PB-224 416

CULVERTS AS FLOW MEASURING DEVICES

Va-son Boonkird

Colorado State University

Prepared for:

Agency for International Development

February 1972

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COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO
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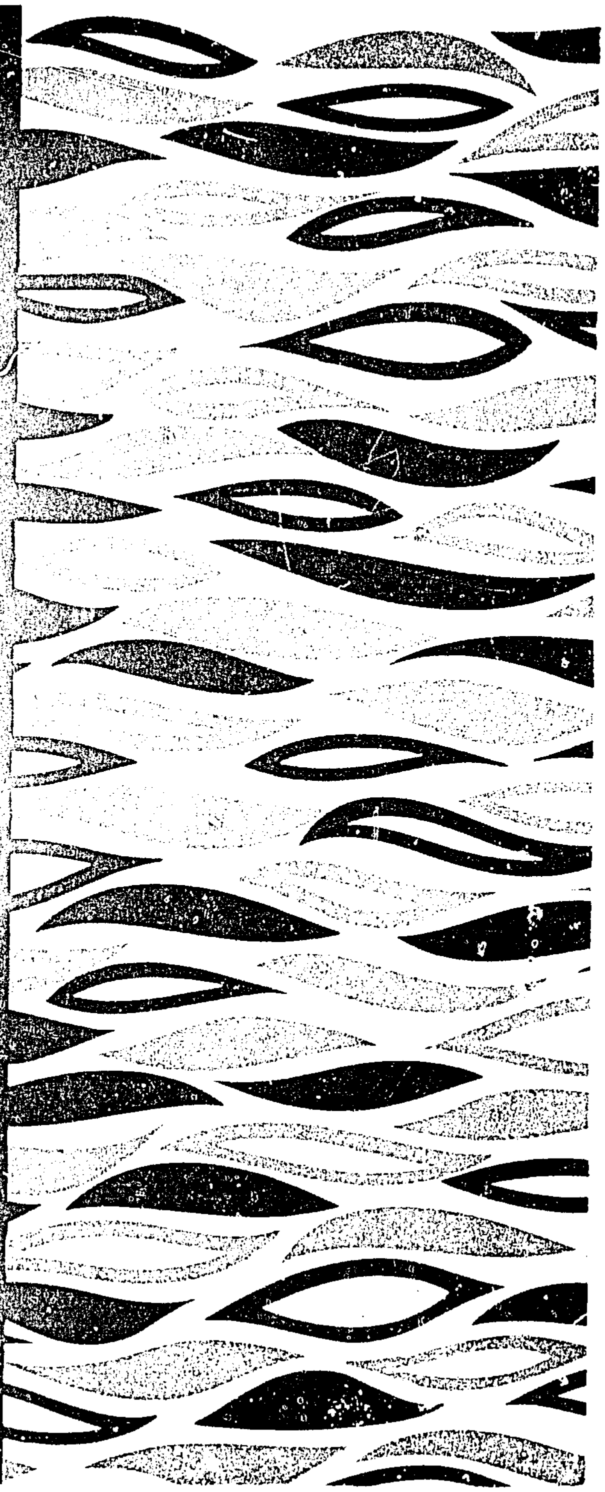

WATER MANAGEMENT
TECHNICAL REPORT NO.17

BIBLIOGRAPHIC DATA SHEET

1. Report No. 631.7-B724

2.

3. Recipient's Accession No. 224 416 64

4. Title and Subtitle

"Culverts as Flow Measuring Devices"

5. Report Date Feb 72

6.

7. Author(s) Va-son Boonkird.

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Colorado State Univ.

10. Project/Task/Work Unit No. 931-11-120-489

11. Contract/Grant No. AID/csd-2460-~~212(d)~~

12. Sponsoring Organization Name and Address

Department of State
Agency for International Development
Washington, D.C. 20523

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts

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A 12-inch diameter corrugated metal pipe has been used in the laboratory to test the validity of the submerged flow analysis employed with flow measuring flumes and weirs in describing free surface outlet control in culverts. Various slopes and culvert lengths were studied.

This study has shown that discharge ratings under free surface outlet control flow conditions can be developed. Such ratings ean be developed. Such ratings can be related

~~17. Key Words and Document Analysis. 17a. Descriptors~~

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17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 631

18. Availability Statement

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 106

22. Price $4.25

FORM NTIS-35 (REV. 3-72)

USCOMM-DC 14952-P72

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Water Management Technical Report No. 17

by

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Prepared under support of

United States Agency for International Development
Contract No. AID/csd-2460
Improving Capacity of CUSUSWASH Universities
for Water Management for Agriculture

Agricultural Engineering Department
College of Engineering
Colorado State University
Fort Collins, Colorado 80521

February, 1972

AER71-72VB7

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ABSTRACT

CULVERTS AS FLOW MEASURING DEVICES

Culverts are encountered throughout irrigation systems. Many of these culverts operate under free surface flow conditions. Usually, the flow depths in the culvert are governed by downstream flow conditions. This particular flow condition can be described as free surface outlet control. Only an approximate solution for determining discharge has been available for this situation.

A 12 inch diameter corrugated metal pipe has been used in the laboratory to test the validity of the submerged flow analysis employed with flow measuring flumes and weirs in describing free surface outlet control in culverts. Various slopes and culvert lengths were studied.

This study has shown that discharge ratings under free surface outlet control flow conditions can be developed. Such ratings can be related to the discharge relationships for inlet control and submerged outlet control. Thus, culverts can be used as flow measurement structures in irrigation systems.

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February, 1972

ACKNOWLEDGMENTS

In completing this thesis, I owe a debt of gratitude to Mr. Gaylord V. Skogerboe, Associate Professor of Agricultural Engineering, who suggested this research and gave generously of his time throughout the conduct of this study. His kindly guidance, advice, suggestions and encouragement are deeply appreciated.

I am also appreciative for the kind suggestions by my research committee: Mr. Donald L. Miles, Extension Irrigation Engineer, Agricultural Engineering Department, and Mr. Charles W. Thomas, Professor of Civil Engineering.

Thanks are also due to Mr. Wynn R. Walker, Ray S. Bennett, J.W.H. Barrett and Tsu-Yang Wu for their help and painstaking efforts throughout the experimental program. Especially, I am grateful to Mr. Walker for his assistance regarding the analysis of experimental results.

For their extra efforts in typing this manuscript, I wish to thank Mrs. Barbara Mancuso and Miss Kevin Feigan.

Special thanks go to my parents, Mr. and Mrs. Sa-ard Boonkird, whose constant encouragement, understanding, love and kindness helped in the completion of this research.

The effort reported herein was made possible through the support of the United States Agency for International

Development under Contract No. AID/csd-2460, "Improving Capacity of CUSUSWASH Universities for Water Management for Agriculture."

This study is part of an overall program in the Agricultural Engineering Department to fill research gaps in present-day knowledge regarding small irrigation structures found in irrigation distribution systems and farm irrigation systems.

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NOMENCLATURE

C = Inlet control flow coefficient

C_1 = Free surface subcritical flow coefficient

C_2 = A constant for the approximate submergence distribution in the free surface subcritical flow equation

C_3 = Submerged outlet flow coefficient

D = Pipe diameter, in ft

g = Gravitational acceleration, in ft per sec^2

h,TW = Tailwater depth at culvert outlet, or a flow depth equivalent

H = Difference in water levels upstream and downstream

H_c = Specific energy, in ft

H_e = Head increment, in ft

HW = Headwater depth, the vertical distance from the culvert invert

HW+Z = Upstream water surface elevation above invert of culvert outlet, in ft

K_e = Entrance loss coefficient

L = Length of culvert, in ft

n = Channel friction factor

n_1 = Inlet control flow exponent

n_2 = Free surface subcritical flow exponent

n_3 = Submerged outlet flow exponent

Q = Flow rate, in cfs

S = Submergence, which is the ratio of a downstream flow depth to an upstream flow depth, but using a common datum such as the invert of the culvert outlet

S_o = Barrel slope, in ft per ft

S_t = Transition submergence, which is the value of submergence at which a change in tailwater depth creates a change in the headwater depth

V = Velocity, in ft per sec

Y_c = Critical depth, in ft

Z = Vertical distance from invert at the culvert outlet (reference datum) to the invert at the culvert inlet, in ft

CHAPTER I

INTRODUCTION

Background

Water measuring devices have been very important in irrigation systems for years. Nowadays, increased emphasis on water resource development to support rapidly increasing population, with consequent expanding water demands by municipalities, industry and agriculture has rendered the optimum use of water resources extremely important. There is no doubt that water measuring devices will play an even greater role in the near future for the allocation and distribution of water supplies. Water measuring devices are important for successful business-like management, meeting legal obligations, water conservation, and insuring an equitable distribution of water.

There are many types of both open channel and closed conduit water measuring devices available. Culverts can serve as a combination open channel and closed conduit flow measurement structure, depending upon the type of flow condition in the culvert.

The advantages of having culverts as flow measuring devices are:

1. Sufficient accuracy over a rather wide range of discharges is obtainable in most cases;

2. A sturdy structure that can be constructed of steel, concrete or masonry;
3. The smaller sizes (diameter and/or length) of metal culverts are suitable as portable structures;
4. Ease of installation;
5. Easy to operate and maintain; and
6. There are no silting problems due to the increased velocity in culverts, thereby allowing the transportation of suspended and bed load material through the structure.

Problem

Most of the research involving the hydraulics of culverts has been concerned with the use of such structures under highways. Most frequently, a highway culvert is designed to operate with full flow (closed conduit) at the design discharge. Much of this research has been concerned with inlet control and submerged outlet control.

Numerous culverts are found in irrigation conveyance and distribution systems, as well as in farm head ditches and at points of tailwater runoff from croplands. Culverts are commonly placed through canal banks to divert water into laterals, with a headgate placed at the culvert inlet to control the quantity of flow delivered to the lateral. Rather than constructing small bridges, culverts are frequently placed in the conveyance channel, with an earth embankment placed over the culvert, to allow vehicles such as farm machinery to cross the channel.

For culverts placed in an irrigation conveyance channel usually free surface (open channel) flow occurs in the culvert. In addition, downstream conditions will likely control the depth of flow in the culvert. For this particular condition of free surface subcritical culvert flow, only an approximate solution is presently available for determining the discharge.

If accurate discharge ratings could be developed for free surface subcritical culvert flow, then the culverts found in irrigation systems could be used as a flow measurement structure. Also, small culverts could be used as a portable flow measuring device, which could be easily installed while water was flowing in the channel. If the ratings included the effect of barrel slope, then the culvert would not have to be perfectly horizontal, like most flow measuring flumes, in order to obtain accurate discharge measurements.

Purpose

A culvert is usually a constriction to the flow. Culverts placed in irrigation conveyance channels are open channel constrictions. Since only an approximate solution is presently available for determining the discharge under free surface subcritical culvert flow, the possibility of utilizing the submerged flow analysis recently developed for flow measuring flumes and weirs to provide an accurate discharge equation will be investigated. If the submerged flow analysis can be applied to this special problem, the transition from inlet control to free surface subcritical culvert flow can be described. Then, a method for describing the transition from free surface subcritical culvert flow to submerged outlet control will be explored.

Scope

A single diameter (12-inch) corrugated metal pipe will be used to test the validity of the submerged flow analysis in describing free surface subcritical culvert flow. Three lengths of culvert will be used; namely 5 feet, 10 feet, and 20 feet. A number of culvert barrel slopes (sloping downward in the direction of flow) will be used in the experimental program. Three flow conditions will be investigated, which are inlet control, free surface subcritical flow, and submerged outlet control. A range of discharges will be used in the testing program. A single culvert inlet geometry will be used, which will be a square-edged entrance with a flush headwall.

CHAPTER II

HYDRAULICS OF CULVERTS

The classification of the hydraulic performance of culverts can take several forms. Three primary groupings will be used to describe the hydraulics of culverts. The primary groups are based on the three parts of the culvert that exert primary control on the culvert performance and its capacity: the inlet, the barrel, and the outlet.

Usually, one of the primary controls determine the performance and capacity of the culvert. An example of this is a projecting, square-edged inlet with the barrel on a steep slope and flowing partly full. If the inlet is not submerged, the upstream water level (headwater) is determined by the inlet characteristics alone. At other times, two or even all three primary controls can simultaneously affect the performance and capacity. For example, if the inlet and outlet are submerged and the barrel is full, then the elevation of the headwater is determined by adding the outlet losses, the barrel friction losses, and the inlet losses to the tailwater elevation.

The classification is further subdivided under each main group, as shown in Table 1 (3). The classification is presented to indicate the number of items the designer must

Table 1. Classification of culvert hydraulic controls (3).

I. Inlet
  A. Unsubmerged
    1. Weir
    2. Surface profile
  B. Submerged
    1. Orifice
    2. Vortex
    3. Full

II. Barrel
  A. Length
    1. Short
    2. Long
  B. Slope
    1. Mild
      i. Barrel slope less than critical slope
        a. Part full, normal depth greater than critical depth
        b. Full, not applicable
      ii. Barrel slope less than friction slope
        a. Part full, depth increases along barrel
        b. Full, barrel under pressure
    2. Steep
      i. Barrel slope steeper than critical slope
        a. Part full, normal depth less than critical depth
        b. Full, not applicable
      ii. Barrel slope steeper than friction slope
        a. Part full, depth decreases along barrel (increases if the inlet causes the depth inside the inlet to be less than the normal depth)
        b. Full, barrel under suction
  C. Flow
    1. Part full
    2. Slug and mixture
    3. Full

III. Outlet
  A. Part full
    1. Critical depth
    2. Tailwater
  B. Full
    1. Free
    2. Submerged

consider when determining the performance of a culvert and computing its capacity.

Only those items that exert a control on the hydraulic performance of a culvert are listed in Table 1. Many alternatives are possible for each control. For example, each type of inlet will have a different effect on the culvert performance, and each effect must be evaluated.

Many of the items listed in Table 1 are interrelated, which further complicates an already difficult problem. For instance, the depth of flow just inside the culvert entrance depends on the inlet geometry. If this depth is less than the normal depth of flow, a water surface profile must be computed beginning with the contracted depth of flow to determine the flow depth at the culvert outlet. If the computed outlet depth exceeds the barrel height, the culvert is hydraulically long, the barrel will fill, and the control will be the inlet, the barrel, and the outlet. If the computed depth at the outlet is less than the barrel height, the barrel is only part full and the culvert is considered hydraulically short, will not fill, and the control will remain at the inlet. Whether a culvert is hydraulically long or hydraulically short depends on such items as the culvert slope and the culvert material. In fact, just changing from corrugated pipe to concrete pipe can change the hydraulic length of a culvert from long to short. A similar effect could result from a change in the inlet geometry.

The determination of culvert performance is not a simple problem. If the culvert is on a steep slope, a re-entrant, sharp-edged inlet will produce part-full flow in the barrel until the headwater level reaches some indeterminate high level. A flush, square-edged entrance will act similarly, but the barrel will fill at some lower head. A well-rounded inlet will cause the barrel to fill at a low submergence of the inlet crown. These performance characteristics of inlets are evaluated by experiment.

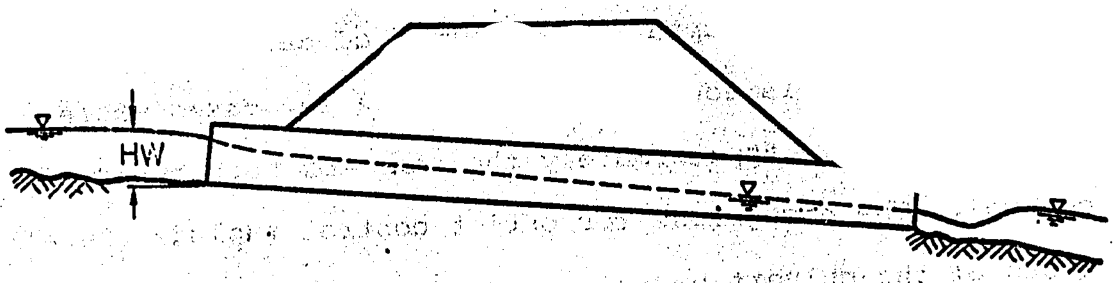
Flow in culverts is also controlled by the hydraulic capacity of one section of the installation. The discharge is either controlled at the culvert entrance or at the outlet and is designated inlet control and outlet control, respectively. In general, inlet control will exist as long as the ability of the culvert pipe to carry the flow exceeds the ability of water to enter the culvert through the inlet. Outlet control will exist when the ability of the pipe barrel to carry water away from the entrance is less than the flow that can enter the inlet. The location of the control section will shift as the relative capacities of the entrance and barrel sections change with increasing or decreasing discharge.

The probable type of flow under which a culvert will operate for a given set of conditions can be determined by involved hydraulic computations. The need for making these computations may be avoided, however, by using published nomographs (1, 9, 10, 20) to compute headwater depths for both inlet control and outlet control and then using the higher value to indicate the type of control and to determine the headwater depth. This method of determining the type of control is accurate except for a few cases where the headwater is approximately the same for both types of control. The nomographs for outlet control include the effects of the culvert barrel.

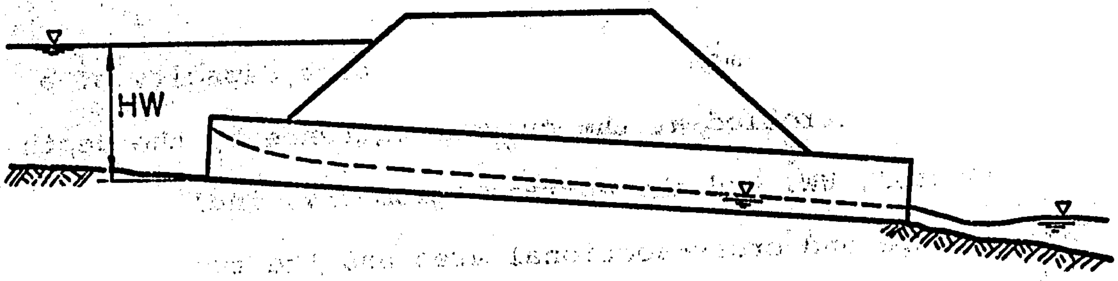
Inlet Control

Inlet control means that the discharge capacity of a culvert is controlled at the culvert entrance by the depth of headwater, HW, and the entrance geometry, including the barrel shape and cross-sectional area and the type of inlet edge. Inlet control flow for both unsubmerged and submerged projecting entrances are shown in Figs. 1(a) and 1(b). A submerged mitered entrance with inlet control is shown in Fig. 1(c). With inlet control, the roughness and length of the culvert barrel, as well as outlet conditions (including depth of tailwater), are not factors in determining culvert capacity. An increase in barrel slope reduces headwater to a small degree and any correction for slope can be neglected for conventional or commonly used culverts flowing with inlet control (20).

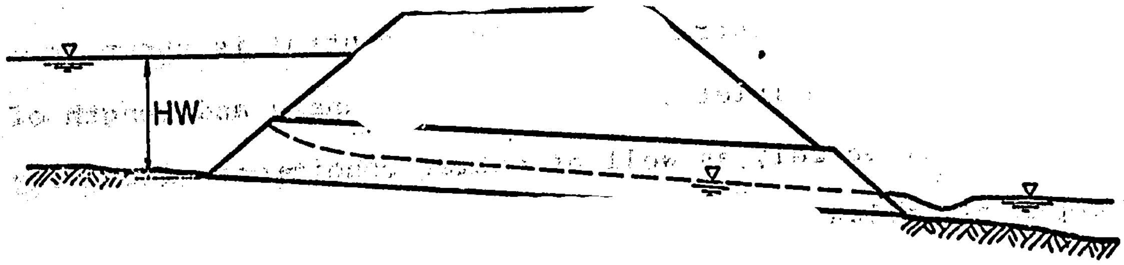
In all culvert design, headwater or depth of ponding at the entrance to a culvert is an important factor in culvert capacity. The headwater depth (or headwater, HW) is the vertical distance from the culvert invert at the



(a) Projecting entrance with unsubmerged (free surface) inlet.



(b) Projecting entrance with submerged inlet.



(c) Mitered entrance with submerged inlet.

Figure 1. Inlet control flow conditions.

entrance to the energy line of the headwater pool (depth and velocity head). Because of the low velocities in the most entrance pools, the water surface and the energy line at the entrance are assumed to be coincident. For the purposes of measuring headwater, the culvert invert at the entrance is the low point in the culvert opening at the beginning of the full cross-section of the culvert barrel.

Headwater-discharge relationships for the various types of circular and pipe-arch culverts flowing with inlet control are based on laboratory research using models and verified for some entrances by prototype tests. Based upon the research data, nomographs for determining culvert capacity for inlet control have been developed (1, 9, 10, 20). These nomographs give headwater-discharge relationships for most conventional culverts flowing with inlet control through a range of headwater depths and discharges.

For free surface inlet control flow, the following equation has been used in preparing nomographs.

$$\frac{HW}{D} + 0.5S_0 = \frac{H_c}{D} + \frac{H_e}{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where HW = headwater depth, in ft.

S_0 = barrel slope, ft. per ft.

H_c = specific energy, in ft.

H_e = head increment, in ft.

D = culvert diameter, in ft.

The above relationship is valid until a limiting upper value of H_e, corresponding to a discharge factor of about

3.25, is reached. This value has been experimentally determined and is given in Table 2 (e.g., the discharge factor is 4.00 for a thin edge projecting entrance). The empirical relationship between the head increment, H_e, and the discharge factor, $Q/D^{5/2}$, is given by the equation:

$$H_e/D = k(1.273Q/D^{5/2})^m \qquad \text{.........................(2)}$$

The values of k and m have been experimentally determined and are given in Table 2 for a number of entrance shapes.

