ANALYSIS OF A SKEWED SLOT ORIFICE

A Thesis

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ABSTRACT

The object of this study was to develop design criteria for a skewed slot orifice fishway exit. Using these criteria the fishway exit can be constructed in culvert wingwalls. The outlet would terminate in a skew angle, and be designed to create flow conditions necessary for fish passage.

Values of slot orifice contraction ratios varied from 0.65 to 0.82 of culvert width; culvert slope varied from .015 to .045; skew angles measured varied from 30° to 75°; three lateral positions of the fishway channel were tested. Dimensional analysis was used to determine the significant design parameters. Design curves, displaying the relationship between the backwater ratio, H/h, and the Froude number, are presented.

The design curves and an equation, based on the momentum principle are used to design two types of skewed orifice exits. One problem uses the same contraction ratio for the skewed exit and normal slot orifices placed downstream; the other uses different values of contraction ratio for the skewed exit and normal slot orifices downstream. Necessary criteria regarding suitability of flow for fish passage are also discussed.

CHAPTER I

INTRODUCTION

"Unrestricted passage of fish in streams is essential to the survival of wild fish populations, "Gebhards and Fisher (1972). A segment of Idaho's economy is dependent upon the maintenance and preservation of its fisheries. Unless free access is provided to spawning areas, valuable fisheries could be diminished or lost completely.

To insure successful fish migration to upstream spawning areas it is essential that the velocity of downstream flow in man constructed structures be kept to a minimum. Examples of velocities for various selected slopes for a given discharge in circular and box culverts are reported in the appendix. These velocities are generally much higher than would occur for the same discharge in a natural channel on a similar slope.

Earlier efforts to minimize the velocity within culvert barrels include pool and weir fishways, alternate paired baffles, and offset baffles (Dass, 1970). However, these measures sometimes proved uneconomical and operated unsatisfactorily when operating at other than design head. Hydraulic efficiency is reduced and if the stream carries a heavy bed load, the fishway may fill with material and thus would be ineffective. When baffles are installed in the barrel of a culvert, water will pool upstream of the culvert to a depth necessary to drive the water through the culvert. This backwater could cause overtopping of the roadway fill and damage to the culvert roadway or nearby property. This damage to the culvert and associated structures is primarily due to the rapid scour below the culvert outfall and silt deposition upstream from the culvert.

Dass (1970), in his research of the fish passage problem, proposed a slot orifice fishway. In this design, the exit of the fishway (upstream end of the culvert) would be built adjacent to the culvert barrel, the remainder of the fishway would be constructed within the main culvert barrel. Slot orifices would be evenly spaced inside the fishway passage at regular intervals to the upstream exit. The flow pattern, energy, and momentum concepts were developed and discussed. A sketch of the fishway is shown in Figure 1.

Design criteria for the fishway that were considered include the contraction ratio m, the slope S, the fishway width B, and the slot constriction n. The contraction ratio is defined as a measure of relative constriction imposed on a given channel. It is the ratio of slot opening width to the total fishway channel width. The range of culvert slopes tested ranged from horizontal to five percent. The effect of tailwater on the flow conditions at the fishway entrance was studied and the backwater - discharge relation for the slot orifice also was developed. The purpose of Dass's study was to develop drag coefficients for the vertical slot orifices, and obtain non-dimensional curves, relating the discharge through the entrance orifice to the ratio of the upstream depth to the downstream depth. These were used to solve the design equation (based on the momentum principle) which enables the designer to find the rate and velocity of flow through the fishway. The design procedure required a trial and error solution of two sets of hydraulic relationships. The reader is referred to Dass (1970) for additional details.

Because of economic restraints, it is frequently desirable to terminate the fishway at the skewed wing wall of a culvert. The fishway exit should be constructed at a sufficient distance from the culvert

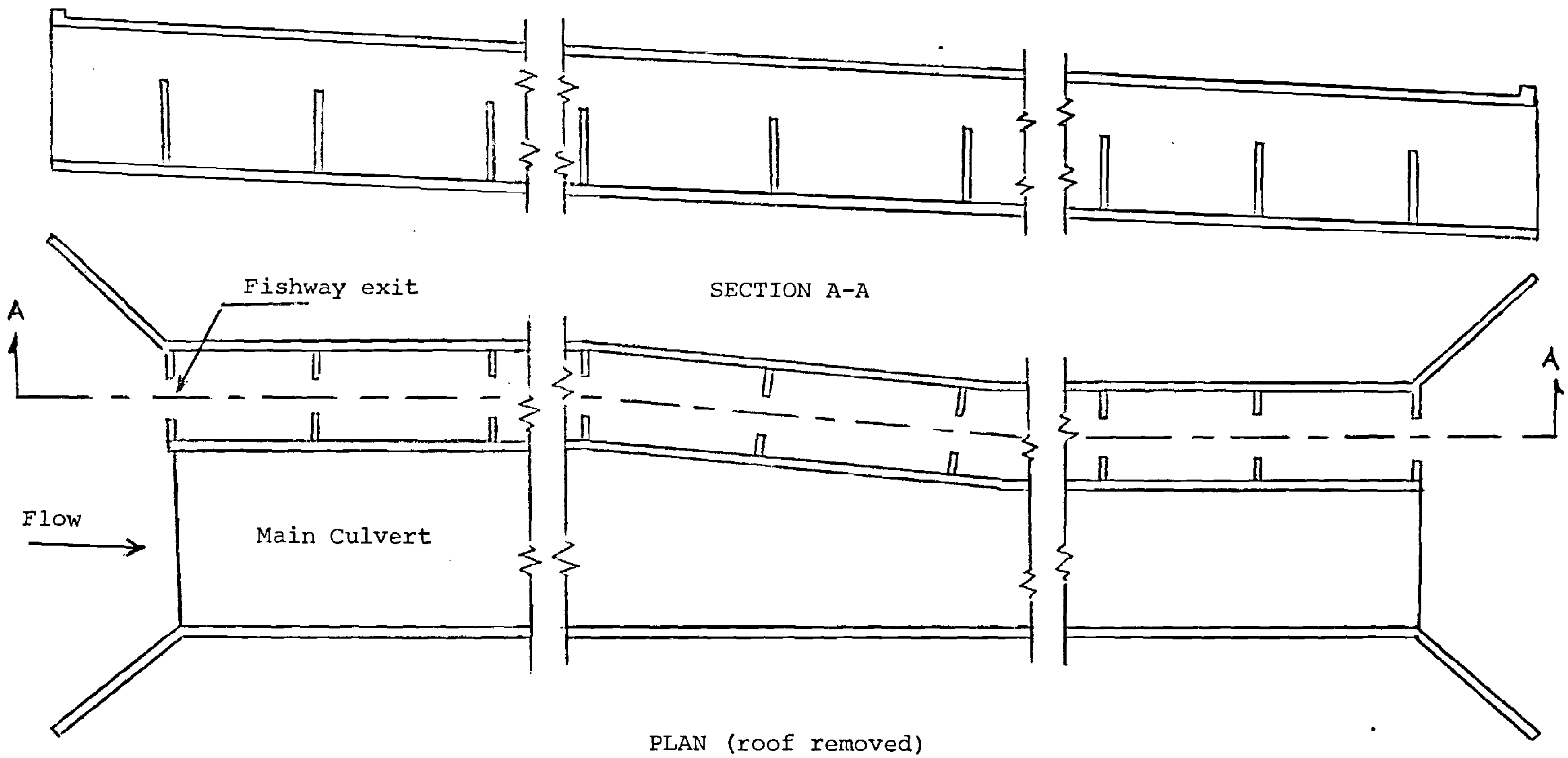


Figure 1. Proposed fishway structure analyzed by Dass (1970).

entrance such that the probability of fish sweepback is reduced.

To analyze the skewed slot, it is necessary to have an appropriate coefficient of discharge for the skewed slot. This coefficient is a function of skew angle, position of slot relative to the culvert side wall and the relative width of the slot (throat width of slot orifice divided by width of fishway).

The purpose of this study is to determine the hydraulics of the fishway exit (water entrance) for a skewed slot orifice exit where the exit is at an angle other than normal to the centerline of the culvert. Figure 2 illustrates this type of fishway. In previous studies of fishway culverts (Dass, 1970) the fishway exit was placed normal to the direction of flow.

The objectives of this study are to:

1. Determine design criteria for skewed slot orifices and complete the development of a design procedure for vertical slot orifice fishways.

2. Determine the coefficient of discharge for a skewed slot orifice experimentally by using a hydraulic model.

3. Prepare design graphs needed for analysis and design of slot orifice fishways.

The basic requirements of the orifice fishway are that the flow should remain subcritical in the entire reach and the maximum velocity at the constricted slot section must be less than the performance capacity of the fish which will use the waterway.

Fish Speed Considerations

Swimming ability (speed) of a fish is a function of its size;

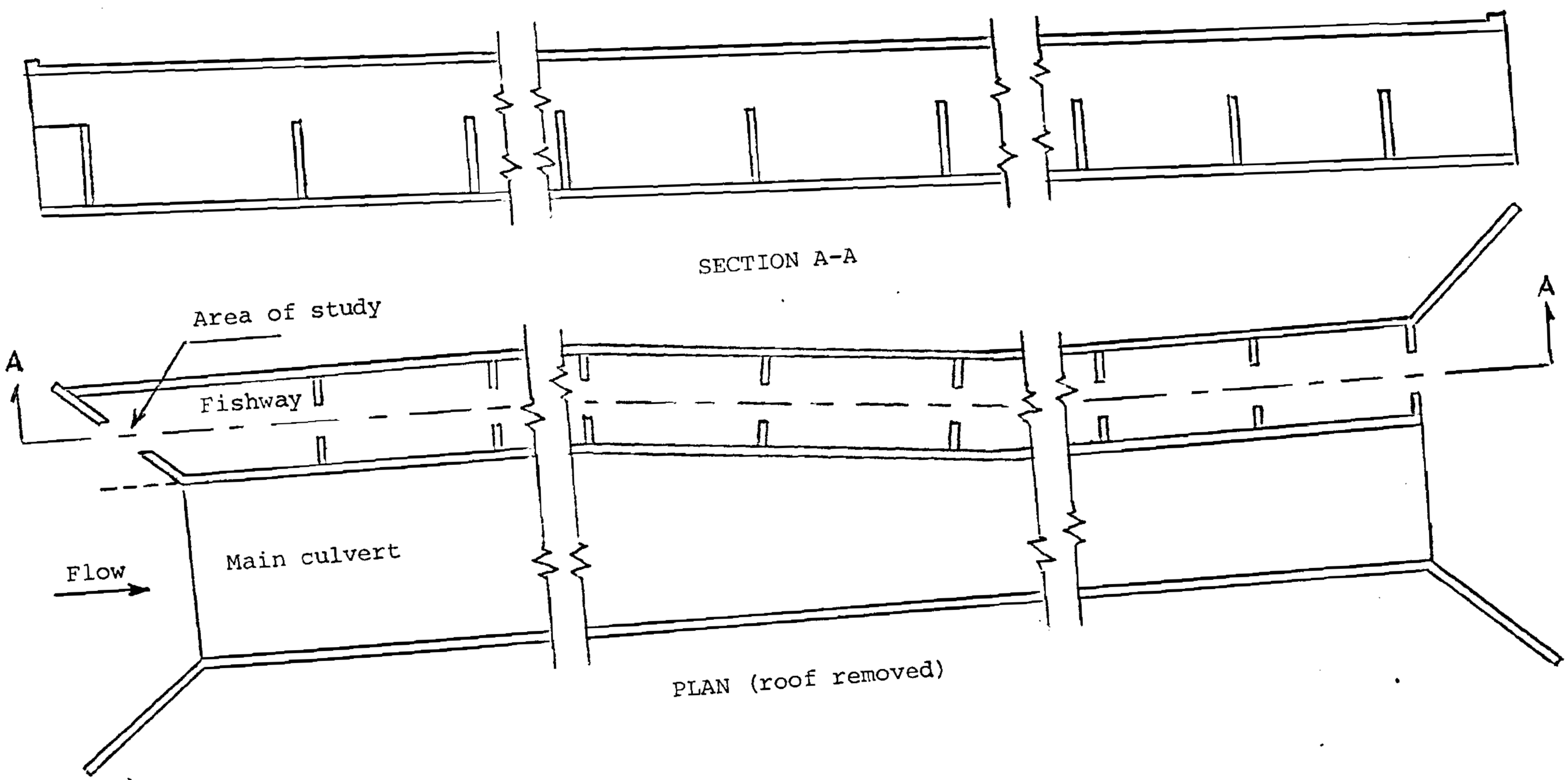


Figure 2. Proposed fishway structure with skewed orifice exit.

the larger the fish, the faster it can swim. Salmonids are capable of burst speeds equivalent to 10 body-lengths per second. A 12-inch trout, therefore, could be expected to reach a burst speed of 10 f.p.s., and a one-inch fish, 0.8 f.p.s. Maximum endurance speeds for salmonids are around four body lengths per second for a period of several minutes, depending upon water temperature, (Gebhards and Fisher, 1972; Blaxter, 1969). Swimming performance may be reduced by high or low temperature pollutants, or low dissolved oxygen.

Ability may also vary between species. Maximum swimming speeds for short distances in excess of 26 feet per second have been recorded for adult steelhead and 22 feet per second for adult chinook salmon (Collins and Elling, 1960). This does not mean that water velocities up to 26 feet per second can be tolerated for steelhead passage. Maximum design velocities must provide for a "fish safety factor" which will allow total or near total passage for a given run of fish. A particular run of fish may consist of three or four age classes with a wide range in fish lengths. The smallest fish, therefore, will set the design criteria, and design velocities should be such that maximum passage is achieved. Controlled experiments testing passage efficiency of salmon and steelhead in water velocities ranging from 2 to 16 f.p.s. showed a velocity of 2 f.p.s. afforded the best passage condition (Collins and Elling, 1960).

At any given water velocity, a fish can be expected to swim for only a given period of time before falling back. Endurance then becomes an important factor in determining proper culvert velocities and length of culvert. A 40 foot culvert with 8 f.p.s. velocity may satisfactorily pass fish whereas one 80 feet long with the same velocity would not (Gebhards and Fisher, 1972).

Fishway Characteristics

To accomodate the satisfactory and effective passage of fish, the fishway should be self-cleaning; i.e., heavy particles must flush from it. The fishway should be efficient with little reduction of flow capacity in the culvert. Stable low velocity flow should exist throughout a wide range of discharge. It should also be simple and economical to construct. The fishway should have its inside orifices arranged such that slackwater areas exist between the slot opening. This allows dissipation of the kinetic energy content of water in each pool and allows a relatively quiescent rest area for the fish prior to each ascent.

The advantage of introducing a skewed slot orifice is primarily to facilitate construction. Since most culverts used for fish passage use angled wingwalls along their upstream exit, it would be comparatively simple and economical to insert a fishway with a skewed exit alongside the main culvert.

Proposed Fishway Structure

A structure which satisfies criteria for the fishway outlined in Section I is shown in Figure 2. This figure is discussed in the following sentences.

1. The fishway exit (upstream end of the culvert) would be constructed outside the culvert barrel. The critical cross section for culverts on steep grades is the entrance section and there would be no

decrease in culvert efficiency. At a distance downstream of the inlet, such that there is no interference to flow entering the culvert, the fishway would enter the culvert barrel and occupy the region adjacent to a wall. The effect of this is to raise the level of flow in the lower culvert reach. However, since this reach is below the contracted entrance section and in the supercritical flow zone, it would not affect the culvert headwater level.

2. The second major feature of the fishway would be the use of vertical slot orifices appropriately spaced throughout the entire length of the fishway. The series of vertical slots extending the full section depth would be effective over a very large range of discharges and would provide a suitable environment for fish passage.

3. The invert of the fishway exit would be set at a slightly lower elevation than the culvert inlet invert, thus all of the low flow would be routed through the fishway. Fish passage could be possible even during very low flows.

4. If degradation is expected at the culvert's lower end, the fishway invert can be constructed to the elevation of expected degradation. The slot orifice should function well throughout a large range of tailwater depths.

5. The orifice fishway could be constructed entirely outside of the culvert barrel. However, it appears that this arrangement would be more costly as considerably more material would be required for the roof and floor. From a construction viewpoint, forming of the roof in place would be impractical.

Design Criteria

Gebhards and Fisher (1972) outlined the design procedures required in Idaho for culvert installation to provide fish passage. They are stated as follows:

1. Gradient of the culvert should not exceed 1/2 of one percent. Gradients in excess of this are acceptable if water velocities within the culvert influence zone do not exceed swimming performances of the species involved during the critical passage period. Velocities can be maintained within fishery standards by use of baffles, controls and separators on gradients up to 5 percent. A fishway (vertical slot orifice) may also be incorporated with a culvert, allowing passage with gradients up to 10 percent (Dass, 1970).

2. The bottom of the culvert at the outfall should be placed six inches below the natural streambed, or as may be required to maintain streambed stability.

3. Minimum depths of water at any point in the culvert shall be eight inches for adult salmon or steelhead. Depths shall vary otherwise, depending upon species and size of fish involved, as recommended by the regional fisheries biologist. It may be necessary to utilize a stop log and separator wall to provide adequate depths during minimal flows.

4. Water velocities should not exceed 8 f.p.s. at any point within the influence zone of the culvert, computed on a ten-year average peak flow. If flow data are unavailable, peak flow shall be estimated by existing high water mark, stream gradient, and other physical data.

These specifications allow for the use of the slot orifice fishway; however, methodology for evaluating the hydraulics (point velocities) of the fishway are not included. The purpose of this experiment and thesis is to provide this design methodology.

CHAPTER II

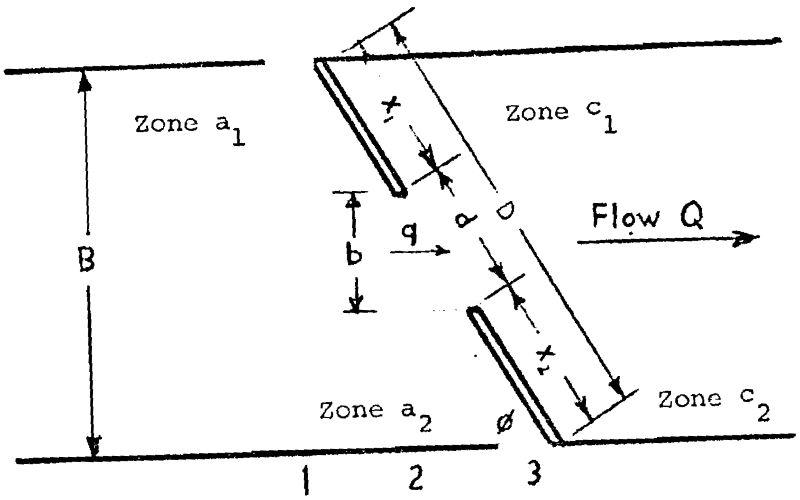
ANALYSIS OF THE PROBLEM

Flow Pattern Description

The successful application of the results from this study to practical field problems will depend considerably on an understanding of the flow field. A plan and elevation view of a skewed slot orifice are shown in Figure 3. The fluid is accelerated when it passes through the slot opening. The beginning of the acceleration zone upstream of the constriction is indicated by a slight decrease in water surface level at a distance upstream from the constriction. This distance is approximately equal to the width of the opening.

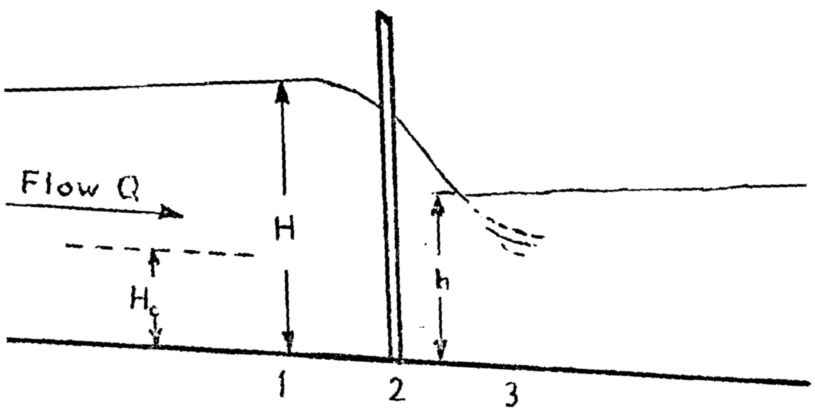
Deceleration occurs along the outer boundary of the culvert wall and a separation zone is created in the corner adjacent to the constriction (Zone a_1). This separation zone is considerably smaller for the skewed angle entrance than for the normal angle entrance. A stagnant zone occurs alongside the constriction face due to the divergent streamflow paths as most of the flow is directed toward the main culvert barrel (Zone a_2). This phenomenon would obviously be greater for a skew angle of 30^o, for example, than for a skew angle of 75^o, where conditions would approach that of a normal opening.

Water from the sides enters the opening as a sharply curved and contracting stream, thus indicating that it is being accelerated in directions both normal and parallel to the streamlines. Just as the longitudinal acceleration and the consequent negative pressure gradient are reflected as a drop in the longitudinal profile, the normal acceleration



PLAN

Figure 3a.



ELEVATION

Figure 3b.

Figure 3. Flow profile parameters for a skewed slot orifice.

accounts for a considerable difference in level between outside filaments of flow and the central filaments of flow. Considerable energy is used to carry the flow filaments through the opening from the culvert barrel side (Zone a_2).

As the water passes through the constriction, the contracted stream approaches a minimum width at Section 2 which corresponds to the vena contracta in orifice flow. The flow is bounded here by an eddying body of water, which marks a second separation zone (Zone c). For the skewed orifice, this eddy is greater on the outer boundary of the fishway (Zone c_1). The stream passes through the constriction normal to the orifice face. The stream is immediately dispersed inside the constriction for a high skew angle.

Expansion of the live stream begins at the vena contracta and ends at the section downstream approximately equal to five times the slot opening. Here the live stream again covers the full width of the channel section. This phenomenon is similar in both the normal and the skewed orifice. The amount by which the jet issuing through the slot is drowned by the "dead" water on each side adjacent to the orifice, depends on the flow rate, channel slope, slot spacing further downstream extent of constriction, and tailwater depth. It also depends on the skew angle, and occurs at a shorter distance from the constriction face for a greater skew angle.

The upper portion of the water jet may be free of side effects for a considerable distance, issuing initially as a vertical sheet, with appreciable surface slope. In this particular case the cross section undergoes considerable change in form between Sections 2 and 3, developing a flange at the top surface which broadens as the surface height decreases and loses its identity in three-dimensional flow. For the skewed orifice, this phenomenon occurs more rapidly toward the outer surface of the fishway (Zone c_1). Depth H was observed to be quite stable, with little fluctuation of the water surface.

Flow through a slot orifice constructed normal to the flow direction has been well described by Dass (1970) and Kindsvater (1955). This study verified the conditions described in the previous paragraphs for a skewed slot orifice fishway exit.

Momentum Concepts

Dass (1970) derived and applied the momentum equation for the hydraulic analysis of slot orifice fishways. The momentum equation and experimental data were used in his study to evaluate the drag coefficients necessary for the solution of the design equation. The drag coefficients deduced can be used by the designer to find the rate of flow through slot orifice fishways. The work performed by Dass will be summarized in the following paragraphs.

According to the momentum principle, the change of momentum in the body of water in a flowing channel is equal to the resultant of all the external forces that are acting on the body. This principle was applied to a channel of small slope. The expression for the momentum change for the body of water between sections 1 and 2 of Figure 4 can be written as

$$\frac{Q\gamma}{g}(V_2 - V_1) = P_1 - P_2 + W\sin\theta - F_{fr} - F_{or} \qquad [1]$$

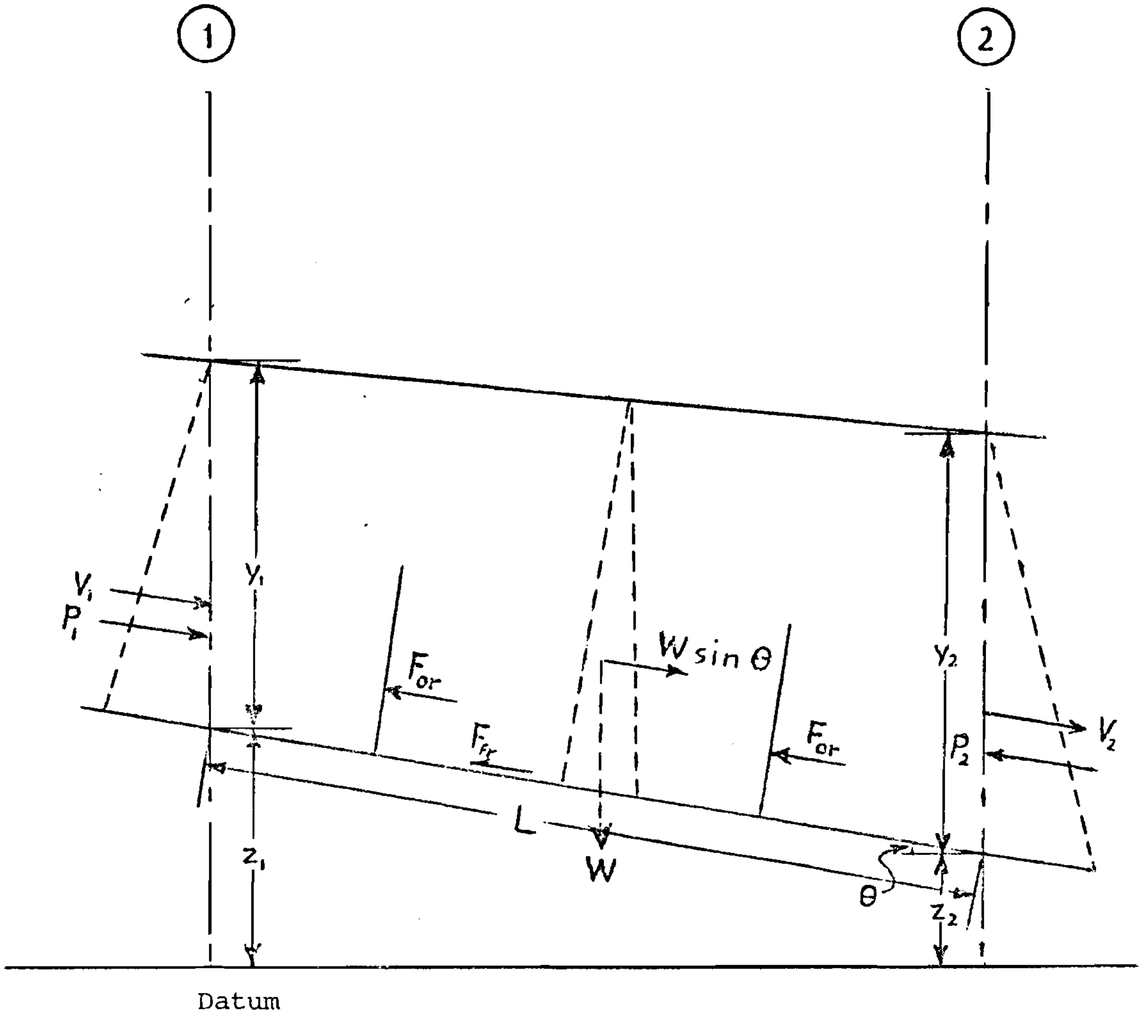


Figure 4. Definition sketch for application of the momentum principle.

