Designation: D5243 – 92 (Reapproved 2013)

Standard Test Method for Open-Channel Flow Measurement of Water Indirectly at Culverts[1]

This standard is issued under the fixed designation D5243; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the computation of discharge (the volume rate of flow) of water in open channels or streams using culverts as metering devices. In general, this test method does not apply to culverts with drop inlets, and applies only to a limited degree to culverts with tapered inlets. Information related to this test method can be found in ISO 748 and ISO 1070.

1.2 This test method produces the discharge for a flood event if high-water marks are used. However, a complete stage-discharge relation may be obtained, either manually or by using a computer program, for a gauge located at the approach section to a culvert.

1.3 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1129 Terminology Relating to Water

D2777 Practice for Determination of Precision and Bias of Applicable Test Methods of Committee D19 on Water

D3858 Test Method for Open-Channel Flow Measurement of Water by Velocity-Area Method

2.2 *ISO Standards:*[3]

ISO 748 Liquid Flow Measurements in Open Channels-Velocity-Area Methods

ISO 1070 Liquid Flow Measurements in Open Channels-Slope-Area Methods

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology D1129.

3.2 Several of the following terms are illustrated in Fig. 1.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *alpha* (α)—a velocity-head coefficient that adjusts the velocity head computed on basis of the mean velocity to the true velocity head. It is assumed equal to 1.0 if the cross section is not subdivided.

3.3.2 *conveyance (K)*—a measure of the carrying capacity of a channel and having dimensions of cubic feet per second.

3.3.2.1 *Discussion*—Conveyance is computed as follows:

$$K = \frac{1.486}{n} R^{2/3} A$$

where:

n = the Manning roughness coefficient,
A = the cross section area, in ft^2 (m^2), and
R = the hydraulic radius, in ft (m).

3.3.3 *cross sections* (numbered consecutively in downstream order):

3.3.3.1 The approach section, Section 1, is located one culvert width upstream from the culvert entrance.

3.3.3.2 Cross Sections 2 and 3 are located at the culvert entrance and the culvert outlet, respectively.

3.3.3.3 Subscripts are used with symbols that represent cross sectional properties to indicate the section to which the property applies. For example, A_1 is the area of Section 1. Items that apply to a reach between two sections are identified by subscripts indicating both sections. For example, $h_{f_{1-2}}$ is the friction loss between Sections 1 and 2.

[1] This test method is under the jurisdiction of ASTM Committee D19 on Waterand is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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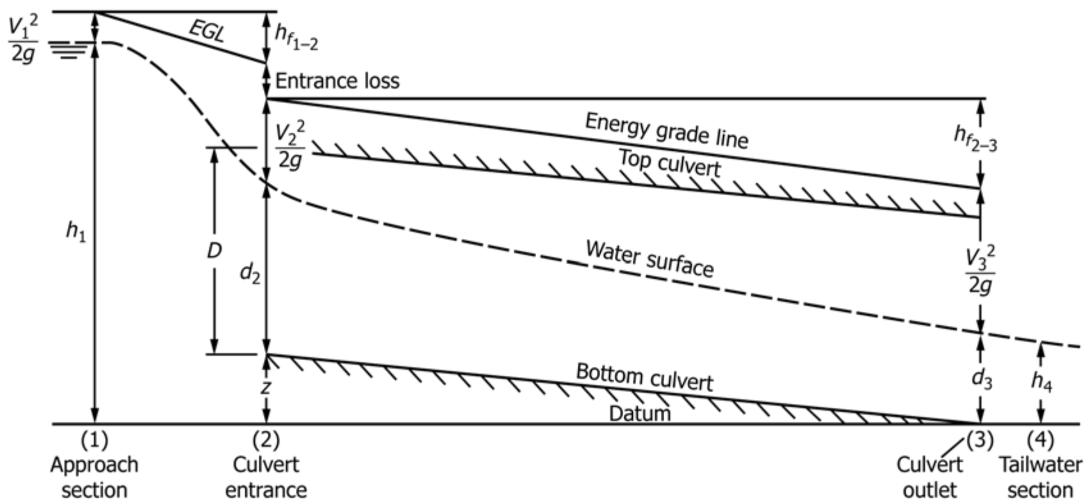
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.



NOTE 1—The loss of energy near the entrance is related to the sudden contraction and subsequent expansion of the live stream within the culvert barrel.

FIG. 1 Definition Sketch of Culvert Flow

3.3.4 *cross sectional area (A)*—the area occupied by the water.

3.3.5 *energy loss (h_f)* —the loss due to boundary friction between two locations.

3.3.5.1 *Discussion*—Energy loss is computed as follows:

$$h_f = L\left(\frac{Q^2}{K_1 K_2}\right)$$

where:

Q = the discharge in ft^3/s (m^3/s), and
L = the culvert length in ft (m).