With the entrance submerged, the operating characteristics of pipe culverts flowing with inlet control are defined by the equation:

$$\frac{HW}{D} + 0.5S_0 = \frac{h_1}{D} + k_1 \left(\frac{Q}{D^{5/2}}\right)^2 \qquad \text{...............(3)}$$

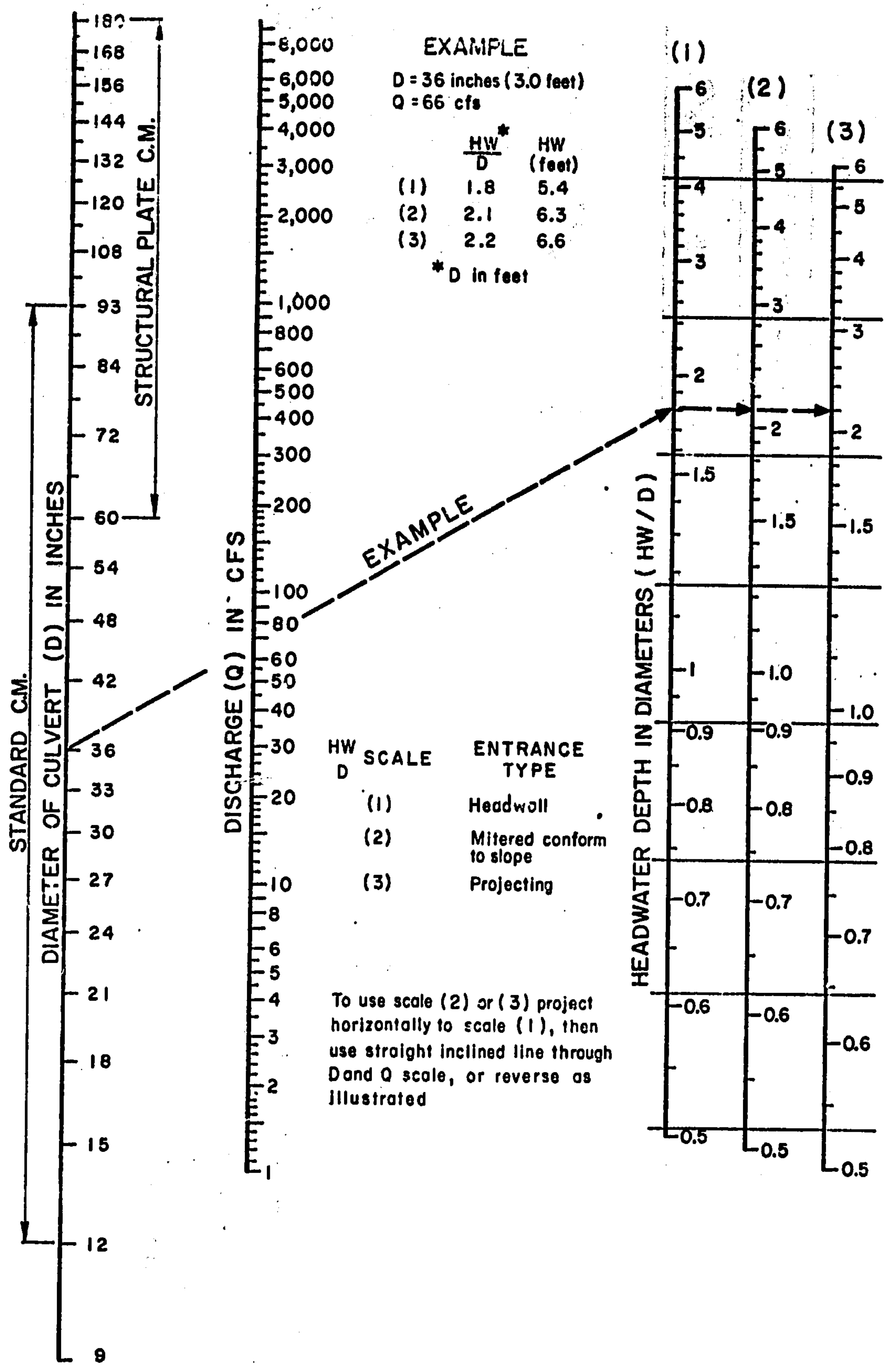
This equation is valid for values of the discharge factor, $Q/D^{5/2}$, exceeding an experimentally determined minimum given in Table 2. The factor k_1 and the quantity h_1/D are also empirical and are given in Table 2.

The instructions for using the inlet control nomographs such as Fig. 2 are given below:

1. To determine headwater (HW), given Q, and size and type of culvert
   a. Connect with a straightedge the given culvert diameter or height (D) and the discharge Q, or Q/B for box culverts; mark intersection of straightedge on HW/D scale marked (1)

Table 2. Inlet control performance coefficients.

Entrance Shape	Submerged inlet flow			Nonsubmerged inlet flow		
	h_1/D	k_1	$Q/D^{5/2}$	k	m	H_e/D
With headwall						
Groove edge, .05 D x .07 D	0.74	0.0468	3.30	0.0018	2.50	0.035
Rounded edge, .15 D radius	0.74	0.0419	2.58	0.00065	2.67	0.016
Square edge	0.67	0.0645	2.58	0.0098	2.00	0.105
Headwall and 45° wingwalls						
Groove edge, .05 D x .07 D	0.73	0.0472	3.00	0.0018	2.50	0.035
Square edge	0.70	0.0594	3.50	0.0030	2.67	0.072
Headwall and parallel wingwalls						
Groove edge, .05 D x .07 D	0.74	0.0528	4.00	0.0020	2.67	0.048
Miter (square edge)						
2:1 embankment slope	0.74	0.0750	4.00	0.0210	1.33	0.091
Projecting entrance						
Groove edge, .05 D x .07 D	0.70	0.0514	2.58	0.0045	2.00	0.049
Square edge (thick wall)	0.64	0.0668	3.50	0.0145	1.75	0.116
Thin edge	0.53	0.0924	4.00	0.0420	1.33	0.205



EXAMPLE

D = 36 inches (3.0 feet)
Q = 66 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	1.8	5.4
(2)	2.1	6.3
(3)	2.2	6.6

*D in feet

$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Headwall
(2)	Mitered conform to slope
(3)	Projecting

To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scale, or reverse as illustrated

Figure 2. Headwater depth for corrugated metal pipe culverts with inlet control.

b. If HW/D scale marked (1) represents entrance type used, read HW/D on scale (1); if another of the three entrance types listed on the nomograph is used, extend the point of intersection in (a) horizontally to scale (2) or (3) and read HW/D

c. Compute HW by multiplying HW/D by D

. To determine discharge (Q) per barrel, given HW, and size and type of culvert

a. Compute HW/D for given conditions

b. Locate HW/D on scale for appropriate entrance type; if scale (2) or (3) is used, extend HW/D point horizontally to scale (1)

c. Connect point on HW/D scale (1) as found in (b) above and the size of culvert on the left scale; read Q or Q/B on the discharge scale

d. If Q/B is read in (c) multiply B (span of box culvert) to find Q

3. To determine culvert size, given Q, allowable HW, and type of culvert

a. Using a trial size, compute HW/D

b. Locate HW/D on scale for appropriate entrance type; if scale (2) or (3) is used, extend HW/D point horizontally to scale (1)

c. Connect point on HW/D on scale (1) as found in (b) above to given discharge and read diameter, height, or size of culvert required for HW/D value

d. If D is not that originally assumed, repeat procedure with a new D

Barrel Control

Under barrel control, the discharge in the culvert is controlled by the combined effect of entrance, length, slope, and roughness of the pipe barrel. The characteristics of the flow do not always identify the type of flow. It is possible, particularly at low flows, for length, slope, and roughness to control the discharge without causing the pipe to flow full. This is, however, not a common occurrence at design discharges. The usual condition for this type of flow at design discharges is one in which the pipe cross-section flows full for a major portion of the length of the culvert. The discharge in this case is controlled by the combined effect of all hydraulic factors.

Culvert slope. The slope of the culvert barrel has a decided influence on the operating characteristics of pipe culvert installations. By means of the slope, energy is added to the flow within the pipe barrel to compensate in part or overcome the effect of friction. The effect of slope operates to a greater or lesser degree, depending on the length of the culvert. It is always necessary to ascertain the effect of slope to determine the location of the control section (10).

Often a cursory analysis of the effect of slope will suffice for design purposes. Such an analysis can be made for long culverts in which it can be assumed that the flow will approach or stabilize at normal depth. In this case, a comparison of normal depth to the critical depth for the particular discharge will establish the type of control. If the normal depth is less than the critical depth, the control for the particular discharge will be at the entrance and the culvert will operate with inlet control. Conversely if the normal depth is greater than the critical depth, the culvert, except in very few cases, essentially operates with outlet control.

The computations for determining the effect of slope on the location of the control section in long culverts can be greatly simplified by generalizing the factors that are involved. This has been done in Fig. 3 (10). In this diagram, relative depths are used in which the normal depth, y, and critical depth, y_c, are expressed in terms of the pipe diameter, D, which are plotted on the ordinate in Fig. 3. The discharge factor, $Q/D^{5/2}$, is plotted on the abscissa. The combined effect of roughness, pipe size, and barrel slope may be expressed as a ratio of actual barrel slope, S_o, to the optimum critical slope $(S_c)_{op}$. The ratio of $S_o/(S_c)_{op}$ is referred to as the relative slope, s_o, and may be used to establish the relative depth, y/D, at various values of the discharge factor. Further, relative critical depth, y_c/D, may be plotted on the same graph to obtain an

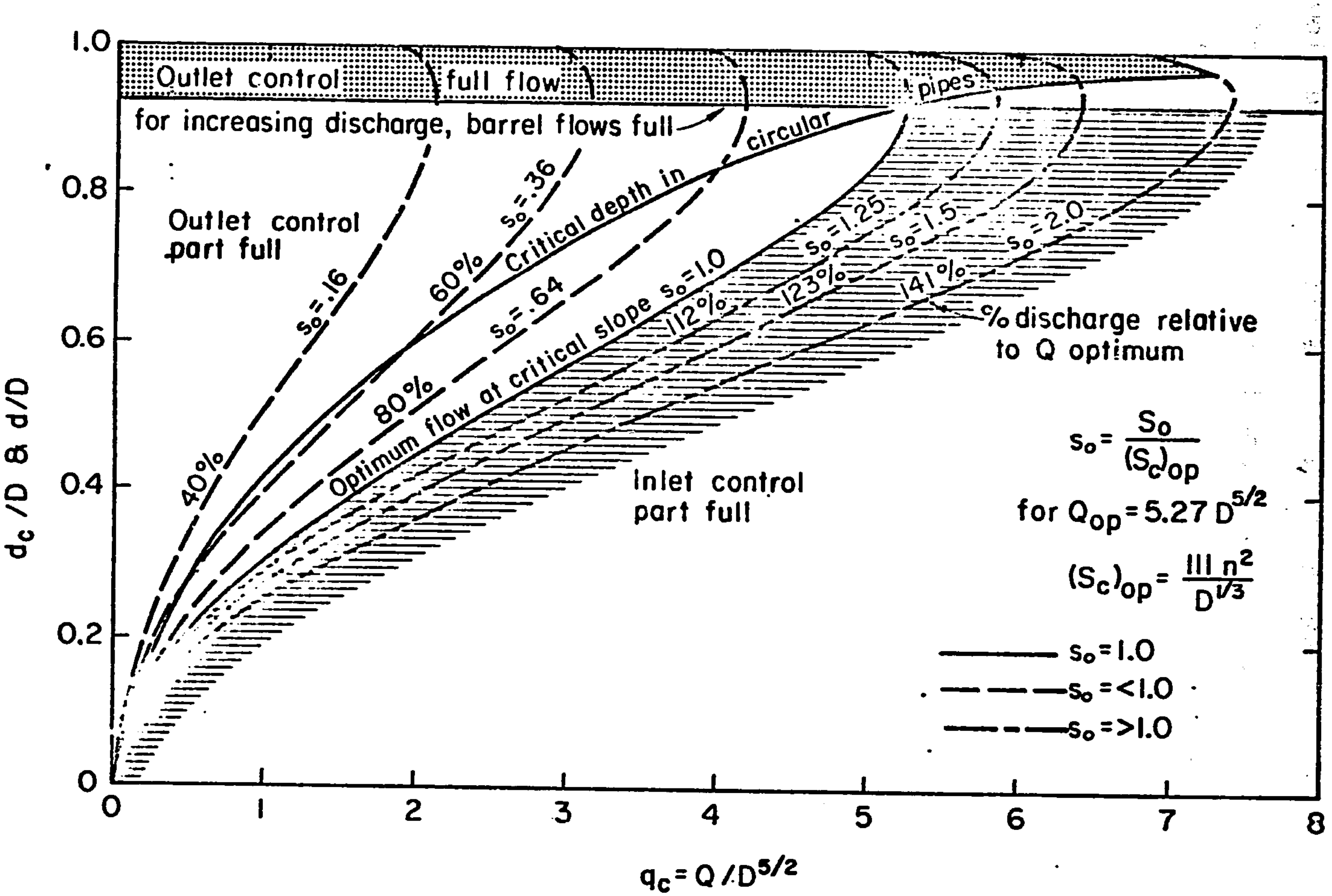


Figure 3. Flow conditions for long circular culvert barrels flowing part full (10).

immediate comparison of normal depth and critical depth for any discharge.

Slope and discharge at a given depth are related by the Manning equation, so that $Q \propto S^{1/2}$. Therefore, discharges in culverts with slopes relative to the optimum critical slope are also proportional at equal values of y/D. Thus, the curves for relative slope in Fig. 3 are also represented by values of relative discharge expressed in terms of per cent of the discharge in a pipe placed at a slope equal to the optimum critical slope.

Several important characteristics of flow in pipes are illustrated by the curves in the diagram of Fig. 3. First, it will be noted that major portions of the curve for relative slopes greater than 0.64 lie below the critical depth curve. This means that the normal depths for a large range of discharges are less than the critical depth. The control will be at the entrance whenever the normal depth is less than the critical depth. This establishes an area on the diagram in which the culvert will flow part full with inlet control (10).

At low values of relative slope, major portions of the diagram (Fig. 3) lie above the critical depth curve. In this area, the normal depth is greater than critical depth and the flow will be controlled by friction and conditions at the outlet. This establishes an area of part-full flow with outlet control. It should be recognized, however, that this diagram is based on flow in long culverts in which the depth of flow is constant. An attempt to apply this to short culverts would be overconservative inasmuch as actual depths in short culverts are somewhat less than normal depth (10).

An important point illustrated in Fig. 3 is the shape of the curves. The maximum discharge that can be carried by a pipe with a free water surface at any slope is at a relative depth of 0.93. Any increase in discharge from this maximum point can only be carried by a pipe flowing full. A third area is thus established in which the culvert will flow full with outlet control. Any discharge in excess of the maximum indicated by the appropriate curve will fall into this area and will cause a long culvert to flow full.

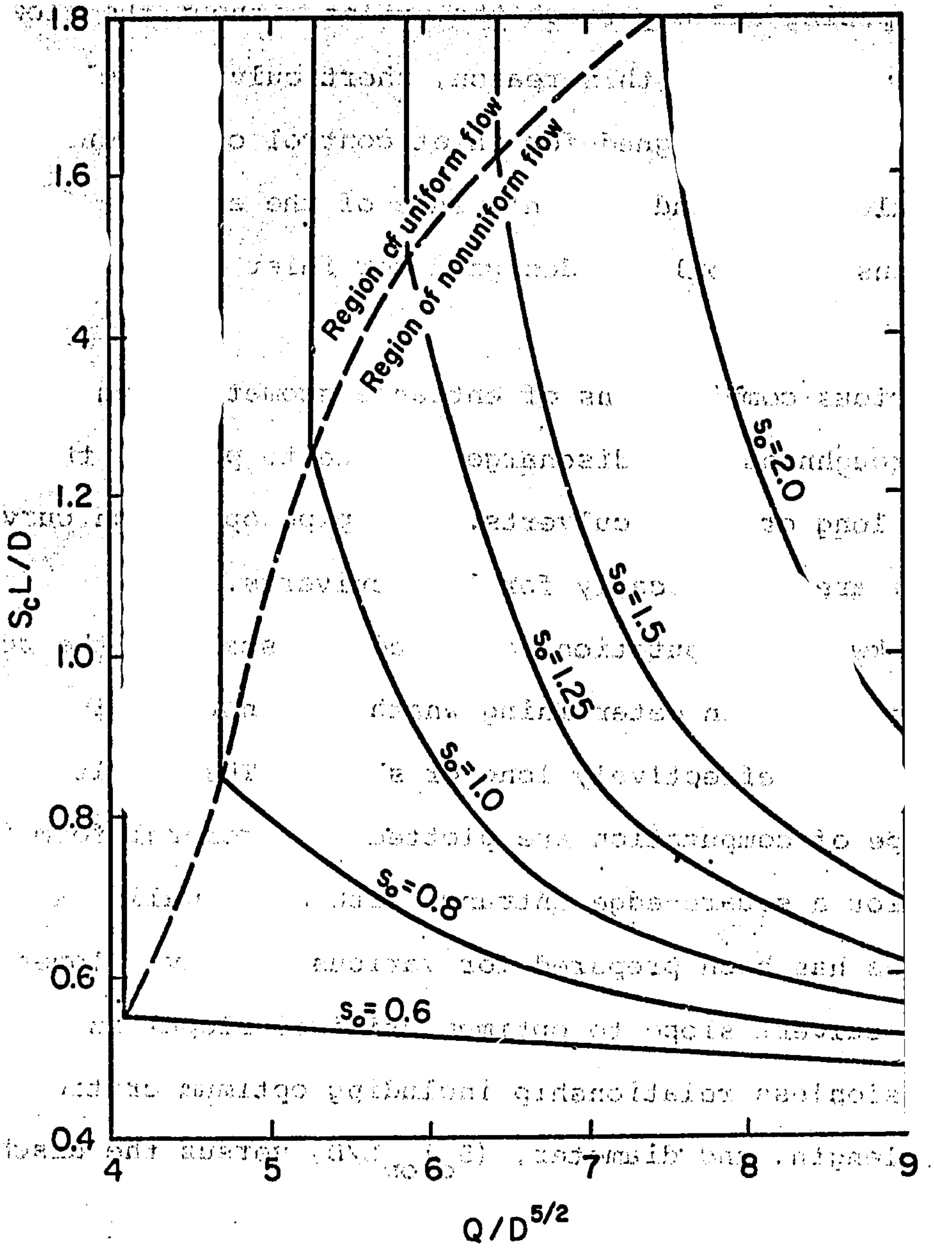
The curves of Fig. 3 will be most useful for making a quick check of the probable type of culvert operation. Flow in a pipe culvert approaches normal depth from depths less than normal. Therefore, depths of flow in culverts of moderate or short length will be less than indicated by the curve. Because of this characteristic, it is not necessary to check the type of operation further if the appropriate curve in Fig. 3 indicates that the culvert will flow part full with inlet control.

Culvert length. The geometry of culvert entrances causes the flow entering the culvert to contract in a manner similar to the operation of an orifice. As with the orifice, the degree of contraction is governed by the edge geometry. The contractions at culvert inlets in pipes flowing part full always result in water surfaces well below the critical depth of flow and usually below the normal depth of flow. The effect of the contraction is projected well downstream of the opening and may reach the outlet without the flow becoming uniform. For this reason, short culverts seldom flow full and may be designed for inlet control operation. Also, steep culverts extend the influence of the entrance flow conditions and should be designed for inlet control operation.

Various combinations of entrance geometry, length, slope, roughness, and discharge combine to produce the effect of long or short culverts. The pipe operation curves (Fig. 3) are specifically for long culverts.

Backwater computations are used to establish the controlling length in determining whether or not a culvert installation is effectively long or short. The results of this type of computation are plotted in a general form in Fig. 4 for a square-edge entrance with a headwall. A family of curves has been prepared for various relative slopes (actual culvert slope to optimum critical slope) in terms of a dimensionless relationship including optimum critical slope, length, and diameter, $(S_c)_{op}L/D$, versus the discharge factor, $Q/D^{5/2}$.

Uniform flow conditions are indicated in Fig. 4 with a dashed line showing the extent of flow at a depth of 0.93D. At discharges less than that defined by the intercept of the dashed curve with the curves for S_o, the culvert is part full and operates independently of length. At greater



igure 4. Culvert control length for square-edge entrance with a headwall (10).

discharges, the culvert operation is influenced by the length. The culvert will be part full for $(S_c)_{op}L/D$ and $Q/D^{5/2}$ intercepts falling below the appropriate relative slope curve. Similar points lying above the appropriate relative slope curve indicate that the culvert will flow full. Culverts thus defined as flowing full are long culverts and the pipe operation curves of Fig. 3 are applicable (10)

The control length curves are intended to be used as a means of making a close estimate of the length of culvert pipe required to force the pipe to flow full as a result of friction. Thus, knowing the discharge factor and relative slope, the value of $(S_c)_{op}L/D$ can be selected. The length required to cause the culvert to flow full can then be determined. Culverts shorter than the computed length would be expected to operate with inlet control; culverts longer than the computed length would be expected to operate with outlet control at the design discharge. These curves, therefore, are useful in establishing the criteria for long or short culverts.

The control length curves can also be used to establish the approximate discharge rate at which a culvert of given size, length, and slope can be expected to flow full. At discharges exceeding the computed amount, the culvert will operate with outlet control, while for lesser discharges it will operate with inlet control. Exact operational characteristics are uncertain along the curve. Design should be conservative when a clear case of inlet or outlet control cannot be established.

Outlet Control

Culverts flowing with outlet control can flow with the culvert barrel full or part full for part of the barrel length, or for all of it (Fig. 5). If the entire cross section of the barrel is filled with water for the total length of the barrel, the culvert is said to be in full flow or flowing full, as shown in Figs. 5a and 5b. This flow condition is called submerged outlet control flow. Two other common types of outlet control flow are shown in Figs. 5c and 5d. Procedures are available for determining the headwater depth for the flow conditions shown in Figs. 5a, 5b, and 5c. The method given for part full flow condition, Fig. 5d, gives a solution for headwater depth that decreases in accuracy as the headwater decreases.

The outlet control nomographs have been constructed to solve the equation for flow in pipe culverts flowing with outlet control. The equation is

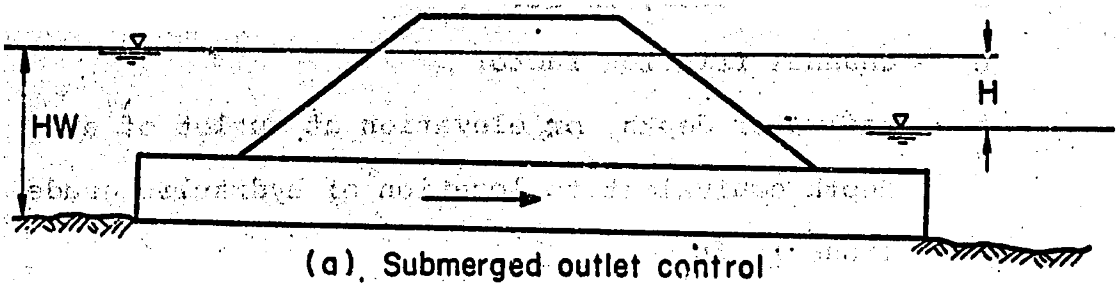
$$H = \left[\frac{2.5204\ (1+K_e)}{D^4} + \frac{4.66.18n^2L}{D^{16/3}}\right]\left(\frac{Q}{10}\right)^2 \quad ..(4)$$

where $H = HW + LS_0 - h$

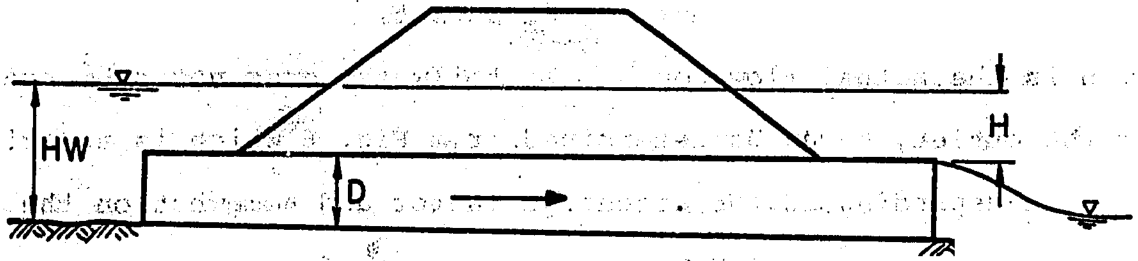
HW = headwater depth, in ft.

S_0L = energy gain due to slope, in ft.

