UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, Director

Technical Paper No. 13, Series B

Importance of Inlet Design on Culvert Capacity

Limited Distribution Preprint of Paper Presented Before
32nd Annual Meeting, Highway Research Board in Washington, D.C., January 16, 1953

by

LORENZ G. STRAUB,
ALVIN G. ANDERSON,
and
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January, 1953
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ABSTRACT

The design of a culvert inlet has a significant bearing upon the relationship of the head to the discharge of a culvert. Its relative importance hinges upon the type of flow occurring in the culvert, which in turn is governed by the location of the control section. For part-full flow the control may be either at the inlet or the outlet depending on whether the slope is hydraulically steep or mild. In the case of short culverts, control may be at the inlet even for horizontal or mild slopes. For full flow, barrel friction provides the control.

The head-discharge curves of culverts having square-edge inlets have been compared with those for culverts having rounded inlets to illustrate the conditions for which a head-advantage may be obtained by using a rounded inlet. These comparisons have been made for three categories of culvert flow: long culverts on steep slopes, long culverts on mild slopes, and short culverts. Dimensionless head-discharge curves have been plotted for culvert flow in each category. For culverts on steep slopes, experimental data have been compared with the computed values and, since the agreement was reasonably good, serve as a basis for the analysis of flow in culverts operating under conditions other than those for which the tests were made.

The greatest head-advantage for a particular discharge of the rounded inlet over that of a square-edge inlet was found for those cases in which the control section was located at the inlet. These were long culverts on steep slopes or short culverts where the length was negligible. For long culverts on mild slopes, the head-advantage was far less pronounced.

CONTENTS

Page

LIST OF ILLUSTRATIONS

IMPORTANCE OF INLET DESIGN
ON CULVERT CAPACITY

I. INTRODUCTION

From a practical point of view, probably the most serious deficiency in the planning of simple culverts used in highways is in the culvert inlet. All too frequently the culvert is assumed to have much greater capacity than, in fact, it has; this reduction in capacity is frequently attributable to inadequacy of the culvert inlet.

Quite generally, the deficiencies of the inlet are thought of only in terms of their effect upon the head loss; in reality this effect is of relatively minor importance in differentiating between good inlets and the poorest inlets customarily used. The important consideration is the overall hydraulics of the culvert in conveying run-off from one side of an embankment to the other, without impairing the roadway by overflow during high rates of run-off. (Supplementing this paper are moving pictures demonstrating qualitatively and quantitatively the pertinent conditions involved.)

In general, the objective in designing a culvert is to provide a structure which will, under the conditions imposed, discharge a given flow with the least head; if the head and discharge are specified, the objective is to provide the most economical culvert which, normally, is one with the least cross-sectional area.

The factors which combine to determine the character of flow in a culvert include all the design variables: slope, size, shape, length, and roughness of the culvert, the headwater and tailwater elevations, and inlet and outlet geometry. A convenient hydraulic classification of culverts is based on the location of the culvert control which is, in turn, determined by the relative magnitudes of the design variables. The principal flow characteristics are determined by location of the culvert control either at the inlet, the outlet, or in the barrel because of friction.

When the culvert inlet serves as a control section, the relationship between head and discharge is independent of the characteristics of the barrel or outlet and depends only upon the geometry of the inlet. For culverts on a mild slope, flowing partly full, the control is at the outlet and the head-discharge relationship depends upon the characteristics of the barrel as well as the geometry of the inlet. When the culvert flows full, unless it is very short, the barrel friction provides the control and the head-discharge curve is dependent upon all of the design variables.

The importance of inlet design as related to culvert capacity hinges to a large extent upon the position of the control section. For inlet control, the geometry of the inlet has a very significant influence upon the head required for a given discharge. A square-edge 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 for flow. As a result of the availability of additional head in the culvert, the required water surface elevation in the headwater pool is reduced--frequently very significantly reduced. When the control is at the outlet or when barrel friction acts as the control, the geometry of the inlet becomes far less significant.

A comprehensive discussion of culvert entrances would necessarily be rather lengthy because of the many types involved. For example, the culvert may have a rounded, beveled, square, or bell-mouthed inlet. It may be in a defined or an undefined channel. It may be installed with the inlet flush or protruding (reentrant) through a vertical or sloping headwall. Wing walls or warped transitions may be utilized. In most instances these variations will have a bearing on the culvert capacity. The square-edge inlet and the rounded inlet represent, in a sense, two extremes of inlet geometry. It appears that culverts constructed of commercial concrete or corrugated pipe would possess inlets that fall somewhere between the two limits. The curves presented in this paper represent (for the case of a flush headwall) these two extremes of head-discharge curves, with the curves for other types falling between.

Experimental and analytical investigations have for several years been undertaken at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, for the purpose of studying specific hydraulic characteristics on both full-scale culverts of various roughnesses* and dimensions (up to 3 ft in diameter) and on smaller scale models. Tests with specific regard to entrance

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*Lorenz G. Straub and Henry M. Morris, Hydraulic Data Comparison of Concrete and Corrugated Metal Culvert Pipes (Paper No. 3), Hydraulic Tests on Concrete Culvert Pipes (Paper No. 4), and Hydraulic Tests on Corrugated Metal Culvert Pipes (Paper No. 5), University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Papers, Series B, July, 1950.

conditions of culverts were conducted under the sponsorship of the Minnesota State Highway Department and the United States Bureau of Public Roads.[*] These have been supplemented by student thesis research. It is this experimental research on inlet conditions that forms the basis of the present paper.[**]

General Description of Tests

The experimental investigation was conducted in an apparatus constructed primarily for studies of this type. It consists of a channel 12 in. deep, 30 in. wide, and 50 ft long in which culvert models of various sizes can be installed. The upstream 10-ft section is separated from the remainder of the channel by a transverse bulkhead which normally forms the headwall of the culvert. This section has walls 28 in. high, as compared with 12 inches in the remainder of the channel, to permit variation of the head pool elevation. A second bulkhead is installed in the channel at the outlet end of the culvert model. The slope of the complete unit can be varied from 0 to 10 per cent. Figures 1 and 2 illustrate the basic equipment. The model used in the studies was constructed of 4-in. diameter Lucite pipe and had an overall length of 35 ft. The ends of the pipe were flush with the bulkheads which formed the end walls of the culvert. The inlet section was removable so that square and rounded inlets could be interchanged. Piezometers were located at frequent intervals along the culvert for pressure measurements.

