# ANALYSIS OF SLOT ORIFICE FISHWAYS

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# ABSTRACT

The object of this study was to develop design criteria for a slot orifice fishway. Sizing and spacing of slot orifices inside the fishway can be designed to create flow conditions satisfactory for fish passage. The slot orifice fishway will function well in a wide range of discharges and should not have any serious silting problems.

Values of drag coefficients for the slot orifice constrictions were evaluated by model studies for a range of slot openings varying from 0.6 to 0.85 of fishway width and culvert slope varying from horizontal to five percent. Three longitudinal spacings, 4, 5, and 6 times the fishway width, were considered for the slot orifices in the fishway. The effect of tailwater on the flow conditions at the fishway entrance was studied. The backwater relation of the slot orifice also was developed in the above range.

Nondimensional curves are given for the values of the drag coefficients of the slot orifice constrictions and also for the backwater relations for the slot orifices. An equation, based on momentum principle, is developed which enables the designer to find the rate of flow through the fishway. Necessary criteria regarding suitability of flow for fish passage are also developed.

# CHAPTER I

## INTRODUCTION

High velocity flow generated in steep culverts blocks upstream migration of fish. In general, this degrades fish habitat and results in a great loss of recreational value of the stream.

As a solution of this fish barrier problem, different measures have been proposed and put into use in the past. Early efforts centered around the use of a pool and weir fishway (4, 5, 12).[1] Satisfactory hydraulic conditions are not achieved unless the culvert is wide and shallow. This becomes quite uneconomical from a construction point of view. Other efforts include alternate paired baffles and offset type baffles (9). Their performance is unsatisfactory when operating at other than design head. Also, all of these fishway structures suffer from silt deposition and the baffles result in a reduction of the hydraulic efficiency of the culvert.[2]

The purpose of this study was to develop a culvert fishway with the following characteristics:

1. Stable low velocity flow in the fishway throughout a wide range of discharge;

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[1] The numbers within parenthesis refer to the references listed at the end of the paper.

[2] Efficiency is defined (9) as the ratio of the 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.

2. Self-cleaning,i.e., deposited and other heavier particles should be flushed out of the fishway;

3. Efficient, i.e., the flow capacity of the culvert should not be reduced;

4. Simple and economical to construct.

After careful considerations, it appeared that a fishway made up of a series of a vertical slot orifices constructed beside the main culvert, would come the closest to meeting the above criteria. Extra construction cost of the slot orifice fishway will be offset by a reduction in the cost of the supercritical reach of the main culvert.

The momentum equation is used to develop a design procedure for the fishway. The backwater relation for the slot orifice and the value of the drag coefficient for the slot orifice constriction are needed to solve this equation. These were obtained by experimental studies on a hydraulic model and are presented as nondimensional plots. For a given slope and length of a culvert and for given depths of headwater and tailwater, criteria developed in this study provide the designer a flexible analytic procedure whereby he can obtain a flow velocity inside the fishway compatible with the performance capability of the fish.

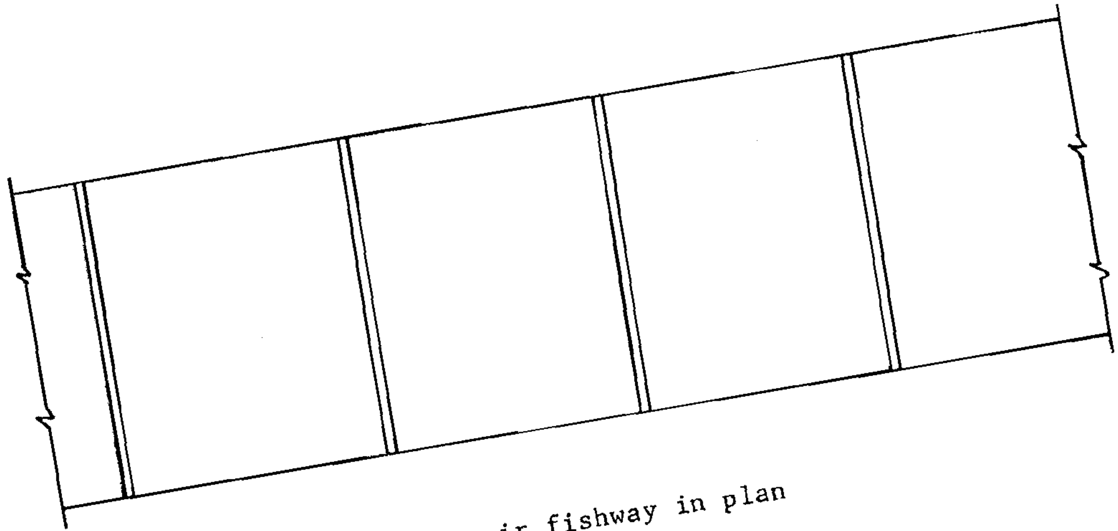
# CHAPTER II

# ANALYSIS OF THE PROBLEM

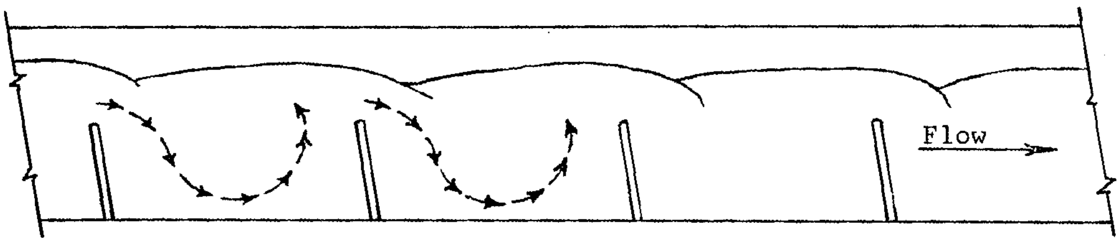
The importance of providing a fishway in culvert structures is explained in the previous introductory chapter. Migration of fish takes place both upstream and downstream depending upon the season and flow conditions. Downstream migration of fish through culverts under any flow conditions (other than low flow) is not considered a problem. As an example, a study (10) conducted at Glines Dam on the Elwho River in 1952 indicated a 92 percent survival rate of yearling silver salmon which passed over a dam crest and free fell 180 feet into a pool. Nothing approaching this type of drop will be encountered at culvert installations. The problem is limited to upstream migration only.

## Culvert Fishways Already Used

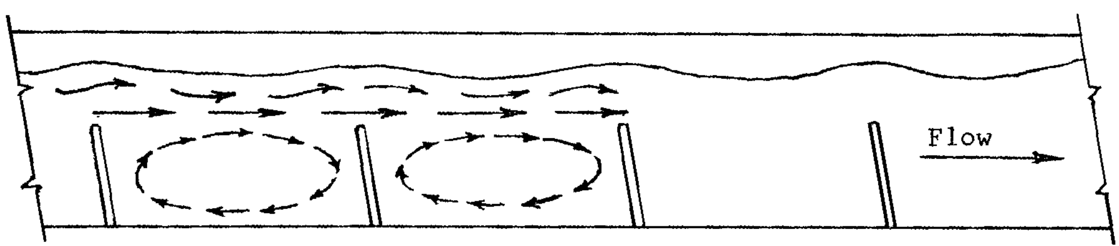
Early efforts to solve the fish barrier problem centered around the use of a pool and baffled fishway. Vertical baffles were placed on the culvert floor perpendicular to the centerline, spaced at regular intervals forming a series of pools and overfall weirs. Two distinct types of flow (Figure 1) can occur in this type of fishway, "plunging" or "streaming". When plunging flow occurs the water drops from pool to pool in a step fashion. The kinetic energy is dissipated in each pool, thus affording the fish a relatively quiescent resting area prior to each ascent of a weir. For larger flows streaming flow exists. During streaming flow, water skims over the weir tops



Pool and weir fishway in plan




Plunging flow in profile




Streaming flow in profile

Figure 1. Flow profiles in pool and weir fishway

at a high velocity with little energy dissipation, a type of flow which is unsatisfactory for fish passage.

Various tests conducted on pool and weir fish ladders (4, 5, 12) with centerline slopes ranging from 5 to 12-1/2 percent, indicated that plunging flow occurs with depths of flow over the weir up to nearly 1.4 feet and streaming flow for any greater depth. If the culvert is to be an effective fishway, it must be of sufficient width so that flow depth over the weirs does not exceed 1.4 feet for any sustained length of time. This necessitates a wide shallow expensive culvert as the construction cost of the culvert roof and floor rises at a much higher rate than the rate of increase in the culvert width. Another factor which limits the effectiveness of baffles is bed load deposition in the pools. The material carried in most steep streams rapidly fills the pools between the baffles resulting in streaming flow even at low discharges. It is not economical to clean the pools as the work must be done by hand. Usually, the shallow head room and the baffles on the floor prohibit any form of mechanical cleaning.

Alternate paired baffles illustrated in Figure 2 have not proven effective. During low flows, depths in successive pools are below minimum depth for fish passage and extremely turbulent unstable flow patterns unsuitable for fish passage occur during high flows (9).

The baffle system which has worked most effectively is the offset baffle design (Figure 3). Throughout a large range of flow depths, a counterclockwise roll of relatively stagnant water forms in the region below the crest of the baffle in the apex between the baffle and the wall. This roll affords a resting area for the fish as they

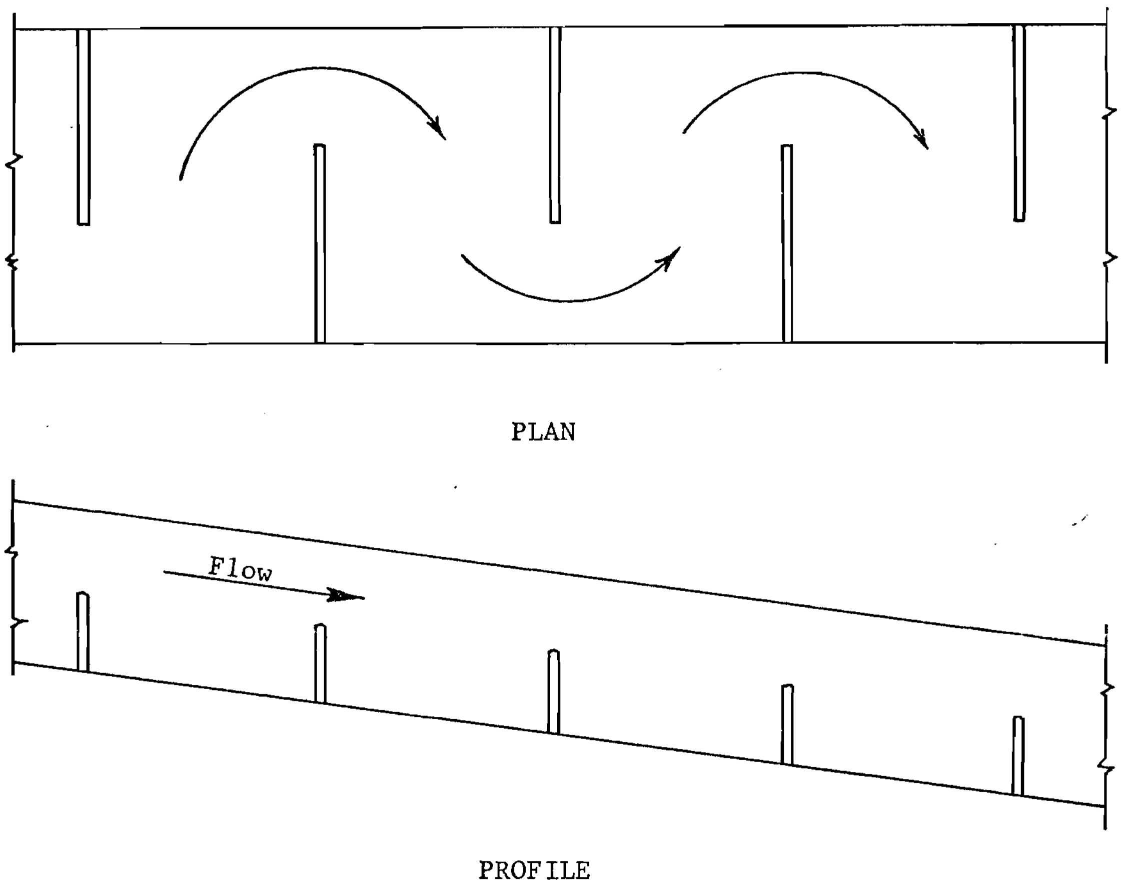



Figure 2. Alternate paired baffle spillway

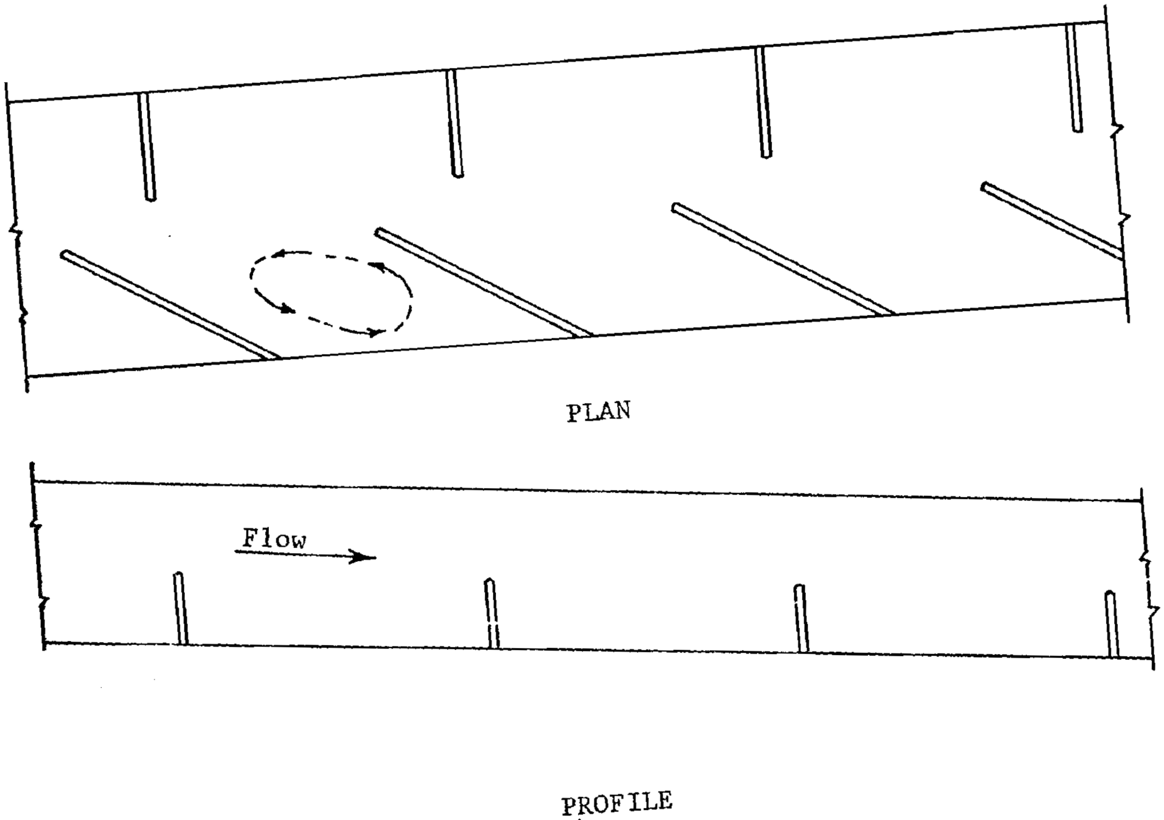



Figure 3. Offset baffle spillway

make successive advances through the gap between baffles. Another advantage of this baffle system is that the passage area is parallel to the direction of fish movement. Testing of the offset baffles (9) indicated good cleaning characteristics. Although this may be so for small sizes of bed material, the strength of circulation required to sweep out material several inches in diameter would surely result in an unsuitable resting area.

Another undesirable feature of any type of floor baffle is the loss of efficiency. Model tests on offset baffles simulating a 10-foot wide culvert with one foot high baffles (9) indicated an efficiency of 69 percent. With 1.4 feet high baffles, the efficiency was 57 percent. This is an important consideration when existing culverts are modified to meet the fishway requirements. If baffles are constructed in a culvert, water will pool upstream of the culvert to a depth necessary to drive the water through. This extra headwater may overtop the roadway fill or may do damage to the culvert or nearby property. New structures designed by taking this fact into account will have a corresponding increase in structure width and cost.

## Suggested Structure

A structure which satisfies criteria for the fishway outlined above is shown in Figure 4. The fishway exit (upstream end of the culvert) will be constructed outside the culvert barrel and the remainder of the fishway will be constructed along the side of the culvert. The critical cross section for culverts on steep grades is the entrance section. Thus, with the exit located outside the barrel, there will be no decrease in the efficiency of the culvert. After a short transitional distance in the upstream portion of the culvert, the flow will become supercritical and will flow at a shallow depth. At a section downstream of the transition zone the width of the culvert barrel may be reduced without affecting the headwater level. At this point the fishway will enter the main culvert barrel and will occupy a portion of the barrel (see section A-A, Figure 4 and Figure 12).

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

The discharge of a slot orifice is a function of the area of the slot and velocity of flow. The velocity through the slot is primarily a function of the difference in elevation of the water surfaces upstream and downstream of the orifice providing the flow remains subcritical. Thus, the velocity of flow through the slot orifice does not change appreciably with a change in discharge (Figure 5). For this reason, the slot orifice fishway provides an essentially constant velocity of flow in a very wide range of discharges varying from low flow to maximum flood flow and thus provides a suitable environment for fish passage.

The invert of the fishway exit can be set at a slightly lower elevation than the culvert inlet invert, thus routing most of the low flow through the fishway. This will enable fish passage even during very low flows.

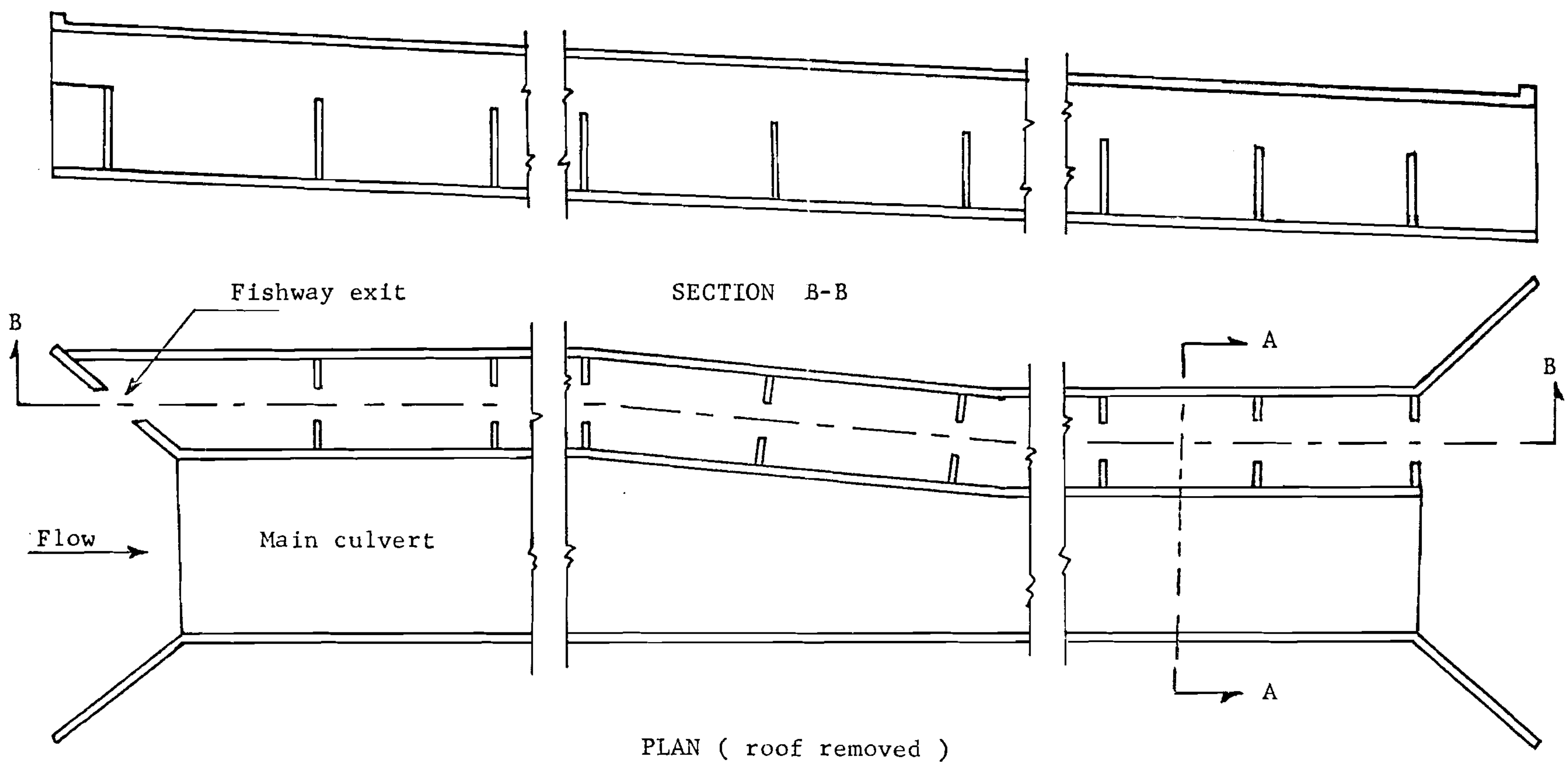
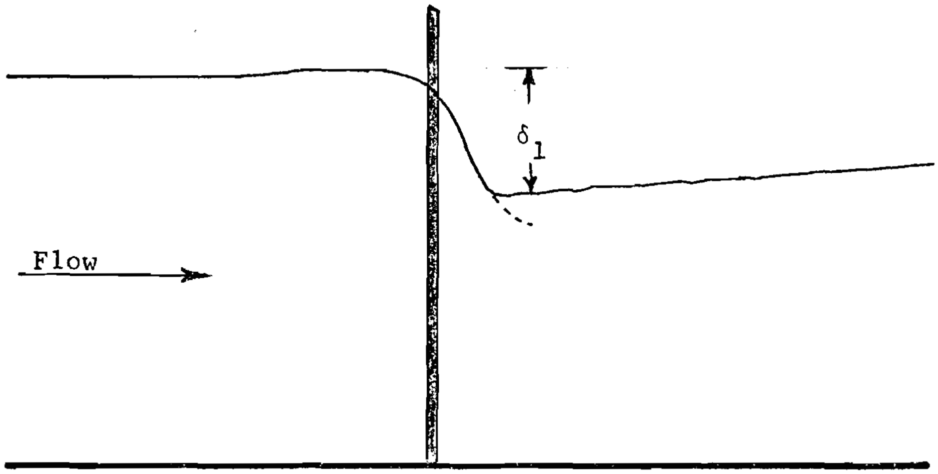
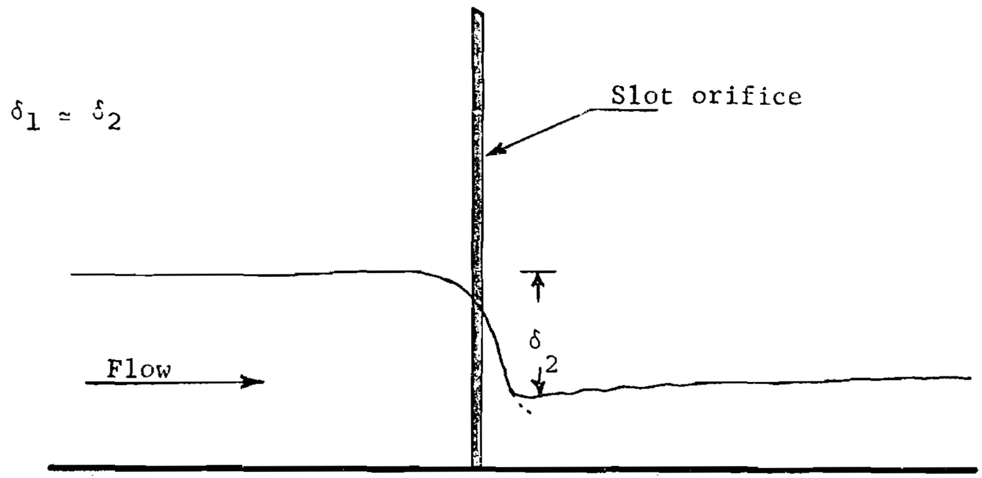



Figure 4. Proposed fishway structure




Flow at high stage




Flow at low stage

Figure 5. Water surface profile

If scouring is expected at the lower end of the culvert, 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.