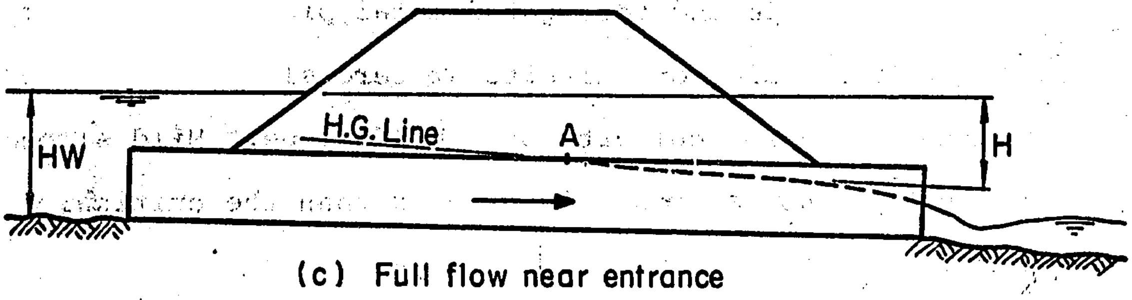
K_e = entrance loss coefficient



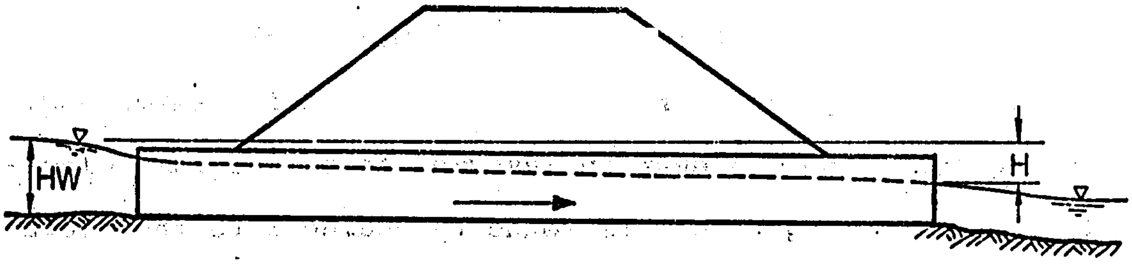
(a) Submerged outlet control



(b) Full flow with $y_c = D$



(c) Full flow near entrance



(d) Free surface outlet control

Figure 5. Outlet control flow conditions.

Q = discharge, in cfs

D = pipe diameter, in ft.

n = channel friction facto

h = tailwater depth, or elevation at outlet of a depth equivalent to location of hydraulic grade line, in ft.

If tailwater submerges the outlet, the proper value of h is the actual flow depth. If tailwater does not submerge the outlet, h can be determined from Fig. 6 which is a variable depending on the discharge factor and somewhat on the slope of the pipe. Two curves are given for each type of pipe (concrete pipe and corrugated metal pipe). The upper curves in Fig. 6 are for culverts at zero slope, while the lower curves are for culverts on a mild slope. Mild slopes exist when the normal depth is greater than the critical depth.

Finding the value of H from the nomograph is only part of the solution for this headwater depth or elevation. In the case of Fig. 5a where the outlet is totally submerged, the headwater pool elevation (assumed to be the same elevation as the energy line) is found by adding H to the elevation of the tailwater. The headwater depth is the difference in elevations of the pool surface and the culvert invert at the entrance.

When the tailwater is below the crown of the culvert, the submerged condition discussed above no longer exists and the determination of headwater is somewhat more difficult.

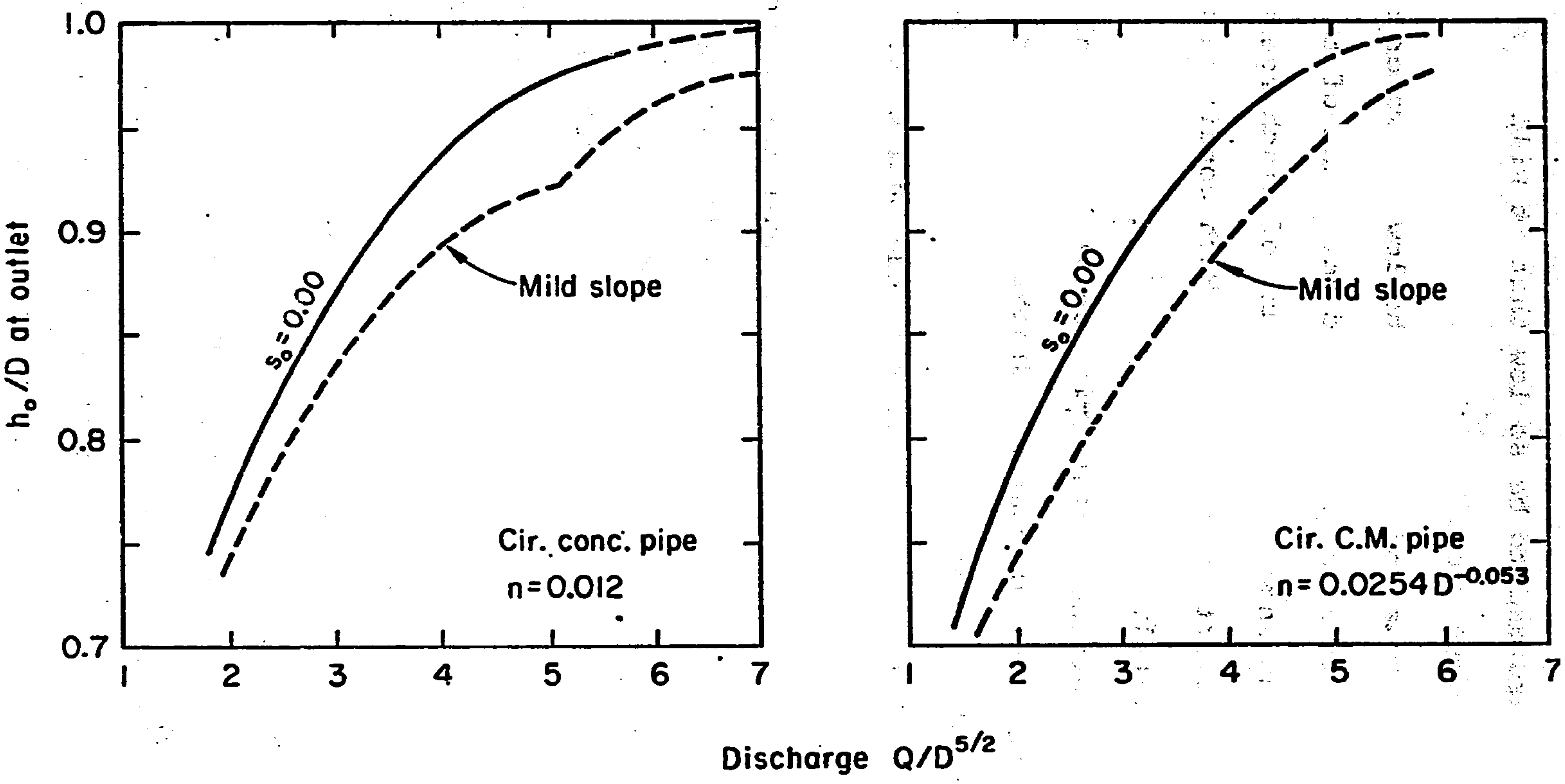


Figure 6. Pressure term at culvert outlet for flowing-full conditions.

In discussing outlet control flow for this condition, tailwater will be assumed to be so low that it will have no effect on the culvert flow.

The common types of flow for the low tailwater conditions are shown in Figs. 5b, 5c, and 5d. Each of these flow conditions are dependent on the amount of discharge and the shape of the culvert cross section. Each condition will be discussed separately.

Full flow at the outlet, Fig. 5b will occur only with the higher rates of discharge. Graphs are provided (e.g., Fig. 9) to aid in determining this full flow condition. The curves give the depth of flow at the outlet for a given discharge when a culvert is flowing with outlet control. This depth is the critical depth, y_c. When the discharge is sufficient to give a critical depth equal to the crown of the culvert barrel, full flow exists at the outlet, as shown in Fig. 5b. The hydraulic grade line will pass through the crown of the culvert at the outlet for all discharges greater than the discharge causing critical depth to reach the crown of the culvert. Head H can be measured from the crown of the culvert in computing the water surface elevation of the headwater pool.

When critical depth falls below the crown of the culvert at the outlet, the water surface drops as shown in either Figs. 5c or 5d depending again on the discharge. To accurately determine headwater for these conditions, computations for locating a backwater curve are usually required.

These backwater computations are tedious and time consuming. Fortunately, headwater for the flow condition shown in Fig. 5c can be solved by using nomographs.

For the condition shown in Fig. 5c, the culvert must flow full for part of its length. The hydraulic grade line for the portion of the length in full flow will pass through a point where the water breaks with the top fo the culvert as represented by point A in Fig. 5c. Backwater computations show that the hydraulic grade line, if extended as a straight line, will cut the plane of the outlet cross section at a point above critical depth (water surface). The point is at a height approximately equal to one half the distance between critical depth and the crown of the culvert. The elevation of this point can be used as an equivalent hydraulic grade line and H, as determined by the nomographs, can be added to this elevation to find the water surface elevation of the headwater pool.

The full flow condition for part of the barrel length, Fig. 5c, will exist when the headwater depth, HW, as computed from the above headwater pool elevation, is equal to or greater than the quantity

$$D + (1 + K_e) \frac{V^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where V is the mean velocity for the full cross section of the barrel; K_e, the entrance loss coefficient; and D, the inside height of the culvert. If the headwater is less than the above value, a free water surface as shown in Fig. 5d will extend through the full length of the culvert barrel.

The part full flow condition of Fig. 5d must be solved by a backwater computation if accurate headwater depths are desired. The solution used is the same as that given for the flow condition of Fig. 5c with the reservation that headwater depths become less accurate as the discharge for a particular culvert decreases. Generally, for design purposes, this method is satisfactory for headwater depths above 0.75 D, where D is the height of the culvert barrel.

Headwater depth, HW, can be expressed by a common equation for all outlet control conditions, including all depth of tailwater. This is accomplished by designating the vertical dimension from the culvert invert at the outlet to th elevation from which H is measured as h_0. The headwater depth, HW, equation is (for all outlet-control conditions)

$$HW = H + h_0 - LS_0 \quad \text{..........................} (6)$$

All the terms in this equation are in feet. H is found from the full-flow nomographs, whereas L is the length of the culvert in feet and S_0 the barrel slope in foot per foot. The distance, h_0, is discussed in the following paragraphs for the various conditions of outlet control flow. Headwater, HW, is the distance in feet from the invert of the culvert at the inlet to the water surface of the headwater pool.

When the elevation of the water surface in the outlet channel is equal to or above the elevation of the top of the culvert opening at the outlet (Fig. 5a), h_0 is equal to the tailwater depth. Tailwater depth, TW, is the distance in feet from the culvert invert at the outlet to the water surface in the outlet channel. A definition sketch for submerged outlet control, which shows the terms in Equation 6, is shown in Fig. 7.

If the tailwater elevation is below the top of the culvert opening at the outlet (Figs. 5b, 5c, and 5d), h_0 is more difficult to determine. The discharge, size and shape of culvert, and TW must be considered. In these cases, h_0 is the greater of the two values (1) TW depth as defined above, or (2) $\frac{y_c + D}{2}$. The latter dimension is the distance to the equivalent hydraulic grade line. In this fraction, y_c is the critical depth and D is the culvert height. The value of y_c can never exceed D, making the upper limit of this fraction equal to D. Where tailwater is the greater of these two values, critical depth is submerged sufficiently to make the tailwater effective in increasing the headwater. The sketch in Fig. 8 shown the terms of Equation 6 for this low tailwater condition, and is drawn similar to Fig. 5c, but a change in discharge can change the water surface profile to that of Fig. 5b or Fig. 5d.

Outlet control nomographs solve Equation 4, for head H, when the culvert barrel flows full for its entire length. They are also used to determine head H for some part-full flow conditions with outlet control. These nomographs do not give a complete solution for finding headwater, HW,

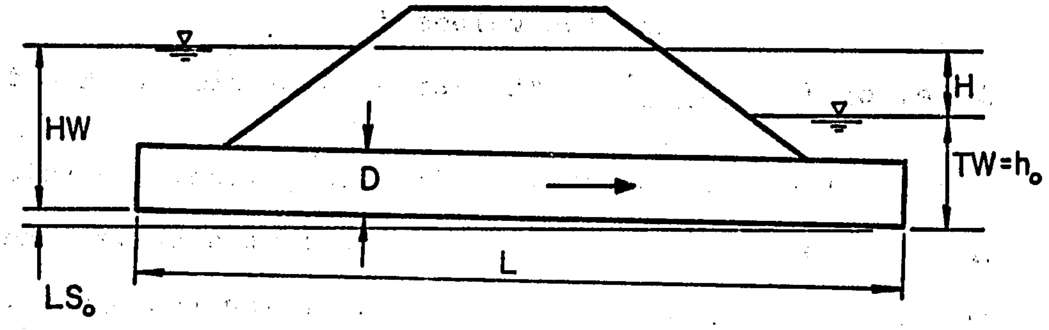


Figure 7. Definition sketch for submerged outlet control.

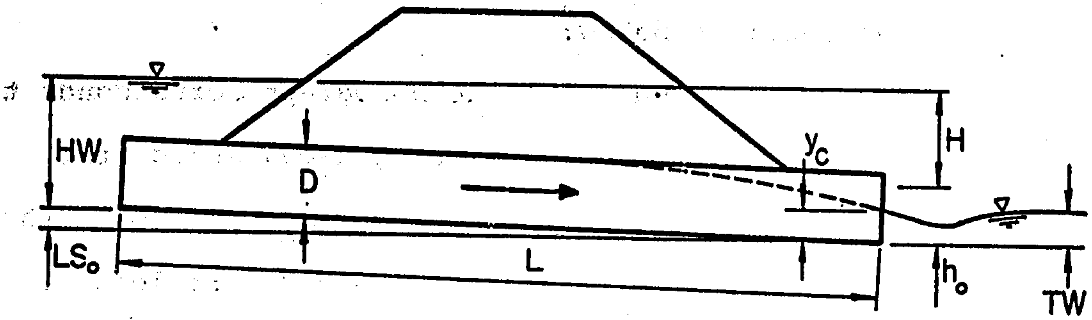


Figure 8. Definition sketch for outlet control with critical depth occurring at culvert exit.

since they only gave H in Equation 6. To determine head H for a given culvert and discharge Q,

1. Locate the appropriate nomograph for the type of culvert selected and find K_e for the type of entrance to be used
2. Begin the nomograph solution by locating a startin point on the length scale; to locate the proper starting point on the length scales, follow the instructions below:
   a. If the n value of the nomograph corresponds to that of the culvert being used, select the length curve for the proper K_e and locate the starting point at the given culvert length. If a K_e curve is not shown for the selected K_e see (b) below. If the n value for the culvert selected differs from that of the nomograph, see (c) below.
   b. For the n of the nomograph and a K_e intermediate between the scales given, connect the given length on adjacent scales by a straight line and select a point on this line spaced between the two chart scales in proportion to the K_e values.
   c. For a different roughness coefficient, n, then that of the chart n, use the length scales shown with an adjusted length, L_1, calculated by the formula

$$L_1 = L \left(\frac{n_1}{n}\right)^2 \qquad \text{......................................(7)}$$

3. Using a straightedge, connect the point on the length scale to the size of culvert barrel and mark the point of crossing on the "turning line"
4. Pivot the straightedge between the point on the turning line and the given discharge rate. Read head in feet on the head (H) scale. For values beyond the limit of the chart scales, find H by solving Equation 4.

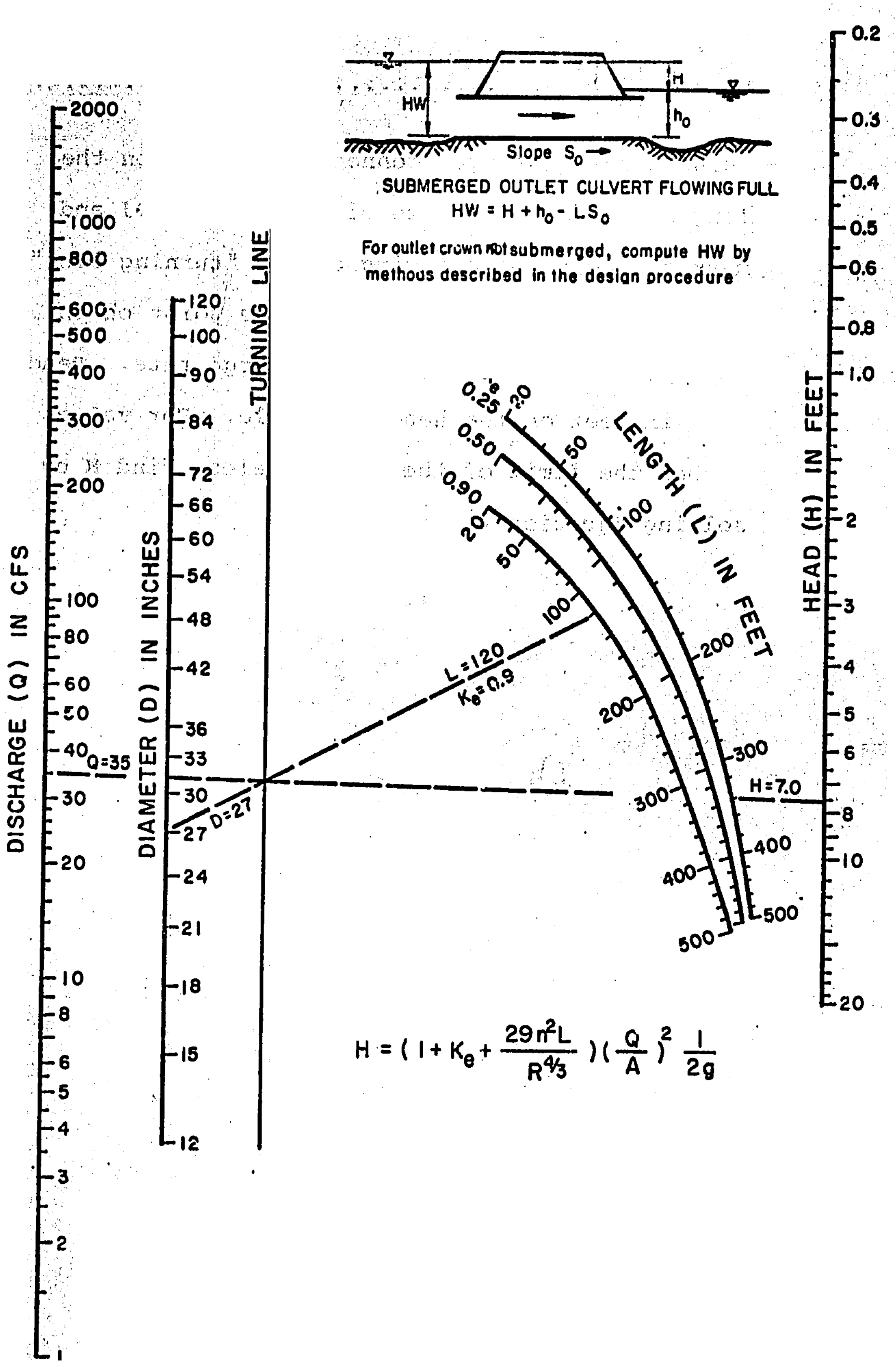


Figure 9. Head for corrugated metal pipe culverts flowing full with outlet control. (n = 0.024)

CHAPTER 3

METHOD OF FLOW ANALYSIS

In irrigation systems, free surface flow with outlet control is commonly encountered, which is the type of flow condition illustrated in Fig. 5d. This same flow condition is listed in Table 1 under outlet control with part full flow determined by the depth of tailwater. Also, culverts in irrigation systems are usually short, while being installed on a mild slope. As described in the previous chapter, a technique is not presently available for analytically describing free surface subcritical flow in culverts.

In recent years, an analytical technique for subcritical flow at open channel constrictions has been developed (12). This technique has been shown to apply to flow measuring flumes (13, 14), weirs (15), and bridge constrictions (16). Since a culvert is a flow constriction, this method of subcritical flow analysis should be applicable to describing free surface subcritical outlet control flow in culverts.

For culverts in irrigation systems placed on a mild slope and having a short length, three flow conditions should describe the types of flow to be encountered. Beginning with free surface inlet control, the downstream flow depth can be increased until the headwater is increased just slightly. Free surface flow will still exist, but flow conditions are now affected by changes in tailwater. This flow condition can be described as free surface outlet control. Finally, the tailwater can be raised sufficiently to submerge the outlet. For a short culvert installed on a mild slope, a submerged outlet should result in a submerged inlet, with the flow condition being submerged outlet control.

The method of flow analysis is different for each of the three flow conditions mentioned above. The technique for developing the discharge equation describing each of the flow conditions will be presented below.

Inlet Control

Under free surface inlet control conditions, critical depth occurs in the vicinity of the culvert entrance. This critical depth makes it possible to determine the flow rate knowing only the upstream depth, HW. This is possible because whenever critical depth occurs in the culvert, the upstream depth, HW, is not affected by changes in the downstream depth, TW, as shown in Figs. 10 and 11, thereby resulting in a unique relationship between discharge, Q, and headwater, HW.

For culvert operation with inlet control, a plot is made of flow rate, Q, in cfs, against headwater depth, HW, with Q as the ordinate and HW as the abscissa. When these

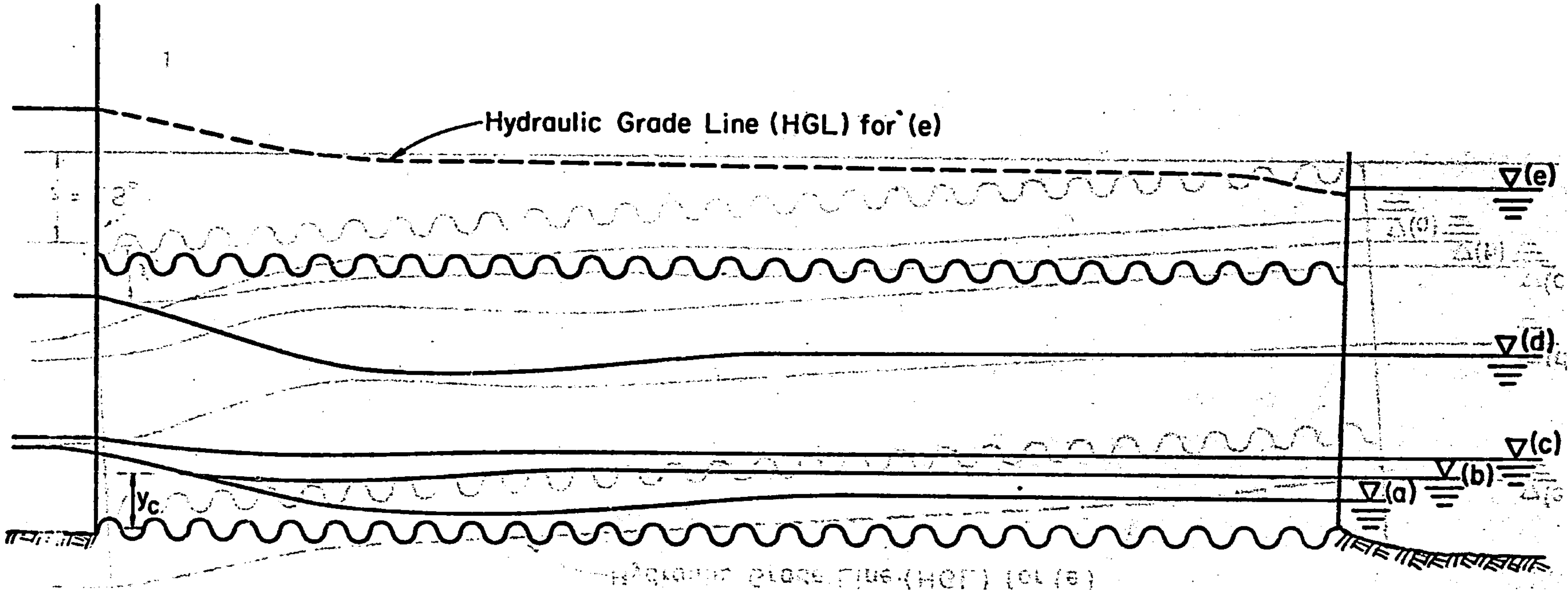


Figure 10. Illustration of flow conditions in a horizontal culvert.