Subscripts refer to Sections 1 and 2 in Figure 4; P_1 and P_2 are the pressure resultants acting on the two sections; w is the weight of water enclosed between the sections; F_{fr} is the total external friction force acting at the surface of contact between the water and channel; F_{or} is the force acting on the orifices.

Dass assumed a hydrostatic pressure distribution and gradually varied flow. The slope was considered small, the channel was assumed to have constant width, and the term F_{fr} was considered a function of the number of slots between Sections 1 and 2 and the amount of contraction in each slot.

The weight of water between Sections 1 and 2 was obtained by multiplying the average depth of water between the entrance and exit orifices by the length of the fishway. The reader is referred to Dass's work for details.

Dass substituted the drag force equation, $F_d = \frac{1}{2}\rho\, C_d\, Av^2$, into the design momentum equation. (The term C_d represents a dimensionless coefficient of drag associated with the slot orifices). The term F_{fr} in Equation (1) can be replaced by an expression similar to the one given for F_d.

After summing the drag forces associated with each orifice, the final design equation for the slot orifice fishway was given as

$$m\, C_d \sum_i \frac{1}{y_i} = 2\left(\frac{1}{y_1} - \frac{1}{y_f}\right) + \frac{g\, B^2}{Q^2}\left(y_1^{\,2} - y_f^{\,2}\right) + \frac{g\, B^2\, N\, n\, S}{Q^2}\left(y_1 + y_t\right) \qquad [2]$$

where y_1 = initial water depth above first slot orifice, or downstream depth below the skewed fishway exit orifice,

y_f = water depth below the last slot or upstream of the tailgate, and y_t = tailwater depth.

To design a slot orifice fishway with a skewed orifice entrance, the momentum equation must be combined with rating equations developed in this study for the skewed orifice exit. The design procedure for a fishway will be described in a later section.

Dimensional Analysis

It is required to select the variables which have a major role in influencing the flow pattern through the skewed slot orifice. All significant variables which appear to apply to this problem will be examined. Dimensional analysis will be used to generate the appropriate parameters to be included in the final equations and curves for use by the designer.

Selection of Variables

The variables selected and illustrated in Figure 3 are sufficient to describe the flow characteristics. Q denotes the total discharge; B is the width of the channel; b denotes the width of the opening; H is the water level upstream of the constriction; h is the water level downstream of the constriction and g is the gravitational constant.

The selected variables can be assembled in a functional relationship,

$$f_1 \; (Q, d, B, H, h, e, s, \phi) = 0. \qquad [3]$$

They can be combined by methods of dimensional analysis into a mimimum number of significant ratios,

$$f_2 \; \left(\frac{Q}{B\,H\,\sqrt{g\,H}}, \frac{d}{D}, \frac{H}{h}, e, s, \phi \right) = 0. \qquad [4]$$

The first ratio is known as the Froude number and is discussed in the following paragraph. The second ratio is representative of the geometric properties of the boundary. The third ratio is a depth measurement parameter relating the headwater to tailwater on either side of the constriction. The parameter e is the eccentricity of the orifice, s is the slope of the channel and ϕ is the skew angle. The significance of these parameters is described in the next sections.

Froude Number

The flow pattern in the vicinity of an open channel constriction is influenced by the physical properties of water, the rate of flow and the shape of the constriction and adjacent channel reaches. For the purpose of this study, the influence of fluid weight is assumed to be the dominant characteristic among the physical forces that govern the motion. The two properties that apply in this particular case are inertial forces and gravity forces. These forces can be combined to form a critical flow parameter. This dimensionless parameter, which is a ratio of inertial forces to gravitational forces, is known as the Froude number, F. It is expressed as:

$$F = \frac{V}{\sqrt{g\, H}}, \qquad [5]$$

V is the mean velocity of flow and H is a significant depth.

Because only tranquil flows have been considered in this study, the Froude number is always less than unity, or subcritical. (If $F = 1$, the flow is critical, and if $F > 1$, the flow is supercritical.) The velocity and unit discharge are limited to comparatively narrow bounds because the range of depth is fixed by arbitrarily defined, normal, natural channel conditions.

From the principle of continuity, $V = Q/BH$; thus the Froude number can be expressed by

$$F = \frac{Q}{BH\sqrt{g\,H}} ;$$

or

$$F = \frac{Q}{\sqrt{g}\,BH^{3/2}} . \qquad [6]$$

It is noted that, for any given form of boundary, the configuration of the free surface is a unique function of the Froude number of the contracted stream, that is the discharge coefficient is a constant for any given boundary and value of the Froude number.

Channel Contraction Ratio

The width ratio, d/D, has been used by previous authors as a convenient measure of boundary geometry. For a rectangular cross section, this ratio is proportional to an area ratio. With a uniform velocity distribution across the section, this ratio is also equivalent to a discharge ratio. If the ratio q/Q is substituted for d/D, however, q/Q is seen to possess a greater significance. As illustrated in Figure 3, q is that part of the total discharge Q which occupies an area of width d in the total cross section upstream from the constriction. To extend this definition to the general case, q is defined as the normal discharge capacity of the channel having area characteristics of the opening. As ordinarily defined the "contraction ratio" is a measure of the relative constriction imposed on a given channel. Therefore, if m is defined as the channel-contraction ratio,

$$m = 1 - \frac{d}{D} = \frac{D - d}{D} , \qquad [7]$$

$$\text{or } m = 1 - \frac{q}{Q} = \frac{Q - q}{Q} . \qquad [8]$$

A significant physical interpretation of the channel-contraction ratio is suggested by the last term in Equation [8]. That is, m can be interpreted as a measure of that part of the total flow which enters from the sides into the contracted stream.

For this study, $m = 1 - \frac{d}{D}$ is used to represent the geometric properties of the boundary.

Slope

The slope, S, is dimensionless and represents the longitudinal slope of the fishway.

Eccentricity

The degree of eccentricity, represented by the ratio e, is defined as the ratio of the length x_1 of the shorter obstruction to the length x_2 of the longer obstruction. This may be expressed as:

$$e = \frac{x_1}{x_2} . \qquad [9]$$

Figure 3a illustrates eccentricity. The degree of eccentricity will have a value between zero and unity.

Skewness

The skew angle or angularity, ϕ, is defined as the acute angle between the plane of constriction and a line parallel with the thread of the stream passing through the culvert.

General Discharge Equation

The functional relationship for the coefficient of discharge becomes

$$f_3 \left(F, \frac{H}{h}, m, S, e, \phi\right) = 0; \qquad [10]$$

or if F is selected as the dependent variable,

$$F = f_4 \left(\frac{H}{h}, m, s, e, \phi\right). \qquad [11]$$

These parameters will be examined experimentally to determine which have a significant effect on the design of fishways.

CHAPTER III

APPARATUS

Flume Description

The studies were performed in a recirculating tilting flume located in the hydraulics laboratory at the University of Idaho. A low volume centrifugal pump in series with an air activated regulating valve and electromagnetic flow meter delivered the flow to the flume headbox. The tilting flume is 24 feet in length and 1.5 feet (18 inches) wide with transparent side walls 2 feet high. The slope of the flume is adjustable from -3% to +5% with a hydraulic mechanism. The slope of the flume was determined by conventional leveling procedures (Figures 5 and 6).

Model Details

The details of the hydraulic model are shown in Figures 5, 6 and 7 and a detailed drawing is shown in Figure 8. The model consists of the main culvert barrel and the orifice fishway. An 8-3/4 inch wide culvert was constructed on the right half of the flume. A 9 inch wide fishway was provided on the left half of the flume, separated by a 3/4 inch thick plywood wall. This model represents one-half of the entire culvert dimensions, symmetrical about the centerline.

Four different slots were placed at the fishway exit. The slots were fabricated from .051 inch thick galvanized sheet metal 8 inches high. The slot widths examined were 1.16 inches, 1.36 inches, 1.82 inches, and 2.22 inches. These slot widths correspond to contraction ratios of 0.82, 0.79, 0.72, and 0.65, respectively. Water pressure held the slots in

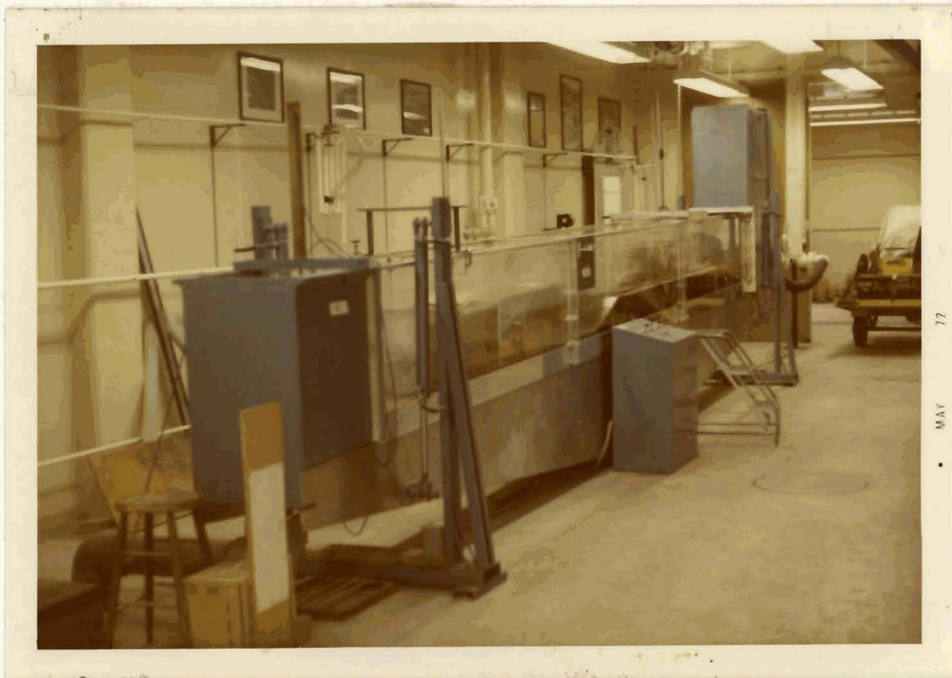


Figure 5. Tilting flume with fishway culvert and accessories.

Figure 6. Main culvert and fishway.

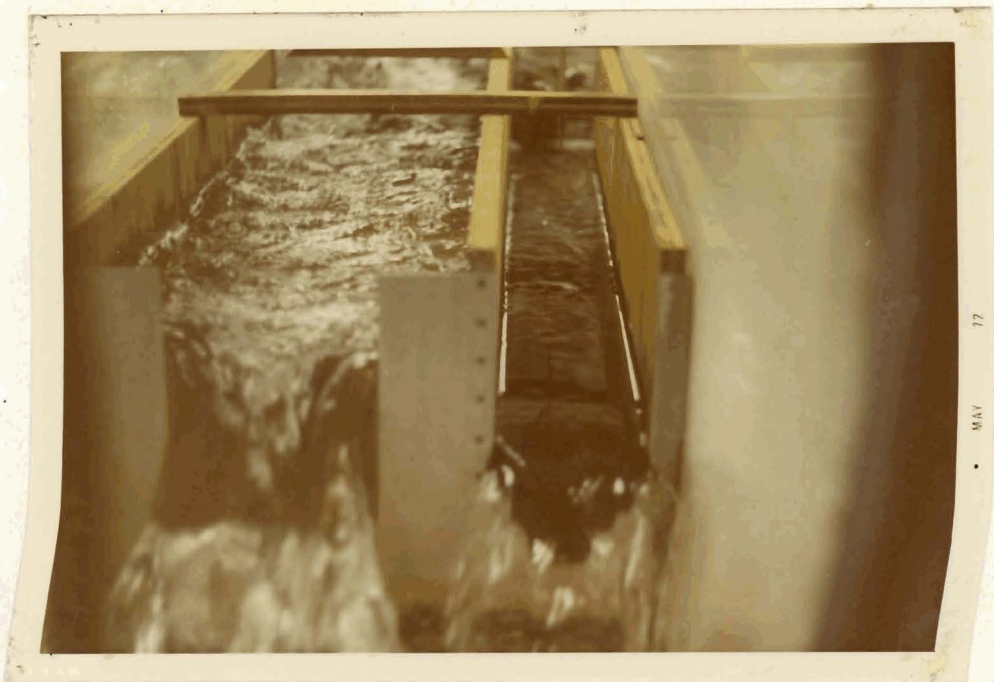


Figure 7. Measuring Weirs.

Width of Flume = 18 1/4"

Length of study reach from upper slope change to lower slope change = 103"

All plywood 3/4" exterior grade

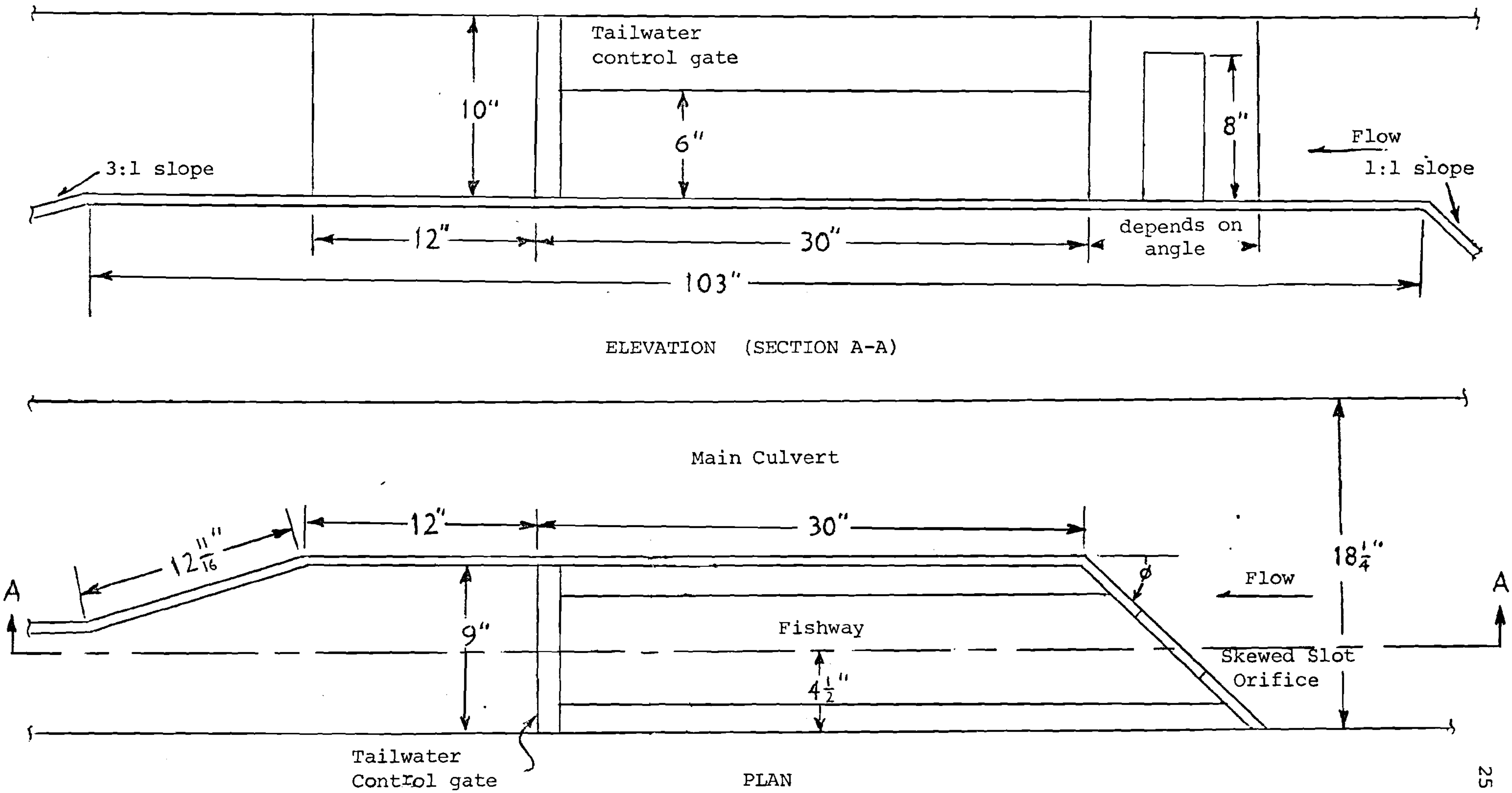


Figure 8. Details of Fishway Culvert Model.

place for the tests.

A slotted strip gate was constructed at the extreme downstream end of the fishway. Metal plates of variable area were placed across the gate to regulate tailwater depth.

Fishway widths were 3-1/4 inches, 4-1/2 inches, 5-1/2 inches, and 6 inches for skew angles of 30, 45, 60, and 75 degrees, respectively. Filler boards of varying widths were attached to the fishway sides to obtain the appropriate widths (Figures 11 to 15).

This entire assembly rested on a 7 inch high wooden frame. The purpose of this was to elevate the culvert sufficiently so that tailwater from the measuring weir would not affect flow through the flume; thus the hydraulics of the fishway were not affected by the downstream measuring weir. To provide a smooth transition, the upstream face of the assembly was tapered to a 1:1 slope and the downstream face was tapered to a 3:1 slope. Enough clearance was provided between this frame and the sides of the flume to accommodate any wood expansion.

Discharge Measuring Device

Culvert and fishway flows were kept separate by a dividing wall between the channels. Flow passing through the fishway was channeled through a stilling basin and was measured by a sharp edged V-notched weir. The weir arrangements inside the flume are shown in Figure 7. Dimensions are shown in Figure 10. Because of the slope ranges covered in these experiments, it was necessary to correct point gage measurements taken upstream of the weir. This technique is illustrated in Figure 9. It is important to note that the point gage was mounted in the channel itself. Thus, the point gage reading corresponding to Point C when the

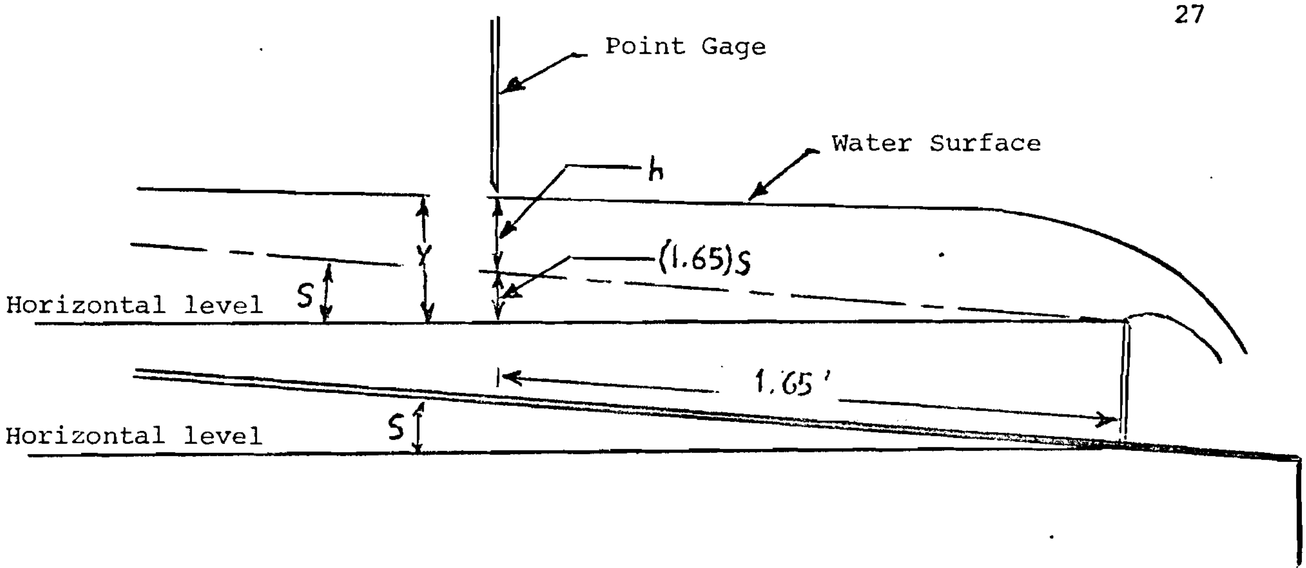


Figure 9. Slope correction for head over a weir.

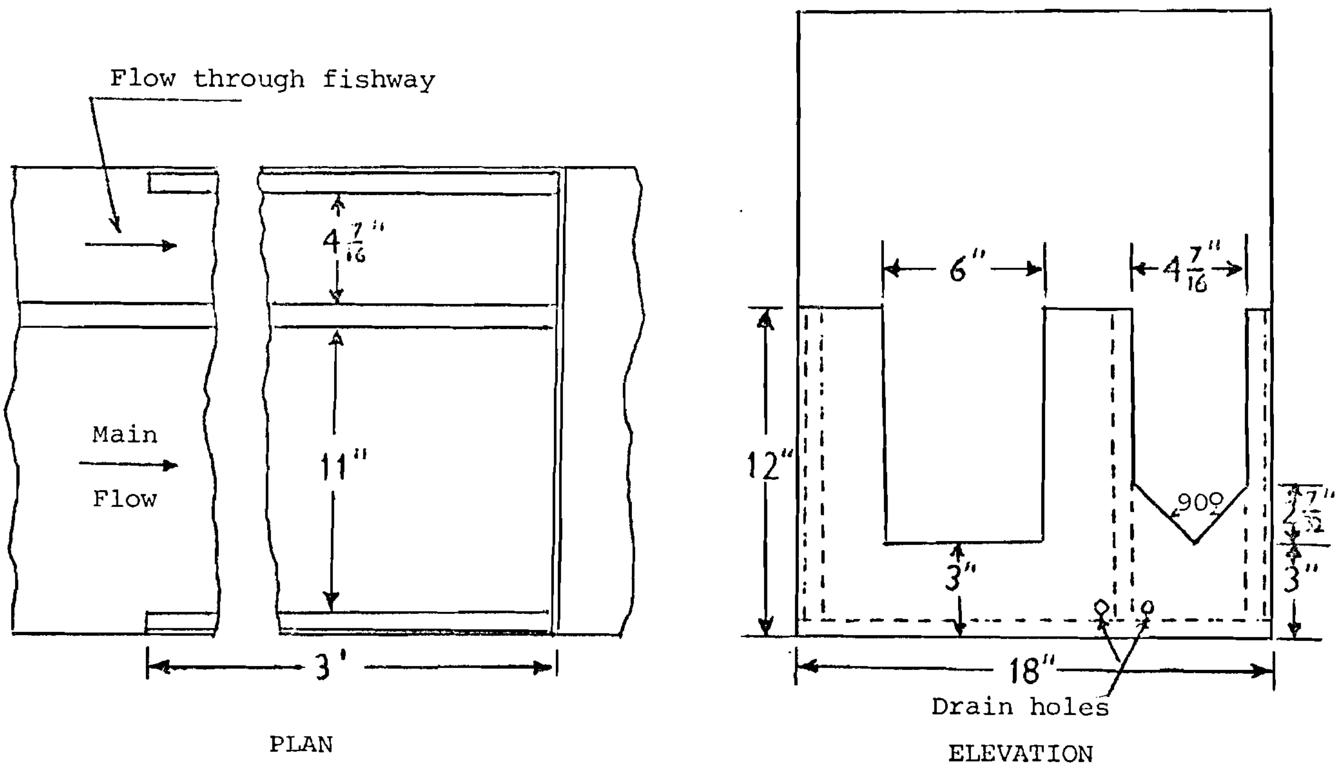


Figure 10. Details of measuring weirs.

Figure 11. Skewed slot orifice exit for fishway. Plan and elevation view. $\phi = 45^{o}$.

channel was horizontal remains the same for Point A in a sloping channel. The depth d can be measured by the point gage and the correction (1.65) S is added to this value to obtain the net static head. The volume of flow through the fishway was obtained from the weir rating curve.

Another point gage was located at the skewed slot orifice fishway exit to measure water depth both above and below the slot. These data were used to compute the ratio of water depth, H, above the orifice to water depth, h, below the orifice.

All readings of H and h were converted into feet. For each set of data, the Froude number was computed and the ratio H/h was obtained. Altogether 720 readings were obtained in this study. Typical data sheets are shown in the appendix.

CHAPTER IV

PROCEDURE

The purpose of the first set of runs was to examine the operating characteristics of the skewed slot orifice entrance and to ascertain which of the dimensionless parameters were significant. The initial observations were performed with a skewed angle of 45°. Data was obtained with four different contraction ratios: .65, .72, .79 and .82. Four different slopes were observed: .015, .025, .035 and .045. Three different fishway positions were also observed. In addition to the center location, the fishway location was also translated one inch to the left and one inch to the right. This corresponds to an eccentricity of .484 for each of the right and left positions. Figures 12 to 15 show the various configurations which were examined. The data collected for different slopes and positions of the fishway model were examined to determine if slope and position would be important factors along with angles and contraction ratios in the final design rating curves.