The orifice fishway could be constructed entirely outside of the culvert barrel. However, 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. Another point against a separate fishway is the lack of light. It is generally agreed (although not conclusively proven, Reference 15) that a lighted fishway is more conducive to fish movement than a dark fishway. When the fishway is constructed within the barrel the lighting condition is fulfilled in the entire supercritical reach of the culvert.

## Design Criteria for the Suggested Structure

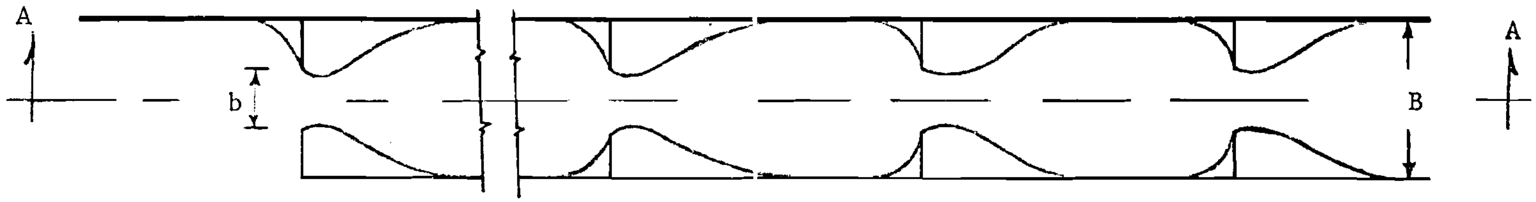
The design criteria for the proposed structure is developed by using a combination of hydraulic laws and hydraulic modeling. The basic requirements of the orifice fishway is that the flow should remain subcritical in the entire reach and the maximum velocity at the constricted slot section must be less than the performance capacity of the fish wich will use the waterway. Reference 18 specifies limiting velocities for fish as a function of size and specie.

The flow regime at the fishway exit is quite complex. However, by model study the quantity of inflow through a slot orifice can be determined for different sizes and spacings of the slots in the fishway and for different slopes and varying headwater and tailwater conditions of the fishway structure.

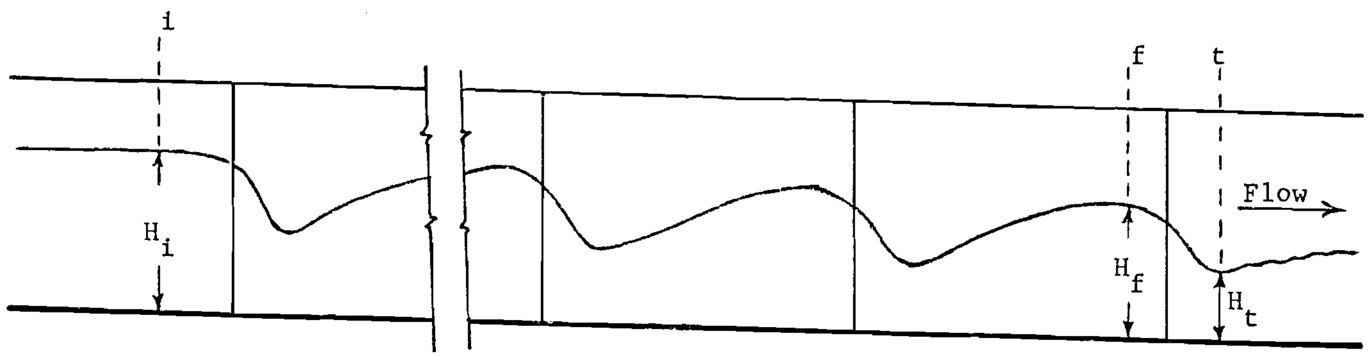
## Description of the Flow Pattern

The details of the hydraulic model prepared for this study are explained in the next chapter together with other apparatus needed for the experimental work. For the successful application to practical problems of the results obtained from the model study, it is quite important to have an understanding of the internal mechanism of the flow. Equally important is an understanding of the external characteristics of the flow pattern so that data required for proper application of the results can be determined. Furthermore a knowledge of the flow pattern in the fishway will immensely help in deciding its suitability for fish passage.

The flow profiles both in plan and elevation in the orifice fishway are shown in Figure 6. Figure 7 shows an enlarged view of one slot opening. The flow is accelerated when it passes through the slot opening. The beginning of acceleration approaching a constriction is indicated by a slight decrease in water surface level at a distance upstream from the face of the constriction approximately equal to the width of the opening. Deceleration occurs along the outer boundaries, and a separation zone is created in the corner adjacent to the constriction (Zone a in Figure 7). The size of the separation zone and the amount by which its surface level differs from the full stagnation level is a function of the channel characteristics and the geometry of the constriction.




PLAN ( only fishway portion shown )




SECTION A-A

Figure 6. Flow profile through a slot orifice fishway

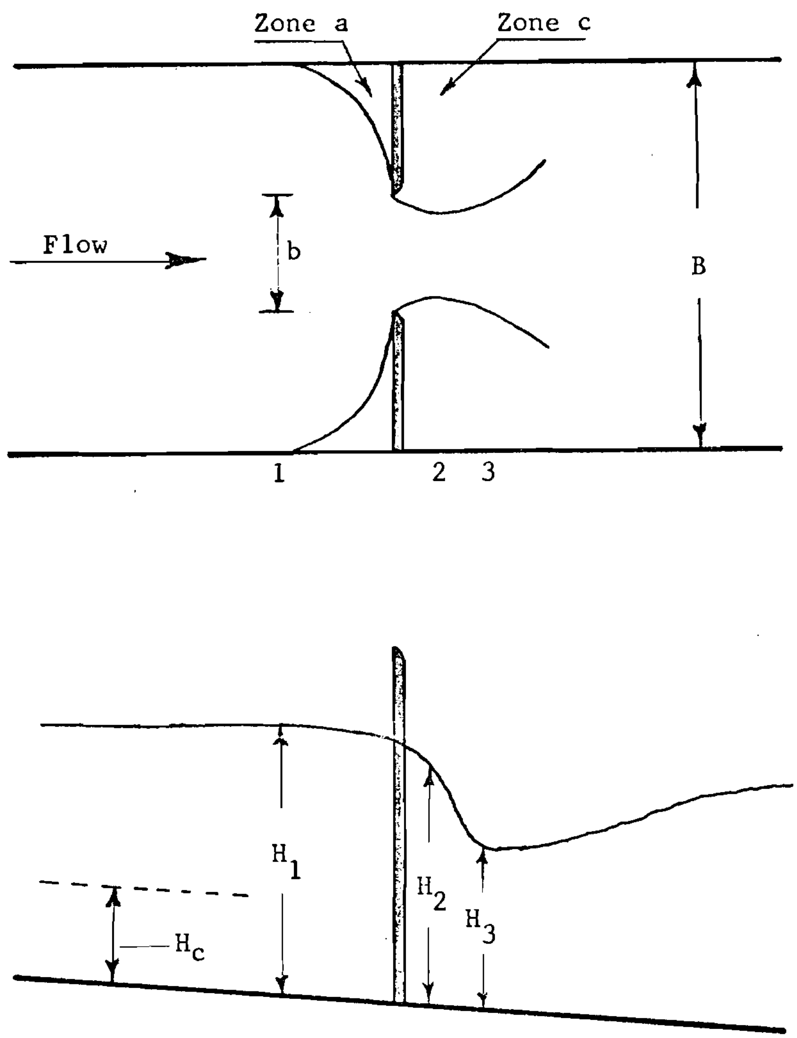



Figure 7. Description of flow pattern in a slot orifice constriction

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 is reflected as a drop in the longitudinal profile, the normal acceleration accounts for a considerable difference in level between outside filaments of flow and the central filaments of flow.

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, Zone c, which marks a second separation zone. Expansion of the live stream begins at the vena contracta and ends at the section downstream by an amount nearly equal to five times the slot opening. Here the live stream again covers the full width of the channel section. The amount by which the jet issuing through the slot is drowned by the "dead" water on each side, adjacent to the plate, depends upon the flow rate, the channel slope, the slot spacing, the extent of constriction, and the tailwater depth. Depending on these conditions, the upper portion of the jet may be free of side effects for a considerable distance, issuing initially as a vertical sheet, with appreciable surface slope. In this case, the cross section suffers considerable change in form between Sections 2 and 3, developing a flange at the top surface which broadens as the surface height decreases and looses its identity in three dimensional flow. Depth $H_1$ was observed to be quite stable having very little fluctuation in the water surface.

## The Channel Contraction Ratio

The contraction ratio is defined as a measure of relative constriction imposed on a given channel. It is expressed by (see Figure 7):

$$m = 1 - \frac{b}{B} \qquad (1)$$

where

m = contraction ratio or coefficient of contraction;

b = width of the slot orifice; and

B = channel width.

## Energy Loss in a Slot Orifice

The slot orifice has been studied in the past as a flow measuring device. This literature was examined in the hope of evaluating the energy loss associated with flow through a slot orifice placed in a channel. It was anticipated that it would be possible to make use of this information in the design of slot orifice fishways.

In 1955, Kindsvater and Carter (8) developed a relation to find rate of flow through a constriction in a horizontal channel. The constrictions used in their experimental studies included all forms of slot orifices with vertical walls of various lengths, widths, and corner roundings. They developed curves to find the coefficient of discharge of a slot orifice. An effort was made to evaluate head loss through a slot orifice by using the results of this study but no consistent figures could be obtained. In their study, the water depth was measured in the dead water pocket just behind the constriction. This depth was assumed equal to the water depth at the vena contracta. This assumption is not valid for flow through an orifice placed in a channel on a steep slope.

In 1958, Vallentine (16) developed a relation to use a slot orifice as a flow measuring device in open channel flow. These studies covered both supercritical and subcritical flow ranges. The dimensionless parameters affecting the coefficient of discharge are the contraction ratio and the Froude number. The Froude number is based on normal depth of flow in the channel. Head loss due to the construction could not be evaluated from these studies because of the large head loss in the reach between the constriction and the section where normal flow occured.

In 1969, Hill, Ford and Unny (7) gave a little different approach than that of Vallentine on the use of the slot orifice as a flow measuring device. Nondimensional parameters considered in their study were the slot contraction ratio and the ratio of the water depth measured just upstream of the constriction to the width of the slot opening. For the limited number of contraction ratios they considered, supercritical flow occurred downstream of the slot. To cover the subcritical range, tailwater depth was regulated and submergence correction was evaluated. After examining the results, it was observed that in place of head loss at the constriction, there is an apparent gain in energy. Simplifying assumptions and experimental errors may be the reasons for this discrepancy.

## Application of Momentum Principle

Use of the energy equation to find the rate of flow through the fishway was not possible since the head loss through a slot orifice can not be computed from the data available in the literature. The momentum equation can be used to find the rate of flow provided the coefficient of drag of a slot orifice constriction is known. Values of drag coefficients are evaluated in this study by using the momentum principle based on the balance of impulse and momentum.

According to the principle, the rate of 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. Applying this principle to the flow conditions of the orifice fishway shown in Figure 6, the expression for the momentum change per unit time in the body of water enclosed between sections i and f is:

$$\frac{Q\gamma}{g} (\beta_f V_f - \beta_i V_i) = \frac{1}{2} \gamma B \cos\theta (H_i^2 - H_f^2) + W \sin\theta - F_R \qquad (2)$$

where

$Q$ = steady rate of flow ($ft^3$/sec);

$\gamma$ = weight density of water (lb/$ft^3$);

$g$ = acceleration due to gravity (ft/$sec^2$);

$\beta$ = momentum correction factor;

$V$ = velocity of flow (ft/sec);

$i,f$ = subscripts denoting section initial and section final, respectively;

$B$ = width of the fishway (ft);

$H$ = depth of flow measured perpendicularly from the water surface (ft);

$W$ = weight of water enclosed between sections i and f (lb);

$\theta$ = angle of direction of flow with the horizontal; also fishway slope; and

$F_R$ = total resisting force due to the slot constrictions and the channel surface friction (lb).

The amount of frictional force between the fishway boundary and the body of water is negligible. Therefore, the term $F_R$ is a function of the number of slots between section i and f and the amount of contraction in each slot. Rewriting the above equation:

$$F_R = \frac{Q\gamma}{g} (\beta_i V_i - \beta_f V_f) + \frac{1}{2} \gamma B \cos\theta (H_i^2 - H_f^2) + W \sin\theta. \qquad (3)$$

A series of preliminary measurements indicated that $\beta_i \simeq \beta_f \simeq 1$. The above equation may then be written as:

$$F_R = \frac{\rho Q^2}{B} \left(\frac{1}{H_i} - \frac{1}{H_f}\right) + \frac{1}{2} \gamma B \cos\theta (H_i^2 - H_f^2) + W \sin\theta \qquad (4)$$

where

$\rho = \frac{\gamma}{g}$ = mass density of water (slugs/ft$^3$).

All the terms on the right-hand side of the equation can be determined experimentally with the exception of W. To evaluate W, the volume of water between sections i and f has to be estimated. This can be accomplished by obtaining a complete water profile between the two sections. This procedure is quite time-consuming and therefore another method was used. To find an alternative method, water profiles were established for slopes varying from zero to five percent. The slots used in the fishway model were 21 inches apart, and each slot had a coefficient of contraction equal to 0.68. Water depths were measured in each case at the contracted sections of the fishway and at sections one slot width upstream and downstream of the constriction. Depths were also measured at third points between two consecutive slots. Table A-1 in the Appendix shows these depths for different slopes of the channel. The water profiles are plotted in Figures 8 and 9.

To evaluate W in Equation 4, section i was chosen 1.3 inches upstream of the first slot; and section f was chosen 1.3 inches upstream of the last slot. Weight of water between these two sections under the water surface profile was calculated by the trapezoidal rule. The weight of water computed by this method was compared to an approximate weight obtained by multiplying the average of the depths at section i and t (Figure 6) by the length separating the sections i and f. As shown in Table 1, the approximate weight was very close to the weight computed by the laborious trapezoidal method. Henceforth the approximate method was used for weight calculations.

Table 1. Deviation in Weight of Water Obtained by Approximate Method

| Slope (%) | Weight of body of water between section i and f | | Deviation from actual weight (%) |
|---|---|---|---|
| | Weight (actual) (lb) | Weight (estimated) (lb) | |
| 0 | 27.5 | 26.3 | 4.4 |
| 1 | 25.3 | 25.1 | 0.8 |
| 2 | 25.0 | 24.7 | 1.2 |
| 3 | 23.85 | 23.75 | 0.4 |
| 4 | 23.0 | 23.1 | -0.4 |
| 5 | 22.45 | 22.5 | -0.2 |

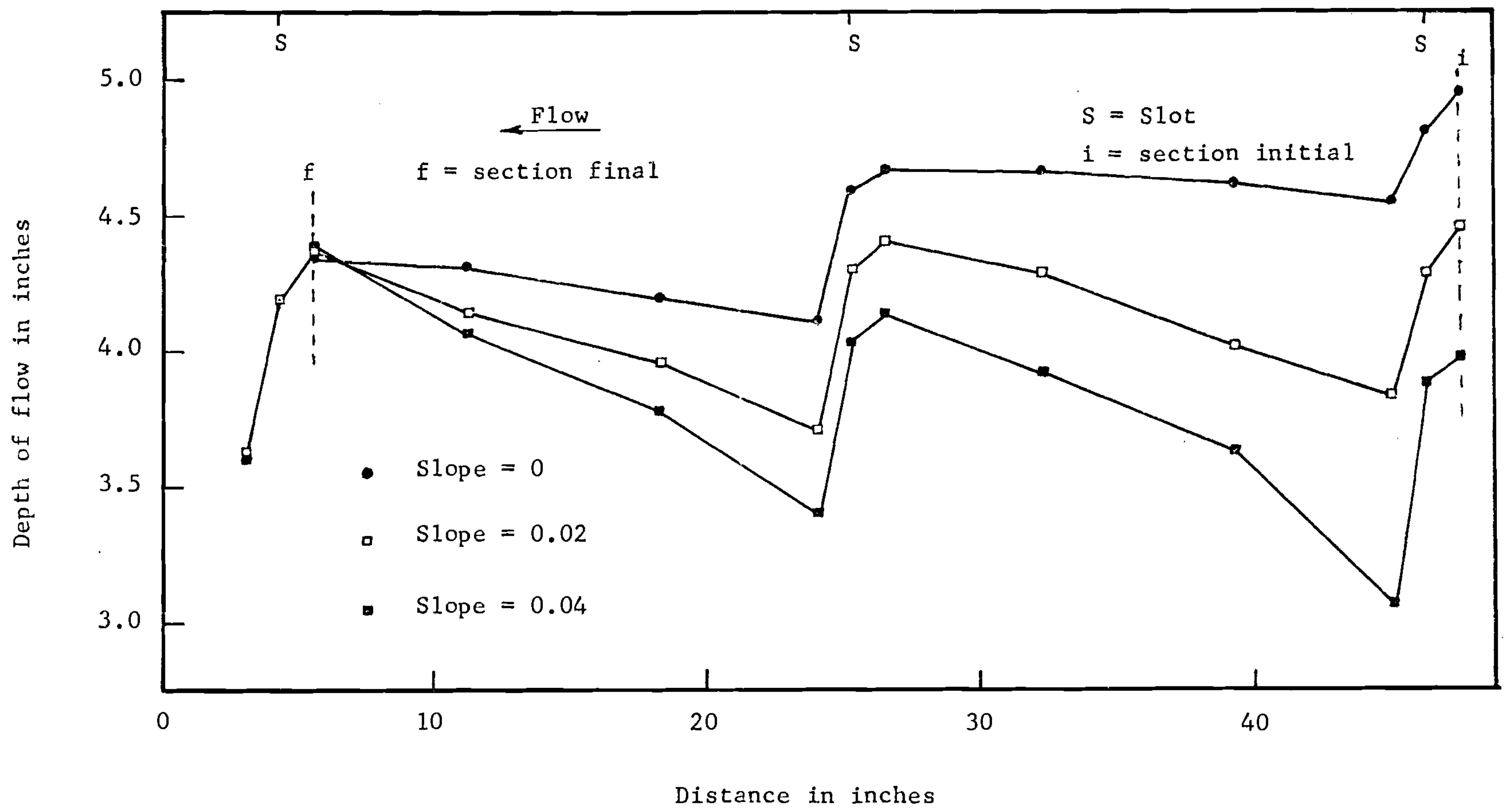



Figure 8. Longitudinal flow profile in a slot orifice fishway

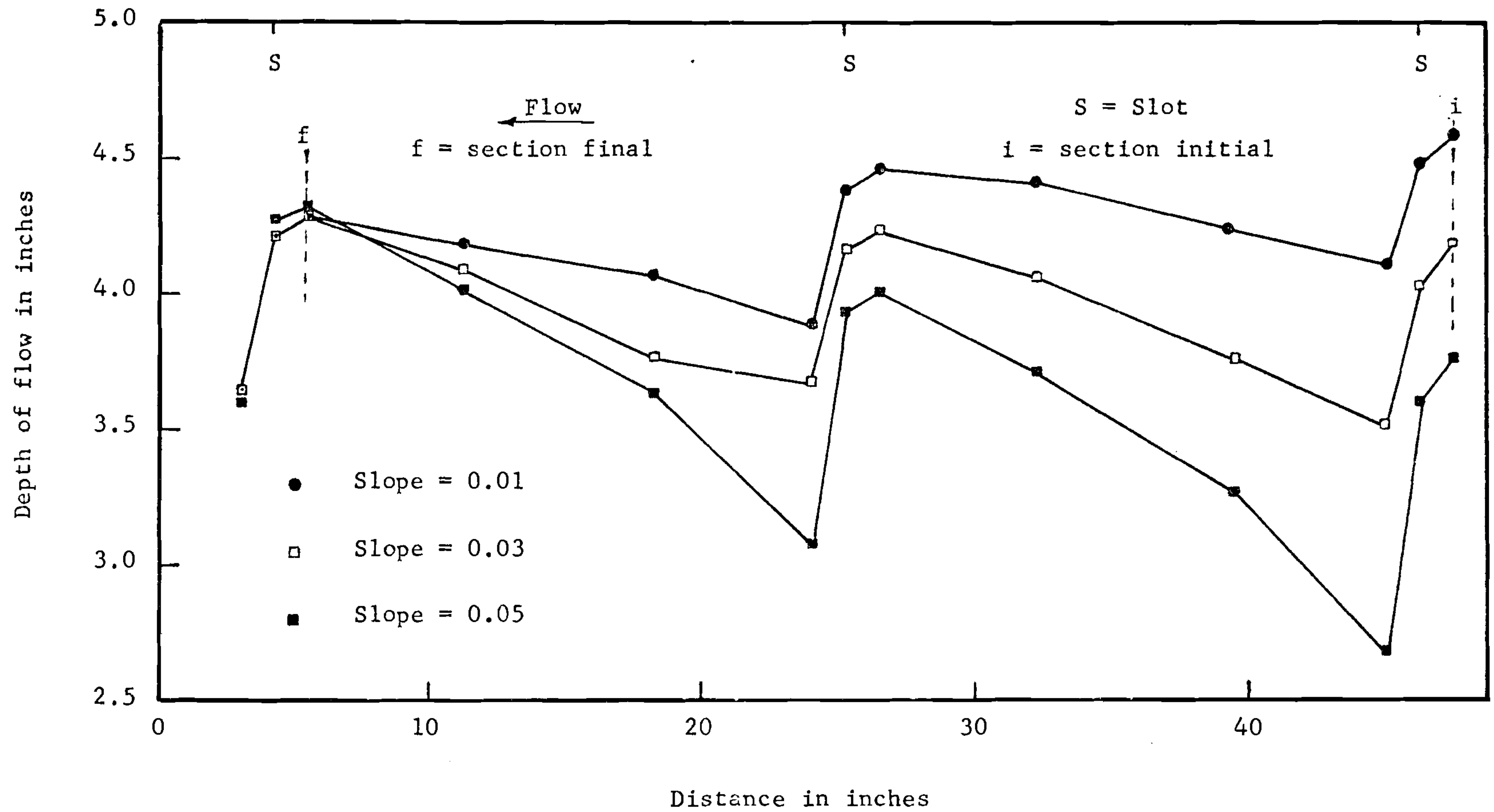



Figure 9. Longitudinal flow profile in a slot orifice fishway

Equation 4 can now be written as:

$$F_R = \frac{\rho Q^2}{B} \left(\frac{1}{H_i} - \frac{1}{H_f}\right) + \frac{1}{2} \gamma\ B \cos\theta \left(H_i^{\ 2} - H_f^{\ 2}\right)$$

$$+ \frac{1}{2} (H_t + H_i) \ (B\ n\ Sp\ \gamma\ \sin\theta) \qquad (5)$$

where

Sp = spacing between two consecutive slot orifices;

t = subscript denoting tailwater section; and

n = number of constrictions (slot orifices) between initial and final sections.

If a plate is held against a fluid flowing at uniform velocity, the resisting force applied by the fluid on the plate is given by:

$$F_D = \frac{1}{2} \rho\ C_D\ A\ V^2 \qquad (6)$$

where

$F_D$ = drag force applied by plate on flowing fluid (lb);

$C_D$ = coefficient of drag;

A = projected area of the plate on a plane perpendicular to direction of flow ($ft^2$); and

V = velocity of flowing fluid (ft/sec).

