ST. ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

Project Report No. 37

EFFECT OF INLET DESIGN ON CAPACITY OF CULVERTS ON STEEP SLOPES

Submitted by
LORENZ G. STRAUB
Director

Prepared by
LORENZ G. STRAUB, ALVIN G. ANDERSON,
and CHARLES E. BOWERS

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PREFACE

The St. Anthony Falls Hydraulic Laboratory has been a focal point for research on flow through culverts of various types since its establishment some fifteen years ago. The experimental studies have been conducted under the sponsorship of various agencies and also as graduate research of students working toward advanced degrees. One phase of this work has been sponsored by the Minnesota Highway Department and the U. S. Bureau of Public Roads. The present report is intended to provide the terminal analytical treatment of the results of studies sponsored under the latter program, although it is not confined or limited to the interpretation of data under this sponsorship.

Two previous project reports sponsored primarily by the Minnesota Highway Department and the Bureau of Public Roads included, respectively, a summary and bibliography of literature relating to flow through culverts, and a preliminary report dealing with the velocity distribution in the neighborhood of culvert inlets and full-flow head losses in a model culvert.[*] The current and terminal report of this series deals primarily with the effect of inlet shape on the hydraulics and capacity of circular culverts. It makes full use of the data obtained in the course of model studies on a culvert 4 inches in diameter and 105 diameters long fitted successively with a rounded and square-edged flush inlet. It draws also upon data accumulated in connection with extensive thesis research and the fund of information from other experimental studies at the St. Anthony Falls Hydraulic Laboratory in recent years.

The primary experiments involved measurements made of the head and discharge with the culvert placed on various slopes greater than the critical slope and with each inlet fitted to the culvert. Supplementary measurements were made to determine the effect of tailwater elevation on the head required for a particular discharge. The experimental results were plotted to show the relationship between the head and discharge for both the square-edged and rounded inlet.

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[*] C. L. Larson and H. M. Morris, Hydraulics of Flow in Culverts, (University of Minnesota, St. Anthony Falls Hydraulic Laboratory Project Report No. 6, 1948), 1622 pages, 18 figures, 5 tables; and

Henry M. Morris, Preliminary Flow Tests on a Model Culvert, (University of Minnesota, St. Anthony Falls Hydraulic Laboratory Project Report No. 7, 1949), 26 pages, 13 figures, 5 tables.

The body of the report is devoted primarily to the analytical treatment of the data and a summarized statement of the implications and deductions from these data. This might be considered in the nature of a synthesis not only of the work undertaken under the sponsorship of the Minnesota Highway Department but also of other sources of information.

The more detailed analysis of the head-discharge curves, behavior curves, and description of the experimental apparatus are included in the various appendices. Thus, Appendix I is a description of the experimental setup and of the model culvert used in the experiments sponsored by the Highway Department. Appendix II contains curves showing the various properties of circular segments, information concerning the latter being needed for the analytical treatment of part-full flow conditions. Appendix III is a summary of some basic open channel flow principles also drawn upon in the analytical study. The analysis of behavior curves is included in Appendix IV. Appendix V gives tabulated test data of the experiments conducted under the Minnesota Highway Department sponsorship.

The research program was under the general supervision of Lorenz G. Straub, Director of the Laboratory. Henry M. Morris was project leader on the experimental studies for the Highway Department, and he was succeeded by Charles E. Bowers. The thesis study more particularly pertinent to and supplementing the Highway Department project was made by Madhav Manohar, covering the range of orifice flow through the square-edged inlet and the pulsating phase for rounded inlets. Alvin G. Anderson was concerned primarily with the preparation of this report from the experimental data.

The experimental studies and analytical treatments are complete in themselves within this report; however, the desirability of further research on this subject is evident. Thus research, both experimental and analytical, into other geometrically shaped entrances is desirable, particularly in view of the significance of the character of the entrance upon the culvert hydraulics for many types of installations. Optimum practical designs should be established which take cognizance of factors, such as side slope of the embankment, which have thus far resulted in arbitrarily selected scoop designs that might definitely be improved hydraulically.

The exit geometry of the culvert is another aspect that deserves further study and standardization on an optimum functional basis. Here one is concerned more with means of energy dissipation incorporated within the culvert exit to avoid harmful erosion than with increased hydraulic efficiency as regards capacity. These are typical of the problems remaining to be studied in the hydraulics of culverts.

ABSTRACT

The geometry of the inlet has a significant bearing on the relationship between headwater elevation and discharge for culverts with a free outlet. The relative importance of inlet design depends upon the location of the control section.

The primary purpose of the research reported here was to examine the effect of inlet design upon the head-discharge curve of a model culvert. Two types of flush inlets, selected to represent extreme conditions for flush inlets, were tested--a square-edged inlet and a well rounded inlet. For each inlet the head-discharge curve was measured and the two curves compared. The comparison indicated that for certain conditions an appreciable head-advantage was gained by using a rounded inlet. Observation and analysis of the flow characteristics indicated that this gain phenomenon occurred in the region where for the same head a square-edged inlet caused separation and inhibited full flow, while the rounded inlet promoted full flow in the culvert with a corresponding increase in discharge.

In connection with measurements to establish friction factors and entrance losses in the model culvert for use in the analysis of the experimental data, a few behavior curves were determined. An analysis of behavior curves is included in Appendix IV. The results obtained were compared with experimental curves and other published curves.

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EFFECT OF INLET DESIGN ON CAPACITY OF CULVERTS ON STEEP SLOPES

I. INTRODUCTION

The objective in designing a culvert is, in general, to provide a structure which will discharge a given flow with the minimum upstream head. If the head and the discharge are both specified, the objective is to provide the most economical culvert, normally one with the least cross-sectional area. Conversely, if the culvert size is arbitrarily selected "sufficiently large," it still should be designed to have maximum capacity to handle peak flows most effectively.

This report presents a summary and analysis of experimental data collected to determine the effect of inlet shape on the relationship between the head on the culvert and the discharge that results because of this head—the head-discharge curve. Because of the large number of variables involved, the majority of experiments were performed with the culvert on an appreciable slope and with the outlet free. A few experiments were made with the tailwater above the outlet. The details of the apparatus and expanded discussion of some of the factors involved in the analysis are given in the several appendices.

The experiments described here were performed in the same apparatus used in earlier tests on velocity distribution and barrel friction [1].[*] The model culvert, channel, and inlets are described in detail in Appendix I. Experiments were performed using two inlet designs, rounded and square-edged. In the rounded inlet, the radius of rounding was 15 per cent of the culvert diameter ($r/D = 0.15$) based largely on experiments of Hamilton [2], in which it was indicated that the entrance loss was negligible for degrees of rounding equal to or greater than 14 per cent of the pipe diameter. In the square-edged inlet, the corner was machined square ($r/D = 0$). In these experiments data were obtained on the elevation of the head pool water surface above the culvert invert for variations in the inlet type, discharge, and culvert slope. In all of the experiments on inlet geometry influence, the outlet was free; that is, the tailwater elevation was below the culvert invert at the outlet. As long as the tailwater does not influence the flow in the culvert near the outlet, the outlet may be considered free.

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[*] Numbers in brackets refer to the Bibliography on p. 19.

A culvert may flow either full or partly full, depending upon the specific hydraulic conditions. In part-full flow the culvert behaves as an open channel with a free surface, the depth of flow being less than the vertical height or diameter of the culvert. The headwater elevation may be below or above the crown of the culvert, for a culvert does not necessarily flow full when the headwater is above the crown. In full flow the culvert behaves as a closed conduit or pipe, the hydraulic gradient no longer necessarily coincides with the water surface, and the headwater elevation is above the crown of the culvert. The complete range of the relationship between head and discharge for a culvert includes both part-full and full flow conditions.

The factors which combine to determine the character of the flow in a culvert are the design variables such as slope, size, shape, length and roughness of the culvert, headwater and tailwater elevations, and inlet and outlet geometry. It is apparent that many combinations of these variables are possible, each of which serves to establish a flow regime. Therefore an hydraulic classification that would divide the possible flows into several distinct types so that each could be treated separately would be advantageous. Such a classification may be based upon the location of the culvert control section, which, in turn, is determined by the relative magnitude of the design variables. In culverts flowing partly full, the control section is that section where the depth of flow depends only upon the discharge and the geometry of the cross section. When the culvert flows full the depth of flow in the culvert depends only upon the cross-section geometry. The culvert barrel then, in this sense, serves as a control, with the outlet as the effective control section. The control may be either at the inlet or the outlet for part-full flow, depending for any specific discharge upon the culvert slope, but in the case of "short culverts," depending also upon the culvert length.

If the culvert inlet serves as a control section, the relationship between head and discharge is independent of the characteristics of the barrel or tailwater elevation and depends only upon the geometry of the inlet. When the control section is at the outlet, as for long culverts with a free outlet on a mild slope flowing partly full, the head-discharge relationship depends upon the characteristics of the barrel as well as the inlet geometry. When the culvert flows full for whatever reason, unless it is very short with a free outlet, barrel friction provides the flow control and the head-discharge curve is dependent upon all of the design variables. In rare instances two control sections may exist, one at the inlet and one at the outlet. In this case the head is governed by the inlet control section.

The importance of inlet design depends to a large extent upon the position of the control section. With the control section at the inlet, very significant differences are found in the head-discharge curves for square-edged and rounded inlets. A square-edged inlet causes separation to occur at the entrance and inhibits full flow in the culvert. A properly rounded inlet, on the other hand, avoids the separation and promotes full utilization of the barrel cross section for flow. As a result of the additional head made available when the culvert flows full on a positive slope, the required water surface elevation or head of the upstream pool is reduced. When the control is at the outlet or when the culvert flows full, the additional head is available for both types of inlet and the differences in inlet geometry become far less significant. The square-edged inlet and the rounded inlet represent in a sense two extremes of inlet geometry. It appears that commercial culverts would possess, in various degrees, inlets that fall somewhere between these two limits, particularly if a flush headwall is used. The results presented in this report then represent (for a circular culvert with a flush headwall) these two extremes of inlet geometry.

II. LOCATION OF CONTROL SECTION

It has been well established that the control section of an open channel (or culvert flowing part full) is that section at which a transition from subcritical flow to supercritical flow occurs. At this section critical flow conditions exist for which it can be shown that (Appendix III)

$$\left(\frac{Q_c}{D^{5/2}}\right)^2 = \left(\frac{\pi}{4}\right)^3 g \frac{(A/A_o)^3}{b/D} \tag{1}$$

where Q_c is the critical discharge corresponding to a depth d,

D is the culvert diameter,

g is the acceleration due to gravity,

A and A_o are, respectively, the cross-sectional area of the flow stream of depth d and the cross-sectional area of the culvert, and

b is the water surface width.

Equation (1) indicates that for each depth of flow in a circular culvert there is a discharge for which the flow will be critical, or, conversely, for any specified discharge Eq. (1) gives the depth for which the flow will be critical. The relations between the depth of flow and other properties of circular segments are given in Appendix II.

The slope on which normal flow at critical depth may exist depends upon the resistance properties of the culvert as included in a flow formula such as the Manning formula $\left[Q = (1.486/n)\ AR^{2/3}\ S^{1/2}\right]$. Combination of the Manning formula with Eq. (1) results in an expression for the critical slope (that is, the slope at which normal flow exists at critical depth) in terms of the flow geometry defined by the depth of flow, and can be written as (Appendix III)

$$\frac{S_c\ D^{1/3}}{n^2} = 2.26\ g\ \frac{(A/A_o)}{(b/D)(R/R_o)^{4/3}} \tag{2}$$

where, in addition to terms already defined,

S_c is the critical slope corresponding to Q_c,

n is the Manning roughness coefficient, and

R and R_o are, respectively, the hydraulic radii of the flow stream and of the culvert.

Equations (1) and (2) have been plotted in Fig. 1 in terms of the relative depths d/D. For very small depths and for depths approaching the culvert diameter, the critical slope becomes large, approaching infinity at the two extremes; but over the wide, intermediate, normal range of part-full flow conditions through the culvert the critical slope varies within narrower limits. Figure 1 indicates that for each discharge $Q/D^{5/2}$, there is a particular depth and slope for which the flow is critical at normal depth, or for a given depth of flow there is a critical discharge and slope. If for a given discharge $Q/D^{5/2}$, the actual slope of the culvert is greater than S_c (from Fig. 1), the normal flow in the culvert will be supercritical; if less than S_c, the normal flow will be subcritical. It is also apparent that an actual culvert may have such a slope that for very small discharges the part-full flow will be subcritical, while for intermediate discharges with intermediate relative critical depths the flow will be supercritical and then

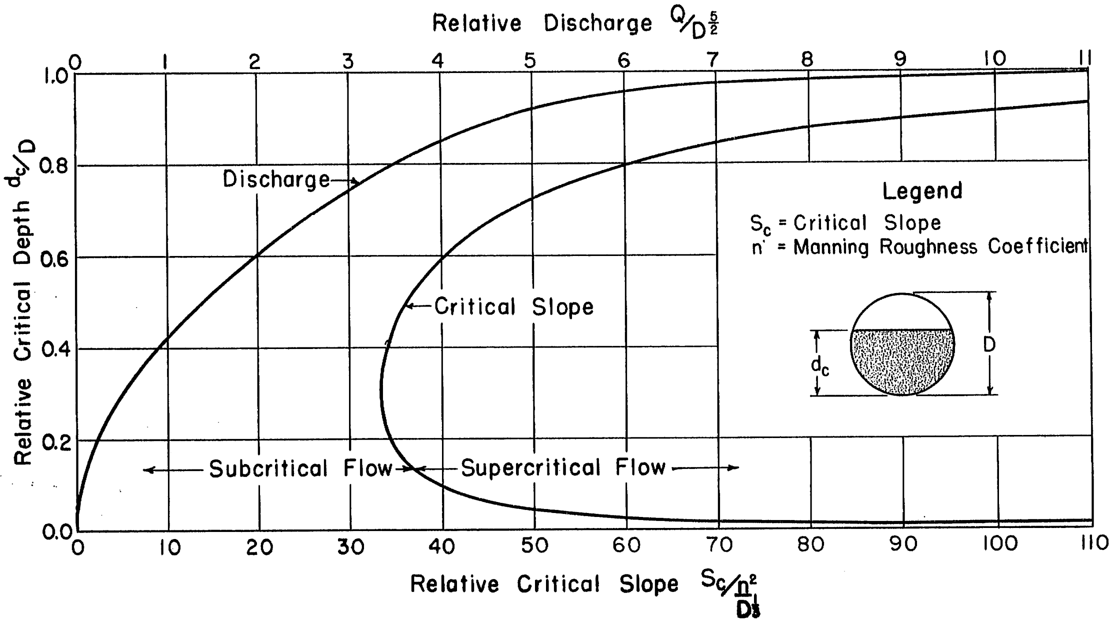


Fig. 1 - Critical Culvert **Slope** and Critical Depth as a Function of Discharge

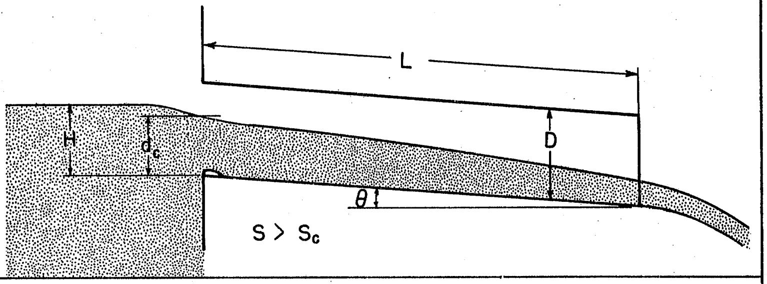
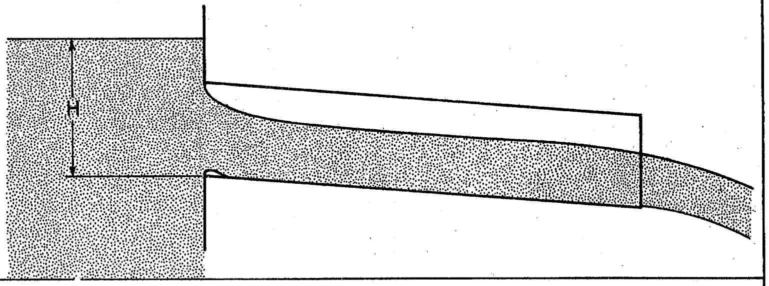
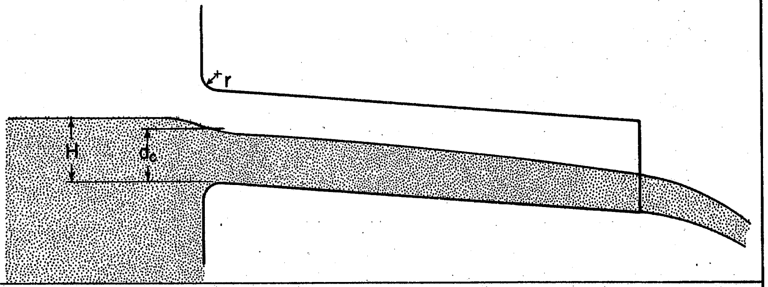
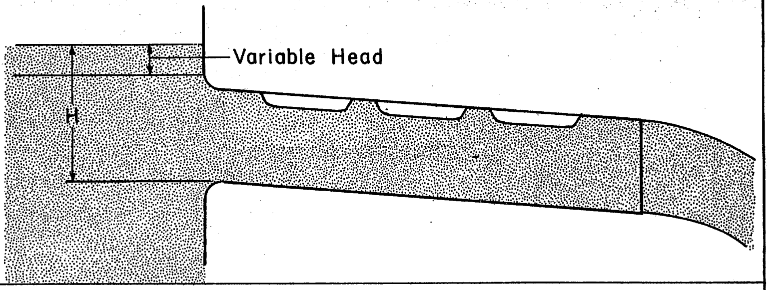
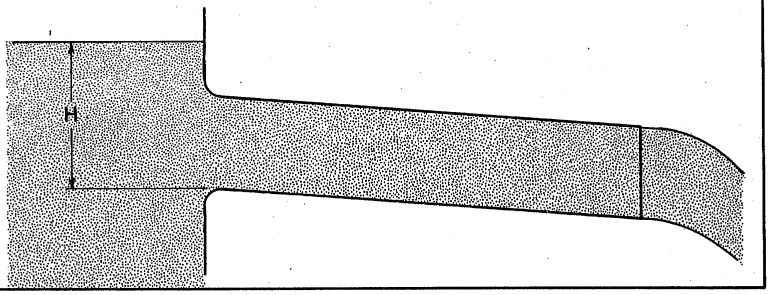
FLOW TYPE	ILLUSTRATION
(a) Square Entrance $H/D < 1.3$ Supercritical Flow Control: Critical Section at Inlet.	
(b) Square Entrance $H/D > 1.3$ Supercritical Flow Control: Orifice Flow at Inlet.	
(c) Round Entrance $H/D < 1.25$ Supercritical Flow Control: Critical Section at Inlet.	
(d) Round Entrance $H/D > 1.25$ Slug Flow Control: Pulsating	
(e) Round Entrance Full Flow Control: Barrel Outlet	

Fig. 2 – Typical Flow Conditions for Culverts on a Steep Slope

subcritical again for still higher discharges. As the depth of flow approaches the culvert crown, however, the irregularities and fluctuations of the water surface may make contact with the culvert to fill the pipe completely and make the flow character indeterminate.

For supercritical part-full flow in a culvert the control section is at the inlet, at which point the transition between subcritical flow in the approach channel and supercritical flow in the culvert occurs. The inlet also serves as a control when the headwater is above the culvert crown if the contraction of the stream entering the culvert causes the depth to be less than critical. Such is the case even though the culvert is on a mild slope $(S < S_c)$, provided a hydraulic jump does not form in the culvert. (This might be the case for a culvert of small L/D ratio, that is, for a "short culvert.") For part-full flow on a mild slope $(S < S_c)$ the control is at the outlet.

III. HEAD-DISCHARGE CURVE FOR CULVERTS ON STEEP SLOPES AND WITH FREE OUTLETS--EXPERIMENTAL RESULTS

The experimental results relating the head in the approach channel above the culvert invert at the inlet to the discharge are given in Fig. 3 for the square-edged inlet and in Fig. 4 for the rounded inlet. Curves drawn through the experimental points for both the square-edged inlet and the rounded inlet are replotted in Fig. 5 for purpose of comparison to show the effect of the inlet shape upon the discharge for a given head. Since the model culvert is circular in section the data were plotted in terms of relative head H/D, and relative discharge $Q/D^{5/2}$. In order that the relative discharge be truly dimensionless, the discharge term should be written as $Q/g^{1/2}D^{5/2}$. However, since the acceleration due to gravity g may be assumed to be a constant, the relative discharge is given as $Q/D^{5/2}$. A description of the flow phenomena resulting in these several curves is given in the following sections.