3.3.6 *Froude number (F)*—an index to the state of flow in the channel. In a rectangular channel, the flow is subcritical if the Froude number is less than 1.0, and is supercritical if it is greater than 1.0.

3.3.6.1 *Discussion*—The Froude number is computed as follows:

$$F = \frac{V}{\sqrt{gd_m}}$$

where:

V = the mean velocity in the cross section, ft/s (m/s),
d_m = the average depth in the cross section, in ft (m), and
g = the acceleration due to gravity (32 ft/s^2) (9.8 m/s^2).

3.3.7 *high-water marks*—indications of the highest stage reached by water including, but not limited to, debris, stains, foam lines, and scour marks.

3.3.8 *hydraulic radius (R)*—the area of a cross section or subsection divided by the wetted perimeter of that section or subsection.

3.3.9 *roughness coefficient (n)*—Manning's *n* is used in the Manning equation.

3.3.10 *velocity head (h_v)*—is computed as follows:

$$h_v = \frac{\alpha V^2}{2g}$$

where:

α = the velocity-head coefficient,
V = the mean velocity in the cross section, in ft/s (m/s), and
g = the acceleration due to gravity, in ft/s/s (m/s/s).

3.3.11 *wetted perimeter (WP)*—the length along the boundary of a cross section below the water surface.

4. Summary of Test Method

4.1 The determination of discharge at a culvert, either after a flood or for selected approach stages, is usually a reliable practice. A field survey is made to determine locations and elevations of high-water marks upstream and downstream from the culvert, and to determine an approach cross section, and the culvert geometry. These data are used to compute the elevations of the water surface and selected properties of the sections. This information is used along with Manning's *n* in the Manning equation for uniform flow and discharge coefficients for the particular culvert to compute the discharge, *Q*, in cubic feet (metres) per second.

5. Significance and Use

5.1 This test method is particularly useful to determine the discharge when it cannot be measured directly with some type of current meter to obtain velocities and sounding equipment to determine the cross section. See Practice D3858.

5.2 Even under the best of conditions, the personnel available cannot cover all points of interest during a major flood. The engineer or technician cannot always obtain reliable results by direct methods if the stage is rising or falling very rapidly, if flowing ice or debris interferes with depth or velocity measurements, or if the cross section of an alluvial channel is scouring or filling significantly.

5.3 Under flood conditions, access roads may be blocked, cableways and bridges may be washed out, and knowledge of the flood frequently comes too late. Therefore, some type of indirect measurement is necessary. The use of culverts to determine discharges is a commonly used practice.

6. Apparatus

6.1 The equipment generally used for a "transit-stadia" survey is recommended. An engineer's transit, a self-leveling level with azimuth circle, newer equipment using electronic circuitry, or other advanced surveying instruments may be used. Necessary equipment includes a level rod, rod level, steel and metallic tapes, survey stakes, and ample note paper.

6.2 Additional items of equipment that may expedite a survey are tag lines (small wires with markers fixed at known spacings), vividly colored flagging, axes, shovels, hip boots or waders, nails, sounding equipment, ladder, and rope.

6.3 A camera should be available to take photographs of the culvert and channel. Photographs should be included with the field data.

6.4 Safety equipment should include life jackets, first aid kit, drinking water, and pocket knives.

7. Sampling

7.1 Sampling as defined in Terminology D1129 is not applicable in this test method.

8. Calibration

8.1 Check adjustment of surveying instruments, transit, etc., daily when in continuous use or after some occurrence that may have affected the adjustment.

8.2 The standard check is the "two-peg" or "double-peg" test. If the error is over 0.03 in 100 ft (0.091 m in 30.48 m), adjust the instrument. The two-peg test and how to adjust the instrument are described in many surveying textbooks. Refer to manufacturers' manual for the electronic instruments.

8.3 The "reciprocal leveling" technique (**1**)[4] is considered the equivalent of the two-peg test between each of two successive hubs.

8.4 Visually check sectional and telescoping level rods at frequent intervals to be sure sections are not separated. A proper fit at each joint can be checked by measurements across the joint with a steel tape.

8.5 Check all field notes of the transit-stadia survey before proceeding with the computations.

9. Description of Flow at Culverts

9.1 Relations between the head of water on and discharge through a culvert have been the subjects of laboratory investigations by the U.S. Geological Survey, the Bureau of Public Roads, the Federal Highway Administration, and many universities. The following description is based on these studies and field surveys at sites where the discharge was known.

9.2 The placement of a roadway fill and culvert in a stream channel causes an abrupt change in the character of flow. This channel transition results in rapidly varied flow in which acceleration due to constriction, rather than losses due to boundary friction, plays the primary role. The flow in the approach channel to the culvert is usually tranquil and fairly uniform. Within the culvert, however, the flow may be subcritical, critical, or supercritical if the culvert is partly filled, or the culvert may flow full under pressure.