The velocity of flow, V, is assumed to be uniform over the entire cross-sectional area. For the fishway it can be expressed by:

$$V = \frac{Q}{BH} \ . \qquad (7)$$

The term $F_R$ in Equation 5 can be replaced by an expression similar to the one given for $F_D$. Rate of flow, Q, is constant for every constriction in steady state flow conditions. The cross-sectional area of a constriction can be expressed by:

$$A_j = m\ B\ H_j \tag{8}$$

where

$A_j$ = cross-sectional area for the $j^{th}$ constriction; and

$H_j$ = uniform depth of flow upstream of $j^{th}$ constriction

$F_R$ is then obtained from:

$$F_R = \frac{1}{2}\ \rho\ C_D \frac{m\ Q^2}{B} \sum_j \frac{1}{H_j} \tag{9}$$

where $\sum_j$ is summation for all the slots between initial and final section. Thus depth $H_j$ corresponds to $H_i$, $H_2$, $H_3$, . . . , $H_{f-1}$.

To measure H for each constriction is time consuming; and therefore another method was used. It was observed from Figures 8 and 9 that depth $H_j$ varied linearly with distance from depth $H_i$ to $H_f$. The change in water depth for each constriction, $\Delta H$, is given by:

$$\Delta H = \frac{H_i - H_f}{n}\ . \tag{10}$$

Thus $H_2 = H_i - \Delta H$; $H_3 = H_i - 2\Delta H$, and so on until finally $H_{f-1} = H_i - (n-1)\Delta H = H_f + \Delta H$.

Using the value of $F_R$ from Equation 9, and taking $\cos\theta$ equal to unity, Equation 5 becomes:

$$m\, C_D \sum_j \frac{1}{H_j} = 2\left(\frac{1}{H_i} - \frac{1}{H_f}\right) + \frac{g\, B^2}{Q^2}\left(H_i^{\,2} - H_f^{\,2}\right) + \frac{g\, B^2\, Sp\, n\, S\,(H_i + H_t)}{Q^2} \qquad (11)$$

where

$S = \sin\theta \simeq \tan\theta$ = slope of the channel.

The above equation will be used for the design of a fishway prototype. Two unknown variables $C_D$ and $H_f$ are determined by experimental studies.

## Factors Affecting $C_D$ Values

By model studies the value of $C_D$ can be evaluated by incorporating the effects of the significant variables. Dimensional analysis and careful study of flow characteristics through the range of variables examined indicated that $C_D$ is a function of the following dimensionless independent parameters.

1. The contraction ratio of the orifice, $m = 1 - \frac{b}{B}$ .

2. Slope of the channel, S.

3. Ratio of longitudinal spacing of orifices divided by fishway width, Sp/B.

4. Ratio of tailwater depth to headwater depth, $H_t/H_i$.

## Factors Affecting the Backwater Ratio, $H_f/H_t$

For a slot orifice of known contraction ratio, it should be possible to find $H_f$ if Q and $H_t$ are known (16). Flow mechanism for a slot with downstream control is illustrated in Figure 10. Depth $H_f$ should be a function of Q, $H_t$, b, B and S. Dimensional analysis indicated that $H_f/H_t$ is a function of following dimensionless independent parameters.

1. The contraction ratio of the orifice, $m = 1-\frac{b}{B}$.
2. Slope of the channel, S.
3. Froude number, $\frac{Q}{B\ H_t\ \sqrt{gH_t}}$ .

When designing a fishway, the length and slope of the culvert and the headwater and tailwater depths for different discharge conditions will be known. Assuming a suitable width for the fishway, values of m and n can be chosen so as to produce desirable flow conditions inside the fishway for satisfactory passage of fish.

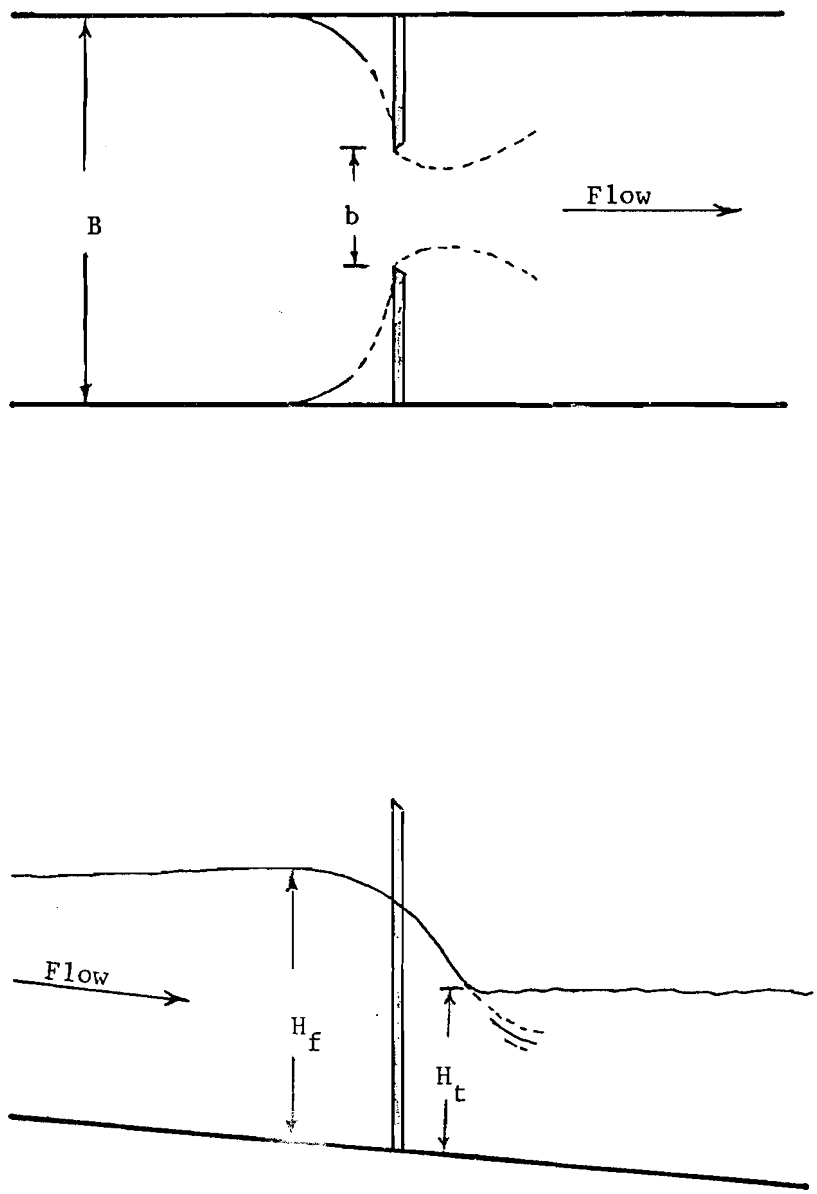



Figure 10. Flow profile through a slot orifice

# CHAPTER III

# EXPERIMENTAL WORK

Equation 11 will be used for the design of a slot orifice fishway. The rate of flow, $Q$ , can be found from this equation if the values of $C_D$ and $H_f$ are known. Various factors affecting these two variables are listed in the previous chapter. Experimental work was undertaken to evaluate the effect of these factors. The contraction ratios of the slots considered in the present study were 0.61, 0.68, 0.76 and 0.84. For each of these contraction ratios, slots were spaced longitudinally at 4B, 5B, and 6B where B is the width of the fishway. Slope of the fishway was varied from 0 percent to 5 percent. The apparatus and general procedure used is explained in this chapter.

## Apparatus

The studies were performed in a recirculating tilting flume. A low volume centrifugal pump in series with an air activated regulating valve and an electromagnetic flow meter, delivered the flow to the headbox of the flume.

The tilting flume was 24 feet in length and 1.5 feet wide with transparent side walls 2 feet high. The slope of the flume could be adjusted from a negative 3 percent to a positive 5 percent with a hydraulic mechanism. The slope of the flume was determined by conventional leveling procedures. The flume with culvert model and other details is shown in Figure 11.

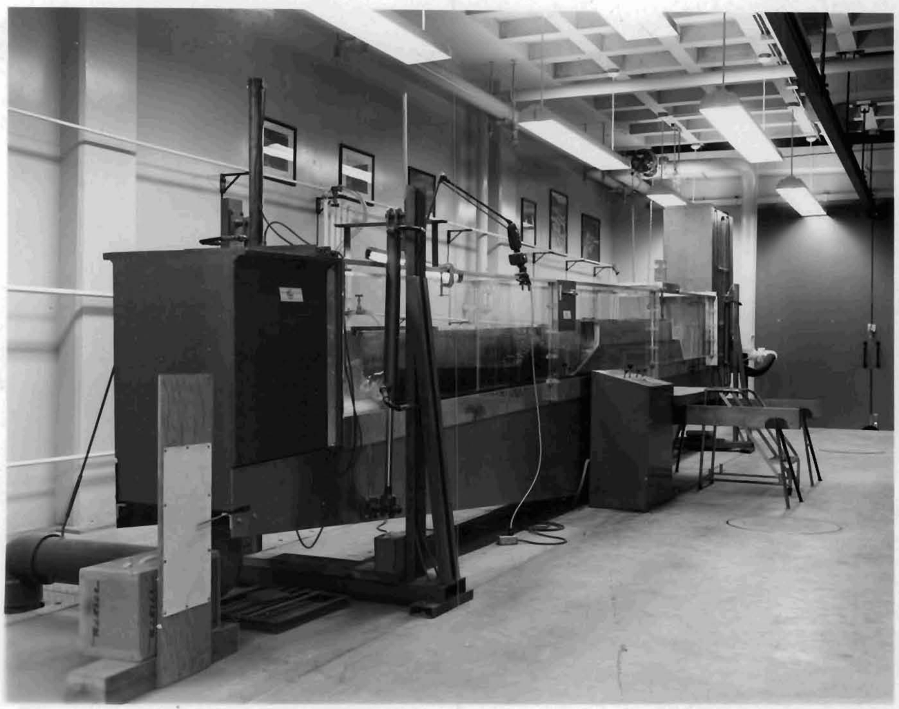


Figure 11. Tilting flume with fishway culvert model and accessories

The Model Details

The general outline of the hydraulic model is shown in Figure 12, and its detailed drawing is shown in Figure 13. The hydraulic model is a simplified case of the proposed prototype shown in Figure 4. The model consisted of the main culvert and the orifice fishway. A 6-inch wide culvert was centered within the 18-inch wide flume. A 4-inch wide fishway was provided next to the culvert separated by a 3/4-inch thick plywood wall. Total length of this model was 8 feet including an 11-inch approach section at the upstream end of the culvert. The height of the culvert and fishway walls was 6 inches. The model as viewed from upstream end of the culvert is shown in Figure 14.

Baffles made from 0.051 inch thick galvanized sheet metal 6 inches high were placed in the fishway at right angles to the longitudinal axis. Four sets of baffles with slot widths of 0.64, 0.96, 1.28, and 1.56 inches were examined. These slot widths correspond to contraction ratios of 0.84, 0.76, 0.68, and 0.61, respectively. The baffles were fastened to the fishway walls with screws, so that the longitudinal spacing of slots within the fishway could be varied as desired. A slotted strip gate at the extreme downstream end of the fishway was used to regulate tailwater depth.

This entire assembly rested on a 7-inch high wooden frame. The purpose of this was to elevate the culvert sufficiently so that tailwater could be controlled by the gate and not be affected by the backwater created by the measuring notch downstream. 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

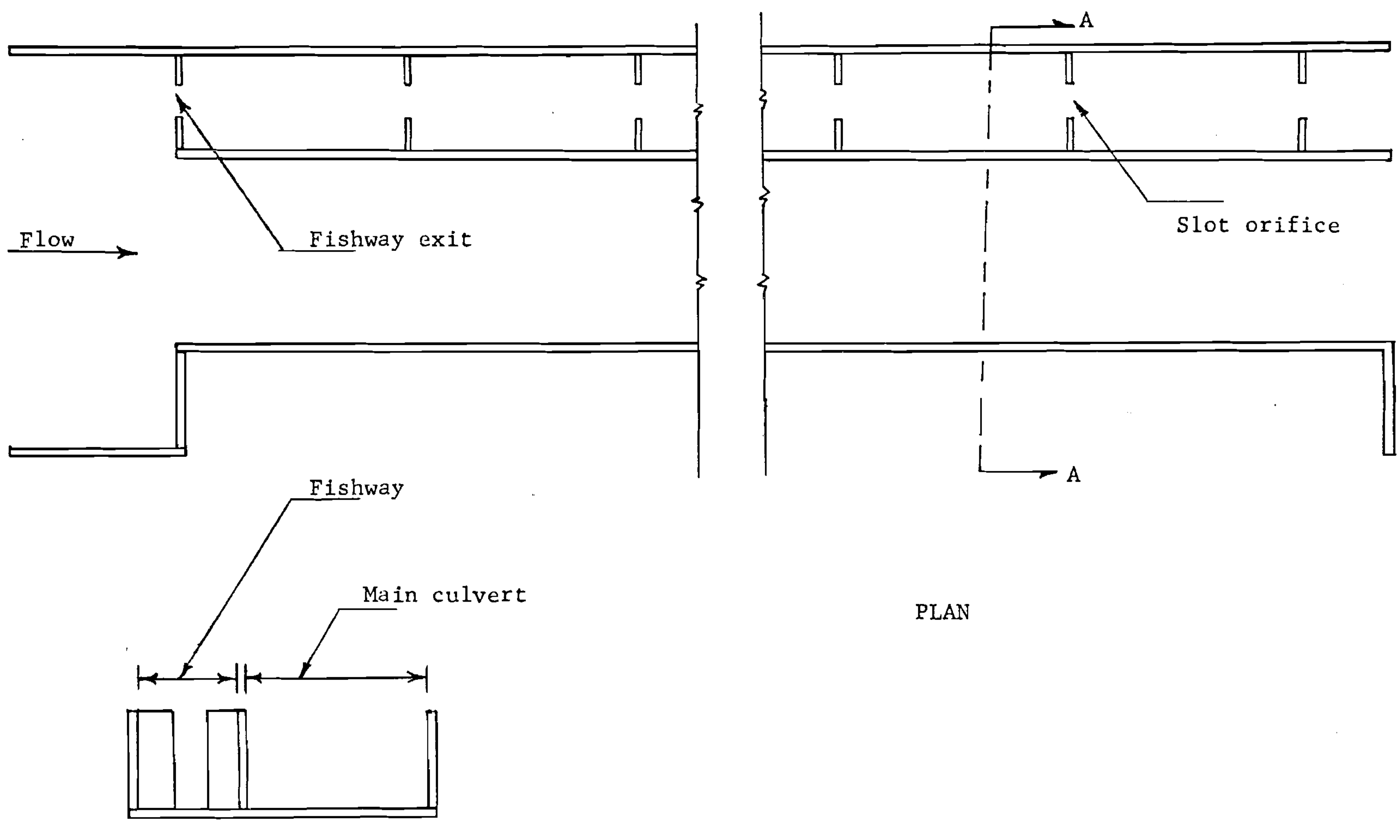



Figure 12. Fishway culvert model

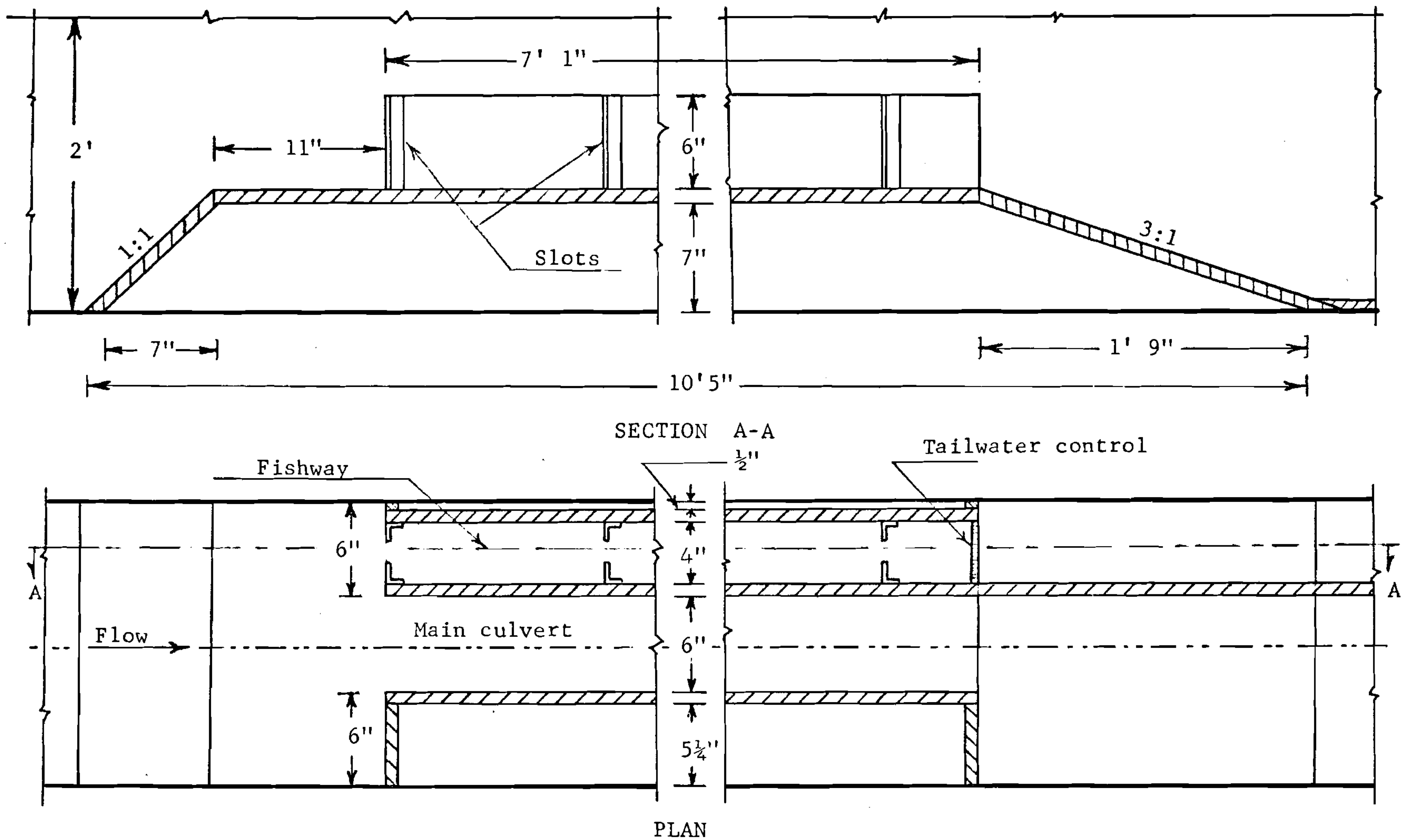



Figure 13. Details of fishway culvert model

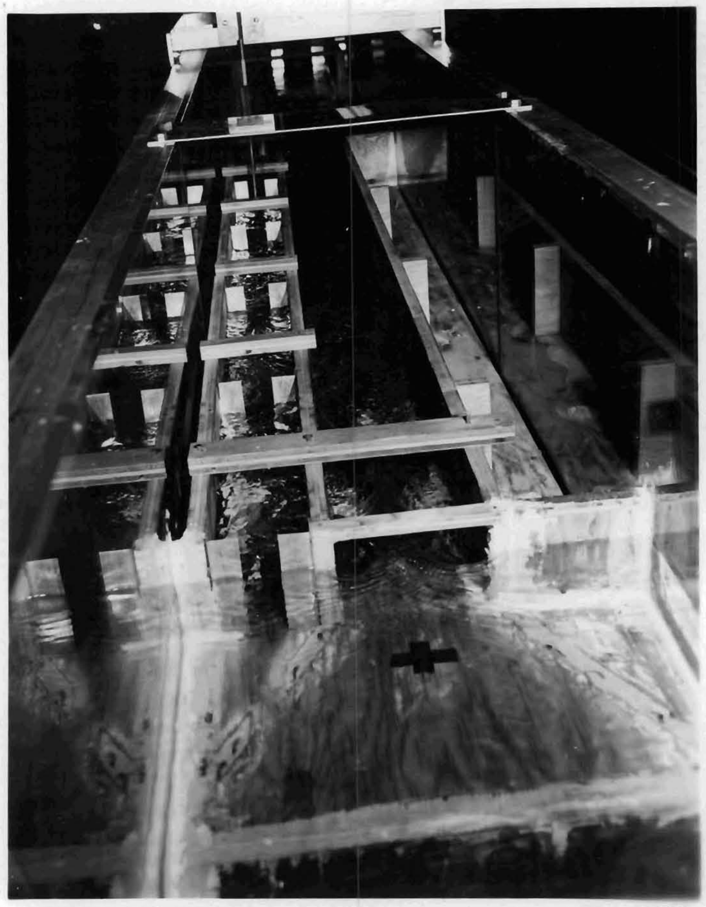


Figure 14. Fishway culvert model looking downstream

clearance was provided between this frame and the sides of the flume to accommodate any possible wood expansion.

## Discharge Measuring Devices

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 thence over a V-notched weir. The culvert discharge was channeled through a stilling basin and was measured by a sharp edged rectangular weir. The weir arrangements inside the flume are shown in Figure 15. Dimensions of the weirs are shown in Figure 16. A computer program used to prepare the data for the rating curves of both these weirs is given in Appendix B. Because of the large range of slope covered by the experiment, it was necessary to correct point gage measurements taken upstream of the weir. The technique used is illustrated in Figure 17. It is important to note that the point gage was mounted on the channel itself. Thus, the point gage reading corresponding to point C when the 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 it to get the net static head h. The sum of the rate of flow through the fishway and the main culvert was compared with the rate of flow given by an electromagnetic flow meter. The discrepancies were within ± 5 %.