The rounded inlet used in these tests had a radius of rounding equal to 15 per cent of the pipe diameter.

In an earlier series of tests, the culvert was tested with both the inlet and outlet submerged in order to obtain data on frictional losses and entrance loss coefficients for full flow. However, in the series of tests here concerned the outlet was completely free.

Data were obtained on the height of the head pool above the inlet invert for variations in inlet type, discharge, and culvert slope. When the culvert flowed full for at least a portion of the length, such as sometimes occurred when using a rounded inlet, data on the hydraulic gradient and the magnitude of pressure fluctuations were obtained.

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[*] Unpublished except for project reports.

[**] There will also be issued for limited distribution through the sponsor a project report of the St. Anthony Falls Laboratory giving the results of the culvert inlet experiments in more detail.

II. CULVERTS WITH FREE OUTLETS

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 diameter or height of the culvert. In full flow, the culvert behaves as a closed conduit or pipe. The pressure gradient then no longer necessarily coincides with the water surface. When a straight culvert flows full, the headwater level is of course above the crown of the culvert; however, the culvert does not necessarily flow full when the headwater is above the crown, even though this height may be several times the diameter of the culvert. The complete range of hydraulic relationships between discharge and head on the culvert includes both part-full and full flow conditions, and the different types of flow follow different algebraic relationships. These relationships can now be quite adequately defined.

For part-full flow, the total energy per unit weight of water referred to the culvert invert is called the specific energy H_o and may be written as

$$H_o = \frac{\alpha v^2}{2g} + d \tag{1}$$

where v is the mean velocity,

d is the depth,

g is the acceleration due to gravity, and

α is a kinetic energy correction factor the numerical value of which depends upon the velocity distribution over the cross section. (For uniform velocity distribution, α is unity.)

The minimum value of the specific energy corresponds to the critical flow conditions, for which it can be shown analytically

$$\frac{Q^2}{g} = \frac{A^3}{\alpha b} \tag{2}$$

where Q is the discharge,

A is the cross-sectional area of the flow, and

b is the surface width.

In order to eliminate Q, if Eq. (2) is combined with the Manning formula $\left[Q = (1.486/n)\, AR^{2/3}\, S_c^{\ 1/2}\right]$ an expression results for the critical slope and may be written as

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

In this equation S_c is the critical slope of the culvert, D is the culvert diameter, n is the Manning roughness coefficient, A and A_o are respectively the cross-sectional areas of the flow stream and the entire culvert, and R and R_o are respectively the hydraulic radii of the flow stream and the culvert section. In Fig. 3, $S_c/(n^2/D^{1/3})$ has been plotted as a function of d/D. For very small depths and for depths approaching the magnitude of the culvert diameter, the critical slope becomes quite large, but over the wide intermediate normal range of part-full flow conditions through the culvert the critical slope varies within narrower limits. If the slope is greater than S_c [Eq. (3)], the flow in the culvert will be supercritical and the depth less than critical. If the slope is less than S_c, the flow will be subcritical and the depth greater than critical.

III. CULVERTS WITH FREE OUTLETS ON STEEP SLOPES

In the case of culverts with steep slopes [that is, $S > S_c$ (Fig. 3)] the transition from subcritical flow in the approach channel to the supercritical flow in the culvert takes place at the culvert inlet (Figs. 4a and 5a) and corresponds to the condition under which Eq. (2) applies. If we assume that the energy loss from the head pool to the critical section is negligible, we may write

$$\frac{H}{D} = \frac{\alpha V_c^{\ 2}}{2gD} + \frac{d}{D} \tag{4}$$

where from Eq. (2) $$\frac{\alpha V_c^{\ 2}}{2gD} = \frac{A}{2bD} = \frac{\pi}{8} \frac{(A/A_o)}{(b/D)}$$

For a square-edge inlet (Fig. 4a), α is dependent upon the degree of contraction of the flow around the square edge and may be written as

$$\alpha = \frac{1}{C_c} \tag{5}$$

For a fully rounded inlet where no separation of the flow occurs, it will be found that $\alpha = 1.0$; that is, the velocity is uniform over the pipe cross section just inside the entrance.

The head-discharge curves for part-full flow for rounded and square-edge inlets are shown in Fig. 6. The curves agree well with the experimental data for values of H/D up to about 1.2 where H is the head above the invert.

As the discharge increases, the headwater elevation eventually becomes higher than the culvert crown and the flow will normally be in contact with the wall entirely around the periphery of the entrance. If the culvert has a square-edge inlet, separation at the corner will cause a contraction of the jet (Fig. 4b). If in addition the culvert is on a steep slope, the depth in the culvert will be less than at the inlet and the culvert will not flow full. Hence, the inlet operates in the same manner as an orifice. The equation for the discharge through an orifice under low heads may be written as

$$\frac{Q}{D^{5/2}} = C_c \frac{\pi}{4} \sqrt{2g} \left(\frac{H}{D} - \frac{1}{2}\right)^{1/2} \left[1 - \frac{1}{128(H/D - 1/2)^2}\right] \tag{6}$$

The term in brackets represents the effect of head on the velocity distribution in the orifice, particularly for low heads, and may be considered as a coefficient of velocity such that

$$C_v = \left[1 - \frac{1}{128(H/D - 1/2)^2}\right] \tag{7}$$

which value rapidly approaches unity with increase in head. The coefficient of contraction also varies somewhat with the head and may be approximated by a consideration of the geometry of the inlet and the head pool. The computed head-discharge curve for the square-edge inlet for values of $H/D > 1.4$ when the inlet acts as an orifice is shown in Fig. 6 as a continuation of the curve for part-full flow at the inlet.