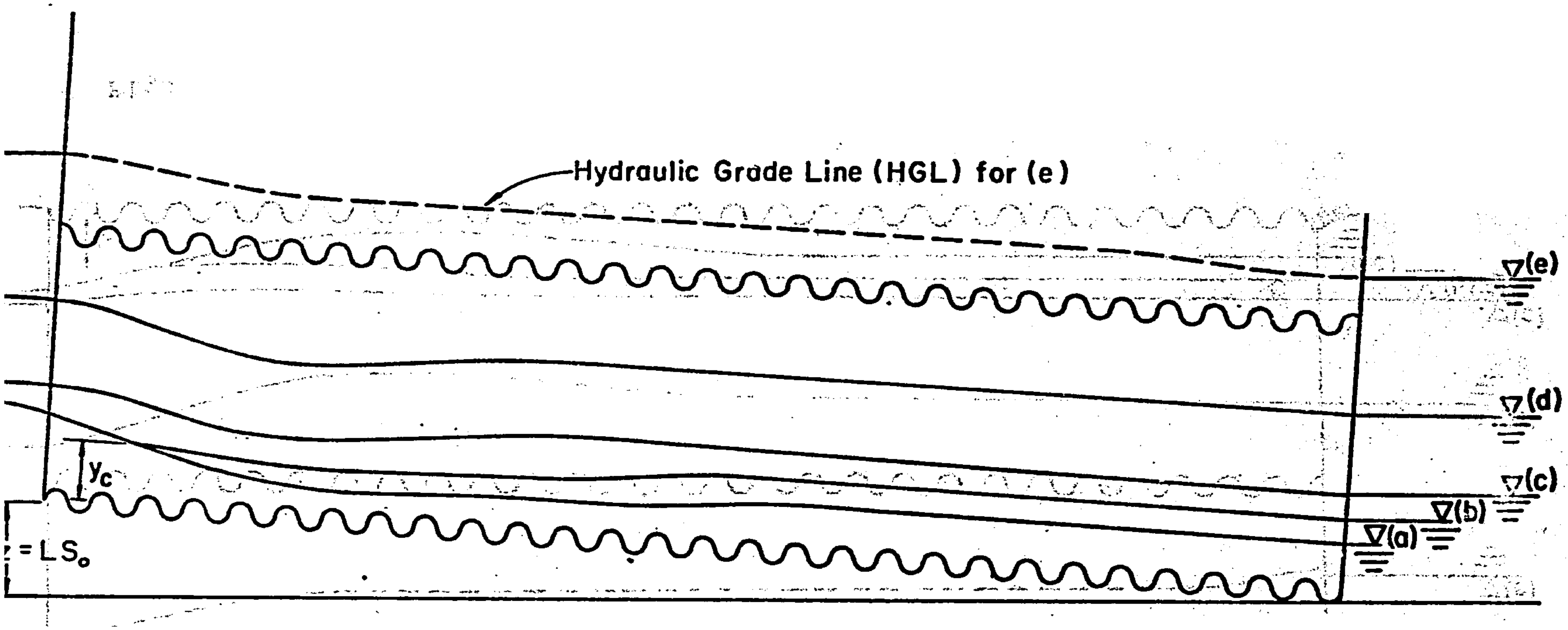


Figure 11. Illustration of flow conditions in a sloping culvert.

two variables are plotted on logarithmic paper, all of the points will fall on a straight line as shown in Fig. 12. The equation for this inlet control flow rating can be written as

$$Q = C(HW)^{n_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where Q = flow rate, in cubic feet per second;

C = inlet control flow coefficient;

HW = headwater depth, the vertical distance from the culvert invert at the entrance to the elevation of the upstream pool water surface, in feet; and

n_1 = inlet control flow exponent.

The value of the inlet control flow coefficient and inlet control flow exponent can be obtained by plotting the hydraulic data as shown in Fig. 12, where the slope of the rating is n_1 and C is the value of Q when HW is 1 foot.

Free Surface Outlet Control

When the flow conditions are such that the downstream flow depth, TW, is raised to the extent that the flow depths at any point through the structure become greater than critical depth, resulting in a change in the upstream depth, HW, then the culvert is operating under free surface subcritical flow, as shown in Figs. 10c, 10d, 11c, and 11d. The term which will be used to describe this particular flow condition will be "free surface outlet control." A culvert operating under free surface outlet control flow conditions

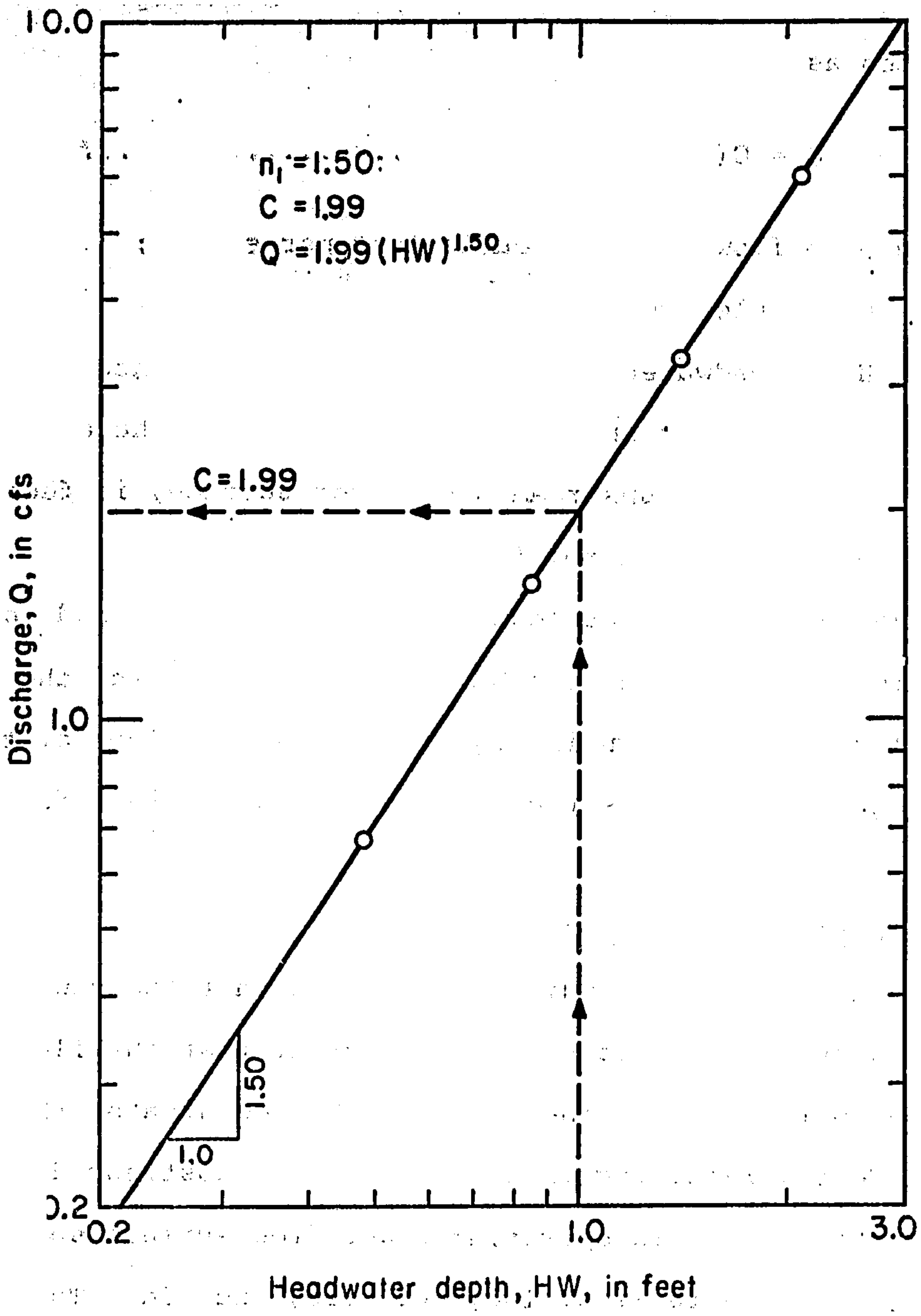


Figure 12. Typical inlet control flow rating curve showing actual data points and development of inlet control flow equation.

requires that two flow depths be measured, one upstream (HW) at the culvert invert, and one near the downstream end (one corrugation from outlet) of the culvert, such as TW.

The definition given to submergence, shown as S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth:

$$S = TW/HW \quad \text{.................................} (9)$$

For the more general case shown in Fig. 11, where the culvert is placed with a positive slope (sloping downward in the direction of flow), the submergence, S, is defined by the following expression:

$$S = TW/(HW + z) \quad \text{.............................} (10)$$

where z is the drop in elevation of the culvert invert between inlet and outlet. Thus, Equation 9 is only a special case of the more general definition for submergence represented by Equation 10. In other words, Equation 9 is valid when the culvert is horizontal (z=o). The drop of the culvert, which is z, can also be expressed as the culvert length, L, multiplied by the slope of the culvert barrel, S_o. Thus,

$$z = LS_o \quad \text{.....................................} (11)$$

and

$$S = TW/(HW + LS_o) \quad \text{............................} (12)$$

Free surface outlet control flow calibration curves are determined for the culvert by preparing three dimensional plots of the parameters describing free surface subcritical flow. The data are plotted on logarithmic paper with the discharge, Q, as the ordinate; difference in upstream and downstream depths of flow, (HW+z) - TW or H, as the abscissa; and the submergence, TW/(HW+z), as the varying parameter. Lines are then drawn connecting points of equal submergence. These are straight lines having a slope identical to the slope of the inlet control rating curve (which is n_1) for the same geometry.

From the submerged flow plots, an equation has been developed (12) which can be used to describe the flow rate through the culvert. The equation is:

$$Q = \frac{C_1 (H)^{n_1}}{\left[-\log(S+C_2)\right]^{n_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where Q = flow rate in cfs;

H = difference between upstream and downstr depths, HW+z-TW, in feet;

HW = upstream flow depth, in feet;

TW = downstream flow depth, in feet;

C_1 = free surface outlet control coefficient

n_1 = inlet control flow exponent;

n_2 = free surface outlet control exponent;

S = submergence, TW/(HW+z); and

C_2 = a constant for the approximate free surface subcritical flow distribution.

For the case of the culvert, C_2 can be chosen as being equal to zero. Therefore, Equation 13 can be reduced to:

$$Q = \frac{C_1 (H)^{n_1}}{(-\log S)^{n_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

In order to obtain values for n_2 and C_1 for the culvert, the following steps were taken:

1. The free surface outlet control rating plots were drawn for the culvert;
2. The lines of constant submergence were extended until they crossed the abscissa at $H = 1.0$, where the corresponding ordinate value of Q, designated as $Q_{H=1}$, is noted (Fig. 13);
3. A plot was then prepared on logarithmic paper with $Q_{H=1}$ plotted on the ordinate and -log S plotted along the abscissa (Fig. 14). A single straight line having a negative slope will result from plotting the data. The general format of the equation describing this relationship is:

$$Q_{H=1} = C_1 (-\log S)^{-n_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

4. The free surface outlet control coefficient, C_1, is the value of $Q_{H=1}$ when -log S = 1.0, as illustrated by Fig. 14

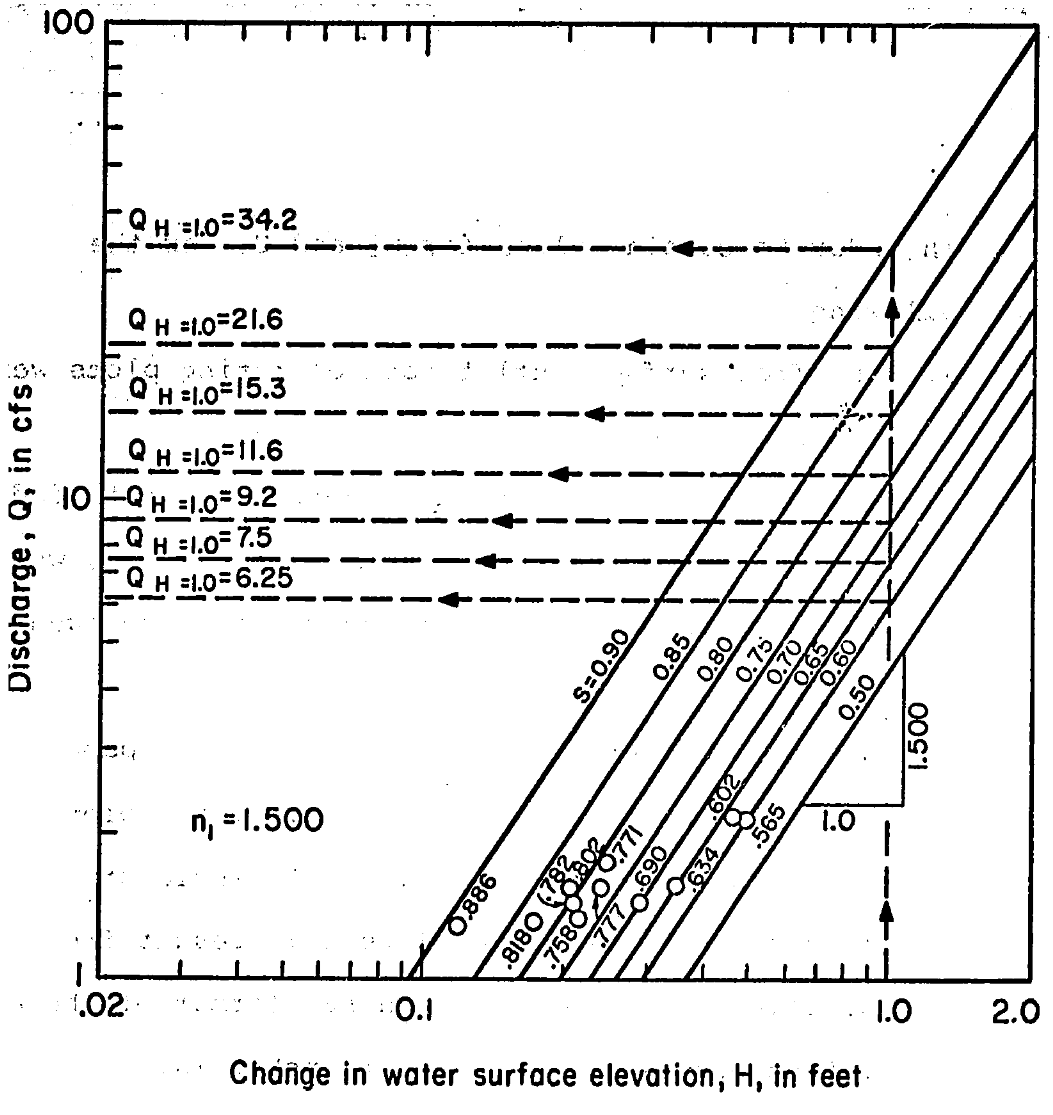


Figure 13. Typical free surface subcritical flow rating curves for 12" ϕ corrugated metal pipe 10' long with 0.0000 slope.

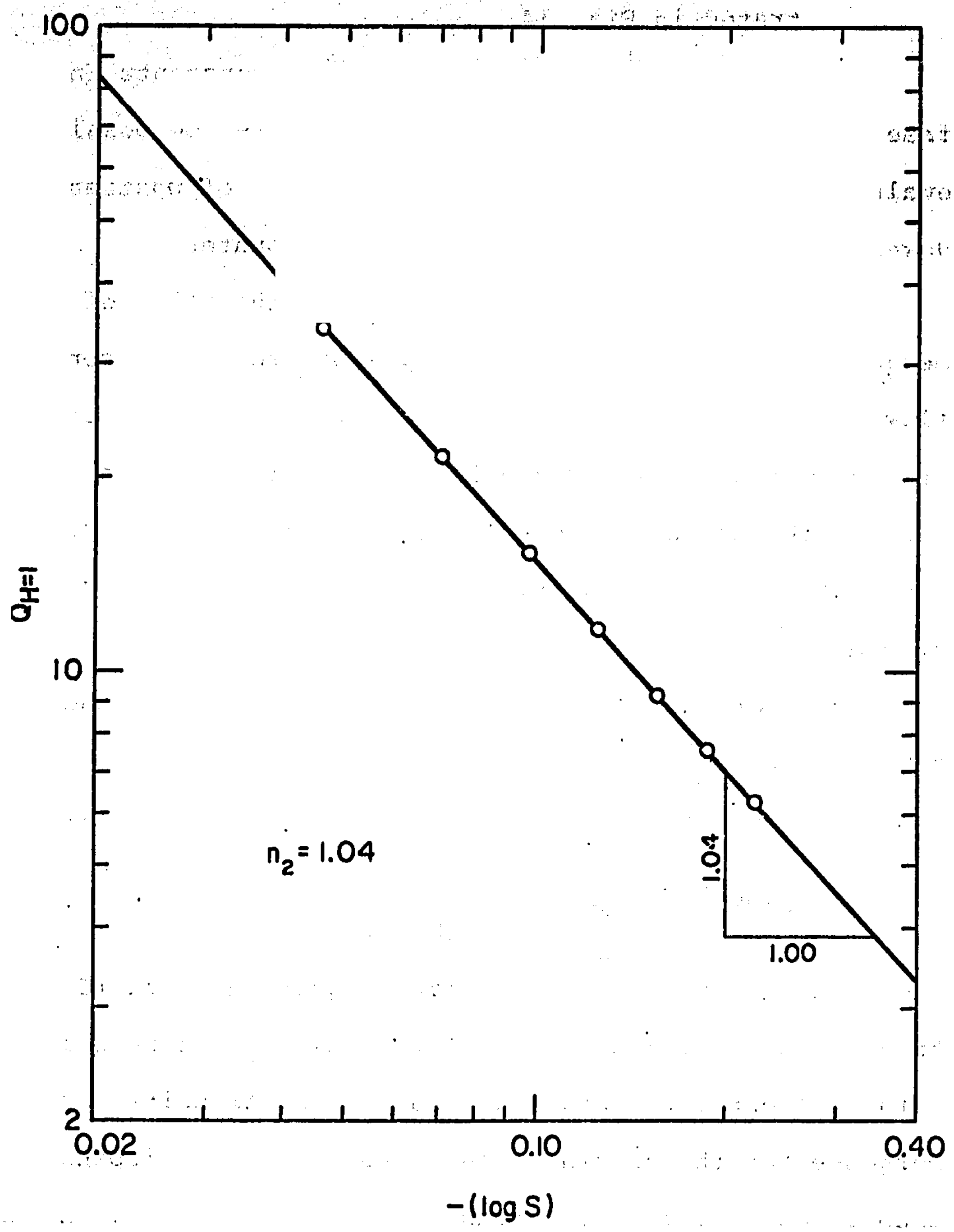


Figure 14. Typical plot for developing free surface subcritical flow coefficient, C_1, and free surface subcritical flow exponent, n_2.

5. The free surface outlet control exponent, n_2, is the slope of the straight-line relationship illustrated in Fig. 14.

Having determined the values of the constants in the free surface outlet control equation, it is now possible to evaluate the flow rate for any combination of upstream and downstream flow depths that might be encountered.

The transition submergence, S_t, is the value of submergence at which the discharge passes from inlet control flow condition to free surface outlet control flow condition or vice versa (Figs. 10 and 11). Under this unique condition, both the inlet control flow equation and the free surface outlet control equation will predict the same value of discharge.

To determine the transition submergence, S_t, the inlet control flow equation and the free surface outlet control equation are set equal to one another (Eqs. 8 and 14).

$$C(HW)^{n_1} = \frac{C_1(HW + z - TW)^{n_1}}{\left[-\log \left[TW/(HW+z)\right]\right]^{n_2}} \quad \ldots\ldots\ldots\ldots\ldots (16)$$

The value of submergence, S, makes Equation 16 valid is the transition submergence, S_t. This equation can be solved by trial and error to obtain a value of the transition submergence for the special case where z=0. For sloping open channel constrictions, a transition submergence can be obtained if energy is used, rather than flow depths (16).

Submerged Outlet Control

When the flow conditions are such that the downstream flow depth, TW, is raised to the extent that the culvert is completely full throughout the culvert length, resulting in a change in the upstream depth, HW, then the culvert is operating under submerged outlet control as shown in Figs. 10 and 11 (water surface profile e). The culvert operating under submerged outlet control flow conditions also requires that two flow depths be measured, one upstream (HW) at the culvert invert, and one downstream near the end (one corrugation from outlet) of the culvert (TW).

For the submerged outlet control flow condition, a plot is made of flow rate, Q, against the difference between upstream and downstream flow depths, H, with Q as the ordinate and H as the abscissa. When these two variables are plotted on logarithmic paper, all of the points will fall on a straight line as shown in Fig. 15. The equation for this submerged outlet control flow rating can be written as:

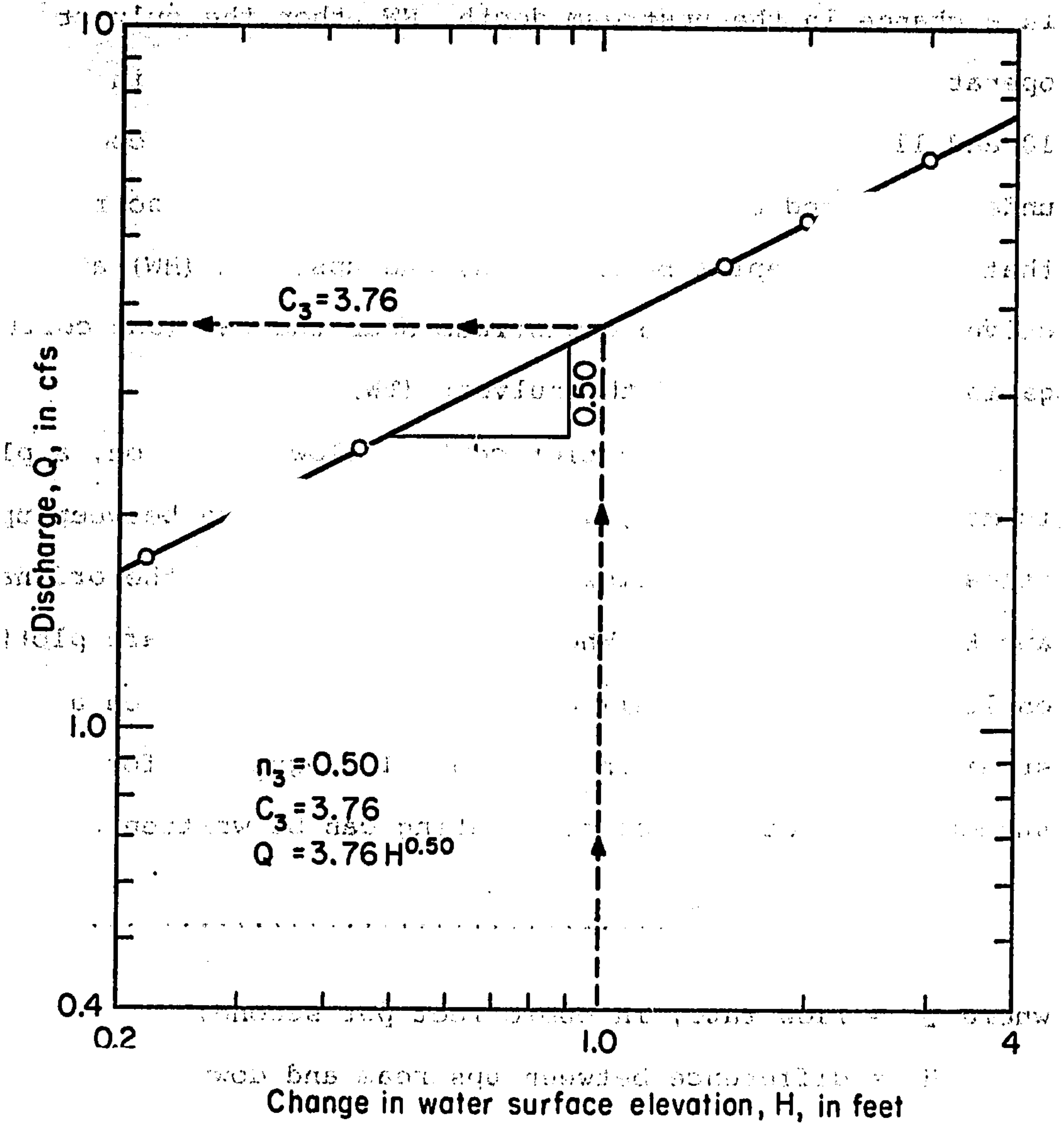
$$Q = C_3(H)^{n_3} \quad \text{.................................} (17)$$

where Q = flow rate, in cubic feet per second;

H = difference between upstream and downstream flow depths, HW+z-TW;

C_3 = submerged outlet control flow coefficient, which is the value of Q when H = 1 foot; and

n_3 = submerged outlet control flow exponent, which is the slope of the submerged outlet control flow



Typical submerged outlet control flow rating curve showing actual data points and development of submerged subcritical flow equation.

rating when plotted on logarithmic paper.