## Procedure

The general procedure used to evaluate $C_D$ was to install within the fishway a series of slot orifices of a particular contraction ratio

Figure 15. Discharge measuring weirs

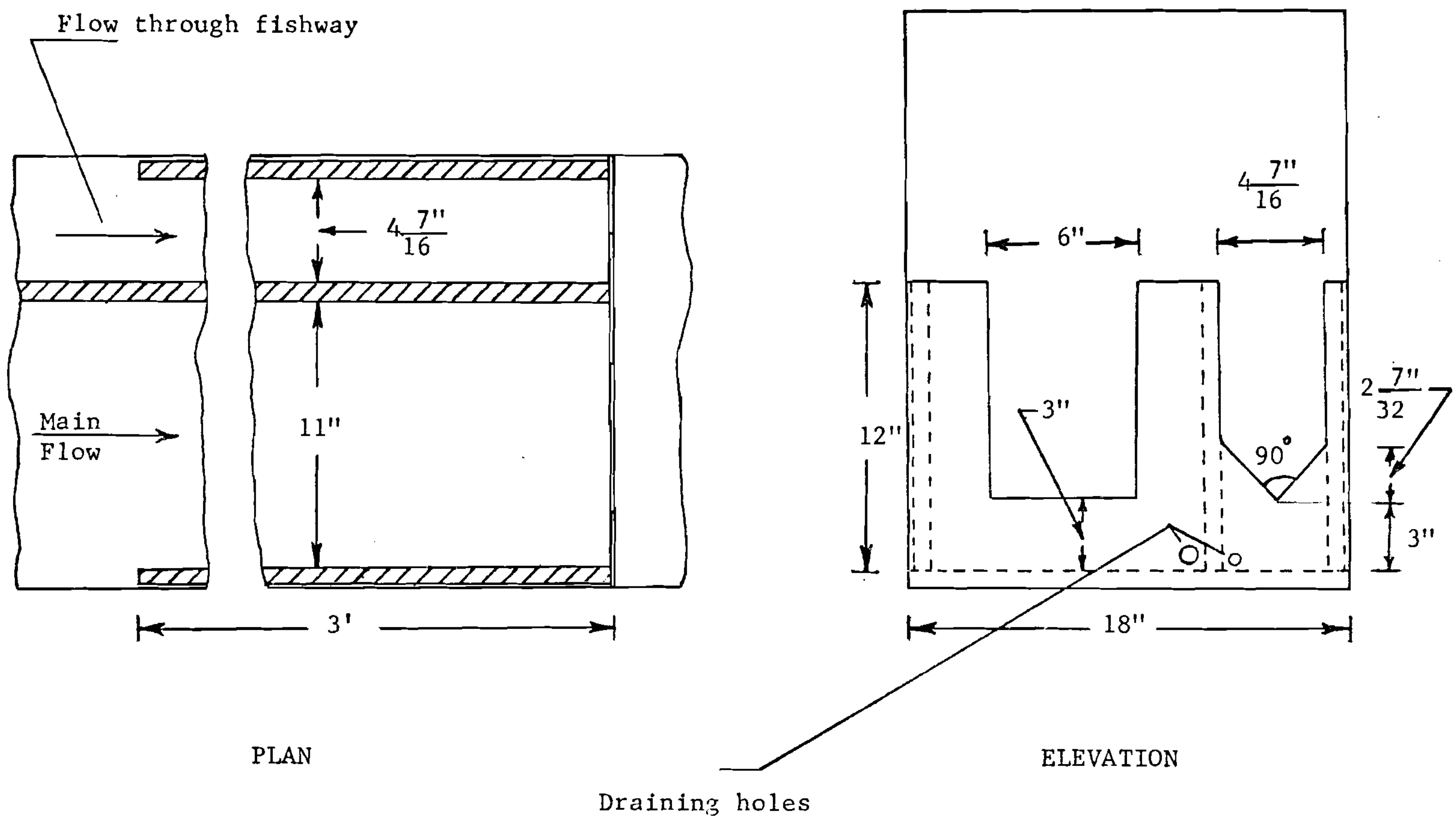



Figure 16. Details of measuring weirs

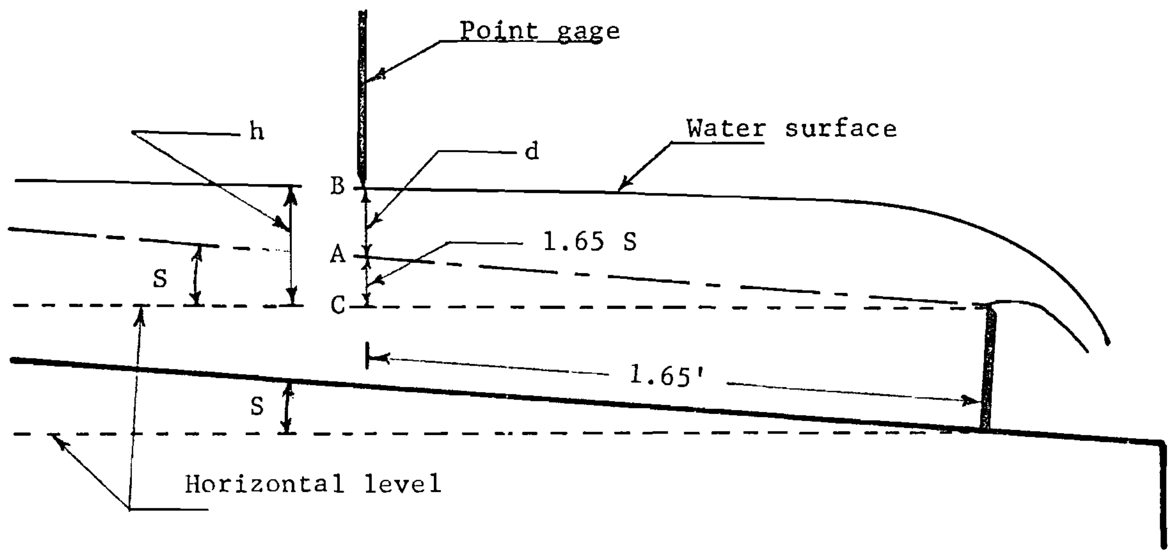



Figure 17. Slope correction for head over a weir

at a constant longitudinal spacing with the first slot fixed at the fishway exit. The channel was set at the required slope and the desired headwater was established at the entrance. The tailwater was adjusted at the downstream end of the fishway, then the necessary data, water surface elevations, and the discharge flowing through the fishway were recorded.

Water surface readings were obtained along the centerline of the fishway. The first section was upstream of the first slot (fishway exit) at a distance equal to the slot opening. This reading was denoted by $H_i$. The second section was located a distance of one slot opening upstream of the last slot. This reading was recorded as $H_f$. The tailwater depth was measured in the dead water pockets just behind this last slot. Water depths were measured on both sides of the slot opening and their average was recorded as $H_t$. This averaging was necessary because the water jet coming out of the slot orifice was usually not symmetrical about the center line of the fishway; thus the water depths on the two sides were unequal. The last step was to measure the water level upstream of the weir to find the rate of flow through the fishway. Equation 11 was then used to calculate $C_D$.

The following variables were examined. The analysis and conclusions drawn from these data are presented in a later section.

Effect of Upstream Head

To study the effect of $H_i$ on the value of $C_D$, observations were taken while keeping all other factors constant. By changing the discharge, $H_i$ was varied from 3.91 inches to 5.32 inches, almost the maximum range available. These data are given in Table A-6.

Effect of Tailwater

Keeping all other variables constant, $H_t/H_i$ ($H_i$ was also constant) was varied from 0.5 to 0.9. This was repeated at five different slopes varying from 1 percent to 5 percent. Data are given in Table A-9.

Effect of Number of Slots Considered to Evaluate $C_D$

The drag coefficient $C_D$ was evaluated by applying the momentum equation between two sections usually 3 or 4 slots apart. To study the effect on $C_D$ of the number of slots considered, observations for $H_f$ and $H_t$ were taken at two different sections; one near the extreme downstream slot and the other near the slot just upstream of this slot. These observations are given in Table A-7.

Effect of Contraction Ratio and Spacing

As mentioned earlier, the slots of four contraction ratios; 0.61 0.68, 0.76 and 0.84 were examined. For each of these contraction ratios, slots were spaced longitudinally at 4B, 5B, and 6B; thus 12 runs were taken. For the spacing of 4B, the channel slope was varied from 0 percent to 5 percent. For the other two spacings, slope was varied from 1 percent to 5 percent. These data are given in Table A-8 to Table A-19.

Check for Velocity and Froude Number

To maintain satisfactory flow conditions for fish passage, it is necessary to consider the maximum velocity and Froude number which may occur anywhere inside the fishway. The critical sections are the vena contraca formed by the extreme downstream slot and the vena contracta formed by the slot just upstream of the above referred slot. Depths and widths were measured at these sections to evaluate velocity and Froude number. These observations are given in Table A-20.

Backwater Relation

For each value of m, observations for $H_f$ and $H_t$ were taken for the extreme downstream slot and flow through the orifice was recorded. $H_t/H_i$ was varied in a wide range from 0.5 to 0.9. Observations were repeated for slopes varying from 1 percent to 5 percent. These observations are given in Tables A-2 to A-5.

# CHAPTER IV

# RESULTS

The main accomplishment of this investigation was to develop the necessary criteria for the design of an effective orifice fishway structure. All variables which could affect the flow in the fishway were considered and their effects analyzed. A method is developed for sizing and spacing the slots in such a way as to insure subcritical flow inside the fishway satisfactory for fish movement. This criteria is developed for different slopes and varying upstream headwater conditions. A tailwater range at the downstream end of the fishway for satisfactory fishway performance is also suggested.

## Effect of Tailwater

Sufficient depth of tailwater is required at all times to provide satisfactory entrance conditions at the downstream end of the fishway. Also a certain level of tailwater (such that downstream control always occurs) is required to maintain subcritical flow conditions inside the fishway. In the process of developing the design criteria for the fishway, the effect of tailwater on $C_D$ values was studied in detail. Figure 18 shows the variation in the values of $C_D$ for tailwater depths varying from 50 percent to 90 percent of the upstream headwater. From a practical viewpoint, this covers the entire range necessary to maintain suitable entrance conditions for the fish. The tailwater effect on $C_D$ values was studied for five slopes varying

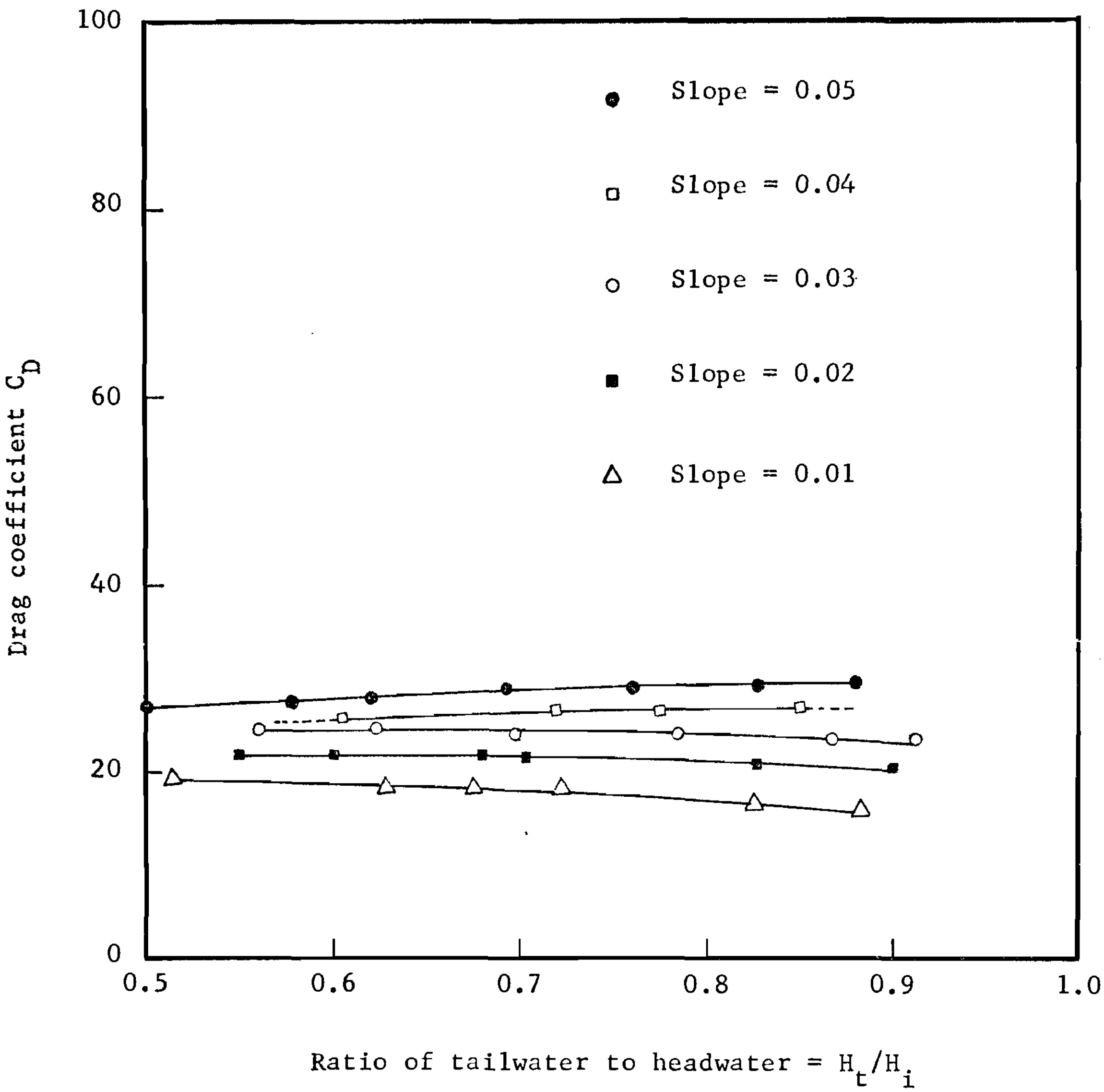



Figure 18. Effect of tailwater on the value of drag coefficient

from 1 percent to 5 percent. It is obvious after examining Figure 18 that tailwater depth has negligible effect on $C_D$ values within the range specified.

## Effect of Upstream Head Variation

The effect of upstream head variation on the $C_D$ values was studied by keeping other independent variables constant. Table 2 shows the values of $C_D$ for different depths of headwater. These values of $H_i$ could not be varied in the lower range and the upper range was limited by the model height. For the limited range considered, it is obvious that $C_D$ values are not affected by variation in headwater.

Table 2. Effect of upstream head variation on $C_D$ values

| m | Sp/B | Slope | $H_i/B$ | $H_t/B$ | $C_D$ |
|---|---|---|---|---|---|
| 0.76 | 4 | .03 | 0.9775 | 0.7575 | 34.7 |
| 0.76 | 4 | .03 | 1.0825 | 0.7575 | 33.3 |
| 0.76 | 4 | .03 | 1.165 | 0.755 | 33.4 |
| 0.76 | 4 | .03 | 1.2425 | 0.7525 | 34.8 |
| 0.76 | 4 | .03 | 1.33 | 0.750 | 33.7 |

## Change in $C_D$ Values for Different Lengths of Channel With Constant Longitudinal Spacing of Slots

The following tests were performed to investigate the effect of fishway length (i.e. the number of pairs of slots) on the value of $C_D$

per slot. Four slot orifices with m = 0.76 set at a spacing of 4B were examined at two different slopes, 2 percent and 4 percent. Then, the fishway length was extended by a length of 4B and a fifth slot orifice was installed. The fishway was tested again at the same two slopes. Computed values of $C_D$ for the two series of runs are shown in Table 3. The data clearly indicates that the effect of change in number of slots on $C_D$ is insignificant; therefore, this was not investigated further. This is an indirect indication that quasi uniform flow exists for any fishway with 4 or more sets of slots within the range of variables examined.

## $C_D$ Values for Sp/B = 4

$C_D$ values were evaluated for slots with constant contraction ratios at a spacing of four times the fishway width opening. Four different contraction ratios, 0.61, 0.68, 0.76, and 0.84, were studied; each at six different slopes varying from horizontal level up to a slope of 5 percent. The results are plotted on a semi-logarithmic scale in Figure 19.

## $C_D$ Values for Sp/B = 5

$C_D$ values were evaluated for the same four contraction ratios referred to above. Slots for each contraction ratio were fixed at a longitudinal spacing of 5B. The slope was varied from 1 percent to 5 percent. These results are plotted in Figure 20.

The point of interest was to check if there was any relation between the $C_D$ values at a spacing of 5B with those obtained at a

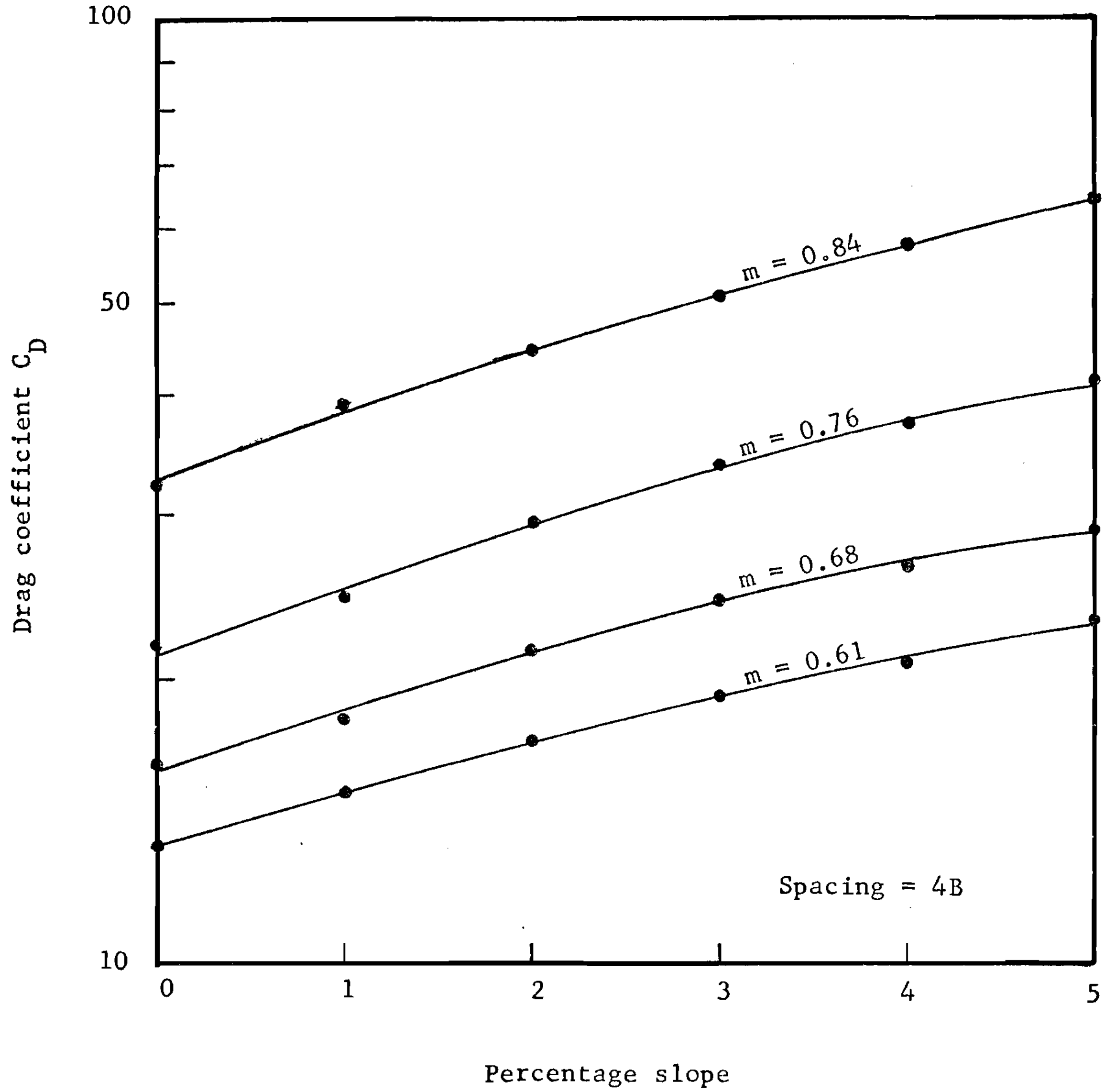



Figure 19. Drag coefficient for a slot orifice constriction at a spacing of 4B

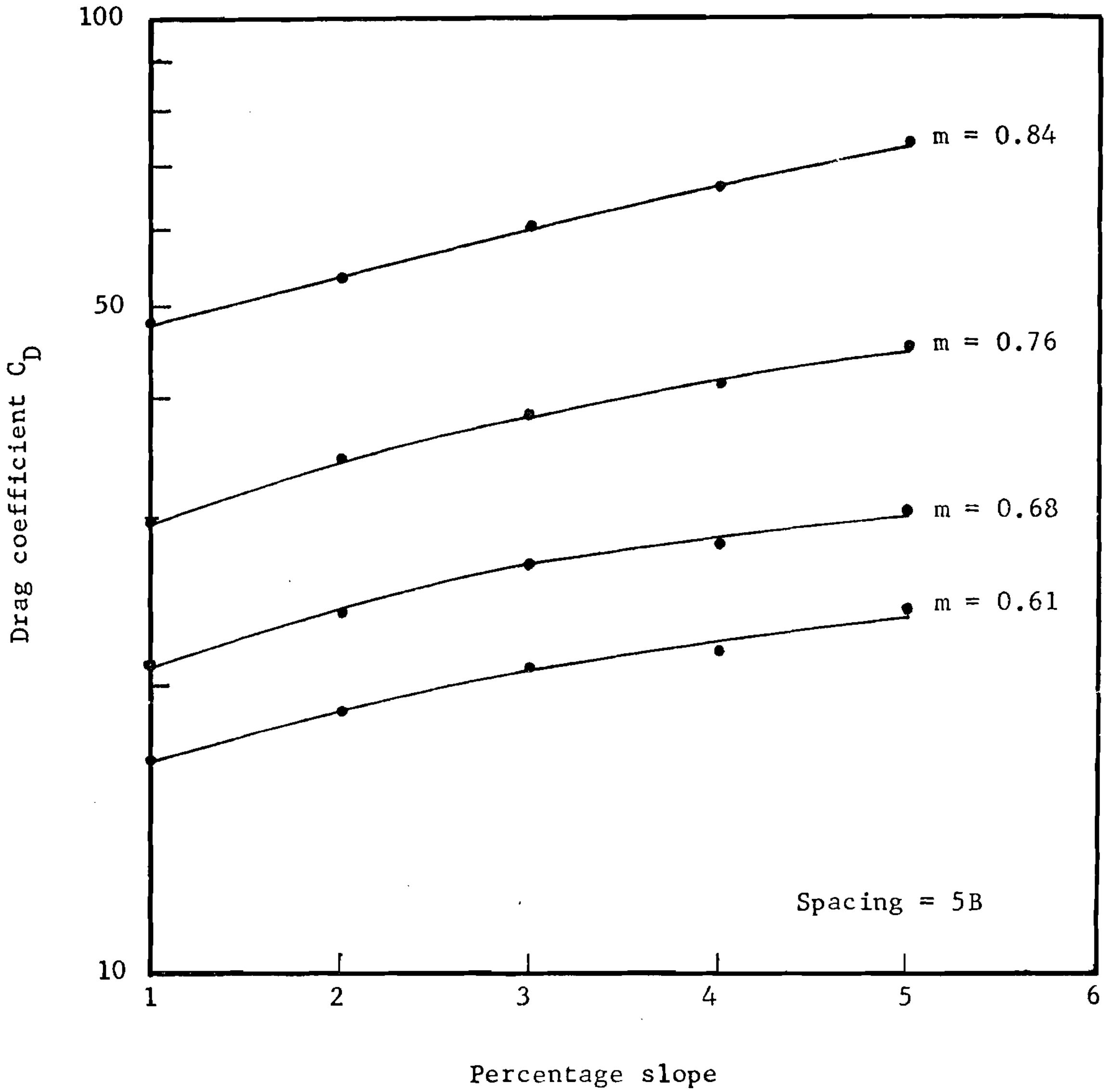



Figure 20. Drag coefficient for a slot orifice constriction at a spacing of 5B

Table 3. Variation in $C_D$ Values as a Function of Culvert Length

| m | Sp/B | Slope | $H_i/B$ | No. of slots = 4 | | No. of slots = 5 | |
|---|---|---|---|---|---|---|---|
| | | | | $H_t/H_i$ | $C_D$ | $H_t/H_i$ | $C_D$ |
| .76 | 4 | .02 | 1.120 | .766 | 30.5 | .665 | 29.7 |
| .76 | 4 | .02 | 1.1225 | .780 | 30.8 | .690 | 29.9 |
| .76 | 4 | .02 | 1.1225 | .804 | 30.3 | .735 | 29.7 |
| .76 | 4 | .04 | 1.115 | .756 | 38.6 | .682 | 37.2 |
| .76 | 4 | .04 | 1.115 | .776 | 39.2 | 717 | 37.6 |
| .76 | 4 | .04 | 1.1175 | .792 | 39.4 | .740 | 38.1 |

spacing of 4B. The ratio of $C_D$ values at a spacing of 5B to corresponding $C_D$ values at a spacing of 4B are given in Table 4, and a plot of these ratios is given in Figure 21. These curves indicate that this ratio is increasing with increasing contraction ratio and with decreasing slope.

## $C_D$ Values for Sp/B = 6

$C_D$ values were evaluated for the same four contraction ratios, but slots were fixed at a spacing equal to six times the fishway width opening. For each contraction ratio, observations were taken at five different slopes varying from 1 percent to 5 percent. These results are plotted in Figure 22.