On the other hand, when the inlet is well rounded, separation at the inlet does not occur (Fig. 5b); consequently, the culvert begins immediately 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 toward the outlet, an added head due to the slope of the culvert becomes effective. This added head tends to increase the discharge in the culvert above that of the inflow to the approach channel. The increased discharge causes a lowering of the water surface just upstream of the inlet. When the water surface approaches the culvert crown, air is sucked into the culvert and increases the pressure to atmospheric. This breaks the seal and with the loss of the added velocity 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 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 phenomena ceases and the culvert flows full continuously. When the culvert is flowing full, the head-discharge relationship may be determined by the application of Bernoulli's theorem to the flow so that

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

where L is the length of culvert,

θ is the angle of inclination of the culvert from the horizontal so that $S = \sin\theta$,

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. (8) indicates that for full flow the head-discharge curve depends upon slope, length, and roughness of the culvert as well as the entrance loss; therefore the dimensionless curve will be different for each culvert as well as for each slope. In these computations the factors corresponding to the experiments were used in order that a comparison with the experimental results might be made. Here $L/D = 105$, $K_e = 0.08$, and the value of f as a function of Reynolds number, were obtained from previous experiments on the same culvert. In Fig. 6 a comparison may be made of the effect on the head-discharge curve of rounding the inlet corners. It is apparent that for headwater elevation above the crown of the culvert, a very pronounced advantage in the head which is required to pass a given discharge, accrues to the culvert with the rounded inlet. In the region where the flow passes through critical at the inlet (that is, $H/D < 1.5$), the head-advantage in a rounded inlet is less pronounced.

Example of Culvert Flow on Steep Slopes

In order to illustrate the foregoing principles, assume that a prefabricated concrete culvert 3 ft in diameter and 300 ft long is to be laid on a 4 per cent slope to discharge 140 cfs. Assume further that the outlet is free and that a headwall at the entrance provides a flush inlet. For the concrete pipe the following factors apply:

$$\frac{L}{D} = 100 \qquad \frac{Q}{D^{5/2}} = 9.0$$

$$n \text{ (partly full flow)}^{*} = 0.010$$

$$f \text{ (full flow)}^{*} = 0.015 \quad (n = 0.011 \text{ approximately})$$

The factor $$\frac{S}{n^2/D^{1/3}} = \frac{0.04}{(0.010)^2/(3.0)^{1/3}} = 578$$

is considerably greater than the values given in Fig. 3 for the critical slope throughout the greater portion of the depth. Consequently, the culvert lies on a steep slope. If it is assumed that a square-edge inlet has been provided, the head required for a discharge of 140 cfs can be obtained directly from Fig. 6 since the head-discharge curve for culverts on steep slopes with square-edge inlets is independent of the characteristics of the barrel. From the figure it appears that for

$$\frac{Q}{D^{5/2}} = 9.0, \ \frac{H}{D} = 5.80$$

Consequently, to discharge 140 cfs through the culvert will require a head of 17.4 ft above the invert or 14.4 ft over the culvert crown.

If the inlet were rounded so that no separation at the inlet occurred, the culvert would flow full when the upstream water surface became high enough to seal the entrance. If it is assumed that for a discharge of 140 cfs the

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*See also reference on page 2.

culvert will flow full, Eq. (8) will describe the flow or, in addition to the factors given above, we have

$$\frac{L}{D}\sin\theta = 100 \times .04 = 4.0$$

$$K_e = 0.08$$

Then

$$\frac{H}{D} - \frac{1}{2} + 4.0 = .0252\ (1 + 0.08 + 1.50)\ 9^2$$

$$\frac{H}{D} = 1.77$$

Since H/D as computed is greater than 1.5, the assumption that the culvert flows full for the prescribed discharge is satisfied. For a rounded inlet then the head required to discharge 140 cfs is 5.3 ft above the invert or only 2.3 ft above the crown of the culvert as compared to 14.4 ft above the crown if the inlet had been square-edged. The difference is attributable entirely to the entrance condition.

IV. CULVERTS WITH FREE OUTLETS AND HORIZONTAL OR MILD SLOPES

When the culvert is horizontal, or at least the slope is less than S_c as defined by Eq. (3), the flow in the culvert at depths less than D must be subcritical and the control section moves to the outlet end of the culvert. For larger discharges the culvert will flow full and the control is exercised by barrel friction. For those discharges where the culvert flows partly full, the water surface assumes the profile of a drawdown curve passing through critical depth at the outlet and acquiring a relative depth at the inlet end of the culvert that depends on the slope, length, and roughness of the culvert (Figs. 4c and 5c). This relative depth is independent of the geometry of the inlet, and hence is the same whether the inlet is square-edged or rounded. If Bernoulli's equation is written between a point upstream of the inlet and a point within the culvert just downstream of the inlet, there is obtained for the head upstream the expression

$$\frac{H}{D} = \frac{d}{D} + \frac{8}{\pi^2 \cdot g}\ (1 + K_e)\left(\frac{Q}{D^{5/2}}\right)^2 \qquad (9)$$

where H/D is the relative head acting on the culvert and d/D is the relative depth within the inlet. Equation (9) applies both to the square-edge and rounded inlets; the difference is in the magnitude of the entrance loss coefficient K_e. [Experiments on the 4-in. Lucite culvert indicated that for the square-edge inlet $K_e = 0.43$ and for a well rounded inlet $(r/D = 0.15)$ $K_e = 0.08$. Experiments on full-scale prefabricated concrete culverts* with bell-mouthed inlets showed that for reentrant inlets $K_e = 0.15$, and for flush inlets $K_e = 0.10$. For culverts fabricated from corrugated metal pipes, the corresponding entrance losses* were as follows: projecting (reentrant) inlet $K_e = 0.85$, flush inlet $K_e = 0.50$.] For larger relative discharges, a point will be reached when the culvert will flow full throughout its length (Figs. 4d and 5d). When this occurs, Eq. (8) applies to this case of the mild slope as well as to culverts on steep slopes. Here again the difference in head for a given discharge through a particular culvert will depend on the magnitude of K_e corresponding to whether the inlet is square-edged or rounded. The same factors applicable to part-full flow may also be applied to full flow. The head-discharge curves for culverts on a zero slope may be compared in Fig. 7 to show the effect of inlet rounding on the required head.