The water depth, H, above the orifice was held constant while the water depth, h, below the orifice was established systematically at six different levels. Readings were obtained for the floor and water surface in the fishway and subtracted from each other. Four readings were obtained, two immediately upstream and two immediately downstream of the slot orifice. Locations of these measuring points are illustrated in Figure 16. The results were then averaged. Weir measurements for obtaining discharge were also obtained. The purpose of obtaining six different levels of h while holding H constant was to obtain different

B = .270 ft = 3.25 in.

e = .484

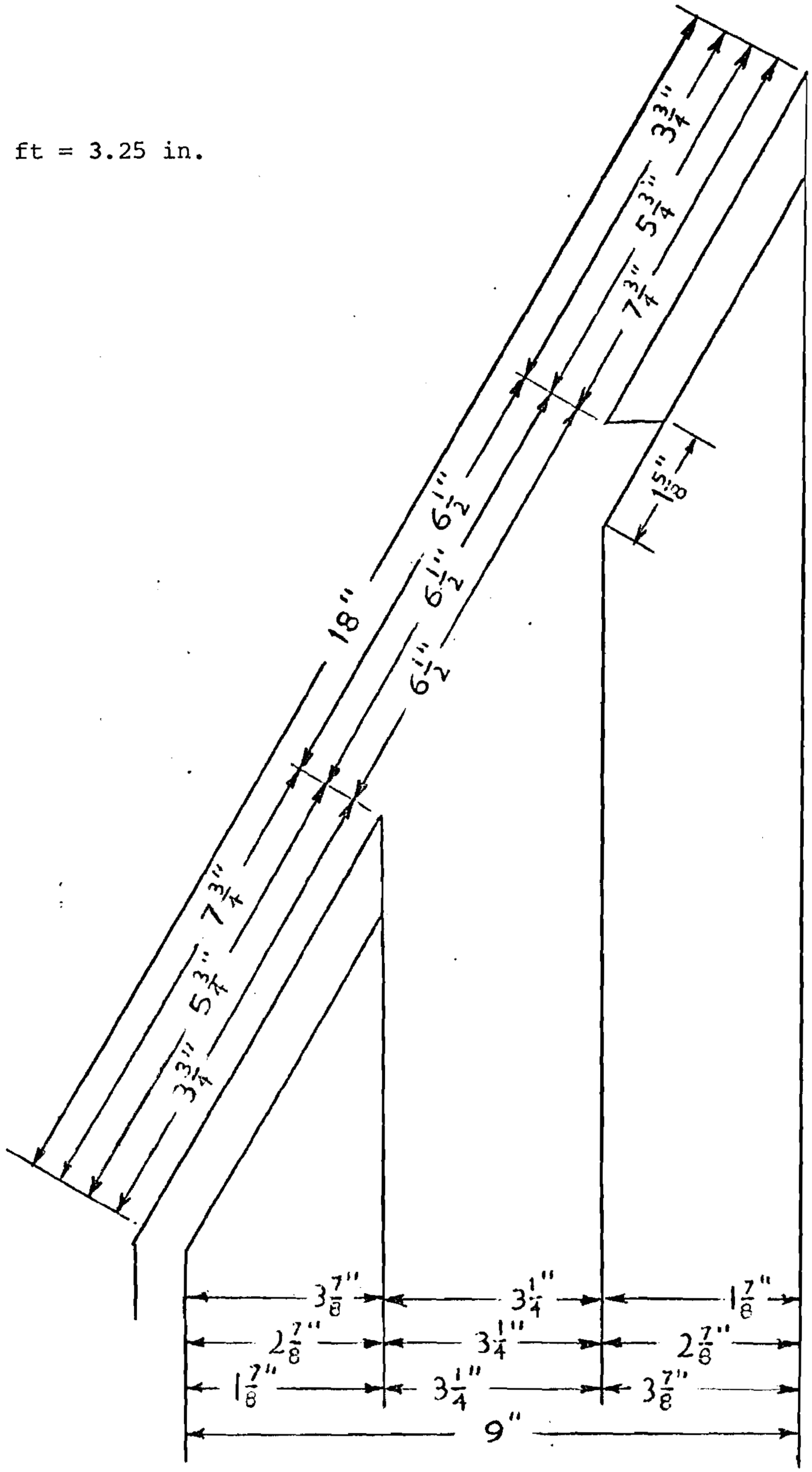


Figure 12. Dimension details for
30° skewed slot orifice.

B = .375 ft = 4.50 in.

e = .385

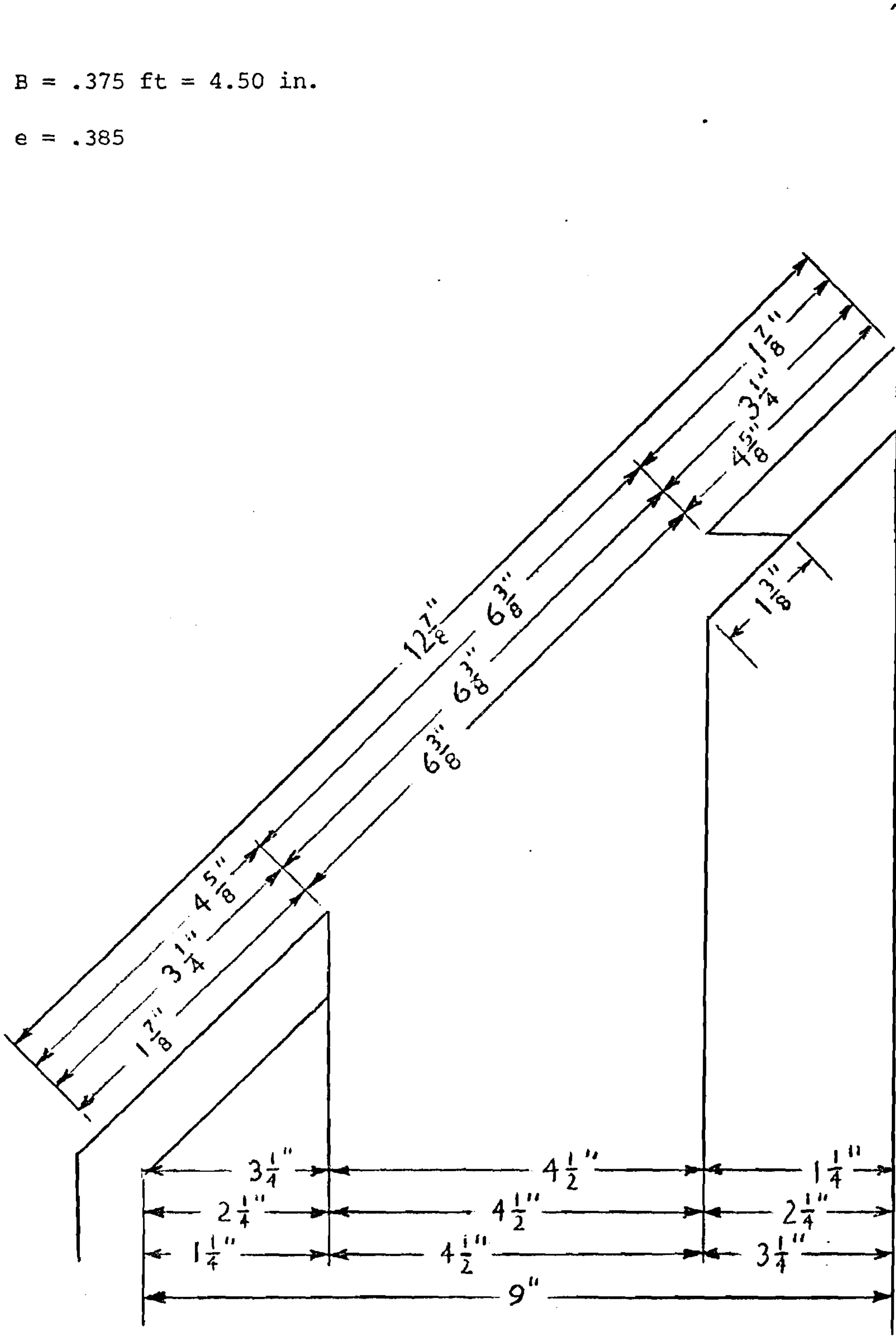


Figure 13. Dimension details for 45° skewed slot orifice.

B = .460 ft = 5.50 in

e = .273

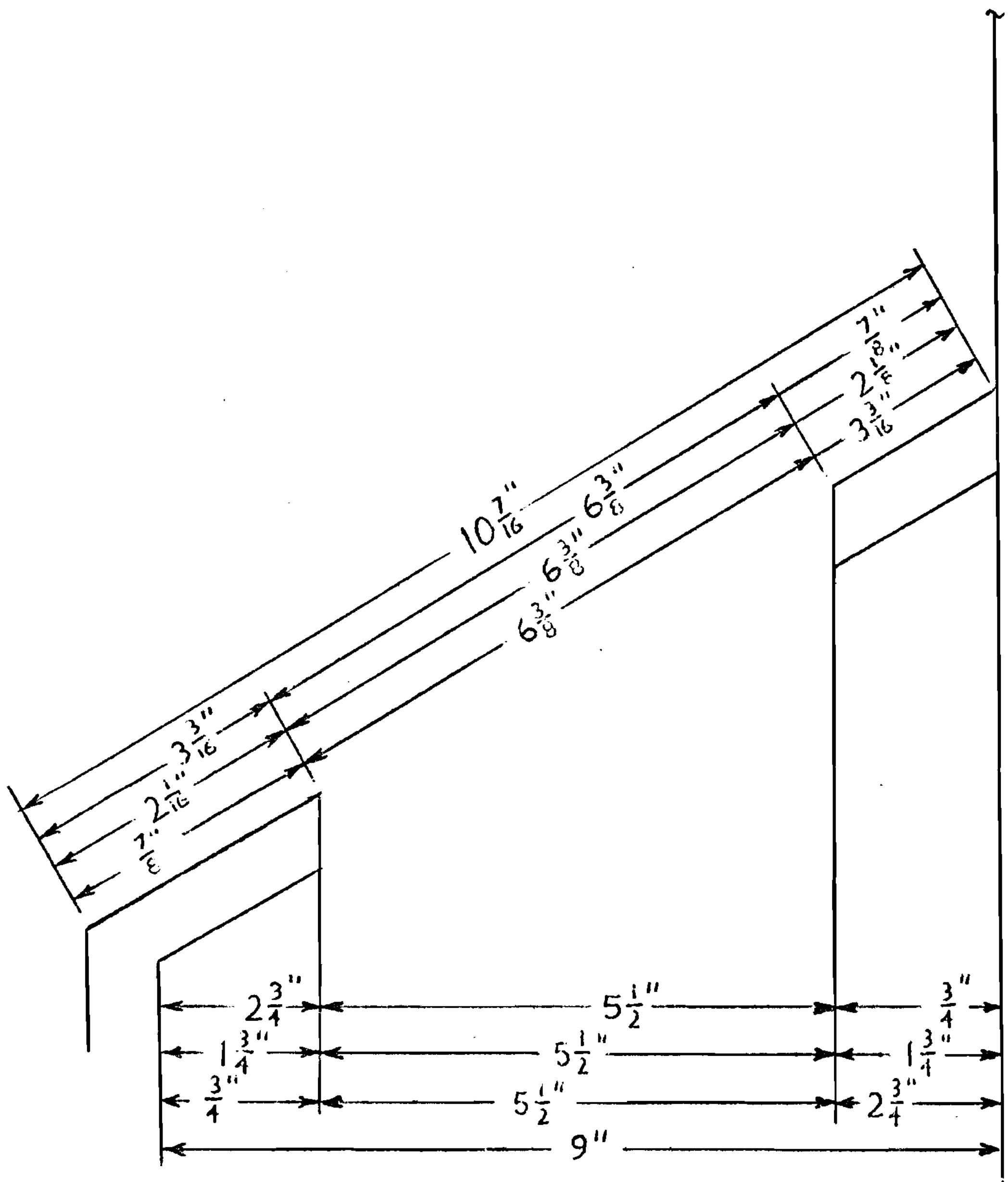


Figure 14. Dimension details for 60° skewed slot orifice.

B = .500 ft = 6.00 in

e = .200

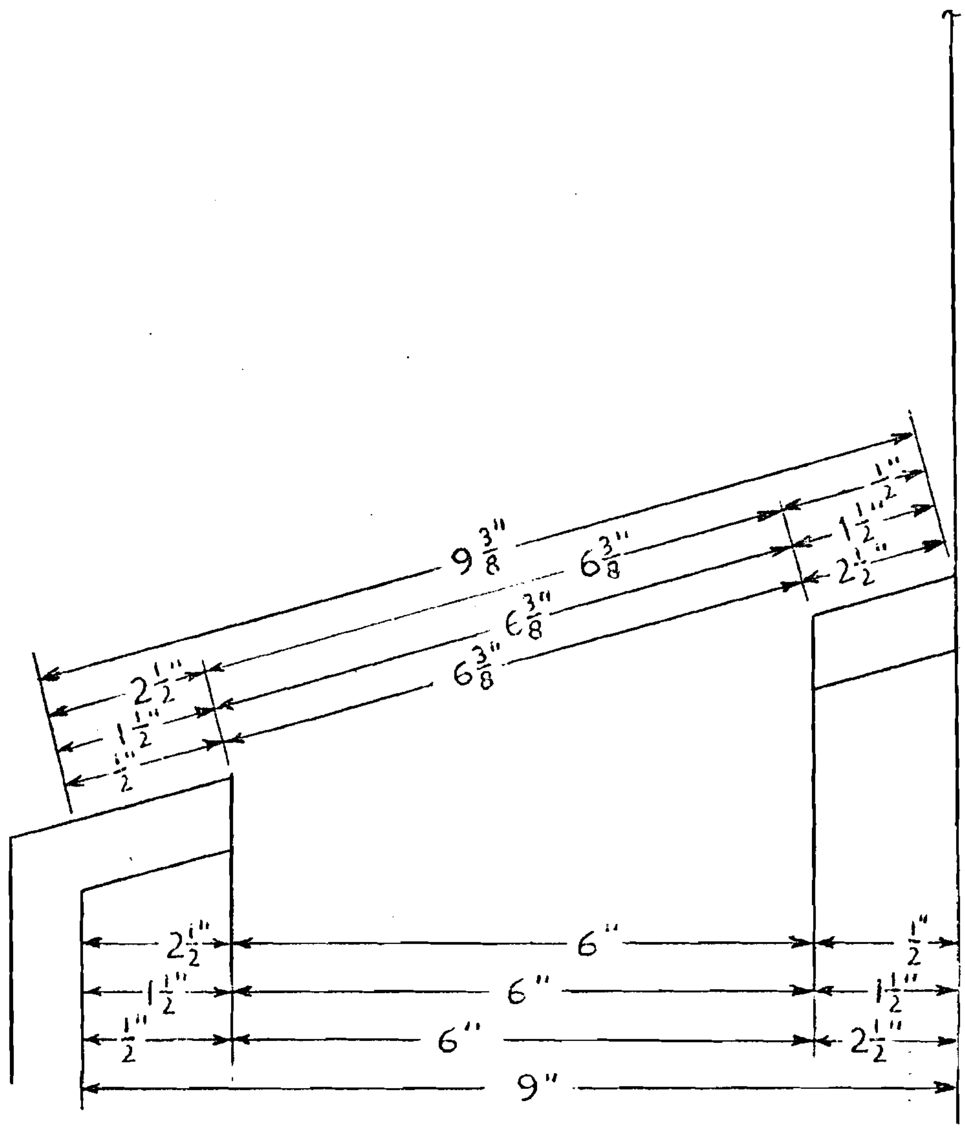


Figure 15. Dimension details for 75° skewed slot orifice.

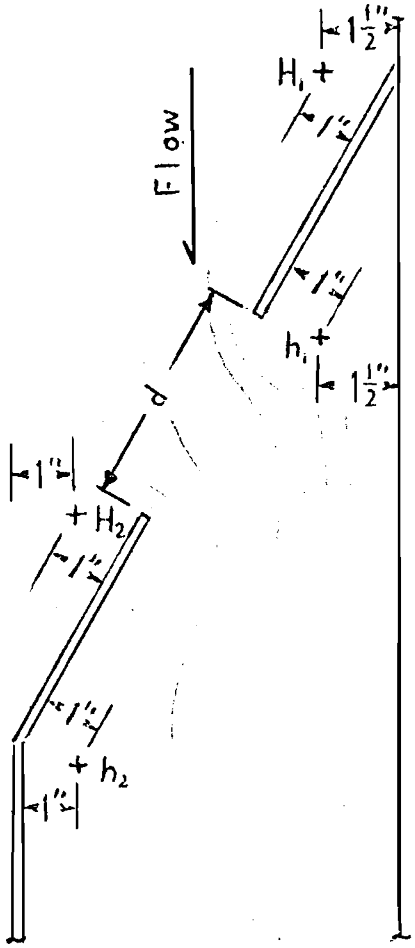


Figure 16a. ϕ = 30°.

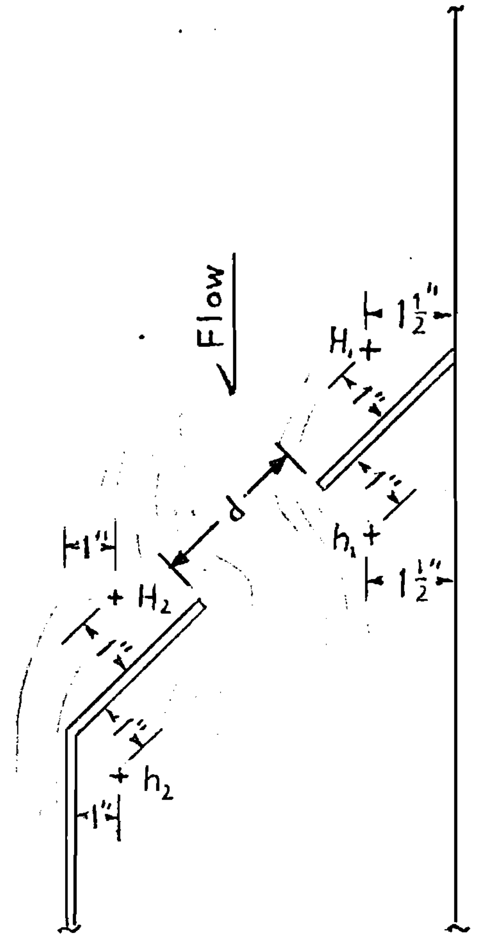


Figure 16b. ϕ = 45°.

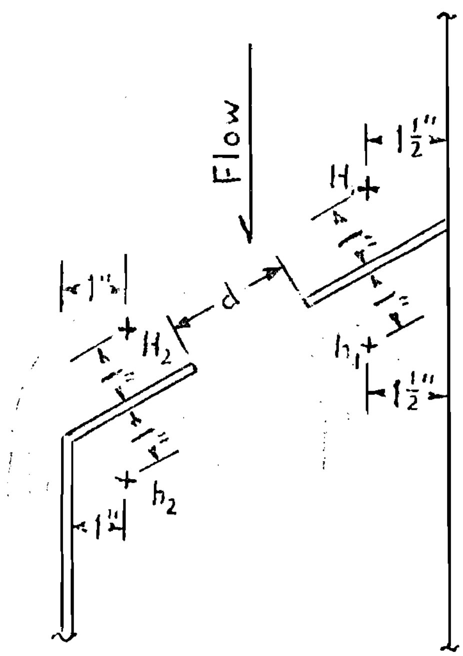


Figure 16c. ϕ = 60°.

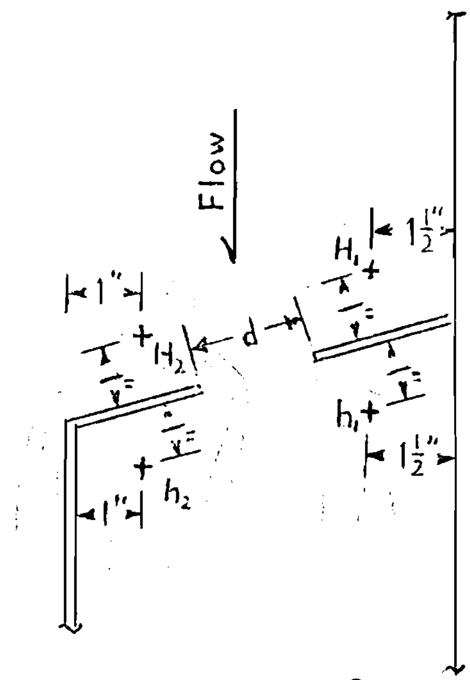


Figure 16d. ϕ = 75°

Figure 16. Flow through skewed slot orifices.
Measurement points for H_1, H_2, h_1, and h_2.

discharges for each run. This procedure was repeated for every contraction ratio, slope and position.

Two important parameters, slope and eccentricity of fishway entrance, are discussed in detail in the following paragraphs. It was originally hypothesized that they would not have a significant effect on the final equations and rating curves.

Effect of Eccentricity

Kindsvater and Carter (1955) performed a study on the effect of eccentricity on open channel constrictions. The opening is described as being eccentrically located when the length of one of the obstructions which comprise the constriction is greater than the other. The eccentricity is defined as the ratio of the shorter length of the channel constriction to the length of the longer channel constriction and ranges from zero to unity. He suggested that the principal effect of eccentricity would be to change the significance of channel contraction ratio in the functional relationship of the discharge coefficient C. The experiments showed that the effect of eccentricity on the standard value of C (a measure of discharge through the weir) was so small that it can be ignored in most cases.

In their work Kindsvater and Carter (1955) determined that for values of e = 0.0, the discharge is reduced only four percent. If e = 0.1, the discharge is reduced only one percent. For any value of e greater than 0.12, there is no reduction of discharge.

The respective eccentricities obtained for the 30°, 45°, 60°, and 75° observations were .484, .375, .273, and .200. This would indicate that the correction factor for eccentricity should be unity for all observations.

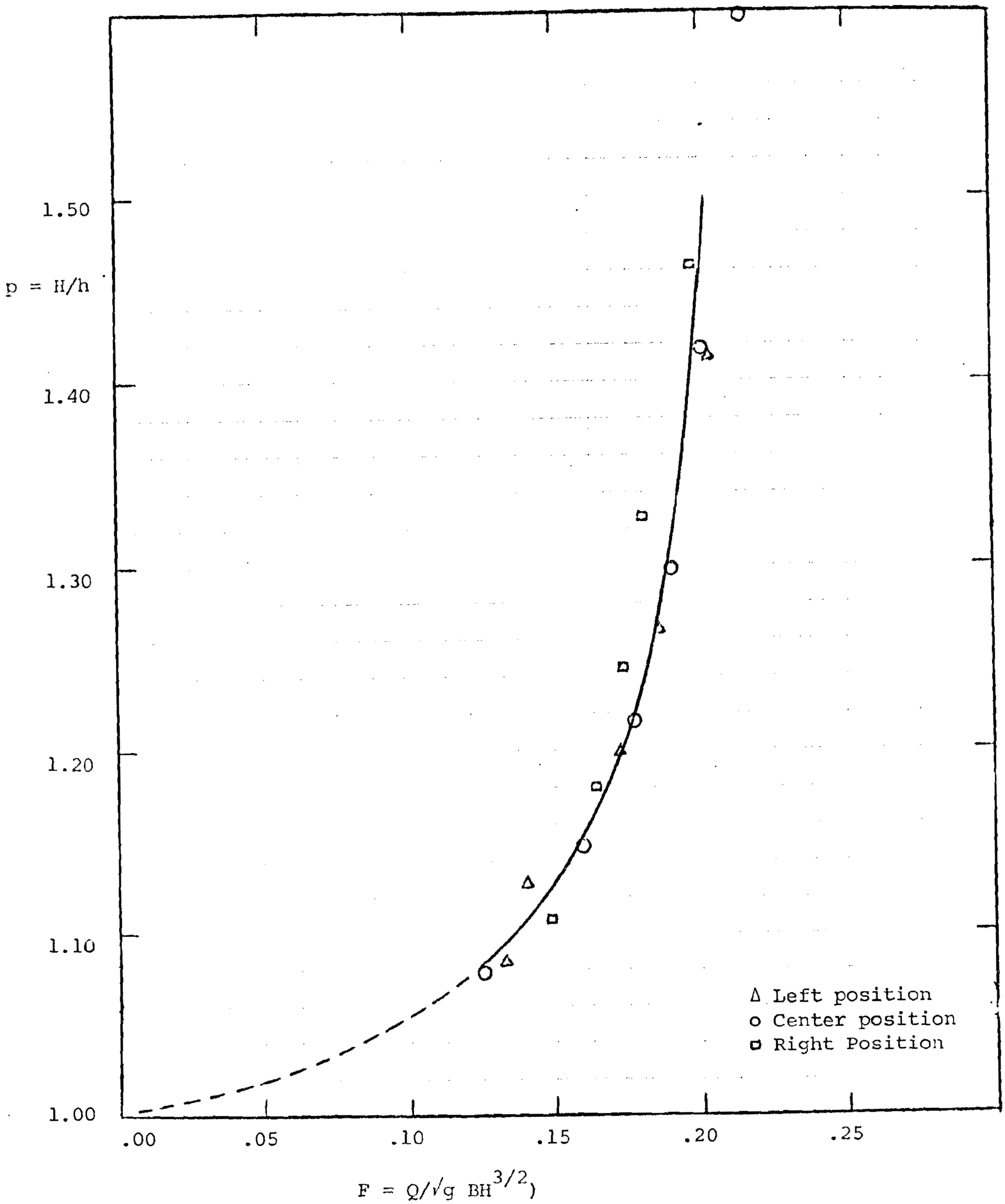


Figure 17. Effect of Position. $\phi = 45^{\circ}$; $m = .72$; $S = .025$.

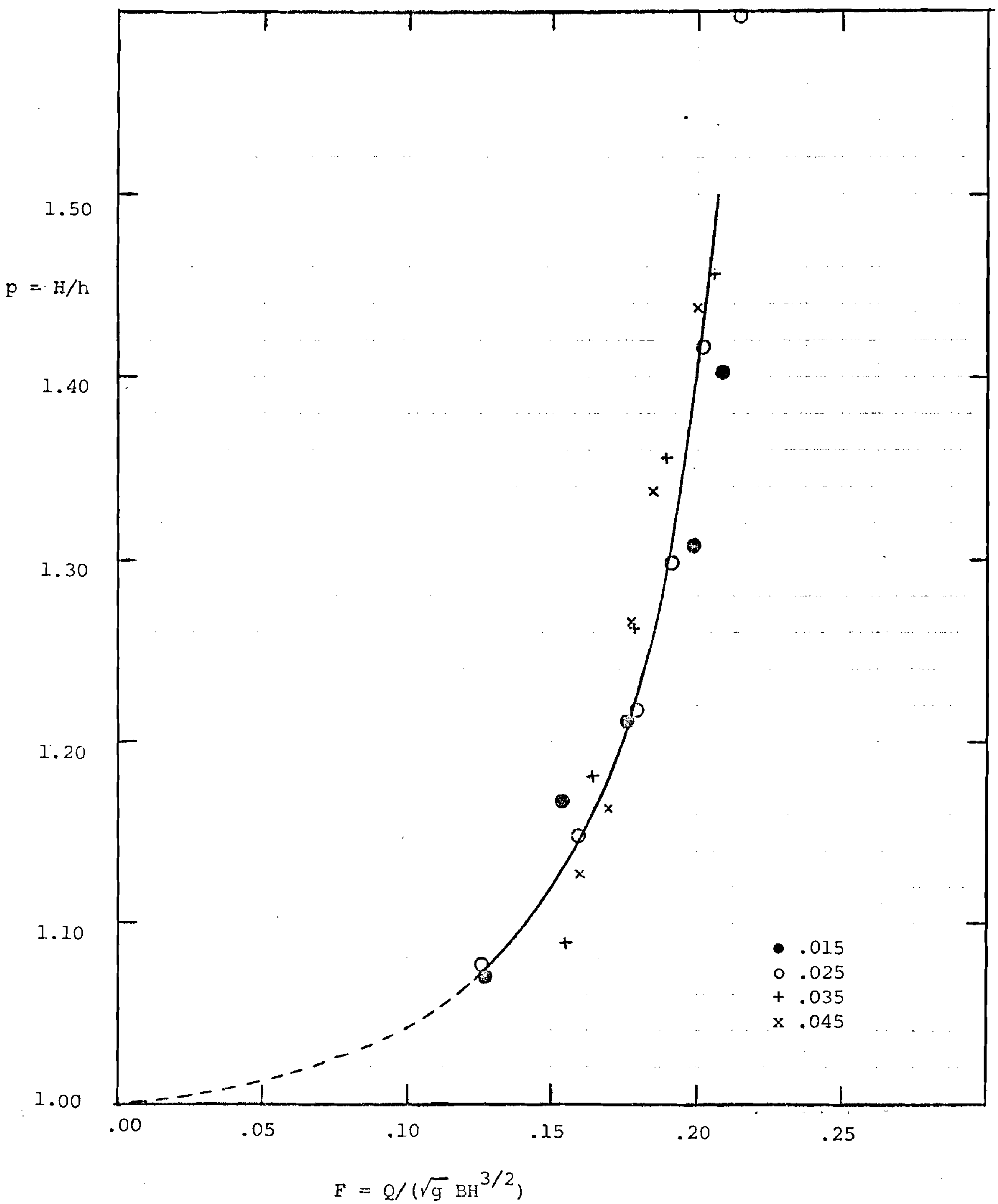


Figure 18. Effect of Slope. $\phi = 45^o$; m = .72; center position.

that the correction factor for eccentricity should be unity for all observations. It was deduced that this concept should apply for either normal constrictions, as performed by Kindsvater, or for skewed constrictions, as performed in this experiment. Data for the 45^{o} skew angle runs shown in Figure 17 show there is no systematic deviation of discharge with eccentricity for the range examined.

