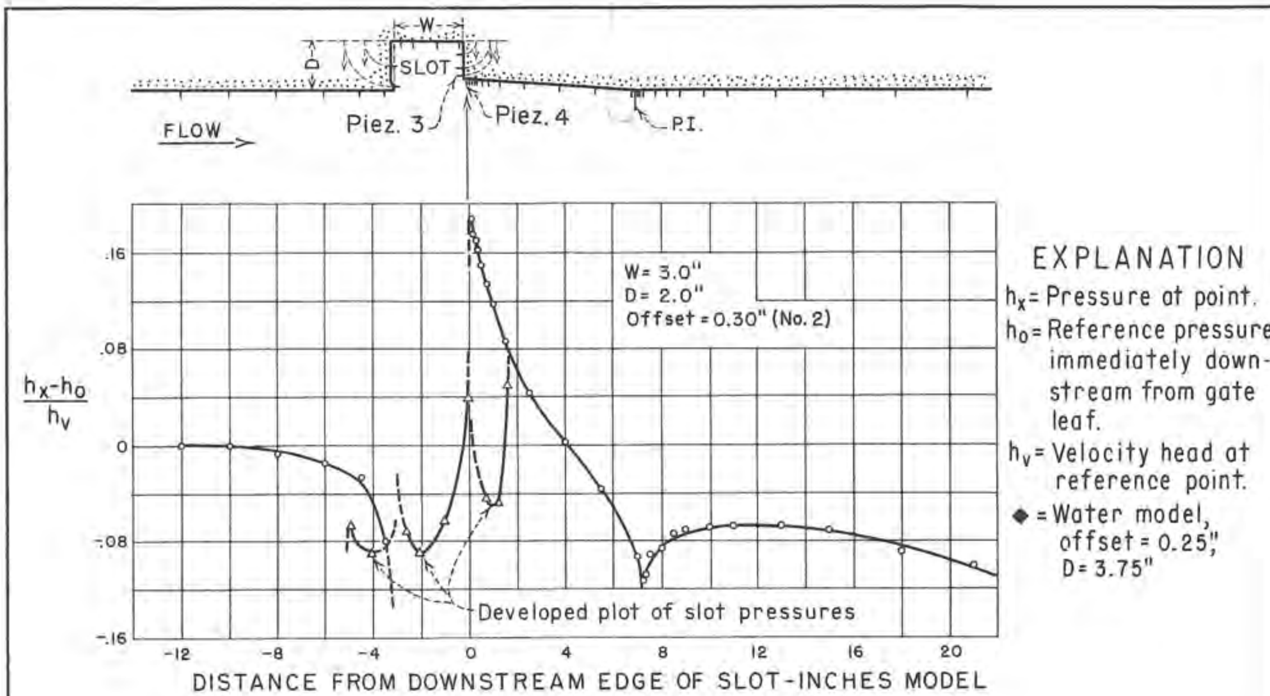
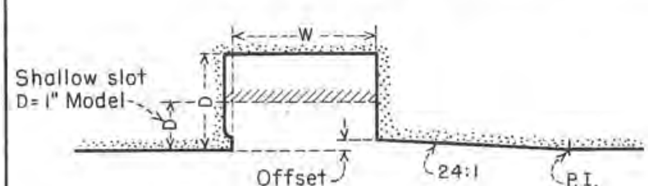
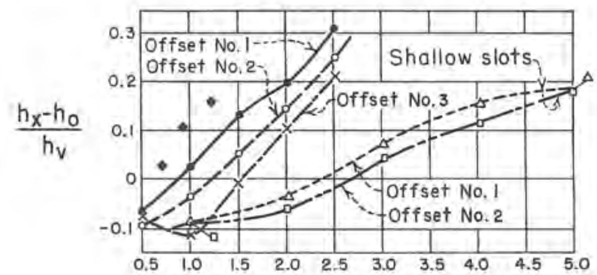


A. TYPICAL PRESSURE DISTRIBUTION CURVE



B. DIAGRAM OF SLOTS



E. PRESSURE IN SLOT AT DOWNSTREAM CORNER
(PIEZOMETER No. 3)

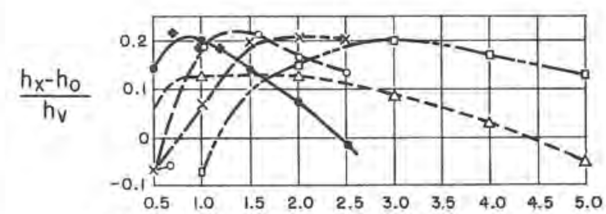
2" SLOT DEPTH

W/D	0.5	1.0	1.5	2.0	2.5
OFFSET NO. 1	0.15 W	0.075 W	0.05 W	0.037 W	0.03 W
OFFSET NO. 2	0.30 W	0.15 W	0.10 W	0.075 W	0.06 W
OFFSET NO. 3	0.45 W	0.225 W	0.15 W	0.112 W	0.09 W