9.2.1 The physical features associated with culvert flow are illustrated in Fig. 1. They are the approach channel cross section at a distance equivalent to one opening width upstream from the entrance; the culvert entrance; the culvert barrel; the culvert outlet; and the tailwater representing the getaway channel.

9.2.2 The change in the water-surface profile in the approach channel reflects the effect of acceleration due to contraction of the cross-sectional area. Loss of energy near the entrance is related to the sudden contraction and subsequent expansion of the live stream within the barrel, and entrance geometry has an important influence on this loss. Loss of energy due to barrel friction is usually minor, except in long rough barrels on mild slopes. The important features that control the stage-discharge relation at the approach section can be the occurrence of critical depth in the culvert, the elevation of the tailwater, the entrance or barrel geometry, or a combination of these.

9.2.3 Determine the discharge through a culvert by application of the continuity equation and the energy equation between the approach section and a control section within the culvert barrel. The location of the control section depends on the state of flow in the culvert barrel. For example: If critical flow occurs at the culvert entrance, the entrance is the control section, and the headwater elevation is not affected by conditions downstream from the culvert entrance.

10. General Classification of Flow

10.1 *Culvert Flow*— Culvert flow is classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations to height of culvert. The six types of flow are illustrated in Fig. 2, and pertinent characteristics of each type are given in Table 1.

10.2 *Definition of Heads*—The primary classification of flow depends on the height of water above the upstream invert. This static head is designated as $h_1 - z$, where h_1 is the height above the downstream invert and z is the change in elevation of the culvert invert. Numerical subscripts are used to indicate the section where the head was measured. A secondary part of the classification, described in more detail in Section 18, depends on a comparison of tailwater elevation h_4 to the height of water at the control relative to the downstream invert. The height of water at the control section is designated h_c.

10.3 *General Classifications*—From the information in Fig. 2, the following general classification of types of flow can be made:

10.3.1 If h_4/D is equal to or less than 1.0 and $(h_1 - z)/D$ is less than 1.5, only Types 1, 2 and 3 flow are possible.

10.3.2 If h_4/D and $(h_1 - z)/D$ are both greater than 1.0, only Type 4 flow is possible.

[4] The boldface numbers in parentheses refer to a list of references at the end of the text.

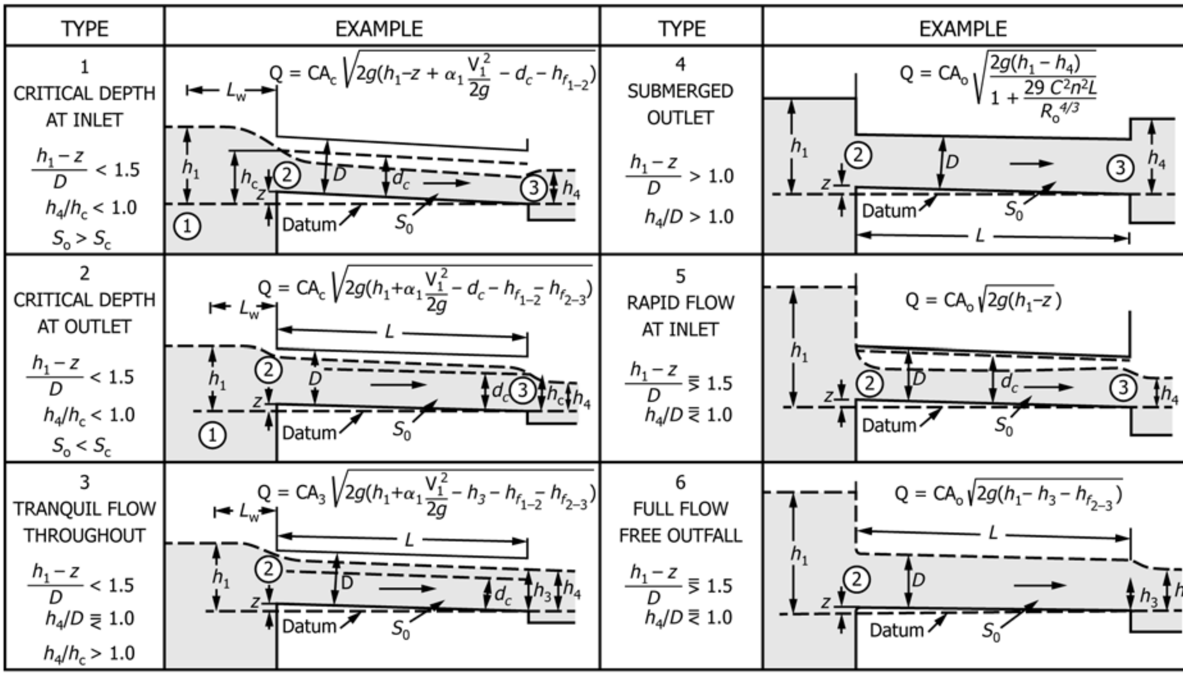


FIG. 2 Classification of Culvert Flow

TABLE 1 Characteristics of Flow Types

NOTE 1—D = maximum vertical height of barrel and diameter of circular culverts.