Table 4. Ratio of $C_D$ Values

| m | Sp/B | Slope | | | | |
|---|---|---|---|---|---|---|
| | | 1% | 2% | 3% | 4% | 5% |
| | 4 | 15.3 | 17.25 | 19.25 | 20.7 | 23.0 |
| .61 | 5 | 16.7 | 18.9 | 20.8 | 21.9 | 24.0 |
| | Ratio | 1.09 | 1.09 | 1.08 | 1.06 | 1.04 |
| | 4 | 18.3 | 21.5 | 24.2 | 26.4 | 28.9 |
| .68 | 5 | 21.0 | 24.0 | 26.8 | 28.0 | 30.3 |
| | Ratio | 1.15 | 1.12 | 1.11 | 1.06 | 1.05 |
| | 4 | 24.5 | 29.5 | 33.8 | 37.3 | 41.8 |
| .76 | 5 | 29.5 | 34.5 | 38.5 | 41.0 | 45.2 |
| | Ratio | 1.20 | 1.17 | 1.14 | 1.10 | 1.08 |
| | 4 | 39.2 | 44.9 | 51.0 | 57.5 | 64.5 |
| .84 | 5 | 48.1 | 53.3 | 60.6 | 66.8 | 73.8 |
| | Ratio | 1.23 | 1.19 | 1.19 | 1.16 | 1.14 |

The ratios of $C_D$ values at spacing of 6B to corresponding $C_D$

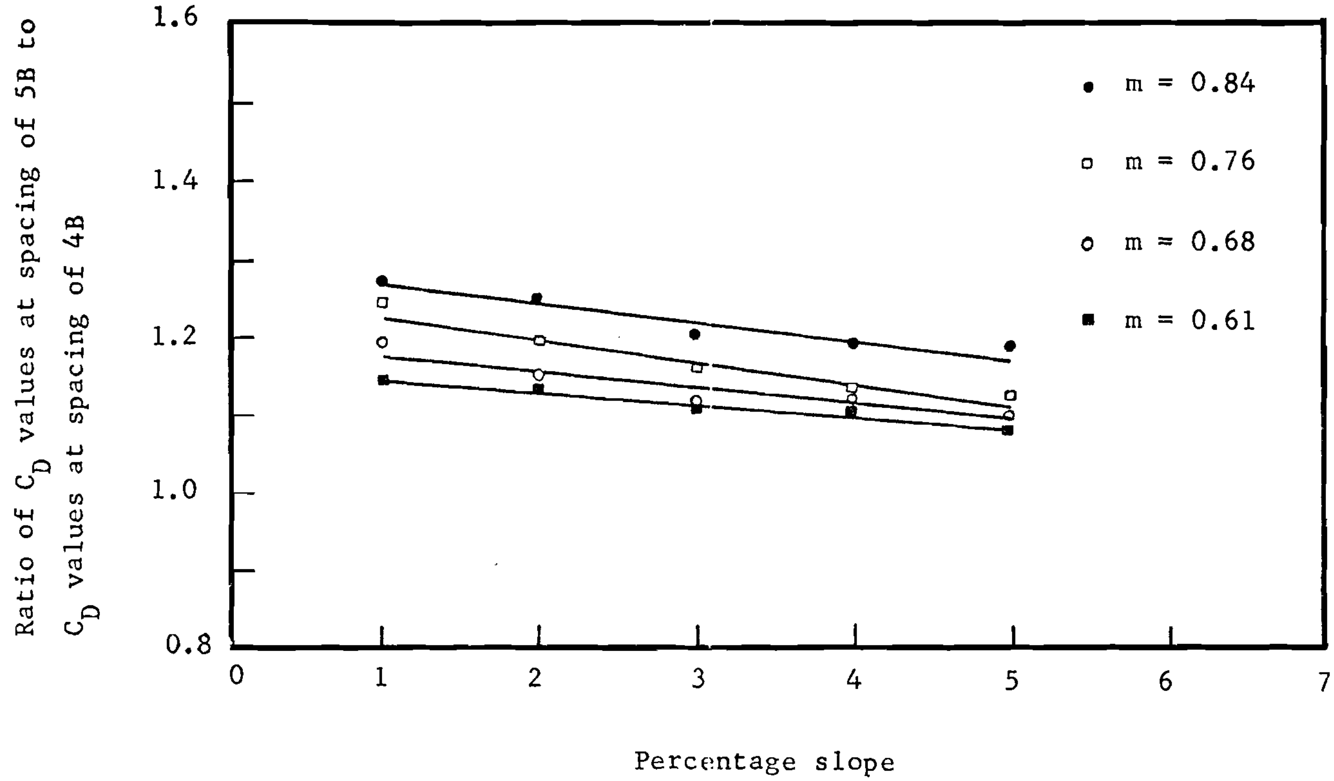



Figure 21. Effect of longitudinal spacing of slots on drag coefficient

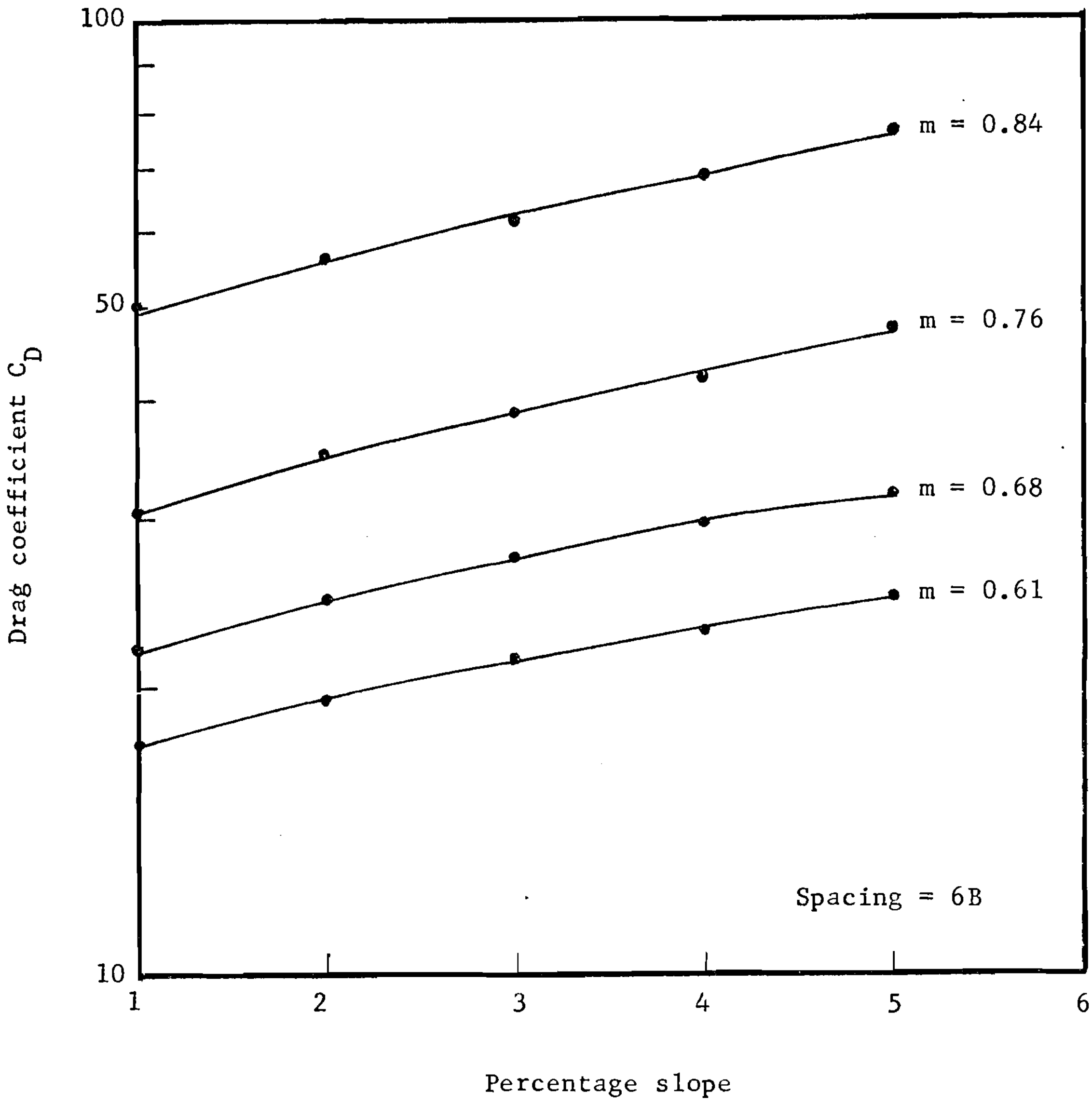



Figure 22. Drag coefficient for a slot orifice constriction at a spacing of 6B

values at spacing of 4B are given in Table 5. These ratios are plotted in Figure 23. The curves indicate the same trend as obtained earlier in Figure 20; i.e., $C_D$ values increasing with increasing contraction ratio and with decreasing slope.

Table 5. Ratio of $C_D$ Values

| m | Sp/B | Slope | | | | |
|---|---|---|---|---|---|---|
| | | 1% | 2% | 3% | 4% | 5% |
| | 4 | 15.3 | 17.25 | 19.25 | 20.7 | 23.0 |
| .61 | 6 | 17.5 | 19.4 | 21.3 | 22.9 | 24.9 |
| | Ratio | 1.14 | 1.13 | 1.11 | 1.11 | 1.08 |
| | 4 | 18.3 | 21.5 | 24.2 | 26.4 | 28.9 |
| .68 | 6 | 21.8 | 24.6 | 27.2 | 29.6 | 31.8 |
| | Ratio | 1.19 | 1.15 | 1.12 | 1.12 | 1.10 |
| | 4 | 24.5 | 29.5 | 33.8 | 37.3 | 41.8 |
| .76 | 6 | 30.5 | 35.0 | 38.7 | 42.0 | 47.0 |
| | Ratio | 1.24 | 1.19 | 1.15 | 1.13 | 1.12 |
| | 4 | 39.2 | 44.9 | 51.0 | 57.5 | 64.5 |
| .84 | 6 | 50.0 | 56.0 | 61.3 | 68.5 | 76.5 |
| | Ratio | 1.27 | 1.25 | 1.20 | 1.19 | 1.185 |

For the curves shown in Fugure 20 and Figure 22, no satisfactory relation could be obtained for increase in the value of $C_D$ with regard to either slope or contraction ratio. For this reason, it is necessary to consider longitudinal spacing as a design parameter.

## Backwater Ratio for a Slot Orifice

Experiments were conducted to establish the backwater relations for the slot orifices considered. The width of the fishway, B, was

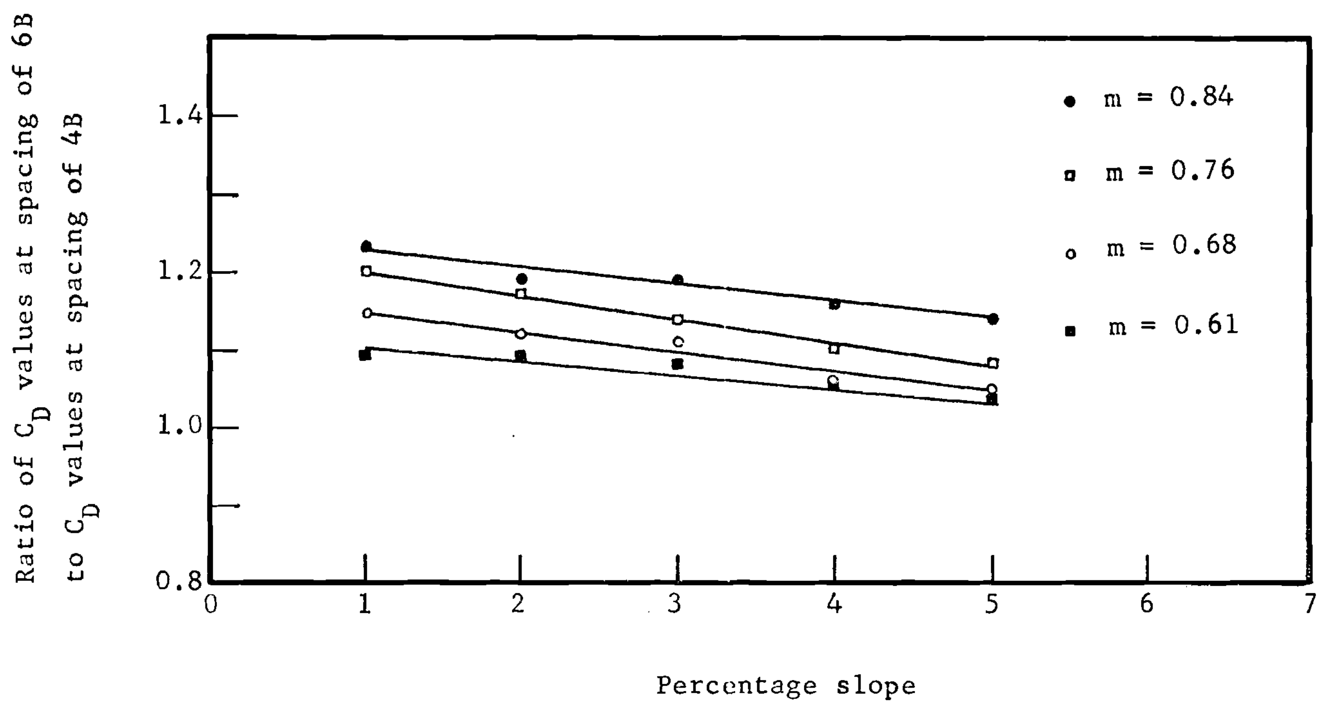



Figure 23. Effect of longitudinal spacing of slots on drag coefficient

kept constant and orifices with four contraction ratios were examined. For each slot contraction ratio, slope was varied from 1 percent to 5 percent. Backwater ratio $H_f/H_t$ was found to be a function of contraction ratio m and Froude number referred to tailwater depth and the width of the fishway. Figure 24 shows that this relation is not affected by slope. These curves for all contraction ratios are shown in Figure 25. Experimental points are omitted for the sake of clarity.

A straight line was found to be the best fit for these curves. The equations of these straight lines as obtained by polynomial regression are:

| m value | Equation | |
|---|---|---|
| 0.61 | $H_f/H_t = 2.126\ Fr + .814$ | (12) |
| 0.68 | $H_f/H_t = 2.578\ Fr + .815$ | (13) |
| 0.76 | $H_f/H_t = 3.025\ Fr + .823$ | (14) |
| 0.84 | $H_f/H_t = 3.806\ Fr + .806$ | (15) |

where Fr denotes the Froude number $(Q/B\ H_t\ \sqrt{gH_t})$.

Further analysis of the above equations was found to be conclusive. Another polynomial regression on the values of m and coefficients of Fr gave the following equation:

$$\lambda = 7.141\ m - 2.275 \qquad (16)$$

where $\lambda$ denotes the coefficient of Fr in the above four equations. Table 6 shows the variables $\lambda$ and m and also the residual in the value of $\lambda$ after subtracting its estimated value obtained from straight line fit from its original value. The residual is less than 3 percent in

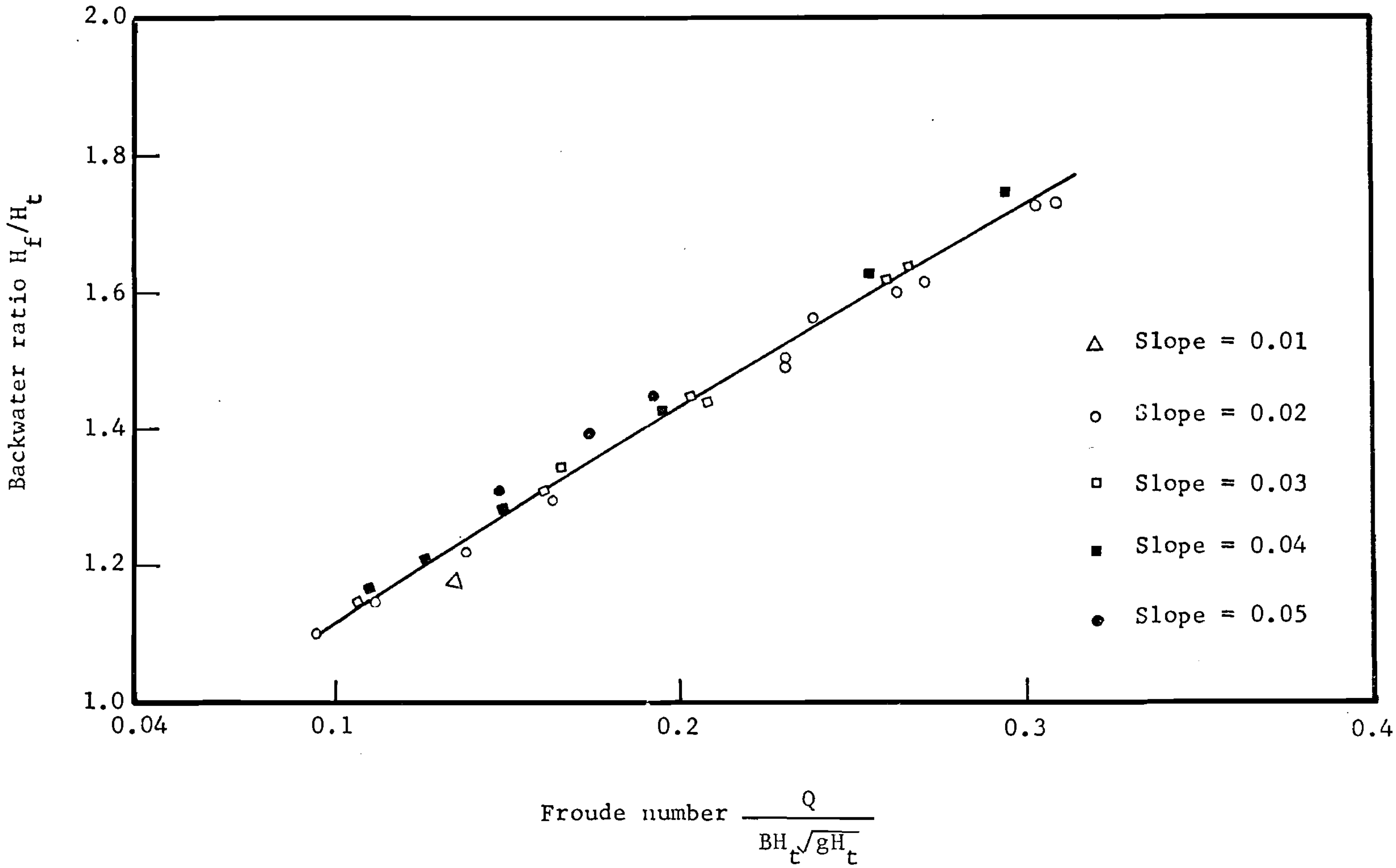



Figure 24. Relation between backwater ratio and Froude number for slot orifice with m = 0.76

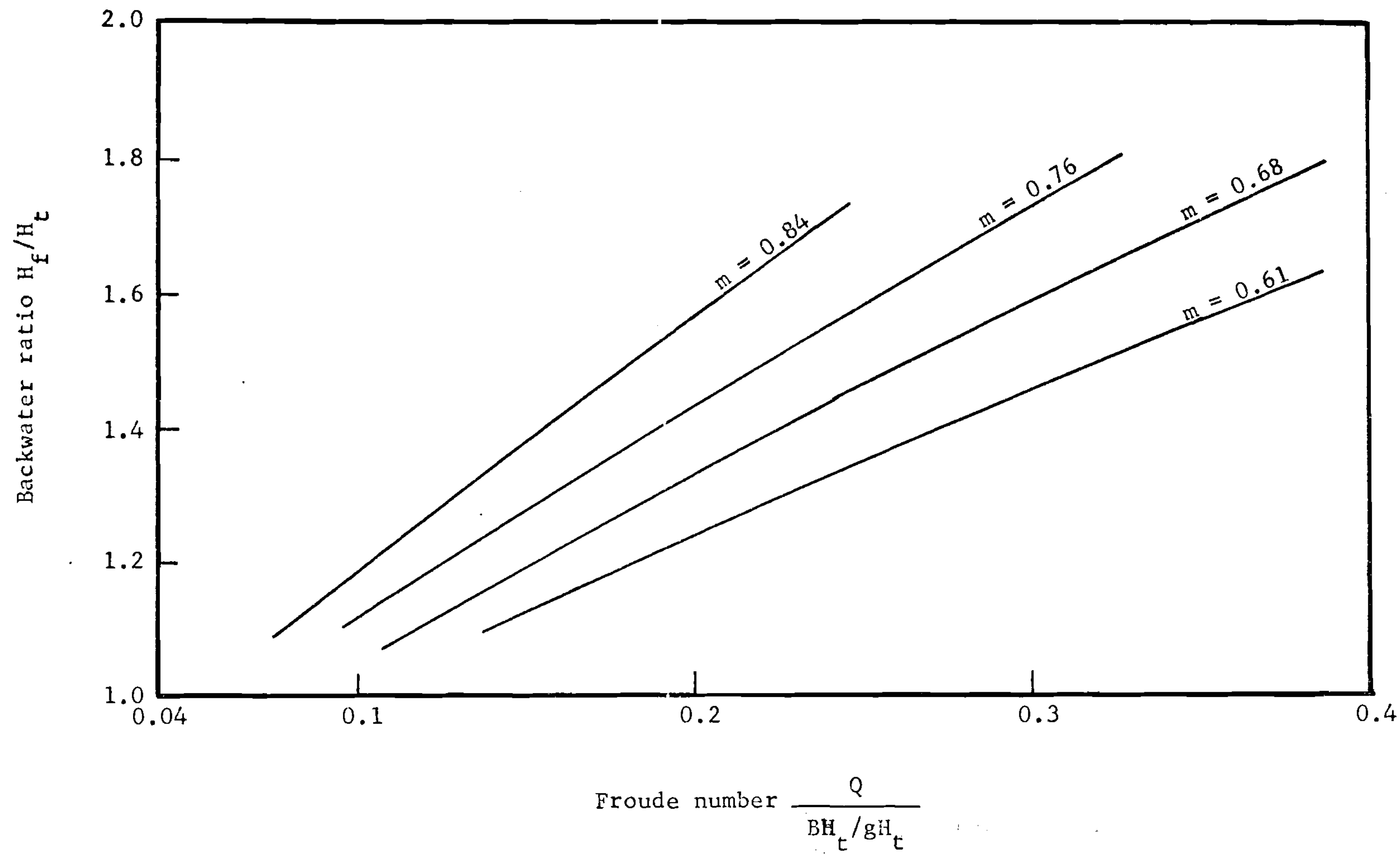



Figure 25. Backwater relation for the slot orifices

the entire range of the m values considered.

The last term on the right-hand side in the above four equations remains fairly constant. An average value of .815 is adopted. Maximum variation from this average value is limited to 1 percent which is acceptable for all practical purposes.

Table 6. Residuals Left After Polynomial Regression

| m value | λ value | λ estimate | Residual |
|---|---|---|---|
| .61 | 2.126 | 2.080 | 0.046 |
| .68 | 2.578 | 2.580 | -0.002 |
| .76 | 3.025 | 3.151 | -0.126 |
| .84 | 3.806 | 3.722 | 0.084 |

Thus a common equation which replaces the four curves of Figure 25 is:

$$H_f/H_t = (7.141\ m - 2.275)\ \mathbf{Fr} + 0.815 \qquad (17)$$

Within the limit of experimental errors, use of the above equation is fully justified for design purposes. A design example is worked out later in this chapter where the results obtained by using the above equation are compared with those obtained by using the experimental curve of Figure 25.

## Drag Coefficients for Interpolated m Values

Contraction ratios considered in this study are 0.61, 0.68, 0.76, and 0.84. For design and construction purposes, rounded values such as 0.60, 0.75, etc. may be preferred. From the curves for the above four m values, curves can safely be interpolated for the m values in the range of 0.60 to 0.85 with intermediate m values at 0.65, 0.70, 0.75, and 0.80. These curves are given in Figures 26, 27, and 28 for spacings of 4B, 5B, and 6B, respectively.

## Suitability of Flow Conditions Inside Fishway For Satisfactory Fish Passage

The following two points are of interest.

(1) The water jet after passing through the orifice falls into the water pocket downstream of the constriction and creates turbulence. This turbulence was observed to increase with increasing slot width.

(2) Maximum velocity of the water occurs at the vena contracta formed behind the slot. This velocity should be low enough to allow the fish to swim across. Reference 18 describes the limiting velocities for various kinds of fish. It was observed in this study that velocity increased with increase in slot contraction ratio. At higher contraction ratios there is more backwater thus producing a higher head on the flow through the slot.