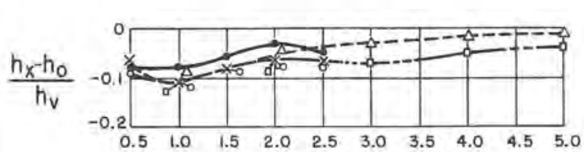
1" SLOT DEPTH

W/D	1	2	3	4	5
OFFSET NO. 1	0.15 W	0.075 W	0.05 W	0.037 W	0.03 W
OFFSET NO. 2	0.30 W	0.15 W	0.10 W	0.075 W	0.06 W

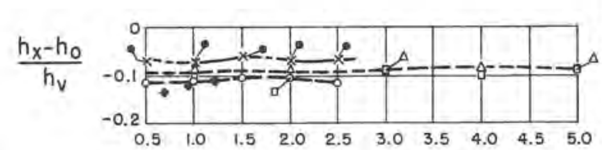
C. OFFSETS RELATIVE TO SLOT WIDTH



F. PRESSURE BELOW DOWNSTREAM CORNER OF SLOT
(PIEZOMETER No. 4)



D. LOWEST PRESSURE IN SLOT



G. PRESSURE DOWNSTREAM OF P.I.

FIGURE 23. PRESSURE CHARACTERISTICS-SLOTS WITH OFFSET DOWNSTREAM CORNERS AND 24:1 CONVERGING DOWNSTREAM WALLS

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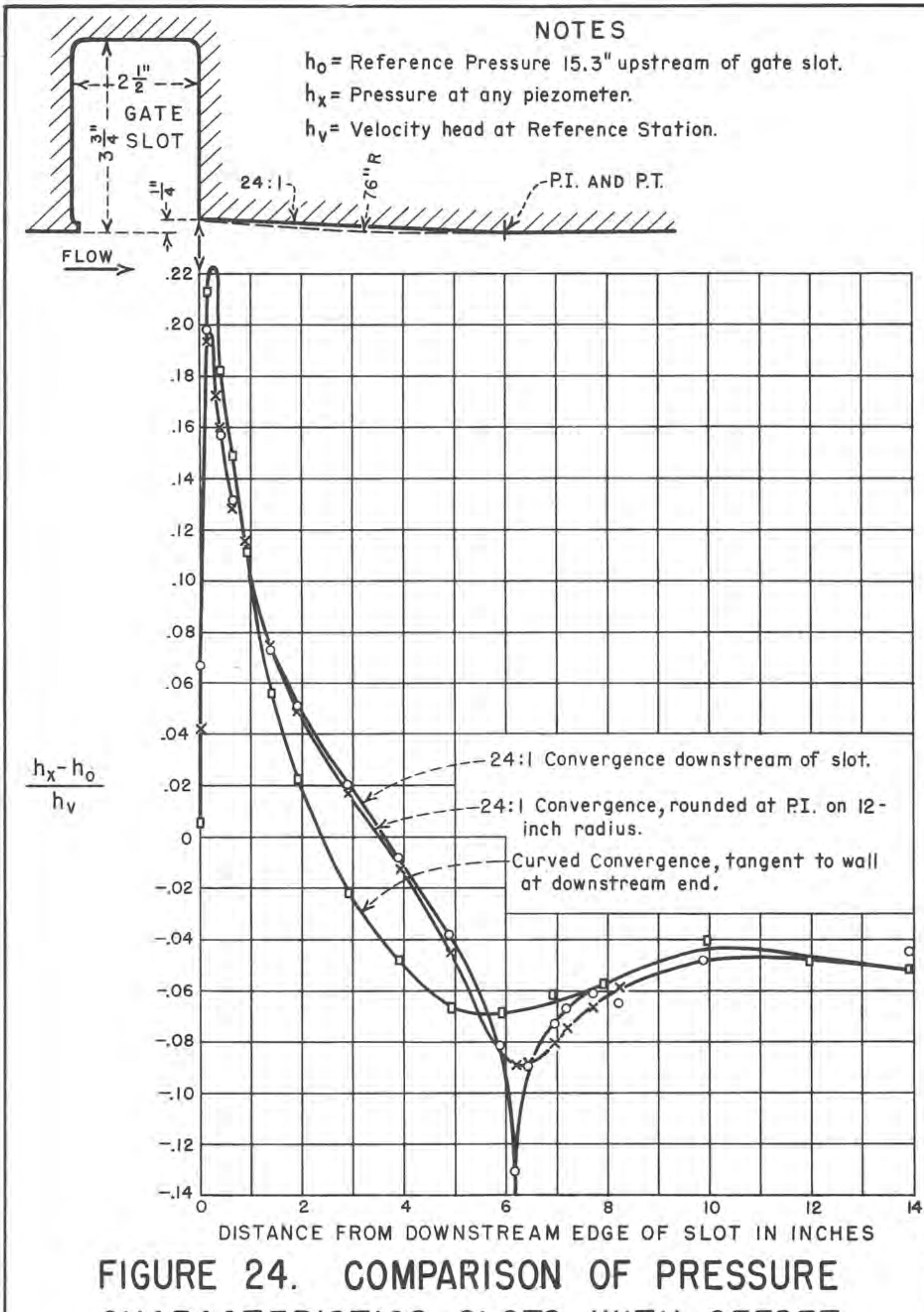
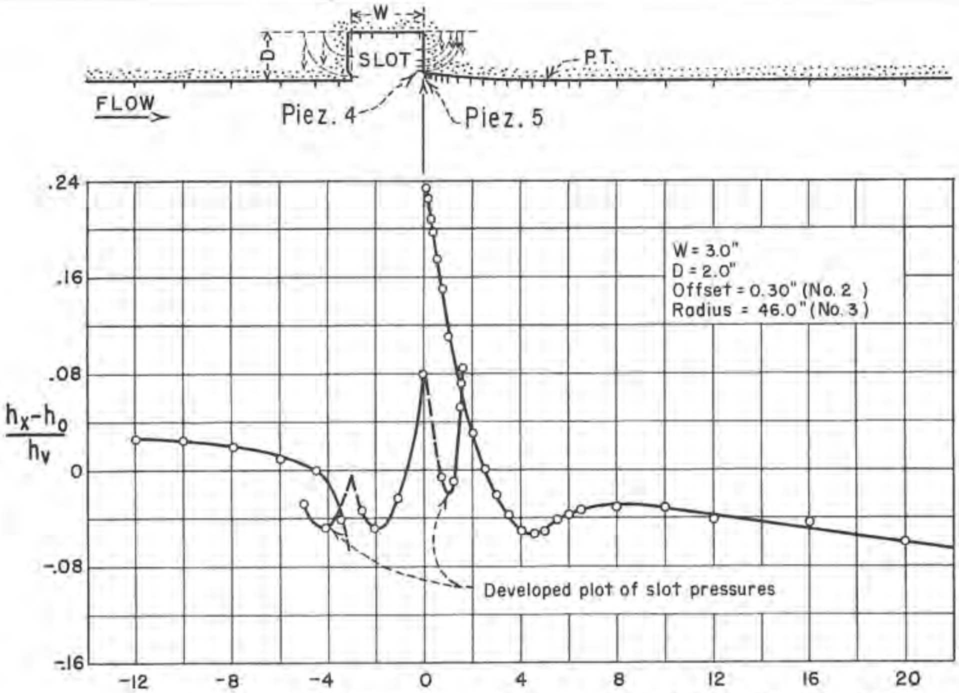


FIGURE 24. COMPARISON OF PRESSURE CHARACTERISTICS—SLOTS WITH OFFSET DOWNSTREAM CORNERS AND CONSTANT AND VARIABLE-RATE CONVERGING DOWNSTREAM WALLS

552



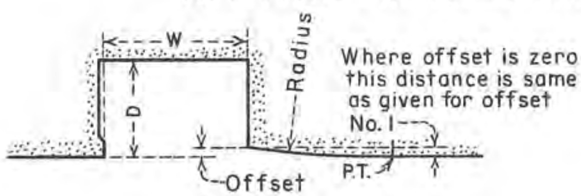
EXPLANATION

h_x = Pressure at point.