Example of Flow in Horizontal Culvert (Zero Slope)

If it is assumed that the culvert described in the previous example had been laid horizontally rather than on a 4 per cent slope, the influence of inlet geometry on the flow in culverts on mild slopes may be illustrated. Again the factors which apply, assuming a square-edge or rounded inlet are as follows:

$\frac{L}{D} = 100$ $\qquad$ K_e (square-edge) $= 0.43$

$\frac{Q}{D^{5/2}} = 9.0$ $\qquad$ K_e (rounded) $= 0.08$

$\sin\theta = 0$ $\qquad$ $f = 0.015$ (or about 0.010 for Manning "n")

If it is assumed as before that the culvert flows full, then

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

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*See reference on page 2.

For the square-edge inlet

$$\frac{H}{D} = .0252\ (1 + 0.43 + 1.50)\ 9^2 + 0.50 - 0 = 6.47$$

$$H = 6.47 \times 3.0 = 19.41 \text{ ft above invert}$$

For the rounded inlet

$$\frac{H}{D} = .0252\ (1 + 0.8 + 1.50)\ 9^2 + 0.50 = 5.77$$

or $$H = 5.77 \times 3.0 = 17.31 \text{ ft above invert}$$

The computed value of H/D indicates that the assumption that the culvert flows full is valid.

In this case the advantage of using a rounded inlet is approximately 2.1 ft of head.

V. SHORT CULVERTS

When a culvert is short, the flow characteristics become relatively independent of the slope, and the factors that involve the length become comparatively unimportant. Consequently, the control section is essentially at the inlet for all conditions. Therefore the head-discharge relationship for part-full flow should be much the same as for culverts on a steep slope in the case of both the square-edge and rounded inlets. The head-discharge curve for the square-edge inlet when the headwater elevation is above the top of the pipe should also be much the same as that for a similar culvert on a steep slope. In the case of the short culvert with the rounded inlet flowing full, Eq. (8) with $L \rightarrow 0$ becoming very small would describe the flow, the magnitude of $L/D \sin\theta$ and $f(L/D)$ both being negligible. Between the part-full phase and the full-flow phase there exists a transition zone of pulsating flow in which the culvert is alternately full and partly full.

The head-discharge curves for short culverts of any slope have been computed on the above basis and plotted in Fig. 8 for comparison. In these computations it was assumed that L could be considered equal to zero, and the entrance loss coefficient K_e for the rounded inlet, as before, was assumed equal to 0.08.

It is apparent from the plot that a considerable advantage in head is gained for the larger discharges by the simple expedient of rounding the inlet to reduce the degree of contraction of the jet.

Example of Flow in Short Culverts

If the culvert previously described is again modified by reducing its length to a negligible amount, the slope of the culvert will also become unimportant. Then, using the same discharge as before $(Q/D^{5/2} = 9.0)$, we may take the value of H/D directly from the curve for the square-edge inlet in Fig. 8, since H/D is a function of inlet geometry only. Therefore

$$\frac{H}{D} = 5.80$$

or $$H = 5.80D = 17.4 \text{ ft above the invert}$$

On the other hand, if the inlet is rounded, the value of H/D may also be taken from Fig. 8 since in this case too the head-discharge relationship depends only on the inlet geometry. Here

$$\frac{H}{D} = 2.55$$

and $$H = 2.55D = 7.65 \text{ ft above the invert}$$

In this case the advantage in head of the rounded inlet over the square-edge inlet amounts to 9.75 ft, a quite significant amount.

ACKNOWLEDGMENT

The experiments described here and used in the discussion of the influence of inlet geometry on the capacity of culverts were performed at the St. Anthony Falls Hydraulic Laboratory under the general supervision of Lorenz G. Straub, director. The project leader of those under the sponsorship of the Minnesota State Highway Department and the U. S. Public Roads Administration was Henry M. Morris who did a considerable part of the analysis. As part of a thesis project Madhav Manohar performed a rather extensive series of experiments to study the flow in culverts on steep slopes using both a square-edge and a rounded inlet. His experiments covered the range of orifice flow through the square-edge inlet, and the slug-flow and mixed-flow phases for rounded inlets, and supplement earlier tests.