Effect of Slope

Measurements of upstream water level H were taken immediately upstream of the skewed orifice. Measurements of downstream water level h were taken immediately downstream of the skewed orifice. The water level measurements were taken approximately one inch perpendicular to the slot orifice face. This resulted in an effective length along the flow path of less than two inches, or .17 feet. The maximum slope used in the 45^{o} experiment was .045, resulting in a maximum correction factor of only .008 feet. This was considered small enough to not affect the values of H and h, and was thus disregarded. The other slopes used with the 45^{o} observations, .035, .025, and .015, would have even smaller slope corrections and thus were not considered. It was then deduced that because of the comparatively short distance between the points measured and the relatively small slopes the height observed to compute the parameter H/h and discharge to use in the Froude number expression would not be affected. Dass (1970) found no discernible difference due to slope in his observations for normal constrictions. This was true for skewed constrictions examined in this experiment. An examination of Figure 18 shows that slope is not a significant factor for skewed constrictions. Therefore it was decided to reduce the slope values to .015 and .025 in the successive 30^{o}, 60^{o}, and 75^{o} measurements. No differences were noted in the H/h values and corresponding discharge values for use in the Froude number expression. Therefore it can be said that the slope does not affect the value of Froude number with given H/h ratio.

Effect of Contraction Ratio

The discharge and Froude number are sharply reduced for higher values of the contraction ratio, m. This resulted in steeper curves for H/h vs. Froude number for higher values of m (Figure 19). After flow approaches critical depth at the constriction the discharge is no longer affected by tailwater depth thus is no longer a function of H/h. Two other researchers, Hill (1969) and Vallentine (1958) observed this in their studies. Kindsvater (1955) showed that the coefficient of discharge was reduced to a value of 0.68 for the values of m used in this study.

Effect of Angularity

The discharge and Froude number are sharply reduced for higher values of skew angle. This resulted in steeper curves for H/h vs. Froude Number for higher values of ϕ(Figure 20). The observations of both the 60^{o} and 75^{o} skewed openings show almost identical results.

The Froude number is a direct function of discharge. For this reason the Froude number is significantly larger for the wider opening associated with 30^{o} and 45^{o} skew angles.

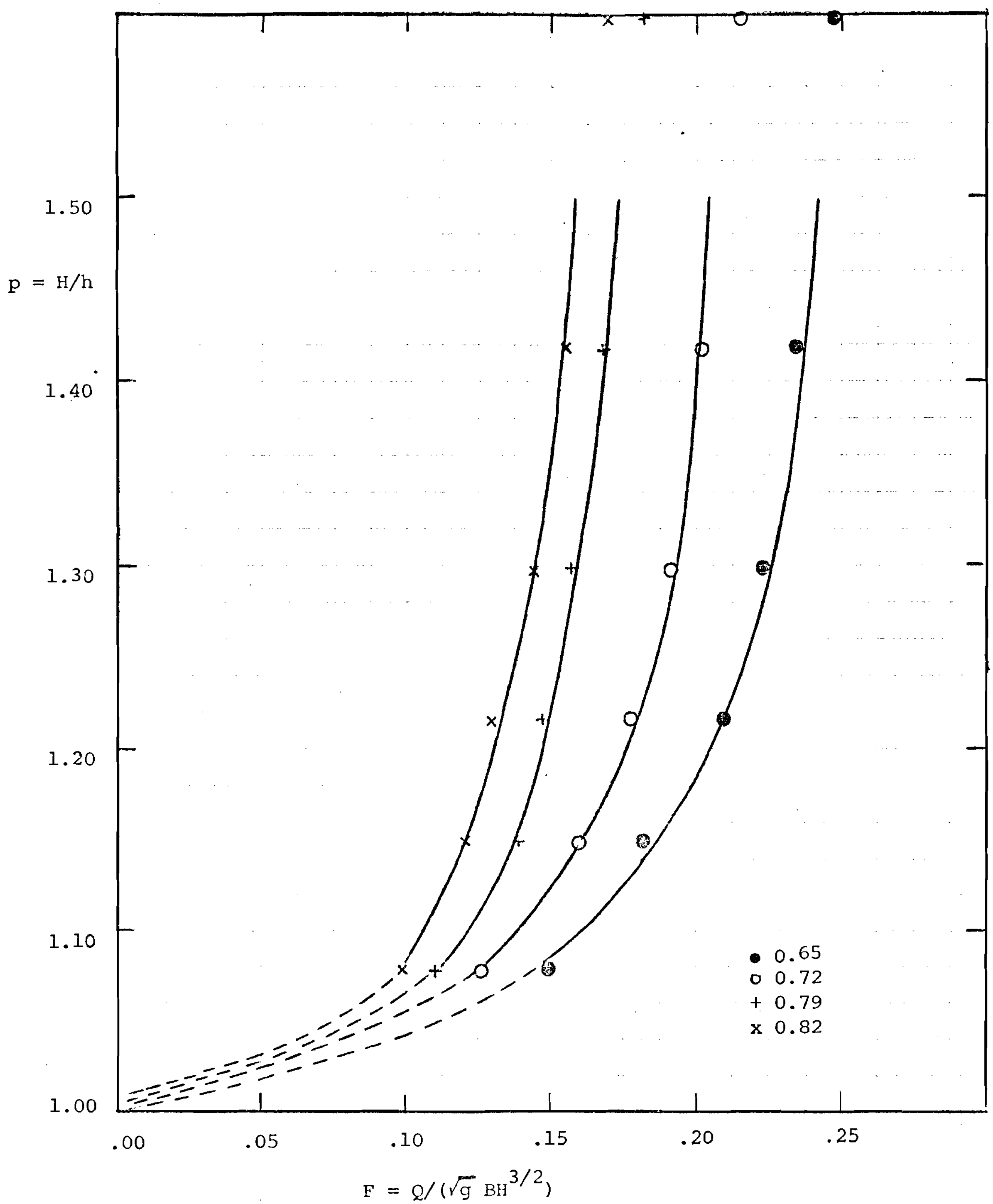


Figure 19. Effect of Contraction Ratio. ϕ = 45°; S = .025; center position.

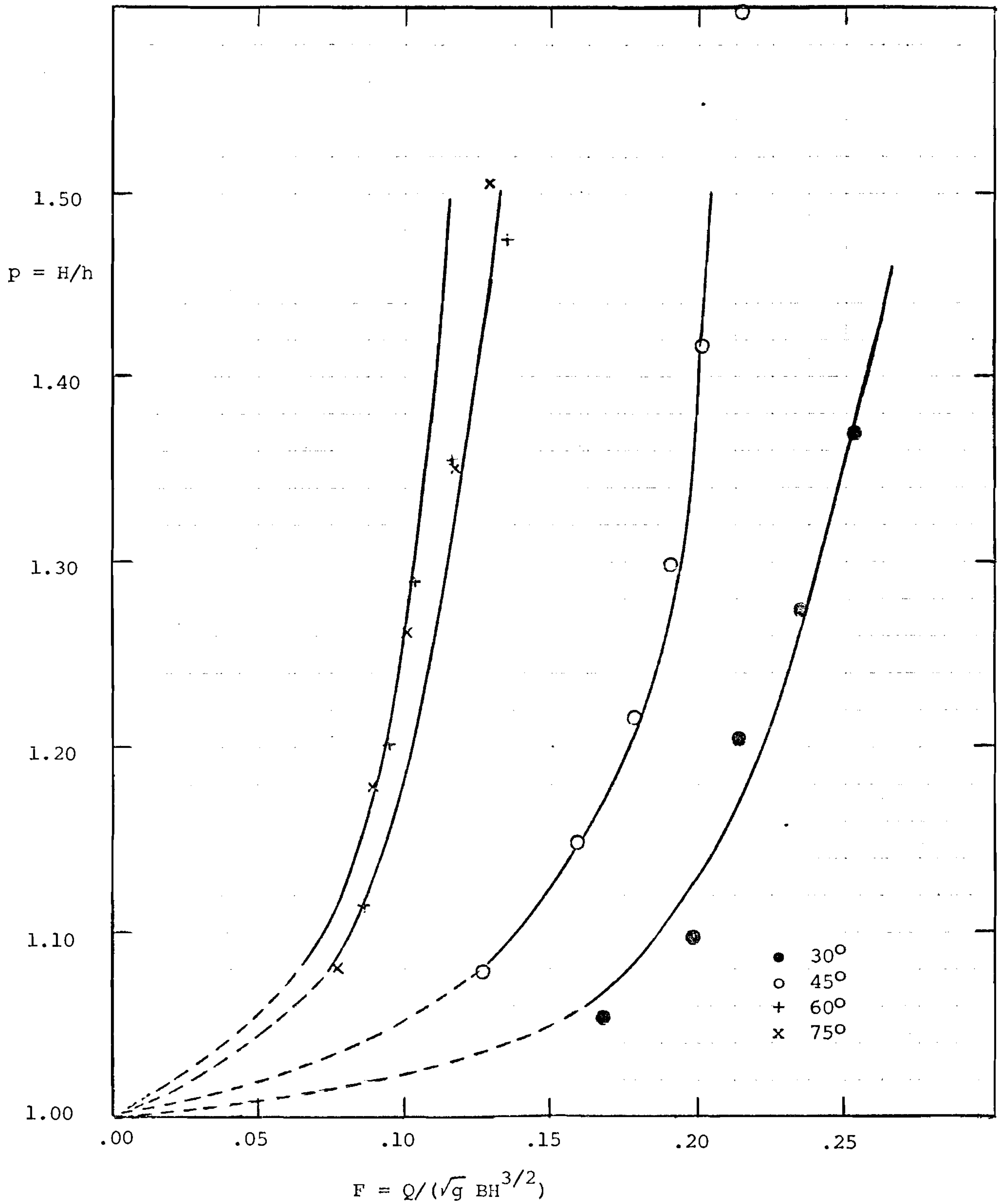


Figure 20. Effect of Skew Angle. S = .025; m = .72; center position.

CHAPTER V

RESULTS

The primary objective of this experiment was to develop the necessary parameters for the design of an effective skewed slot orifice fishway structure. The parameters which must be considered are the headwater to tailwater ratio H/h, the Froude number F (which gives an indication of velocity and discharge through the fishway), the contraction ratio m, and the angularity ϕ, of the upstream entrance orifice to the fishway.

H/h and Froude Number Relationship

Sufficient depth of tailwater was maintained at all times to provide satisfactory entrance conditions at the fishway downstream end. A certain tailwater level was also maintained (such that downstream control always occurs) to maintain subcritical flow conditions inside the fishway.

The ratio of headwater to tailwater was recorded for each measurement; the Froude number was calculated for each run by using the discharge obtained from the weir and measured water depths, as explained previously. Graphs of H/h and Froude number F are shown in Figures 17 to 36.

The maximum Froude number obtained was .331, for the 30° angle. For all observations, the flow was subcritical. The maximum Froude number obtained for other angles were .252, .184, and .166, for 45°, 60° and 75°, respectively.

Effect of Skewness

Skew = 30°

Data were evaluated and plotted in Figures 21 to 24 for contraction ratios of .65, .72, .79 and .82. The maximum H/h and F values obtained were 1.778 and .331, respectively; the minimum H/h and F values obtained were 1.054 and .099, respectively.

Considerably more turbulence was noted for the 30° skewed orifice than was noted for any of the other angles tested. In addition the data were widely scattered. This was probably due to the highly skewed angle and consequent turbulence. Several small eddies and vortices were noticed immediately below the slot orifice. The lateral width of the contraction walls may also have been a factor. For all measurements, water fluctuations made evaluation of exact water depths somewhat difficult. Several observations had to be repeated.

Although the 30° skewed entrances are not recommended for use, the curves drawn through the data points of Figures 17 to 20 can be used for design purposes.

Skew = 45°

Data were evaluated and plotted in Figures 25 to 28 for contraction ratios of .65, .72, .79, and .82. The maximum H/h and F values obtained were 1.713 and .253, respectively; the minimum H/h and F values obtained were 1.070 and .091, respectively.

Turbulence was also present in the 45° observations, although not as pronounced as was observed during the 30° runs. Small eddies and vortices were apparent although they were not as extensive as those observed for the 30° orifice.

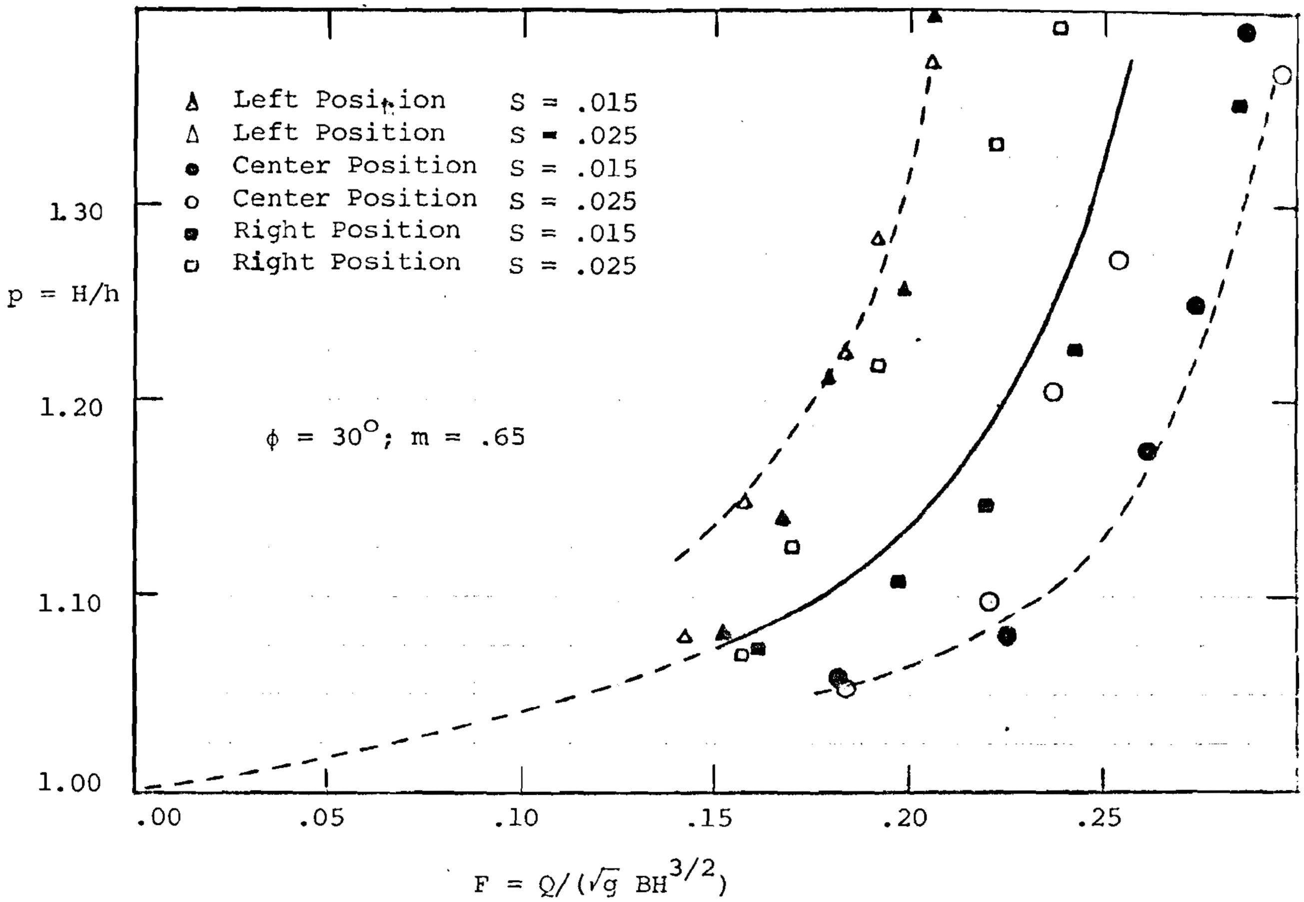


Figure 21. Relationship between Froude number and water depth ratio.

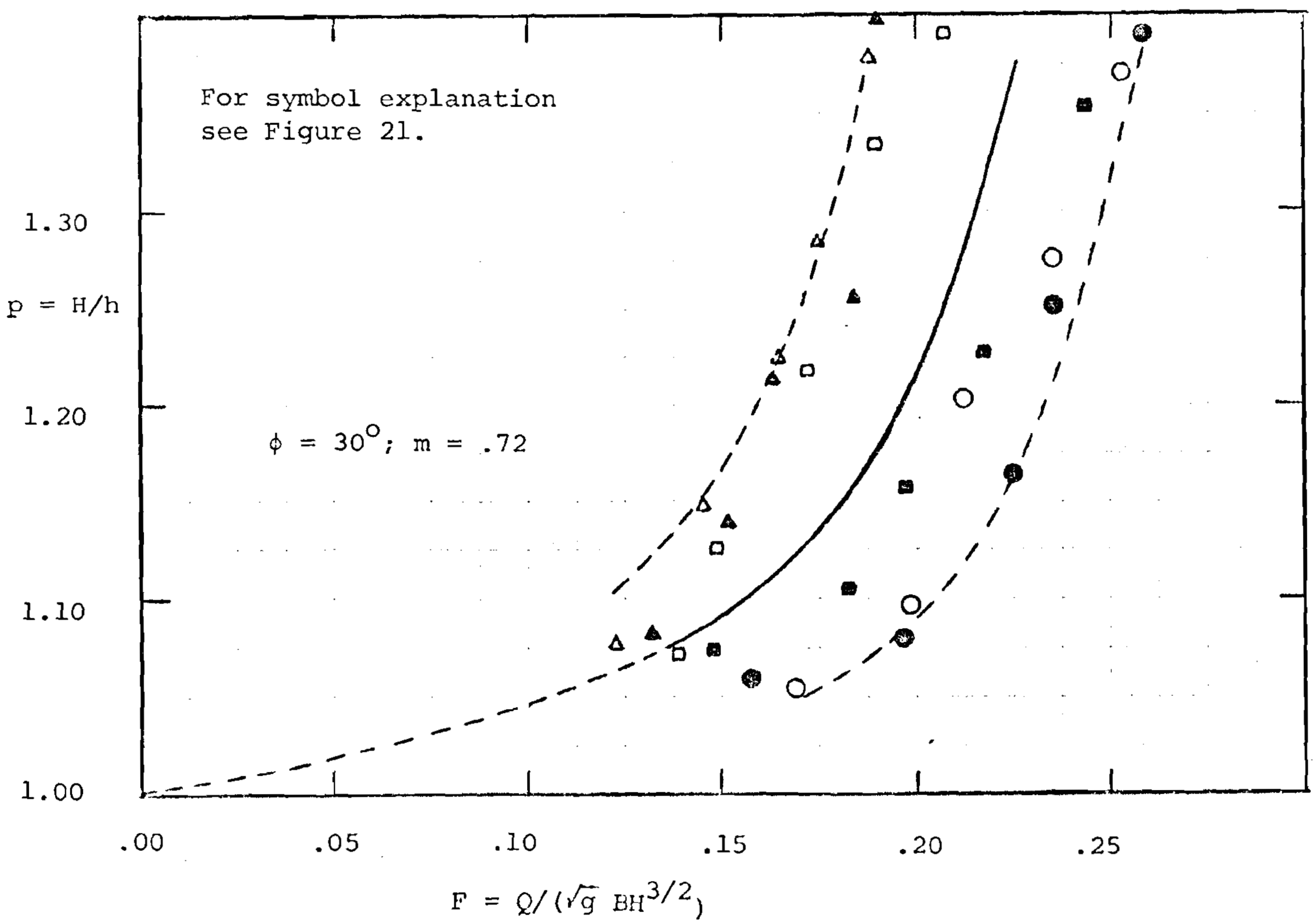


Figure 22. Relationship between Froude number and water depth ratio.

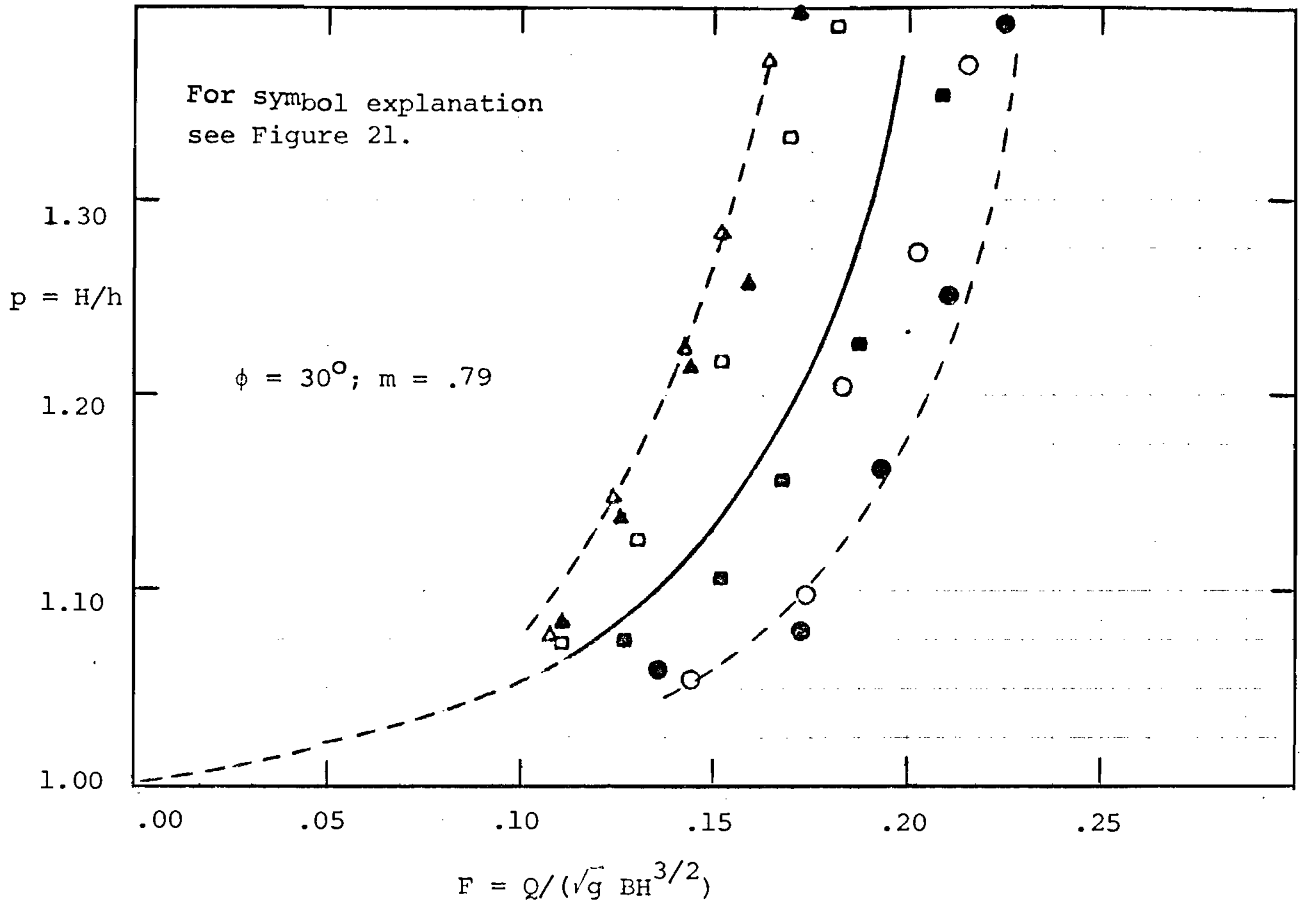


Figure 23. Relationship between Froude number and water depth ratio.

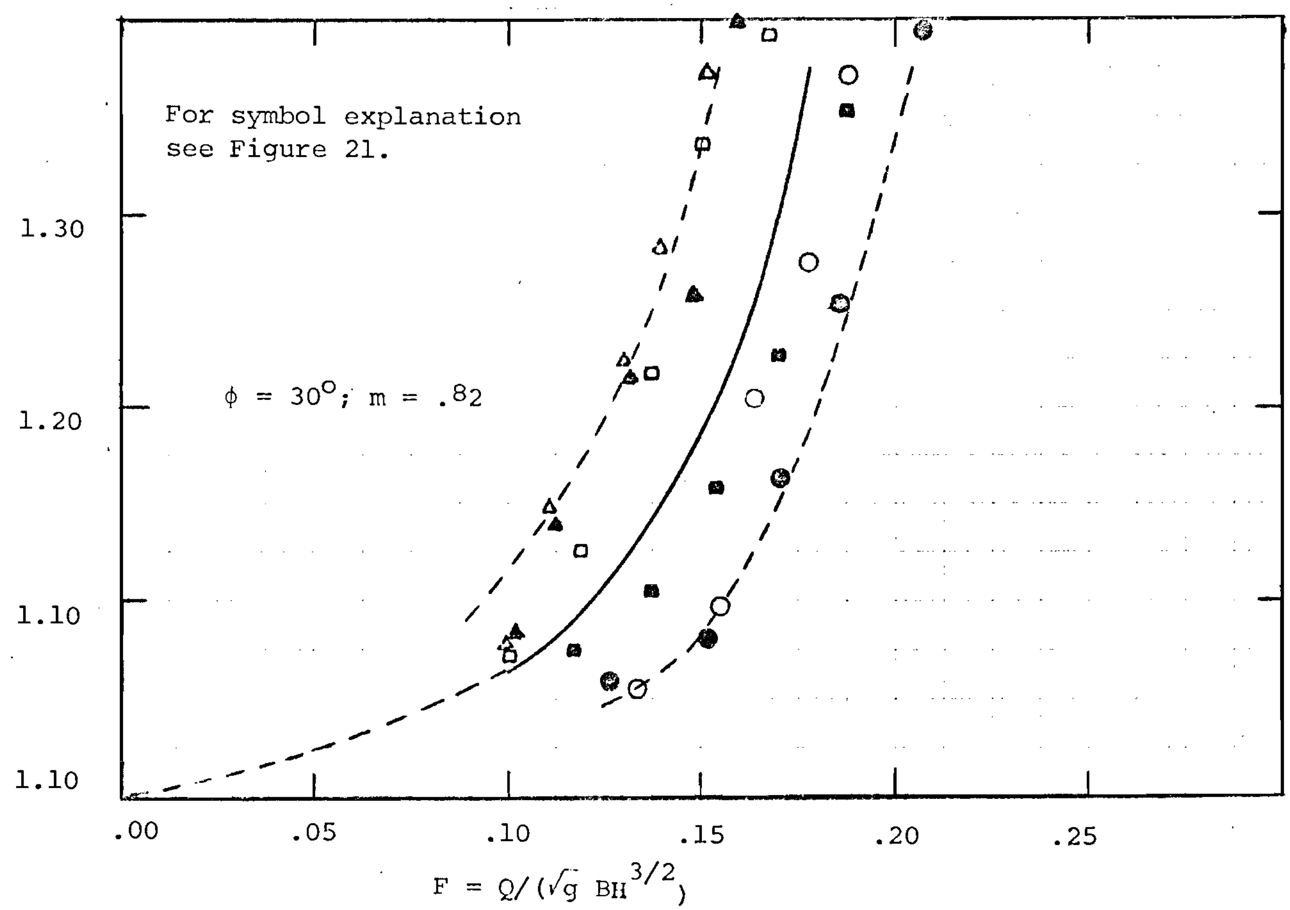


Figure 24. Relationship between Froude number and water depth ratio.