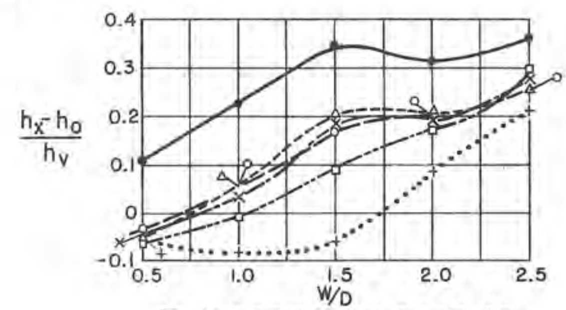
h_o = Reference pressure immediately downstream from gate leaf.

h_v = Velocity head at reference point.

A. TYPICAL PRESSURE DISTRIBUTION CURVE



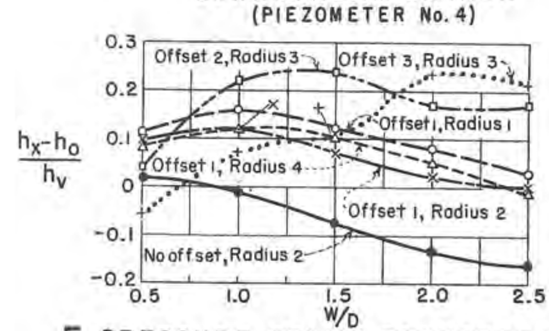
B. DIAGRAM OF SLOTS



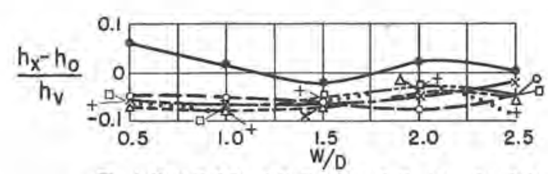
E. PRESSURE IN SLOT AT DOWNSTREAM CORNER (PIEZOMETER No. 4)

W/D	0.5	1.0	1.5	2.0	2.5
OFFSET NO. 1	0.15W	0.075W	0.05W	0.037W	0.03W
OFFSET NO. 2	0.30W	0.15W	0.10 W	0.075W	0.06W
OFFSET NO. 3	0.45W	0.225	0.15 W	0.112W	0.09W
RADIUS NO. 1	12.6W	6.30W	4.20W	3.15 W	2.52W
RADIUS NO. 2	42.5W	21.25W	14.167W	10.625W	8.50W
RADIUS NO. 3	46.0W	23.0W	15.33W	11.50W	9.20W
RADIUS NO. 4	97.8W	48.90W	32.60W	24.45W	19.56W