Flow Type	Barrel Flow	Location of Terminal Section	Kind of Control	Culvert Slope	$\frac{h_1 - z}{D}$	$\frac{h_4}{h_c}$	$\frac{h_4}{D}$
1	Partly full	Inlet	Critical depth	Steep	<1.5	<1.0	⋜1.0
2	do	Outlet	do	Mild	<1.5	<1.0	⋜1.0
3	do	do	Backwater	do	<1.5	>1.0	⋜1.0
4	Full	do	do	Any	>1.0	. . .	>1.0
5	Partly full	Inlet	Entrance geometry	do	⋝1.5	. . .	⋜1.0
6	Full	Outlet	Entrance and barrel geometry	do	⋝1.5	. . .	⋜1.0

10.3.3 If h_4/D is equal to or less than 1.0 and $(h_1 - z)/D$ is equal to or greater than 1.5, only Types 5 and 6 flow are possible.

10.3.4 If h_4/D is equal to or greater than 1.0 on a steep culvert and $(h_z - z)/D$ is less than 1.0, Types 1 and 3 flows are possible. Further identification of the type of flow requires a trial-and-error procedure that takes time and is one of the reasons use of the computer program is recommended.

11. Critical Depth

11.1 *Specific Energy*—In Type 1 flow, critical depth occurs at the culvert inlet, and in Type 2 flow critical flow occurs at the culvert outlet. Critical depth, d_c, is the depth of water at the point of minimum specific energy for a given discharge and cross section. The relation between specific energy and depth is illustrated in Fig. 3. The specific energy, H_o, is the height of the energy grade line above the lowest point in the cross section. Thus:

$$H_o = d + \frac{V^2}{2g}$$

where:

H_o = specific energy,
d = maximum depth in the section, in ft,
V = mean velocity in the section, in ft/s, and
g = acceleration of gravity (32 ft/s^2) (9.8 m/s^2).

11.2 *Relation Between Discharge and Depth*—It can be shown that at the point of minimum specific energy, that is, at critical depth, d_c, there is a unique relation between discharge (or velocity) and depth as shown by the following equations:

$$\frac{Q^2}{g} = \frac{A^3}{T}$$

and:

$$\frac{V^2}{g} = d_m = \frac{A}{T}$$

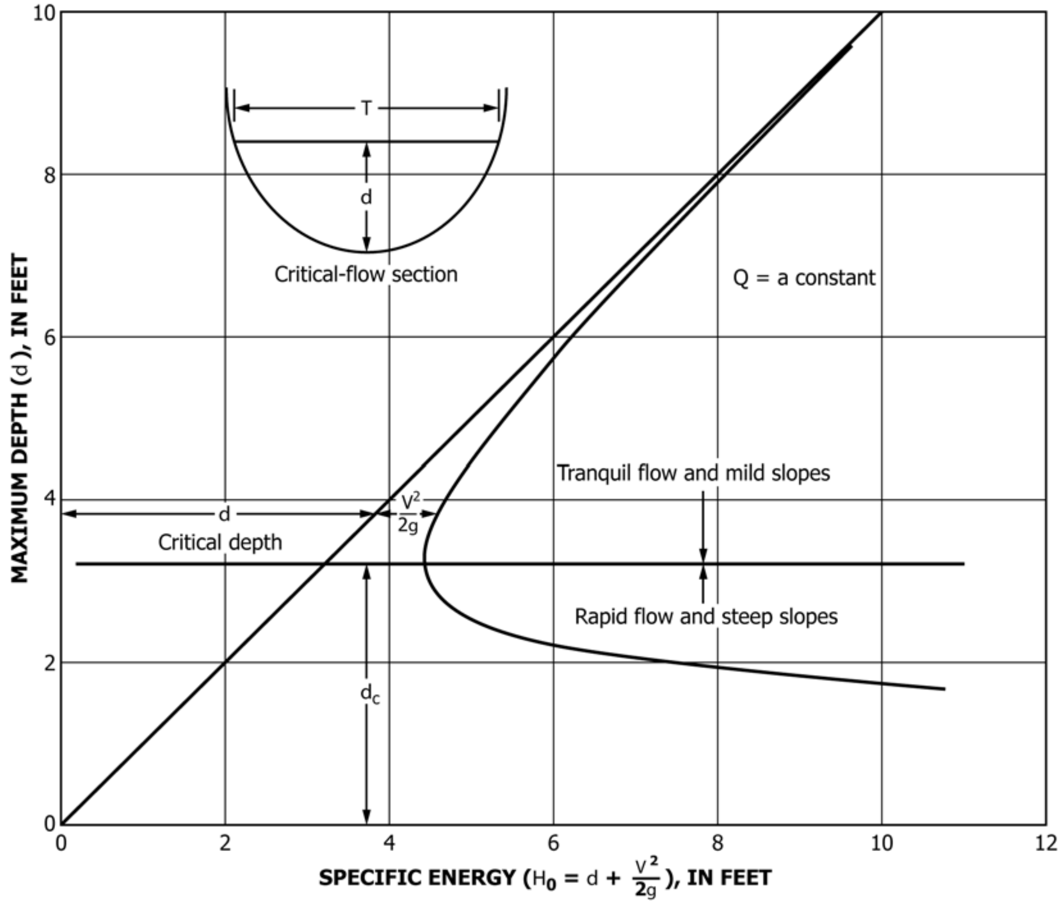


FIG. 3 Relation Between Specific Energy and Depth

where:

Q = discharge, in ft^3/s (m^3/s),
A = area of cross section below the water surface, ft^2 (m^2),
T = width of the section at the water surface, in ft (m),
d_c = maximum depth of water in the critical-flow section, in ft (m), and
d_m = mean depth in section = A/T, in ft (m).

Therefore, assuming either depth of discharge fixes the other. The computational procedures utilize trial iterations where critical depth is assumed and the resultant discharge is used as a trial value for computing energy losses, which are in turn used to compute a discharge from variations of the continuity equation. Iterations continue until the trial and computed discharges agree.

11.3 *Discharge at Critical Depth*—For the condition of minimum specific energy and critical depth, the discharge equation for a section of any shape can be written as follows:

$$Q = A_c^{3/2} \sqrt{\frac{g}{T}} \quad (1)$$

or:

$$Q = A_c \sqrt{g d_m} \quad (2)$$

11.4 *Discharge and Shape of Sections*—The discharge equation can be simplified according to the shape of the sections. Thus, for rectangular sections:

$$Q = 5.67 b d_c^{3/2} \quad (3)$$

and for circular sections:

$$Q = C_q D^{5/2} \quad (4)$$

where:

b = width of section, in ft (m),
C_q = function of d_c/D, and is obtained from tables,
d_c = maximum depth of water in the critical-flow section, in ft (m), and
D = inside diameter of a circular section, in ft (m).

Eq 4 also applies to sections having a pipe arch cross section in which D becomes the maximum inside height (rise) of the arch.

12. Discharge Equations

12.1 *Development*—Discharge equations have been developed for each type of flow by application of the continuity and energy equations between the approach section and the control or terminal section. For most types of flow, the discharge may be computed directly from these equations after the type of flow and various energy losses have been identified.

12.2 *Flow at Critical Depth*—Flow at critical depth may occur at either the upstream or the downstream end of a culvert, depending on the headwater elevation, the slope of the culvert, the roughness of the culvert barrel, and the tailwater elevation.

12.2.1 *Type 1 Flow:*

12.2.1.1 In Type 1 flow, as illustrated on Fig. 2, the water passes through critical depth near the culvert entrance. The headwater-diameter ratio, $(h_1 - z)/D$, is limited to a maximum of 1.5 and the culvert barrel flows partly full. The slope of the culvert barrel, S_o, must be greater than the critical slope, S_c, and the tailwater elevation, h_4, must be less than the elevation of the water surface at the control section, h_c. In this case, $h_c = h_2$.

12.2.1.2 The discharge equation for Type 1 flow is as follows:

$$Q = CA_c \sqrt{2g\left(h_1 - z + \frac{\alpha_1 V_1^2}{2g} - d_c - h_{f_{1-2}}\right)} \quad (5)$$

where:

C = the discharge coefficient,
A_c = the flow area at the control section, in ft^2 (m^2),
V_1 = the mean velocity in the approach section, in ft/s (m/s),
α_1 = the velocity-head coefficient at the approach section computation explained in 18.5.4,
$h_{f_{1-2}}$ = the head loss due to friction between the approach section and the inlet = $L_w(Q^2/K_1K_2)$, and
K = conveyance $= (1.486/n)\,R^{2/3}A$, and subscripts indicate Sections 1 and 2.

12.2.2 *Type 2 Flow*— Type 2 flow, as shown in Fig. 2, passes through critical depth at the culvert outlet. The headwater-diameter ratio does not exceed 1.5, and the barrel flows partly full. The slope of the culvert is less than critical, and the tailwater elevation does not exceed the elevation of the water surface at the control section h_3. The discharge equation for Type 2 flow is as follows:

$$Q = CA_c \sqrt{2g\left(h_1 + \frac{\alpha_1 V_1^2}{2g} - d_c - h_{f_{1-2}} - h_{f_{2-3}}\right)} \quad (6)$$

where terminology is as explained in 12.2.1.2 with the addition of $h_{f_{2-3}}$ = the head loss due to friction in the culvert, barrel = $L(Q^2/K_2K_3)$, and subscripts indicate Sections 2 and 3.