Two critical sections were considered inside the fishway. One was the entrance to the fishway. The other was a section at the vena contracta downstream of any slot. If the spacing between the slots was too great and the channel was on a steep slope, the flow did not remain in an acceptable subcritical range. This critical section in the present study was observed to be at the vena contracta of the slot just

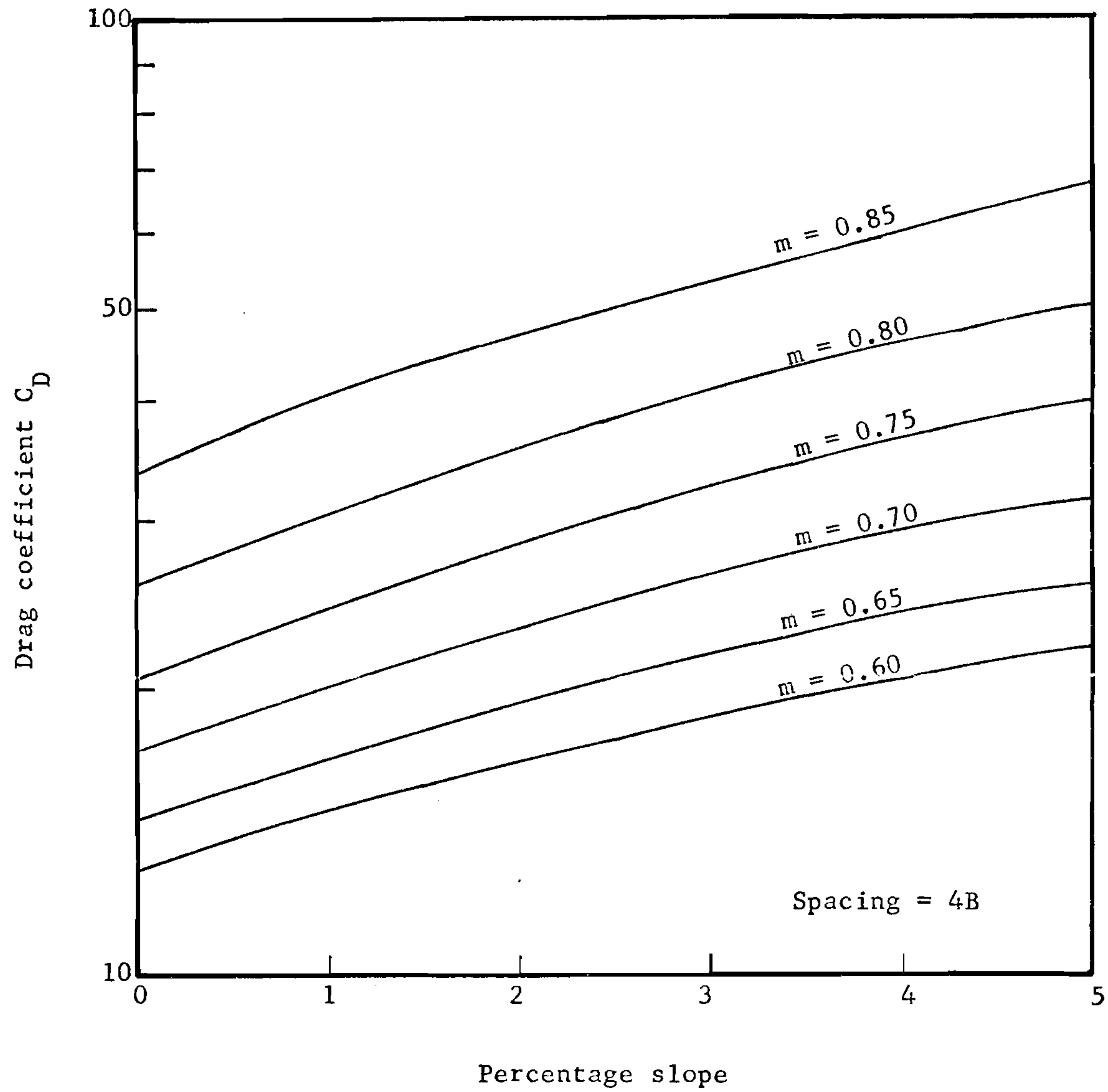



Figure 26. Value of drag coefficient for interpolated m values at a spacing of 4B

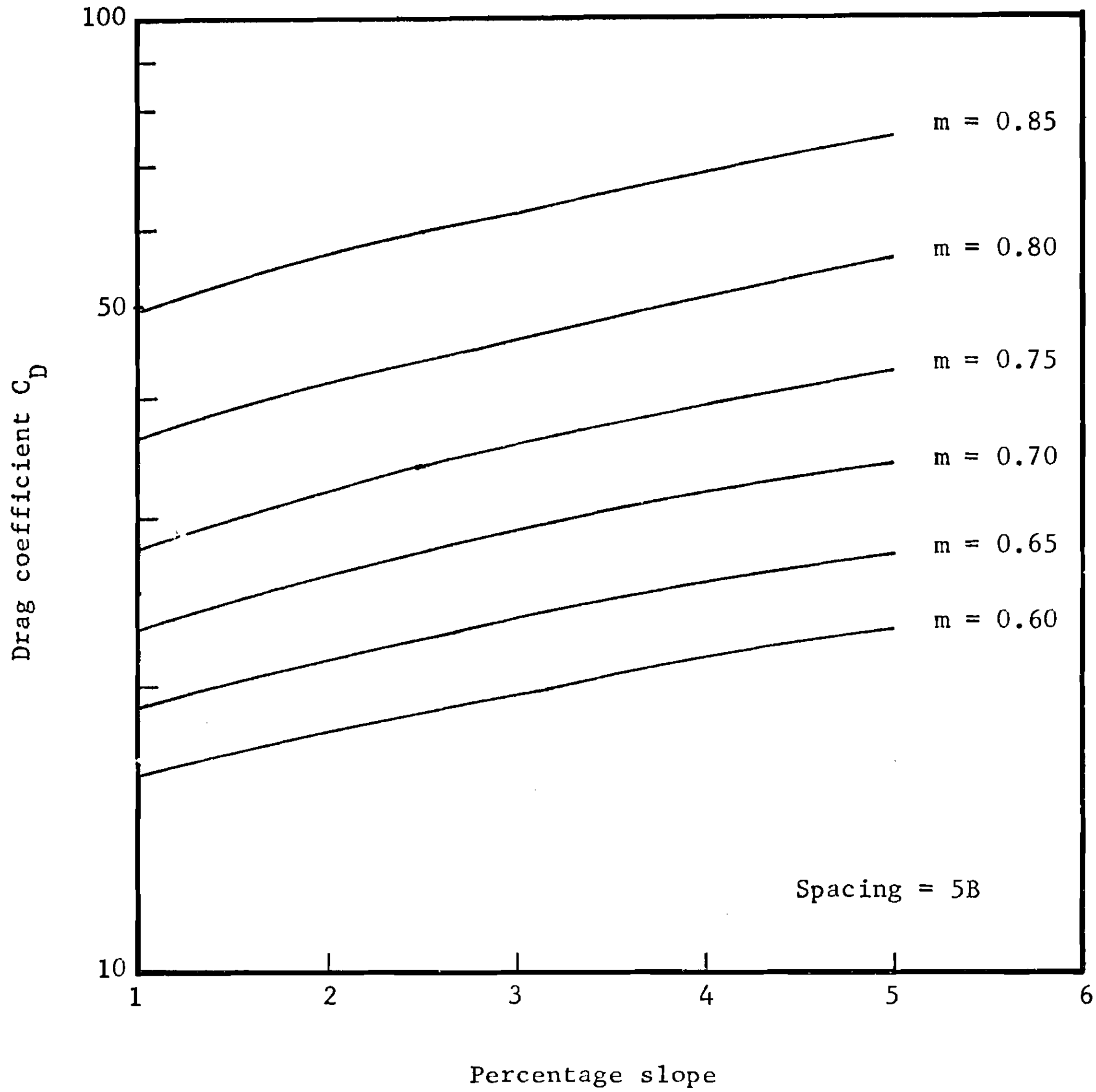



Figure 27. Value of drag coefficient for interpolated m values at a spacing of 5B

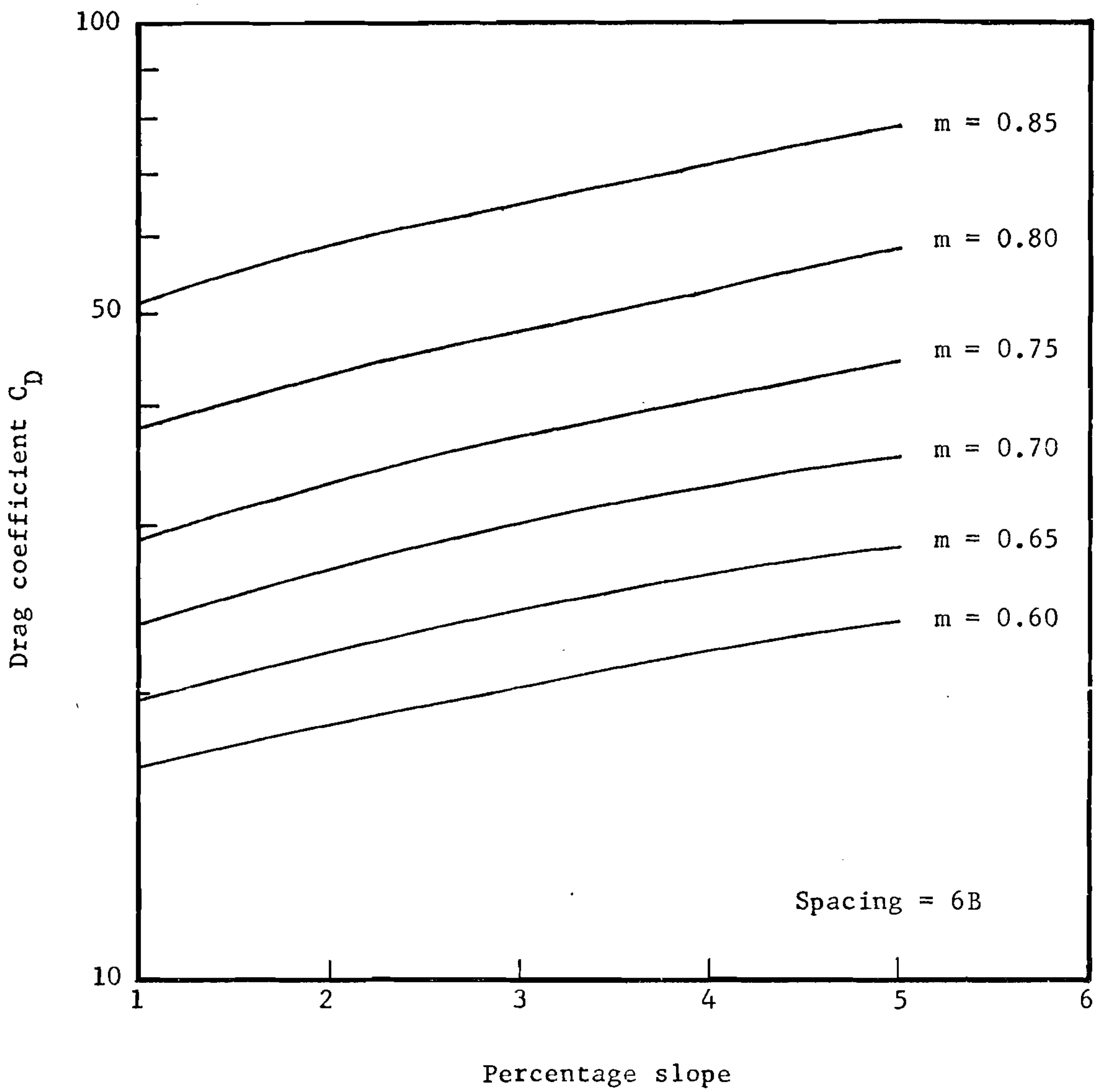



Figure 28. Value of drag coefficient for interpolated m values at a spacing of 6B

upstream of the fishway entrance slot.

Depth and width at the vena contracta and flow rate through the fishway were measured. Unfortunately the width at the vena contracta could not be measured precisely due to lateral fluctuations of the jet in the horizontal plane. The results are shown in Table 7. The ratio $H_t/H_i$ appeared to be an important factor.

On the assumption that the Froude number is the predominant factor affecting flow conditions, the velocity in a prototype, $V_p$, is given by

$$V_p = V_m \sqrt{L_r} \tag{18}$$

where

$V_m$ = maximum velocity in the fishway model; and

$L_r$ = geometric ratio of prototype to model.

Values of $V_m$ given in Table 7 may thus be converted to prototype velocities.

Flow conditions were found to be satisfactory in the entire range of variables covered in this study. It was observed, however, that for a contraction ratio of 0.61 at a spacing of 6B and at slopes of 4 percent and 5 percent excessive turbulence occurred. This may be unsatisfactory for fish passage. It is, therefore, suggested that up to a spacing of 6B and a slope of 5 percent, the flow conditions are satisfactory for slot contraction ratios varying from 0.65 to 0.85. Fishways with a contraction ratio of 0.61 and a slot spacing of 6B should be limited to slopes less than 3%.

Table 7. Table Showing Froude Number and Velocities at Downstream Slot and at the Slot just Upstream.

| m | Sp/B | Slope | $H_t/H_i$ | Downstream slot | | Upstream slot | | Maximum | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Velocity (ft/sec) | Froude number | Velocity (ft/sec) | Froude number | Velocity (ft/sec) | Froude number |
| .84 | 4 | .05 | .67 | 2.02 | .62 | 2.0 | .61 | 2.02 | .62 |
| .76 | 4 | .05 | .65 | 1.95 | .595 | 1.94 | .59 | 1.95 | .595 |
| .68 | 4 | .05 | .64 | 1.75 | .54 | 1.70 | .525 | 1.75 | .54 |
| .61 | 4 | .05 | .59 | 1.70 | .53 | 1.70 | .51 | 1.70 | .53 |
| .84 | 5 | .05 | .67 | 2.18 | .65 | 2.21 | .67 | 2.21 | .67 |
| .76 | 5 | .05 | .68 | 1.95 | .58 | 1.97 | .59 | 1.97 | .59 |
| .68 | 5 | .05 | .63 | 1.81 | .55 | 1.81 | .55 | 1.81 | .55 |
| .61 | 5 | .05 | .69 | 1.69 | .50 | 1.68 | .495 | 1.69 | .50 |
| .84 | 6 | .05 | .64 | 2.32 | .695 | 2.33 | .70 | 2.33 | .70 |
| .76 | 6 | .05 | .57 | 2.22 | .675 | 2.20 | .67 | 2.22 | .675 |
| .68 | 6 | .05 | .67 | 1.93 | .59 | 1.92 | .58 | 1.93 | .59 |
| .61 | 6 | .05 | .67 | 1.94 | .575 | 1.84 | .545 | 1.94 | .575 |

## Design Problem

The problem specified is to design a suitable fishway culvert 100 ft. in length placed on a 3 percent slope. Maximum allowable velocity in the fishway is limited to 6 ft/sec, and the fishway width is to be 3 feet. The upstream head is 3 feet and the tailwater depth is 2 feet. Channel friction may be neglected.

It is proposed to use slots having a contraction ratio of 0.68 at a longitudinal spacing of 12 feet (spacing = 4B). The results obtained by using Figure 25 will be compared with those obtained by using Equation 17. As explained earlier, Equation 17 is a very close fit to the curves of Figure 25.

In 100 feet of length, the total number of slot orifices needed is 9. The first slot is fixed at the fishway exit and the last slot is located 4 feet upstream from the fishway entrance.

At a 3 percent slope for m = 0.68 and Sp/B = 4, $C_D$ = 24.2 from Figure 19.

Unknowns are Q and $H_f$ which are related as shown in Figure 25. Thus successive use of Figure 25 and Equation 11 will yield the required rate of flow.

As a first approximation let $H_f/H_t$ be 1.4, then $H_f$ = 2.8 ft. On the assumption that the water depth upstream of any slot drops linearly from $H_i$ to $H_f$,

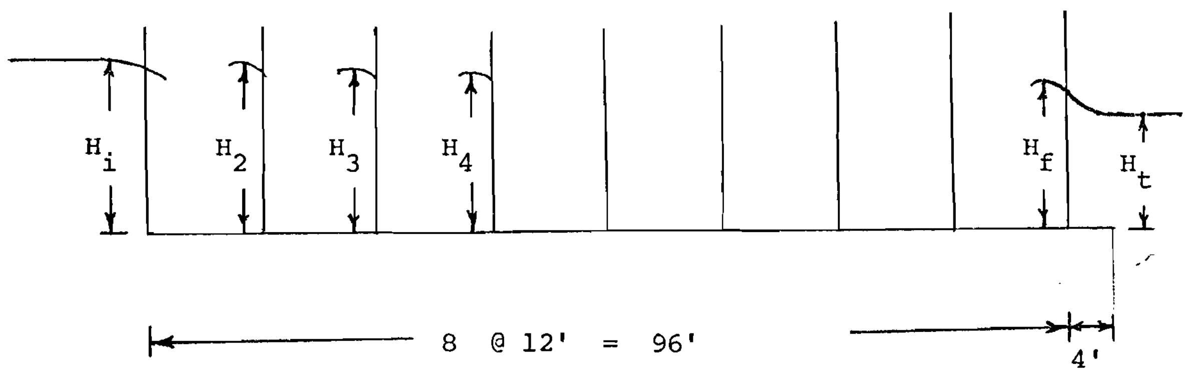
Drop per slot = $\Delta H = (H_i - H_f)/8 = .025$ ft.

$H_2 = H_i - \Delta H = 3.0 - .025 = 2.975$ ft.

$H_3 = H_2 - \Delta H = 2.975 - .025 = 2.950$ ft.

$H_4 = H_3 - \Delta H$, etc., then

$$\sum_{j=i,2,3,\ldots(f-1)} \frac{1}{H_j} = 2.748$$




m = 0.68; Sp = 4B; Slope = 3%.

For use of Equation 11, known data are:

$m = 0.68$;

$C_D = 24.2$;

$Sp = 12$ ft.;

$H_i = 3$ ft.;

$H_t = 2$ ft.;

$B = 3$ ft.;

$S = .03$;

$n = 8$;

$g = 32.2\ \text{ft/sec}^2$.

Using Equation 11, $Q = 9.98\ ft^3/sec$.

$$\text{Froude number} = \frac{Q}{B\ H_t\ \sqrt{gH_t}} = 0.207$$

For $m = 0.68$ and $Fr = 0.207$, Figure 25 gives,

$$H_f/H_t = 1.355$$

$$H_f = 2.71\ ft.$$

Taking this value of $H_f$, the above procedure is repeated which gives the next value of $Q = 10.07\ ft^3/sec$ and a corresponding Froude number of 0.2085. For this Froude number, Figure 25 gives,

$$H_f/H_t = 1.3575 \quad \text{or} \quad H_f = 2.715\ ft.$$

The above procedure when repeated for this value of $H_f$ gives $Q = 10.07\ ft^3/sec$ which shows no further improvement in the value of Q.

An approximate check on velocity at the throat of the vena contracta of the fishway entrance slot is obtained by assuming the width and depth at vena contracta equal to the width of the slot opening and tailwater depth, respectively.

$$\text{Velocity} = \frac{Q}{bH_t} = \frac{Q}{(1-m)BH_t} = 5.25\ ft/sec.$$

An estimate of this velocity can also be obtained by assuming that the drop in water surface in the slot orifice is changed into the velocity head at the vena contracta.

Drop in water surface at the slot $= H_f - H_t = 0.715$ ft.

$$\text{Velocity} = \sqrt{2g \times 0.715} = 6.80\ ft/sec.$$

In the above expression for velocity, the approach velocity upstream of the slot is neglected and the coefficient of velocity for the slot orifice is assumed to be unity. This procedure leads to an overestimate of the throat velocity.

The use of Equation 17 gives $Q = 10.06\ ft^3/sec$ and $H_f/H_t = 1.3545$. These values are in close agreement with those calculated above. A computer program for this design, using Equation 17, is given in the Appendix B.

Rates of flow as obtained by using a few different arrangements of m and Sp are tabulated below.

| Contraction ratio | Spacing of slots (ft) | Discharge $ft^3/sec$ | Approximate velocity (ft/sec) |
|---|---|---|---|
| 0.75 | 12 | 8.28 | 5.52 |
| 0.65 | 15 | 11.61 | 5.55 |
| 0.75 | 15 | 8.83 | 5.89 |
| 0.85 | 15 | 6.35 | 7.05 |
| 0.75 | 16 | 9.40 | 6.26 |

# CHAPTER V

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

A study of the habits and requirements of fish and of the difficulties encountered in providing satisfactory fish passage through existing culverts resulted in the study of a vertical slot orifice fishway structure. Design criteria for the slot orifice fishway is developed by using a combination of hydraulic laws and hydraulic modeling. Curves are developed to evaluate the value of the drag coefficient of a slot orifice and a procedure to design a slot orifice fishway is explained. It is expected that this type of fishway will function satisfactorily over a wide range of discharges with no loss in the hydraulic efficiency of the main culvert. Debris and other material brought in with the flow should pass through the slot orifice. The fishway will be well lighted except for a short reach in the upper portion of the fishway.

The following points are observed in this study:

1. The effect of the tailwater on drag coefficient was found to be negligible when tailwater depth was restricted to the range of 0.5 to 0.9 of the upstream head.

2. The variation in the drag coefficient found by taking the average over a number of slots was not significant for different lengths of the fishway.

3. Variation in headwater elevation in the limited range available, did not affect the value of the drag coefficient.

4. The only significant factors affecting the drag coefficient were the contraction ratio, the spacing between the slots, and the slope of the fishway. Four contraction ratios, 0.61, 0.68, 0.76, and 0.84 were studied. Each contraction ratio was studied at three longitudinal spacings: 4, 5, and 6 times the fishway width. The spacing of 4B was studied for a slope varying from horizontal to 5 percent. The other two spacings were studied for slopes varying from 1 percent to 5 percent.

5. For design purposes, it was necessary to establish a relationship between $H_f$ and $H_t$ for the entrance orifice. For known tailwater, it was then possible to evaluate the water depth upstream of the entrance slot orifice. Other factors involved were rate of flow through the orifice, width of fishway, and slot contraction ratio.

6. The velocity at the vena contracta of a slot orifice was found to increase slightly with an increase in the contraction ratio. The effect of an increased contraction ratio was to create a higher backwater level thus producing a larger velocity.

7. Rate of flow through fishway was observed to increase with increasing slope, increasing spacing, and decreasing contraction ratio.

8. For a contraction ratio of 0.61 at a spacing of 6B and at slopes of 4 percent and 5 percent, increased turbulence inside the fishway may be undesirable, and therefore this design should not be used. In general, up to a spacing of 6B and a slope of 5 percent, the flow conditions inside the fishway should be satisfactory for a slot contraction ratio in the range of 0.65 to 0.85. For design, the throat velocity at the vena contracta of the fishway entrance slot should be

kept less than the performance capacity of the fish. Within the specified range of variables, it was observed that the maximum upstream velocity did not exceed this throat velocity.

9. For design purposes, the values of the drag coefficients obtained for four contraction ratios of 0.61, 0.68, 0.76, and 0.84 are interpolated for contraction ratios of 0.60, 0.65, 0.70, 0.75, 0.80, and 0.85. The curves expressing the backwater created by the downstream slot in terms of tailwater for the above four contraction ratios are generalized in the form of an equation which is applicable for any contraction ratio in the range of 0.60 to 0.85.

## Recommendations

Due to limited time and resources available, many aspects were not fully covered and need further study and field verification. These are mentioned below.

1. The upstream face of the proposed fishway structure (Figure 4) is set at an angle to the center line of the culvert. For model studies the entrance orifice was set perpendicular to this centerline (Figure 12). A suitable correction for the rate of flow when the entrance orifice is at an angle other than 90 degree should be determined.

2. The range of the slot contraction ratio, Sp/B and the channel slope may be expanded to provide more flexibility in design.

3. The effect of upstream head variation on the drag coefficient was not fully studied. From the limited study made, it appears that the findings of this work are valid for a wide range of head variation, however, this should be verified.

4. Regarding the suitability of flow for fish passage through the fishway, it is necessary to have a check on the maximum velocity occurring anywhere inside the fishway and also on the intensity of the turbulence created. An approximate check on the maximum velocity was obtained in this study. Regarding the intensity of turbulence acceptable for fish passage, the writer's guess in this study should be confirmed by field studies. A precise study for maximum velocity is also recommended.