A. Square-edged Inlet

In Fig. 3 it is apparent that the head-discharge curve for the square-edged inlet consists of two parts: that portion of the curve pertaining to part-full flow at the inlet, and that portion for which the inlet is completely submerged. It appears that the portion of the curve pertaining to part-full flow at the inlet extends to values of H/D of about 1.3.

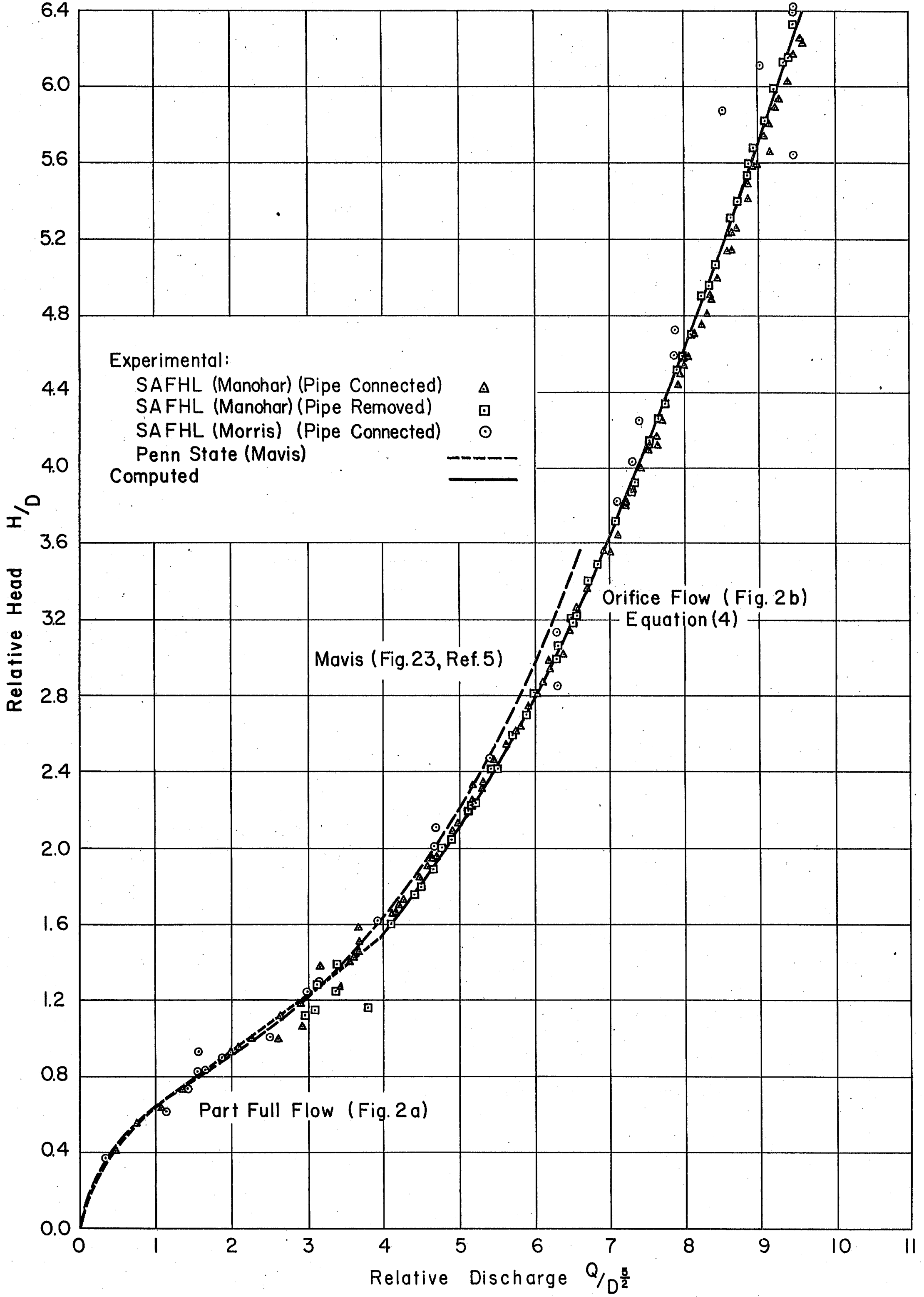


Fig. 3 - Head-Discharge Curve for Square-Edged Inlet

(Lucite Culvert Model on Steep Slope)

1. Part-full Flow at the Inlet: $H/D < 1.3$

In the case of culverts on steep slopes $\left[S > S_c \text{ (Fig. 1)} \right]$ flowing partly full, the control is at the inlet. In this region the depth will pass through critical, and Eq. (1) should relate the depth of flow at this point to the discharge. When the approach pool is large, as was the case in these experiments, the velocity head of approach becomes negligible and the energy grade line lies essentially in the water surface. If it is assumed that the energy loss in the transition from the approach channel to the culvert inlet is also negligible, the relative head may be written as

$$\frac{H}{D} = \frac{V_c^{\,2}}{2gD} + \frac{d_c}{D} \tag{3}$$

where H is the elevation of the head pool above the culvert invert (Fig. 2a) and $V_c^{\,2}/2gD$ can be computed in terms of d/D as shown in Appendix III, Eq. (III-11). However, the applicability of Eqs. (1) and (3) depends upon the characteristics of the inlet. For the square-edged inlet the stream is contracted as it enters the culvert, therefore the velocity is not uniformly distributed as required by Eq. (3). Consequently the experimental head-discharge curve should be shifted upward from the curve computed using Eqs. (1) and (3). The experimental results for part-full flow at the inlet for $H/D < 1.3$ are shown in Fig. 3.

2. Full Flow at the Inlet: $H/D > 1.3$

As the discharge increases the head eventually becomes great enough to submerge the inlet. The flow would then normally be in contact with the culvert entirely around the periphery of the inlet. However, for the square-edged inlet, separation at the inlet occurs; and if, in addition, the culvert is on a steep slope with a free outlet, the culvert will not flow full and atmospheric pressure will be maintained on the water surface from the outlet end. This situation existed for the experimental points plotted in Fig. 3 for the submerged square-edged inlet.

If it is assumed that the inlet operates as an orifice when the inlet is submerged and the slope is steep, the discharge may be written in terms of the head. Manohar [3] derived the following orifice equation taking into account the velocity distribution that exists for low heads in the form

$$\frac{Q}{D^{5/2}} = C_c \frac{\pi}{4} \sqrt{2g} \left(\frac{H}{D} - \frac{1}{2}\right)^{1/2} \left[1 - \frac{C_c}{128\left(\frac{H}{D} - \frac{1}{2}\right)^2}\right] \tag{4}$$

where C_c is a contraction coefficient and the term in brackets

$$\left[1 - \frac{C_c}{128\left(\frac{H}{D} - \frac{1}{2}\right)^2}\right]$$

represents the effect of the velocity distribution. This term rapidly approaches unity with an increase in head and is equal to about 0.99 when $H/D = 1.5$. Experiments were also performed with the culvert removed, leaving only the square-edged inlet. These points are also plotted in Fig. 3 and agree very well with those obtained with the pipe attached to the inlet. These data include experiments for slopes of the culvert from 4 to 8 per cent with the pipe either removed or attached. Equation (4), using a coefficient of contraction of 0.624 shows good agreement with the experimental data. These experimental data also agree well with the experimental curve obtained by Mavis [5] in the Penn State tests using a square-edged inlet.

B. Rounded Inlet

The results obtained from the experiments using the rounded inlet are plotted in Fig. 4 and show the head required for a particular discharge. The curves fall into three zones: part-full flow, alternating or slug flow, and full flow dependent upon discharge and head.

1. Part-full Flow at the Inlet: $H/D < 1.3$

As with the square-edged inlet, the control section is at the inlet when the culvert is on a steep slope. Consequently, Eqs. (1) and (3) should suffice to complete the head-discharge relationship for part-full flow at the inlet, since no separation occurs and the streamlines follow the contour of the inlet. In Fig. 4 the experimental values agree very well with the computed curve using these equations up to a value of $H/D = 1.3$.

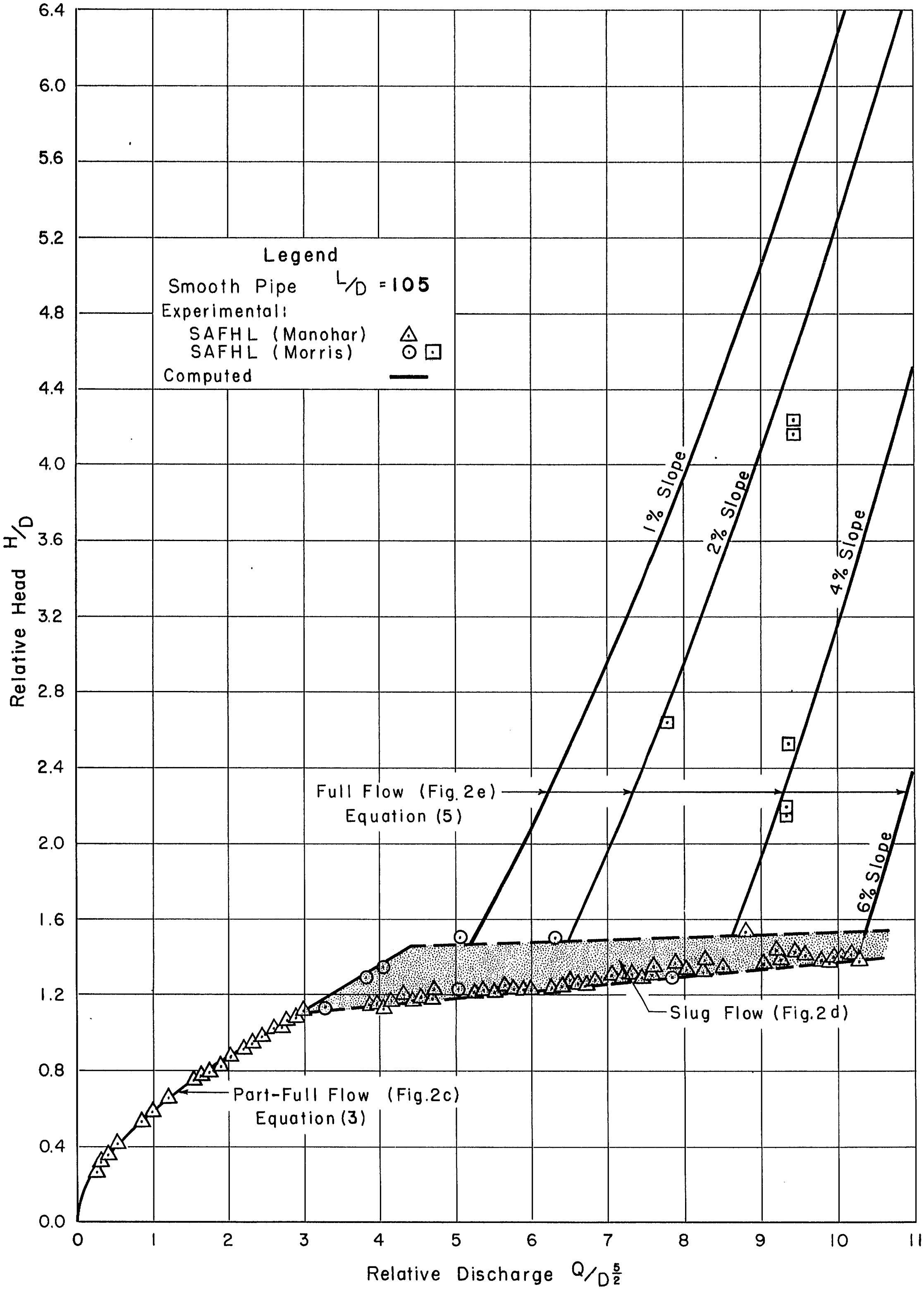


Fig. 4 – Head-Discharge Curves for Rounded Inlet
(Lucite Culvert Model on Steep Slope)

2. Full Flow at the Inlet: $H/D > 1.3$

When the inlet is well rounded so that separation does not occur (Fig. 2d), the culvert immediately begins to flow full in the neighborhood of the inlet. The zone of full flow rapidly extends down the culvert toward the outlet. In the process of moving down the culvert, an increasing additional head due to the slope of the culvert becomes effective. This additional head tends to increase the discharge in the culvert above that of the inflow into the approach channel. The increased discharge causes a lowering of the water surface in the approach channel. The level may be lowered sufficiently for a vortex to form and air to be sucked into the culvert, with a consequent increase in the pressure within the culvert. This breaks the seal at the upper end. With the loss of the added culvert head, the discharge decreases below that of the inflow and the water surface rises until the inlet is again sealed and the culvert again starts to flow full. The cycle then repeats itself; pulsating flow develops through the culvert. When the inflow discharge is large enough to permit the "slug" to extend the entire length of the culvert before the headwater is drawn down sufficiently to permit the intake of air, the "slug" or mixed flow phenomenon ceases and the culvert flows full continuously. The relationship between head and discharge during the pulsating or "slug" flow is not amenable to an analytical solution but the experimental data clearly define the relationship. In the next phase when the culvert flows full (Fig. 23), the head-discharge relationship may be determined in the usual way by the application of Bernoulli's theorem to the flow, assuming that the hydraulic grade line is at the center of the culvert at the outlet when the outlet is free so that

$$\frac{H}{D} - \frac{1}{2} + \frac{L}{D}\sin\theta = \frac{8}{\pi^2 g}\left(1 + K_e + f\frac{L}{D}\right)\left(\frac{Q}{D^{5/2}}\right)^2 \qquad (5)$$

where L is the length of the culvert,

θ is the angle of inclination of the culvert from the horizontal so that $S = \sin\theta$ or $F = L\sin\theta$ where F is the fall in length L,

f is the friction factor which for smooth culverts is a function of the Reynolds number, and

K_e is the entrance loss coefficient for full flow.

Inspection of Eq. (7) indicates that for full flow the head-discharge curve depends upon slope, length, and roughness of the culvert as well as entrance loss; therefore the curve will be different for each culvert as well as for each slope. In order to compare the results of experiments with computed results, the factors pertaining to these particular experiments are required. Here $L/D = 105$, $K_e \cong 0.08$, and f as a function of Reynolds number were obtained from previous experiments on the same culvert [1]. The computed head-discharge curves for the experimental culverts with a rounded inlet on various slopes are plotted in Fig. 4. The few experiments performed at full flow have been plotted along with the curves to show the agreement obtained.

The entire curve shows how the head increases with an increase in discharge. As the discharge increases in the part-full stage, the head increases along the part-full curve and is independent of the barrel characteristics. When the discharge is great enough to raise the head somewhat above the inlet crown, pulsating flow occurs with the head fluctuating between rather narrow limits. In this zone again the head-discharge relationship is independent of the barrel characteristics. The curve continues in this pulsating zone until it reaches the point where the full-flow curve for the particular culvert on a particular slope intersects the pulsating flow curve, after which the head follows along the full-flow curve as the discharge increases.

As noted above, the mixed-flow region is characterized by a pulsating, unsteady flow. The discharge as well as the pressure in the region of the inlet varies with time. The pressure and velocity fluctuations are associated with a fluctuation of the head pool, the magnitude of which is roughly shown in Fig. 4. If it is assumed that the flow is steady and the head pool does not fluctuate, it is possible to compute an approximate value of the average pressure near the inlet of the model. Writing Bernoulli's equation between the surface of the head pool and the centerline of the culvert at the inlet, the following table can be developed; it is assumed that the head pool elevation is given by the lower line defining slug flow in Fig. 4.

Table I

Computed Average Pressures at Inlet of Rounded-Inlet Culvert Model on Steep Slope

(1) $Q/D^{5/2}$	(2) H/D	(3) $1/D \left(\frac{P_2}{w}\right)$ (on centerline)	(4) $1/D \left(\frac{P_3}{w}\right)$ (at invert)
4	1.1	+ 0.17	+ 0.67
6	1.2	- 0.27	+ 0.23
8	1.3	- 0.93	- 0.43
10	1.4	- 1.80	- 1.30

The only purpose in making this computation is to illustrate the order of magnitude of pressures at the inlet. Columns (3) and (4) indicate the relative pressure (feet of water divided by culvert diameter) at the centerline and invert of the culvert for various values of relative discharge. If, for a specified discharge, the slope is such that the culvert has full flow instead of mixed or slug flow, the computed values would not be valid; if full flow develops, an increase in discharge should be accompanied by an increase in pressure.

Additional studies, both small and large scale, are probably desirable to check factors such as the pressure, scale-effect, and effect of culvert length in the slug-flow region.

For purposes of comparison, the head-discharge curves for the culvert with a square-edged inlet and with a rounded inlet have been plotted together in Fig. 5. The experimental points have not been included in this figure. It is apparent that a considerable head-advantage accrues to the culvert with the rounded inlet in and above the region of pulsating flow. The advantage is greater as the slope is greater provided the slope is supercritical. In the region where the culvert flows part-full at the inlet ($H/D < 1.3$), the head-advantage is much less pronounced.

C. An Example of Culvert Flow on a Steep Slope

In order to illustrate the application of the foregoing results to a particular example, assume that a culvert 3 ft in diameter and 300 ft long has a Manning roughness coefficient "n" of 0.013. Assume further that the outlet is free and that a headwall at the entrance provides a flush inlet.

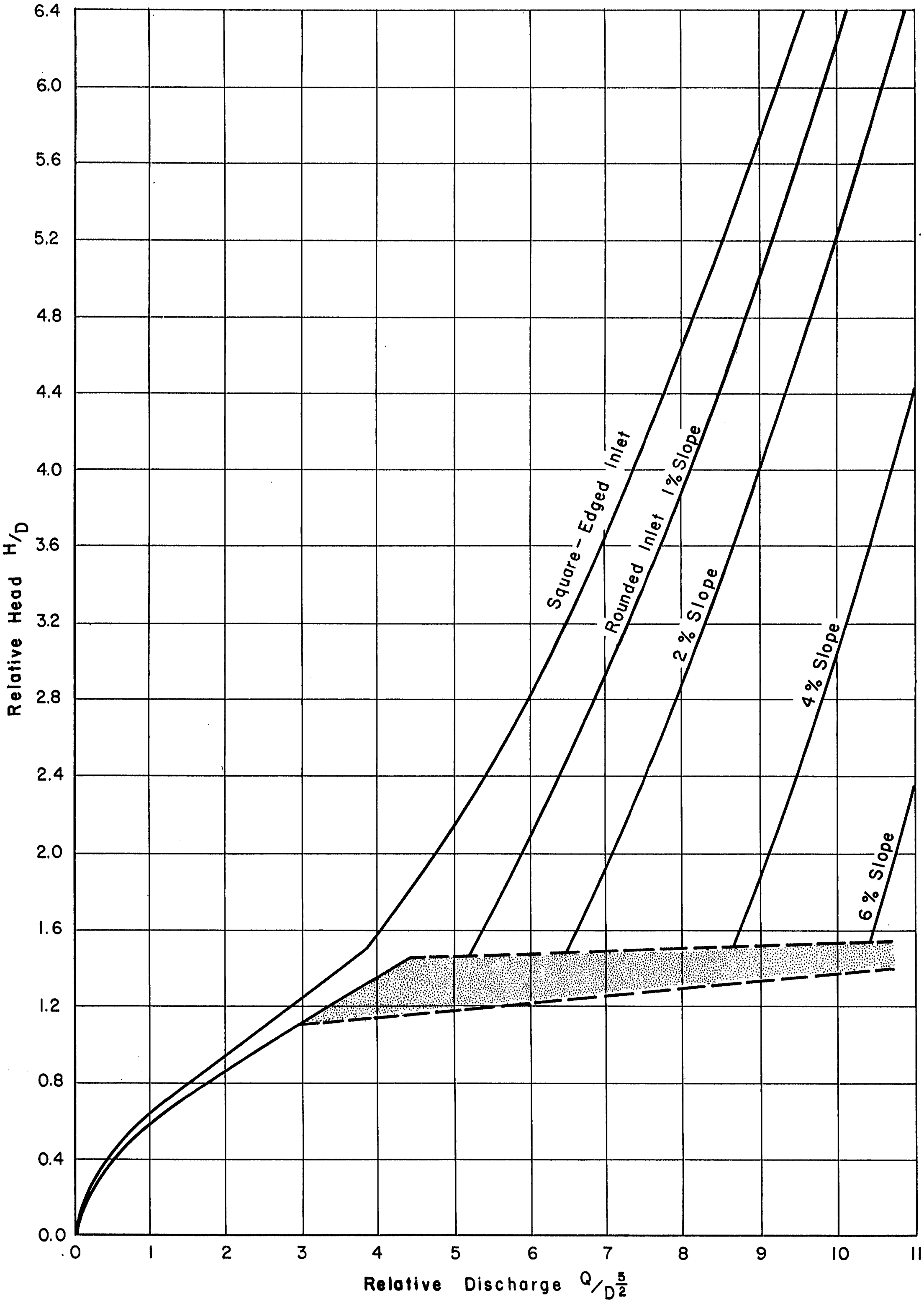


Fig. 5 - Head-Discharge Curves for Square-Edged and Rounded Inlets

(Lucite Culvert Model on Steep Slope)

In the first case let the culvert slope be 4 per cent and let the discharge be 125 cfs so that $(Q/D^{5/2}) = 8.0$. Using Eqs. (1) and (2) and Fig. II-2, the factor

$$\frac{S_c}{n^2/D^{1/3}}$$

for critical conditions is

$$\frac{S_c}{n^2/D^{1/3}} = 264$$

For the actual slope of 4 per cent the existing culvert factor is

$$\frac{S}{n^2/D^{1/3}} = \frac{0.04}{(0.013)^2/3.0^{1/3}} = 342$$

Since the actual value of the factor is considerably greater than that for critical flow, the culvert is on a steep slope for this discharge.