12.3 *Backwater*—When backwater is the controlling factor in culvert flow, critical depth cannot occur and the upstream water-surface elevation for a given discharge is a function of the surface elevation of the tailwater. The two types of flow in this classification are Types 3 and 4.

12.3.1 *Type 3 Flow*— Type 3 flow is tranquil throughout the length of the culvert, as indicated in Fig. 2. The headwater-diameter ratio is less than 1.5, and the culvert barrel flows partly full. The tailwater elevation does not submerge the culvert outlet, but it does exceed the elevation of critical depth at the outlet. If the culvert slope is steep enough that under free-fall conditions critical depth at the inlet would result from a given elevation of headwater, the tailwater elevation must be higher than the elevation of critical depth at the inlet for Type 3 flow to occur. The discharge equation for Type 3 flow is as follows:

$$Q = CA_3 \sqrt{2g\left(h_1 + \frac{\alpha_1 V_1^2}{2g} - h_3 - h_{f_{1-2}} - h_{f_{2-3}}\right)} \quad (7)$$

where the terminology is as explained in 12.2.1.2 except that A_3 is the area at the outlet.

12.3.2 *Type 4 Flow*— In Type 4 flow the culvert is submerged by both headwater and tailwater, as is shown in Fig. 2. The headwater-diameter ratio can be anything greater than 1.0. No differentiation is made between low-head and high-head flow on this basis for Type 4 flow. The culvert flows full and the energy equation between Sections 1 and 4 becomes as follows:

$$h_1 + h_{v_1} = h_4 + h_{v_4} + h_{f_{1-2}} + h_e + h_{f_{2-3}} + h_{f_{3-4}} + \left(h_{v_3} - h_{v_4}\right) \quad (8)$$

where:

h_e = head loss due to entrance contraction, and all other terms are as previously defined.

In the derivation of the discharge equation shown below, the velocity head at Section 1 and the friction loss between Sections 1 and 2 and between Sections 3 and 4 have been neglected. Between Sections 3 and 4 the energy loss due to sudden expansion is assumed to be ($h_{v_3} - h_{v_4}$).
Thus:

$$h_1 = h_4 + h_e + h_{f_{2-3}} + h_{v_3} \quad (9)$$

or in terms of Q the equation becomes:

$$Q = CA_o \sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{29C^2n^2L}{R_o^{4/3}}}} \quad (10)$$

where the subscript o refers to the area and hydraulic radius of the full culvert barrel.

12.4 *High-Head Flow*— High-head flow will occur if the tailwater is below the crown at the outlet and the headwater-diameter ratio is equal to or greater than 1.5. The two types of flow under this category are Types 5 and 6. The type of flow is determined from curves in 18.10.1. French **(2)** points out that a particular inlet and barrel does not necessarily have a single and unique performance curve relating the pool level to rate of discharge at a given culvert slope. In general, the performance will vary widely depending upon the characteristics of the approach channel and in particular the effects of these characteristics on the degree of vortex action over the inlet. It follows that the subatmospheric pressure that must be present at the inlet throat in order for full conduit flow to exist cannot, under adverse conditions, be relied upon to produce a full culvert Type 6 flow in moderately steep culverts. Adverse approach conditions involving strong air-carrying vortices over the inlet may cause inlet control, Type 5, flow. Within a certain range either Type 5 or Type 6 flow may occur, depending upon factors that are very difficult to evaluate. For example, the wave pattern superimposed on the water-surface profile through the culvert can be important in determining full or part-full flow. Within the range of geometries tested, however, the flow type generally can be determined from a knowledge of entrance geometry and length, culvert slope, and roughness of the culvert barrel.

12.4.1 *Type 5 Flow*— As shown in Fig. 2, part-full flow under a high head is classified as Type 5. Type 5 flow is rapid at the inlet. The headwater-diameter ratio exceeds 1.5, and the tailwater elevation is below the crown at the outlet. The top edge of the culvert entrance contracts the flow in a manner similar to a sluice gate. The culvert barrel flows partly full and at a depth less than critical. The discharge equation for Type 5 flow is as follows:

$$Q = CA_o\sqrt{2g(h_1 - z)} \quad (11)$$

The occurrence of Type 5 flow requires a relatively square entrance that will cause contraction of the area of live flow to much less than the area of the culvert barrel. In addition, the combination of barrel length, roughness, and bed slope must be such that the contracted jet will not expand to the full area of the barrel. If the water surface of the expanding flow comes in contact with the top of the culvert, Type 6 flow will occur, because the passage of air to the culvert will be sealed off causing the culvert to flow full throughout its length. The headwater elevation for a given discharge is generally lower for Type 6 flow than for Type 5, indicating a more efficient use of the culvert barrel.