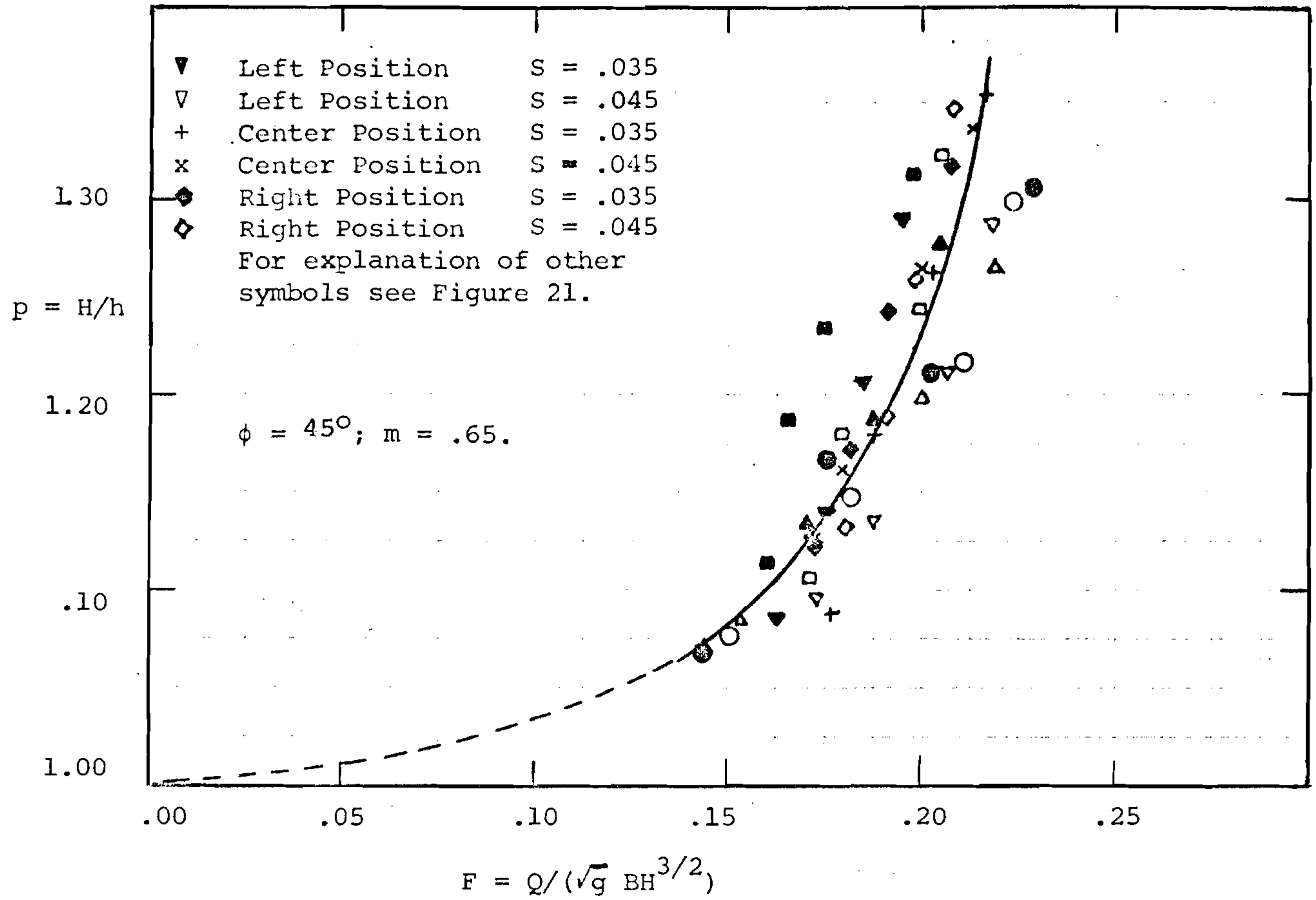


Figure 25. Relationship between Froude number and water depth ratio.

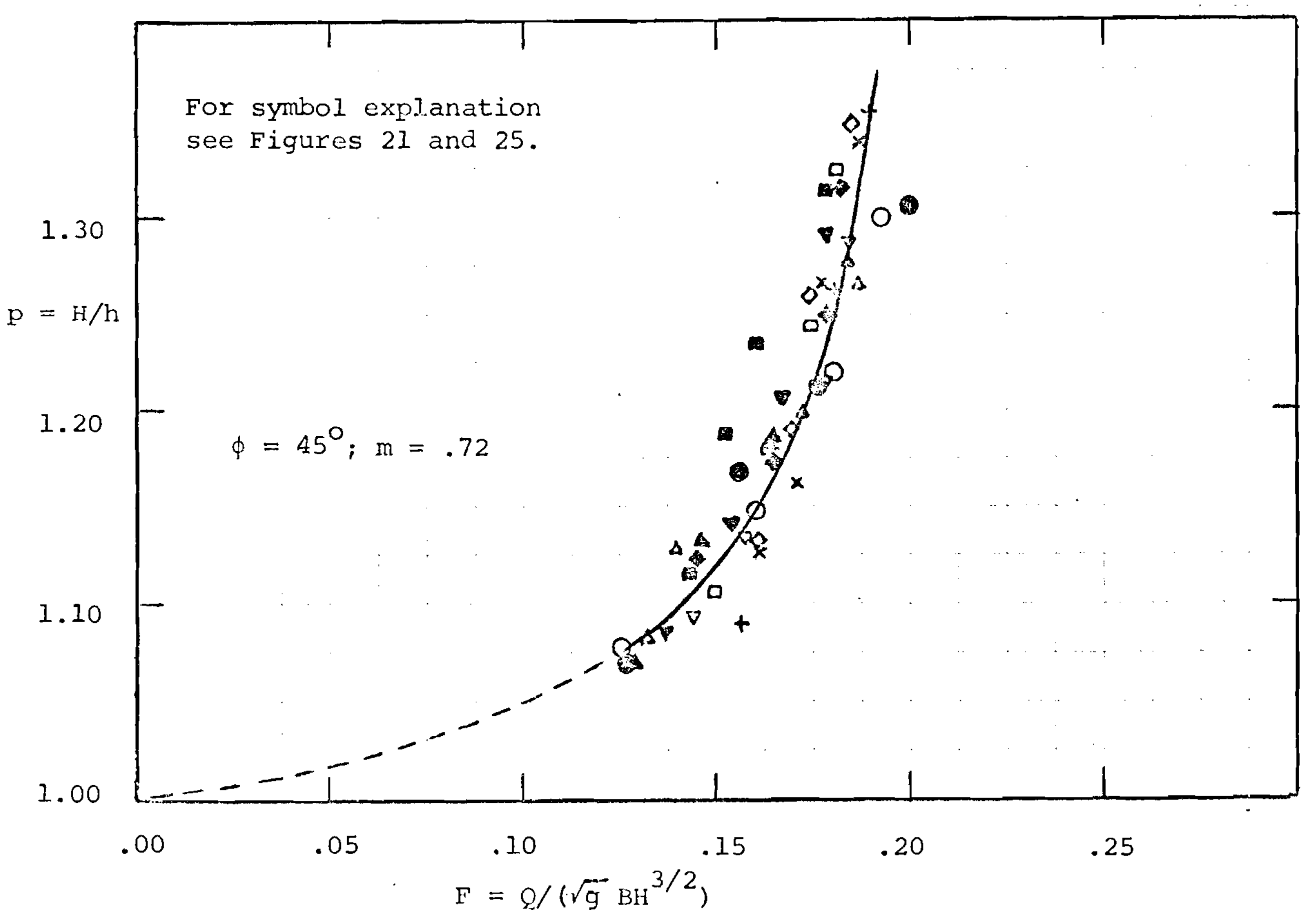


Figure 26. Relationship between Froude number and water depth ratio.

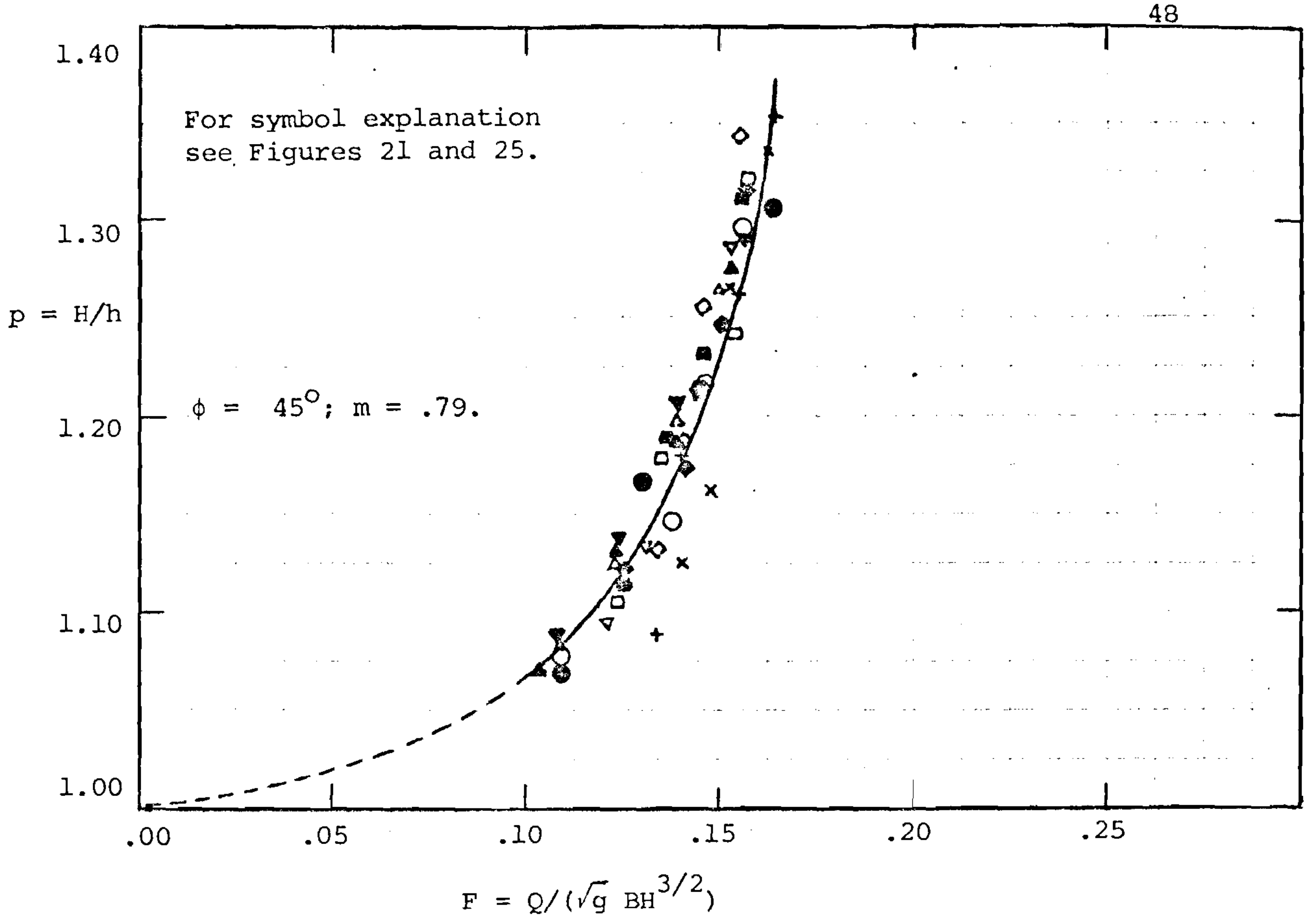


Figure 27. Relationship between Froude number and water depth ratio.

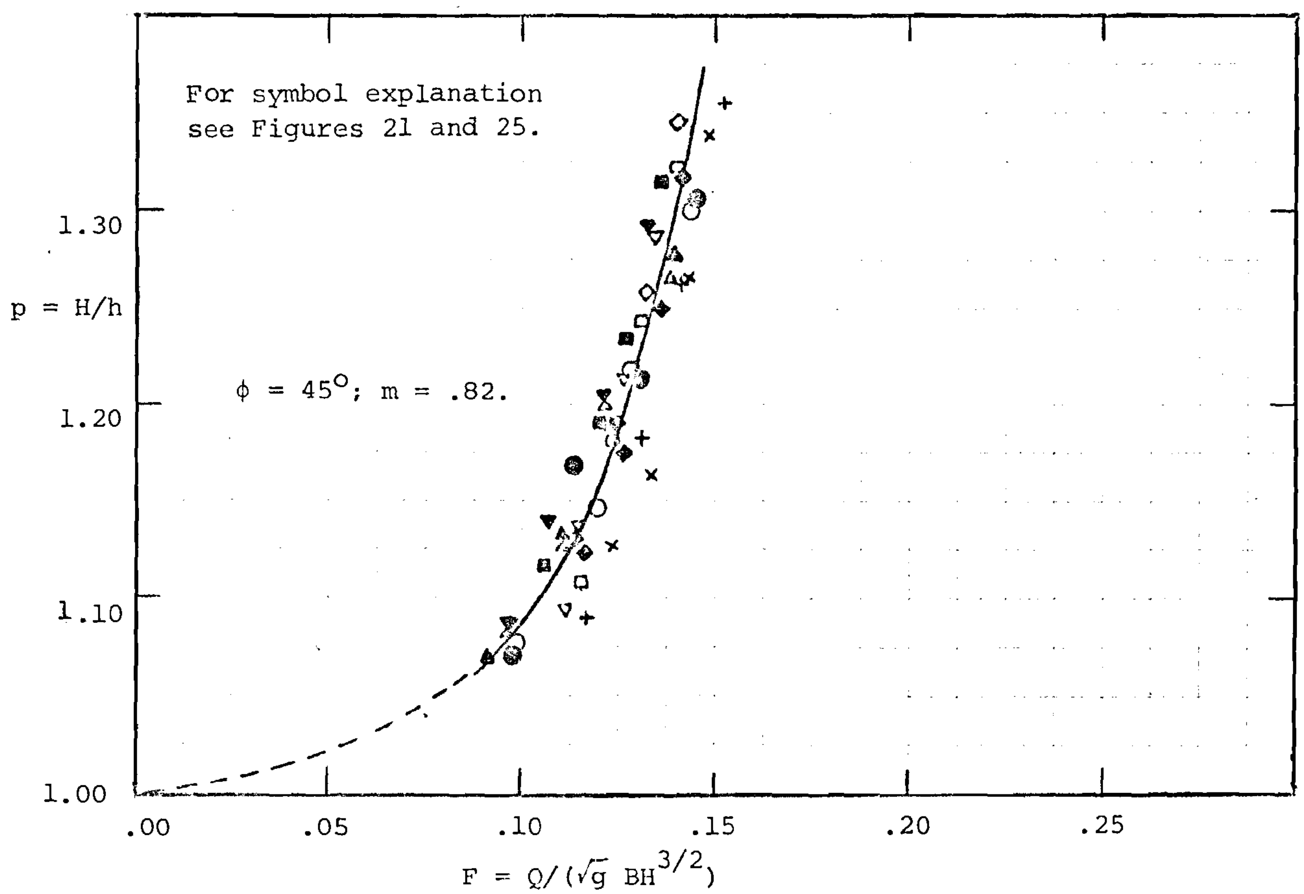


Figure 28. Relationship between Froude number and water depth ratio.

Skew = 60°

Data were evaluated and plotted in Figures 29 to 32. The contraction ratios were similar to 30° and 45° observations, .65, .72, .79 and .82. The maximum H/h and F values obtained were 1.780 and .184 respectively; the minimum H/h and F valuesobtained were 1.096 and .061, respectively.

Some turbulence was observed during the 60° runs. The intensity was less than that observed during the 30° and 45° runs. Some eddies and vortices occurred, but on a lesser scale than were apparent during the 30° and 45° runs. These occurred primarily during the small contraction ratio runs. The water level was considerably more stable than during the 30° and 45° runs.

Skew = 75°

Data were evaluated and plotted in Figures 33 to 36. The contraction ratios were the same as for the 30°, 45° and 60° readings; .65, .72, .79 and .82. The maximum H/h and F values obtained were 1.746 and .166, respectively. The minimum H/h and F values obtained were 1.068 and .051, respectively. Slope and fishway position did not affect the readings.

Figures 37a and 37b show that turbulence occurs in the fishway, even when the orifice was set 75° normal to the flow axis. Rhodamine B dye was added to the water through a perforated tube. The purpose of this was to observe the flow direction through the fishway and culvert barrel. However, a smooth laminar pattern did not occur, as the pictures illustrate. Some evidence of eddies and vortices is present.

The flow regime of all four angles can be classified as subcritical turbulent for all observations in this experiment.

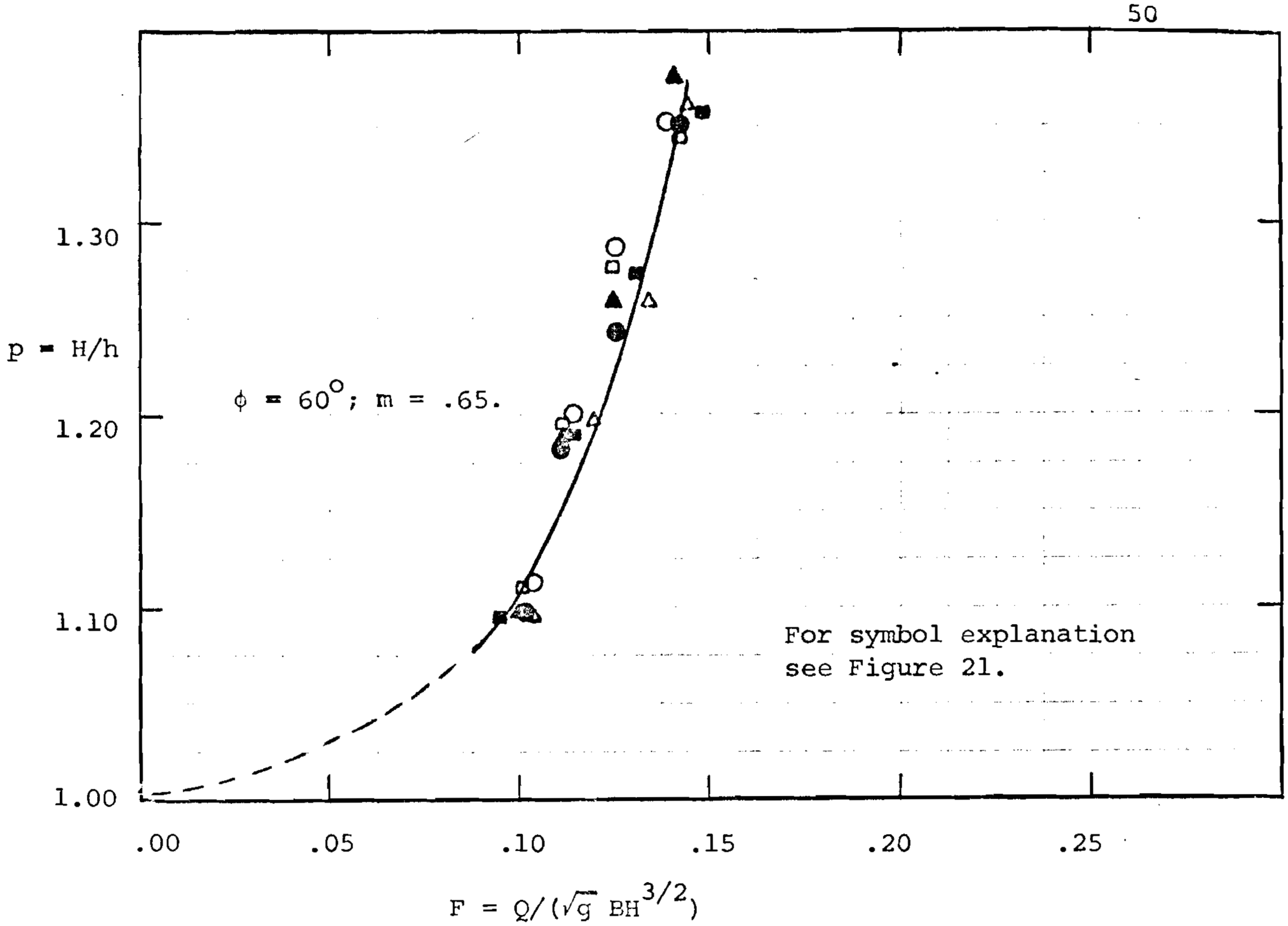


Figure 29. Relationship between Froude number and water depth ratio.

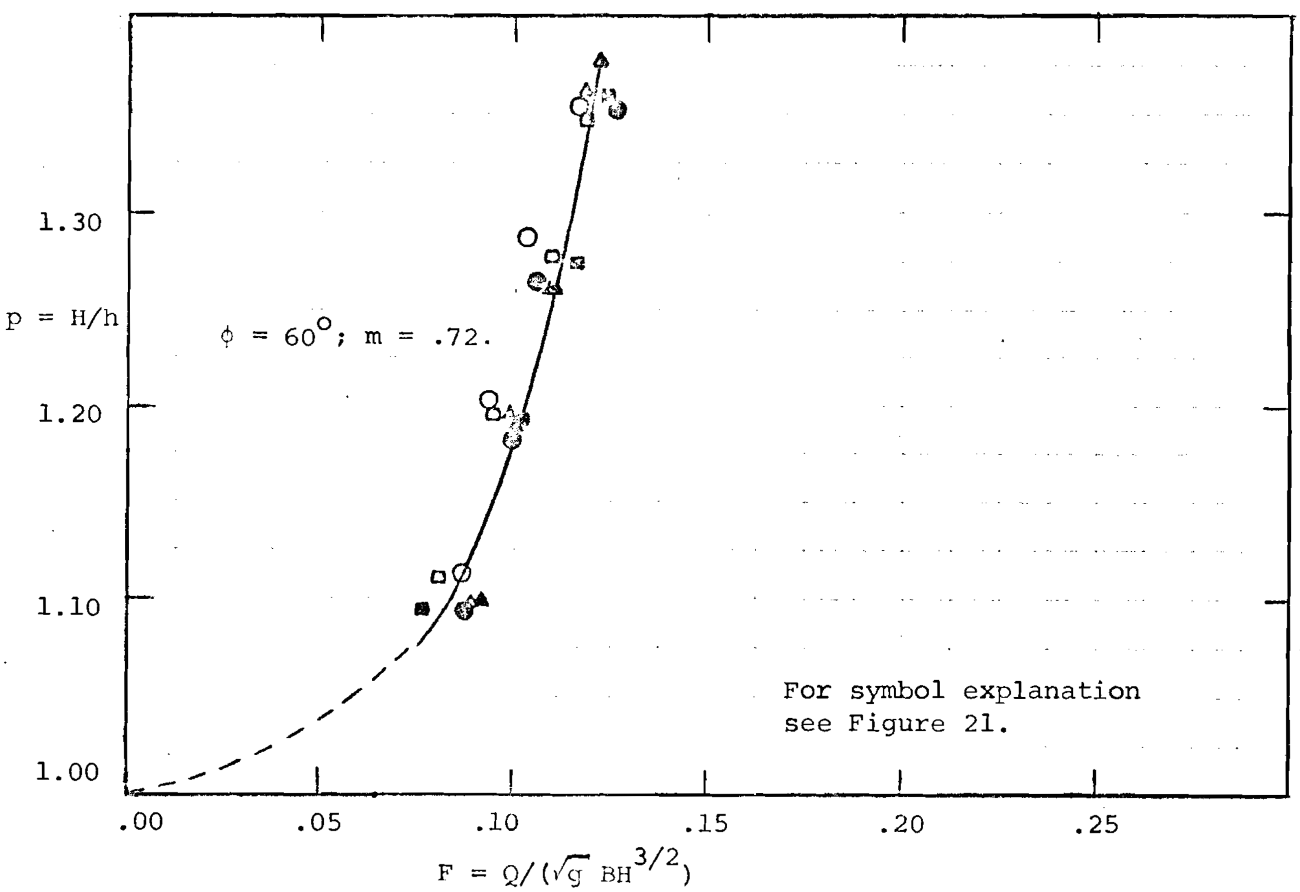


Figure 30. Relationship between Froude number and water depth ratio.