If it is assumed that a <u>square-edged</u> inlet has been provided, the head required to pass this discharge can be obtained directly from Fig. 3 since the head-discharge curve for culverts on steep slopes and square-edged inlets is independent of the barrel characteristics. From the figure it appears that for

$$\frac{Q}{D^{5/2}} = 8.0, \quad \frac{H}{D} = 4.6$$

Consequently a discharge of 125 cfs through the culvert will require a head of 13.8 ft above the invert or 10.8 ft above the crown. Due to the contraction at the inlet the culvert would not run full since the slope is considerably above the critical.

If the inlet were <u>rounded</u> so that no separation at the inlet occurred, the culvert would tend to run full when the upstream water surface became high enough to seal the inlet. If it is assumed that the culvert flows full, Eq. (5) will describe the flow. In addition to the factors previously given

$$\frac{L}{D}\sin\theta = (100)\ 0.04 = 4.0$$

$$K_e = 0.08$$

$$f = 0.022 \text{ (for } n = 0.013)$$

Then

$$\frac{H}{D} - \frac{1}{2} + 4.0 = 0.0252\ (1 + 0.08 + 2.20)\ 8^2$$

or

$$\frac{H}{D} = 1.8 \text{ ft}$$

Since H/D as computed is greater than the upper limit of pulsating flow for $Q/D^{5/2} = 8.0$ (Fig. 4), the assumption that the culvert flows full for the prescribed discharge is satisfied. Therefore the head required to discharge 125 cfs through the culvert with the rounded inlet is 5.4 ft above the invert or 2.4 ft above the crown, as compared with 10.8 ft above the crown for the square-edged culvert.

The supposition that the culvert with the rounded inlet will flow full is based on the upper limit of H/D for pulsating flow given in Fig. 4, as found by experiment on a 4-in. Lucite model. This upper limit is determined by H/D where vortices first form at the inlet as the head is drawn down by the filling of the barrel. This point may be relatively higher for prototype culverts and should be established by further experiment. If this were the case, the culvert used in the example might not flow full, but pulsating flow would occur with the culvert flowing alternately full and part full. If the culvert had been constructed on a steeper slope, pulsating flow would be even more likely. In any case, the head on the culvert would be significantly reduced by fitting the culvert with a rounded inlet.

As another case, assume that the culvert is on a 2 per cent slope and the discharge is 70 cfs ($Q/D^{5/2} = 4.48$); the diameter, length, and friction factor are assumed to be the same as for the first case.

Referring to Fig. 1

$$\frac{S_c}{n^2/D^{1/3}} = 84, \qquad \text{for} \qquad \frac{Q}{D^{5/2}} = 4.48$$

For the actual slope of 2 per cent, the culvert factor is:

$$\frac{S}{n^2/D^{1/3}} = \frac{0.02}{(0.013)^2/3.0^{1/3}} = 171$$

Thus, for a discharge of 70 cfs the culvert slope is steeper than critical. It may also be determined by use of Eq. (2) and Manning's formula that the critical depth is 2.64 ft and the normal depth for a 2 per cent slope is 1.86 ft.

If the culvert is equipped with a square-edged inlet, Fig. 3 indicates that the required relative head (H/D) will be 1.85 for $Q/D^{5/2} = 4.48$.

If the inlet is rounded, we may assume as a starting point that the culvert flows full. Using Eq. (5),

$$\frac{H}{D} - \frac{1}{2} + 2.0 = 0.0252\ (1 + 0.08 + 2.20)\ 4.48^2$$

or

$$\frac{H}{D} = 0.15$$

Since an H/D value in excess of 1.0 would be required for full flow, it is obvious that the initial assumption of full flow is not correct. Therefore, the inlet must act as a control. Referring to Fig. 4, the flow must be either part-full or mixed, with an H/D (based on model data) of 1.1 to 1.5. As noted above, further large-scale tests are desirable to check the model data. However, on the basis of the available data it would appear that the rounded inlet would require a relative head of about 1.5, as compared to 1.85 for the square-edged inlet, for a discharge of 70 cfs.

It may be of interest to note that the full-flow curves in Fig. 4 are dependent on the inlet geometry, diameter, length, and roughness of the culvert. The ones shown are for the Lucite model. Similar curves could be computed for specified types of culverts using Eq. (5).

These examples illustrate only the effect of inlet shape on the discharge. An acceptable final design of a culvert depends upon all of the design factors including a scour-preventing outlet. The question of whether culverts such as those described in the examples would be used depends upon other considerations in addition to the design of the inlet.

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APPENDICES

APPENDIX I

DESCRIPTION OF APPARATUS AND TESTS

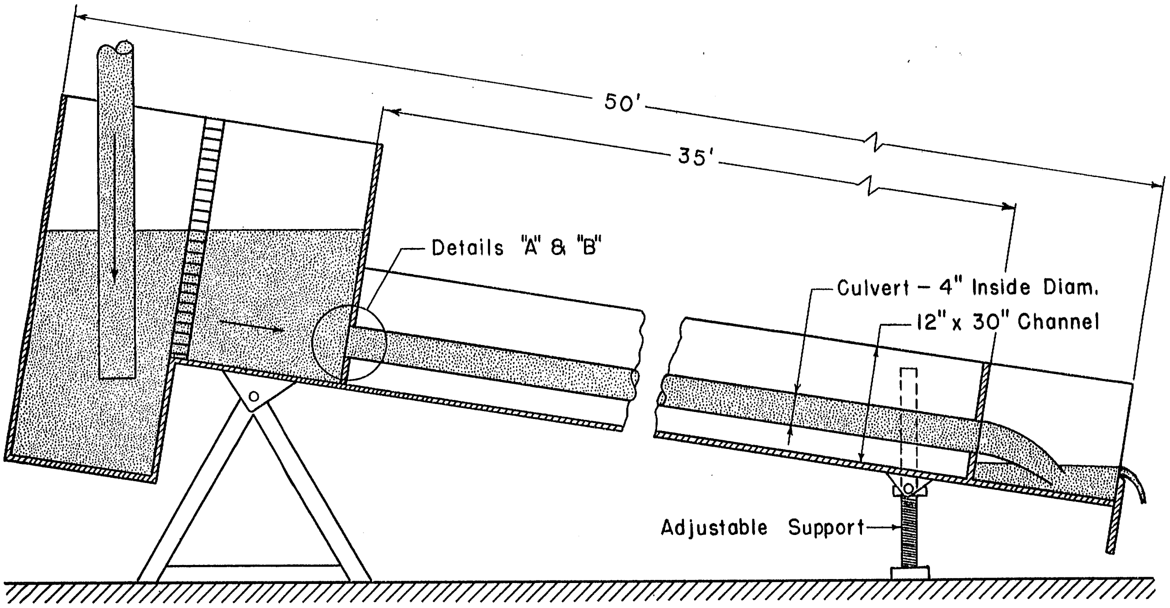
The experimental investigation was conducted in an apparatus constructed primarily for studies of this type. It consisted of a channel 12 in. deep, 30 in. wide, and 50 ft long in which culvert models of various sizes and arrangements could be installed. The upstream 10-ft section was separated from the remainder of the channel by a transverse bulkhead which normally forms the base for headwall arrangements. This section had walls 28 in. high, as compared to 12 inches in the remainder of the channel, to permit variations of the head pool elevations as shown in Fig. I-2. A second bulkhead could be installed in the channel at the outlet end of the culvert model. The tailwater level could be controlled by a manually operated gate for experiments in which the culvert outlet was submerged (Fig. I-3).

The slope of the channel and the culvert could be varied from zero to 10 per cent by means of motor driven jack-screws. The position of the hydraulic gradient for a given flow could be determined by point gage reading, to 0.001 ft, of the elevation of the water surface in a stilling well at each station. The stilling well was made of 3-in. diameter Lucite tubing connected to a pressure tap in the culvert wall. Stilling wells were also connected to the head pool and the tailwater pool. The point gage was attached to a movable carriage which rolled on horizontal tracks.

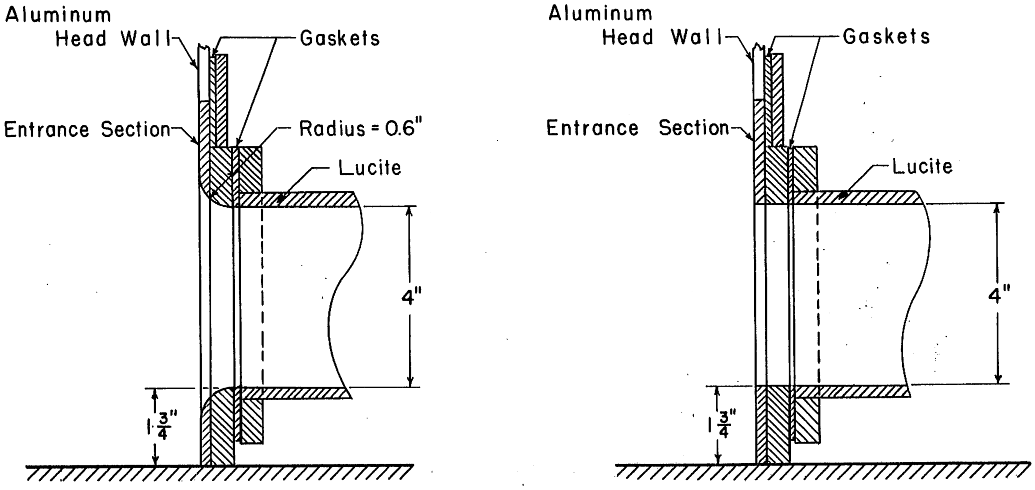
The discharge through the culvert was measured by means of a calibrated orifice in the supply line, the pressure taps of which were connected to a 50-in. differential gage.

In this investigation all experiments were performed on a model culvert of 4-in. inside diameter and 35 ft or 105 diameters long. The culvert shown in Fig. I-4 was constructed of sections of Lucite tubing each 52-1/2 in. long joined together by means of flanges attached to each end of the sections. Measuring stations were placed at nine points in the first section (just downstream of the inlet) and at three points in the last section. Each intermediate section had one measuring point at its midpoint. Two types of interchangeable inlets were provided, one square-edged inlet and one rounded inlet with the radius of curvature of rounded portion equal to 15 per cent of the diameter of the culvert. The inlets were arranged to be mounted flush with the upstream bulkhead. They are sketched in Fig. I-1. The flush mounting of the inlets and the character of the flow into the culvert are shown in Fig. I-5.

In these experiments, pressures were measured in the culvert by means of a differential gage attached to one of the taps in the culvert. One side of the manometer was open to the atmosphere so that the pressure in the barrel could be measured directly in feet of water.



Sketch of Test Setup



Detail "A"

Rounded Inlet

Detail "B"

Square-Edged Inlet

Fig. I-1 - Equipment and Inlets Used in Model Tests

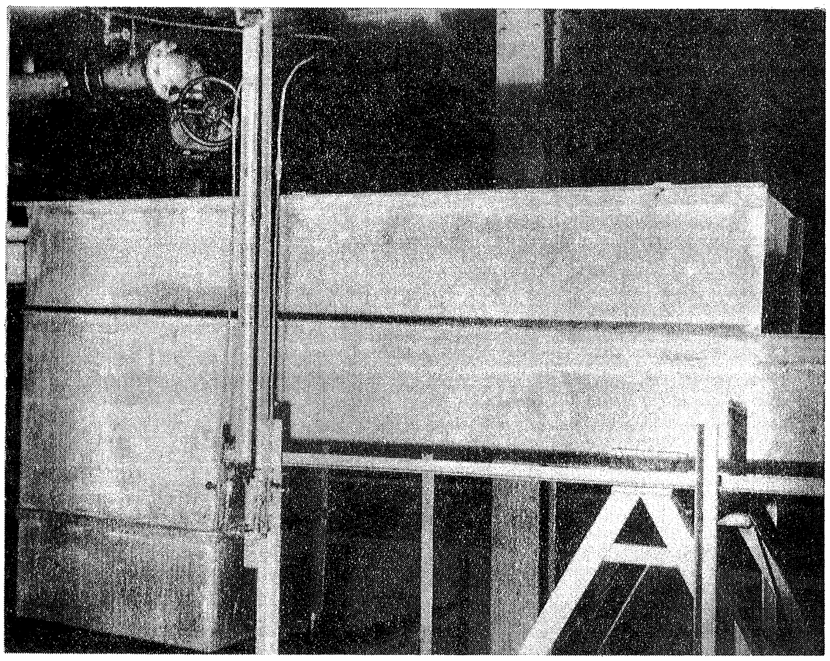


Fig. I-2 - Flume Inlet, Approach Channel to Culvert, and Orifice for Measuring Discharge Connected to Differential Gage

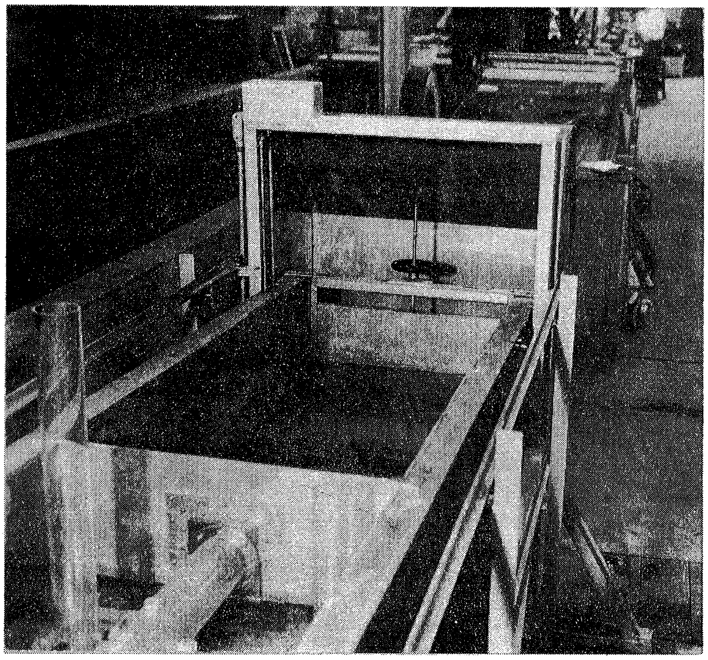


Fig. I-3 - Culvert Outlet, Tailwater Channel, and Tailwater Elevation Control

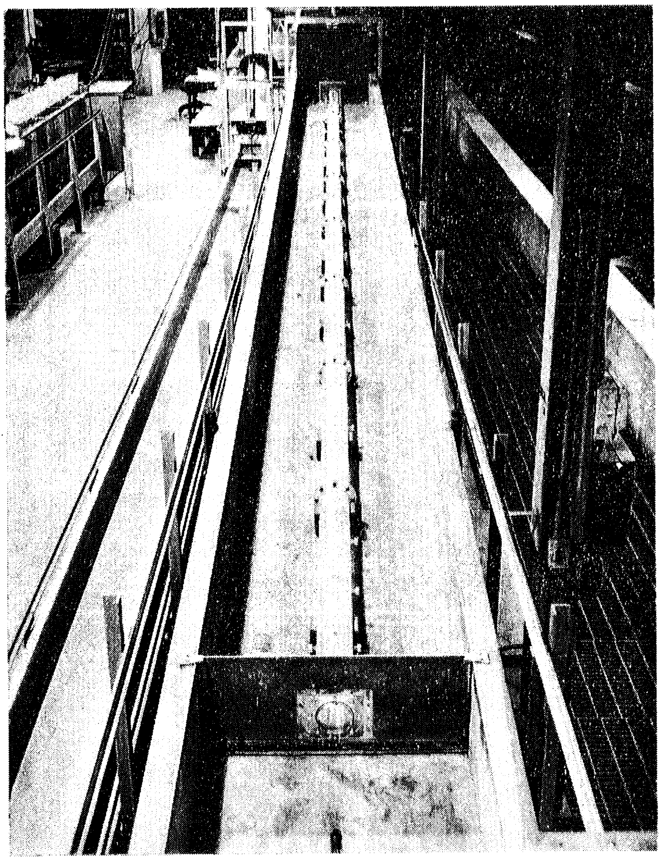


Fig. I-4 - Overall View of Culvert Flume and Model Culvert

Fig. I-5 - Headwater Pool and Culvert Inlet

APPENDIX II

PROPERTIES OF CIRCULAR SEGMENTS

Because of the frequent use that is made of the properties of circular segments in connection with the computations required for circular culverts, it is desirable to summarize these properties in the form of convenient graphs.

In Fig. II-1 the various terms are defined and the properties of the segments may easily be related to the angle θ subtending the flow segments

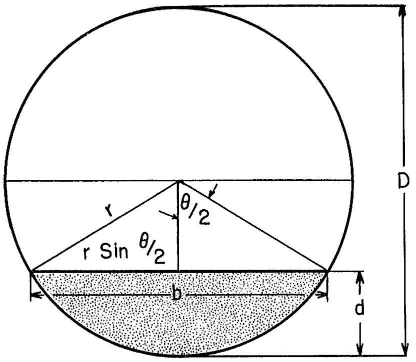


Fig. II-1 - Definition Sketch for Properties of Circular Segments

d = depth of flow
D = diameter of culvert
A = cross-sectional area of flow
A_o = cross-sectional area of culvert
b = surface width of flow stream
P = wetted perimeter of flow stream
P_o = perimeter of culvert
R = hydraulic radius of flow stream
R_o = hydraulic radius of culvert

$$\frac{d}{D} = \frac{D/2\ (1 - \cos\theta/2)}{D} = \frac{1}{2}\ (1 = \cos\frac{\theta}{2}) \qquad (1)$$

$$\frac{A}{A_o} = \frac{1/2\, r^2\theta - 2 \cdot 1/2\, r^2 \sin\theta/2 \cos\theta/2}{\pi r^2} \quad \frac{1/2\, r^2\ (\theta - \sin\theta)}{\pi r^2} = \frac{\theta - \sin\theta}{2\pi} \qquad (2)$$

$$\frac{b}{D} = \frac{2\ r \sin\theta/2}{D} = \sin\frac{\theta}{2} \qquad (3)$$

$$\frac{P}{P_o} = \frac{r\theta}{2\pi r} = \frac{\theta}{2\pi} \qquad (4)$$

$$\frac{R}{R_c} = \frac{A/A_o}{P/P_o} = \frac{\theta - \sin\theta}{2\pi} \cdot \frac{2\pi}{\theta} = 1 - \frac{\sin\theta}{\theta} \qquad (5)$$

In Fig. II-2, A/A_o, b/D, P/P_o, and R/R_o have been plotted in terms of d/D so that for any value of d/D the corresponding values of the ratios may be determined from the curves.