APPENDIX

Figures 1 to 8

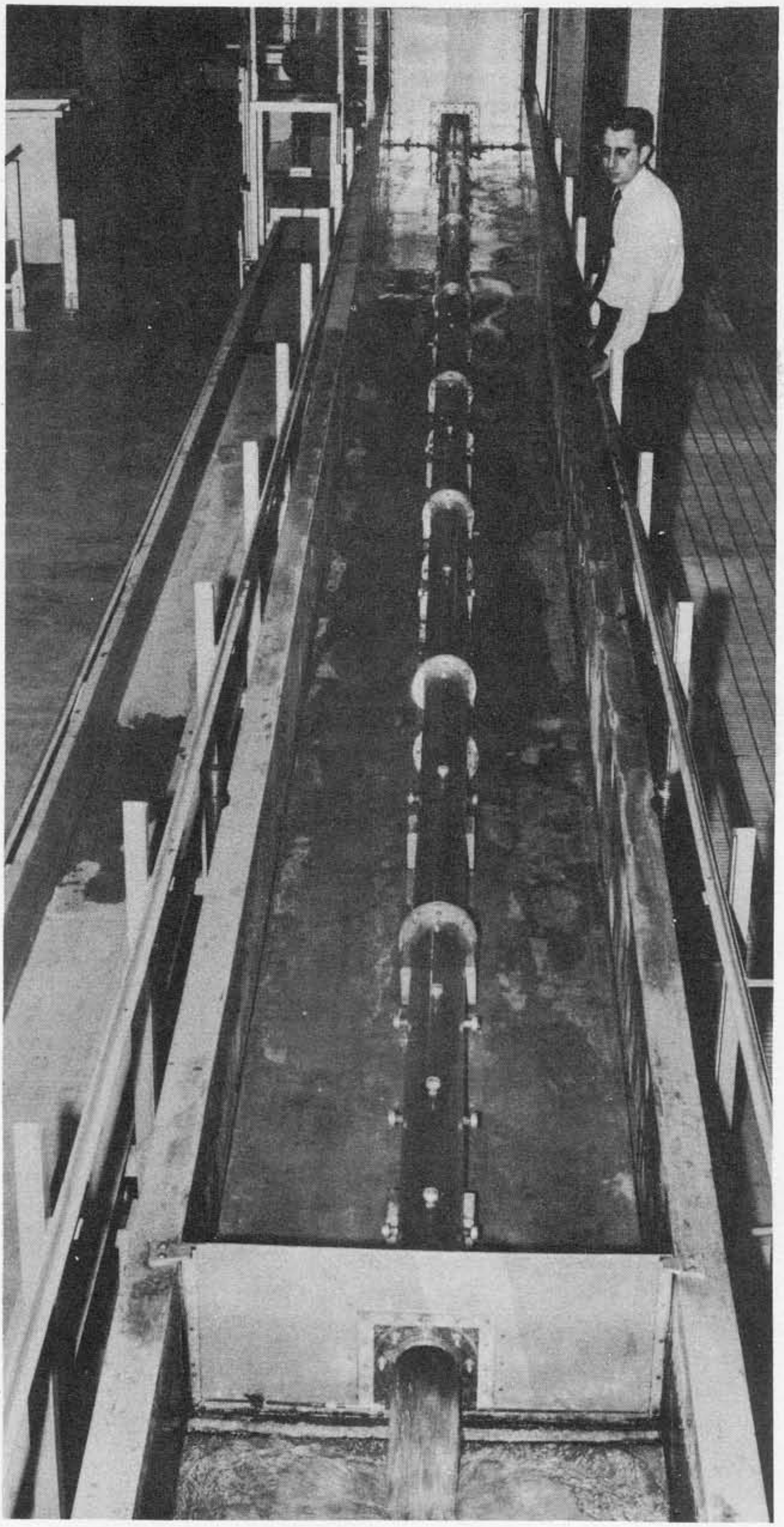
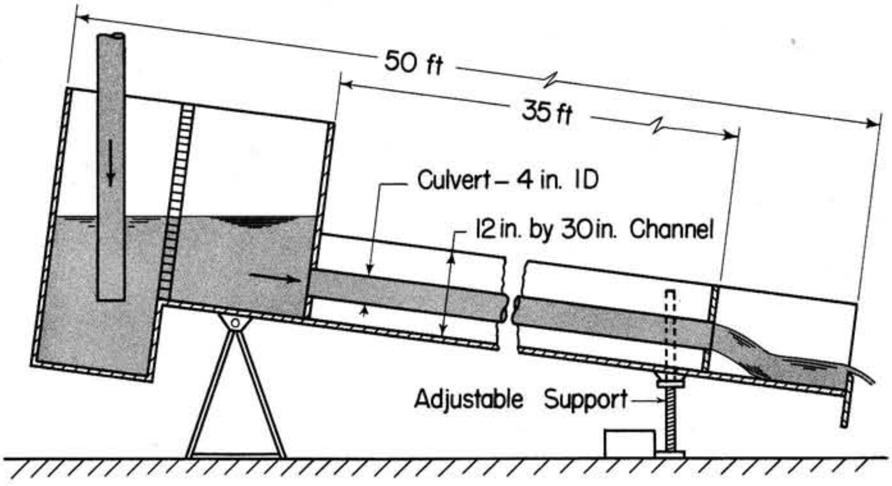
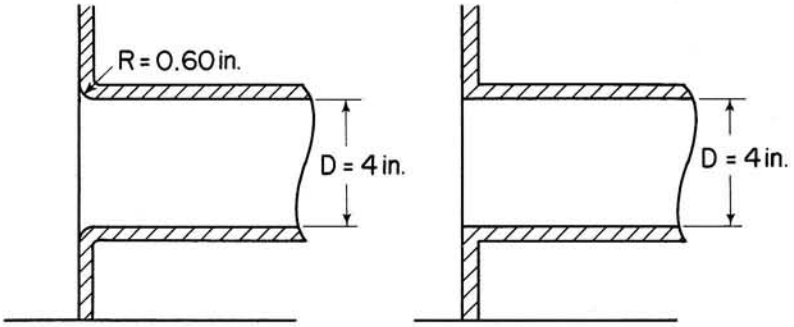