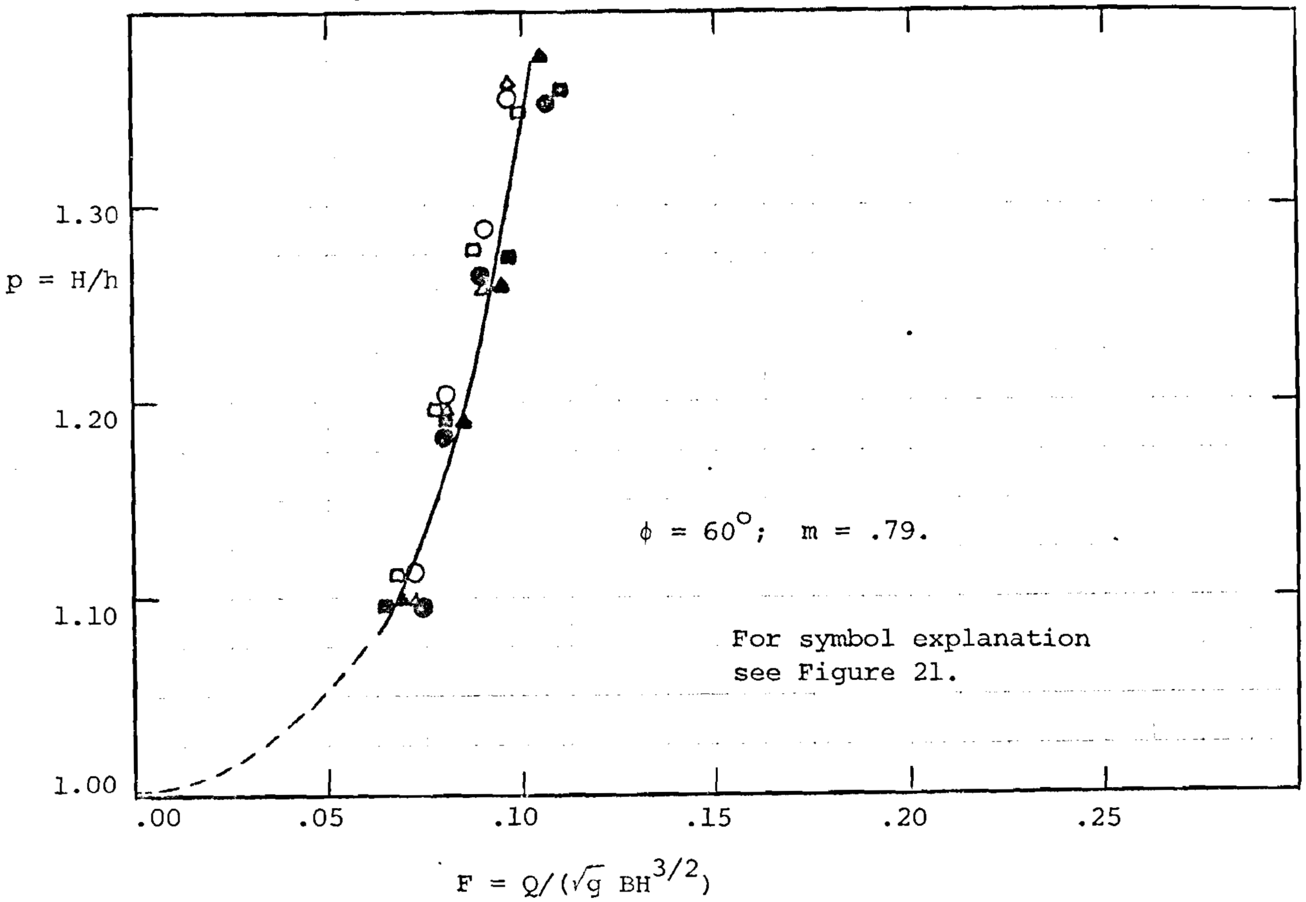


Figure 31. Relationship between Froude number and water depth ratio.

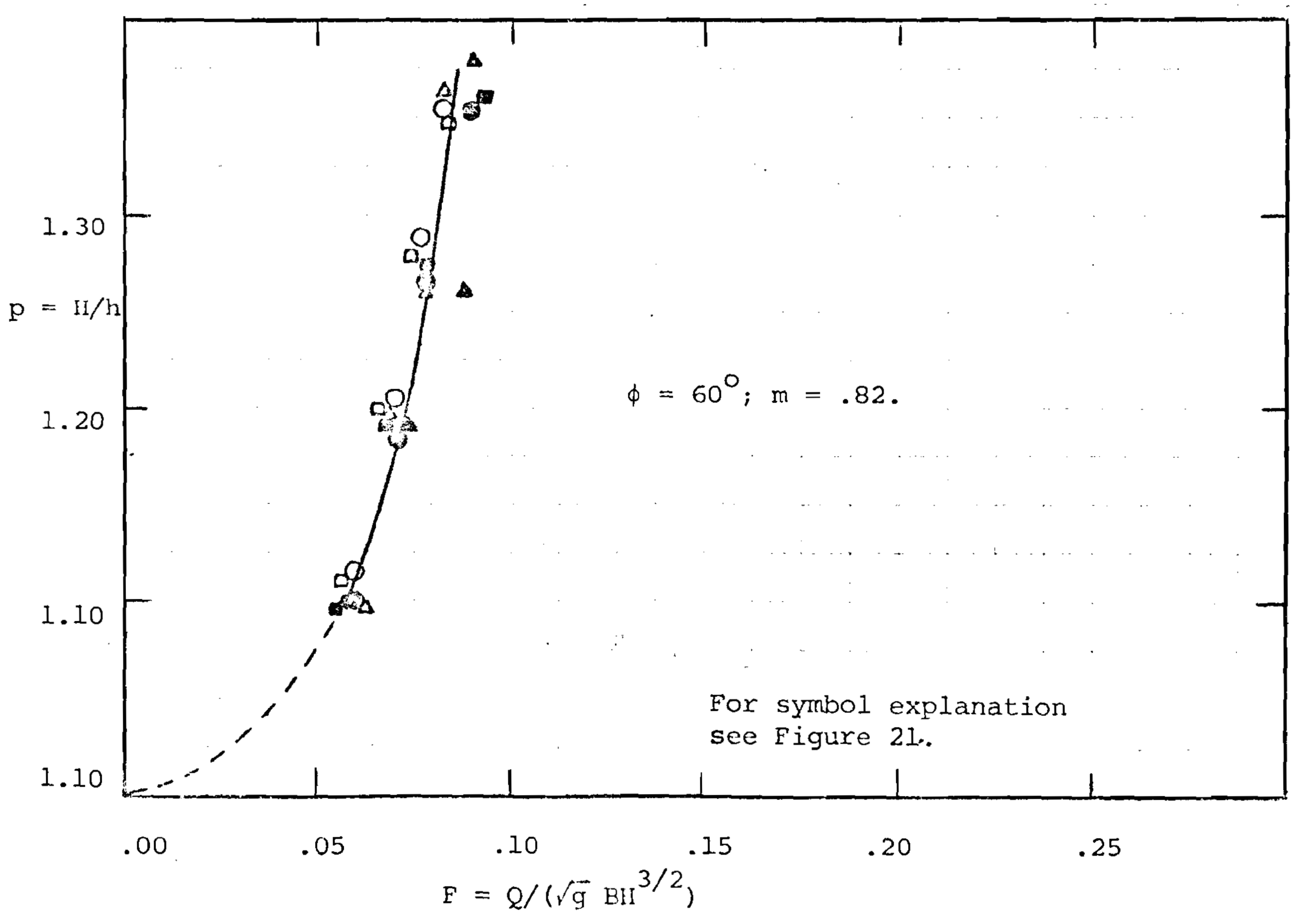


Figure 32. Relationship between Froude number and water depth ratio.

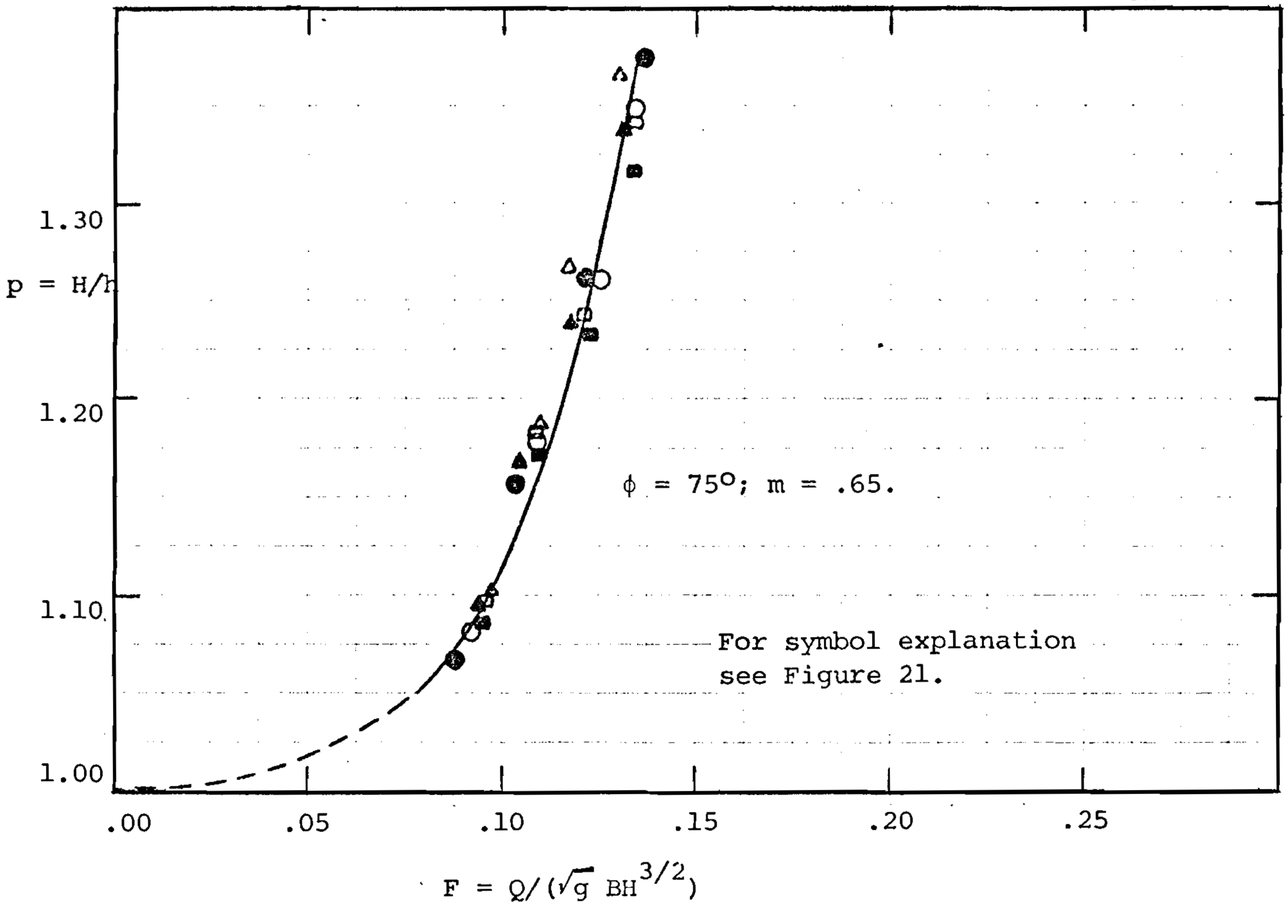


Figure 33. Relationship between Froude number and water depth ratio.

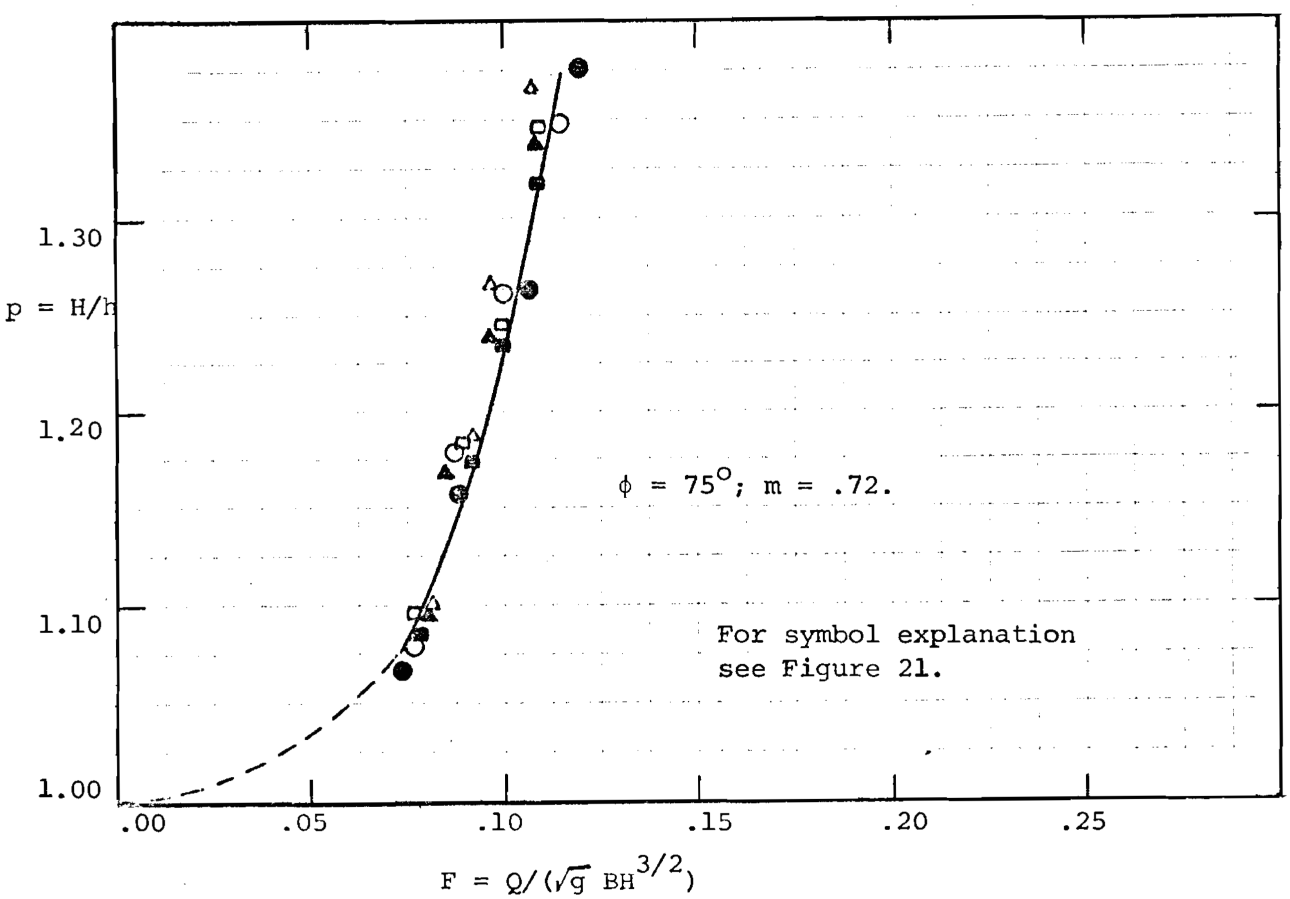


Figure 34. Relationship between Froude number and water depth ratio.

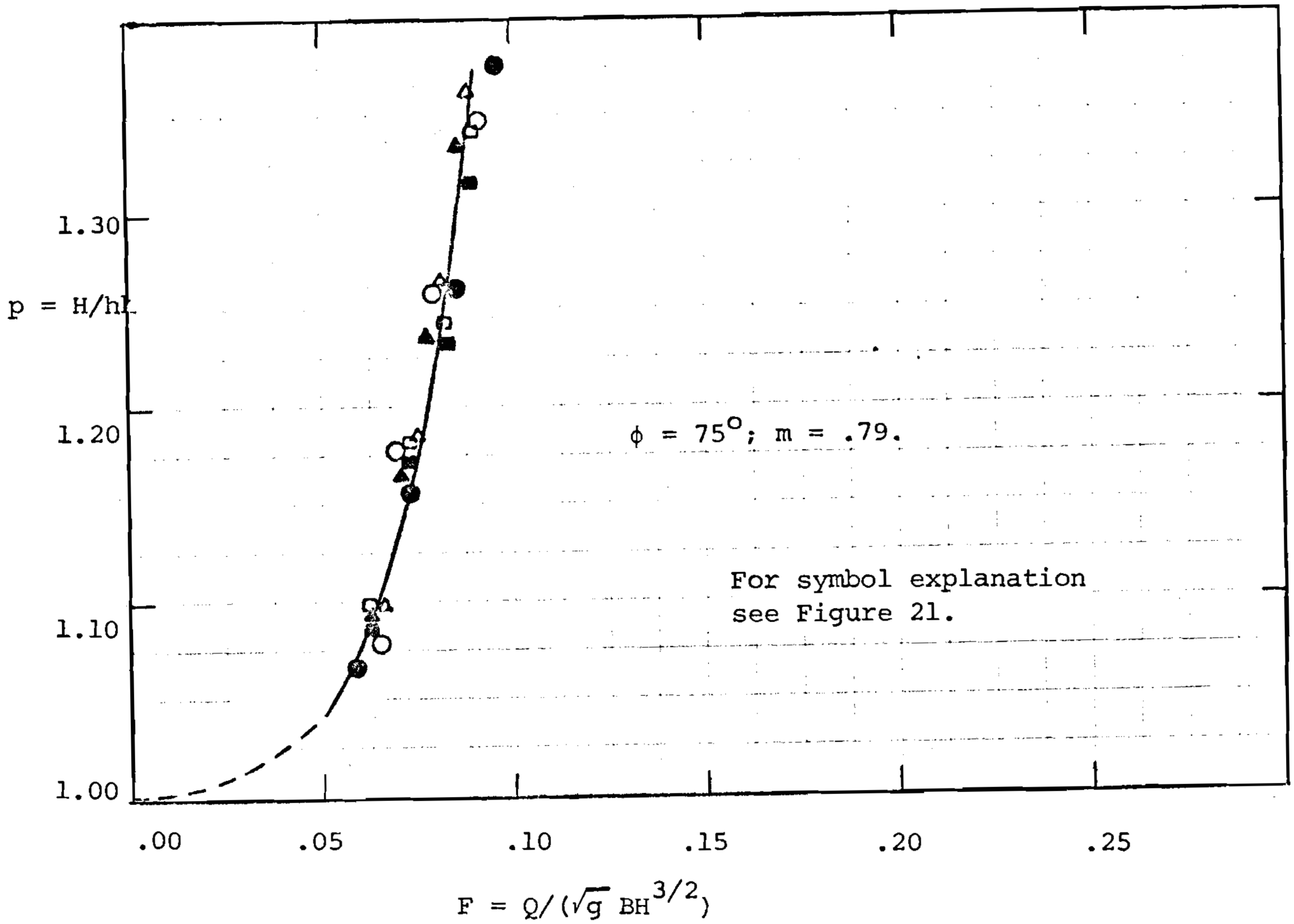


Figure 35. Relationship between Froude number and water depth ratio.

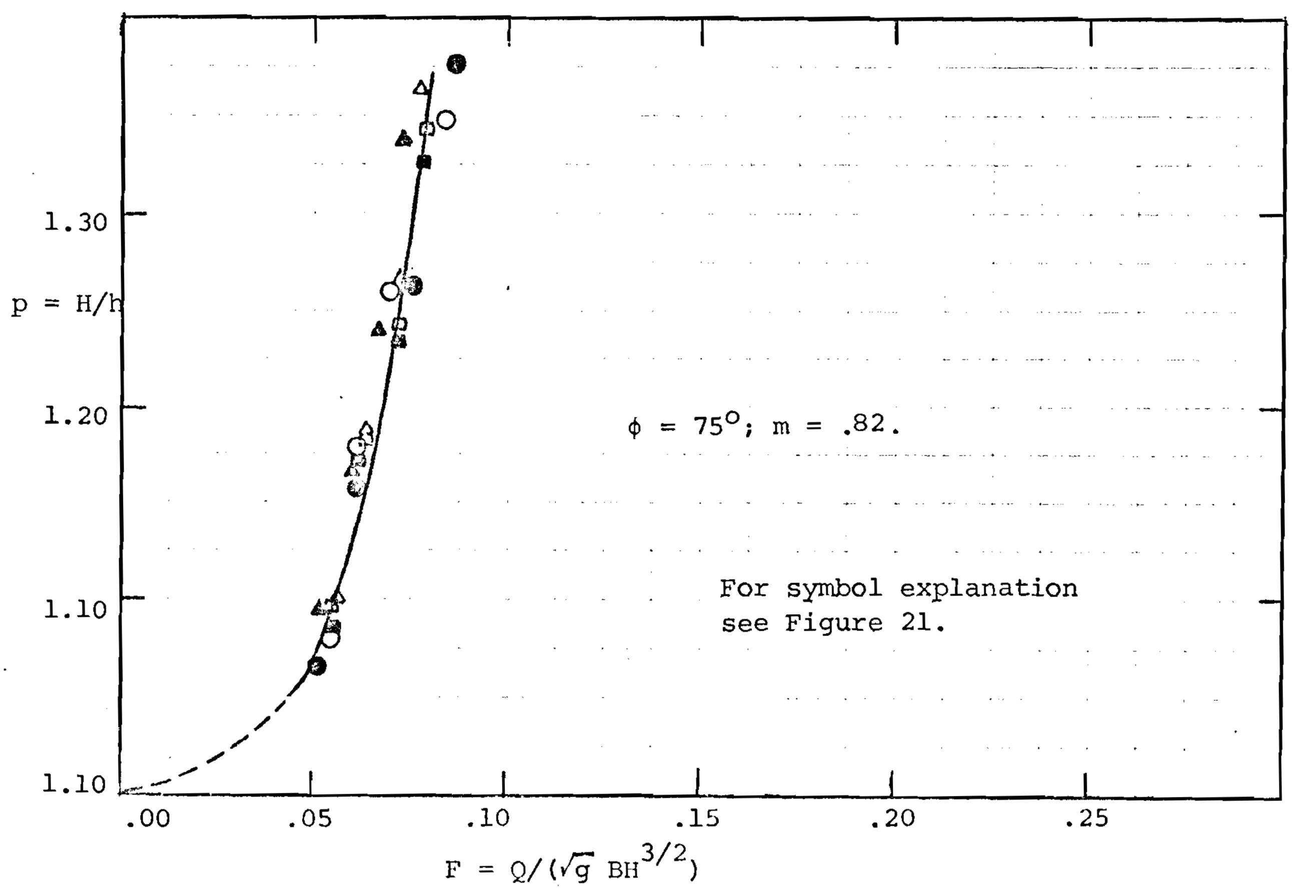


Figure 36. Relationship between Froude number and water depth ratio.

Figure 37. Measurement of streamflow patterns by injection of Rhodamine B dye into the water. $\phi = 75^{\circ}$.

CHAPTER VI

DISCUSSION OF RESULTS

A low value of the Froude number at any point in a free-surface flow pattern ordinarily indicates that gravity, or fluid weight, has a large influence on the motion at that point. In this particular case, since this study involves tranquil flow exclusively, the Froude number values are always less than critical. Within this low range, however, larger values of F for the contracted stream are usually indicative of a large drop in water level, H-h, or higher backwater ratio, H/h.

The Froude number is directly proportional to H/h, up to a value of about 1.3 to 1.4; then it is independent of H/h. This is consistent with the work performed by Hill (1969) et.al., in which the discharge reaches a maximum and is unaffected for values of H/h greater than 1.5. An example problem in the next section best illustrates the use of the design curves.

Procedure for Designing Fishway Culvert

1. Select: B; b; S; ϕ; H; H_t; V_{max}; L; g = 32.2.
2. Select: N = Spacing; n = number of spaces.
3. Calculate $m_{sl} = \frac{B - b}{B}$ and $m_{or} = \frac{D - d}{D}$.
4. Find C_d by using Figure A-2 in the appendix and selecting the appropriate orifice spacing.
5. Assume a value for discharge, Q.
6. Analyze entrance conditions to determine H_f (depth immediately upstream from entrance gate). Calculate $F = Q/(5.674\ BH^{3/2})$. With this value

of F obtain H_f/H_t from Figure A-3 in the appendix. From this result, H_f can be determined from the given value of H_t.

7. Analyze exit conditions to determine h_1 (depth immediately downstream from skewed orifice exit). Calculate $F = Q/(5.674\ BH^{3/2})$. With this value of F_1 obtain H/h_1 from Figures 17 to 36 obtained in this study. From this result, h_1 can be determined from the given value of H.

8. Δh is determined from h_1 to h_f by $\Delta h = \frac{h_i - H_f}{n}$. From this, h_n may be obtained. f - 1 = n.

9. $\sum_{i=1}^{n} \frac{1}{h_i} = \frac{1}{h_1} + \ldots + \frac{1}{h_n}$. For simplification in calculations, use
$$\sum_{i=1}^{n} \frac{1}{h_i} = \frac{n}{2}\left(\frac{1}{h_1} + \frac{1}{h_n}\right).$$

10. $h_2 = h_i - \Delta h$; $h_3 = h_2 - \Delta h$; . . .; $h_f = h_n - \Delta h$.

11. Use the given values in the momentum equation:
$$m\, C_d \sum_{i=1}^{n} \frac{1}{h_i} = 2\left(\frac{1}{h_1} - \frac{1}{h_f}\right) + \frac{gB^2}{Q^2}\left(\left(h_1^{\,2} - h_f^{\,2}\right) + NnS\ (h_1 + h_f)\right).$$

12. Evaluate both sides of the equation. If the equation is in balance the assumed Q is correct. If the left side of the equation is less than the right side, the assumed Q is too small; if the left side of the equation is greater than the right side, the assumed Q is too large. In the latter two cases, repeat step 5 until both sides of equation agree.

13. If step 12 is satisfied, check velocities at critical points in the fishway to insure that they equal or are less than the maximum design velocity. Specifically, velocities should be checked at the following locations:

    a. Velocity V_{up} through the skewed slot exit. $V_{up} = \frac{Q}{(1-m)DH}$

b. Velocity V_1 through the upper normal slot orifice. $V_1 = \frac{Q}{(1-m)\ Bh_1}$

c. Velocity V_f through the lowest normal slot orifice immediately upstream from the entrance orifice. $V_f = \frac{Q}{(1-m) B\ h_n}$

d. Velocity V_t through the fishway entrance. $V_t = \frac{Q}{(1-m)\ B\ H_t}$

14. If all of the velocities in step 13 are equal to or less than V_{max} the design is all right. If any of the velocities are greater than V_{max}, select new values for steps 1 and 2 and repeat the entire procedure until all velocities are equal or less than V_{max}.

Design Examples

This design procedure will be illustrated with two sample problems in which Q and the water depths inside the slots are to be determined. One problem will have the same contraction ratio m for normal width of the upstream skewed slot and the downstream slots; the other will use different contraction ratios for the skewed slot and the normal slots downstream.

Example 1

The first problem is to design a suitable fishway culvert 100 ft. in length placed on a 5 percent slope. The maximum velocity at the throat of the entrance orifice is to be less than 6 ft/sec, and fishway width is 1.5 feet. The upstream depth is 4 feet and downstream or tailwater depth is 3 feet. Channel friction may be neglected.

Given:

$H = 4.00$ ft.
$H_t = 3.00$ ft.
$B = 1.50$ ft.
$b = 0.525$ ft.
$d = 0.742$ ft.
$\phi = 45^o$

$S = .05$
$L = 100$ ft.
$N = 9$ ft.
$n = 10$ slots (plus entrance and exit slots)
$V_{max} = 6.00$ ft/sec.

$m = \frac{1.50-.525}{1.50} = 0.65$

$C_d = 28.0$ (Fig. A-2).

Design a fishway culvert with the given dimensions and specifications above to meet the maximum velocity using the graphs obtained in this study and studies performed by Dass (1970).

Try 1:

Assume Q = 7.00 cfs.