C. OFFSETS AND RADII RELATIVE TO SLOT WIDTH



F. PRESSURE BELOW DOWNSTREAM CORNER OF SLOT (PIEZOMETER No. 5)



D. LOWEST PRESSURE IN SLOT

G. LOWEST PRESSURE ON CURVED CONVERGING WALL

FIGURE 25. PRESSURE CHARACTERISTICS-SLOTS WITH OFFSET DOWNSTREAM CORNERS AND CURVED CONVERGING WALLS

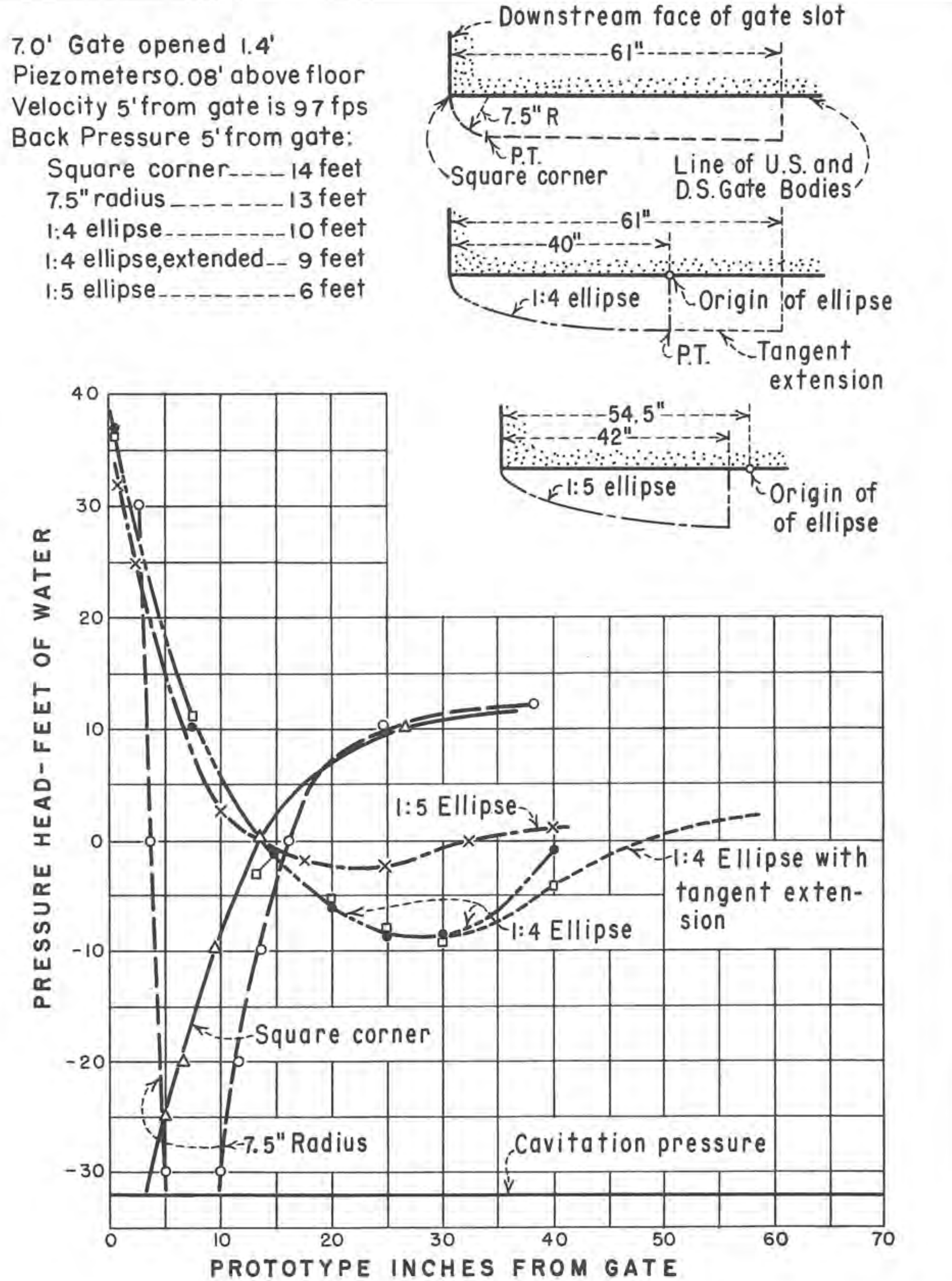


FIGURE 26. PRESSURES ON DOWNSTREAM WALLS ELLIPTICAL SHAPES PROJECTING INTO FLOW

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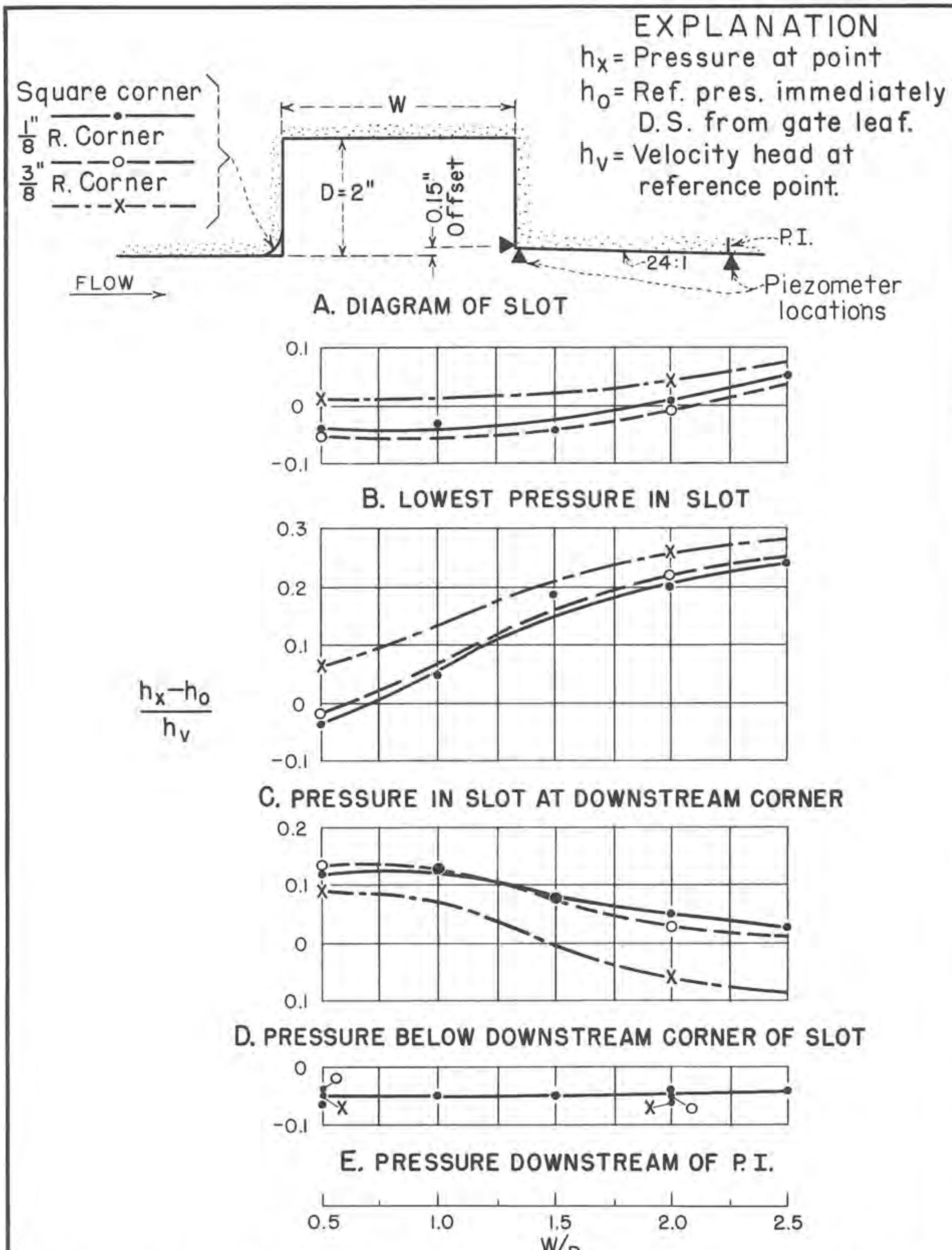


FIGURE 27. PRESSURE CHARACTERISTICS-SLOTS WITH ROUNDED UPSTREAM CORNERS AND OFFSET DOWNSTREAM CORNERS WITH 24:1 CONVERGING DOWNSTREAM WALLS