Fig. 1- Variable-Slope Culvert Model



Sketch of Test Set-Up



Rounded Inlet

Square-Edge Inlet

Fig. 2 — Equipment and Inlets Used in Model Tests

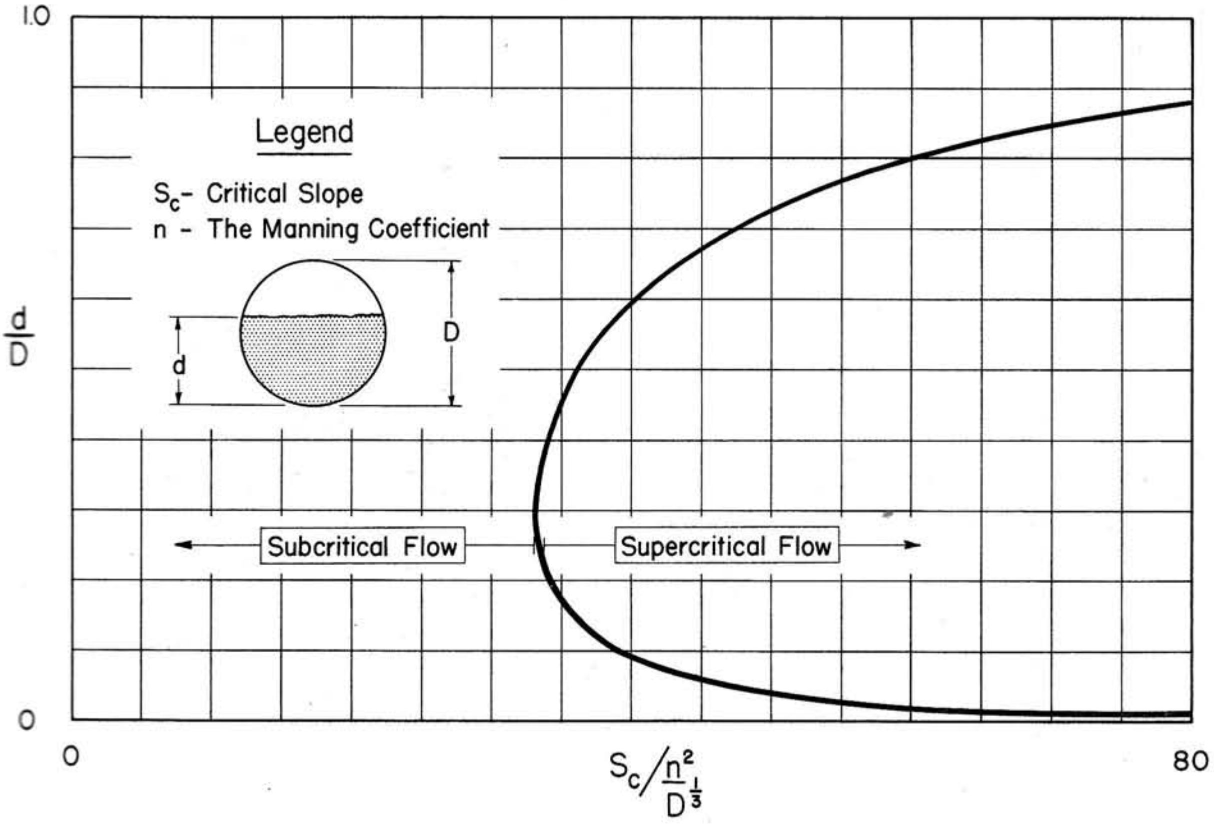


Fig. 3 - Critical Culvert Slope as a Function of Depth

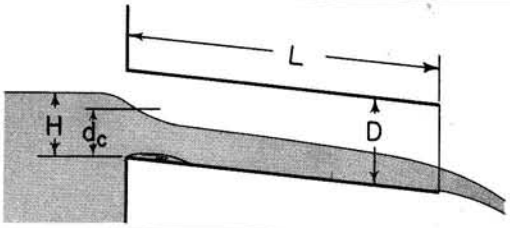
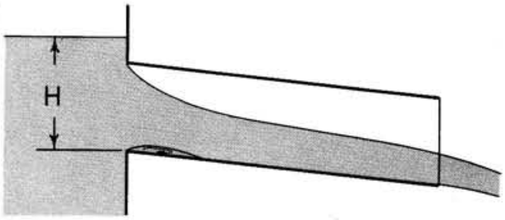
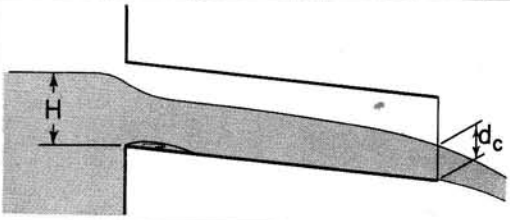
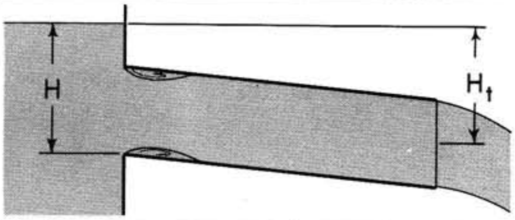
FLOW TYPE	ILLUSTRATION
(a) STEEP SLOPE H/D < 1.3 SUPERCRITICAL FLOW Control : critical section at inlet	
(b) STEEP SLOPE H/D > 1.3 SUPERCRITICAL FLOW Control : orifice flow at inlet	
(c) MILD SLOPE SUBCRITICAL FLOW Control : critical depth at outlet	
(d) MILD SLOPE FULL FLOW Control : barrel friction	

Fig. 4 — Typical Flow Conditions for Square-edge Inlet

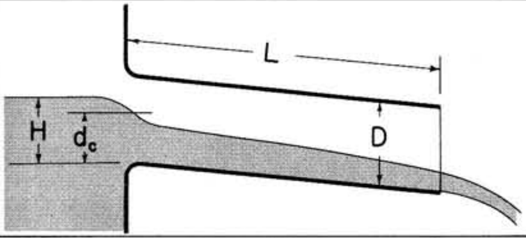
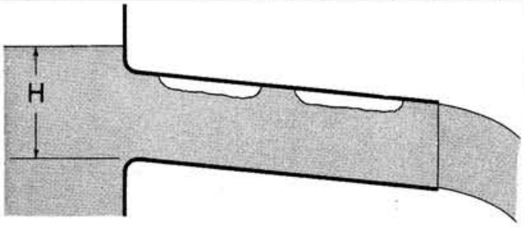
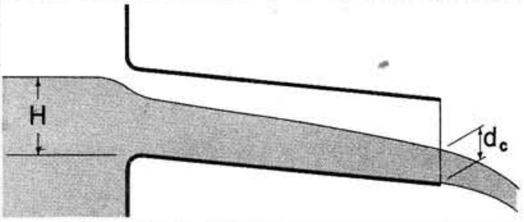
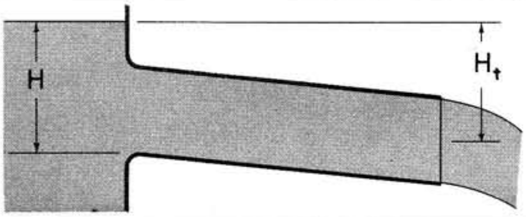
FLOW TYPE	ILLUSTRATION
(a) STEEP SLOPE H/D < 1.25 SUPERCRITICAL FLOW Control: critical section at inlet	
(b) STEEP SLOPE H/D > 1.25 SLUG FLOW Control: pulsating	
(c) MILD SLOPE SUBCRITICAL FLOW Control: critical depth at outlet	
(d) MILD SLOPE FULL FLOW Control: barrel friction	