## NOTATION

$A$ = cross sectional area of flow;

$b$ = width of slot orifice;

$B$ = width of the fishway;

$C_D$ = coefficient of drag;

$d$ = vertical depth used to measure head over a weir;

$f$ = used as a subscript to denote "final";

$F_D$ = drag force;

$F_R$ = force of resistance to flow;

$Fr$ = Froude number;

$g$ = acceleration due to gravity;

$h$ = static head over a weir;

$H$ = depth of flow measured perpendicularly from the water surface;

$i$ = used as a subscript to denote "initial";

$j$ = used as a subscript;

$L_r$ = geometric ratio of prototype to model;

$m$ = contraction ratio; also subscript for model;

$n$ = number of constrictions (slot orifices) between initial and final sections considered;

$p$ = used as a subscript to denote "prototype";

$Q$ = volume rate of flow, which is the total discharge at a channel cross section;

$S$ = slope of the channel;

NOTATION (Continued)

Sp = longitudinal spacing between the slot orifice constrictions;

t = used as a subscript to denote "tailwater";

V = velocity of flow;

W = weight of the body of water between two sections considered;

$\beta$ = momentum correction factor;

$\gamma$ = specific weight or weight per unit volume;

$\Delta$ = a symbol denoting "change" or "difference";

$\theta$ = slope of the channel in radians; and

$\rho$ = density or mass per unit volume.

$\lambda$ = variable denoting coefficient of Froude number;

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# APPENDICES

# APPENDIX A

## OBSERVATION DATA

TABLE A-1

Contraction Ratio: 0.68
Spacing: 21 inches

Data to Draw Flow Profiles

| Section | Interval in inches | Water Depths for Channel Slopes of 0% | 1% | 2% | 3% | 4% | 5% |
|---|---|---|---|---|---|---|---|
| 1 | | 4.95 | 4.58 | 4.45 | 4.18 | 3.98 | 3.76 |
| | 1.30 | | | | | | |
| * 2 | | 4.81 | 4.48 | 4.28 | 4.02 | 3.88 | 3.60 |
| | 1.30 | | | | | | |
| 3 | | 4.55 | 4.11 | 3.84 | 3.51 | 3.06 | 2.67 |
| | 5.70 | | | | | | |
| 4 | | 4.62 | 4.24 | 4.02 | 3.76 | 3.62 | 3.26 |
| | 7.00 | | | | | | |
| 5 | | 4.66 | 4.41 | 4.29 | 4.06 | 3.93 | 3.71 |
| | 5.70 | | | | | | |
| 6 | | 4.67 | 4.46 | 4.40 | 4.23 | 4.14 | 4.00 |
| | 1.30 | | | | | | |
| * 7 | | 4.59 | 4.38 | 4.30 | 4.16 | 4.03 | 3.93 |
| | 1.30 | | | | | | |
| 8 | | 4.11 | 3.89 | 3.71 | 3.42 | 3.40 | 3.07 |
| | 5.70 | | | | | | |
| 9 | | 4.20 | 4.06 | 3.95 | 3.76 | 3.78 | 3.63 |
| | 7.00 | | | | | | |
| 10 | | 4.31 | 4.18 | 4.14 | 4.09 | 4.06 | 4.01 |
| | 5.70 | | | | | | |
| 11 | | 4.33 | 4.28 | 4.35 | 4.27 | 4.35 | 4.32 |
| | 1.30 | | | | | | |
| *12 | | 4.18 | 4.20 | 4.18 | 4.18 | 4.21 | 4.27 |
| | 1.30 | | | | | | |
| 13 | | 3.66 | 3.64 | 3.63 | 3.60 | 3.60 | 3.60 |

* position of a slot orifice constriction

TABLE A-2

Contraction Ratio: 0.61
Spacing: 16 inches

Data for Slot Orifice to Establish Backwater Relation

| S | Q | $H_f$ | $H_t$ |
|---|---|---|---|
| | gpm | inches | inches |
| .01 | 21.98 | 3.85 | 3.24 |
| .01 | 21.84 | 3.91 | 3.32 |
| .01 | 22.12 | 3.77 | 3.07 |
| .02 | 24.20 | 3.90 | 3.04 |
| .02 | 23.91 | 4.01 | 3.20 |
| .02 | 23.91 | 4.07 | 3.32 |
| .03 | 26.37 | 4.19 | 3.27 |
| .03 | 26.37 | 4.12 | 3.14 |
| .03 | 26.37 | 4.10 | 3.10 |
| .02 | 24.48 | 3.62 | 2.37 |
| .02 | 24.48 | 3.65 | 2.45 |
| .02 | 24.32 | 3.71 | 2.61 |
| .02 | 23.21 | 4.21 | 3.60 |
| .02 | 24.20 | 3.79 | 2.79 |
| .02 | 23.07 | 4.24 | 3.64 |
| .02 | 22.66 | 4.39 | 3.90 |
| .02 | 22.25 | 4.55 | 4.13 |
| .02 | 26.51 | 4.81 | 4.25 |
| .02 | 27.11 | 4.68 | 4.00 |
| .02 | 27.86 | 4.45 | 3.61 |
| .02 | 28.93 | 3.87 | 2.38 |
| .02 | 28.77 | 3.92 | 2.48 |
| .02 | 28.77 | 3.96 | 2.59 |
| .02 | 28.61 | 4.03 | 2.77 |

TABLE A-3

Contraction Ratio: 0.68
Spacing: 16 inches

Data for Slot Orifice to Establish Backwater Relation

| S | Q | $H_f$ | $H_t$ |
|---|---|---|---|
| | gpm | inches | inches |
| .01 | 18.72 | 4.17 | 3.75 |
| .01 | 17.49 | 4.26 | 3.96 |
| .02 | 26.22 | 4.08 | 2.65 |
| .02 | 25.63 | 4.52 | 3.60 |
| .02 | 26.36 | 4.05 | 2.55 |
| .02 | 26.51 | 3.94 | 2.25 |
| .03 | 22.39 | 3.81 | 2.52 |
| .03 | 22.25 | 3.97 | 2.81 |
| .03 | 22.39 | 4.12 | 3.15 |
| .03 | 22.12 | 4.35 | 3.56 |
| .03 | 21.58 | 4.55 | 3.92 |
| .03 | 21.17 | 4.72 | 4.14 |
| .04 | 22.52 | 3.98 | 2.60 |
| .04 | 22.80 | 3.89 | 2.29 |
| .04 | 23.91 | 4.07 | 2.72 |
| .04 | 23.63 | 4.29 | 3.25 |
| .04 | 23.35 | 4.44 | 3.49 |
| .04 | 23.07 | 4.64 | 3.85 |
| .05 | 24.20 | 3.88 | 2.29 |
| .05 | 24.77 | 4.24 | 2.79 |
| .05 | 24.48 | 4.50 | 3.42 |
| .05 | 24.32 | 4.68 | 3.73 |
| .05 | 24.20 | 4.82 | 3.98 |
| .05 | 24.91 | 4.13 | 2.59 |
| .05 | 25.49 | 4.03 | 2.26 |
| .05 | 24.63 | 4.39 | 3.13 |

TABLE A-4

Contraction Ratio: 0.76
Spacing: 16 inches

Data for Slot Orifice to Establish Backwater Relation

| S | Q | $H_f$ | $H_t$ |
|---|---|---|---|
| | gpm | inches | inches |
| .01 | 16.23 | 3.80 | 3.24 |
| .02 | 15.78 | 4.49 | 4.08 |
| .02 | 17.37 | 3.59 | 2.39 |
| .02 | 17.61 | 3.50 | 2.17 |
| .02 | 16.23 | 4.25 | 3.71 |
| .02 | 16.69 | 4.00 | 3.28 |
| .02 | 17.26 | 3.86 | 2.99 |
| .02 | 19.09 | 3.88 | 2.49 |
| .02 | 19.09 | 3.80 | 2.55 |
| .02 | 19.09 | 3.72 | 2.33 |
| .02 | 19.35 | 3.65 | 2.11 |
| .02 | 20.77 | 3.87 | 2.24 |
| .03 | 17.98 | 3.77 | 2.62 |
| .03 | 18.10 | 3.65 | 2.23 |
| .03 | 19.73 | 3.88 | 2.40 |
| .03 | 17.28 | 4.53 | 3.96 |
| .03 | 17.73 | 4.03 | 3.08 |
| .03 | 18.22 | 3.87 | 2.68 |
| .04 | 19.35 | 3.80 | 2.18 |
| .04 | 19.35 | 3.90 | 2.40 |
| .04 | 18.84 | 4.55 | 3.77 |
| .04 | 18.71 | 4.78 | 4.10 |
| .04 | 18.96 | 4.34 | 3.88 |
| .04 | 19.35 | 4.09 | 2.87 |
| .04 | 19.09 | 4.24 | 3.17 |
| .05 | 19.48 | 4.34 | 3.12 |
| .05 | 19.35 | 4.50 | 3.44 |
| .05 | 19.60 | 4.22 | 2.92 |

TABLE A-5

Contraction Ratio: 0.84
Spacing: 16 inches

Data for Slot Orifice to Establish Backwater Relation

| S | Q | $H_f$ | $H_t$ |
|---|---|---|---|
| | gpm | inches | inches |
| .02 | 13.24 | 3.92 | 3.22 |
| .02 | 13.24 | 3.89 | 3.15 |
| .02 | 13.34 | 3.78 | 2.98 |
| .02 | 13.04 | 4.14 | 3.56 |
| .02 | 13.24 | 3.93 | 3.20 |
| .02 | 12.84 | 4.28 | 3.79 |
| .02 | 12.45 | 4.51 | 4.14 |
| .02 | 13.54 | 3.38 | 2.00 |
| .02 | 13.44 | 3.47 | 2.24 |
| .02 | 13.44 | 3.65 | 2.64 |
| .02 | 13.44 | 3.55 | 2.45 |
| .02 | 15.78 | 3.95 | 2.56 |
| .02 | 15.78 | 4.00 | 2.70 |
| .02 | 15.67 | 4.05 | 2.82 |
| .02 | 15.56 | 4.17 | 3.07 |
| .02 | 15.12 | 4.67 | 3.99 |
| .02 | 14.58 | 4.90 | 4.37 |
| .02 | 11.51 | 3.99 | 3.56 |
| .02 | 11.61 | 3.85 | 3.34 |
| .03 | 13.95 | 3.35 | 2.88 |
| .03 | 13.85 | 3.95 | 3.07 |
| .03 | 13.76 | 4.06 | 3.22 |

TABLE A-6

Contraction ratio: 0.76; spacing: 16 inches
Number of slots: 5; Slope: .03

Data for Effect of Head Variation on $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | $C_D$ |
|---|---|---|---|---|
| gpm | inches | inches | inches | |
| 14.90 | 3.91 | 3.74 | 3.03 | 34.7 |
| 17.26 | 4.33 | 3.94 | 3.03 | 33.4 |
| 18.96 | 4.66 | 4.08 | 3.02 | 33.5 |
| 20.25 | 4.97 | 4.20 | 3.01 | 34.9 |
| 22.38 | 5.32 | 4.40 | 3.00 | 33.7 |

TABLE A-7

Contraction Ratio: 0.76
Spacing: 16 inches

Data for $C_D$ Variation for Varying Number of Slots Considered

| | | | Section: 1, n*= 3 | | | Section: 2, n= 4 | | |
|---|---|---|---|---|---|---|---|---|
| Q | $H_i$ | S | $H_f$ | $H_t$ | $C_D$ | $H_f$ | $H_t$ | $C_D$ |
| gpm | inches | | inches | inches | | inches | inches | |
| 17.03 | 4.48 | .02 | 4.06 | 3.43 | 30.5 | 3.84 | 2.98 | 29.7 |
| 16.92 | 4.49 | .02 | 4.09 | 3.50 | 30.8 | 3.90 | 3.10 | 29.9 |
| 16.69 | 4.49 | .02 | 4.17 | 3.61 | 30.3 | 4.01 | 3.30 | 29.7 |
| 18.71 | 4.46 | .04 | 4.25 | 3.37 | 38.6 | 4.15 | 3.04 | 37.2 |
| 18.59 | 4.46 | .04 | 4.27 | 3.46 | 39.2 | 4.22 | 3.20 | 37.6 |
| 18.47 | 4.47 | .04 | 4.33 | 3.54 | 39.4 | 4.28 | 3.31 | 38.1 |

* Length considered = 16 n inches.

TABLE A-8

Contraction Ratio: 0.61
Spacing: 16"; Number of Slots: 5

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ (Average) |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | |
| 19.99 | 4.54 | 3.56 | 3.00 | .00 | .661 | 13.9 | |
| 19.60 | 4.56 | 3.69 | 3.23 | .00 | .708 | 13.3 | |
| 19.09 | 4.57 | 3.78 | 3.36 | .00 | .735 | 13.0 | 13.4 |
| 21.98 | 4.48 | 3.85 | 3.24 | .01 | .723 | 15.1 | |
| 21.84 | 4.49 | 3.91 | 3.32 | .01 | .739 | 15.0 | |
| 22.12 | 4.47 | 3.77 | 3.07 | .01 | .687 | 15.4 | 15.3 |
| 24.20 | 4.44 | 3.90 | 3.04 | .02 | .685 | 17.3 | |
| 23.91 | 4.45 | 4.01 | 3.20 | .02 | .719 | 17.2 | |
| 23.91 | 4.47 | 4.07 | 3.32 | .02 | .743 | 17.2 | 17.25 |
| 26.37 | 4.51 | 4.19 | 3.27 | .03 | .725 | 19.1 | |
| 26.37 | 4.51 | 4.12 | 3.14 | .03 | .696 | 19.3 | |
| 26.37 | 4.51 | 4.10 | 3.10 | .03 | .687 | 19.3 | 19.25 |
| 27.71 | 4.48 | 4.32 | 3.26 | .04 | .728 | 20.8 | |
| 28.01 | 4.48 | 4.20 | 3.06 | .04 | .683 | 20.6 | |
| 27.71 | 4.48 | 4.33 | 3.25 | .04 | .725 | 20.8 | 20.7 |
| 28.46 | 4.44 | 4.20 | 2.62 | .05 | .590 | 22.6 | |
| 28.77 | 4.49 | 4.39 | 3.02 | .05 | .673 | 22.9 | |
| 28.77 | 4.49 | 4.42 | 3.21 | .05 | .715 | 23.3 | |
| 28.77 | 4.49 | 4.49 | 3.30 | .05 | .735 | 23.1 | 23.0 |

TABLE A-9

Contraction Ratio: 0.68
Spacing: 16"; Number of Slots: 5

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ (Average) |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | |
| 17.14 | 4.50 | 3.44 | 2.84 | 0.0 | 0.631 | 17.7 | |
| 16.92 | 4.51 | 3.54 | 3.01 | 0.0 | 0.667 | 17.1 | |
| 16.69 | 4.51 | 3.61 | 3.15 | 0.0 | 0.698 | 16.6 | |
| 16.46 | 4.52 | 3.70 | 3.29 | 0.0 | 0.728 | 15.9 | 16.4 |
| 20.38 | 4.49 | 3.40 | 2.31 | 0.01 | 0.514 | 19.2 | |
| 20.01 | 4.51 | 3.65 | 2.83 | 0.01 | 0.627 | 18.6 | |
| 19.73 | 4.52 | 3.77 | 3.05 | 0.01 | 0.675 | 18.3 | |
| 19.35 | 4.53 | 3.87 | 3.27 | 0.01 | 0.722 | 18.3 | |
| 18.72 | 4.55 | 4.17 | 3.75 | 0.01 | 0.824 | 16.6 | |
| 17.49 | 4.48 | 4.26 | 3.96 | 0.01 | 0.884 | 16.1 | 18.3 |
| 21.44 | 4.51 | 3.67 | 2.47 | 0.02 | 0.548 | 21.9 | |
| 20.90 | 4.53 | 3.96 | 3.07 | 0.02 | 0.678 | 21.9 | |
| 20.90 | 4.52 | 4.00 | 3.18 | 0.02 | 0.704 | 21.6 | |
| 20.12 | 4.51 | 4.29 | 3.73 | 0.02 | 0.827 | 20.9 | |
| 19.60 | 4.52 | 4.49 | 4.05 | 0.02 | 0.896 | 20.2 | |
| 21.31 | 4.52 | 3.77 | 2.71 | 0.02 | 0.600 | 22.0 | 21.5 |
| 22.39 | 4.50 | 3.81 | 2.52 | 0.03 | 0.560 | 24.7 | |
| 22.25 | 4.51 | 3.97 | 2.81 | 0.03 | 0.623 | 24.7 | |
| 22.39 | 4.52 | 4.12 | 3.15 | 0.03 | 0.697 | 24.2 | |
| 22.12 | 4.54 | 4.35 | 3.56 | 0.03 | 0.784 | 24.1 | |
| 21.58 | 4.52 | 4.55 | 3.92 | 0.03 | 0.867 | 23.8 | |
| 21.17 | 4.53 | 4.72 | 4.14 | 0.03 | 0.914 | 23.5 | 24.2 |
| 24.20 | 4.50 | 3.88 | 2.29 | 0.04 | 0.509 | 25.1 | |
| 23.91 | 4.50 | 4.07 | 2.72 | 0.04 | 0.604 | 25.7 | |
| 23.63 | 4.51 | 4.29 | 3.25 | 0.04 | 0.721 | 26.5 | |
| 23.35 | 4.51 | 4.44 | 3.49 | 0.04 | 0.774 | 26.6 | |
| 23.07 | 4.52 | 4.64 | 3.85 | 0.04 | 0.852 | 26.8 | 26.4 |
| 24.63 | 4.50 | 4.29 | 2.89 | 0.05 | 0.642 | 28.4 | |
| 25.49 | 4.55 | 4.03 | 2.26 | 0.05 | 0.497 | 26.9 | |
| 24.91 | 4.49 | 4.13 | 2.59 | 0.05 | 0.577 | 27.6 | |
| 24.77 | 4.50 | 4.24 | 2.79 | 0.05 | 0.620 | 28.1 | |
| 24.63 | 4.52 | 4.39 | 3.13 | 0.05 | 0.692 | 29.0 | |
| 24.48 | 4.50 | 4.50 | 3.42 | 0.05 | 0.760 | 29.2 | |
| 24.32 | 4.51 | 4.68 | 3.73 | 0.05 | 0.827 | 29.4 | |
| 24.20 | 4.52 | 4.82 | 3.98 | 0.05 | 0.881 | 29.6 | 28.9 |

TABLE A-10

Contraction Ratio: 0.76
Spacing: 16"; Number of Slots: 5

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 14.36 | 4.51 | 3.46 | 2.94 | 0.0 | 0.652 | 22.6 | |
| 14.26 | 4.50 | 3.55 | 3.10 | 0.0 | 0.689 | 21.1 | |
| 13.24 | 4.54 | 3.87 | 3.61 | 0.0 | 0.795 | 18.8 | |
| 14.06 | 4.53 | 3.60 | 3.15 | 0.0 | 0.695 | 21.7 | |
| 13.85 | 4.54 | 3.65 | 3.24 | 0.0 | 0.714 | 21.7 | 21.7 |
| 16.92 | 4.49 | 3.45 | 2.54 | 0.01 | 0.566 | 24.8 | |
| 16.23 | 4.52 | 3.80 | 3.24 | 0.01 | 0.717 | 24.1 | |
| 15.67 | 4.53 | 4.06 | 3.67 | 0.01 | 0.810 | 22.5 | |
| 15.78 | 4.55 | 3.80 | 3.58 | 0.01 | 0.787 | 26.8 | |
| 15.67 | 4.56 | 3.88 | 3.30 | 0.01 | 0.724 | 25.7 | 24.5 |
| 17.26 | 4.54 | 3.86 | 2.99 | 0.02 | 0.659 | 30.1 | |
| 16.69 | 4.50 | 4.00 | 3.28 | 0.02 | 0.729 | 30.1 | |
| 16.23 | 4.51 | 4.25 | 3.71 | 0.02 | 0.823 | 29.4 | |
| 16.81 | 4.46 | 3.94 | 3.18 | 0.02 | 0.713 | 29.2 | |
| 16.46 | 4.47 | 4.15 | 3.54 | 0.02 | 0.792 | 28.6 | 29.5 |
| 18.22 | 4.54 | 3.87 | 2.68 | 0.03 | 0.590 | 34.4 | |
| 17.73 | 4.47 | 4.03 | 3.08 | 0.03 | 0.689 | 34.2 | |
| 17.28 | 4.49 | 4.53 | 3.96 | 0.03 | 0.882 | 32.8 | |
| 17.73 | 4.47 | 4.16 | 3.31 | 0.03 | 0.740 | 33.4 | |
| 17.73 | 4.47 | 4.14 | 3.23 | 0.03 | 0.723 | 33.4 | 33.8 |
| 19.35 | 4.53 | 3.90 | 2.47 | 0.04 | 0.545 | 36.4 | |
| 19.35 | 4.54 | 4.09 | 2.87 | 0.04 | 0.632 | 36.5 | |
| 19.09 | 4.54 | 4.24 | 3.17 | 0.04 | 0.698 | 37.2 | |
| 18.96 | 4.55 | 4.34 | 3.38 | 0.04 | 0.743 | 37.8 | |
| 18.84 | 4.52 | 4.26 | 3.20 | 0.04 | 0.708 | 37.6 | |
| 18.84 | 4.52 | 4.33 | 3.31 | 0.04 | 0.732 | 37.3 | 37.3 |
| 19.60 | 4.52 | 4.22 | 2.92 | 0.05 | 0.646 | 41.5 | |
| 19.48 | 4.52 | 4.34 | 3.12 | 0.05 | 0.690 | 41.9 | |
| 19.35 | 4.53 | 4.50 | 3.44 | 0.05 | 0.759 | 42.7 | |
| 19.73 | 4.57 | 4.33 | 3.05 | 0.05 | 0.667 | 41.8 | |
| 19.73 | 4.57 | 4.54 | 3.41 | 0.05 | 0.746 | 41.5 | 41.8 |

TABLE A-11

Contraction Ratio: 0.84
Spacing: 16 inches; Number of Slots: 5

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 10.97 | 4.49 | 3.53 | 3.10 | 0.0 | 0.690 | 32.5 | |
| 10.88 | 4.50 | 3.59 | 3.19 | 0.0 | 0.709 | 31.8 | |
| 10.97 | 4.50 | 3.59 | 3.19 | 0.0 | 0.709 | 31.3 | 32.0 |
| 12.55 | 4.54 | 3.61 | 2.90 | 0.01 | 0.639 | 40.5 | |
| 12.36 | 4.54 | 3.76 | 3.18 | 0.01 | 0.700 | 39.2 | |
| 12.26 | 4.55 | 3.85 | 3.33 | 0.01 | 0.732 | 38.5 | 39.2 |
| 13.24 | 4.49 | 3.92 | 3.22 | 0.02 | 0.717 | 44.3 | |
| 13.24 | 4.50 | 3.89 | 3.15 | 0.02 | 0.700 | 44.9 | |
| 13.34 | 4.49 | 3.78 | 2.98 | 0.02 | 0.664 | 45.3 | 44.9 |
| 13.95 | 4.44 | 3.85 | 2.88 | 0.03 | 0.649 | 50.8 | |
| 13.85 | 4.45 | 3.95 | 3.07 | 0.03 | 0.690 | 51.3 | |
| 13.76 | 4.45 | 4.06 | 3.22 | 0.03 | 0.724 | 50.8 | 51.0 |
| 14.69 | 4.52 | 4.16 | 3.15 | 0.04 | 0.697 | 57.3 | |
| 14.58 | 4.51 | 4.20 | 3.23 | 0.04 | 0.716 | 57.7 | |
| 14.81 | 4.51 | 4.04 | 2.93 | 0.04 | 0.650 | 56.5 | 57.5 |
| 15.01 | 4.50 | 4.21 | 3.03 | 0.05 | 0.673 | 64.4 | |
| 14.79 | 4.50 | 4.49 | 3.57 | 0.05 | 0.793 | 66.1 | |
| 15.01 | 4.50 | 4.25 | 3.12 | 0.05 | 0.693 | 64.5 | 64.5 |