552

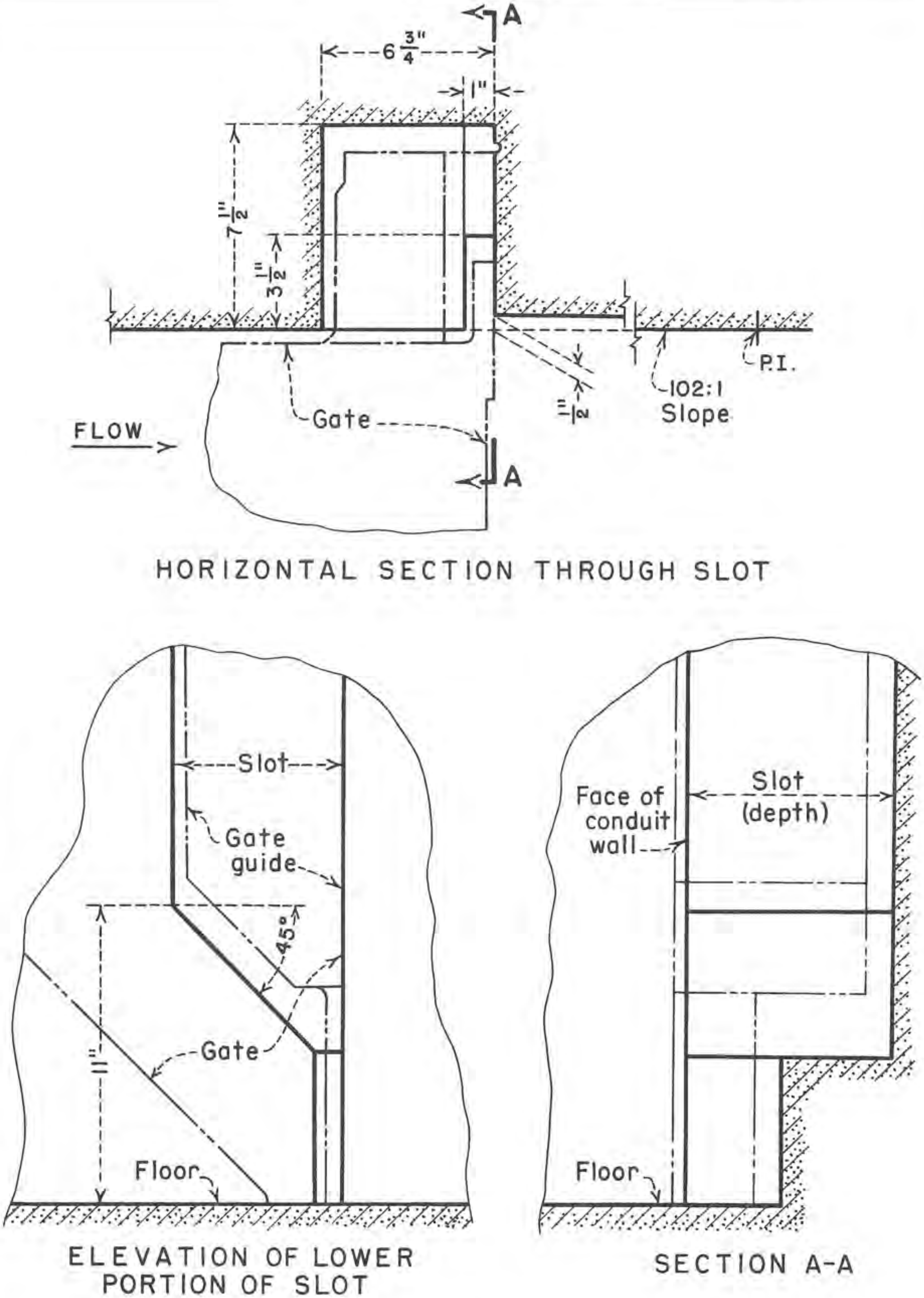


FIGURE 28. SLOT NARROWED NEAR GATE FLOOR

552

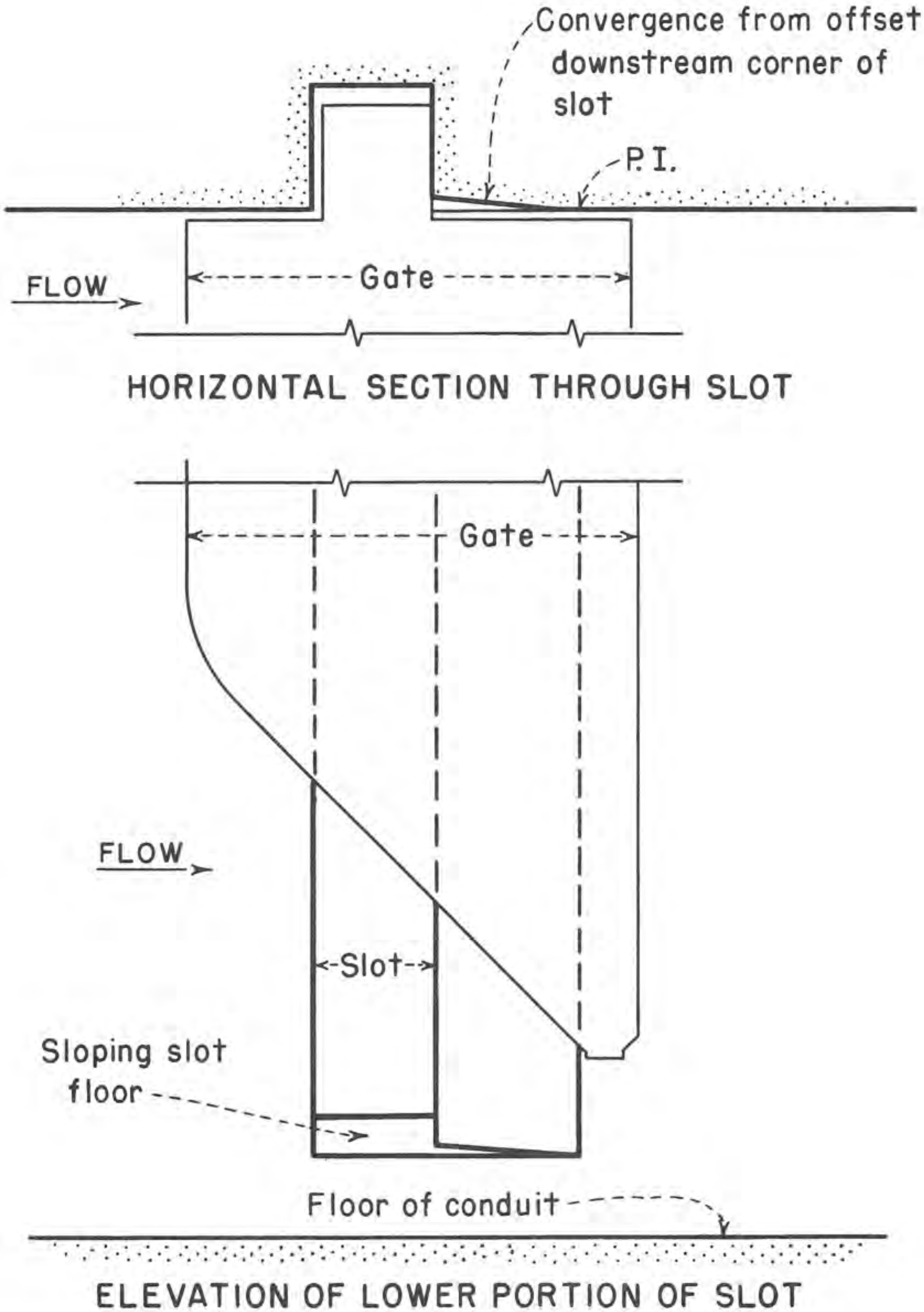


FIGURE 29. SLOT MOVED UPSTREAM RELATIVE TO GATE LEAF

552