Fig. 5 - Typical Flow Conditions for Rounded Inlet

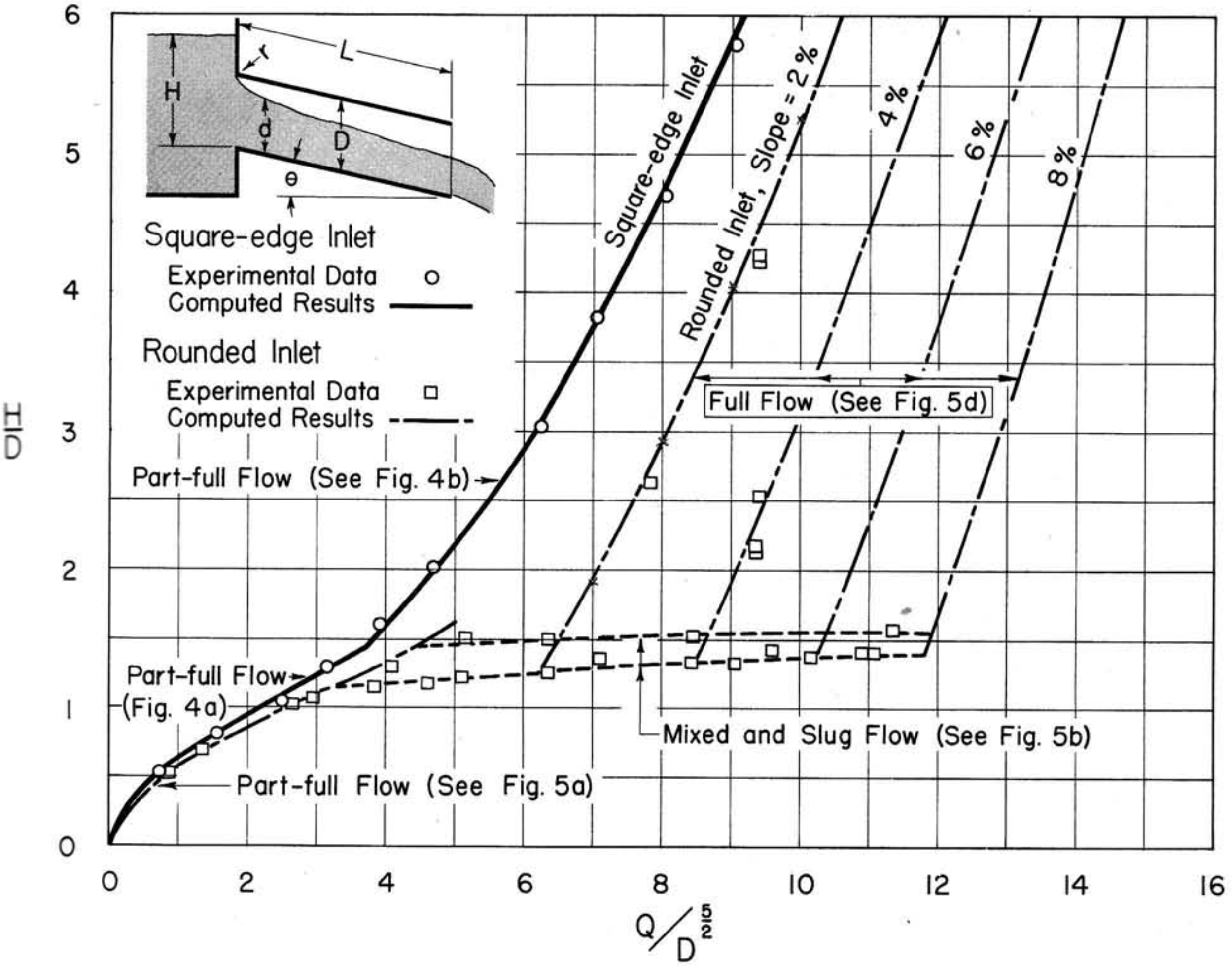


Fig. 6- Comparison of Head-Discharge Curves for Square-edge and Rounded Inlets (Long Culvert on Steep Slope)