TABLE A-12

Contraction Ratio: 0.61
Spacing: 20 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 22.80 | 4.50 | 4.00 | 3.20 | 0.01 | 0.711 | 16.7 | |
| 22.94 | 4.49 | 3.95 | 3.06 | 0.01 | 0.682 | 16.8 | 16.7 |
| 25.34 | 4.49 | 4.13 | 3.11 | 0.02 | 0.693 | 18.9 | |
| 25.05 | 4.50 | 4.19 | 3.24 | 0.02 | 0.720 | 19.0 | 18.9 |
| 27.26 | 4.52 | 4.41 | 3.31 | 0.03 | 0.732 | 20.7 | |
| 27.41 | 4.52 | 4.29 | 3.03 | 0.03 | 0.670 | 21.0 | 20.8 |
| 29.54 | 4.54 | 4.56 | 3.21 | 0.04 | 0.707 | 21.9 | |
| 29.54 | 4.54 | 4.50 | 3.01 | 0.04 | 0.663 | 21.8 | |
| 29.40 | 4.54 | 4.59 | 3.33 | 0.04 | 0.733 | 22.2 | 21.9 |
| 30.80 | 4.52 | 4.63 | 3.11 | 0.05 | 0.688 | 24.0 | |
| 30.64 | 4.53 | 4.69 | 3.21 | 0.05 | 0.709 | 24.2 | |
| 30.64 | 4.52 | 4.75 | 3.37 | 0.05 | 0.746 | 24.1 | 24.0 |

TABLE A-13

Contraction Ratio: 0.68
Sapcing: 20 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 19.99 | 4.53 | 3.98 | 3.25 | 0.01 | 0.717 | 20.6 | |
| 20.25 | 4.53 | 3.87 | 3.04 | 0.01 | 0.671 | 21.5 | 21.0 |
| 21.71 | 4.52 | 4.11 | 3.14 | 0.02 | 0.695 | 24.1 | |
| 21.98 | 4.52 | 4.04 | 3.00 | 0.02 | 0.664 | 24.1 | |
| 21.71 | 4.52 | 4.17 | 3.30 | 0.02 | 0.730 | 23.6 | 24.0 |
| 22.93 | 4.51 | 4.35 | 3.33 | 0.03 | 0.738 | 26.9 | |
| 23.21 | 4.50 | 4.23 | 3.12 | 0.03 | 0.693 | 26.8 | 26.8 |
| 25.20 | 4.53 | 4.47 | 3.20 | 0.04 | 0.706 | 27.7 | |
| 25.20 | 4.53 | 4.35 | 2.94 | 0.04 | 0.649 | 28.1 | |
| 24.91 | 4.54 | 4.59 | 3.50 | 0.04 | 0.771 | 28.3 | 28.0 |
| 26.08 | 4.52 | 4.66 | 3.36 | 0.05 | 0.743 | 30.7 | |
| 26.22 | 4.52 | 4.58 | 3.16 | 0.05 | 0.699 | 30.4 | |
| 26.37 | 4.52 | 4.48 | 2.85 | 0.05 | 0.631 | 29.8 | 30.3 |

TABLE A-14

Contraction Ratio: 0.76
Spacing: 20 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 13.44 | 4.48 | 3.68 | 3.09 | 0.0 | 0.690 | 27.6 | |
| 12.75 | 4.50 | 3.82 | 3.37 | 0.0 | 0.749 | 27.0 | 27.4 |
| 16.11 | 4.50 | 3.84 | 3.02 | 0.01 | 0.671 | 30.0 | |
| 15.89 | 4.51 | 3.93 | 3.16 | 0.01 | 0.701 | 29.5 | |
| 15.67 | 4.51 | 4.00 | 3.34 | 0.01 | 0.741 | 29.1 | 29.5 |
| 17.03 | 4.50 | 4.08 | 3.03 | 0.02 | 0.673 | 34.6 | |
| 16.81 | 4.50 | 4.20 | 3.38 | 0.02 | 0.751 | 34.3 | 34.5 |
| 17.86 | 4.47 | 4.35 | 3.33 | 0.03 | 0.745 | 38.3 | |
| 18.10 | 4.47 | 4.21 | 3.07 | 0.03 | 0.687 | 38.7 | 38.5 |
| 19.47 | 4.47 | 4.38 | 3.12 | 0.04 | 0.698 | 40.7 | |
| 19.47 | 4.47 | 4.31 | 2.97 | 0.04 | 0.664 | 41.0 | |
| 19.22 | 4.48 | 4.48 | 3.31 | 0.04 | 0.739 | 41.5 | 41.0 |
| 20.64 | 4.54 | 4.52 | 3.07 | 0.05 | 0.676 | 44.8 | |
| 20.51 | 4.54 | 4.59 | 3.21 | 0.05 | 0.707 | 45.2 | |
| 20.38 | 4.54 | 4.67 | 3.41 | 0.05 | 0.751 | 45.8 | 45.2 |

TABLE A-15

Contraction Ratio: 0.84
Spacing: 20 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 12.36 | 4.53 | 3.82 | 3.09 | 0.01 | 0.682 | 48.6 | |
| 12.17 | 4.54 | 3.93 | 3.28 | 0.01 | 0.722 | 47.6 | 48.1 |
| 13.44 | 4.53 | 4.01 | 3.05 | 0.02 | 0.673 | 53.9 | |
| 13.34 | 4.53 | 4.12 | 3.30 | 0.02 | 0.728 | 52.8 | 53.3 |
| 14.16 | 4.52 | 4.13 | 2.99 | 0.03 | 0.662 | 61.1 | |
| 14.06 | 4.52 | 4.28 | 3.32 | 0.03 | 0.735 | 60.3 | 60.6 |
| 14.90 | 4.54 | 4.43 | 3.29 | 0.04 | 0.725 | 66.4 | |
| 14.69 | 4.54 | 4.56 | 3.56 | 0.04 | 0.784 | 67.2 | 66.8 |
| 15.34 | 4.53 | 4.46 | 3.04 | 0.05 | 0.671 | 74.0 | |
| 15.45 | 4.54 | 4.55 | 3.27 | 0.05 | 0.720 | 73.5 | |
| 15.34 | 4.54 | 4.66 | 3.49 | 0.05 | 0.769 | 74.1 | 73.8 |

TABLE A-16

Contraction Ratio: 0.61
Spacing: 24 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 23.49 | 4.45 | 3.88 | 3.07 | 0.01 | 0.690 | 17.7 | |
| 23.21 | 4.45 | 3.96 | 3.22 | 0.01 | 0.724 | 17.3 | 17.5 |
| 27.11 | 4.52 | 4.15 | 3.16 | 0.02 | 0.699 | 19.3 | |
| 27.26 | 4.51 | 4.07 | 2.93 | 0.02 | 0.650 | 19.3 | |
| 26.81 | 4.53 | 4.23 | 3.34 | 0.02 | 0.737 | 19.5 | 19.4 |
| 29.38 | 4.53 | 4.34 | 3.06 | 0.03 | 0.675 | 21.3 | |
| 29.08 | 4.53 | 4.43 | 3.26 | 0.03 | 0.720 | 21.4 | |
| 29.08 | 4.53 | 4.49 | 3.38 | 0.03 | 0.746 | 21.2 | 21.3 |
| 31.90 | 4.55 | 4.53 | 3.17 | 0.04 | 0.697 | 22.8 | |
| 31.59 | 4.55 | 4.60 | 3.28 | 0.04 | 0.721 | 23.0 | |
| 31.75 | 4.55 | 4.49 | 3.05 | 0.04 | 0.670 | 23.0 | 22.9 |
| 33.53 | 4.55 | 4.64 | 3.04 | 0.05 | 0.668 | 24.6 | |
| 33.37 | 4.55 | 4.77 | 3.36 | 0.05 | 0.738 | 25.1 | |
| 33.37 | 4.55 | 4.73 | 3.25 | 0.05 | 0.714 | 25.0 | 24.9 |

TABLE A-17

Contraction Ratio: 0.68
Spacing: 24 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 20.77 | 4.51 | 3.87 | 3.09 | 0.01 | 0.685 | 21.9 | |
| 21.03 | 4.51 | 3.80 | 2.96 | 0.01 | 0.656 | 22.1 | |
| 20.64 | 4.52 | 3.93 | 3.21 | 0.01 | 0.710 | 21.7 | 21.8 |
| 23.08 | 4.50 | 4.06 | 3.16 | 0.02 | 0.702 | 24.6 | |
| 23.08 | 4.50 | 4.05 | 3.09 | 0.02 | 0.687 | 24.5 | |
| 22.79 | 4.50 | 4.12 | 3.25 | 0.02 | 0.722 | 24.7 | 24.6 |
| 25.20 | 4.52 | 4.18 | 2.96 | 0.03 | 0.655 | 27.0 | |
| 25.05 | 4.52 | 4.25 | 3.13 | 0.03 | 0.692 | 27.2 | |
| 24.77 | 4.52 | 4.38 | 3.36 | 0.03 | 0.743 | 27.2 | 27.2 |
| 26.51 | 4.48 | 4.37 | 3.01 | 0.04 | 0.672 | 29.1 | |
| 26.35 | 4.48 | 4.41 | 3.16 | 0.04 | 0.705 | 29.7 | |
| 26.05 | 4.48 | 4.50 | 3.35 | 0.04 | 0.748 | 30.2 | 29.6 |
| 28.16 | 4.50 | 4.50 | 3.02 | 0.05 | 0.671 | 31.4 | |
| 28.01 | 4.50 | 4.58 | 3.21 | 0.05 | 0.713 | 31.9 | |
| 27.86 | 4.50 | 4.67 | 3.40 | 0.05 | 0.756 | 32.3 | 31.8 |

TABLE A-18

Contraction Ratio: 0.76
Spacing: 24 inches, Number of Slots: 4

Data for $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 15.12 | 4.51 | 3.52 | 2.89 | 0.0 | 0.641 | 26.2 | |
| 14.69 | 4.54 | 3.64 | 3.11 | 0.0 | 0.685 | 26.2 | |
| 14.79 | 4.54 | 3.62 | 3.06 | 0.0 | 0.674 | 26.3 | |
| 14.47 | 4.56 | 3.75 | 3.29 | 0.0 | 0.721 | 25.0 | |
| 14.90 | 4.54 | 3.57 | 2.97 | 0.0 | 0.654 | 27.0 | 26.2 |
| 17.03 | 4.52 | 3.81 | 3.03 | 0.01 | 0.670 | 30.4 | |
| 16.81 | 4.53 | 3.86 | 3.13 | 0.01 | 0.691 | 30.8 | |
| 16.58 | 4.54 | 3.99 | 3.39 | 0.01 | 0.747 | 30.0 | |
| 16.58 | 4.49 | 3.80 | 3.01 | 0.01 | 0.670 | 31.3 | |
| 16.46 | 4.49 | 3.87 | 3.14 | 0.01 | 0.699 | 30.7 | |
| 16.35 | 4.49 | 3.93 | 3.26 | 0.01 | 0.726 | 30.2 | 30.5 |
| 18.84 | 4.59 | 4.00 | 2.86 | 0.02 | 0.623 | 35.6 | |
| 18.84 | 4.59 | 4.13 | 3.19 | 0.02 | 0.695 | 34.7 | |
| 18.71 | 4.60 | 4.16 | 3.21 | 0.02 | 0.698 | 35.0 | |
| 18.35 | 4.53 | 4.13 | 3.18 | 0.02 | 0.702 | 34.7 | |
| 18.47 | 4.53 | 4.04 | 3.04 | 0.02 | 0.671 | 35.2 | |
| 18.10 | 4.53 | 4.19 | 3.32 | 0.02 | 0.733 | 35.1 | 35.0 |
| 19.73 | 4.53 | 4.36 | 3.34 | 0.03 | 0.737 | 38.9 | |
| 19.73 | 4.53 | 4.31 | 3.21 | 0.03 | 0.709 | 39.0 | |
| 19.86 | 4.53 | 4.17 | 2.94 | 0.03 | 0.649 | 39.3 | |
| 19.47 | 4.46 | 4.23 | 3.10 | 0.03 | 0.695 | 38.7 | |
| 19.23 | 4.46 | 4.42 | 3.50 | 0.03 | 0.785 | 38.6 | |
| 19.35 | 4.46 | 4.30 | 3.30 | 0.03 | 0.740 | 39.1 | 38.7 |
| 21.44 | 4.52 | 4.40 | 3.06 | 0.04 | 0.677 | 40.8 | |
| 21.17 | 4.53 | 4.49 | 3.26 | 0.04 | 0.720 | 42.0 | |
| 21.17 | 4.53 | 4.49 | 3.23 | 0.04 | 0.713 | 41.9 | |
| 21.04 | 4.55 | 4.56 | 3.34 | 0.04 | 0.734 | 42.6 | |
| 21.17 | 4.55 | 4.35 | 2.89 | 0.04 | 0.635 | 42.4 | 42.0 |
| 22.12 | 4.50 | 4.34 | 2.56 | 0.05 | 0.569 | 44.6 | |
| 21.85 | 4.50 | 4.55 | 3.09 | 0.05 | 0.687 | 46.5 | |
| 21.85 | 4.49 | 4.59 | 3.13 | 0.05 | 0.697 | 46.0 | |
| 21.58 | 4.50 | 4.69 | 3.36 | 0.05 | 0.747 | 47.6 | |
| 22.12 | 4.56 | 4.35 | 2.49 | 0.05 | 0.546 | 45.7 | |
| 21.98 | 4.56 | 4.53 | 2.94 | 0.05 | 0.645 | 47.0 | |
| 21.86 | 4.56 | 4.65 | 3.22 | 0.05 | 0.706 | 47.8 | |
| 21.86 | 4.56 | 4.68 | 3.27 | 0.05 | 0.717 | 47.7 | 47.0 |

TABLE A-19

Contraction Ratio: 0.84
Spacing: 24 inches, Number of Slots: 4

Data For $C_D$

| Q | $H_i$ | $H_f$ | $H_t$ | S | $H_t/H_i$ | $C_D$ | $C_D$ |
|---|---|---|---|---|---|---|---|
| gpm | inches | inches | inches | | | | (Average) |
| 12.94 | 4.52 | 3.71 | 2.91 | 0.01 | 0.644 | 50.2 | |
| 12.65 | 4.53 | 3.83 | 3.14 | 0.01 | 0.693 | 50.3 | |
| 12.55 | 4.53 | 3.95 | 3.37 | 0.01 | 0.744 | 48.2 | 50.0 |
| 13.95 | 4.49 | 3.95 | 3.01 | 0.02 | 0.670 | 56.1 | |
| 13.95 | 4.49 | 3.97 | 3.07 | 0.02 | 0.684 | 56.0 | |
| 13.85 | 4.49 | 4.14 | 3.36 | 0.02 | 0.748 | 54.0 | 56.0 |
| 15.23 | 4.48 | 4.02 | 2.84 | 0.03 | 0.634 | 60.8 | |
| 15.01 | 4.48 | 4.13 | 3.09 | 0.03 | 0.690 | 62.0 | |
| 14.90 | 4.48 | 4.29 | 3.38 | 0.03 | 0.754 | 61.3 | 61.3 |
| 15.89 | 4.49 | 4.20 | 2.88 | 0.04 | 0.641 | 68.3 | |
| 15.89 | 4.49 | 4.27 | 3.02 | 0.04 | 0.673 | 68.1 | |
| 15.67 | 4.49 | 4.44 | 3.36 | 0.04 | 0.748 | 69.5 | 68.5 |
| 16.11 | 4.52 | 4.63 | 3.45 | 0.05 | 0.763 | 80.5 | |
| 16.46 | 4.52 | 4.49 | 3.14 | 0.05 | 0.695 | 76.7 | |
| 16.46 | 4.52 | 4.37 | 2.89 | 0.05 | 0.639 | 76.4 | 76.5 |

TABLE A-20

Slope: 0.05

Data for Maximum Velocity and Froude Number

| m | Sp | Q | $H_i$ | $H_f$ | $H_t$ | Extreme d/s slot* depth | Extreme d/s slot* width | slot next to d/s* depth | slot next to d/s* width |
|---|---|---|---|---|---|---|---|---|---|
| | inches | gpm | inches | inches | inches | inches | inches | inches | inches |
| .84 | 16 | 15.01 | 4.50 | 4.21 | 3.03 | 3.97 | 0.60 | 4.01 | 0.60 |
| .76 | 16 | 19.60 | 4.52 | 4.22 | 2.92 | 4.02 | 0.80 | 4.04 | 0.80 |
| .68 | 16 | 24.63 | 4.50 | 4.29 | 2.89 | 3.93 | 1.15 | 4.00 | 1.15 |
| .61 | 16 | 28.46 | 4.44 | 4.20 | 2.62 | 3.93 | 1.35 | 3.91 | 1.40 |
| .84 | 20 | 15.34 | 4.53 | 4.46 | 3.04 | 4.05 | 0.55 | 4.10 | 0.55 |
| .76 | 20 | 20.64 | 4.54 | 4.52 | 3.07 | 4.21 | 0.80 | 4.24 | 0.80 |
| .68 | 20 | 26.37 | 4.52 | 4.48 | 2.85 | 4.06 | 1.15 | 4.05 | 1.15 |
| .61 | 20 | 30.80 | 4.52 | 4.63 | 3.11 | 4.34 | 1.35 | 4.32 | 1.35 |
| .84 | 24 | 16.46 | 4.52 | 4.37 | 2.89 | 4.11 | 0.55 | 4.15 | 0.55 |
| .76 | 24 | 22.12 | 4.50 | 4.34 | 2.56 | 4.03 | 0.80 | 4.00 | 0.80 |
| .68 | 24 | 28.16 | 4.50 | 4.50 | 3.02 | 4.10 | 1.15 | 4.07 | 1.15 |
| .61 | 24 | 33.53 | 4.55 | 4.64 | 3.04 | 4.31 | 1.35 | 4.27 | 1.30 |

* Observation for depth and width are taken at Vena Contracta formed behind the slot orifice.

# APPENDIX B

## COMPUTER PROGRAMS

Computer Program to Develop the Rating Curves for the Measuring Weirs

```
      DIMENSION QU(700),D(1100)
      EQUIVALENCE  (H,HF)
      KI=1
   37 DO 10 I=1,500
      H=I-1
      H=H/1000.
      IF(KI.EQ.1)  GO TO 35
      Q=3.33*(.5-.2*H)*H**(3./2.)
      IF(Q.EQ.O)GO TO 12
      V=12.*Q/(11.*(H+.25))
      HO=V**2/(2.*32.2)
   15 E=HF+HO
      Q=3.33*(.5-.2*H)*((E)**(3./2.)-HO**(3./2.))
      H1=HO
      V=12.*Q/(11.*(H+.25))
      HO=V**2/(2.*32.2)
      HI=(HO-H1)**2
      HJ=HI**.5
      IF(HJ.LT..0005)GO TO 12
      GO TO 15
   35 IF(H.GT.(71./(32.*12.)))GO TO 11
      Q=.6*8./15.*(2.*32.2)**.5*HF**2.5
      IF(Q.EQ.O)GO TO 12
      V=Q*16.*12./(71.*(H+.25))
      HO=V**2/(2.*32.2)
   13 E=HF+HO
      Q=.6*4./15.*(2.*32.2)**.5*(2.*E**2.5+3.*HO**2.5-5.*E*HO**1.5)
      H1=HO
      V=Q*16.*12./(71.*(H+.25))
      HO=V**2/(2.*32.2)
      HI=(HO-H1)**2
      HJ=HI**.5
      IF(HJ.LT..0005)GO TO 12
      GO TO 13
   11 Q=1.28*(2.*H**2.5-(2.*H+.55469)*(H-2.21875/12.)**1.5)+44.375/36.*(
     1H-2.21875/12.)**1.5
     V=Q*16.*12./(71.*(H+.25))
      HO=V**2/(2.*32.2)
   14 E=HF+HO
      Q=1.28*(2.*E**2.5-(2.*E+.55469)*(E-2.21875/12.)**1.5)+44.375/36.*(
     1(E-2.21875/12.)**1.5-HO**1.5)
      H1=HO
      V=Q*16.*12./(71.*(H+.25))
      HO=V**2/(2.*32.2)
      HI=(HO-H1)**2
      HJ=HI**.5
      IF(HJ.LT..0005)GO TO 12
      GO TO 14
```

```
12 QU(I)=Q*7.4805*60.
   D(I)=H
   D(I+500)=QU(I)
10 CONTINUE
   IF(KI.EQ.1) WRITE(3,1)
   IF(KI.EQ.2) WRITE(3,7)
 7 FORMAT('1',T40,'DISCHARGE FROM A RECTANGULAR WEIR'/)
 1 FORMAT('1',T40,'DISCHARGE FROM A V NOTCH WEIR WITH A RECTANGULAR T
  1OP'/)
   WRITE(3,2)
 2 FORMAT(1X'-------------------------------------------------------
  1-------------------------------------------------------------------
  1---------')
   WRITE(3,3)
 3 FORMAT(/2X,'HEIGHT(FEET)   ',T65,'DISCHARGE(GPM)')
   WRITE(3,2)
   WRITE(3,4)
 4 FORMAT(T10,':     .000    :     .001    :     .002    :     .003    :    .
  1004    :     .005    :     .006    :     .007    :     .008    :    .009')
   WRITE(3,5)
 5 FORMAT('+',T11,'----------------------------------------------------
  1-------------------------------------------------------------------
  1_'/)
   DO 20 I=1,50
   HB=I-1
   HB=HB/100.
   K=(I-1)*10
   WRITE(3,6)HB,QU(K+1),QU(K+2),QU(K+3),QU(K+4),QU(K+5),QU(K+6),QU(K+
  17),QU(K+8),QU(K+9),QU(K+10)
 6 FORMAT(3XF3.2,'    : ',F8.2,9F12.2)
20 CONTINUE
   CALL PLOT(001,D,500,2,0,0)
   KI=KI+1
   IF(KI.EQ.2) GO TO 37
   CALL EXIT
   END
```

The following relation is used in the computer program to calculate the rate of flow through a rectangular notch;

$$Q = 3.33\ (L-.2h)\ \{(h+h_o)^{3/2} - (h_o)^{3/2}\}$$

where

$L$ = Length of the weir; and

$h_o$ = The approach velocity head.

The coefficient of discharge for a V-notch weir is taken as 0.60.

## Computer Program for the Design of a Slot Orifice Fishway

```
      WRITE(3,6)
    6 FORMAT(7X,'M       SPACING      SLOPE      CD       WIDTH      LENGTH
     $    HI          HT          HF          Q(CFS)  NO.OF SLOTS'//)
   26 READ(1,1)XL,B,HI,HT,S
    1 FORMAT(5F 10.5)
      IF(XL.EQ.0) GO TO 27
   23 READ(1,2)CD,XM,SP
    2 FORMAT(3F10.5)
      IF(CD.EQ.O)  GO TO 26
      HF=1.4*HT
      QA=O
      N=XL/SP
      XN=N
   21 DH=(HI-HF)/XN
      H=HI
      SUM=O
      G=32.18
      DO 10 I=1,N
      SUM=SUM+1./H
      H=H-DH
   10 CONTINUE
      D=SUM
      A=G*B*B*(HI*HI-HF*HF)
      BB=2.*(1./HI-1./HF)
      C=XN*B*B*SP*G*S*(HI+HT)
      E=XM*D*CD
      Q=SQRT((A+C)/(E-BB))
      FR=Q/(B*HT*(G*HT)**.5)
      HF=HT*((7.141*XM-2.275)*FR+.815)
      IF(ABS(Q-QA).LT.(Q/200.))GO TO 22
      QA=Q
      GO TO 21
   22 V=Q/(B*(1.-XM)*HT)
      K=XN+1.
      WRITE(3,4)XM,SP,S,CD,B,XL,HI,HT,HF,Q,K
    4 FORMAT(10F10.2,I10)
      GO TO 23
   27 CALL EXIT
      END
```