In order to determine whether inlet control or free surface outlet control flow conditions exist in a culvert it is necessary to calculate the submergence, which is then compared with the transition submergence to determine which flow equation should be used. If the submergence is less than the transition submergence, then inlet control conditions exist; but the culvert is operating under free surface outlet control flow conditions if the submergence is greater than the transition submergence, S_t.

In order to determine whether free surface outlet control flow or submerged outlet control flow conditions exist in a culvert, it is at least required that the culvert outlet be just submerged, while the culvert inlet is also submerged. Thus, the downstream flow depth, TW, must exceed the diameter or height of the culvert, D.

CHAPTER IV

EXPERIMENTAL DESIGN

Many of the culverts encountered in irrigation systems have free surface (open channel) flow occurring throughout the length of the culvert. In irrigation channels, downstream conditions will likely control flow conditions in the culvert. Thus, free surface outlet control flow conditions will exist. At the present time, only a crude approximation of the discharge relation is available for free surface flow in culverts affected by downstream conditions (free surface outlet control).

The development of an analytical technique for describing free surface outlet control would be advantageous as an improved technique for designing culverts which will operate under this particular flow condition. More importantly, an accurate analytical method would provide the means whereby culverts could be rated as flow measuring devices. Since numerous culverts are encountered in irrigation systems, the development of discharge ratings would allow each culvert to be used as a flow measurement structure, if desired. Also, the smaller culverts could be used as a portable flow measuring device.

In recent years, an analytical technique for subcritical flow at open channel constrictions has been developed (12). This technique has been shown to apply to flow measuring flumes (13,14), weirs (15), and bridge constrictions (16). Since a culvert is a flow constriction, this method of subcritical flow analysis should be applicable to describing free surface subcritical outlet control flow in culverts.

For culverts in irrigation systems placed on a mild slope and having a short length, three flow conditions should describe the types of flow to be encountered. Beginning with free surface inlet control, the downstream flow depth can be increased until the headwater is increased just slightly. Free surface flow will still exist, but flow conditions are now affected by changes in tailwater. This flow condition can be described as free surface outlet control. Finally, the tailwater can be raised sufficiently to submerge the outlet. For a short culvert installed on a mild slope, a submerged outlet should result in a submerged inlet, with the flow condition being submerged outlet control.

The method of flow analysis is different for each of the three flow conditions mentioned above. The technique for developing the discharge equation describing each of the flow conditions has been described in the previous chapter.

To test the validity of the subcritical flow technique (12) to analytically describe free surface outlet control, a 12-inch diameter corrugated metal culvert was selected. A square-edged flush headwall was attached to the culvert. Thus, only one inlet condition was used in the experimental design. Three culvert lengths, along with four barrel slopes for each length, were incorporated in the experimental program. For a culvert length of 5 feet, barrel slopes of 0.0000 (horizontal), 0.0333, 0.0667, and 0.1167 were used. In addition to the horizontal case, slopes of 0.0167, 0.0333, and 0.0583 were used with the 10-foot culvert length. The 20-foot culvert length utilized slopes of 0.0000, 0.0083, 0.0167, and 0.0292.

Using four slopes for each of three culvert lengths provided 12 cases to be investigated in the laboratory. For each case, sufficient hydraulic data had to be collected in order that discharge ratings could be developed for the three flow conditions of free surface inlet control, free surface outlet control, and submerged outlet control.

CHAPTER V

EXPERIMENTAL FACILITY

This hydraulic experimental study utilized the 4-feet wide by 60-feet long recirculating flume located in the Engineering Research Center at Colorado State University.

The layout of the experimental recirculating flume system is shown in Figs. 16 and 17a. The 12-inch diameter corrugated metal culvert to be tested was set inside the recirculating laboratory flume as shown in Fig. 17b. Water was pumped into the flume system by a centrifugal pump through a discharge pipe into a headbox located at the entrance to the laboratory flume. Water was obtained from the large sump under the laboratory floor and pumped (using a small pump) into the sump of the pump-discharge pipe-flume system. After a suitable volume of water was obtained for the recirculating system, the valve gate connecting the large sump to the small sump could be closed. The flow in the system could be adjusted with the valve in the discharge pipe.

A tailwater gate was located at the flume exit to allow changing the tailwater depth. The gate opening was changed after each run to provide a new tailwater depth, thereby allowing sufficient hydraulic data to be generated for developing discharge relations for free surface outlet control and submerged outlet control.

At the end of the 4-foot laboratory flume, there was a tank which received the falling water from the flume exit.

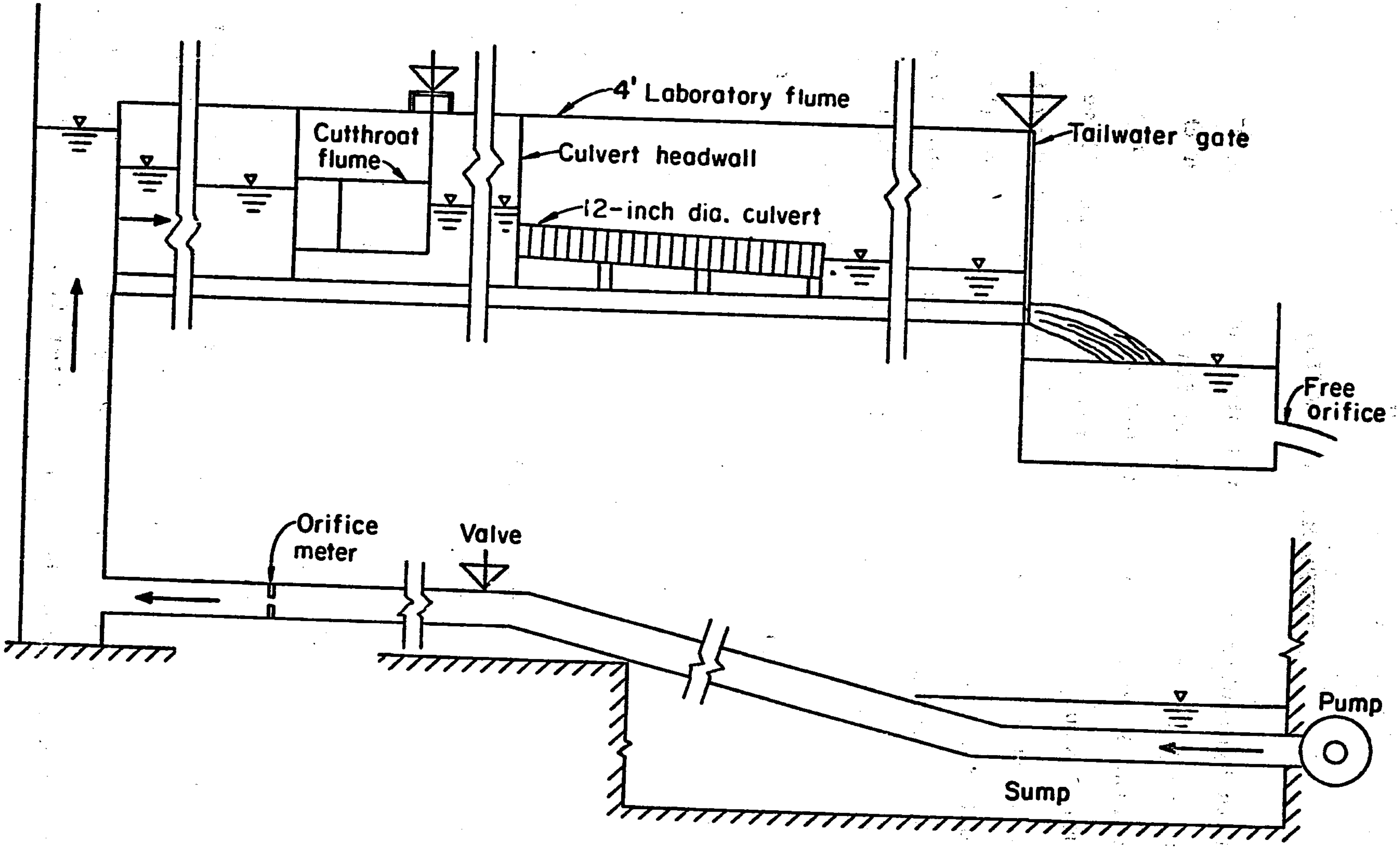
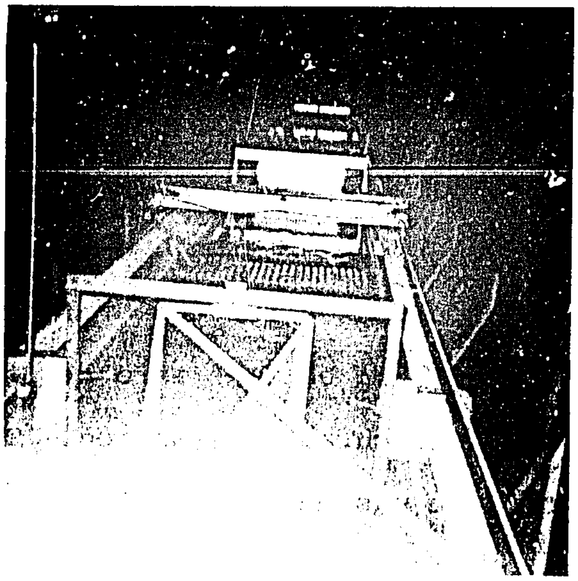
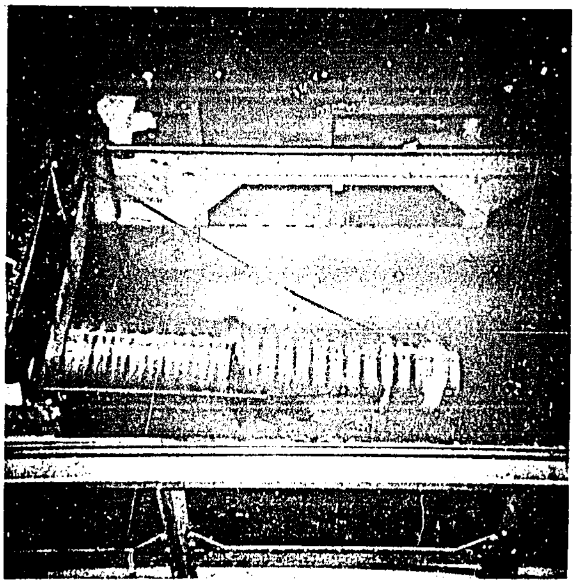


Figure 16. Experimental flume facility.



(a) Experimental flume looking downstream with Cutthroat flume in foreground.



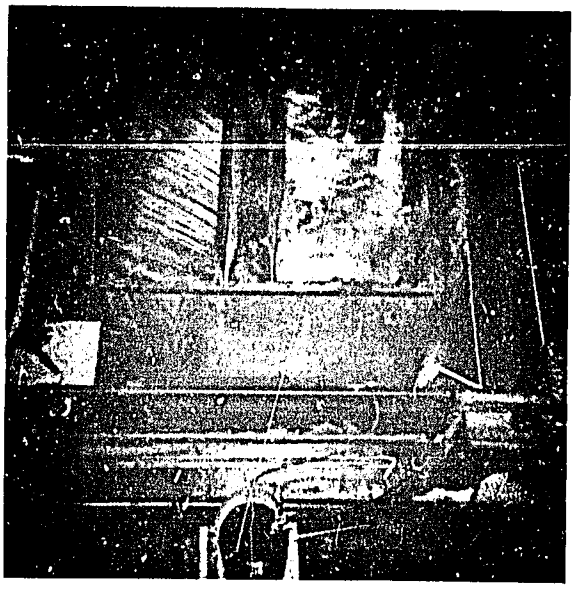
(b) Experimental culvert rigidly attached to rotating headwall.

Figure 17. Experimental flume and culvert.

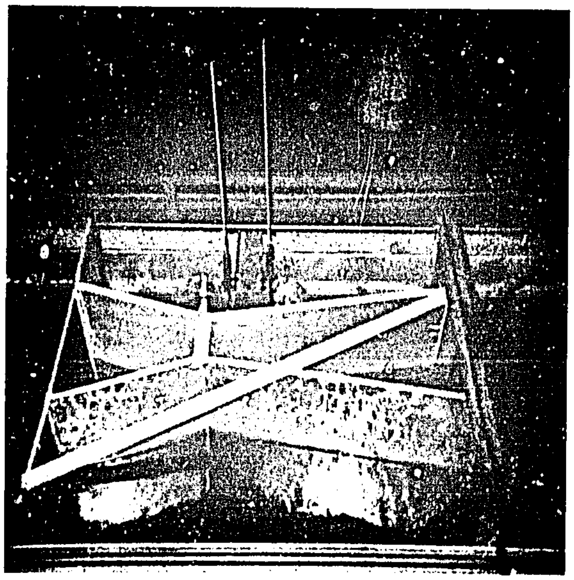
The water was discharged from the tank through a free orifice which was used as a flow measuring device (Fig. 18a). The width of the orifice is controlled by a sliding gate that moves sideways, which can be set for openings of 0.5 feet, 1.0 feet, 1.5 feet, and full opening. Although increments of 0.5 feet were commonly used for the orifice width, it is possible to set any opening between zero and full opening, providing the width is accurately measured. The depth of water above the orifice was measured with a hook gage in a stilling well set beside the tank, which was connected by means of a flexible tube to a piezometer tap located in the wall of the tank (Fig. 18a). The water discharging from the orifice dropped into the sump and then passed through the centrifugal pump, again.

An orifice meter is located in the water delivery pipeline to the experimental flume. Piezometer taps are located upstream and downstream from the orifice meter. The differential head across the orifice is read by means of a manometer board.

The third flow measuring device was a Cutthroat flume having a 6-inch throat width and 54-inch flume length (Fig. 18b). The Cutthroat flume was set horizontally at some height above the laboratory flume floor. Two stilling wells were connected by flexible tubes to the piezometer taps located in the flume wall. The capacity of the recirculating flume system was approximately 5 to 6 cfs with the Cutthroat



(a) Tank with free orifice.



(b) Cutthroat flume.

Figure 18. Flow measuring devices used in experiments.

flume installed. The range of discharges utilized in the experimental program ranged from less than 1 cfs to the full capacity of the system.

The 12-inch diameter corrugated metal pipe (CMP) culvert was placed inside the 4-foot flume with the bottom of the culvert placed 7 inches above the laboratory flume floor. The upstream end of the culvert was welded to the steel headwall, which had a rubber seal around the periphery for leakage protection. The headwall served as the hinge for tilting the culvert. A flexible rubber sheet was used between the headwall of the culvert and the channel iron cutoff attached to the walls and the floor of the laboratory flume, thereby allowing the culvert to be tilted without any leakage occurring. Wood blocks were placed at various points underneath the culvert to support the pipe in order to maintain the required slopes. The maximum drop of the culvert exit was approximately 7 inches.

Piezometer taps were located along the culvert invert. Also, a piezometer tap was placed in the culvert headwall. Plastic tubing was attached to the culvert taps and piezometer taps located in the floor of the laboratory flume. Finally, plastic tubing was used between the floor taps and a tilting manometer board, which allowed reading the flow depths directly.

In running the hydraulic tests, the culvert was set horizontally and 8 different discharges were run with the tailwater gate being fully open, thereby resulting in inlet control flow conditions. Next, a constant discharge was set with the tailgate fully open. Then, the tailgate was lowered into the flow, which resulted in an increased tailwater depth. After recording the piezometer readings, the tailgate was again lowered and the piezometers read again. This procedure was continued until sufficient data had been collected to describe free surface outlet control and submerged outlet control. Then, a new constant discharge was set and another series of hydraulic data collected. Four discharges were run for each slope and each pipe length.

CHAPTER VI

RESULTS

Before presenting the experimental results, some mention must be made regarding the accuracy of the data. Limitations in the experimental facility resulted in considerable variation or scatter in the data, which also necessitated additional laboratory efforts to overcome certain difficulties.

Data Limitations

Three flow measuring devices were installed in the experimental facility in order to provide a check on the discharge measurements. A Cutthroat flume was installed upstream from the experimental culvert, while a free orifice was installed at the outlet of a box which collected the flow exiting from the tilted flume, and an orifice plate (which is the flow measuring device normally used for this particular tilting flume) installed in the water supply line.

Previous investigators had already encountered difficulties in using the orifice plate. Although extreme care was taken in bleeding air from the manometer tubes, the measured differential head produced very erratic discharge measurements. Thus, the free orifice and Cutthroat flume had to be relied upon for accurate discharge measurements.

The accuracy of the free orifice is primarily influenced by the proximity of the orifice plate to the plunging jet entering the tailwater box. The accuracy of the Cutthroat flume was primarily influenced by the degree of submergence. For many of the runs, the submergence in the Cutthroat flume was very high, resulting in larger errors in the discharge measurement.

Another factor which greatly influences the accuracy of discharge measurement in this particular facility is the variation in discharge that occurs in the system. This variation may be due to the accumulation of air in the water supply line, which is periodically removed when the air pockets become too large, thereby resulting in surges through the flow system. Another possibility would be that the pumps do not operate at a constant speed.

Another constraint was the limited range of flow depths that could be utilized. This was a result of using a small culvert diameter (12 inches), the limited submergence of the inlet, and trying to limit the degree of submergence in the Cutthroat flume.

In any event, considerable difficulty was experienced in developing accurate discharge ratings for the experimental culvert under the three flow conditions being studied. However, data of sufficient accuracy was generated to prove that the subcritical flow analysis previously developed for flumes and weirs would apply to free surface outlet control flow conditions in a culvert.

Inlet Control Ratings

The inlet control data were first analyzed using a computer program involving a regression analysis in order to arrive at estimates of the inlet control coefficient, C, and inlet control exponent, n_1. The variation of the inlet control exponent with barrel slope is shown in Fig. 19, which portrays a marked variation in n_1. From a theoretical standpoint, the inlet control exponent would not be expected to have a value less than 3/2. Yet, four of the data points have values of the inlet control exponent less than 3/2. This result must be attributed to the sensitivity of n_1 to small errors in the discharge, Q, since the flow depth, HW, would be a fairly accurate measurement.

Since Fig. 19 shows a somewhat random variation of n_1 around the value 3/2, the next step in the analysis was to let $n_1 = 3/2$ and test the data for the variation in the inlet control coefficient, C. The results of this analysis are shown in Fig. 20, where a fairly consistent relationship for C is developed as a function of the barrel slope for each culvert length investigated.

From Equation 3, the inlet control rating is expected to be a function of the barrel slope when the inlet is submerged (full pipe flow). Utilizing a value of k which

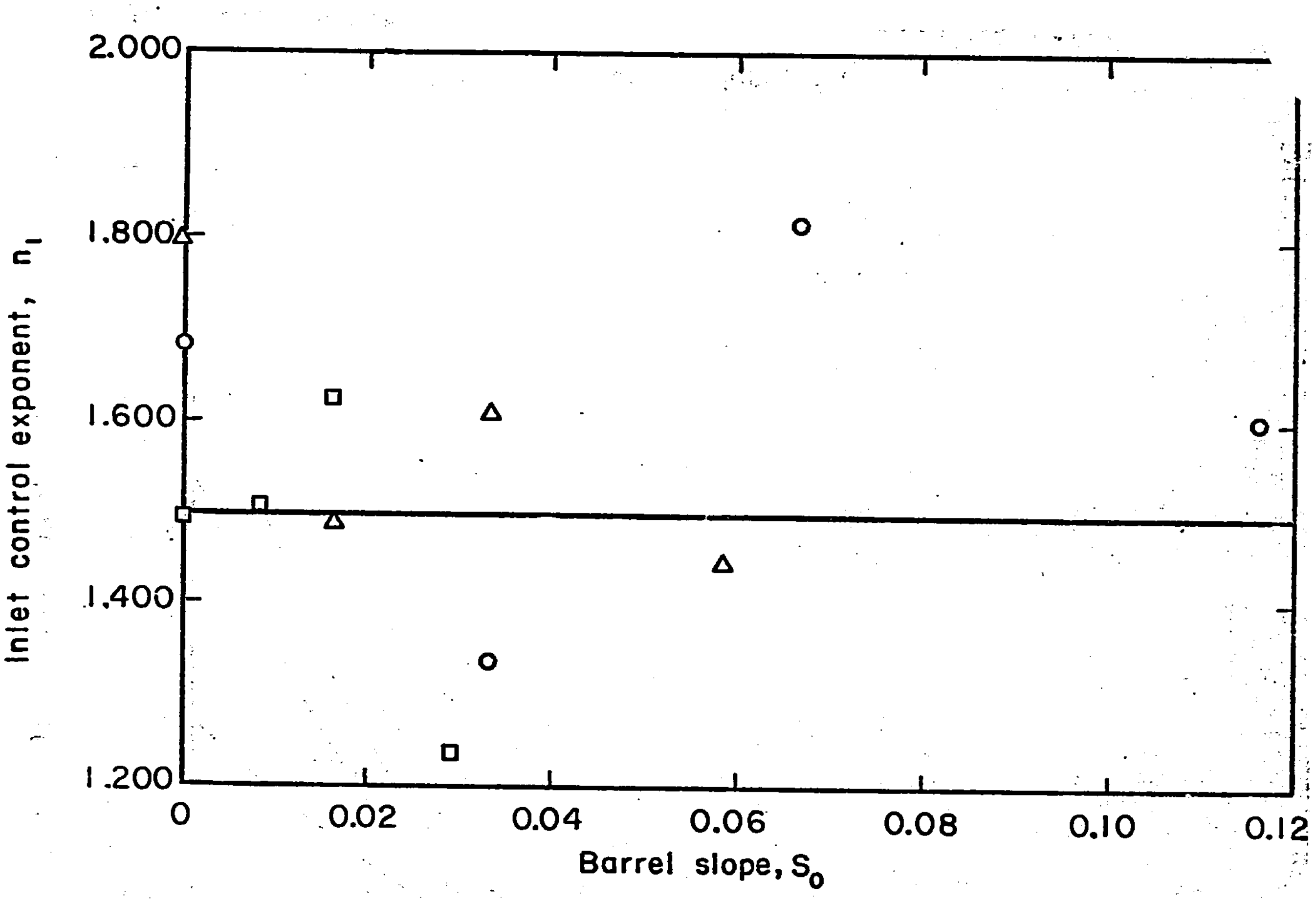


Figure 19. Variation of inlet control exponent with barrel slope.