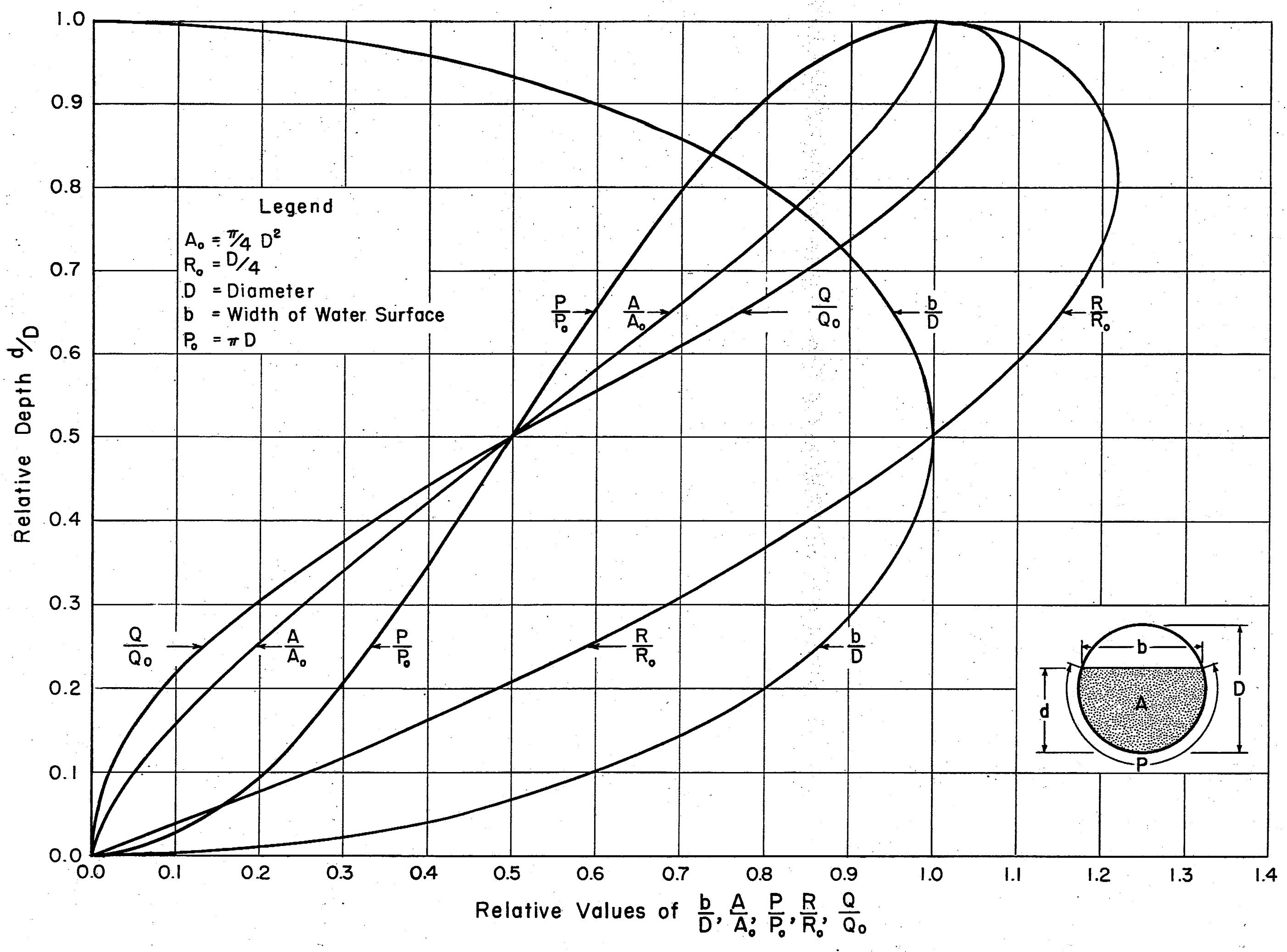


Fig. II-2 – Properties of Circular Segments

APPENDIX III

DETERMINATION OF CRITICAL DEPTH AND SLOPE

A summary of some principles of open channel flow is appended to serve as a basis for establishing the conditions for critical depth and critical slope.

For a given discharge Q, the total energy of the flow, neglecting thermal effects, in foot-pound per pound is the sum of the kinetic energy, pressure energy, and potential energy. In Fig. III-1 the total head per pound of water at a height z_1 from the bottom referred to the bottom of the channel or invert as a datum is

$$H_1 = \frac{V_1^2}{2g} + \frac{P_1}{\gamma} + z_1 \qquad \text{(III-1)}$$

where H_1 is the specific energy, relative to the invert,
V_1 is the velocity at point 1,
P_1 is the pressure at point 1,
γ is the specific weight of water,
g is the acceleration due to gravity, and
z_1 is the vertical distance from the invert to the point 1.

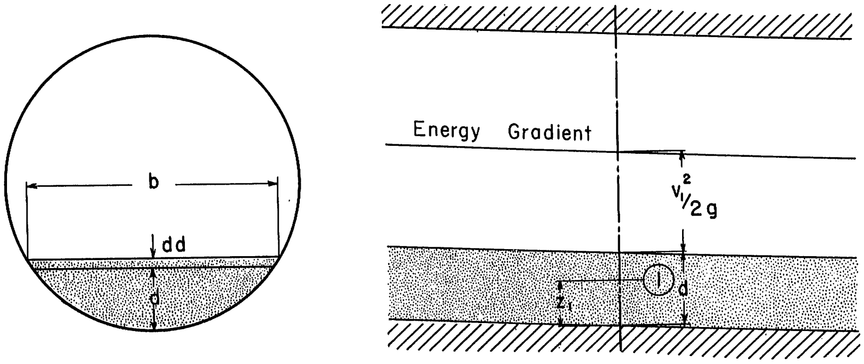


Fig. III-1 - Sketch Showing Properties of Open Channel Flow

If the flow is assumed to be rectilinear and a free surface exists, the pressure is hydrostatically distributed in a vertical and the pressure head at point 1 is

$$\frac{P_1}{\gamma} = d - z_1 \tag{III-2}$$

Substituting in Eq. (III-1), the specific head for the flow at point 1 is

$$H_1 = \frac{V_1^2}{2g} + d \tag{III-3}$$

If the velocity were uniform over the cross section, Eq. (III-3) would apply to all points in the cross section. Since this is usually not the case, a factor α may be introduced so that the average specific energy per pound of water for the entire cross section may be written as

$$H_o = \frac{\alpha V^2}{2g} + d \tag{III-4}$$

where V is now the mean velocity in the section.

The value of α then depends on the shape of the velocity profile and is numerically equal to 1.0 when the velocity is uniform. In Fig. 1 and Eq. (1) it was assumed $\alpha = 1.0$.

It is apparent, since $V = Q/A$ that when a given discharge flows at a small depth the velocity is large and H_o tends toward a large value. When the depth is large, H_o also tends toward a large value. At some intermediate depth of flow the specific energy will be a minimum which may be determined from Eq. (III-4) by setting dH/dd equal to zero. Equation (III-4) may be written as

$$H' = \frac{\alpha Q^2}{A^2 \cdot 2g} + d \tag{III-5}$$

so that

$$\frac{dH}{dd} = - \frac{\alpha Q^2}{A^3 g} \frac{dA}{dd} + 1 = 0 \tag{III-6}$$

where A is the cross-sectional area of the flow stream.

From Fig. III-1, $dA = b dd$ or $dA/dd = b$ where b is the width of the channel at the water surface. Substituting b for dA/dd in Eq. (III-6), the relation between discharge and cross-sectional area for critical flow may be written as

$$\frac{Q_c^{\ 2}}{g} = \frac{A^3}{\alpha b} \tag{III-7}$$

In terms that are independent of the size of the culvert, Eq. (III-7) can be put into the form

$$\left(\frac{Q_c}{D^{5/2}}\right)^2 = \left(\frac{\pi}{4}\right)^3 \frac{g}{\alpha} \frac{(A/A_o)^3}{b/D} \tag{III-8}$$

where A_o is the cross-sectional area of the culvert, and D is the diameter of the culvert. From Eq. (III-7) the critical velocity V_c is

$$\frac{V_c^{\ 2}}{g} = \frac{A}{\alpha b} \tag{III-9}$$

or

$$\frac{\alpha V_c^{\ 2}}{2gD} = \frac{\pi}{8} \frac{A/A_o}{b/D} \tag{III-10}$$

Equation (III-4) can also be written in terms of the properties of the cross section as

$$\frac{H_c}{D} = \frac{\alpha V_c^{\ 2}}{2gD} + \frac{d_c}{D} = \frac{\pi}{8} \frac{A/A_o}{b/D} + \frac{d_c}{D} \tag{III-11}$$

The critical energy head and the critical discharge can be determined from Eqs. (III-8) and (III-11) for various values of d_c/D by making use of the curves in Appendix II.

The slope upon which normal flow will take place at critical depth can be obtained by using a flow formula such as the Manning formula which is

$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2} \tag{III-12}$$

where, in addition to terms previously defined, n is the Manning roughness coefficient, R is the hydraulic radius, and S is the slope of the energy grade line.

Combining Eqs. (8) and (12) to eliminate Q, the critical slope can be written in terms of the properties of the cross section also so that

$$\frac{S_c}{n^2/D^{1/3}} = \frac{2.26g}{\alpha} \frac{A/A_o}{(b/D)(R/R_o)^{4/3}} \qquad \text{(III-13)}$$

By the use of these equations, the critical depth and slope may be determined for any given discharge. If for a given discharge the actual slope of the culvert is larger than that prescribed by Eq. (III-13), the flow will be supercritical; if it is less than S_c, the flow will be subcritical. This relationship is plotted in Fig. 1 in the report proper. Where a change in slope occurs such that the flow changes from a subcritical to supercritical the critical depth occurs at the point of change. This point is known as a control section since the depth of flow will depend only upon the discharge and the geometry of the cross section.

From Eq. (III-13) and Fig. 1 it is apparent that as d_c/D approaches 1.0 as may be required for large discharges the width at the water surface becomes small, that is b/D approaches zero and consequently the critical slope becomes very large, that is, $S_c \rightarrow \infty$. For a given culvert then the culvert slope may be greater than critical for one discharge and subcritical for a greater discharge. The depth at the inlet may also be less than, greater than, or equal to critical depth depending upon the slope of the culvert and whether the flow undergoes a contraction as in the case when the head is above the inlet crown. Figure 1 permits a qualitative description of the character of the flow in the culvert, the form of the water surface profiles, and the effect of length and roughness on these profiles.

APPENDIX IV

CULVERT BEHAVIOR CURVES

The experimental program dealt primarily with the effect of inlet design on the head-discharge curve of culverts with free outlets. A few observations were made to observe the effect of raising the tailwater elevation on the flow characteristics in the culvert. A plot of headwater elevation against the tailwater elevation is called the behavior curve and had previously been investigated in considerable detail by Mavis [5] for specific culverts and discharges. The data and analysis presented here apply specifically to culverts with square-edged inlets, but most of the principles presented can be adapted to culverts with other types of inlets as well.

In Fig. IV-1 are typical behavior curves as measured which show how the headwater elevation changes as the tailwater is raised. These were observed in the model culvert 4 inches in diameter on a 2 per cent slope. Curves for four discharges (0.1, 0.2, 0.3, and 0.4 cfs) are shown. For a free outlet (that is, T - 0) the curves indicate the headwater elevation. As the tailwater is raised, the headwater elevation remains constant until the tailwater reaches the crown at the outlet or slightly above and seals off the outlet. Air is sucked from the culvert by the flow and the pressure is reduced below atmospheric. This reduction in pressure in the pipe causes the headwater to lower and the zone of full or mixed flow to move upstream. In the case of 0.2 cfs discharge, the headwater is lowered to the point where a vortex is formed and air is sucked into the culvert before the zone of full flow reaches the inlet. This is shown by the drop in the behavior curve. The headwater then remains constant as the tailwater is raised, during which period the zone of full flow is being forced toward the inlet. When the zone of full flow reaches the inlet the culvert is flowing full and air is being sucked into the barrel to form a mixed flow. Further increase in tailwater elevation from this point causes a corresponding increase in the headwater elevation so that no more air is sucked into the culvert and the behavior curve rises at 45°, the culvert remaining full for all further increases in tailwater. As the tailwater elevation is reduced, the headwater-tailwater relationship retraces the behavior curve. A similar curve results for a discharge of 0.3 cfs except that for this discharge the initial point is higher, but here again when the tailwater seals the barrel at the outlet, the drop in headwater is

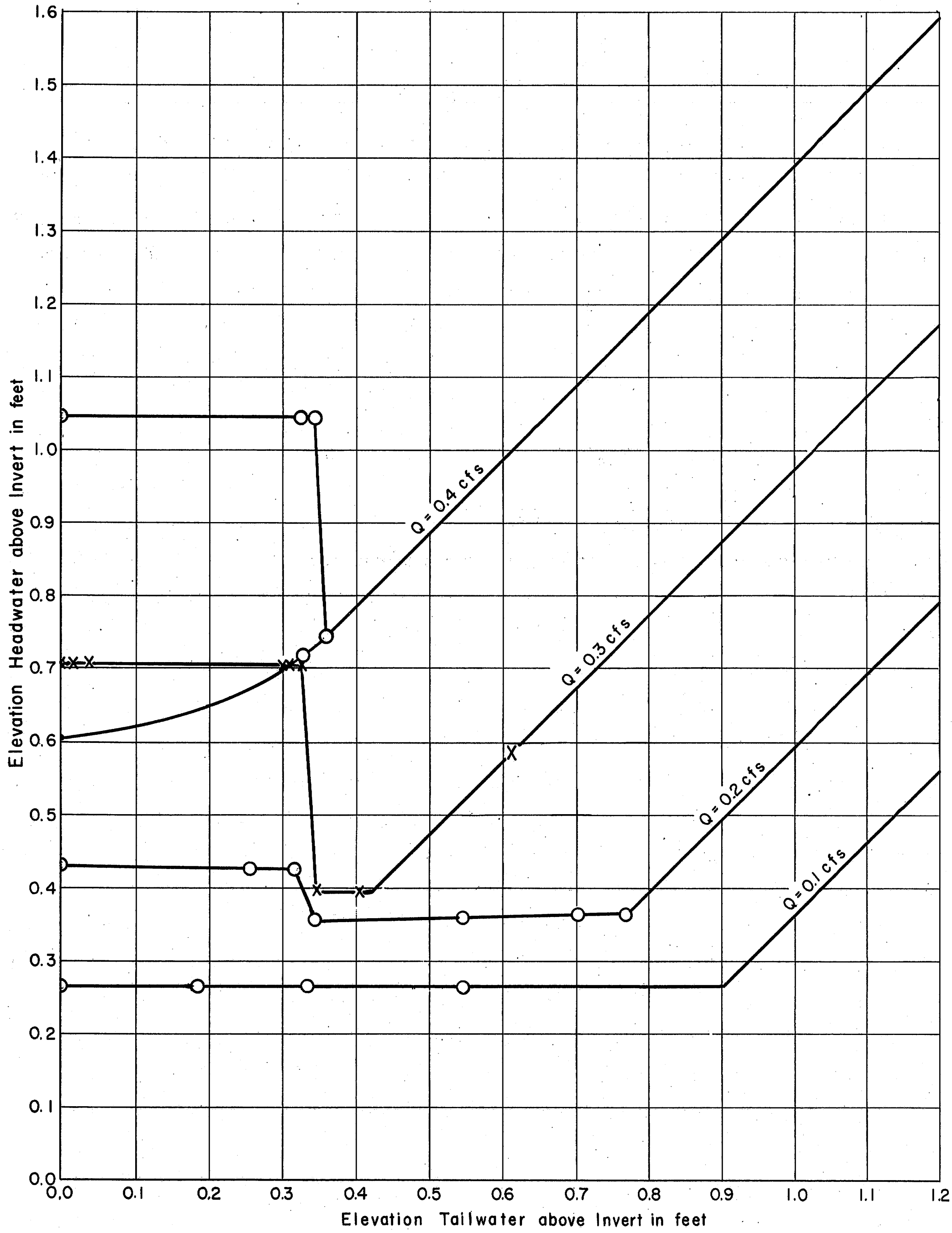


Fig. IV-1 - Behavior Curve, 4-in. Lucite Culvert, 2 Per Cent Slope greater to the point where the vortices form and air is sucked into the barrel. The headwater elevation above the crown δ, where a vortex forms, is greater for this discharge than for 0.2 cfs and the point at which the culvert flows full occurs at a lower tailwater elevation.

When the discharge is increased to 0.40 cfs, with the culvert still on a 2 per cent slope, the headwater elevation when $T = 0$ again corresponds to the head-discharge curve for the square-edged inlet. Again the head remains constant until the tailwater is raised just slightly above the crown at the outlet, at which point the outlet is again sealed. The consequent reduction of pressure in the barrel results in a decrease in headwater elevation and simultaneously in the movement of the zone of full, mixed flow toward the inlet. In this case, however, the zone of mixed flow reaches the inlet before the head has dropped sufficiently for vortices to form so that at that point the curve slopes upward at 45° with increases in tailwater producing equal increases in head. When the curve is retraced by lowering the tailwater, the culvert remains flowing full even though the tailwater is lowered to zero and the outlet is free. The headwater elevation for this condition is considerably lower than that required when the culvert was originally flowing part full.

The behavior curve of a culvert on a steep slope may be roughly divided into two parts: (1) when the tailwater is below the crown of the outlet the curve depends primarily upon discharge and inlet geometry or head-discharge curve with a free outlet, and (2) when the tailwater is above the outlet crown the shape and position of the curve depends upon the discharge and the other design variables.

When the tailwater is high enough to cause the culvert to flow full, the flow is described by

$$\frac{H}{D} = \frac{T}{D} + \frac{8}{\pi^2 g} \left(1 + K_e + f \frac{L}{D}\right) \left(\frac{Q}{D^{5/2}}\right)^2 - \frac{L}{D} \sin \theta \qquad \text{(IV-1)}$$

which is similar to Eq. (7) except that now the hydraulic grade line is determined by the tailwater elevation instead of the assumption that it is at the center of the outlet as in the case of a free outlet. Equation (IV-1) may be written as

$$\frac{H}{D} = \frac{T}{D} + K \qquad \text{(IV-2)}$$

where

$$K = \frac{8}{\pi^2 g}\left(1 + K_e + f\frac{L}{D}\right)\left(\frac{Q}{D^{5/2}}\right)^2 - \frac{L}{D}\sin\theta \qquad \text{(IV-3)}$$

and includes all of the variables of the culvert and the discharge. Equation (IV-2) represents a family of straight lines at 45° with the line for $K = 0$ passing through the origin. The full-flow line for each culvert then will be located in this family of lines in accordance with its value of K and independently of the initial head-discharge curve. Equation (IV-3) indicates that the greater the discharge the greater is K, and the steeper the slope the smaller is K. The value of K based upon the experimental values of Ke and friction factor f previously determined for the Lucite model [1] was computed and plotted in Fig. IV-2 against the experimental values of K as measured from the behavior curves. These same values of Ke and f were used to compute K for the 4-in. and 6-in. Lucite culvert models of Mavis [5] and were compared with the measured values from his curves and plotted also in Fig. IV-2. The agreement between the computed and measured values of K in Fig. IV-2 serves to illustrate the fact that the full-flow portion of the behavior curve for any culvert will be located in accordance with the K that corresponds to the culvert for a particular discharge.

In the case of culverts with square-edged inlets, when the headwater is above the crown at the inlet, another critical point is reached when the tailwater is raised to the crown of the outlet or slightly higher so that the outlet is sealed off from the atmosphere. Air becomes entrained in the stream through the culvert by means of the hydraulic jump or through other mixed-flow phenomena and is then pumped out with the consequent reduction of pressure in the culvert. This reduction in pressure permits the same flow to occur under a lower head so that the headwater elevation is reduced. As the headwater approaches the culvert crown at the inlet, a vortex will form at the inlet and air will be sucked into the culvert, tending to equalize the pressure between that in the culvert and the atmosphere. It is probable that the depth of water above the crown at which the vortex will form depends upon the difference in pressure between the inside of the culvert and the atmosphere which in turn depends on the discharge and diameter. One might expect, therefore, that δ, the difference in elevation between the water surface and the culvert crown at the moment a vortex is formed, would be a function of the discharge. This relationship in terms of δ/D and $Q/D^{5/2}$ is shown in Fig. IV-3 for a square-edged inlet. The points are as determined by experiment.