Downstream analysis:

$$F = \frac{7.00}{(5.674)(1.50)(3.00)^{3/2}} = .1583; \quad \frac{H_f}{H_t} = 1.18 \text{ and } H_f = 3.54 \text{ ft.} \quad \text{(Fig. A-2)}$$

Upstream analysis:

$$F = \frac{7.00}{(5.674)(1.50)(4.00)^{3/2}} = .1028; \quad \frac{H}{h_1} = 1.028 \text{ and } h_1 = 3.89 \text{ ft. (Fig. 25)}$$

$$\Delta h = \frac{3.89-3.54}{10} = 1.035; \quad h_{10} = 3.575$$

$$\sum_{n=1}^{10} \frac{1}{h} = \frac{10}{2}\left(\frac{1}{3.89} + \frac{1}{3.575}\right) = 2.688$$

Substituting into momentum equation:

$$(.65)(28)(2.688) \overset{?}{=} 2\left(\frac{1}{3.89} - \frac{1}{3.54}\right) + \frac{32.2(1.50)^2}{(7.00)^2}\Big((3.89^2 - 3.54^2) +$$

$$(10)(9)(.05)\ (3.89 + 3.54)\Big)$$

$$48.922 \overset{?}{=} .051 + 1.479\ (36.035)$$

$$48.922 \neq 53.245 \text{ or } 48.9 \neq 53.2$$

A higher value of Q is assumed.

Try 2:

Assume Q = 7.30 cfs.

Downstream analysis:

$$F = \frac{7.30}{(5.674)(1.50)(3.00)^{3/2}} = .1651; \ \frac{H_f}{H_t} = 1.21 \text{ and } H_f = 3.63 \text{ ft.} \quad \text{(Fig. A-2)}$$

Upstream analysis:

$$F = \frac{7.30}{(5.674)(1.50)(4.00)^{3/2}} = .1072; \ \frac{H}{h_1} = 1.032 \text{ and } h_1 = 3.88 \text{ ft.} \quad \text{(Fig. 25)}$$

$$\Delta h = \frac{3.88-3.63}{10} = .025; \ h_{10} = 3.655 \text{ ft.}$$

$$\sum_{10} \frac{1}{h} = \frac{10}{2} \left(\frac{1}{3.88} + \frac{1}{3.655}\right) = 2.657$$

Substituting into momentum equation:

$$(.65)(28)(2.657) \underset{-}{?} 2 \left(\frac{1}{3.88} - \frac{1}{3.63}\right) + \frac{32.2(1.50)^2}{(7.30)^2} \Big((3.88^2 - 3.63^2) +$$

$$(10(9)(.05) \ (3.88 + 3.63)\Big)$$

$$48.357 \underset{-}{?} - .036 + 1.360 \ (35.673)$$

$$48.357 \simeq 48.479 \text{ or } 48.4 \simeq 48.5$$

Try 3:

The correct value of Q is between 7.30 and 7.40 cfs.

The best approximate value to equate both sides of momentum equation is Q = 7.31 cfs.

With this value of Q = 7.31 cfs;

Downstream analysis:

$$F = .1655; \ \frac{H_f}{H_t} = 1.21 \text{ and } H_f = 3.63 \text{ ft.} \quad \text{(Fig. A-2).}$$

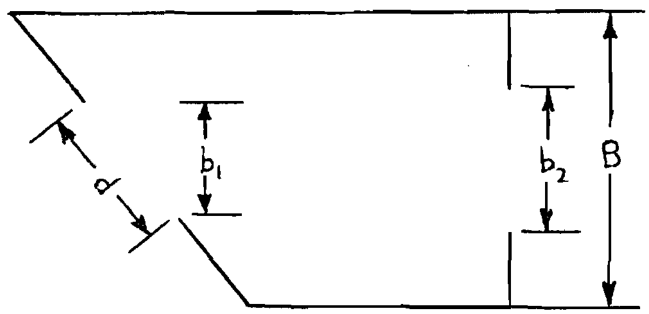


Figure 38. Definition sketch for different contraction ratio m for the skewed opening and normal slots further downstream.

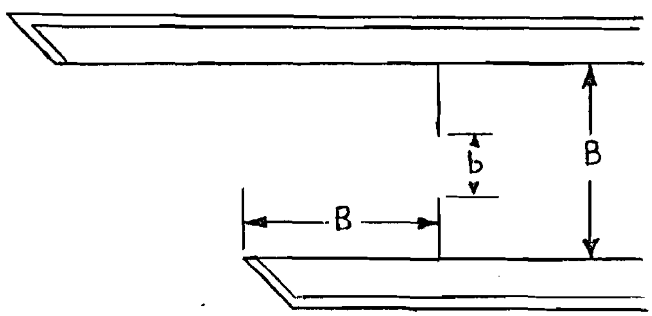


Figure 39. Possible alternate opening proposed by the Idaho Fish and Game Commission.

Upstream analysis:

$F = .1075;\ \frac{H}{h_1} = 1.032$ and $h_1 = 3.88$ ft. (Fig. 25)

$\Delta h = \frac{3.88 - 3.63}{10} = .025;\ h_{10} = 3.655$ ft.

$$\sum_{10} \frac{1}{h} = \frac{10}{2}\left(\frac{1}{3.88} + \frac{1}{3.655}\right) = 2.657$$

Substituting into momentum equation:

$$(.65)(28)(2.657) \stackrel{?}{=} 2\left(\frac{1}{3.88} - \frac{1}{3.63}\right) + \frac{32.2(1.50)^2}{(7.31)^2}\Big((3.87^2 - 3.63^2) + (10)(9)(.05)(3.88 + 3.63)\Big)$$

$$48.357 \stackrel{?}{=} -.034 + 1.356\ (35.673)$$

$$48.357 \simeq 48.339 \text{ or } 48.4 \simeq 48.3 \quad \text{O.K.}$$

Check for velocity:

a. At fishway exit:

$$V_{up} = \frac{7.31}{(.35)(2.12)(4.00)} = 2.46 \text{ ft/sec}$$

b. Through first normal slot:

$$V_1 = \frac{7.31}{(.35)(1.50)(3.85)} = 3.59 \text{ ft/sec}$$

c. Through downstream slot

$$V_f = \frac{7.31}{(.35)(1.50)(3.63)} = 3.84 \text{ ft/sec}$$

d. Through fishway entrance gate:

$$V_t = \frac{7.31}{(.35)(1.50)(3.00)} = 4.64 \text{ ft/sec} \qquad \text{O.K.}$$

The final design is illustrated in Figure 40.

Different Contraction Coefficient for Skewed Exit

The design example illustrated in the previous section takes into consideration that the contraction ratio of the skewed exit is the same value as the other normal positioned slots. This means that the skewed slot opening is larger than the normal slot opening (Figure 38), i.e. $b_1 = b_2$ or $b_2 < d$. In this particular case the contraction ratio of the skewed exit would be smaller than other slots. Though this could create higher velocities through the skewed orifice or decrease the discharge through the fishway, it may in some instances be a satisfactory solution.

Example 2

This example is for a design which is similar to Example 1 except that two different values of m are considered, one for the skewed fishway exit as developed in this study, and the other for the remainder of the orifices in the fishway. The values of fishway width B, slope S, skew angle ϕ, and maximum design velocity are selected. An upstream water depth H and downstream depth h are assumed. A skewed slot width d is selected and set equal to the downstream width b of the normal orifices. The appropriate H/h ratio is determined and the corresponding Froude number is obtained from the curves. A value for discharge Q is assumed. The momentum equation developed by Dass is used to determine the value of Q. The velocity of water through the skewed slot exit, through the upper and lower normal slot orifices, and through the fishway entrance are evaluated and compared to the maximum allowable design velocity.

The problem is to design a suitable fishway culvert 100 ft. in length placed on a 4.5 percent slope. The maximum allowable velocity at the throat of the entrance orifice is 6 ft/sec and fishway width is 1.5 feet. The upstream depth is 5 feet and downstream or tailwater depth is 4 feet. Channel friction is neglected.

The objective of this problem is to design a fishway with different contraction ratios for the skewed upstream orifice exit and normal downstream orifices.

Given:

$H = 5.00$ ft.
$H_t = 4.00$ ft.
$B = 1.50$ ft.
$b = .50$ ft.
$d = .50$ ft.
$D = 2.121$ ft.
$\phi = 45^\circ$

$s = .045$
$L = 100$ ft.
$N = 9$ ft.
$n = 10$ slots (plus entrance and exit slot)
$V_{max} = 6.00$ ft/sec

$$m_{or} = \frac{2.121 - .500}{2.121} = 0.76$$

$$m_{sl} = \frac{1.50 - .50}{1.50} = 0.67$$

$C_d = 31.0$ (Fig. A-2)

Design a fishway culvert with the dimensions and specifications listed above.

Try 1:

Assume $Q = 8.00$ cfs.

Downstream analysis:

$$F = \frac{8.00}{5.674(1.5)(4.00)^{3/2}} = .1175;$$

$H_f/H_t = 1.08$ and $H_f = 4.32$ ft. (Fig. A-3)

Upstream analysis:

$$F = \frac{8.00}{5.674(.15)(5.00)^{3/2}} = .0841;$$

$H/h_1 = 1.05$ and $h_1 = 4.76$ ft. (Fig. 19)

$$\Delta h = \frac{4.76 - 4.32}{10} = .044; \quad h_{10} = 4.364$$

$$\sum_{10} \frac{1}{h} = \frac{10}{2} \left(\frac{1}{4.76} + \frac{1}{4.364}\right) = 2.196$$

Substituting into momentum equation:

$$.67(31)(2.196) \underset{-}{?}\ 2\ (\frac{1}{4.76} - \frac{1}{4.32}) + \frac{32.2(1.5)^2}{(8.00)^2}\Big((4.76^2 - 4.32^2) +$$

$$(10)(9)(.045)(4.76 + 4.32)\Big)$$

$$45.611 \underset{-}{?} -.043 + 1.132\ (40.769)$$

$$45.611 \neq 46.108 \text{ or } 45.6 \neq 46.1$$

Try 2:

Assume $Q = 8.10$ cfs.

Downstream analysis:

$$F = \frac{8.10}{5.674(1.5)(4.00)^{3/2}} = .1190; \qquad \text{(Fig. A-3)}$$

$$\frac{H_f}{H_t} = 1.09 \text{ and } H_f = 4.36 \text{ ft.}$$

Upstream analysis:

$$F = \frac{8.0}{5.674(1.5)(5.00)^{3/2}} = .0851; \qquad \text{(Fig. 19)}$$

$$\frac{H}{h_1} = 1.05 \text{ and } h_1 = 4.76 \text{ ft.}$$

$$\Delta h = \frac{4.76 - 4.36}{10} = .040;\ h_{10} = 4.400 \text{ ft.}$$

$$\sum_{10} \frac{1}{h} = \frac{10}{2}\ (\frac{1}{4.76} + \frac{1}{4.40}) = 2.187$$

Substituting into momentum equation:

$$.67(31)(2.187)\ \underset{-}{?}\ 2(\frac{1}{4.76} - \frac{1}{4.36}) + \frac{32.2(1.5)^2}{(8.10)^2}\Big((4.76^2 - 4.36^2) +$$

$$(10)(9)(0.45)(4.76 + 4.36)\Big)$$

$$45.424 \underset{-}{?} -.039 + 1.104\ (40.584)$$

$$45.424 \simeq 44.766 \text{ or } 45.4 \neq 44.8$$

Try 3:

The correct value for Q is between 8.00 cfs. and 8.10 cfs.

The best approximate value to equate both sides of momentum equation is Q = 8.04 cfs.

With this value of Q = 8.04 cfs:

Upstream analysis:

$$F = .1183; \ \frac{H_f}{H_t} = 1.085 \text{ and } H_f = 4.34 \text{ ft.} \qquad \text{(Fig. A-3)}$$

Downstream analysis:

$$F = .0846; \ \frac{H}{h_1} = 1.05 \text{ and } h_1 = 4.76 \text{ ft.} \qquad \text{(Fig. 19)}$$

$$\Delta h = \left(\frac{4.76 - 4.34}{10}\right) = .042; \ h_{10} = 4.382 \text{ ft.}$$

$$\sum_{10} \frac{1}{y_{10}} = \frac{10}{2} \left(\frac{1}{4.76} + \frac{1}{4.382}\right) = 2.191$$

Substitute into momentum equation:

$$.67(31)(2.191) \overset{?}{=} 2 \left(\frac{1}{4.76} - \frac{1}{4.34}\right) + \frac{32.2(1.5)^2}{(8.04)^2} \Big((4.76^2 - 4.34^2) +$$

$$(10)(9)(.045)\ (4.76 + 4.34)\Big)$$

$$45.507 \overset{?}{=} -.041 + 1.121(40.677)$$

$$45.507 \simeq 45.554 \text{ or } 45.5 \simeq 45.6 \quad \text{O.K.}$$

Check velocities:

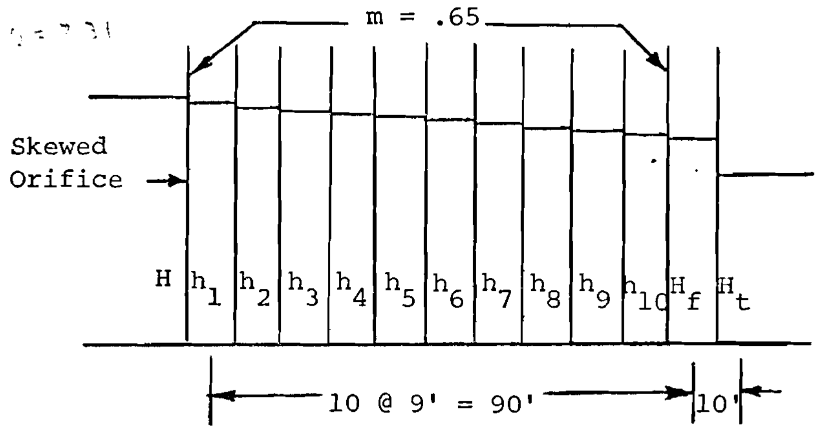
a) At fishway exit $V_u = \frac{8.04}{(.24)(2.12)(5.00)} = 3.16$ ft/sec

b) Through first normal slot $V_1 = \frac{8.04}{(.33)(1.50)(4.76)} = 3.41$ ft/sec

c) Through downstream slot $V_f = \frac{8.04}{(.33)(1.50)(4.382)} = 3.71$ ft/sec

d) Through fishway entrance gate $V_t = \frac{8.04}{(.33)(1.50)(4.00)} = 4.06$ ft/sec.

The final design is illustrated in Figure 41.

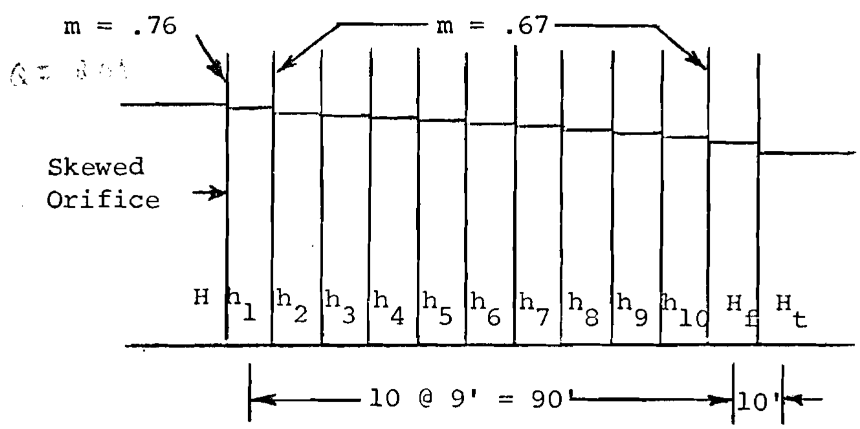


$H = 4.00$ ft.
$h_1 = 3.88$ ft.
$h_{10} = 3.655$ ft.
$H_f = 3.63$ ft.
$H_t = 3.00$ ft.
$D = 2.12$ ft.

$B = 1.50$ ft.
$S = .05$
$N = 9$ ft.
$n = 10$
$\phi = 45^{\circ}$

$b = .525$ ft.
$d = .742$
$V_{max} = 4.64$ ft/sec. at fishway gate.

Figure 40. Final design for Example 1.



$H = 5.00$ ft.
$h_1 = 4.76$ ft.
$h_{10} = 4.382$ ft.
$H_f = 4.34$ ft.
$H_t = 4.00$ ft.
$D = 2.12$ ft.

$B = 1.50$ ft.
$S = .045$
$N = 9$ ft.
$n = 10$
$\phi = 45^{\circ}$

$b = .50$ ft.
$d = .50$ ft.
$V_{max} = 4.06$ ft/sec. at fishway gate.

Figure 41. Final design for Example 2.

Alternate Opening

The Idaho Fish and Game Commission has proposed designing a fishway with the first upstream slot constructed one fishway width (B) downstream from the opening (Figure 39). This distance would be measured from the inside (side alongside the main culvert) edge of the fishway. It was hypothesized that this would be an adequate design. The depth of water upstream of the first opening would be assumed equal to the headwater depth at the wingwall. The remainder of the flume would be analyzed according to the method and procedure outlined by Dass (1970) in his study of fishways.

CHAPTER VII

CONCLUSIONS

A study of the habits and requirements of fish and of difficulties encountered in providing satisfactory fish passage through culverts led to the development of a vertical slot orifice structure. Skewed slot orifices for fishway exits were examined and hydraulic design criterion were developed for hydraulic analysis. This will allow the designer to install the fishway exit in the retaining wall of the culvert. Design criteria were developed by using the concept of hydraulic laws and design aids developed by model studies. A procedure to design a slot orifice fishway was discussed. It is expected that this fishway will function satisfactorily with no loss of hydraulic efficiency in the main culvert. In addition the fishway should be self-cleaning.

Important factors in this analysis are summarized in the following discussion. These points were observed in this study:

1. Flow through a skewed slot orifice is a function of skew angle, contraction ratio and the relative depth of headwater to tailwater on either side of the orifice.

2. Slope and lateral placement of the fishway did not affect the rating curve for the skewed slot orifice.

3. Considerable turbulence was noted in all the observations, including the 75° runs.

4. Fish sweepback through the main culvert barrel will probably occur for the 30° skew orifice when the entrance is placed adjacent to the culvert barrel.

5. For all angles and contraction ratios examined in this experiment, the curve seems to approach a Froude number and discharge of zero as the H/h ratio approaches unity. More measurements for H/h ratios between 1.00 and 1.10 could have been made, specifically for $H/h < 1.05$.

6. Considerable turbulence and vortices were observed in the 30^{o} skewed slot runs, and therefore the use of a 30^{o} skewed slot entrance is not recommended for fishways. The skew angle should range from 45^{o} to 75^{o}.

7. Rate of flow was observed to increase with decreasing contraction ratio.

8. In any design of the fishway, considerations must be given to initial selection of the following variables: slope, fishway spacing, number of slots, headwater depth above skewed orifice, tailwater depth below entrance gate, and contraction ratio. The throat velocity through the fishway entrance slots, both normal and skewed, must be less than the fish performance capacity. In addition the ratio of the headwater to tailwater about the fishway entrance gate, or H_f/H_t, as discussed in Dass(1970) should be checked to insure that velocity through the orifice does not exceed the specified design velocity.

CHAPTER VIII

RECOMMENDATIONS

Because of limited time and resources available, many aspects of this investigation were not completely covered. Some of these are listed below.

1. Additional data for the curve of F vs. H/h for low values of H/h would be helpful. Most prototype design problems for skewed slot orifices will require using H/h values of 1.01 to 1.10. The lowest value obtained for H/h was about 1.05. It was necessary in this study to extrapolate the curve to H/h = 1.0 using a theoretical curve shape.

2. This study did not include measurement of turbulence in the water flow. It appears obvious from the illustrations herein (Figures 37a, 37b) that significant turbulence existed. A check should be made on the intensity of turbulence inside the fishway.

3. An approximate check on the maximum velocity was obtained in this study. However, a study to determine the maximum velocity inside the fishway is recommended.

4. It appears that the results of this study apply for a wide range of head variation. This range of the slot contraction ratio and channel slope should be expanded to provide more flexibility in design.

5. Full scale prototype structures of the fishway should be constructed in the field and evaluated by both engineers and fishery biologists. What appears to be a good solution in the laboratory is not always satisfactory in the field, particularly when biological activity is concerned.

NOTATION

A	cross sectional area of flow	ft^2
B	normal width of fishway	ft.
b	normal width of slot orifice	ft.
C	coefficient of discharge	dimensionless
D	skewed width of fishway	ft.
d	skewed width of slot orifice	ft.
e	eccentricity of slot orifice; x_1/x_2	dimensionless
F	Froude number; $V/\sqrt{gy}$ or $Q/(\sqrt{g}\,BH^{3/2})$	dimensionless
F	force	lb.
g	acceleration due to gravity; 32.2	ft/sec^2
H	depth of flow above skewed slot orifice, measured perpendicular from channel bottom	ft.
h	depth of flow below skewed slot orifice, measured perpendicular from channel bottom	ft.
H_t	depth of flow below tailgate	ft.
k	coefficient	dimensionless
L	length of fishway or culvert	ft.
m	contraction ratio	dimensionless
N	spacing between slots in fishway	ft.
n	number of slots	dimensionless
P	hydrostatic pressure	lb/ft^2
p	ratio of headwater to tailwater at skewed slot orifice; H/h	dimensionless
Q	volume rate of flow; total discharge at channel cross section	ft^3/sec; gal/min
S	slope of channel	dimensionless

V	velocity of flow	ft/sec
W	weight of water between arbitrary sections	lb.
x_1	length of shorter constriction	ft.
x_2	length of longer constriction	ft.
y	vertical depth of water for any location in channel	ft.
z_1	upstream reference point above datum	ft.
z_2	downstream reference point above datum	ft.
γ	specific weight of water; 62.4	lb/ft^3
θ	angle of channel with respect to horizontal datum	dimensionless
ρ	density or mass per unit volume of water; γ/g; 1.935	$\frac{slug}{ft^3}$; $\frac{(lb\ sec^2)}{ft^4}$
ϕ	angle of skewness measured with respect to axis of flow	dimensionless
Δ	change in; difference	depends on term of parameter

Subscripts

c	critical
d	drag force
f	final; above tailgate
fr	frictional or drag force
or	orifice
sl	slot
t	tailwater; downstream
up	upstream

DEFINITIONS

Approach Section - This is the section which marks the beginning of flow acceleration approaching the orifice constriction; it marks the boundary of the culvert's influence zone.

Contraction Ratio - This is the ratio of the obstructed width of orifices in a channel section to the total width of the channel. This width can be normal or skewed with respect to direction of flow. In equation form: $m = \frac{B-b}{B}$ or $m = \frac{D-d}{D}$.

Control Surface - Boundary of a control volume; it is considered to be a fixed region in the channel considered and is used in the analysis of situations where flow occurs in and out of this region. It is normal to the direction of flow.

Critical Flow - The term used to describe open channel flow when certain relationships exist between specific energy and discharge and between specific energy and depth. The Froude Number is unity.

Culvert Barrel - The main section of the fishway model, where most of the water flows downstream. The flow in this section is supercritical. Fish do not use the culvert barrel for their upstream migration, instead they use the adjoining fishway channel.

Fishway Exit - The location of the skewed orifices (in this thesis) which marks the upstream opening of the fish channel.

Froude Number - A dimensionless parameter that indicates whether flow in open channel is subcritical ($F < 1$), critical ($F = 1$), or supercritical ($F > 1$). It is a ratio of inertial forces to gravity forces. In equation form, $F = V/\sqrt{gy}$.

Headwater - Water flow in an open channel immediately above or upstream of an orifice, culvert, spillway, or other inlet.

Headwater depth - elevation of headwater, measured from the channel bottom to the water surface.

Hydraulic Efficiency - The ratio of depth of flow in a culvert operating without baffles divided by the depth of flow for the same discharge and culvert barrel dimensions with baffles in place.

Influence Zone - Region of flow in the vicinity of or within a culvert. The natural flow regime of the channel is altered, and the flow depth and velocity are dependent upon the diameter, slope and length of the culvert.

Invert - In a culvert, this is the lowest point of its cross-sectional area. For a rectangular culvert, it would be the entire bottom surface of its cross section.

Open Channel - A conduit or conveyance device in which water flows with a free surface, or exposed to the atmosphere. This definition also applies to culverts which flow partly full.

Tailwater - Water flow in an open channel immediately below or downstream of an orifice, culvert, spillway, or other outlet.

Tailwater Depth - elevation of tailwater, measured from the channel bottom to the water surface.

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APPENDIX

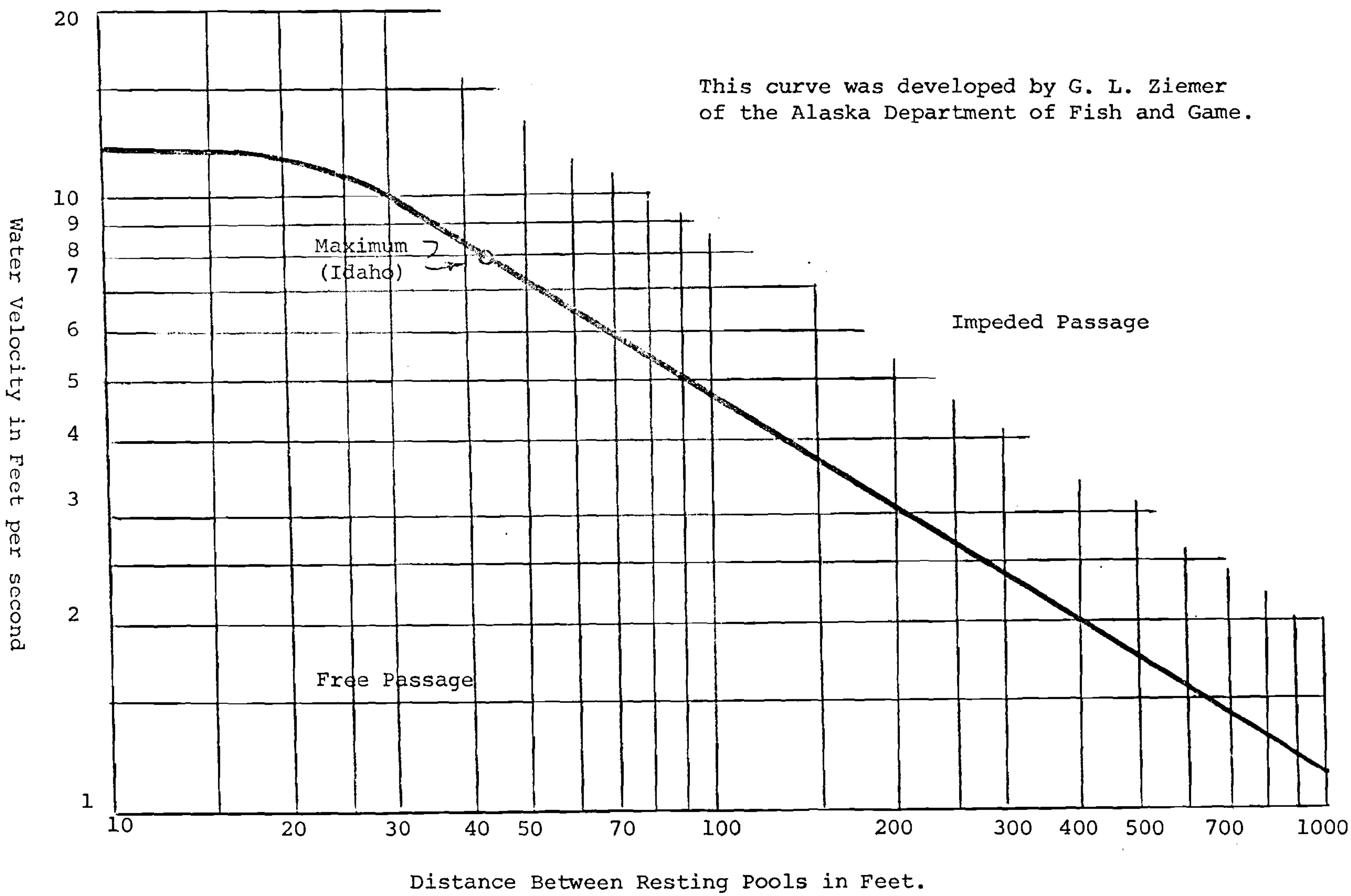

Figure A-1. Swimming Capability of Migrating Salmon.