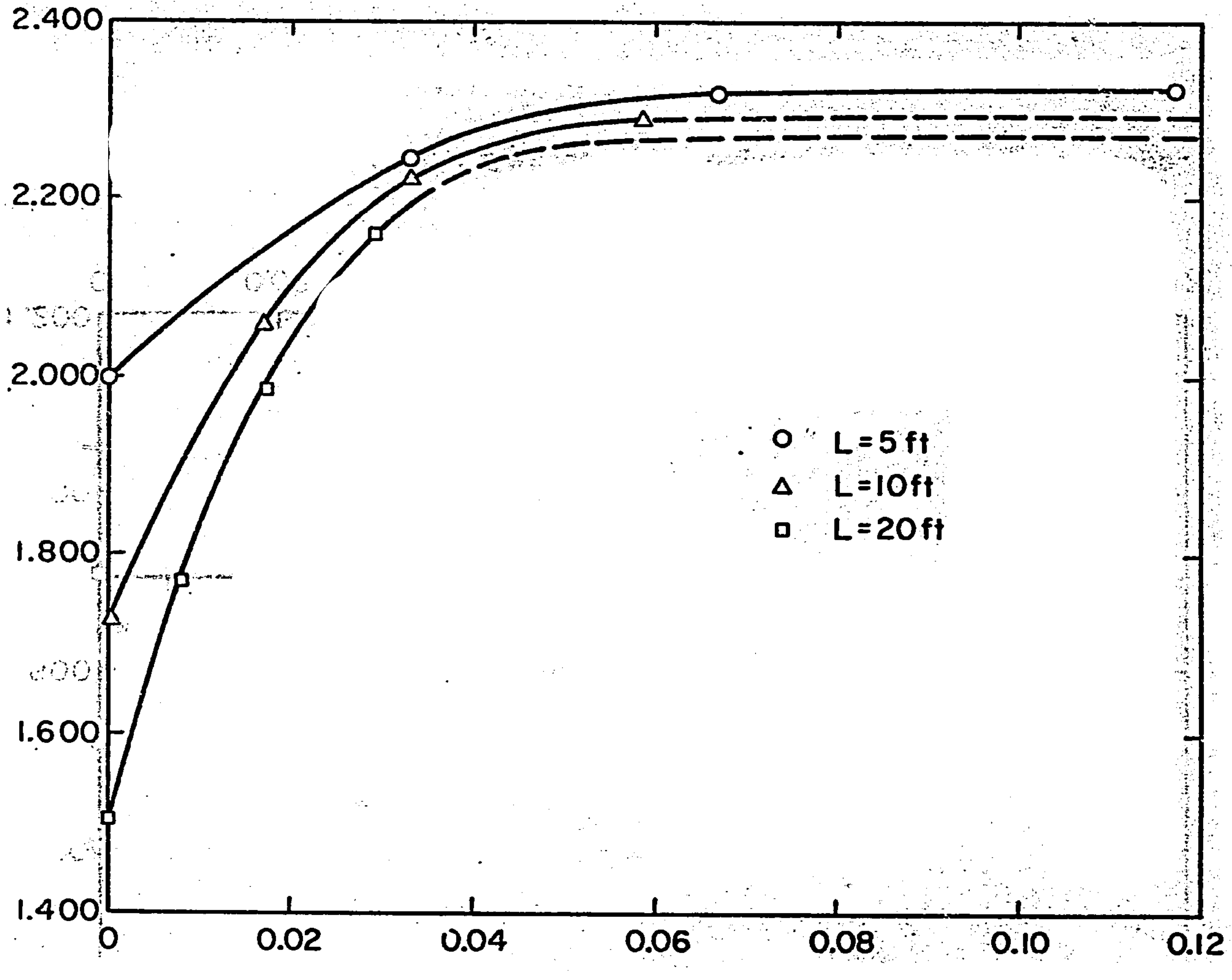
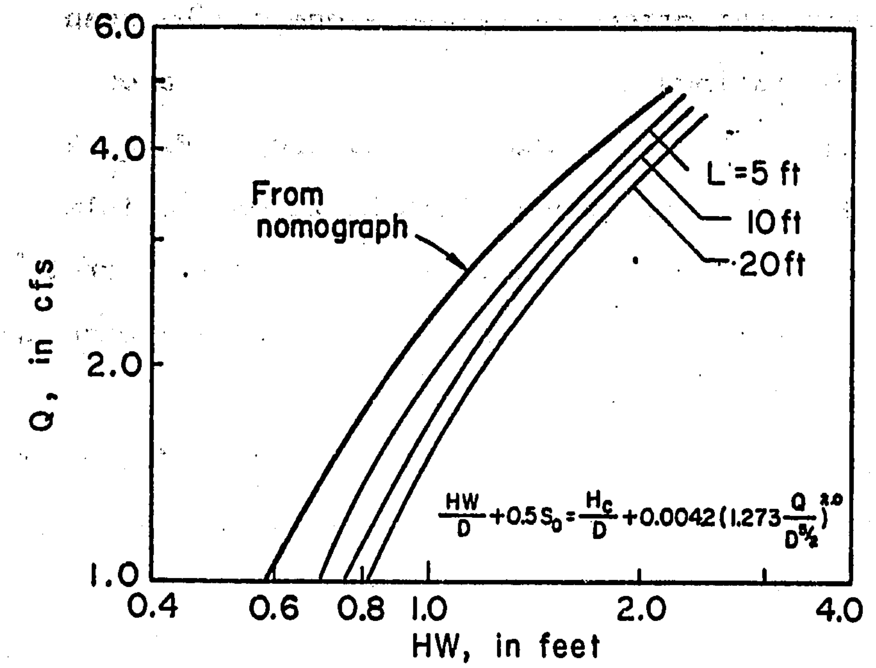


Figure 20. Relationships between inlet control coefficient and barrel slope for $n_1 = 3/2$.

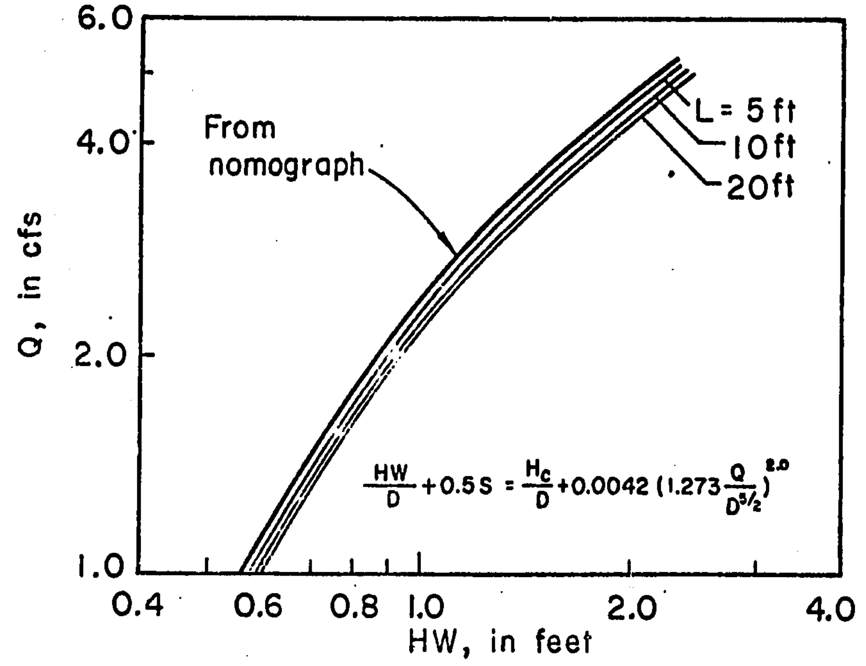
would best fit the experimental data collected as a part of this study, the effect of barrel slope can be seen by comparing the ratings in Figs. 21a and 21b for a constant culvert length. For a constant barrel slope, Figs. 21a or 21b show the effect of culvert length, L, on the inlet control rating. Thus, it can be seen that both barrel slope and culvert length exert considerable influence upon the inlet control rating.

The results of using different techniques for arriving at an inlet control rating are shown in Figs. 22, 23, and 24 for culvert lengths of 5 feet, 10 feet, and 20 feet, respectively. Five different techniques were employed. First of all, the n_1 developed from the line of best fit for the experimental data using regression analysis was tested. Secondly, a value of n_1 developed from smooth curve relationships involving the barrel slope were tested against the data. Next, the line of best fit through the data using a value of the inlet control exponent equal to 3/2 was used. The results of these three analyses are listed in Table 3. Finally, two different values of k were used in Equation 3 for comparison with the actual experimental data.

Because the experimental data covers a narrow range of inlet flow depths, it can be seen from Figs. 22, 23, and 24 that a considerable degree of latitude exists as to the format of the inlet control ratings. For purposes

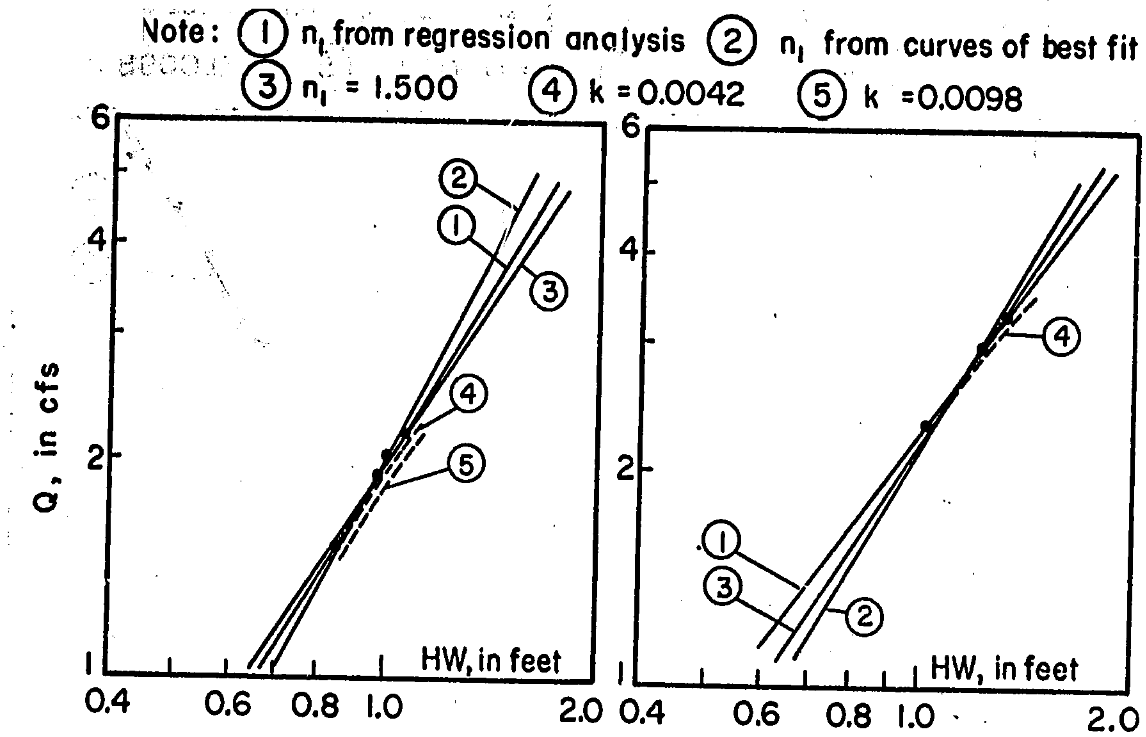


(a) $S_0 = 0.00$

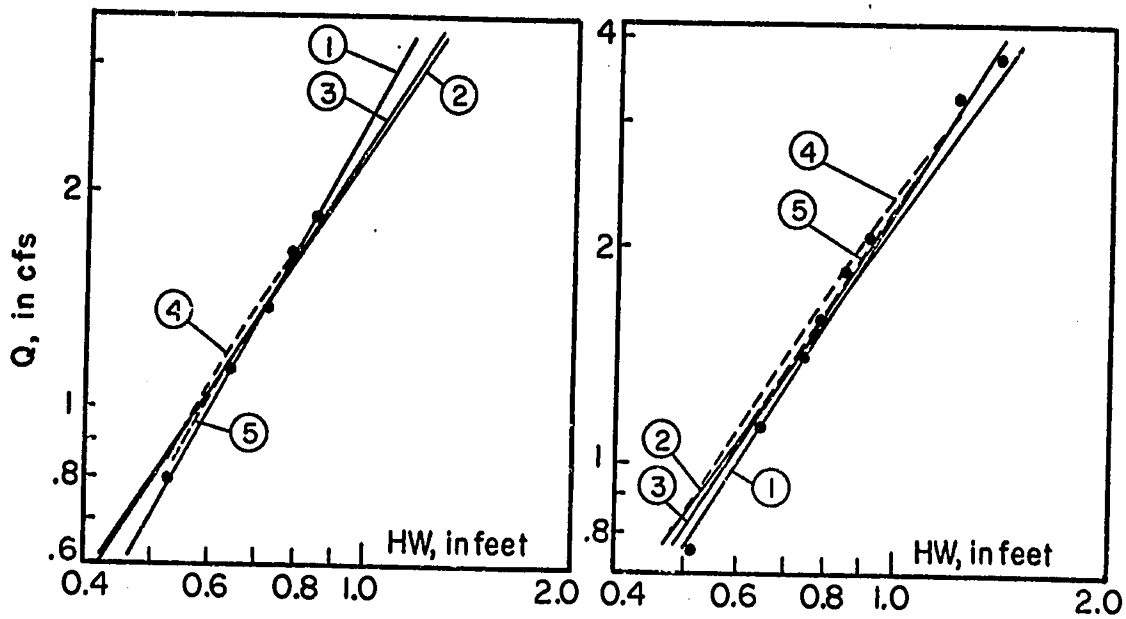


(b) $S_0 = 0.05$

Figure 21. Inlet control flow ratings from previous literature.

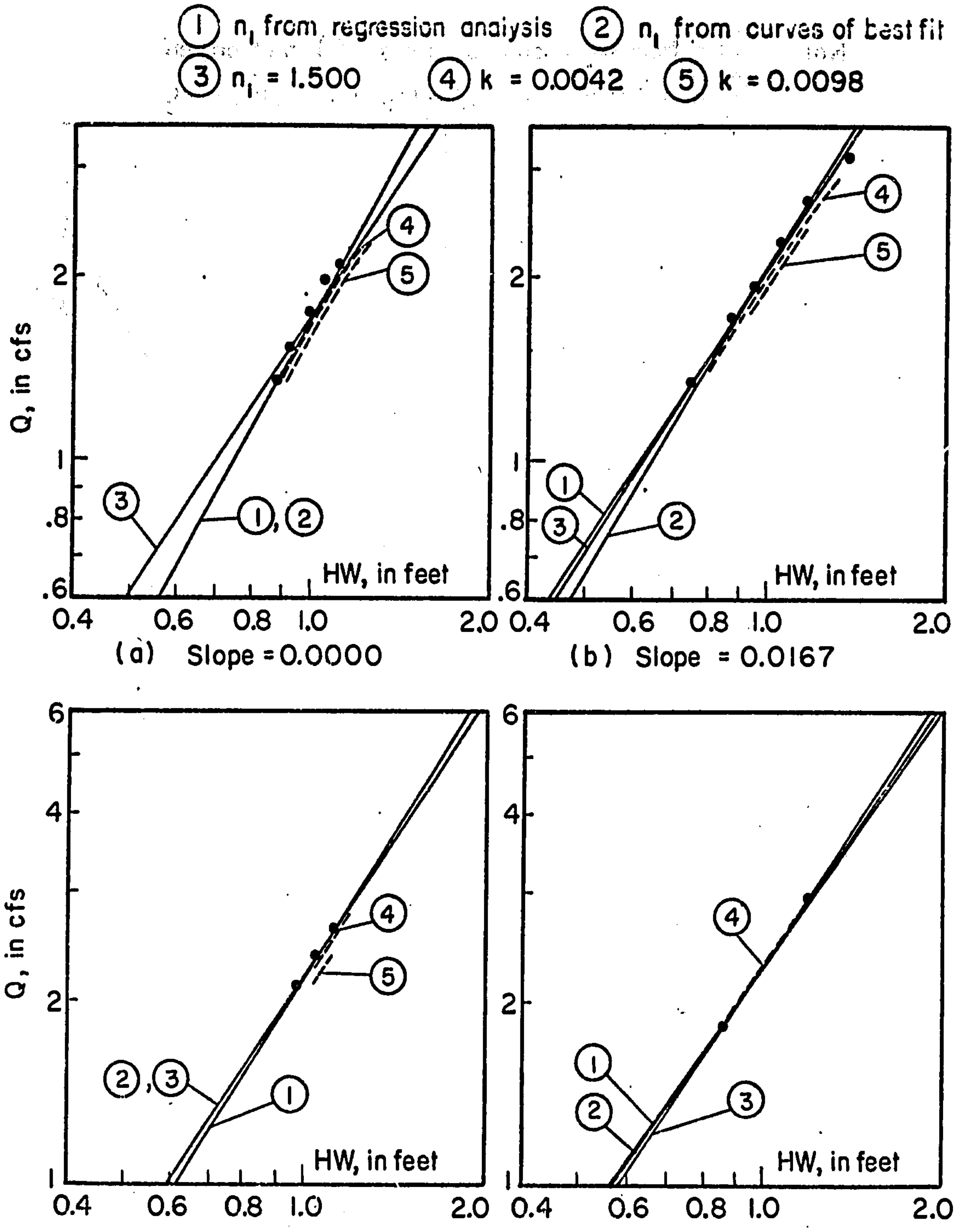


(a) Slope = 0.0000 (b) Slope = 0.0333



(c) Slope = 0.0667 (d) Slope = 0.1167

Figure 22. Inlet control ratings for experimental culvert length of 5 feet using various criteria.



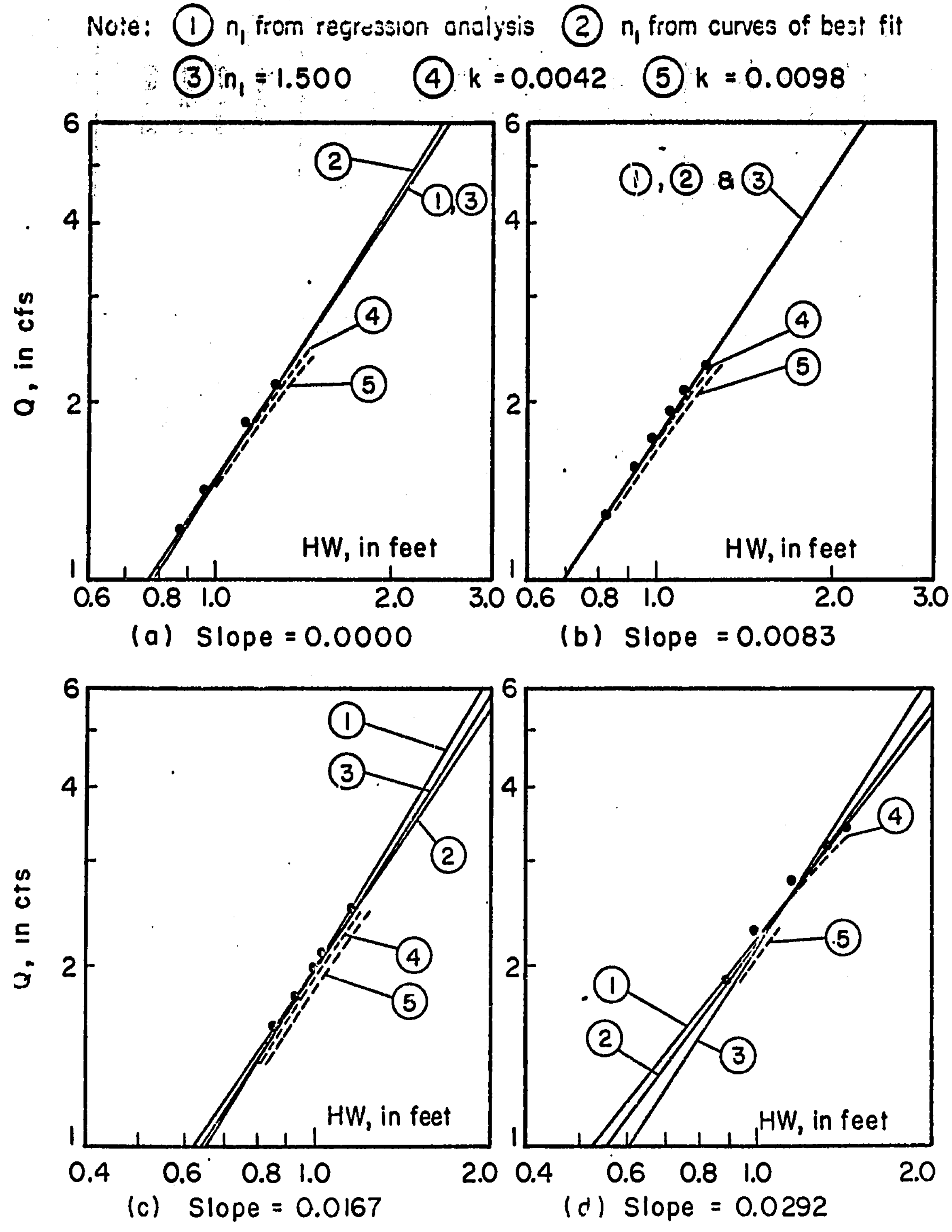
(a) Slope = 0.0000

(b) Slope = 0.0167

(c) Slope = 0.0333

(d) Slope = 0.0583

Figure 23. Inlet control ratings for experimental culvert length of 10 feet using various criteria.



(a) Slope = 0.0000
(b) Slope = 0.0083
(c) Slope = 0.0167
(d) Slope = 0.0292

Figure 24. Inlet control rating for experimental culvert length of 20 feet using various criteria.

Table 3. Comparison of C values obtained from the three straight line fittings for inlet control flow.

Culvert Length and Slope	Criteria No. 1 Mathematical Regression		Criteria No. 2 S_o-n_1 Curves of Best Fit		Criteria No. 3 $n_1 = 3/2$	
L, S_o	n_1	C	n_1	C	n_1	C
L=5 ft						
S_o=0.0000	1.683	2.012	1.910	2.020	1.500	1.999
S_o=0.0333	1.334	2.305	1.665	2.180	1.500	2.244
S_o=0.0667	1.819	2.491	1.515	2.260	1.500	2.319
S_o=0.1167	1.602	2.290	1.413	2.220	1.500	2.324
L=10 ft						
S_o=0.0000	1.799	1.714	1.800	1.700	1.500	1.727
S_o=0.0167	1.489	2.059	1.650	2.060	1.500	2.060
S_o=0.0333	1.606	2.212	1.510	2.221	1.500	2.221
S_o=0.0583	1.443	2.289	1.400	2.288	1.500	2.288
L=20 ft						
S_o=0.0000	1.498	1.506	1.580	1.500	1.500	1.506
S_o=0.0083	1.507	1.772	1.507	1.773	1.500	1.773
S_o=0.0167	1.634	1.995	1.430	1.984	1.500	1.984
S_o=0.0292	1.235	2.251	1.335	2.220	1.500	2.160

of simplicity in the ratings to follow regarding the free surface outlet control and submerged outlet control flow conditions, criterion 3 employing $n_1 = 3/2$ has been selected as representing the inlet control ratings.