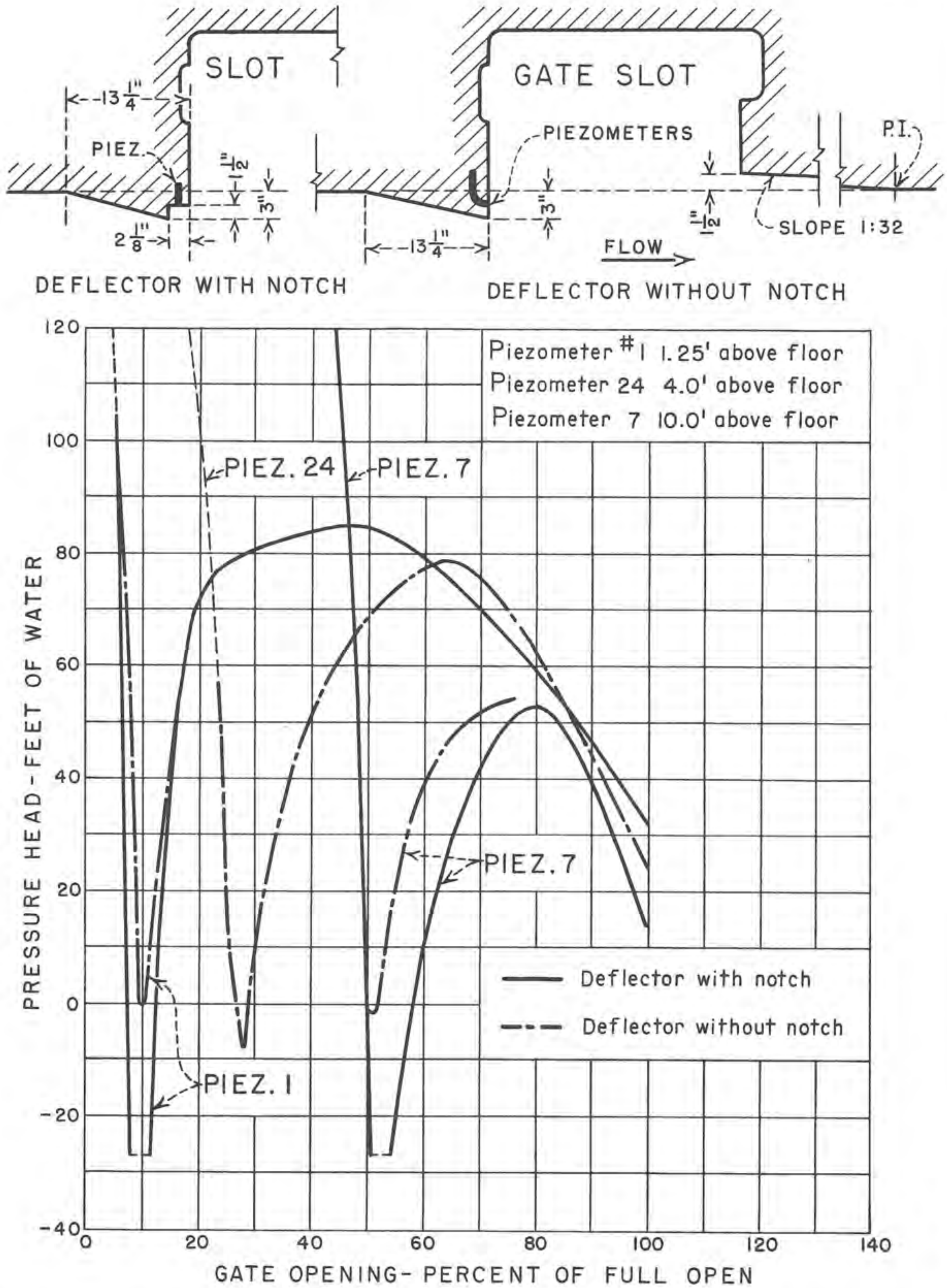


FIGURE 30. EFFECT OF NOTCH IN DEFLECTOR AT UPSTREAM EDGE OF GATE SLOT

552

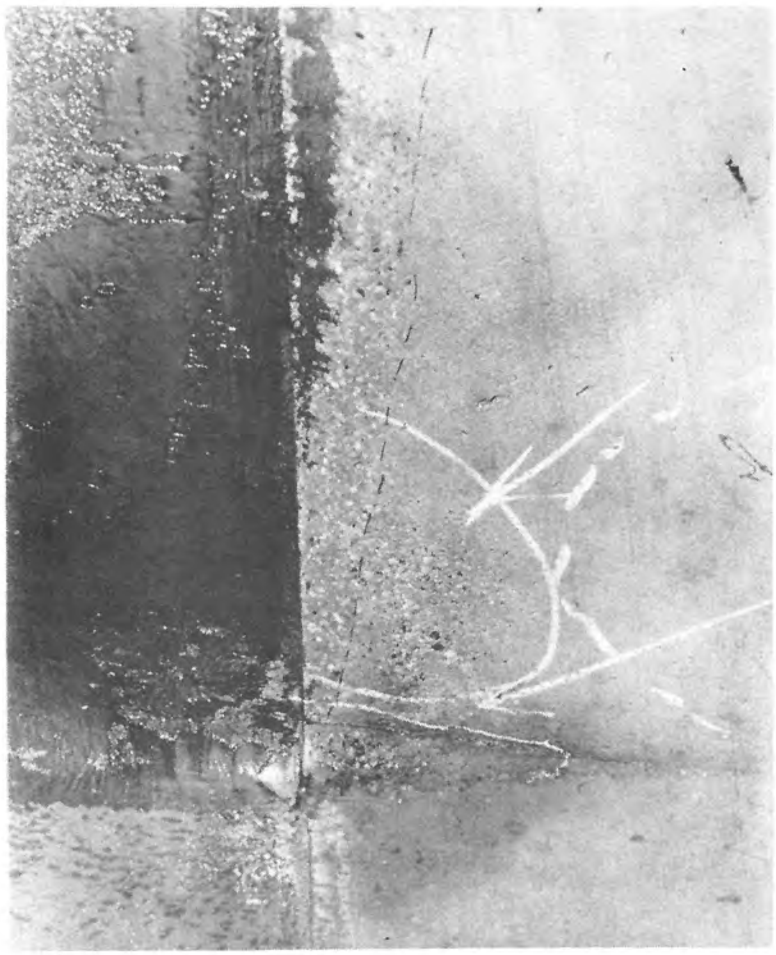
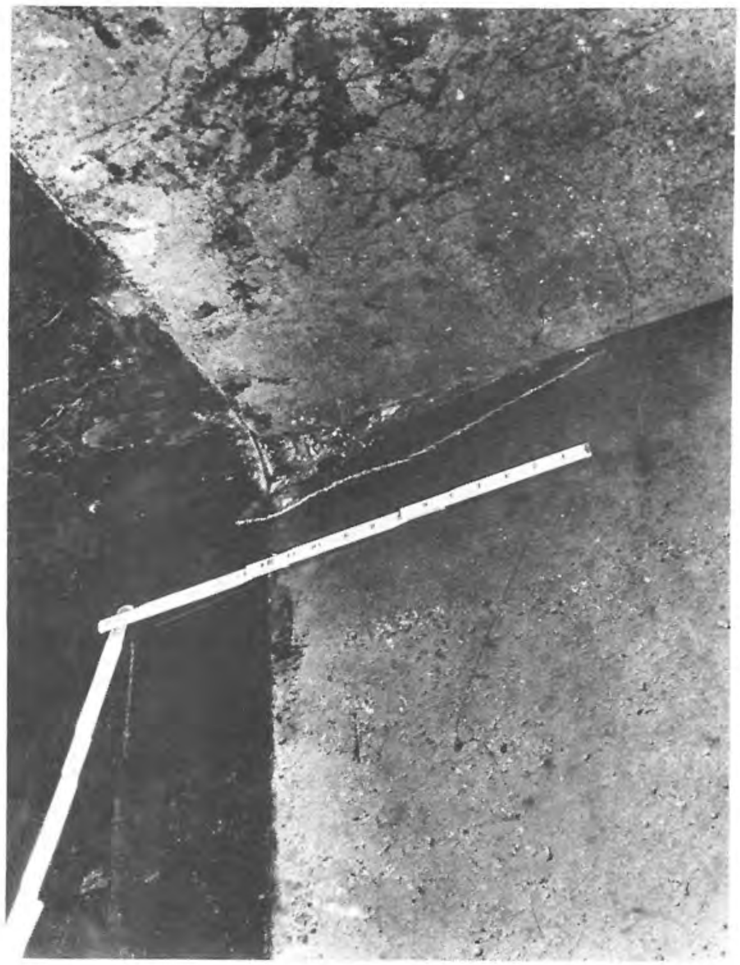