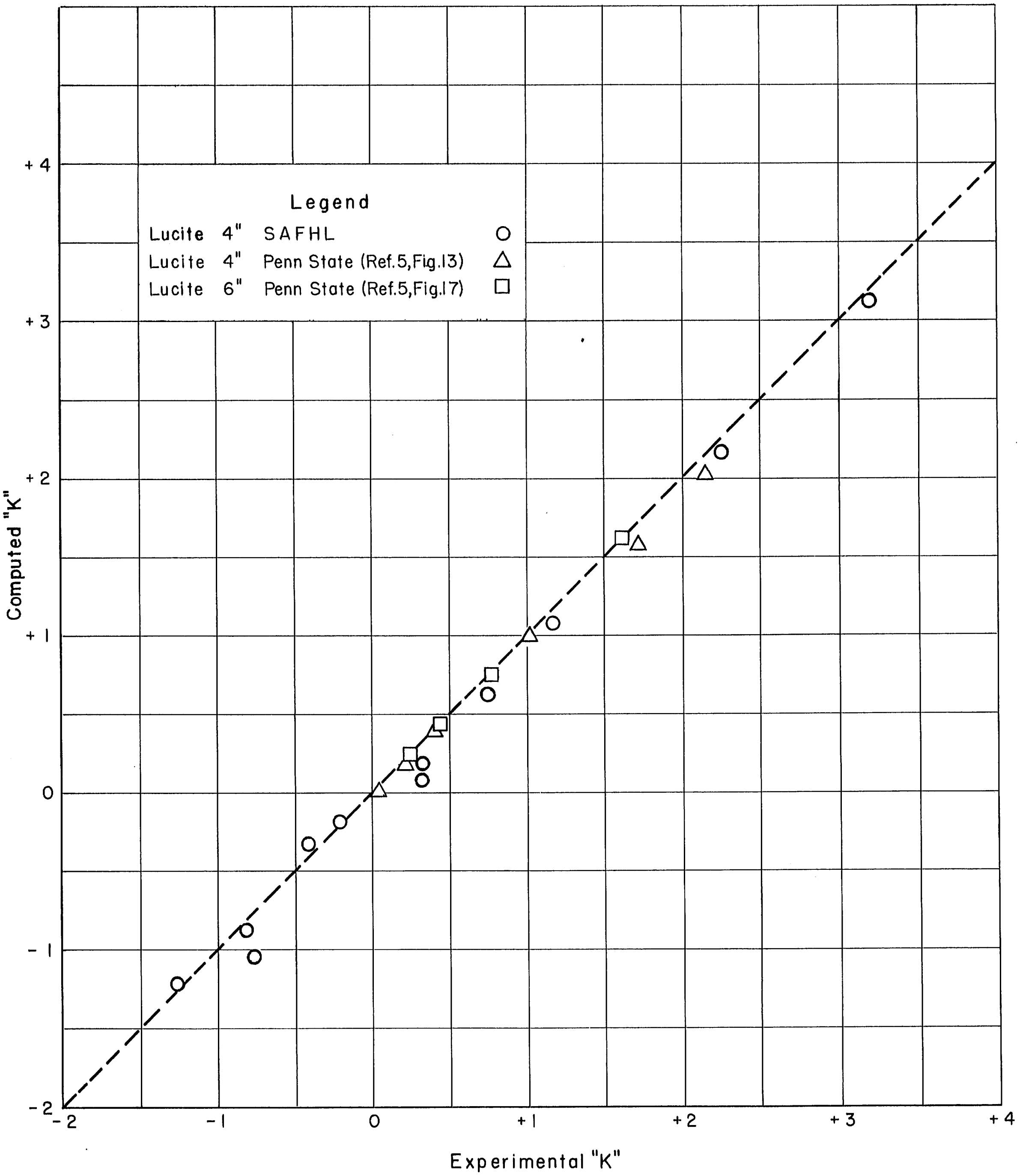


Fig. IV-2 - Computed vs Experimental Values of "K"

Also plotted in Fig. IV-3 are points taken from the behavior curves published by Mavis [5]. It is seen that reasonable agreement is obtained between the results from the two laboratories. These results are based upon model experiments on culverts whose diameters varied from 4 to 12 inches.

On the basis of these results, a somewhat generalized description of the behavior curve of a culvert may be obtained. The starting point is determined by the head-discharge curve for the particular culvert being studied and the curve ends on the particular K-line for the culvert. The value of K may be computed from Eq. (IV-3) and plotted in accordance with Eq. (IV-2). The value of K depends upon the discharge and the properties of the particular culvert. By the use of the head-discharge curve, the curve for δ/D-discharge and the K-curve, the behavior curve for any particular culvert may be deduced. The behavior curve will follow a prescribed path until it intersects the K-curve. For culvert with inlet control the curve for a particular discharge is horizontal until $T/D = 1.0$ or slightly greater. It then drops to a point $H/D = 1 + \delta/D$ and proceeds horizontally until it intersects the proper K-curve. It may intersect the K-curve before $T/D = 1.0$ or before the head has dropped to $H/D = 1 + \delta/D$ in which case it will depart from the original path and proceed along the K-curve. If the initial head is such that $H/D < (1 + \delta/D)$, the curve will proceed horizontally at the initial H/D until it intersects the proper K-curve.

A number of typical behavior curves have been plotted in Figs. IV-5 and IV-6 based on the data and computations tabulated in Table IV-I. Two types of culverts were used in the examples: (1) a 4-in. Lucite culvert, and (2) a 3-ft culvert. The Lucite culvert was chosen so that experimental points could be plotted along with the computed curve. The 3-ft culvert was chosen as being a typical prototype so that the character of its behavior curve could be illustrated. In these computations it is assumed that the culvert has a square-edged inlet and is on a steep slope so that the head-discharge curve plotted in Fig. IV-4 is applicable. It is reproduced from the experimental curve plotted in Fig. 3.

Table IV-1

Q	$\frac{Q}{D^{5/2}}$	$\frac{H}{D}$ (Fig. 5)	$\frac{\delta}{D}$ (Fig. IV-3)	K
	Lucite L/D = 105 Slope = 2%	$L/D \sin \theta = 2.1$	$D^{5/2} = 0.0640$ D = 0.333 ft	
0.1	1.56	0.80	--	-1.859
0.2	3.12	1.27	0.087	-1.240
0.3	4.63	1.92	0.162	-0.310
0.4	6.24	3.12	0.230	+1.070
	Concrete L/D = 100 Slope = 4%	$L/D \sin \theta = 4.0$ f = 0.015	$D^{5/2} = 15.6$ D = 3.0 ft	
23.4	1.50	0.78	--	-3.835
62.4	4.00	1.56	0.132	-2.830
93.6	6.00	2.91	0.220	-1.360
124.7	8.00	4.78	0.290	+0.690

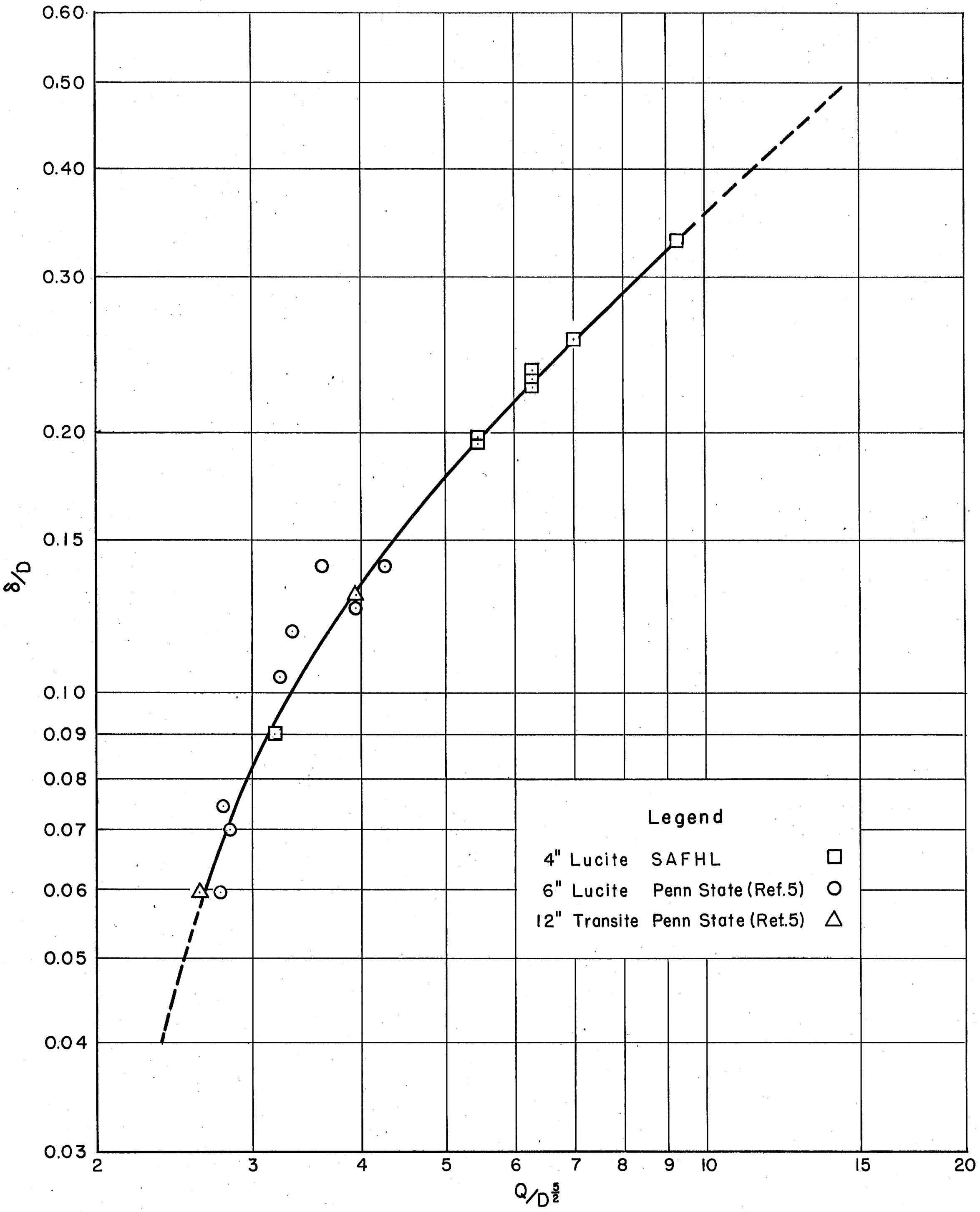


Fig. IV-3 - Relation of δ/D to $Q/D^{5/2}$
(Square-Edged Inlet)

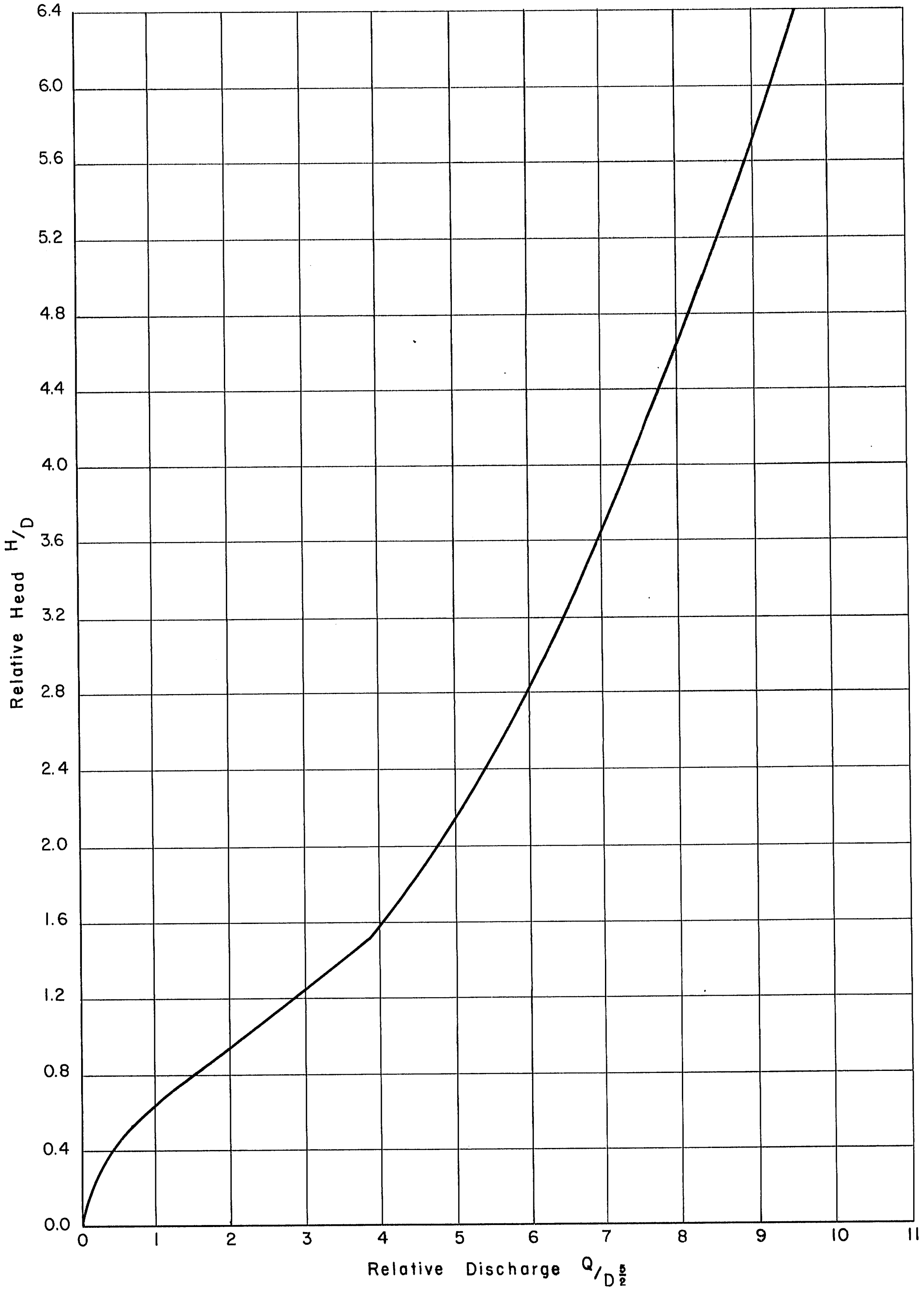


Fig. IV-4 – Head-Discharge Curve for Square-Edged Inlet
(Lucite Culvert on Steep Slope)

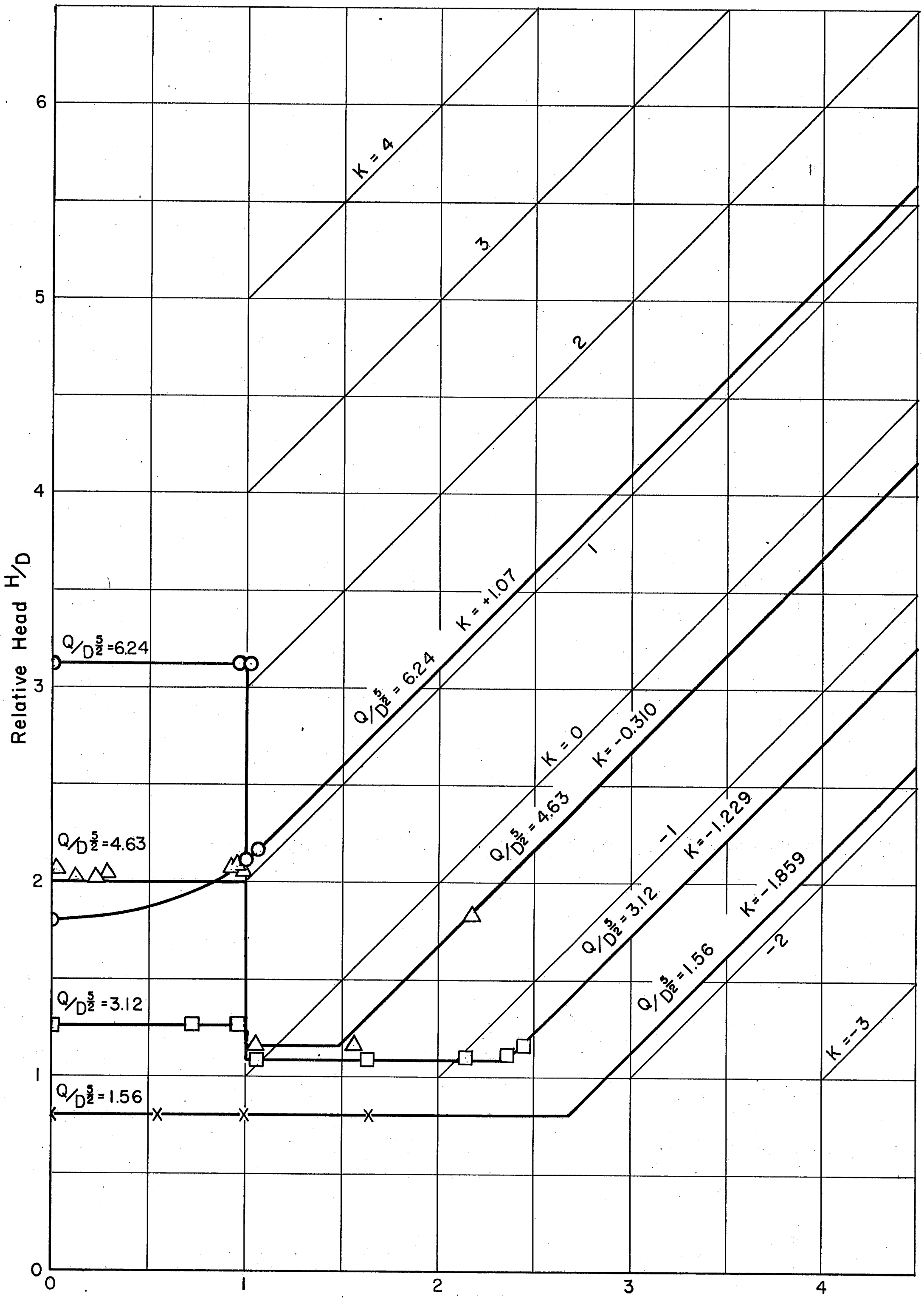


Fig. IV-5 - Behavior Curves, 4-in. Lucite Culvert
(Square-Edged Inlet)

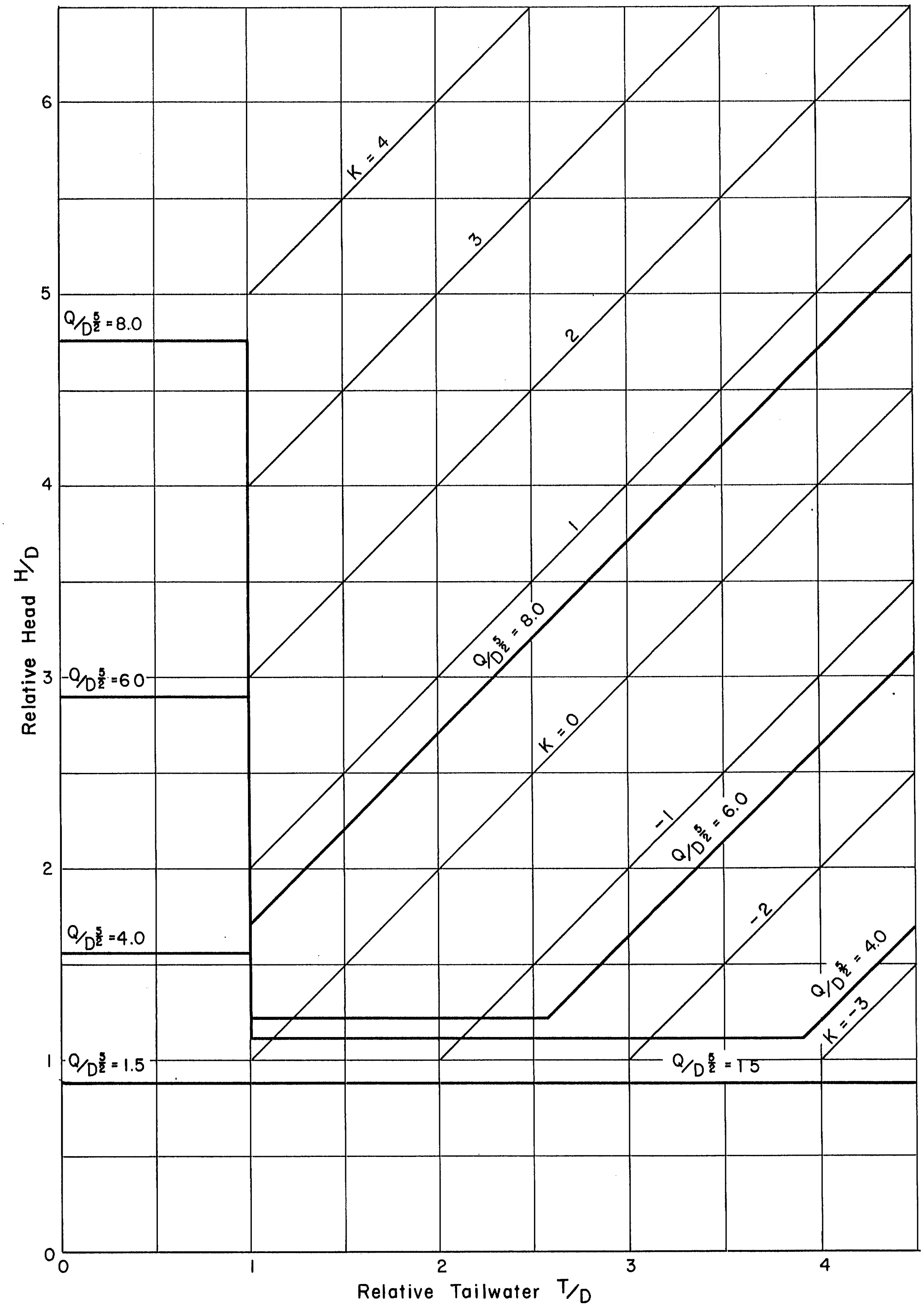


Fig. IV-6 - Computed Behavior Curves, 3-ft Culvert
(Square-Edged Inlet)

APPENDIX V

TABULATION OF EXPERIMENTAL DATA

In this appendix are tabulated the experimental data collected in the course of experiments relating to the research sponsored by the Minnesota Highway Department and the Bureau of Public Roads. The analysis presented in previous sections is based upon these data and supplementary experimental data obtained by students in connection with thesis research.