Free Surface Outlet Control Ratings

In order to determine the free surface outlet control ratings, the coefficient, C_1, and exponent, n_2, in Equation 14 must be evaluated. This is accomplished using the plots shown in Figs. 25, 26, and 27 which have been prepared for the experimental culvert lengths of 5 feet, 10 feet, and 20 feet, respectively. Each rating can be described by Equation 15. The slope of these ratings, which is the free surface outlet control exponent, n_2, has a constant value of 1.04. Thus, the variation in the free surface outlet control ratings due to barrel slope, S_o, and culvert length, L, can be expressed in terms of the free surface outlet control coefficient, C_1.

Because of the difficulties previously described in collecting accurate discharge data, there is considerable scatter in the data points shown in Figs. 25, 26, and 27, which results in inaccuracies in arriving at the value of the coefficient, C_1. To partially overcome this problem, the first estimates of the free surface outlet control coefficient, C_1, were plotted against the barrel slope, S_o, to test for consistency in the relationships. By

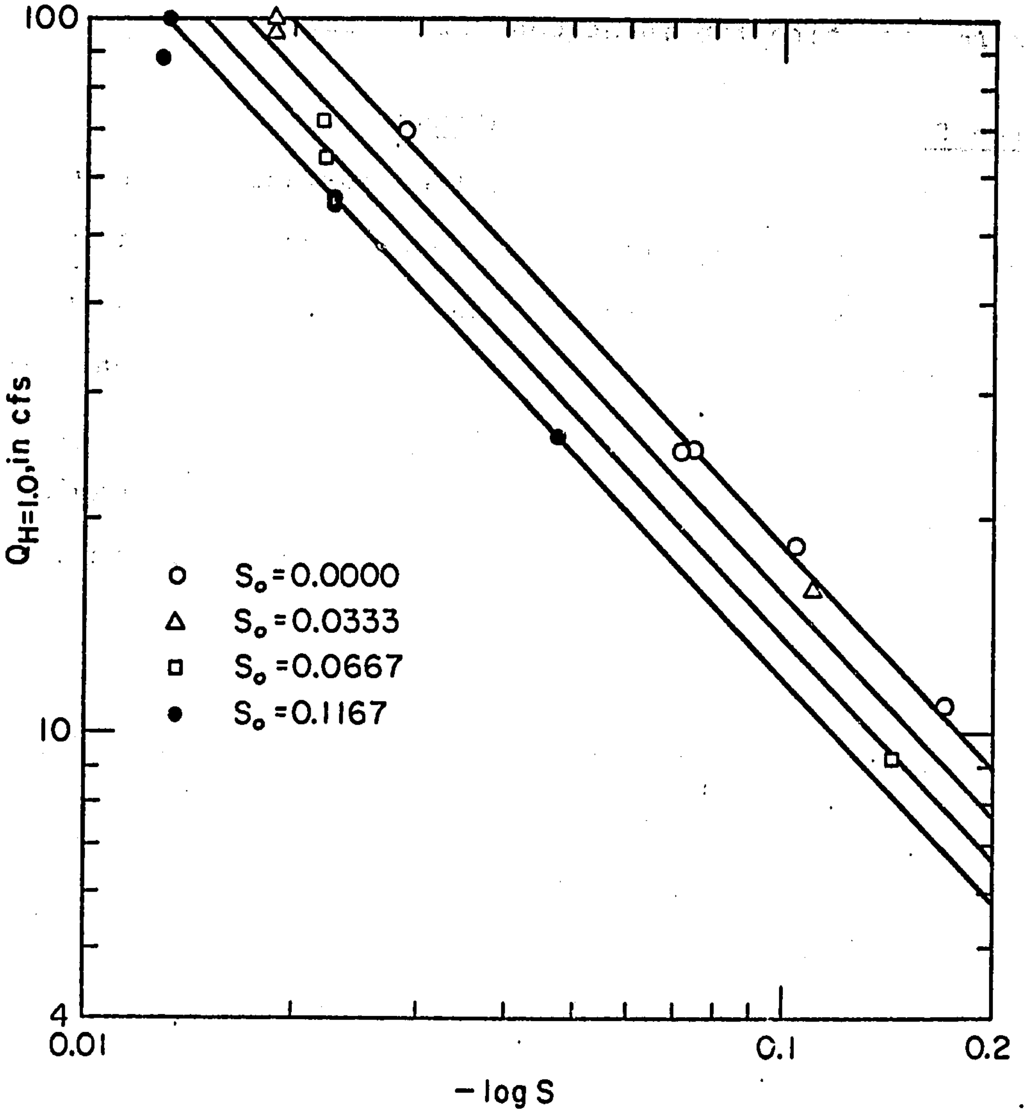


Figure 25. Effect of barrel slope upon free surface outlet control ratings for experimental culvert 5 feet long.

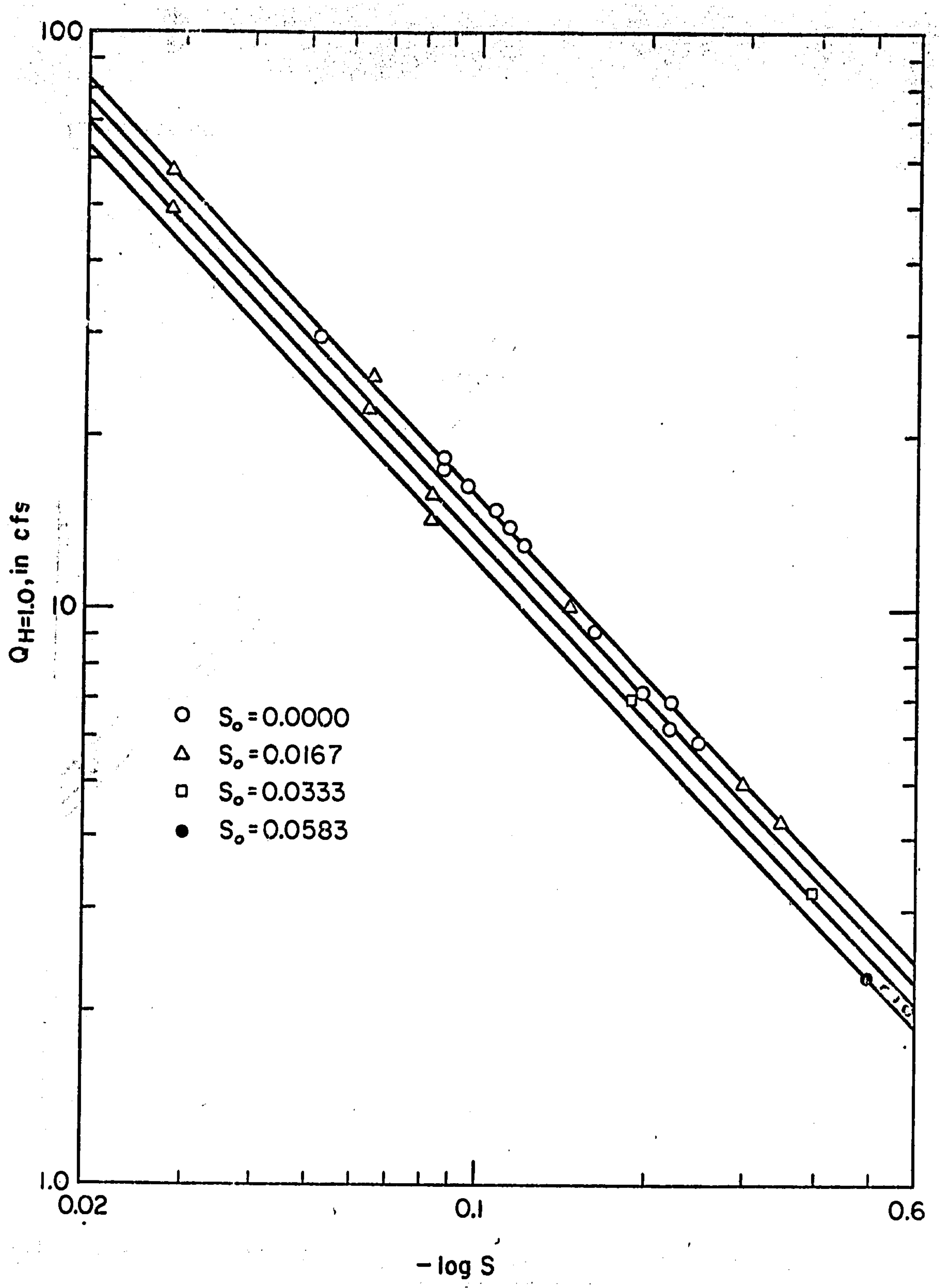


Figure 26. Effect of barrel slope upon free surface outlet control ratings for experimental culvert 10 feet long.

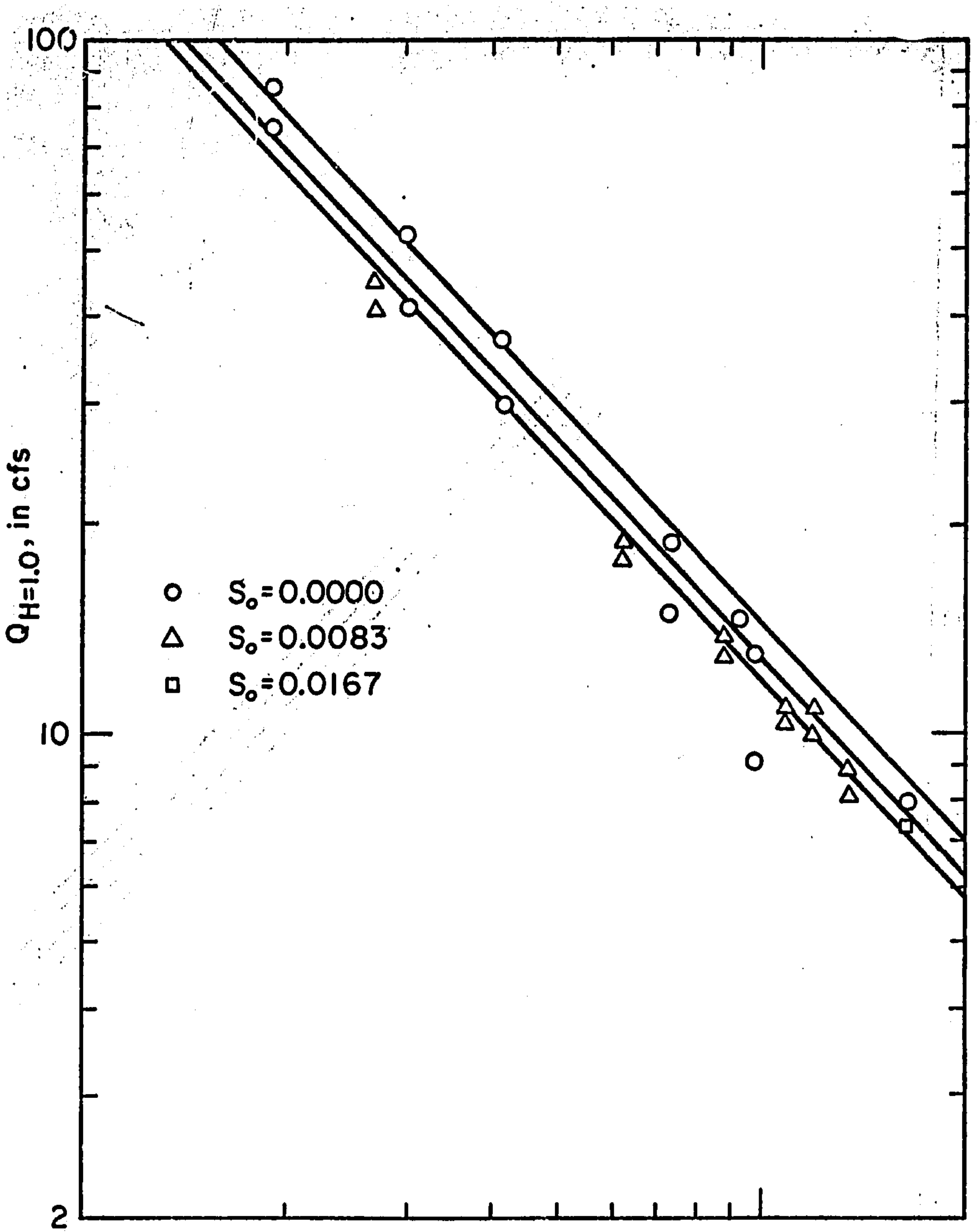


Figure 27. Effect of barrel slope upon free surface outlet control ratings for experimental culvert 20 feet long.

plotting the relationship for each culvert length, L, on the same graph, definite trends in the relationships could be seen. Finally, the curves relating C_1 and S_o were established by eye, which required that three data points be adjusted, with one data point being adjusted for each culvert length. In each case, the original estimate of C_1 was reduced. The degree of adjustment amounted to 8 percent for the one data point on the curve in Fig. 28 for a culvert length of 5 feet, 12 percent for one of the data points for the culvert length of 10 feet, while the adjustment required for the curve in Fig. 28 for a culvert length of 20 feet was 4 percent. After developing the relationships shown in Fig. 28, the final rating curves shown in Figs. 25, 26, and 27 were developed.

The transition submergence, S_t, between inlet control and free surface outlet control was evaluated using Equation 16 for the special case where $Z = 0$ (horizontal culvert). A solution of Equation 16 for sloping culverts is complex because the culvert fall, Z, does not allow a simple unique solution for S_t. The relationship between culvert length, L, and the transition submergence, S_t, is shown in Fig. 29. For culvert lengths of 5 feet, 10 feet, and 20 feet, the transition submergence was 0.64, 0.66, and 0.71, respectively.

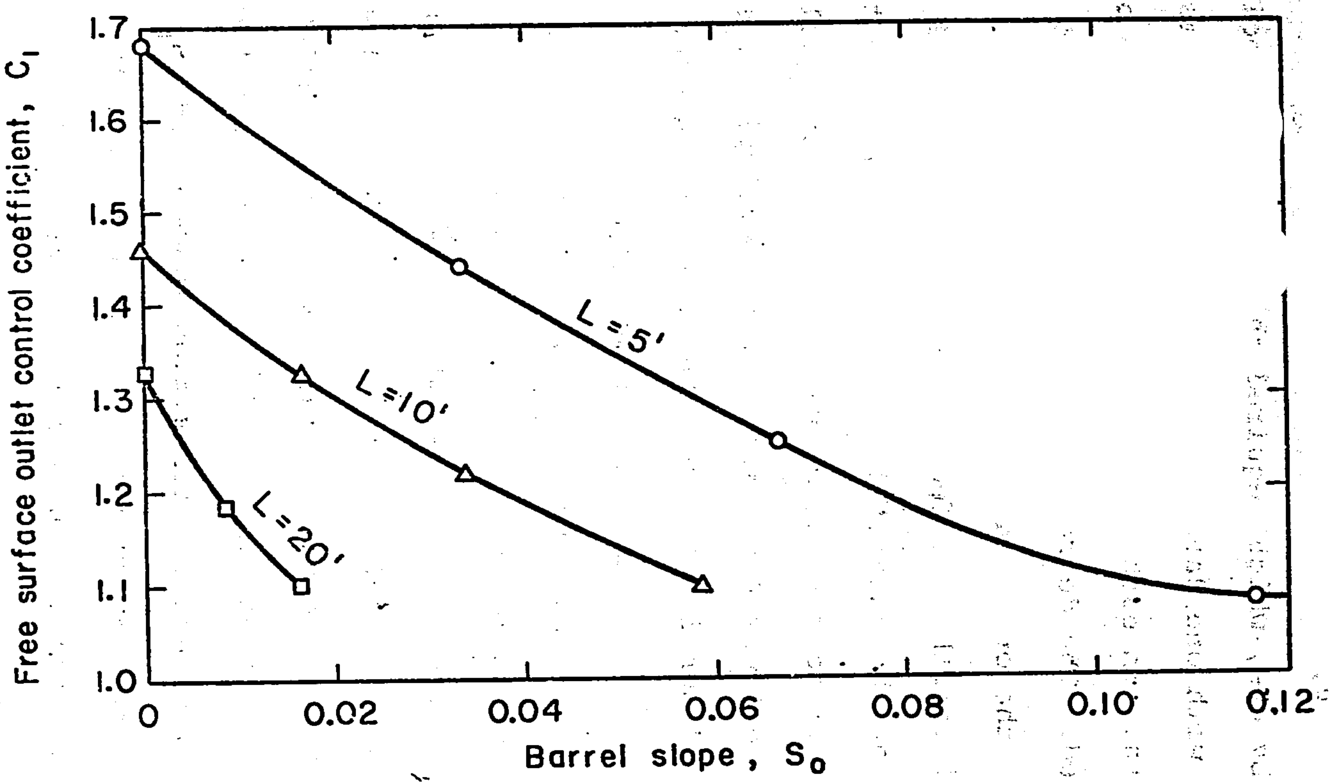


Figure 28. Relationships between barrel slope and free surface outlet control coefficient for experimental culverts.

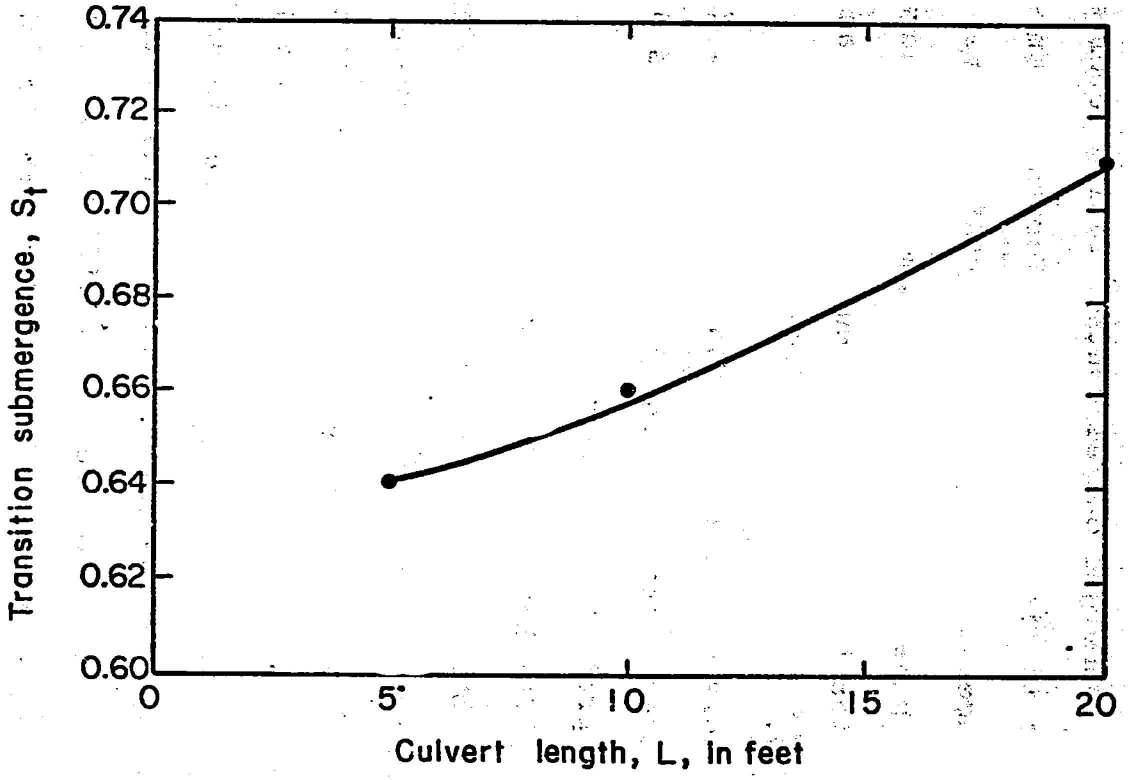


Figure 29. Effect of culvert length upon transition submergence.

Submerged Outlet Control Ratings

Since submerged outlet control ratings are given in the literature (6, 20), a comparison of reported ratings with the data collected for the experimental culverts was undertaken. The submerged outlet control rating reported in the literature is listed in Fig. 30. For the experimental culvert under study, wherein a constant diameter corrugated metal pipe having a square-edged flush headwall, the rating equation is a function of culvert length, as shown in Fig. 30.

The laboratory data for submerged outlet control flow conditions has been plotted in Fig. 31. For purposes of comparison, the predicted discharge ratings from the literature (Fig. 30) have also been shown in Fig. 31. In each case, the laboratory discharge rating predicts lower discharges than the ratings reported in the literature. Using Equation 17 to describe the submerged outlet control rating, the exponent, n_3, has a constant value of 1/2 in all cases. The effect of culvert length on the discharge rating is reflected in the coefficient, C_3. The variation of the submerged outlet control coefficient, C_3, with culvert length, L, is shown in Fig. 32 for both the laboratory ratings and the ratings reported in the literature.

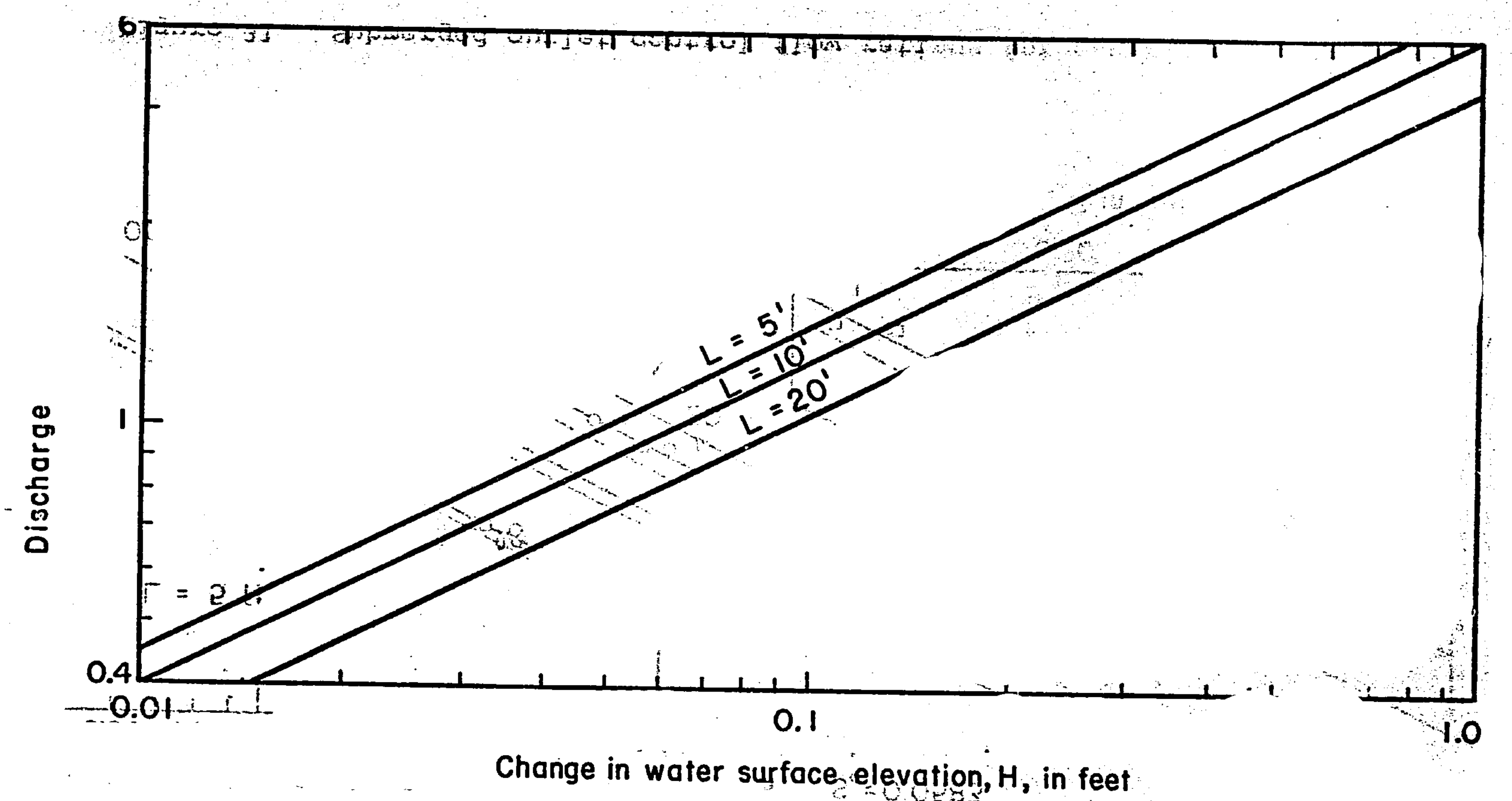


Figure 30. Submerged outlet control flow rating from previous literature.