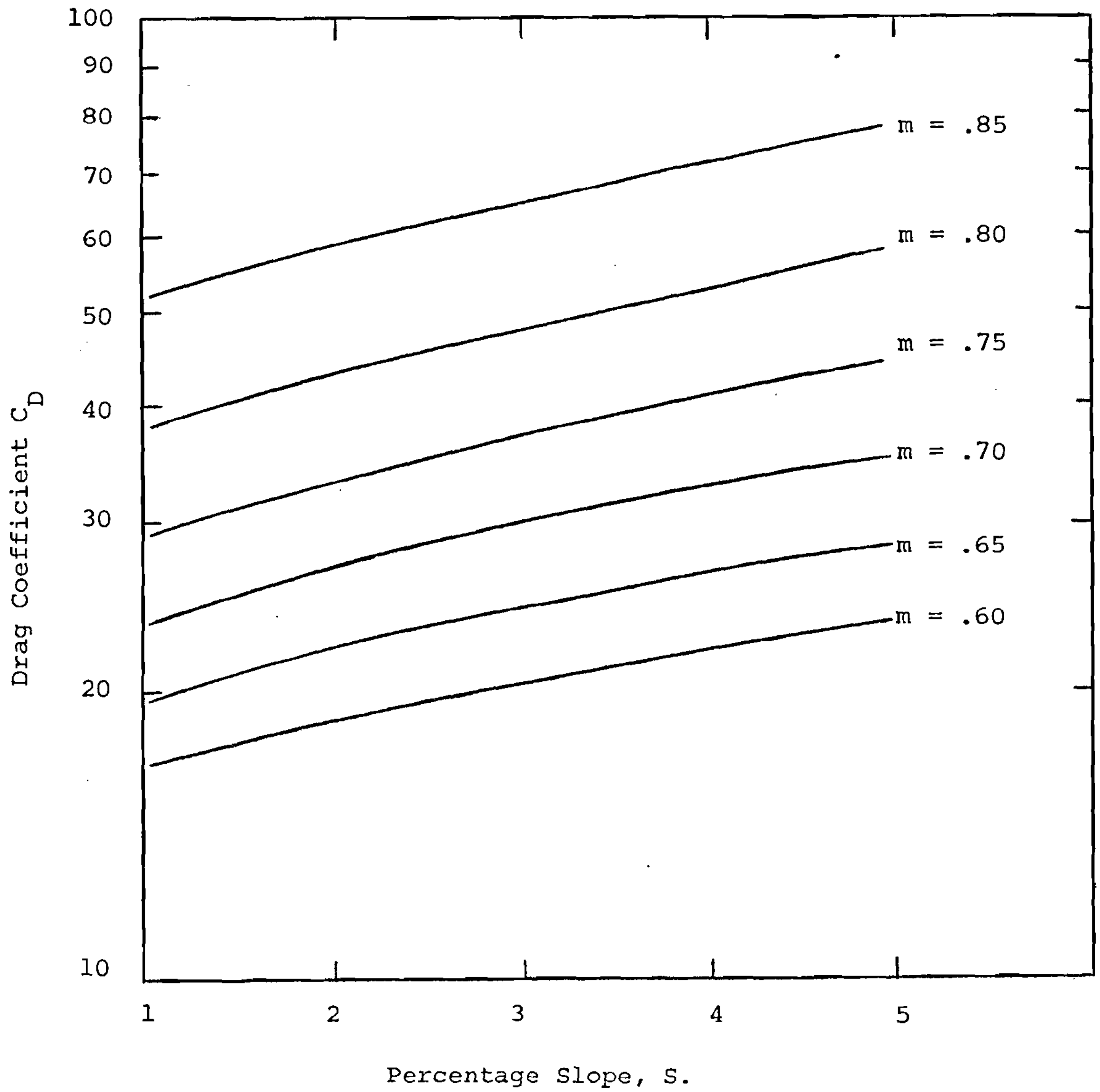

Figure A-2. Value of drag coefficient for interpolated m values at a spacing of 6B (Dass, 1970).

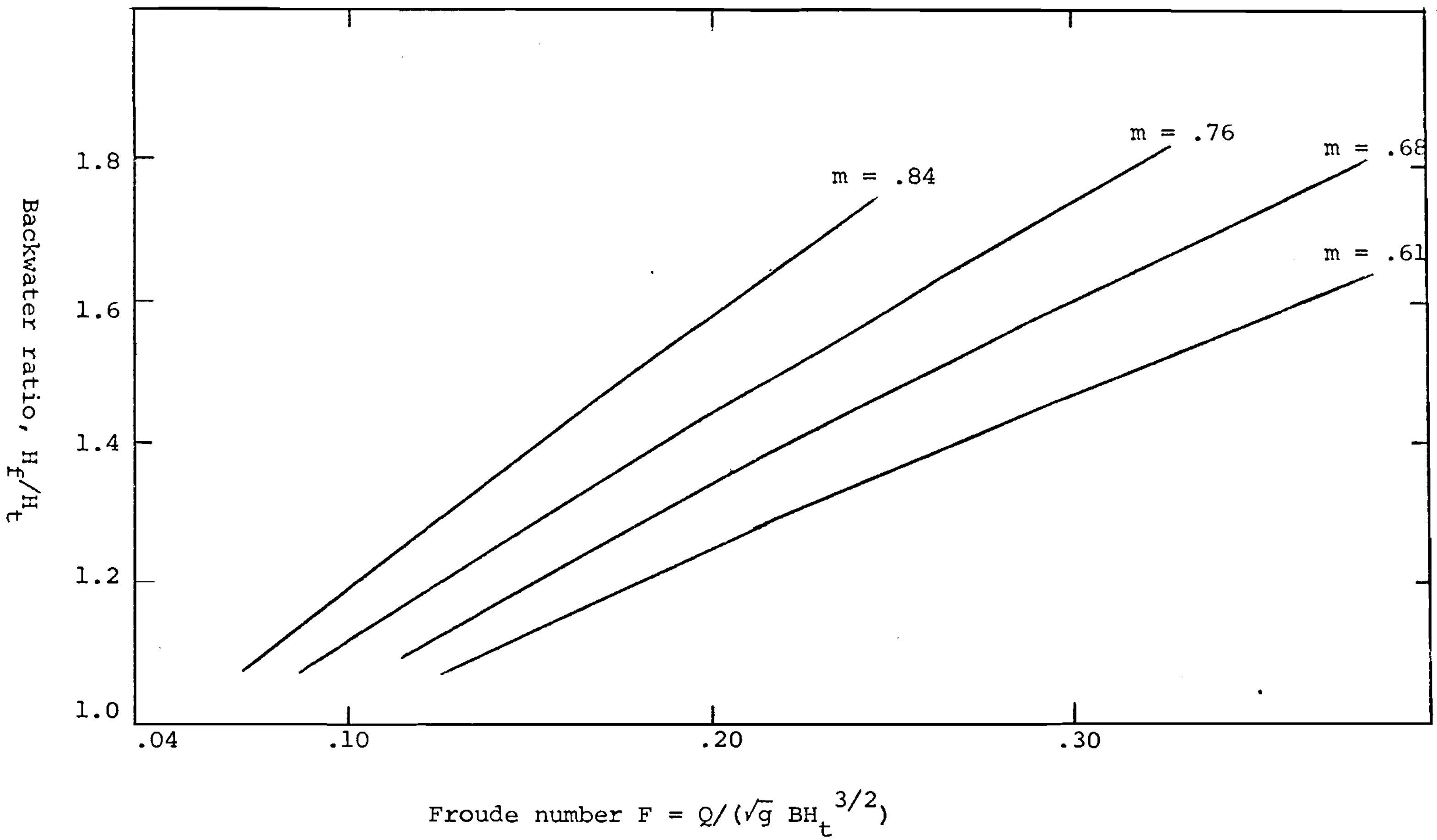

Figure A-3. Backwater relation for the slot orifices (Dass, 1970).

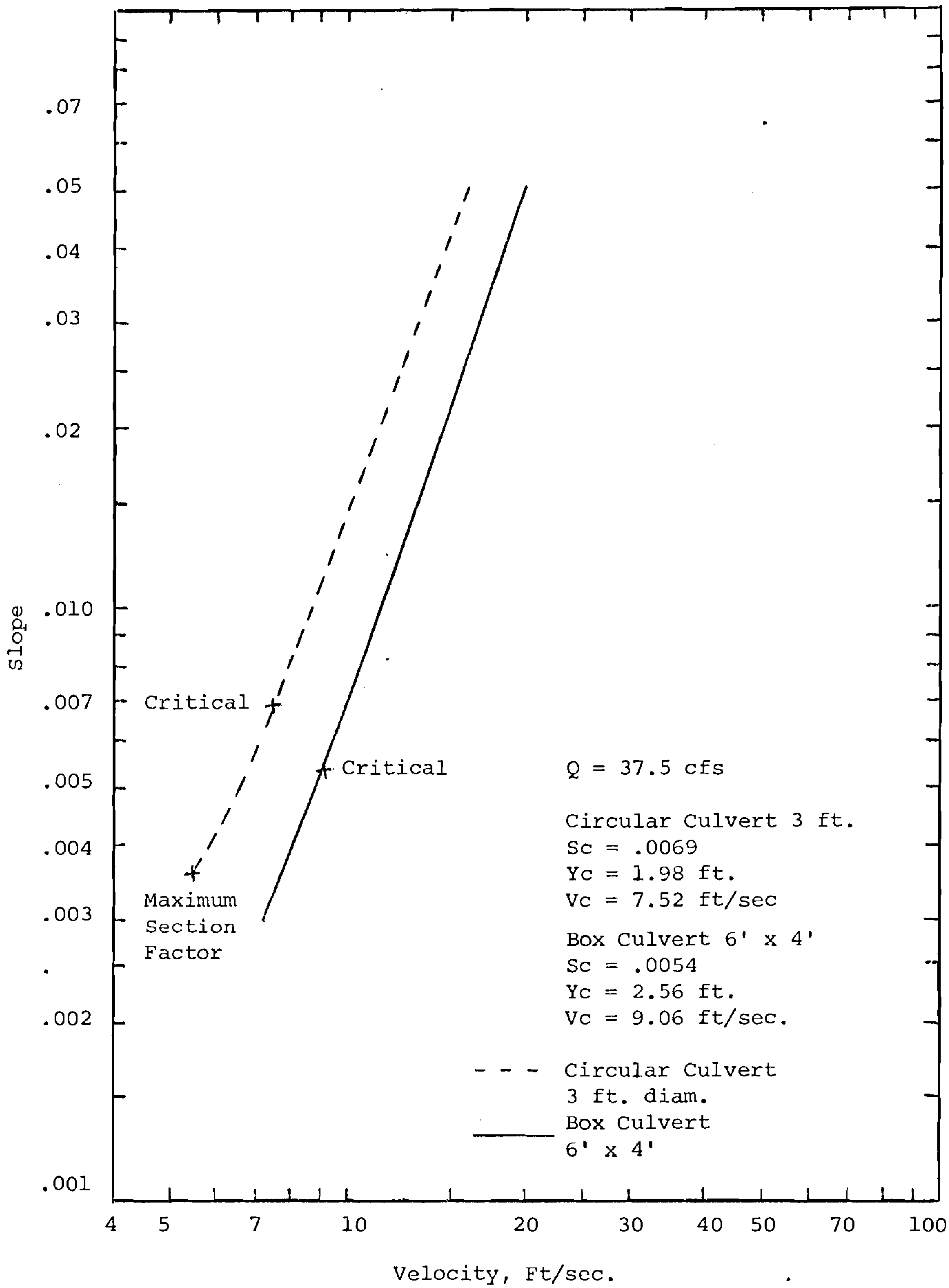

Figure A-4. Critical Velocity as a function of slope for rectangular and circular culverts.

TABLE A-1

Sample observation data. $\phi = 30^{o}$

Angle & Position	30^{o} center	Slope Correction (SL)	.041
Slope	.025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.270 ft = 3¼"	H_t corr = H_t-ref. + SL - W.C.	
Skewed Width	.540 ft = 6½"		

	in	in	in	in	in	in	ft	ft	ft
in.	H_1	H_2	h_1	h_2	H-ref.	h-ref.	H_t	H_t-ref.	$H_t$corr
Ref.	2.01	1.99	2.00	2.00			0.749		
.61	7.34	7.40	5.26	5.40	5.37	3.33	1.285	.536	.327
.68							1.264	.515	.306
.76							1.242	.493	.284
.84							1.227	.478	.269
.61	7.34	7.40	5.91	5.93	5.37	3.92	1.274	.525	.316
.68							1.253	.504	.295
.76							1.233	.484	.275
.84							1.216	.467	.258
.61	7.34	7.40	6.22	6.22	5.37	4.22	1.253	.504	.295
.68							1.241	.492	.283
.76							1.225	.476	.267
.84							1.209	.460	.251
.61	7.34	7.40	6.48	6.44	5.37	4.46	1.243	.494	.285
.68							1.231	.482	.273
.76							1.213	.464	.255
.84							1.202	.453	.244
.61	7.34	7.40	6.94	6.86	5.37	4.90	1.235	.486	.277
.68							1.223	.474	.265
.76							1.208	.459	.250
.84							1.195	.446	.237
.61	7.34	7.40	7.15	7.05	5.37	5.10	1.214	.465	.256
.68							1.204	.455	.246
.76							1.189	.440	.231
.84							1.182	.433	.224

TABLE A-2

Sample observation data. $\phi = 30^{o}$

Angle & Position	30^{o} center	Slope Correction (SL)	.041
Slope 2½%	= .025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.270 ft = 3¼"	$H_t$corr = H_t - ref. + SL - W.C.	
Skewed Width	.540 ft = 6½"		

m	ft H	ft h	H/h	$H^{3/2}$	ft $H_t$corr	gpm Q	cfs Q	F	d/D
.65	.448	.425	1.054	.300	.256	37.87	.084	.183	.343
		.408	1.098		.277	45.31	.101	.220	
		.372	1.204		.285	48.28	.108	.235	
		.352	1.273		.295	52.09	.116	.252	
		.327	1.370		.316	60.47	.135	.294	
		.278	1.611		.327	65.05	.145	.316	
.72	.448	.425	1.054	.300	.246	34.51	.077	.168	.280
		.408	1.098		.265	40.99	.091	.198	
		.372	1.204		.273	43.85	.098	.213	
		.352	1.273		.285	48.28	.108	.235	
		.327	1.370		.295	52.09	.116	.252	
		.278	1.611		.316	60.47	.135	.294	
.79	.448	.425	1.054	.300	.231	29.73	.066	.144	.209
		.408	1.098		.250	35.84	.080	.174	
		.372	1.204		.255	37.53	.084	.183	
		.352	1.273		.267	41.70	.093	.202	
		.327	1.370		.275	44.57	.099	.215	
		.278	1.611		.284	47.90	.107	.233	
.82	.448	.425	1.054	.300	.224	27.60	.061	.133	.180
		.408	1.098		.237	31.67	.071	.155	
		.372	1.204		.244	33.86	.075	.163	
		.352	1.273		.251	36.17	.081	.176	
		.327	1.370		.258	38.55	.086	.187	
		.278	1.611		.269	42.41	.094	.205	

TABLE A-3

Sample observation data. $\phi = 45^o$

Angle & Position	45^o center	Slope Correction (SL)	.041
Slope	.025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.375 ft = 4½"	H_t corr = H_t - ref. + SL - W.C.	
Skewed Width	.530 ft = 6 3/8"		

	in	in	in	in	in	in	ft	ft	ft
in.	H_1	H_2	h_1	h_2	H-ref.	h-ref.	H_t	H_t-ref.	H_t corr
Ref.	2.00	2.00	2.04	2.02			0.749		
.61	7.57	7.59	5.52	5.52	5.58	3.28	1.308	.559	.350
.68							1.285	.536	.327
.76							1.261	.512	.303
.84							1.250	.501	.292
.61	7.57	7.59	5.98	5.94	5.58	3.93	1.299	.550	.341
.68							1.275	.526	.317
.76							1.249	.500	.291
.84							1.239	.490	.281
.61	7.57	7.59	6.36	6.28	5.58	4.29	1.291	.542	.333
.68							1.268	.519	.310
.76							1.241	.492	.283
.84							1.230	.481	.272
.61	7.57	7.59	6.64	6.60	5.58	4.59	1.282	.533	.324
.68							1.259	.510	.301
.76							1.232	.483	.274
.84							1.217	.468	.259
.61	7.57	7.59	6.93	6.85	5.58	4.86	1.261	.512	.305
.68							1.243	.494	.285
.76							1.225	.476	.267
.84							1.210	.461	.252
.61	7.57	7.59	7.23	7.17	5.58	5.17	1.235	.486	.277
.68							1.215	.466	.247
.76							1.200	.451	.242
.84							1.190	.441	.232

TABLE A-4

Sample observation data. $\phi = 45^{\circ}$

Angle & Position	45° center	Slope Correction (SL)	.041
Slope 2½%	= .025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.375 ft = 4½"	$H_t$corr = H_t - ref. + SL - W.C.	
Skewed Width	.530 ft = 6 3/8"		

m	ft H	ft h	H/h	$H^{3/2}$	ft $H_t$corr	gpm Q	cfs Q	F	d/D
.65	.465	.431	1.079	.317	.277	45.31	.101	.150	.349
		.405	1.148		.303	55.23	.123	.182	
		.382	1.217		.324	63.79	.142	.210	
		.358	1.299		.333	67.60	.151	.224	
		.328	1.418		.341	71.06	.158	.234	
		.291	1.598		.350	75.03	.167	.248	
.72	.465	.431	1.079	.317	.257	38.21	.085	.126	.285
		.405	1.148		.285	48.28	.108	.160	
		.382	1.217		.301	54.44	.121	.179	
		.358	1.299		.310	58.03	.129	.191	
		.328	1.418		.317	60.88	.136	.202	
		.291	1.598		.327	65.05	.145	.215	
.79	.465	.431	1.079	.317	.242	33.21	.074	.110	.213
		.405	1.148		.267	41.70	.093	.138	
		.382	1.217		.274	44.21	.099	.147	
		.358	1.299		.283	47.53	.106	.157	
		.328	1.418		.291	50.55	.113	.167	
		.291	1.598		.303	55.23	.123	.182	
.82	.465	.431	1.079	.317	.232	30.04	.067	.099	.183
		.405	1.148		.252	36.51	.081	.120	
		.382	1.217		.259	38.90	.087	.129	
		.358	1.299		.272	43.49	.097	.144	
		.328	1.418		.281	46.78	.104	.154	
		.291	1.598		.292	50.94	.114	.169	

TABLE A-5

Sample observation data. $\phi = 60^o$

Angle & Position	60^o center	Slope Correction (SL)	.041
Slope	.025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.460 ft = 5½"	H_t corr = H_t ∸ ref. + SL - W.C.	
Skewed Width	.530 ft = 6 3/8"		

	in	in	in	in	in	in	ft	ft	ft.
in.	H_1	H_2	h_1	h_2	H-ref.	h-ref.	H_t	H_t-ref	$H_t$corr
Ref.	1.99	1.99	1.98	1.98			0.749		
.61	7.62	7.64	5.20	5.10	5.64	3.17	1.285	.536	.327
.68							1.261	.512	.303
.76							1.234	.485	.276
.84							1.217	.468	.269
.61	7.62	7.64	5.87	5.75	5.64	3.83	1.273	.524	.315
.68							1.251	.502	.293
.76							1.221	.472	.263
.84							1.201	.452	.243
.61	7.62	7.64	6.21	6.07	5.64	4.16	1.253	.504	.295
.68							1.231	.482	.273
.76							1.208	.459	.250
.84							1.193	.444	.235
.61	7.62	7.64	6.41	6.31	5.64	4.38	1.239	.490	.281
.68							1.218	.469	.260
.76							1.201	.452	.243
.84							1.186	.437	.228
.61	7.62	7.64	6.74	6.60	5.64	4.69	1.228	.479	.270
.68							1.207	.458	.249
.76							1.190	.441	.232
.84							1.178	.429	.220
.61	7.62	7.64	7.06	7.02	5.64	5.06	1.217	.468	.259
.68							1.198	.449	.240
.76							1.179	.430	.221
.84							1.164	.415	.206

TABLE A-6

Sample observation data. $\phi = 60^{o}$

Angle & Position	60^{o} center	Slope Correction (SL)	.041
Slope 2½%	= .025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.460 ft = 5½"	$H_t$corr = H_t - ref. + SL - W.C.	
Skewed Width	.530 ft = 6 3/8"		

m	ft H	ft h	H/h	$H^{3/2}$	ft $H_t$corr	gpm Q	cfs Q	F	d/D
.65	.470	.422	1.114	.322	.259	38.90	.087	.103	.349
		.391	1.202		.270	42.77	.095	.113	
		.365	1.288		.281	46.78	.104	.124	
		.347	1.354		.295	52.09	.116	.138	
		.319	1.473		.315	60.06	.134	.159	
		.264	1.780		.327	65.05	.145	.172	
.72	.470	.422	1.114	.322	.240	32.57	.073	.087	.285
		.391	1.202		.249	35.51	.079	.094	
		.365	1.288		.260	39.24	.087	.103	
		.347	1.354		.273	43.85	.098	.117	
		.319	1.473		.293	51.32	.114	.136	
		.264	1.780		.303	55.23	.123	.146	
.79	.470	.422	1.114	.322	.221	26.71	.060	.071	.213
		.391	1.202		.232	30.04	.067	.080	
		.365	1.288		.243	33.53	.075	.089	
		.347	1.354		.250	35.84	.080	.095	
		.319	1.473		.263	40.29	.090	.107	
		.264	1.780		.276	44.94	.100	.119	
.82	.470	.422	1.114	.322	.206	22.45	.050	.059	.183
		.391	1.202		.220	26.42	.059	.070	
		.365	1.288		.228	28.81	.064	.076	
		.347	1.354		.235	30.98	.069	.082	
		.319	1.473		.243	33.53	.075	.089	
		.264	1.780		.259	38.90	.087	.103	

TABLE A-7

Sample observation data. $\phi = 75^{o}$

Angle & Position	75^{o} center	Slope Correction (SL)	.041
Slope	.025	Weir Correction (W.C.)	.250 ft = 3"
Normal Width	.500 ft = 6"	$H_t$corr = H_t - ref. + SL - W.C.	
Skewed Width	.530 ft = 6 3/8"		

	in	in	in	in	in	in	ft	ft	ft
in.	H_1	H_2	h_1	h_2	H-ref.	h-ref.	H_t	H_t-ref	$H_t$corr
Ref.	2.02	2.02	2.00	2.00			0.749		
.61	7.63	7.65	5.23	5.31	5.62	3.27	1.290	.541	.332
.68							1.266	.517	.308
.76							1.240	.491	.282
.84							1.222	.473	.264
.61	7.63	7.65	5.69	5.77	5.62	3.73	1.273	.524	.315
.68							1.253	.504	.295
.76							1.226	.477	.268
.84							1.211	.462	.253
.61	7.63	7.65	6.11	6.21	5.62	4.16	1.260	.511	.302
.68							1.239	.490	.281
.76							1.214	.465	.256
.84							1.201	.452	.243
.61	7.63	7.65	6.42	6.48	5.62	4.45	1.248	.499	.290
.68							1.222	.473	.264
.76							1.198	.449	.240
.84							1.186	.437	.228
.61	7.63	7.65	6.74	6.78	5.62	4.76	1.231	.482	.273
.68							1.208	.459	.250
.76							1.186	.437	.228
.84							1.174	.425	.216
.61	7.63	7.65	7.17	7.23	5.62	5.20	1.214	.465	.256
.68							1.194	.445	.236
.76							1.178	.429	.220
.84							1.164	.415	.206

TABLE A-8

Sample observation data. $\phi = 75^o$

Angle & Position 75° center
Slope 2½% = .025
Normal Width .500 ft = 6"
Skewed Width .530 ft = 6 3/8"

Slope Correction (SL) .041
Weir Correction (W.C.) .250 ft = 3"
$H_t corr = H_t$ - ref. + SL - W.C.

m	H ft	h ft	H/h	$H^{3/2}$	$H_t$corr ft	Q gpm	Q cfs	F	d/D
.65	.468	.433	1.081	.320	.256	37.87	.084	.092	.349
		.397	1.179		.273	43.85	.098	.108	
		.371	1.261		.290	50.17	.112	.123	
		.347	1.349		.302	54.83	.122	.134	
		.311	1.505		.315	60.06	.134	.148	
		.272	1.721		.332	67.17	.150	.165	
.72	.468	.433	1.081	.320	.236	31.29	.070	.077	.285
		.397	1.179		.250	35.84	.080	.088	
		.371	1.261		.264	40.64	.091	.100	
		.347	1.349		.281	46.78	.104	.115	
		.311	1.505		.295	52.09	.116	.128	
		.272	1.721		.308	57.22	.127	.140	
.79	.468	.433	1.081	.320	.220	26.42	.059	.065	.213
		.397	1.179		.228	28.81	.064	.070	
		.371	1.261		.240	32.57	.073	.080	
		.347	1.349		.256	37.87	.084	.092	
		.311	1.505		.268	42.05	.094	.103	
		.272	1.721		.282	47.15	.105	.116	
.82	.468	.433	1.081	.320	.206	22.45	.050	.055	.183
		.397	1.179		.216	25.25	.056	.062	
		.371	1.261		.228	28.81	.064	.070	
		.347	1.349		.243	33.53	.075	.083	
		.311	1.505		.253	36.85	.082	.090	
		.272	1.721		.264	40.64	.091	.100	

TABLE A-9

Skewed slot opening widths

m	.61	.68	.76	.84
d_1 ft.	.185	.151	.113	.097
d_1 in.	2.22	1.82	1.36	1.16

TABLE A-10

Slope corrections

Slope	.015	.025
Corr.	.025	.041
Slope	.035	.045
Corr.	.057	.074