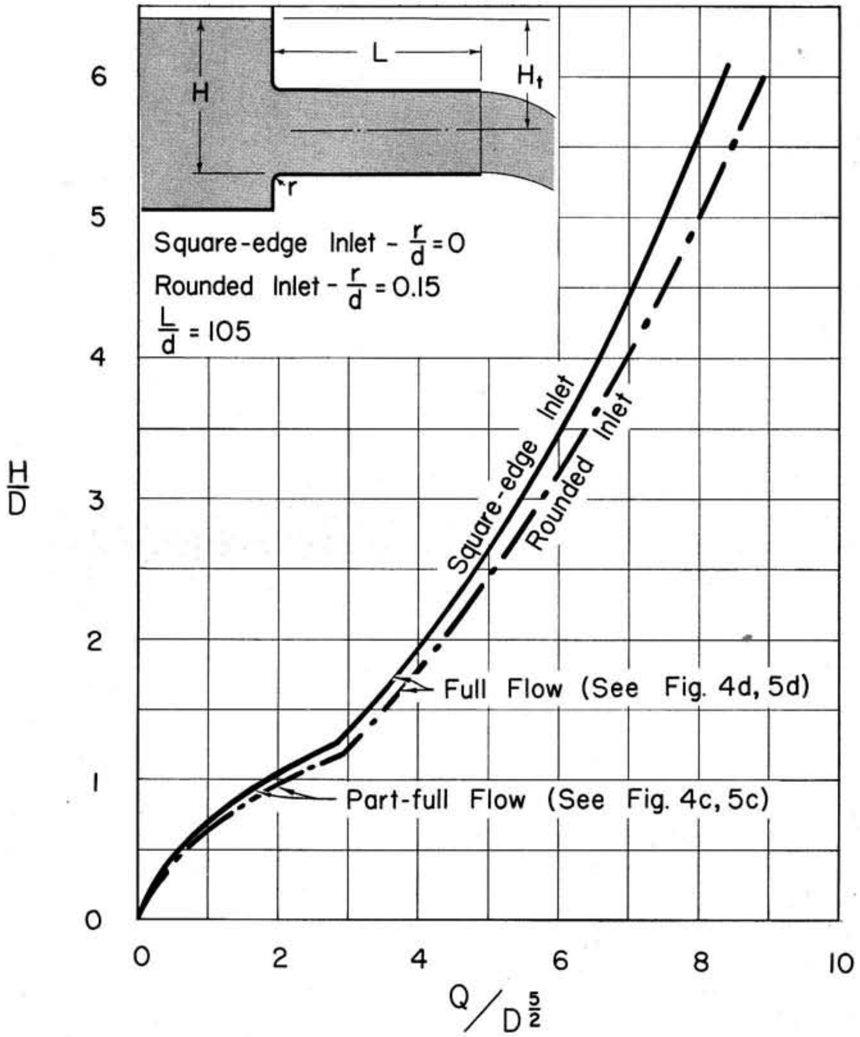


Fig. 7- Comparison of Head-Discharge Curves for Square-edge and Rounded Inlets (Long Culvert on Mild Slope)

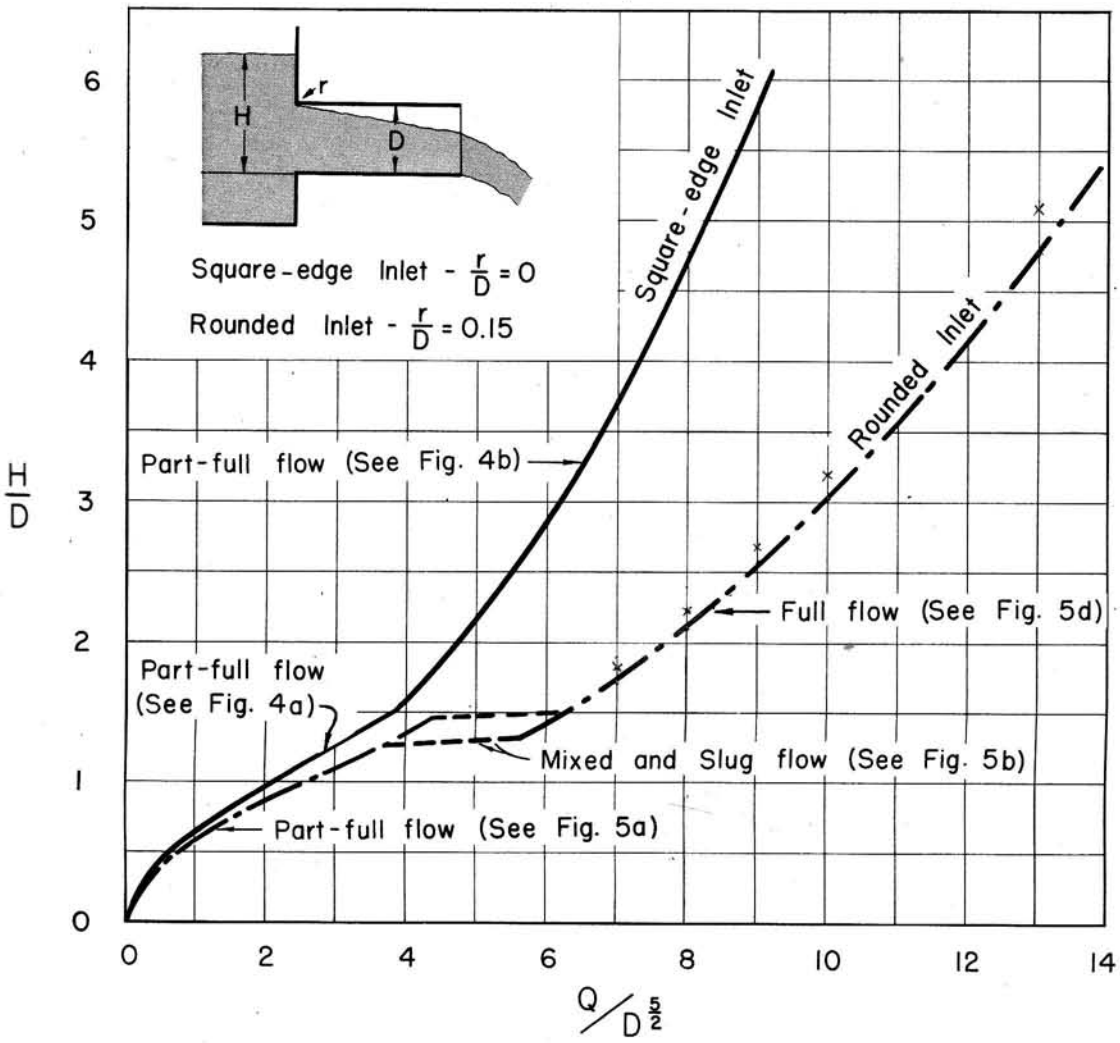


Fig. 8 - Comparison of Head-Discharge Curves for Square-edge and Rounded Inlets (Short Culvert — Control at Inlet)