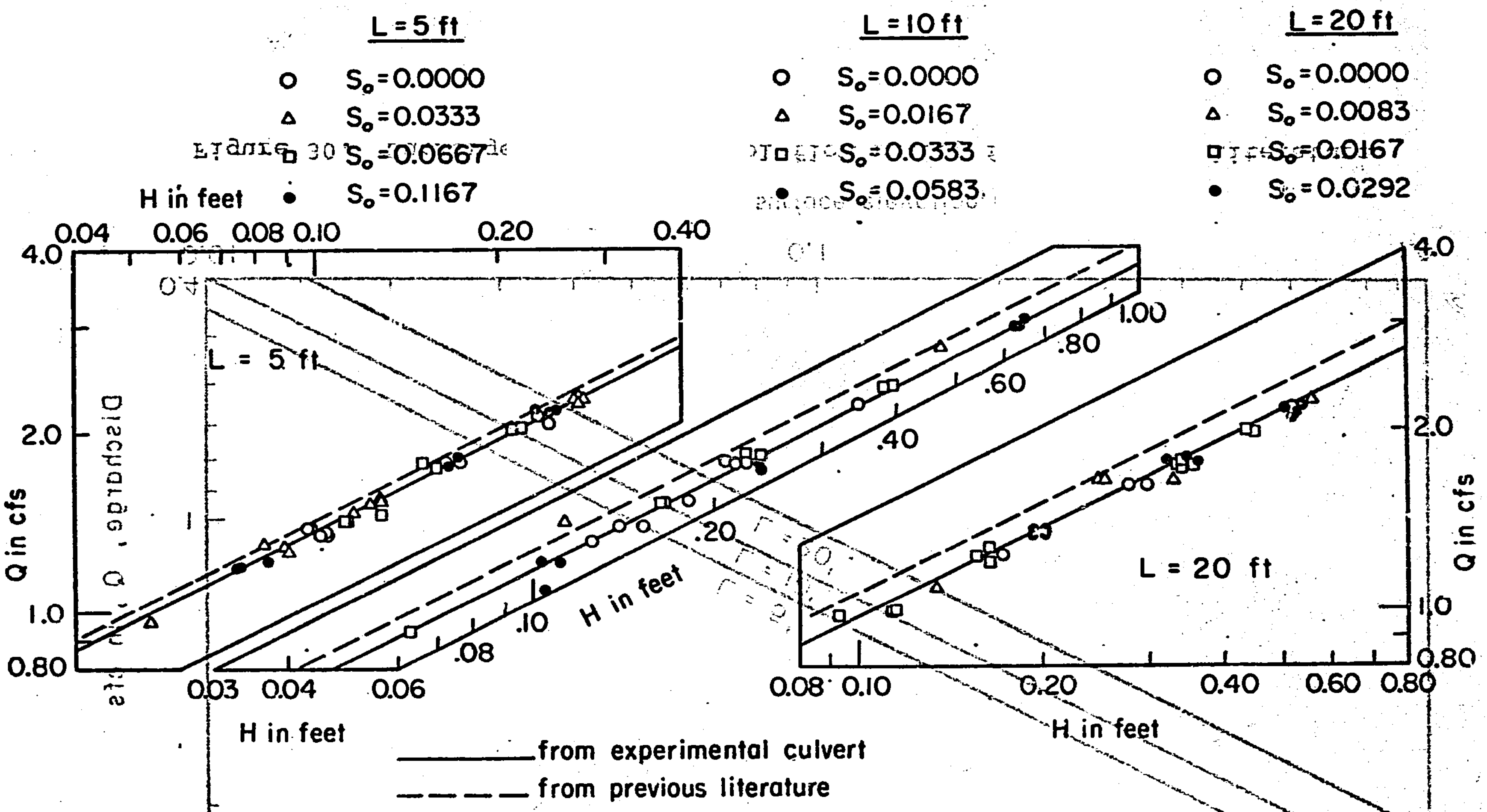


Figure 31. Submerged outlet control flow ratings for experimental culverts.

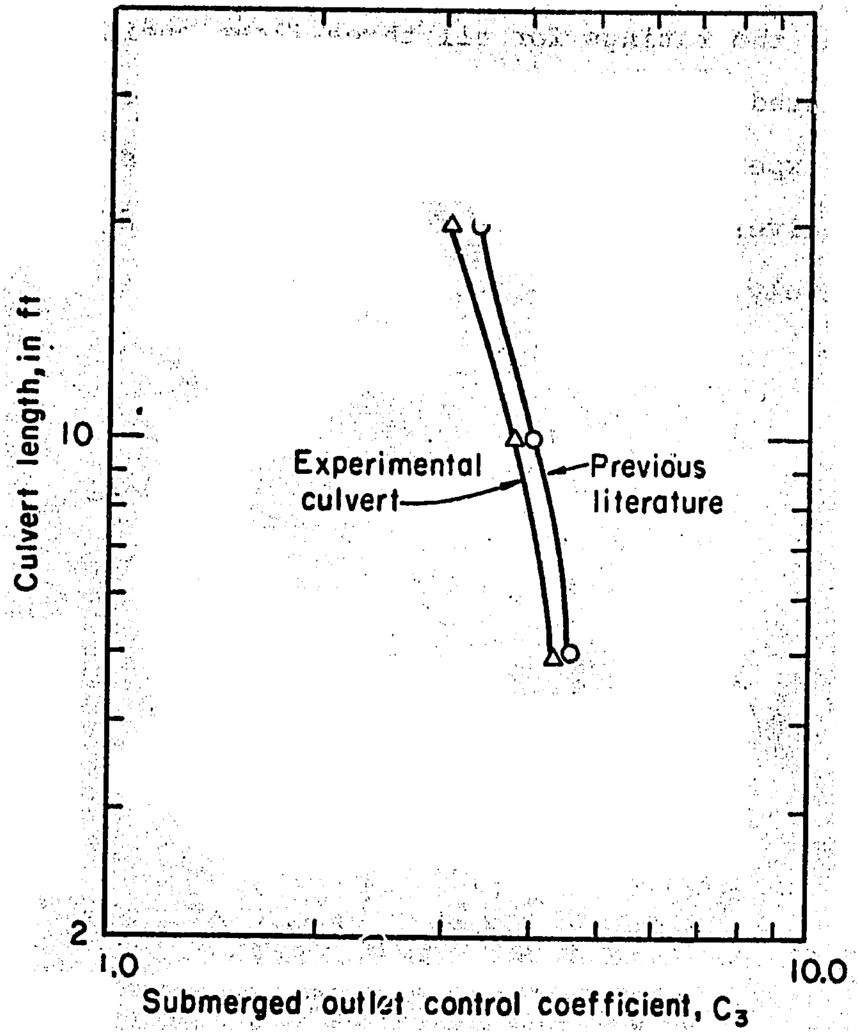


Figure 32. Effect of culvert length upon submerged outlet control coefficient.

Composite Ratings

A summary of the exponents and coefficients in the discharge rating equations for inlet control, free surface outlet control, and submerged outlet control are listed in Table 4. For the special case of horizontal culverts ($S_o = 0$), the ratings for all three flow conditions can be presented on a single graph. The composite ratings for the experimental culvert are shown in Figs. 33, 34, and 35 for culvert lengths of 5 feet, 10 feet, and 20 feet, respectively.

Table 4. Summary of discharge ratings for inlet control, free surface outlet control, and submerged outlet control for the 12-inch diameter corrugated metal pipe.

Culvert Length, L	Barrel Slope, S_o	Inlet Control $Q = C(HW)^{n_1}$		Free Surface Outlet Control $Q = \frac{C_1(HW+Z-TW)^{n_1}}{[-\log\{TW/(HW+Z)\}]^{n_2}}$			Submerged Outlet Control $Q = C_3H^{n_3}$	
ft	ft/ft	n_1	C	n_1	n_2	C_1	n_3	C_3
5	0.0000	1.500	1.999	1.500	1.040	1.680	0.50	4.337
	0.0333	1.500	2.244	1.500	1.040	1.440		
	0.0667	1.500	2.319	1.500	1.040	1.250		
	0.1167	1.500	2.324	1.500	1.040	1.080		
10	0.0000	1.500	1.727	1.500	1.040	1.460	0.50	3.762
	0.0167	1.500	2.060	1.500	1.040	1.325		
	0.0333	1.500	2.221	1.500	1.040	1.220		
	0.0583	1.500	2.288	1.500	1.040	1.100		
20	0.0000	1.500	1.506	1.500	1.040	1.330	0.50	3.032
	0.0083	1.500	1.773	1.500	1.040	1.180		
	0.0167	1.500	1.984	1.500	1.040	1.100		
	0.0292	1.500	2.160					

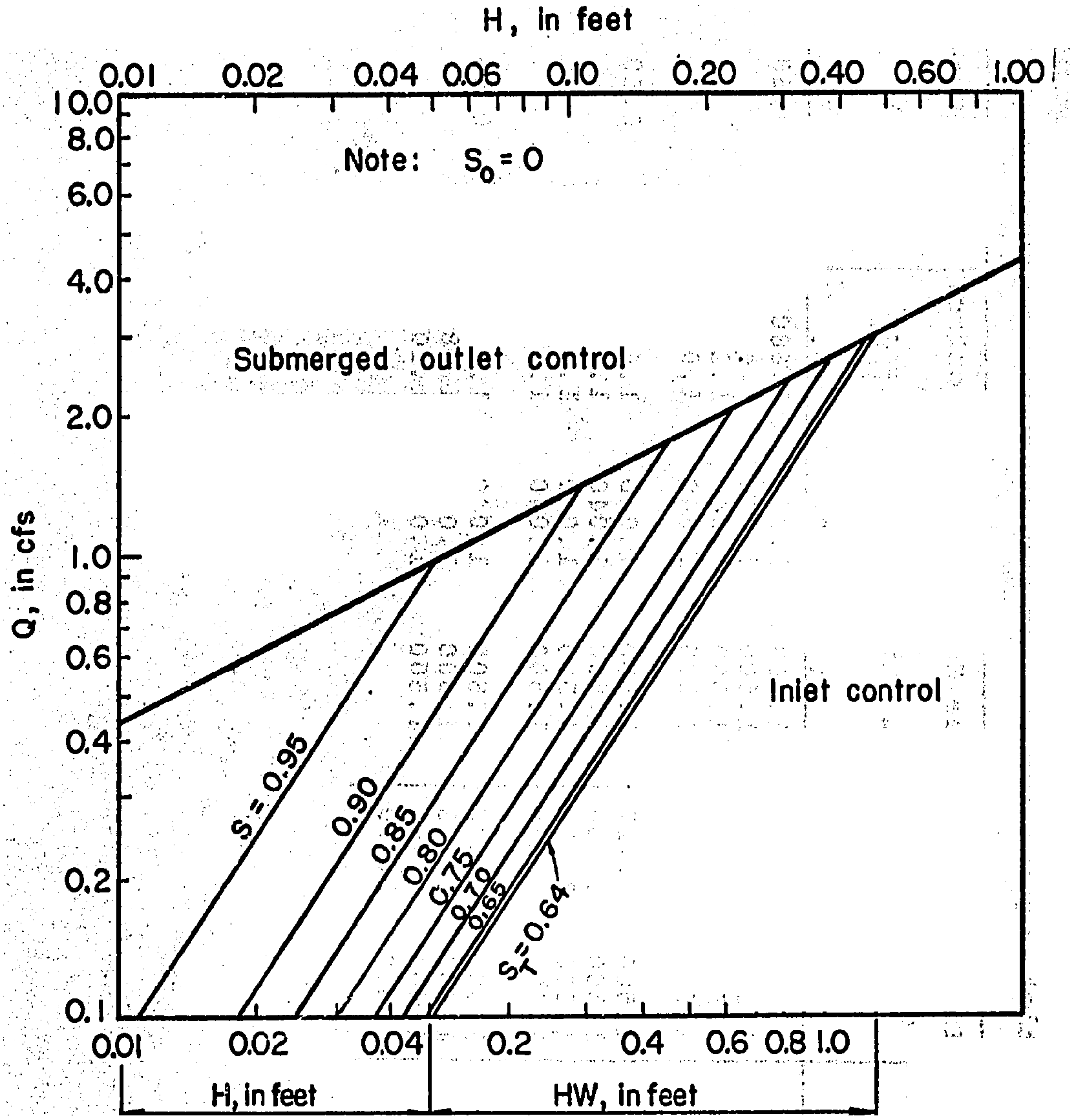


Figure 33. Discharge ratings for horizontal experimental culvert 5 feet long.

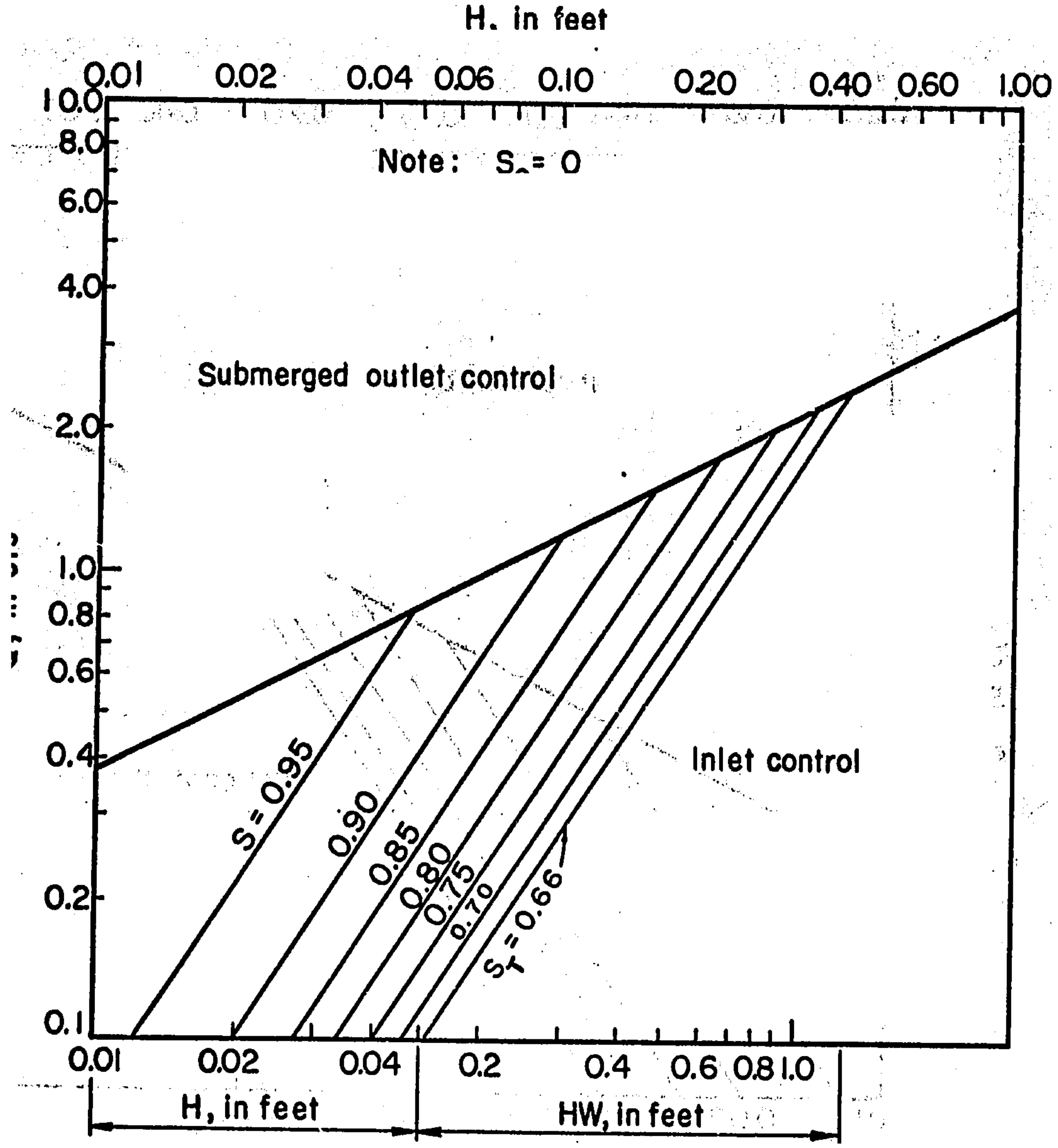


Figure 34. Discharge ratings for horizontal experimental culvert 10 feet long.

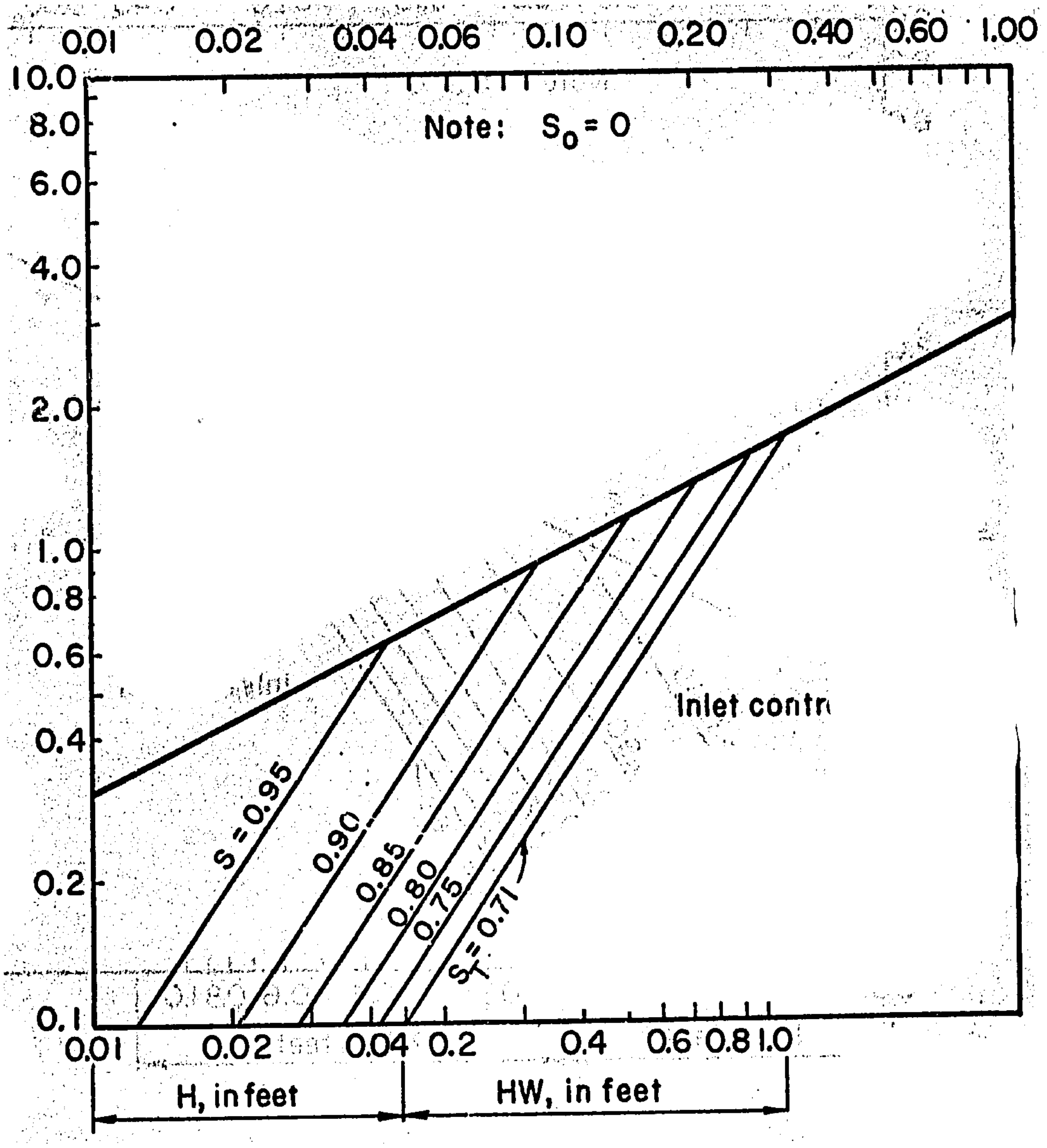


Figure 35. Discharge ratings for horizontal experimental culvert 20 feet long.

CHAPTER VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Culverts are frequently used in irrigation systems. In many cases, culverts encountered in irrigation distribution systems operate under free surface (open channel) flow conditions. For such cases, downstream conditions usually control the depth of flow in the culvert. For this particular flow condition of free surface outlet control, only an approximate solution has been available for determining the discharge.

A 12 inch diameter corrugated metal pipe has been investigated in the laboratory to determine the validity of the submerged flow analysis employed with flow measuring devices, such as flumes and weirs, in describing free surface outlet control in culverts. Various slopes, including horizontal, were used in the experimental program in conjunction with three culvert lengths. A square-edged flush headwall was used in this laboratory investigation.

Three flow conditions were investigated in the laboratory; namely, inlet control, free surface outlet control, and submerged outlet control; comparisons were made between the hydraulic data collected under this study and experimental results published by previous investigators.

Conclusions

This study has shown that the submerged flow analysis used for flow measuring flumes and weirs can be applied to free surface outlet control flow in culverts. Also, discharge ratings for horizontal culverts can be graphically shown on a single plot. Such a plot covers the three flow conditions investigated in this study, which are inlet control, free surface outlet control, and submerged outlet control.

The results of this study have clearly shown that culverts can definitely be used as flow measuring structures in irrigation systems. Thus, existing culverts could be utilized for providing discharge measurements. Also, small culverts could be employed as portable flow measuring devices.

Recommendations

A general experimental program should be undertaken to develop discharge ratings under free surface outlet control flow conditions for a variety of culvert sizes and lengths. Initially, this program should emphasize the development of discharge rating for small culverts which would be used as portable flow measuring devices.

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