Table I is a tabulation of the station locations at which pressure measurements were made showing the distance of each pressure tap from the upstream face of the head wall.

The experimental results obtained in the experiments on the flow through the model culvert fitted with the square-edged inlet are tabulated in Table II. These include the experiments in which the discharge, slope, and tailwater elevation were varied. The head-discharge curves were obtained from the data with a free outlet. The experiments in which the tailwater elevation was varied were for the purpose of establishing behavior curves and to observe phenomena involving the hydraulic jump.

In addition to headwater and tailwater elevations and discharge, the piezometric pressure was measured at numerous stations along the channel. These indicate the hydraulic grade line elevation. The relative elevation of the grade line may be obtained by subtracting the invert elevation of the culvert at the respective station from the grade-line elevation. If the culvert is flowing part-full for the complete length, this difference provides a good indication of the depth. However, if the entrance is submerged and a jump forms in the culvert, a steady-state condition may develop in which a partial vacuum develops upstream of the jump. In order to obtain water depth from the piezometric measurements it is necessary to add the value of the negative pressure to the elevation of the hydraulic grade line. In the following tables the depth computations have been included. Discrepancies between computed and actual depth can be expected in the region of the vena contracta and the hydraulic jump.

Table III summarizes the data in Table II with reference to the head-discharge curves and tailwater elevation, and includes the computation of dimensionless parameters for discharge headwater elevation and tailwater elevation.

Table IV is a tabulation of the experimental results obtained on the model culvert when fitted with a rounded inlet and corresponds to Table II.

The summarized tabulation for the rounded inlet for the determination of head-discharge curves and behavior curves when the rounded inlet was used constitutes Table V.

Table I

Location of Measuring Points

Culvert Diameter 0.333 ft

Station	Distance from Upstream Face of Headwall (ft)
H.W.	0
1	0.23
2	0.56
3	0.90
4	1.23
5	1.56
6	2.06
7	2.63
8	3.40
9	4.06
10	6.62
11	11.00
12	15.38
13	19.76
14	24.12
15	28.50
16	31.75
17	32.85
18	34.00
T.W.	35.13

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET

Run Nos. 011-016
Discharge 0.1 cfs
Slope 0.00048
Temperature 23.3° C

Run No.	Station	Elev Grade	Hydr Line	Elev Invert	Depth
011	H.W.	0.319		0.011	0.308
	1	0.234		0.011	0.223
	5	0.283		0.010	0.273
	10	0.272		0.008	0.264
	13	0.245		0.001	0.244
	16	0.207		-0.004	0.211
	18	0.193		-0.005	0.198
	T.W.	No		-0.006	-
	Note:	Part-full flow, subcritical			
012	H.W.	0.800		0.478	0.322
	1	0.716		0.478	0.238
	5	0.762		0.477	0.285
	10	0.751		0.475	0.276
	13	0.726		0.469	0.257
	16	0.688		0.464	0.224
	18	0.676		0.463	0.213
	T.W.	0.652		0.462	0.190
	Note:	Part-full flow, subcritical			
013	H.W.	0.809		0.478	0.331
	1	0.768		0.478	0.290
	5	0.775		0.477	0.298
	10	0.765		0.475	0.290
	13	0.743		0.468	0.275
	16	0.717		0.463	0.254
	18	0.713		0.462	0.251
	T.W.	0.708		0.461	0.247
	Note:	Part-full flow, Subcritical			

Run No.	Station	Elev Grade	Hydr Line	Elev Invert	Depth
014	H.W.	0.885		0.478	0.407
	1	0.845		0.478	Full
	5	0.854		0.477	Full
	10	0.845		0.475	Full
	13	0.826		0.468	Full
	16	0.808		0.463	Full
	18	0.806		0.462	Full
	T.W.	0.804		0.461	0.343
	Note:	Full flow			
015	H.W.	0.853		0.478	0.375
	1	0.812		0.478	Full
	5	0.820		0.477	Full
	10	0.810		0.475	Full
	13	0.793		0.468	Full
	14	0.785		0.466	Full
	15	0.777		0.465	0.312
	16	0.771		0.463	0.308
	18	0.770		0.462	0.308
	T.W.	0.767		0.461	0.306
	Note:	Full to Station 14, Part-full to outlet			
016	H.W.	0.831		0.478	0.353
	1	0.792		0.478	0.314
	5	0.800		0.477	0.323
	10	0.792		0.475	0.317
	13	0.777		0.468	0.309
	16	0.754		0.463	0.291
	18	0.750		0.462	0.288
	T.W.	0.747		0.461	0.286
	Note:	Part-full flow			

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE EDGED INLET
(Continued)

Run No.	031
Discharge	0.298 cfs
Slope	0.00048
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
031	H.W.	1.162	0.482	0.680
	1	0.786	0.480	0.306
	5	0.670	0.466	0.204
	10	0.642	0.416	0.226
	11	0.611	0.372	0.239
	12	0.579	0.328	0.251
	13	0.531	0.284	0.247
	14	0.506	0.241	0.265
	15	0.474	0.197	0.277
	16	0.428	0.164	0.264
	17	0.428	0.153	0.275
	18	0.429	0.142	0.287
	T.W.	No	0.131	-

Note: Part-full flow

Run Nos.	041-042
Discharge	0.4 cfs
Slope	0.00051
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
041	H.W.	1.772	0.489	1.283
	1	1.182	0.489	Full
	5	1.275	0.488	Full
	10	1.164	0.486	Full
	13	0.900	0.480	Full
	16	0.745	0.474	0.271
	18	0.695	0.472	0.223
	T.W.	No	0.471	-
042	H.W.	1.925	0.489	1.436
	1	1.343	0.489	Full
	5	1.433	0.488	Full
	10	1.322	0.486	Full
	13	1.062	0.480	Full
	15	0.965	0.475	Full
	16	0.882	0.474	Full
	18	0.853	0.472	Full
	T.W.	0.840	0.471	Full

Run Nos.	111-112
Discharge	0.1 cfs
Slope	0.01
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
111	H.W.	0.755	0.481	0.274
	1	0.663	0.479	0.184
	5	0.614	0.465	0.149
	10	0.560	0.415	0.145
	13	0.417	0.283	0.134
	16	0.295	0.163	0.132
	18	0.282	0.140	0.142
	T.W.	No	0.129	-

Note: Part-full flow

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
112	H.W.	0.756	0.481	0.275
	1	0.665	0.479	0.186
	5	0.615	0.465	0.150
	10	0.561	0.415	0.146
	13	0.417	0.283	0.134
	16	0.294	0.163	0.131
	18	0.279	0.140	0.139
	T.W.	0.312	0.129	0.183

Note: Part-full flow

Note: The headwater depth is with reference to the inlet invert, and the tailwater depth with reference to the outlet invert.

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	113-117
Discharge	0.1 cfs
Slope	0.01
Temperature	24° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
113	H.W.	0.756	0.481	0.275
	1	0.665	0.479	0.186
	5	0.616	0.465	0.151
	10	0.563	0.415	0.138
	13	0.420	0.283	0.137
	14	0.382	0.239	0.143
	15	0.466	0.195	0.261
	16	0.469	0.163	Full
	18	0.467	0.140	Full
	T.W.	0.465	0.129	Full
	Note:	Jump at Station 15		
114	H.W.	0.760	0.481	0.279
	1	0.679	0.479	0.200
	5	0.692	0.465	0.227
	10	0.707	0.415	0.292
	11	0.704	0.371	Full
	12	0.696	0.327	Full
	13	0.676	0.283	Full
	16	0.671	0.163	Full
	18	0.668	0.140	Full
	T.W.	0.667	0.129	Full
	Note:	Jump moved to inlet Full flow		
115	H.W.	0.842	0.481	0.261
	13	0.777	0.283	Full
	16	0.759	0.163	Full
	T.W.	0.755	0.129	Full
	Note:	Full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
116	H.W.	0.902	0.481	0.421
	1	0.863	0.479	Full
	5	0.868	0.465	Full
	10	0.859	0.415	Full
	12	0.847	0.327	Full
	13	0.840	0.283	Full
	14	0.834	0.239	Full
	15	0.826	0.195	Full
	16	0.822	0.163	Full
	17	0.820	0.152	Full
	18	0.819	0.140	Full
	T.W.	0.817	0.129	Full
	Note:	Full flow		
117	H.W.	0.804	0.481	0.323
	1	0.756	0.479	0.277
	5	0.771	0.465	0.206
	9	0.764	0.441	0.323
	10	0.757	0.415	Full
	16	0.718	0.163	Full
	T.W.	0.713	0.129	Full
	Note:	Tailwater lowered until part-full flow started (from inlet to Station 9) full from Station 9 to outlet		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	120-128
Discharge	0.2 cfs
Slope	0.01
Temperature	24° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
120	H.W.	0.915	0.482	0.433
	1	0.738	0.480	0.258
	5	0.664	0.466	0.198
	10	0.619	0.416	0.203
	13	0.475	0.284	0.191
	16	0.357	0.164	0.193
	18	0.346	0.142	0.204
	T.W.	No	0.131	-
	Note:	Part-full flow		
121	H.W.	0.916	0.482	0.434
	1	0.739	0.480	0.259
	5	0.664	0.466	0.198
	10	0.621	0.416	0.205
	13	0.481	0.284	0.197
	16	0.357	0.164	0.193
	18	0.344	0.142	0.202
	T.W.	0.384	0.131	0.253
	Note:	Part-full flow		
122	H.W.	0.845	0.482	0.363
	1	0.679	0.480	0.264
	5	0.605	0.466	0.204
	9	0.587	0.441	0.211
	10	0.561	0.416	0.210
	12	0.475	0.328	0.212
	13	0.516	0.284	Full
	14	0.517	0.241	Full
	16	0.480	0.164	Full
	18	0.468	0.142	Full
	T.W.	0.461	0.131	0.330
	Note:	Air Pressure = -0.065' Station 1-12 Jump at Station 13 full with entrained air to outlet		
123	H.W.	0.846	0.482	0.364
	1	0.683	0.480	0.266
	5	0.609	0.466	0.206
	10	0.563	0.416	0.210
	11	0.519	0.372	Full
	12	0.589	0.328	Full
	13	0.571	0.284	Full
	16	0.516	0.164	Full
	18	0.502	0.142	Full
	T.W.	0.503	0.131	0.372
	Note:	Air Pressure = -0.063' Station 1-11 Jump at Station 11 full with entrained air to outlet		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos. 120-128
Discharge 0.2 cfs
Slope 0.01
Temperature 24° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
124	H.W.	0.848	0.482	0.366
	1	0.682	0.480	0.265
	5	0.609	0.466	0.206
	9	0.690	0.441	Full
	10	0.682	0.416	Full
	13	0.617	0.284	Full
	16	0.562	0.164	Full
	18	0.548	0.142	Full
	T.W.	0.547	0.131	Full
	Note:	Air Pressure = -0.063', Station 1-5 Jump at Station 8 Full to outlet		
125	H.W.	0.846	0.482	0.364
	1	0.682	0.480	0.265
	5	0.645	0.466	0.242
	9	0.700	0.441	Full
	10	0.686	0.416	Full
	13	0.622	0.284	Full
	T.W.	0.551	0.131	0.420
	Note:	Air Pressure = -0.063', Station 1-5 Jump at Station 5		
126	H.W.	0.848	0.482	0.366
	1	0.695	0.480	0.286
	5	0.723	0.466	Full
	9	0.707	0.441	Full
	10	0.691	0.416	Full
	13	0.626	0.284	Full
	T.W.	0.554	0.131	0.423
	Note:	Air Pressure = -0.071, Station 1 = -0.063, Station 5 = -0.052, Station 9 = -0.037, Station 10 = -0.023, Station 13 Full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
127	H.W.	0.859	0.482	0.277
	1	0.703	0.480	0.223
	5	0.736	0.466	Full
	10	0.705	0.416	Full
	13	0.641	0.284	Full
	16	0.585	0.164	Full
	18	0.571	0.142	Full
	T.W.	0.570	0.131	0.439
	Note:	Air Pressure = -0.125', Station 1 Full flow		
128	H.W.	0.877	0.482	0.395
	1	0.722	0.480	Full
		-	-	Full
	T.W.	0.587	0.131	0.456
	Note:	Full flow		

Table II

EXPERIMENTAL OBSERVATIONS—SQUARE-EDGED INLET
(Continued)

Run No.	130
Discharge	0.296 cfs
Slope	0.01
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth	Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
130	H.W.	1.162	0.482	0.780	130	14	0.506	0.241	0.265
	1	0.786	0.480	0.306	(Cont)	15	0.474	0.195	0.279
	5	0.670	0.466	0.204		16	0.428	0.164	0.264
	10	0.642	0.416	0.226		17	0.428	0.152	0.276
	11	0.611	0.372	0.239		18	0.429	0.140	0.289
	12	0.579	0.328	0.251		T.W.	No	-	-
	13	0.531	0.284	0.247		Note:	Part-full flow		

Run Nos.	140-141
Discharge	0.4 cfs
Slope	0.01
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth	Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
140	H.W.	1.434	0.482	0.952	141	H.W.	1.587	0.482	1.105
	1	0.844	0.480	Full		1	1.003	0.480	Full
	5	0.932	0.466	Full		5	1.091	0.466	Full
	10	0.823	0.416	Full		10	0.983	0.416	Full
	13	0.598	0.284	Full		13	0.759	0.284	Full
	16	0.403	0.164	Full		16	0.567	0.164	Full
	18	0.350	0.142	Full		18	0.515	0.142	Full
	T.W.	No	0.131	-		T.W.	0.495	0.131	0.364
	Note:	Full flow				Note:	Full flow		

Run Nos.	160-161
Discharge	0.572 cfs
Slope	0.01
Temperature	22° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth	Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
160	H.W.	2.619	0.482	1.137	161	H.W.	2.522	0.482	2.040
	1	1.405	0.480	Full		1	1.305	0.480	Full
	5	1.596	0.466	Full		5	1.491	0.466	Full
	9	1.488	0.441	Full		10	1.272	0.416	Full
	10	1.381	0.416	Full		13	0.839	0.284	Full
	12	1.078	0.328	Full		16	0.451	0.164	Full
	13	0.947	0.284	Full		18	0.342	0.142	Full
	16	0.572	0.164	Full		T.W.	No	0.131	-
	18	0.467	0.142	Full		Note:	Full flow		
	T.W.	0.423	0.131	0.297					
	Note:	Full flow							

Table II

EXPERIMENTAL OBSERVATIONS---SQUARE-EDGED INLET
(Continued)

Run Nos.	210-213
Discharge	0.1 cfs
Slope	0.02
Temperature	23° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
210	H.W.	1.014	0.747	0.267
	1	0.917	0.743	0.174
	5	0.851	0.712	0.139
	9	0.791	0.666	0.125
	10	0.735	0.615	0.120
	13	0.460	0.352	0.108
	16	0.216	0.112	0.104
	18	0.177	0.067	0.110
	T.W.	No	0.045	-
	Note:	Part-full flow		
211	H.W.	1.014	0.747	0.267
	1	0.918	0.743	0.175
	5	0.851	0.712	0.139
	10	0.736	0.615	0.121
	13	0.460	0.352	0.108
	16	0.216	0.112	0.104
	18	0.176	0.067	0.109
	T.W.	0.230	0.045	0.185
	Note:	Part-full flow		
212	H.W.	1.014	0.747	0.267
	16	0.216	0.112	0.104
	18	0.346	0.067	0.279
	T.W.	0.379	0.045	0.334
	Note:	Jump at Station 18 Part-full flow to Station 18		
213	H.W.	1.014	0.747	0.267
	10	0.736	0.615	0.121
	11	0.820	0.527	Full
	12	0.816	0.439	Full
	16	0.792	0.112	Full
	18	0.788	0.067	Full
	T.W.	0.787	0.045	0.742
	Note:	Jump at Station 10½ Full flow with entrained air to outlet		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	220-228
Discharge	0.2 cfs
Slope	0.02
Temperature	22° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
220	H.W.	1.178	0.747	0.431
	1	0.999	0.743	0.256
	5	0.904	0.712	0.192
	10	0.791	0.615	0.176
	13	0.510	0.352	0.158
	16	0.266	0.112	0.154
	18	0.230	0.067	0.163
	T.W.	No	0.045	-
	Note:	Part-full flow		
221	H.W.	1.179	0.747	0.432
	13	0.512	0.352	0.160
	18	0.229	0.067	0.162
	T.W.	0.298	0.045	0.253
	Note:	Part-full flow		
222	H.W.	1.113	0.747	0.366
	1	0.944	0.743	0.264
	5	0.847	0.712	0.198
	10	0.732	0.615	0.230
	13	0.454	0.352	0.165
	16	0.206	0.112	0.157
	18	0.359	0.067	Full
	T.W.	0.394	0.045	0.349
	Note:	Air Pressure = -0.063', Station 1-16 Jump at Station 17 Full flow with entrained air to outlet		
223	H.W.	1.111	0.747	0.364
	1	0.942	0.743	0.263
	5	0.846	0.712	0.198
	10	0.732	0.615	0.192
	12	0.552	0.439	0.177
	13	0.627	0.352	Full
	17	0.599	0.090	Full
	18	0.592	0.067	Full
	T.W.	0.588	0.045	0.543
	Note:	Air Pressure = -0.064', Station 1-12 Jump at Station 13 Full flow with entrained air to outlet		
224	H.W.	1.112	0.747	0.365
	1	0.940	0.743	0.263
	5	0.965	0.712	Full
	9	0.960	0.666	Full
	10	0.946	0.615	Full
	13	0.878	0.352	Full
	17	0.810	0.090	Full
	18	0.804	0.067	Full
	T.W.	0.800	0.045	0.755
	Note:	Air Pressure = -0.066', Station 1 Jump at Station 3½ Full flow with entrained air to outlet		
225	H.W.	1.118	0.747	0.371
	1	1.051	0.743	0.308
	5	0.992	0.712	Full
	10	0.961	0.615	Full
	13	0.895	0.352	Full
	17	0.829	0.090	Full
	18	0.823	0.067	Full
	T.W.	0.816	0.045	0.761
	Note:	Full flow Air pocket to Station 1		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	220-228
Discharge	0.2 cfs
Slope	0.02
Temperature	22° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
226	H.W.	1.134	0.747	0.387
	1	0.978	0.743	Full
	5	1.007	0.712	Full
	10	0.976	0.615	Full
	T.W.	0.831	0.045	0.786
	Note:	Full Flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
227	H.W.	1.123	0.747	0.376
	T.W.	-	0.045	-
	Note:	Full flow		
228	H.W.	1.120	0.747	0.373
	T.W.	0.817	0.045	0.772
	Note:	Full flow		