12.4.2 *Type 6 Flow*— In Type 6 flow the culvert is full under pressure with free outfall as shown in Fig. 2. The headwater-diameter ratio exceeds 1.5 and the tailwater does not submerge the culvert outlet. The discharge equation between Sections 1 and 3, neglecting $V_1^2/2g$ and $h_{f_{1-2}}$, is as follows:

$$Q = CA_o\sqrt{2g(h_1 - h_3 - h_{f_{2-3}})} \quad (12)$$

A straightforward application of Eq 12 is hampered by the necessity of determining h_3, which varies from a point below the center of the outlet to its top, even though the water surface is at the top of the culvert. This variation in piezometric head is a function of the Froude number at the outlet. This difficulty has been circumvented by basing the data analysis upon dimensionless ratios of physical dimensions related to the Froude number. These functional relationships have been defined by laboratory experiment, and they have been incorporated into both manual computation methods and computer programs. The relationships are given in 18.10.2.

12.4.3 *Tapered Inlets and Drop Inlets*—Methods given in this test method for distinguishing between Type 5 and Type 6 flow do not apply to tapered-inlets and drop-inlets and should not be applied to culverts with such inlets. Research by National Institute for Standards Technology (**2**) shows that when tapered end-sections or inlets are used inlet control can occur either at the face or throat of the end-section, depending on culvert slope and relative areas of the face and throat. The research shows further that inlet control at the face can occur at either the outside or inside corner of the end-section wall depending on wall thickness.

13. Procedure

13.1 *Culvert Site*—Make a transit-stadia survey of the culvert site. Obtain elevations of hubs, reference marks, culvert features, and if a flood event is involved, high-water marks to hundredths of a foot and ground elevations to tenths of a foot.

13.2 *Approach Section*—Locate the approach section one culvert width upstream from the culvert entrance to keep it out of the drawdown region. Where wingwalls exist and contraction occurs around the ends of one or both wingwalls, locate it a distance upstream from the end of the wingwalls equal to the width between the wingwalls at their upstream end. Position the section as nearly as possible at right angles to the direction of flow.

13.2.1 An approach section is not needed if only high flows are of interest and the area of the approach channel is estimated to be equal to or greater than five times the area of the culvert barrel. Then the approach velocity is assumed to be zero. However, if no approach section is surveyed one may need to be synthesized for use in computer programs.

13.2.2 Record the stationing where the shape of the channel changes, such as where a low water channel joins a broad flood terrace and where water leaves the banks and goes into a flood plain or overflow area. Also record the stationing of points where bed material or vegetation cover change.

13.3 *High Water Marks:*

13.3.1 For a computation of a flood discharge, obtain high-water mark elevations at both ends of the approach section, preferably from short high-water profiles defined by a minimum of four marks on each bank or by marks along the embankment located at least one culvert width away from the culvert entrance. The elevation at the top of the mark is the elevation needed to be consistent with field methods used to verify the roughness coefficient. High-water elevations on both banks at the approach section are essential. Compute the discharge on basis of the average elevation. Also, a gauge located at one end of the approach section may register higher or lower than the average; therefore, establish a relation between several average elevations and the recorded elevations so that a stage-discharge relation will be correct. Marks will be high on the outside of banks, against the embankment over the culvert, and on upstream side protruding points. Marks will be low on the inside of bends, within the area of drawdown, and below protruding points.

13.3.2 Obtain the tailwater elevations along the downstream banks or embankment if there is any possibility of backwater at the culvert outlet. Locate downstream marks as near the culvert as possible but not within the area affected by the issuing jet.

13.4 *Culvert Geometry and Material:*

13.4.1 Record the type of material used for the culvert and the shape of the culvert, that is concrete pipe, concrete box, corrugated pipe, corrugated pipe arch, multi-plate pipe or pipe arch, etc., and the condition of the culvert. Measure culvert geometry, width (b) and height; or diameter (D); length (L); wingwall angle (θ); and chamfers or entrance rounding. The wingwall angle, theta, is the acute angle between the wing wall and an extension of the headwall. Obtain elevations of invert at inlet and at any place where there is a break in invert slope. Obtain the elevation on the top of corrugations for corrugated pipe and within the minimum diameter for concrete pipe. Measure the elevations of inverts of a box culvert at the end of the culvert along lines perpendicular to the side walls. As a minimum, obtain invert elevations of box culverts at the center and at the walls. Obtain for wide culverts elevations at several places across the culvert. Determine elevations of the crown or top of the barrel at both ends. Locate relative positions of culvert barrel, wingwalls, aprons, and other features. Determine the elevation at the upstream end of the apron if one is present.

13.4.1.1 *Paved Inverts*—Some culverts are completely or partially covered with cement, tar, or asphalt to protect the metal. Frequently corrugations near the bottom of the culvert are filled with the material. If culvert is paved, record that fact and determine the portion of the culvert where corrugations are filled.

13.4.1.2 *Projection*—Measure the amount of projection of corrugated metal pipes. An acceptable method for determining the amount of projection is to measure L_p at various points around the pipe entrance between the invert and the top of the culvert. A good way to designate where each measurement is taken is to represent the culvert barrel as a circular clock face with hands. The location of each measurement is represented as a time on the clock.