Fig. 31. Cavitation-erosion downstream from ground bevel.

X



up

Fig. 32. Condition at bottom right corner fillet below No. 8 gate frame. 8/15/57

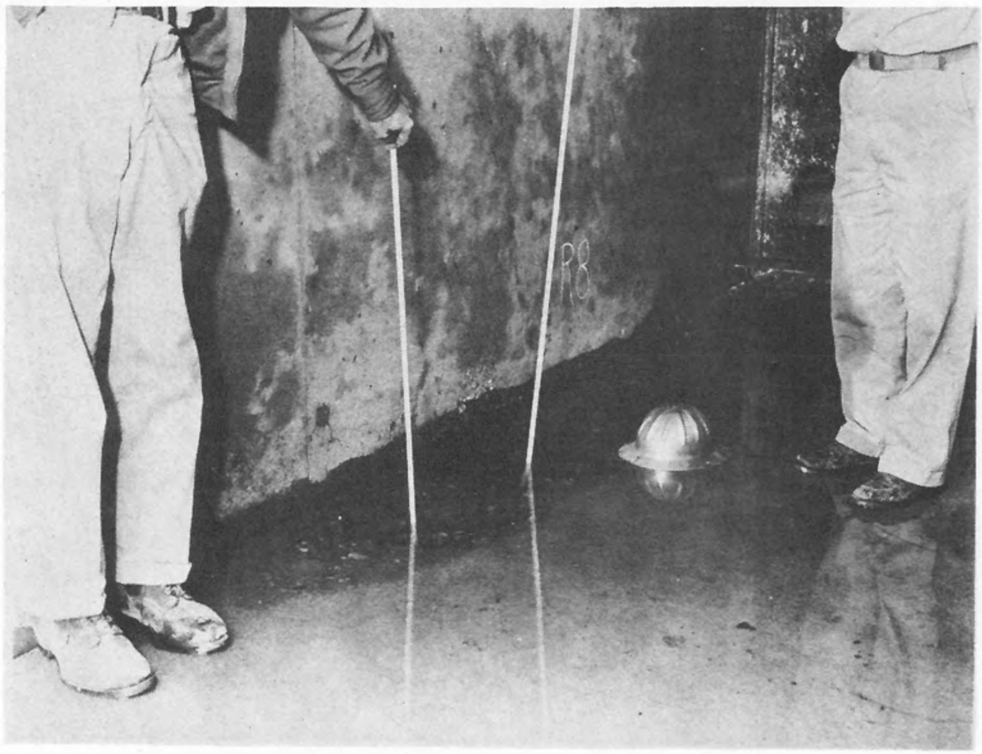


Fig. 33. Cavitation damage at bottom right corner below No. 8 gate frame. 9/17/57

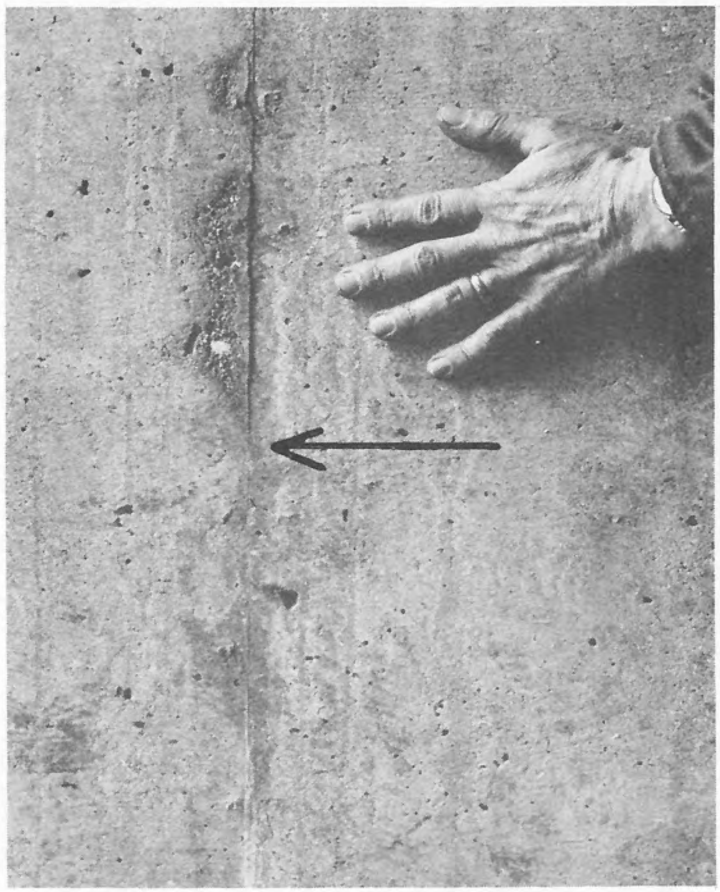


Fig. 34. Cavitation-erosion downstream of 1/8-inch abrupt, into-the-flow offset in concrete wall.