Run Nos.	230-238
Discharge	0.3 cfs
Slope	0.02
Temperature	17.5° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
230	H.W.	1.592	0.889	0.703
	1	1.196	0.884	0.312
	7	1.042	0.835	0.207
	9	1.019	0.808	0.211
	10	0.964	0.757	0.207
	11	0.882	0.669	0.213
	12	0.798	0.582	0.216
	13	0.703	0.494	0.209
	14	0.626	0.406	0.220
	15	0.535	0.319	0.216
	16	0.482	0.259	0.223
	18	0.434	0.209	0.225
	T.W.	0.229	0.193	0.036
	Note:	Part-full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
231	H.W.	1.590	0.889	0.701
	1	1.198	0.884	0.314
	7	1.042	0.835	0.207
	9	1.019	0.808	0.211
	10	0.964	0.757	0.207
	11	0.882	0.669	0.213
	12	0.796	0.582	0.214
	13	0.688	0.494	0.194
	14	0.622	0.406	0.216
	15	0.534	0.319	0.215
	16	0.479	0.259	0.220
	18	0.430	0.209	0.221
	T.W.	0.268	0.193	0.075
	Note:	Part-full flow		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET (Continued)

Run Nos. 230-238
Discharge 0.3 cfs
Slope 0.02
Temperature 17.5° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
232	H.W.	1.590	0.889	0.701
	T.W.	0.235	0.193	0.042
	Note:	Part-full flow		
233	H.W.	1.591	0.889	0.702
	T.W.	0.493	0.193	0.300
	Note:	Part-full flow		
234	H.W.	1.591	0.889	0.702
	T.W.	0.511	0.193	0.318
	Note:	Part-full flow		
235	H.W.	1.286	0.889	0.397
	T.W.	0.540	0.193	0.347
	Note:	Jump at Station 7.5 Full flow to outlet		
236	H.W.	1.285	0.889	0.396
	T.W.	0.598	0.193	0.405
	Note:	Full flow Air pocket at Station 1		
237	H.W.	1.475	0.889	0.586
	T.W.	0.811	0.193	0.618
	Note:	Full flow		
238	H.W.	1.591	0.889	0.702
	T.W.	0.500	0.193	0.307
	Note:	Part-full flow		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET (Continued)

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
260	H.W.	2.629	0.747	1.882
	1	1.296	0.743	Full
	5	1.496	0.712	Full
	10	1.263	0.615	Full
	13	0.784	0.352	Full
	17	0.314	0.090	Full
	18	0.263	0.067	Full
	T.W.	No	0.045	-

Note: Full flow

Run No. 2-0
Discharge 0.467 cfs
Slope 0.02
Temperature 21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
2-0	H.W.	2.092	0.747	1.345
	1	1.303	0.743	0.560
	5	0.903	0.712	0.191
	10	0.834	0.615	0.219
	13	0.593	0.352	0.241
	17	0.362	0.090	0.272
	18	0.345	0.067	0.278
	T.W.	No	0.045	-

Note: Part-full flow

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
261	H.W.	2.764	0.747	2.017
	1	1.454	0.743	Full
	5	1.649	0.712	Full
	10	1.417	0.615	Full
	13	0.945	0.352	Full
	17	0.481	0.090	Full
	18	0.431	0.067	Full
	T.W.	0.425	0.045	0.380

Note: Full flow

Run No. 2-1
Discharge 0.487 cfs
Slope 0.02
Temperature 21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
2-1	H.W.	2.115	0.747	1.368
	T.W.	No	0.045	-

Note: Full flow

Run No. 2-2
Discharge 0.495 cfs
Slope 0.02
Temperature 21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
2-2	H.W.	1.877	0.747	1.130
	T.W.	No	0.045	-

Note: Full flow

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET (Continued)

Run Nos.	240-246
Discharge	0.4 cfs
Slope	0.02
Temperature	21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth	Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
240	H.W.	1.791	0.747	1.044	244	H.W.	1.496	0.747	0.749
	1	1.144	0.743	0.401		1	0.906	0.743	Full
	5	0.920	0.712	0.208		5	0.994	0.712	Full
	10	0.832	0.615	0.217		10	0.883	0.615	Full
	13	0.582	0.352	0.230		13	0.655	0.352	Full
	17	0.337	0.090	0.247		17	0.428	0.090	Full
	18	0.318	0.067	0.251		18	0.403	0.067	Full
	T.W.	No	0.045	-		T.W.	0.401	0.045	0.356
	Note:	Part-full flow				Note:	Full flow		
241	H.W.	1.789	0.747	1.042	245	H.W.	1.466	0.747	0.719
	10	0.832	0.615	0.217		T.W.	0.373	0.045	0.328
	17	0.336	0.090	0.246		Note:	Full flow		
	18	0.316	0.067	0.249					
	T.W.	0.366	0.045	0.321					
	Note:	Part-full flow							
242	H.W.	1.791	0.747	1.044	246	H.W.	1.352	0.747	0.605
	13	0.584	0.352	0.232		1	0.758	0.743	Full
	17	0.335	0.090	Full		5	0.852	0.712	Full
	18	0.316	0.067	Full		18	0.261	0.067	Full
	T.W.	0.381	0.045	0.336		T.W.	No	0.045	-
	Note:	Air Pressure = - 0.004', Station 13-18 Part-full flow				Note:	Full flow Tailwater was first raised to make culvert flow full and then lowered to give free outlet.		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos. 410-412
Discharge 0.1 cfs
Slope 0.04
Temperature 20° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
410	H.W.	1.613	1.343	0.270
	1	1.509	1.331	0.178
	5	1.404	1.278	0.126
	9	1.289	1.178	0.111
	10	1.182	1.076	0.106
	11	1.003	0.902	0.101
	12	0.826	0.726	0.100
	13	0.641	0.550	0.091
	14	0.472	0.376	0.096
	15	0.307	0.200	0.107
	17	0.115	0.025	0.090
	18	0.079	-0.019	0.098
	T.W.	No	-	-
	Note:	Part-full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
411	H.W.	1.613	1.343	0.270
	18	0.079	-0.019	0.098
	T.W.	0.126	-0.066	0.192
	Note:	Part-full flow		
412	H.W.	1.613	1.343	0.270
	18	0.079	-0.019	0.098
	T.W.	0.269	-0.066	0.335
	Note:	Part-full flow		

Run Nos. 420-422
Discharge 0.2 cfs
Slope 0.04
Temperature 20° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
420	H.W.	1.777	1.343	0.434
	1	1.590	1.331	0.259
	5	1.454	1.279	0.175
	9	1.341	1.178	0.163
	10	1.232	1.076	0.156
	11	1.050	0.902	0.148
	12	0.871	0.726	0.145
	13	0.681	0.550	0.131
	14	0.512	0.375	0.137
	15	0.352	0.199	0.153
	17	0.154	0.025	0.129
	18	0.120	-0.020	0.140
	T.W.	No	-	-
	Note:	Part-full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
421	H.W.	1.777	1.343	0.434
	18	0.120	-0.020	0.140
	T.W.	0.190	-0.065	0.255
	Note:	Part-full flow		
422	H.W.	1.705	1.343	0.362
	1	1.531	1.331	-
	5	1.397	1.279	-
	10	1.172	1.076	-
	13	0.623	0.550	-
	17	0.092	0.025	-
	18	0.278	-0.020	-
	T.W.	0.406	-0.065	0.341
	Note:	Air Pressure = -0.063', Station 5 to 17 Jump at Station 17 Full flow with entrained air to outlet		

Table II

EXPERIMENTAL OBSERVATIONS---SQUARE-EDGED INLET
(Continued)

Run Nos.	430-431
Discharge	0.3 cfs
Slope	0.04
Temperature	20° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
430	H.W.	2.027	1.343	0.684
	1	1.666	1.331	0.335
	5	1.476	1.278	0.198
	6	1.456	1.258	0.198
	9	1.374	1.177	0.197
	10	1.263	1.076	0.187
	11	1.087	0.902	0.185
	12	0.908	0.726	0.182
	13	0.721	0.551	0.170
	14	0.547	0.375	0.172
	15	0.367	0.199	0.168
	17	0.192	0.024	0.168
	18	0.152	-0.021	0.173
	T.W.	No	-0.065	-

Note: Part-full flow

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
431	H.W.	1.731	1.343	0.388
	1	1.374	1.331	0.325
	5	1.202	1.278	0.206
	10	0.986	1.076	0.192
	13	0.441	0.552	0.171
	18	0.215	-0.021	Full
	T.W.	0.296	-0.065	0.231

Note: Air Pressure = - 0.282', Station 10-13
Jump at Station 17
Full flow with entrained air to outlet

Table II

EXPERIMENTAL OBSERVATIONS---SQUARE-EDGED INLET
(Continued)

Run Nos.	860-863
Discharge	0.6 cfs
Slope	0.08
Temperature	21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
860	H.W.	4.961	2.839	2.122
	4	2.917	2.759	0.158
	9	2.692	2.533	0.159
	10	2.492	2.336	0.156
	11	2.153	1.979	0.174
	12	1.804	1.629	0.175
	13	1.452	1.277	0.175
	14	1.108	0.929	0.179
	15	0.749	0.574	0.175
	17	0.407	0.226	0.181
	18	0.333	0.139	0.194
	T.W.	No	0.030	-
	Note:	Part-full flow Air pressure = -0.04', Station 1 Air pressure = -0.025', Station 9		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
861	H.W.	4.983	2.839	2.144
	T.W.	No	0.030	-
	Note:	Full flow		
863	H.W.	3.284	2.839	0.445
	5	1.320	2.711	0.229
	10	1.330	2.336	Jump
	13	0.991	1.277	Full
	17	0.484	0.226	Full
	18	0.424	0.139	Full
	T.W.	0.365	0.030	0.335
	Note:	Hydraulic jump at Station 10 Air pressure = -1.62', Station 9 Mixed flow from jump to outlet		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	440-447
Discharge	0.4 cfs
Slope	0.04
Temperature	19° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
440	H.W.	2.389	1.343	1.046
	1	1.756	1.331	0.425
	5	1.481	1.278	0.203
	9	1.377	1.179	0.198
	10	1.280	1.075	0.205
	11	1.107	0.902	0.205
	12	0.932	0.726	0.206
	13	0.739	0.550	0.189
	14	0.575	0.376	0.199
	15	0.423	0.199	0.224
	17	0.214	0.025	0.189
	18	0.189	-0.020	0.209
	T.W.	No	-0.065	-
	Note:	Part-full flow		
441	H.W.	(2.389)	1.343	(1.046)
	18	0.187	-0.020	0.207
	T.W.	0.259	-0.065	0.324
	Note:	Part-full flow		
442	H.W.	(2.379)	1.343	(1.036)
	5	1.478	1.279	0.199
	10	1.275	1.076	0.199
	13	0.737	0.552	0.185
	17	0.209	0.024	0.185
	18	0.183	-0.020	0.203
	T.W.	0.270	-0.065	0.335
	Note:	Part-full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
443	H.W.	1.754	1.343	0.411
	1	0.844	1.331	0.166
	5	0.816	1.278	0.191
	10	0.635	1.075	0.213
	13	0.588	0.550	Full
	14	0.502	0.376	Full
	15	0.424	0.199	Full
	17	0.331	0.025	Full
	18	0.309	-0.020	Full
	T.W.	0.303	-0.065	0.365
	Note:	Air Pressure = - 0.653', Station 1-10 Jump at Station 11½ full with entrained air to outlet		
444	H.W.	1.753	1.343	0.410
	1	0.848	1.331	0.187
	5	0.817	1.278	0.209
	10	0.986	1.075	Full
	13	0.734	0.550	Full
	14	0.664	0.376	Full
	15	0.586	0.199	Full
	17	0.492	0.025	Full
	18	0.469	-0.020	Full
	T.W.	0.470	-0.065	0.535
	Note:	Air Pressure = - 0.670', Station 1-5 Jump at Station 7 full with entrained air to outlet		
445	H.W.	1.753	1.343	0.410
	T.W.	0.590	-0.065	0.655

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos. 440-447
Discharge 0.4 cfs
Slope 0.04
Temperature 19° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
446	H.W.	1.765	1.343	0.422
	1	1.095	1.331	Full
	5	1.230	1.278	Full
	10	1.122	1.075	Full
	13	0.883	0.550	Full
	17	0.647	0.025	Full
	18	0.628	-0.020	Full
	T.W.	0.606	-0.065	0.671
	Note:	Full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
447	H.W.	1.751	1.343	0.408
	14	0.432	0.376	Full
	15	0.341	0.199	Full
	17	0.258	0.025	Full
	18	0.233	-0.020	Full
	T.W.	No	-0.065	-
	Note:	Air Pressure = - 0.616', Station 1-9 Jump at Station 13 full with entrained air to outlet		

Run Nos. 450-455
Discharge 0.5 cfs
Slope 0.04
Temperature 21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
450	H.W.	2.917	1.343	1.574
	1	1.576	1.331	-
	5	1.474	1.278	0.196
	9	1.389	1.178	0.211
	10	1.280	1.075	0.205
	11	1.115	0.902	0.213
	12	0.948	0.726	0.222
	13	0.766	0.551	0.215
	14	0.599	0.375	0.224
	15	0.420	0.200	0.220
	17	0.250	0.024	0.226
	18	0.213	-0.021	0.234
	T.W.	No	-0.065	-
	Note:	Air Pressure = - 0.008', Station 1 Part-full flow		
451	H.W.	2.917	1.343	
	T.W.	0.298	-0.065	
	Note:	Full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
452	H.W.	2.002	1.343	0.659
	10	1.076	1.075	Full
	17	0.381	0.024	Full
	18	0.342	-0.021	Full
	T.W.	0.333	-0.065	0.398
	Note:	Full flow		
453	H.W.	1.851	1.343	0.508
	18	0.209	-0.021	Full
	T.W.	0.188	-0.065	0.253
	Note:	Full flow		
454	H.W.	1.804	1.343	0.461
	T.W.	0.078	-0.065	0.143
	Note:	Full flow		
455	H.W.	1.800	1.343	0.457
	T.W.	No	-0.065	-
	Note:	Full Flow		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	460-466
Discharge	0.6 cfs
Slope	0.04
Temperature	21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
460	H.W.	3.484	1.343	2.141
	2	1.611	1.304	0.307
	5	1.450	1.278	0.172
	9	1.380	1.178	0.202
	10	1.277	1.074	0.203
	11	1.121	0.902	0.219
	12	0.959	0.725	0.234
	13	0.779	0.551	0.228
	14	0.616	0.374	0.242
	15	0.439	0.199	0.240
	17	0.272	0.024	0.248
	18	0.236	-0.022	0.258
	T.W.	No	-0.065	-
	Note:	Part-full flow, pipe ventilated		
461	H.W.	2.538	1.343	1.195
	15	0.367	0.199	Full
	17	0.208	0.024	Full
	18	0.156	-0.022	Full
	T.W.	No	-0.065	-
	Note:	Full flow		
462	H.W.	2.538	1.343	1.195
	10	1.156	1.074	Full
	18	0.153	-0.022	Full
	T.W.	0.013	-0.065	0.078
	Note:	Full flow		
463	H.W.	2.545	1.343	1.202
	17	0.211	0.024	Full
	18	0.158	-0.022	Full
	T.W.	0.085	-0.065	0.150
	Note:	Full flow		
464	H.W.	2.576	1.343	1.233
	18	0.192	-0.022	Full
	T.W.	0.181	-0.065	0.246
	Note:	Full flow		
465	H.W.	2.645	1.343	1.302
	18	0.256	-0.022	Full
	T.W.	0.256	-0.065	0.321
	Note:	Full flow		
466	H.W.	2.735	1.343	1.392
	10	1.353	1.074	Full
	17	0.408	0.024	Full
	18	0.358	-0.022	Full
	T.W.	0.345	-0.065	0.410
	Note:	Full flow		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos. 40-64
Slope 0.04
Temperature 21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
40	Discharge 0.594 cfs			
	H.W.	3.423	1.343	2.080
	5	1.451	1.278	0.173
	9	1.389	1.177	0.212
	10	1.282	1.075	0.207
	11	1.123	0.901	0.222
	12	0.957	0.725	0.232
	T.W.	No	-	-
	Note:	Part-full flow, culvert ventilated		
41	Discharge 0.556 cfs			
	H.W.	3.202	1.343	1.859
	1	1.380	1.333	-
	5	1.463	1.278	0.185
	9	1.390	1.177	0.213
	10	1.285	1.075	0.210
	11	1.122	0.901	0.221
	12	0.954	0.725	0.229
	T.W.	No	-	-
	Note:	Part-full flow, culvert ventilated		
42	Discharge 0.50 cfs			
	H.W.	2.873	1.343	1.530
	1	1.713	1.333	0.380
	5	1.470	1.278	0.192
	9	1.391	1.177	0.214
	10	1.286	1.075	0.211
	11	1.117	0.901	0.216
	12	0.949	0.725	0.224
	T.W.	No	-	-
	Note:	Part-full flow, culvert ventilated		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
43	Discharge 0.451 cfs			
	H.W.	2.617	1.343	1.274
	1	1.913	1.333	0.580
	5	1.480	1.278	0.202
	9	1.389	1.177	0.212
	10	1.284	1.075	0.209
	11	1.114	0.901	0.213
	12	0.940	0.725	0.215
	T.W.	No	-	-
	Note:	Air pressure = -0.005', Station 1 Part-full flow No ventilation		
44	Discharge 0.40 cfs			
	H.W.	2.359	1.343	1.016
	1	1.739	1.333	0.406
	5	1.488	1.278	0.210
	9	1.384	1.177	0.207
	10	1.280	1.075	0.205
	11	1.107	0.901	0.206
	12	0.932	0.725	0.207
	T.W.	No	-	-
	Note:	Part-full flow		
45	Discharge 0.344 cfs			
	H.W.	2.168	1.343	0.825
	1	1.666	1.333	0.333
	5	1.485	1.278	0.207
	9	1.381	1.177	0.204
	10	1.273	1.074	0.199
	11	1.097	0.901	0.196
	12	0.919	0.725	0.194
	T.W.	No	-	-
	Note:	Part-full flow		

Note: In tests 40, 41, and 42 culvert was ventilated at numerous stations by removing caps over probe openings at crown of culvert. When not ventilated the pressure at Station 1 (Run 43) was -0.005 ft; culvert was part full for complete length.