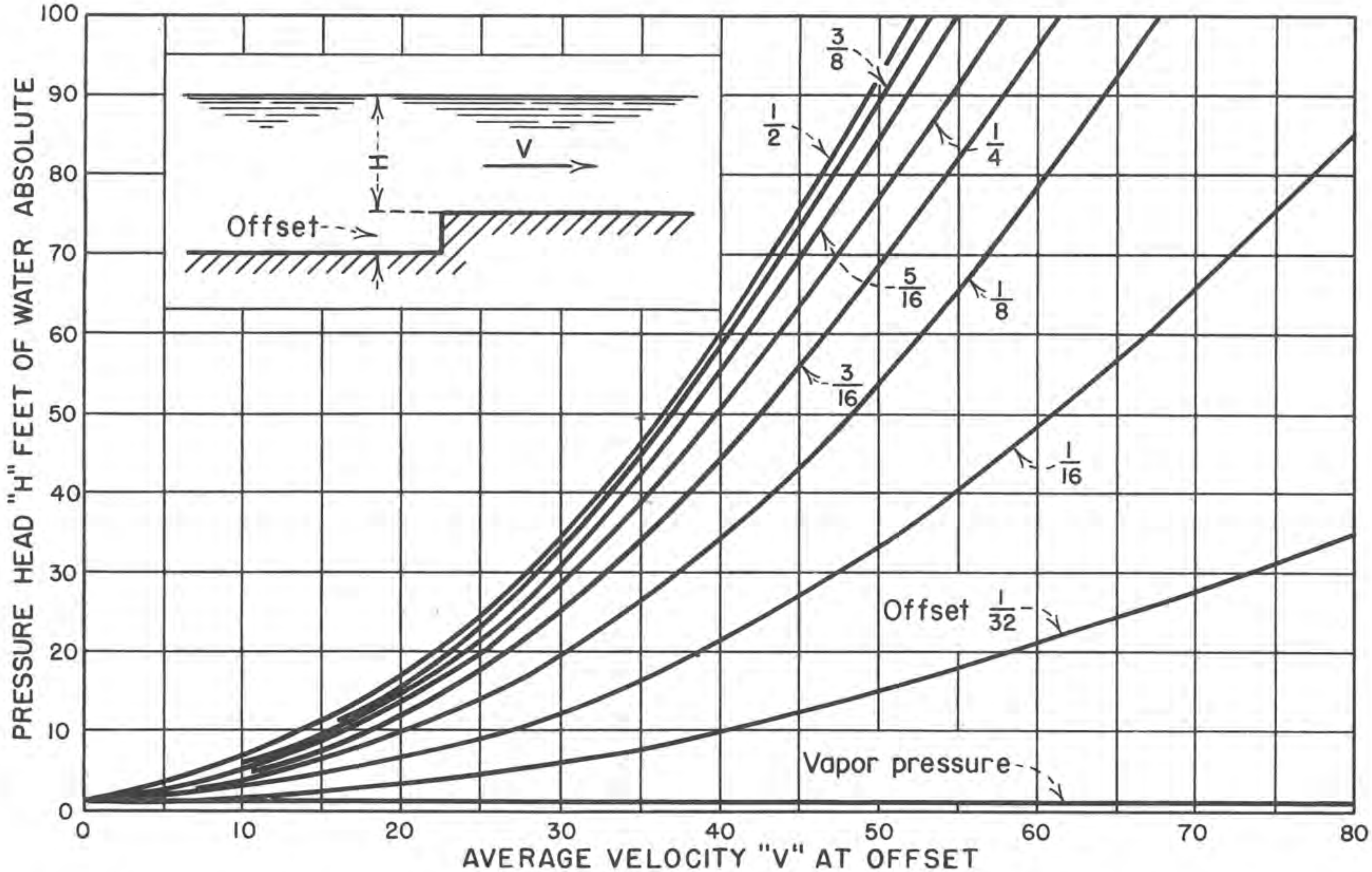


FIGURE 35. HEAD-VELOCITY RELATIONSHIP FOR INCIPIENT CAVITATION—ABRUPT, INTO-THE-FLOW OFFSETS

606

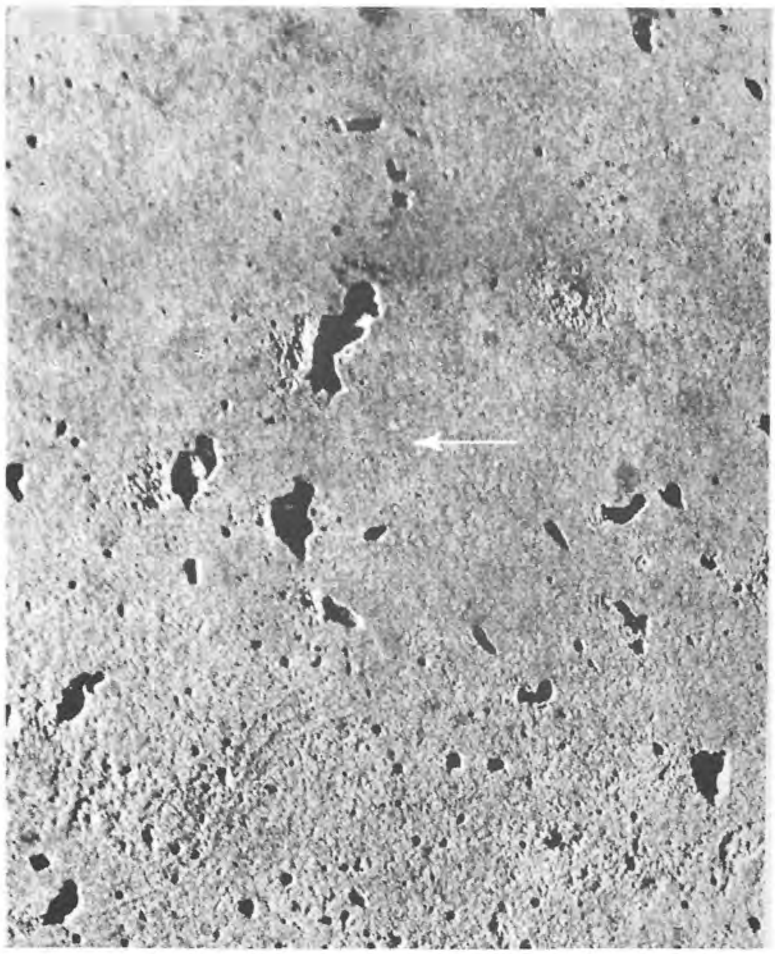


Fig. 36. Cavitation-erosion downstream from "bug holes" in concrete wall.

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