Table II

EXPERIMENTAL OBSERVATIONS—SQUARE-EDGED INLET
(Continued)

Run Nos.	40-64
Slope	0.04
Temperature	21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
46	Discharge 0.30 cfs			
	H.W.	2.023	1.343	0.680
	1	1.637	1.333	0.304
	5	1.478	1.278	0.200
	9	1.374	1.177	0.197
	10	1.266	1.074	0.192
	11	1.086	0.901	0.185
	12	0.907	0.725	0.182
	T.W.	No	-	-
	Note:	Part-full flow		
47	Discharge 0.25 cfs			
	H.W.	1.883	1.343	0.540
	1	1.613	1.333	0.280
	5	1.472	1.278	0.194
	9	1.362	1.177	0.185
	10	1.251	1.074	0.177
	11	1.070	0.901	0.169
	12	0.890	0.725	0.165
	T.W.	No	-	-
	Note:	Part-full flow		
48	Discharge 0.193 cfs			
	H.W.	1.757	1.343	0.414
	1	1.585	1.333	0.252
	5	1.455	1.278	0.177
	9	1.339	1.117	0.222
	10	1.228	1.074	0.154
	11	1.046	0.901	0.145
	12	0.865	0.725	0.140
	T.W.	No	-	-
	Note:	Part-full flow		

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
49	Discharge 0.158 cfs			
	H.W.	1.692	1.343	0.349
	1	1.566	1.333	0.233
	5	1.440	1.278	0.162
	9	1.323	1.177	0.146
	10	1.211	1.074	0.137
	11	1.027	0.901	0.126
	12	0.848	0.725	0.123
	T.W.	No	-	-
	Note:	Part-full flow		
50	Discharge 0.12 cfs			
	H.W.	1.640	1.343	0.297
	1	1.532	1.333	0.199
	5	1.420	1.278	0.142
	9	1.303	1.177	0.126
	10	1.193	1.074	0.119
	11	1.012	0.901	0.111
	12	0.835	0.725	0.110
	T.W.	No	-	-
	Note:	Part-full flow		
51	Discharge 0.105 cfs			
	H.W.	1.620	1.343	0.277
	1	1.515	1.333	0.182
	5	1.410	1.278	0.132
	9	1.294	1.177	0.117
	10	1.184	1.074	0.110
	11	1.005	0.901	0.104
	12	0.826	0.724	0.102
	T.W.	No	-	-
	Note:	Part-full flow		

Table II

EXPERIMENTAL OBSERVATIONS--SQUARE-EDGED INLET
(Continued)

Run Nos.	40-64
Slope	0.04
Temperature	21° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
52	Discharge 0.90 cfs			
	H.W.	1.587	1.343	0.244
	1	1.490	1.333	0.157
	5	1.395	1.278	0.117
	9	1.282	1.177	0.105
	10	1.172	1.074	0.098
	11	0.995	0.901	0.094
	12	0.819	0.724	0.095
	T.W.	No		-
	Note:	Part-full flow		
53	Discharge 0.073 cfs			
	H.W.	1.549	1.343	0.206
	1	1.462	1.333	0.129
	5	1.378	1.278	0.100
	9	1.266	1.177	0.089
	10	1.161	1.074	0.087
	11	0.984	0.901	0.083
	12	0.807	0.724	0.083
	T.W.	No		-
	Note:	Part-full flow		
54	Discharge 0.045 cfs			
	H.W.	1.523	1.343	0.180
	1	1.442	1.333	0.109
	5	1.363	1.278	0.085
	9	1.255	1.177	0.078
	10	1.149	1.074	0.075
	11	0.974	0.901	0.073
	12	0.798	0.724	0.074
	T.W.	No		-
	Note:	Part-full flow		
58	Discharge 0.478 cfs			
	H.W.	2.756	1.343	1.413
	T.W.	No	-0.065	-
	Note:	Part-full flow		
59	H.W.	2.752	1.343	1.409
	T.W.	0.273	-0.065	0.338
	Note:	Part-full flow		
61	H.W.	2.712	1.343	1.369
	T.W.	0.290	-0.065	0.355
	Note:	Part-full flow		
62	H.W.	1.817	1.343	0.474
	T.W.	0.306	-0.065	0.371
	Note:	Full flow		
63	H.W.	1.772	1.343	0.429
	T.W.	0.252	-0.065	0.317
	Note:	Mixed flow		
64	H.W.	1.767	1.343	0.424
	T.W.	No	-0.065	-
	Note:	Mixed flow		

Table III

SUMMARY OF HEAD-DISCHARGE MEASUREMENTS—SQUARE-EDGED INLET

Run No.	Slope	Disch cfs	$\frac{Q}{D^{5/2}}$	Head Above Invert	T.W. Above Invert	$\frac{H}{D}$	$\frac{T}{D}$	Culv Air Pressure	Type of Flow	Dir of T.W.
011	0.00048	0.10	1.56	0.308	-	0.92	-	0	PF - Sub Cr	Up
012	0.00048	0.10	1.56	0.322	0.190	0.97	0.57	0	PF - Sub Cr	Up
013	0.00048	0.10	1.56	0.331	0.247	0.99	0.74	0	PF - Sub Cr	Up
014	0.00048	0.10	1.56	0.407	0.343	1.22	1.03	0	Full Flow	Up
015	0.00048	0.10	1.56	0.375	0.306	1.13	0.92	0	PF to 15	Down
016	0.00048	0.10	1.56	0.353	0.286	1.06	0.86	0	PF	Down
031	0.00048	0.298	4.66	0.680	-	2.04	-	0	PF - Super	Up
041	0.00051	0.40	6.25	1.282	-	3.86	-	0	Full - Free	Up
042	0.00051	0.40	6.25	1.436	0.369	4.31	1.11	0	Full - Sub	Up
111	0.01	0.10	1.56	0.274	-	0.82	-	0	PF - Super	Up
112				0.275	0.183	0.83	0.55		PF - Super	Up
113				0.275	0.336	0.83	1.01		PF - Super	Up
114				0.279	0.538	0.84	1.62		PF to 16.5	Up
115				0.361	0.626	1.09	1.88		Full Flow	Up
116				0.421	0.688	1.27	2.06		Full Flow	Up
117				0.323	0.584	0.97	1.75		PF - Full	Down
120	0.01	0.20	3.13	0.433	-	1.30	-	0	PF - Super	Up
121				0.434	0.253	1.30	0.76	0	PF - Super	Up
122				0.363	0.330	1.09	0.99	-0.065'	PF to 13	Up
123				0.364	0.372	1.09	1.12	-0.063'	PF to 11	Up
124				0.366	0.416	1.10	1.25	-0.063'	PF to 8	Up
125				0.364	0.420	1.09	1.26	-0.063'	PF to 5	Up
126				0.366	0.423	1.10	1.27	Var	PF to 1	Up
127				0.377	0.439	1.13	1.32	-0.125'	Full Flow	Up
128				0.395	0.456	1.19	1.37	0		Up
140	0.01	0.40	6.25	0.952	-	2.86	-	0	Full - Free	-
141				1.105	0.364	3.31	1.09		Full - Sub	Up
160	0.01	0.572	8.94	2.137	0.292	6.41	0.88	0	Full Flow	
161				2.040	-	6.13	-	0	Full Flow	Down
10	0.01	0.296	4.63	0.680	-	2.04	-	0	PF - Super	Up

Table III

SUMMARY OF HEAD-DISCHARGE MEASUREMENTS--SQUARE-EDGED INLET (Continued)

Run No.	Slope	Disch cfs	$\frac{Q}{D^{5/2}}$	Head Above Invert	T.W. Above Invert	$\frac{H}{D}$	$\frac{T}{D}$	Culv Air Pressure	Type of Flow	Dir of T.W.
210	0.02	0.10	1.56	0.267	-	0.80	-	0	PF - Free	Up
211				0.267	0.185	0.80	0.56		PF - Free	Up
212				0.267	0.334	0.80	1.00		PF to 16.5	Up
213				0.267	0.742	0.80	2.23		PF to 10.5	Up
220	0.02	0.20	3.13	0.431	-	1.30	-	0	PF - Super	Up
221				0.432	0.253	1.30	0.76		PF - Super	Up
222				0.366	0.349	1.10	1.05	-0.063'	PF to 17.3	Up
223				0.364	0.543	1.09	1.63	-0.064'	PF to 12.8	Up
224				0.365	0.755	1.10	2.27	-0.066'	PF to 3.5	Up
225				0.371	0.771	1.11	2.32	-0.086'	PF to 1.3	Up
226				0.387	0.786	1.16	2.36	0	Full Flow	Up
227				0.376	-	1.13	-	(-0.086')	PF to 1.3	Down
228				0.373	0.772	1.12	2.32	(-0.086')	PF to 1.3	Down
230	0.02	0.30	4.69	0.703	0.036	2.11	0.01	0	PF	
231				0.701	0.075	2.11	0.02		PF	
232				0.701	0.042	2.11	0.01		PF	
233				0.702	0.300	2.11	0.90		PF	
234				0.702	0.318	2.11	0.96		PF	
235				0.397	0.347	1.19	1.04	-0.267'	PF to 7.5	
236				0.396	0.405	1.19	1.22		PF to 2	
237				0.586	0.618	1.76	1.85		Full Flow	
238				0.702	0.307	2.11	0.92		PF	
240	0.02	0.40	6.25	1.044	-	3.14	-	0	PF - Super	Up
241				1.042	0.321	3.14	0.96		PF - Super	Up
242				1.044	0.336	3.14	1.01	-0.004'	PF - Super	Up
243				Changing	0.356	-	1.07	-0.200'	PF - Super	Up
244				0.749	0.356	2.24	1.07		Full Flow	Up
245				0.719	0.328	2.15	0.99		Full Flow	Down
246				0.605	-	1.82	-		Full Flow	Down
260	0.02	0.60	9.37	1.882	-	5.65	-	0	Full - Free	Up
261		0.593	9.26	2.017	0.380	6.05	1.14		Full - Sub	Up
2-0	0.02	0.465	7.27	1.345	-	4.04	-	0	PF	Up
2-1		0.487	7.61	Changing						
2-2		0.495	7.74	1.130	-	3.40	-		Full - Free	

Table III

SUMMARY OF HEAD-DISCHARGE MEASUREMENTS--SQUARE-EDGED INLET (Continued)

Run No.	Slope	Disch cfs	$\frac{Q}{D^{5/2}}$	Head Above Invert	T.W. Above Invert	$\frac{H}{D}$	$\frac{T}{D}$	Culv Air Pressure	Type of Flow	Dir of T.W.
410	0.04	0.10	1.56	0.270	-	0.81	-	0	PF - Super	
411				0.270	0.192	0.81	0.58		PF - Super	
412				0.270	0.335	0.81	1.01		PF - Super	
420	0.04	0.20	3.13	0.434	-	1.30	-	0	PF - Super	Up
421				0.434	0.255	1.30	0.78		PF - Super	Up
422				0.362	0.471	1.09	1.42	-0.063'	PF to 17.3	
430	0.04	0.30	4.69	0.684	-	2.06	-	0	PF - Super	
431				0.388	0.361	1.17	1.08	-0.282'	PF to 17.7	
440	0.04	0.40	6.25	1.046	-	3.14	-		PF - Super	Up
441				1.046	0.324	3.14	0.97		PF - Super	Up
442				1.046	0.335	3.14	1.01		PF - Super	Up
443				0.411	0.368	1.24	1.11	-0.653'	PF to 11.5	Up
444				0.410	0.535	1.23	1.61	-0.670'	PF to 7	Up
445				0.410	0.655	1.23	1.97		PF to 7	Up
446				0.422	0.671	1.27	2.02		Full Flow	Up
447				0.408	-	1.22	-	-0.617'		Down
450	0.04	0.50	7.81	1.574	-	4.73	-	-0.008'	PF - Super	Up
451				1.574	0.363	4.73	1.09			Up
452				0.659	0.398	1.98	1.20		Full Flow	Down
453				0.508	0.253	1.53	0.76		Full Flow	
454				0.461	0.145	1.39	0.44		Full Flow	
455				0.457	-	1.37	-		Full Flow	
460	0.04	0.60	9.37	2.141	-	6.44	-	0	PF - Super	Up
461				1.195	-	5.86	-		Full Flow	Up
462				1.195	0.078	5.86	0.23		Full Flow	Up
463				1.202	0.150	3.62	0.45		Full Flow	Up
464				1.233	0.246	3.70	0.74		Full Flow	Up
465				1.302	0.321	3.92	0.96		Full Flow	Up
466				1.392	0.410	4.18	1.23		Full Flow	Up

Table III

SUMMARY OF HEAD-DISCHARGE MEASUREMENTS—SQUARE-EDGED INLET
(Continued)

Run No.	Slope	Disch cfs	$\frac{Q}{D^{5/2}}$	Head Above Invert	T.W. Above Invert	$\frac{H}{D}$	$\frac{T}{D}$	Culv Air Pressure	Type of Flow	Dir of T.W.
40	0.04	0.595	9.30	2.080	-	6.25	-	0	PF - Super	
41		0.540	8.44	1.859	-	5.58	-		PF - Super	
42		0.500	7.82	1.530	-	4.60	-		PF - Super	
43		0.450	7.04	1.274	-	3.83	-		PF - Super	
44		0.400	6.25	1.016	-	3.05	-		PF - Super	
45		0.345	5.39	0.825	-	2.48			PF - Super	
46		0.300	4.69	0.680	-	2.04			PF - Super	
47		0.250	3.91	0.540	-	1.62			PF - Super	
48		0.190	2.97	0.414	-	1.24			PF - Super	
49		0.160	2.50	0.349	-	1.05			PF - Super	
50		0.120	1.88	0.297	-	0.89			PF - Super	
51		0.105	1.64	0.277	-	0.83			PF - Super	
52		0.090	1.41	0.244	-	0.73			PF - Super	
53		0.073	1.14	0.206	-	0.62			PF - Super	
54		0.045	0.70	0.180	-	0.54			PF - Super	
58	0.04	0.478	7.47	1.413	-	4.25	-	0	PF	Up
59				1.409	0.338	4.23	1.01	-0.007'	PF	Up
60				-	0.346	-	1.04	-0.013'	PF	Up
61				1.369	0.355	4.11	1.07	-0.018'	PF	Up
62				0.474	0.370	1.42	1.11	-0.039'	Full Flow	Up
63				0.429	0.317	1.29	0.95		Mixed	Down
64				0.424	-	1.27	-		Mixed	Down
860	0.08	0.60	9.37	2.122	-	6.38	-	-0.040	PF - Super	Up
861				2.144	-	6.45	-	0	Full Flow	
863				0.445	0.335	1.34	1.01		Mixed	

Table IV

EXPERIMENTAL MEASUREMENTS--ROUNDED INLET

Run Nos. 1-14
Slope 0.04
Temperature 17.5° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
Discharge 0.405 cfs				
1	H.W.	Max 1.945	1.443	0.502
		Min 1.864	1.443	0.421
	T.W.	No		-
	Note:	Alt. full and part full		
Discharge 0.503 cfs				
2	H.W.	1.872	1.443	0.429
	T.W.	No		-
	Note:	Air Pressure = -0.475' Alt. full and part full		
Discharge 0.540 cfs				
3	H.W.	1.946	1.443	0.503
	T.W.	No		-
	Note:	Air Pressure = -0.458' Full flow		
Discharge 0.603 cfs				
4	H.W.	2.285	1.443	0.842
	T.W.	No		-
	Note:	Air Pressure = -0.250' Full flow		
Discharge 0.326 cfs				
5	H.W.	Max 1.945	1.443	0.502
		Min 1.853	1.443	0.410
	T.W.	No		-
	Note:	Air Pressure - variable Alt. full and part full		
Discharge 0.260 cfs				
6	H.W.	1.890	1.443	0.447
	T.W.	No		-
	Note:	Alt. full and part full		
Discharge 0.168 cfs				
7	H.W.	1.785	1.443	0.342
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.105 cfs				
8	H.W.	1.709	1.443	0.266
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.085 cfs				
9	H.W.	1.677	1.443	0.234
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.050 cfs				
10	H.W.	1.645	1.443	0.202
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.113 cfs				
11	H.W.	1.717	1.443	0.274
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.139 cfs				
12	H.W.	1.752	1.443	0.309
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.212 cfs				
13	H.W.	1.828	1.443	0.385
	T.W.	No		-
	Note:	Part-full flow		
Discharge 0.246 cfs				
14	H.W.	1.873	1.443	0.430
	T.W.	No		-
	Note:	Part-full flow		

Table IV

EXPERIMENTAL MEASUREMENTS--ROUNDED INLET
(Continued)

Run Nos. 010-018
Discharge 0.10 cfs
Slope 0.00048
Temperature 17.5° C

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
010	H.W.	1.215	0.908	0.307
	1	1.185		
	9	1.177		
	10	1.172		
	11	1.163		
	12	1.153		
	13	1.144		
	14	1.132		
	15	1.115		
	17	1.095		
	18	1.085		
	T.W.	No	0.891	-
	Note:	Part-full flow		
011	H.W.	1.212	0.908	0.304
	18	1.086		
	T.W.	0	0.891	-
	Note:	Part-full flow		
012	H.W.	1.212	0.908	0.304
	18	1.087		
	T.W.	0.945	0.891	0.054
	Note:	Part-full flow		
013	H.W.	1.212	0.908	0.304
	18	1.087		
	T.W.	1.020	0.891	0.129
	Note:	Part-full flow		
014	H.W.	1.212	0.908	0.304
	18	1.090		
	T.W.	1.050	0.891	0.159
	Note:	Part-full flow		
015	H.W.	1.228	0.908	0.320
	18	1.142		
	T.W.	1.138	0.891	0.247
	Note:	Part-full flow		
016	H.W.	1.264	0.908	0.356
	18	1.187		
	T.W.	1.187	0.891	0.296
	Note:	Full to Station 12 Part-full flow to outlet		
017	H.W.	1.508	0.908	0.600
	18	1.433		
	T.W.	1.433	0.891	0.542
	Note:	Full flow		
018	H.W.	1.209	0.908	0.301
	18	1.085		
	T.W.	1.010	0.891	0.209
	Note:	Part-full flow		

Run No. 010A
Discharge 0.12 cfs
Slope 0.00048

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
010A	H.W.	1.260	0.908	0.352
	1	1.223		
	9	1.213		
	10	1.205		
	11	1.195		
	12	1.182		
	13	1.171		
010A (Cont)	14	1.157		
	15	1.140		
	17	1.120		
	18	1.111		
	T.W.	-	0.891	
	Note:	Part-full flow		

Table IV

EXPERIMENTAL MEASUREMENTS--ROUNDED INLET (Continued)

Run Nos.	440-445
Discharge	0.40 cfs
Slope	0.04
Temperature	17.5° C
Air Pressure	Variable

Run No.	Station	Elev Hydr Grade Line	Elev Invert	Depth
440	H.W.	Max 1.945	1.443	0.502
		Min 1.865		0.422
	T.W.	No		-
441	H.W.	Max 1.940	1.443	0.497
		Min 1.865		0.422
	T.W.	0.275		
	Note:	Oscillating part-full and full flow Both part-full and full start from upstream end		
442	H.W.	Max 1.955	1.443	0.512
		Min 1.865		0.422
	T.W.	Max 0.270		
		Min 0.305		
	Note:	T.W. oscillates due to varying discharge		
443	H.W.	Max 1.868	1.443	0.425
		Min 1.865		0.422
	T.W.	Max 0.393		
		Min 0.400		
	Note:	Mixed flow Slugs of air 5'-20' length T.W. seals culvert most of the time		
444	H.W.	Max 1.868	1.443	0.425
		Min 1.865		0.422
	T.W.	0.453		
	Note:	Slug flow much steadier than preceding run		
445	H.W.	Max 1.868	1.443	0.425
		Min 1.865		0.422
	T.W.	0.602		
	Note:	Slug flow Jumps form at several points in pipe and are washed out		

Table V

SUMMARY OF HEAD-DISCHARGE DATA--ROUNDED INLET

Run No.	Slope	Disch cfs	$\frac{Q}{D^{5/2}}$	Head Above Invert Max	Head Above Invert Min	$\frac{H}{D}$ Max	$\frac{H}{D}$ Min	Culvert Air Pressure	Type of Flow	Direction of T.W.
1	0.04	0.405	6.31	0.502	0.421	1.51	1.26	0	Alt. Flow	Free outlet
2		0.503	7.85		0.429		1.29	-0.475'	Alt. Flow	Free outlet
3		0.540	8.42	0.503		1.51		-0.458'	Full Flow	Free outlet
4		0.603	9.40	0.842		2.53		-0.250'	Full Flow	Free outlet
5		0.326	5.09	0.502	0.410	1.51	1.23	-0.375'	Alt. Flow	Free outlet
6		0.260	4.06	0.447		1.34		0	Alt. Flow	Free outlet
7		0.168	2.62	0.342		1.03			Part-full	Free outlet
8		0.105	1.64	0.266		0.80			Part-full	Free outlet
9		0.085	1.33	0.234		0.70			Part-full	Free outlet
10		0.050	0.78	0.202		0.61			Part-full	Free outlet
11		0.113	1.76	0.274		0.82			Part-full	Free outlet
12		0.139	2.17	0.309		0.93			Part-full	Free outlet
13		0.212	3.31	0.385		1.15			Part-full	Free outlet
14		0.246	3.84	0.430		1.29			Part-full	Free outlet
				Head	T.W.	H/D	T/D			
010	0.00048	0.10	1.56	0.307	-	0.92	-	0	Part-full	Up
011				0.304	-	0.91	-		Part-full	Up
012				0.304	0.054	0.91	0.16		Part-full	Up
013				0.304	0.129	0.91	0.39		Part-full	Up
014				0.304	0.159	0.91	0.48		Part-full	Up
015				0.320	0.247	0.96	0.74		Part-full	Up
016				0.356	0.296	1.07	0.89		Full to 12	Up
017				0.600	0.542	1.80	1.63		Full flow	Up
018				0.301	0.209	0.90	0.63			Down
				Max	Min	Max	Min			
440	0.04	0.40	6.25	0.502	0.422	1.51	1.27	-0.350'		
441				0.497	0.422	1.49	1.27	-0.466'		
442				0.512	0.422	1.54	1.27	0		
443				0.425	0.422	1.28	1.27	-0.292'		
444				0.425	0.422	1.28	1.27	-0.266'		
445				0.425	0.422	1.28	1.27	-0.250'		