13.5 *Roughness Coefficient*—Select a value of Manning's *n* for the approach reach unless the approach section must be subdivided when more than one *n* is necessary. Assign a value of *n* for each sub-area. If a computer program is to be used to compute discharge, assign the n-values according to specifics of the program. A reasonable evaluation of the resistance to flow in a channel depends on the experience of the person selecting the coefficient and reference to texts and reports that contain values for similar stream and flow conditions. See Ref (**1**) and 9.3 in this test method. Select an *n*-value for the culvert barrel. See Section 15 in this test method.

13.6 *Obstructions*—Describe and evaluate the effect, if possible, of any material or conditions that might obstruct flow through the culvert.

13.7 *Road Overflow*—Note whether or not there was flow over the road nearby that should be included in the total flood discharge. If overflow is possible, survey a profile along the highest part of the road.

13.8 *Skews*—Some culverts, both box and pipe, are skewed; that is, the end or headwall is not normal to the centerline of the culvert. At these sites measure the wingwall angle as for a normal culvert as the acute angle at which the wingwall and headwall join. Measure the invert elevations on a line normal to the axis of the culvert and at the point where a full barrel section begins or ends. Measure the length of the approach reach to the invert line described above and the culvert length is the distance between those lines. If multiple barrels are present, measure invert elevations separately in each barrel.

13.9 *Mitered Pipe and Pipes Arches*—Miter pipes and pipe arches to match the slope of the highway embankment, as shown in Fig. 4. Determine the invert elevations at the extreme ends of the pipe and vertically below the points where the full diameter of the pipe becomes effective. Measure crown elevations at both ends of the full pipe section. Record the total length between the extreme ends, the length of the miter, and the length of the full section of the culvert. Each of these dimensions enters into the computation of discharge as explained in 18.5.

13.10 *Flared and Tapered Inlets*—Culverts may have end sections designed to protect the culvert from deposition of material eroded from embankment and to improve flow conditions (see Figs. 5-7). These are most commonly used on corrugated metal pipes and pipe arches and on concrete pipes, but they may also be used on box culverts. The face of an end section generally is wider than the culvert and at times it may also have a greater depth than the culvert. Improved end sections are of two basic types. One type is open at the top (see Figs. 5 and 6), the other tapers into the culvert from the sides, top, and possibly the bottom (see Fig. 7). By convention and for convenience in distinguishing the two types, designate the

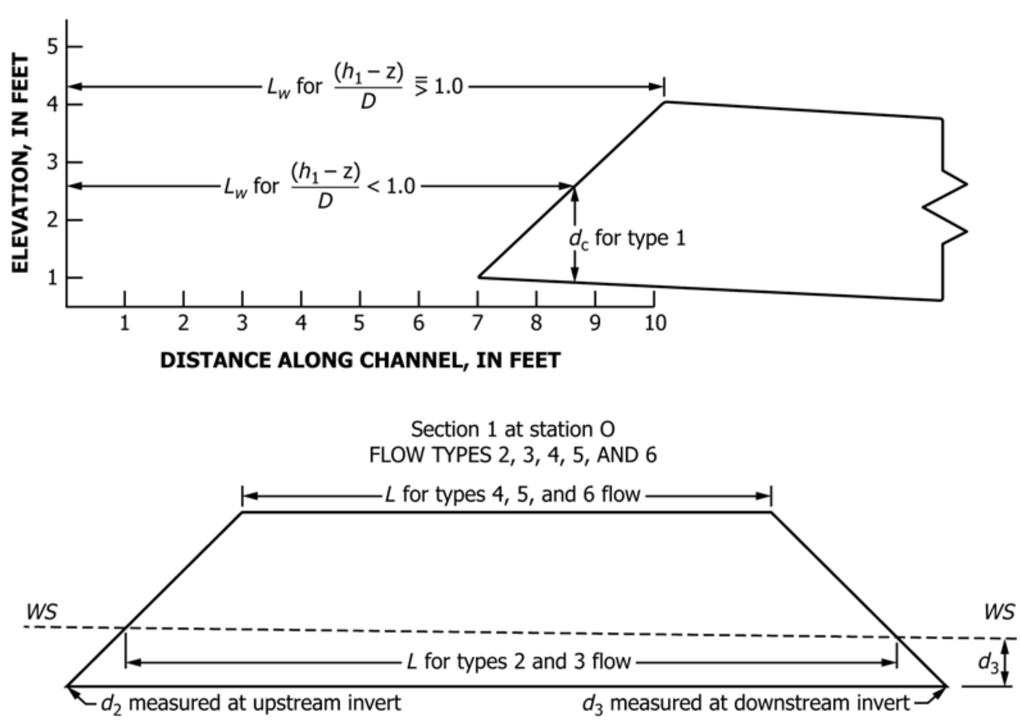
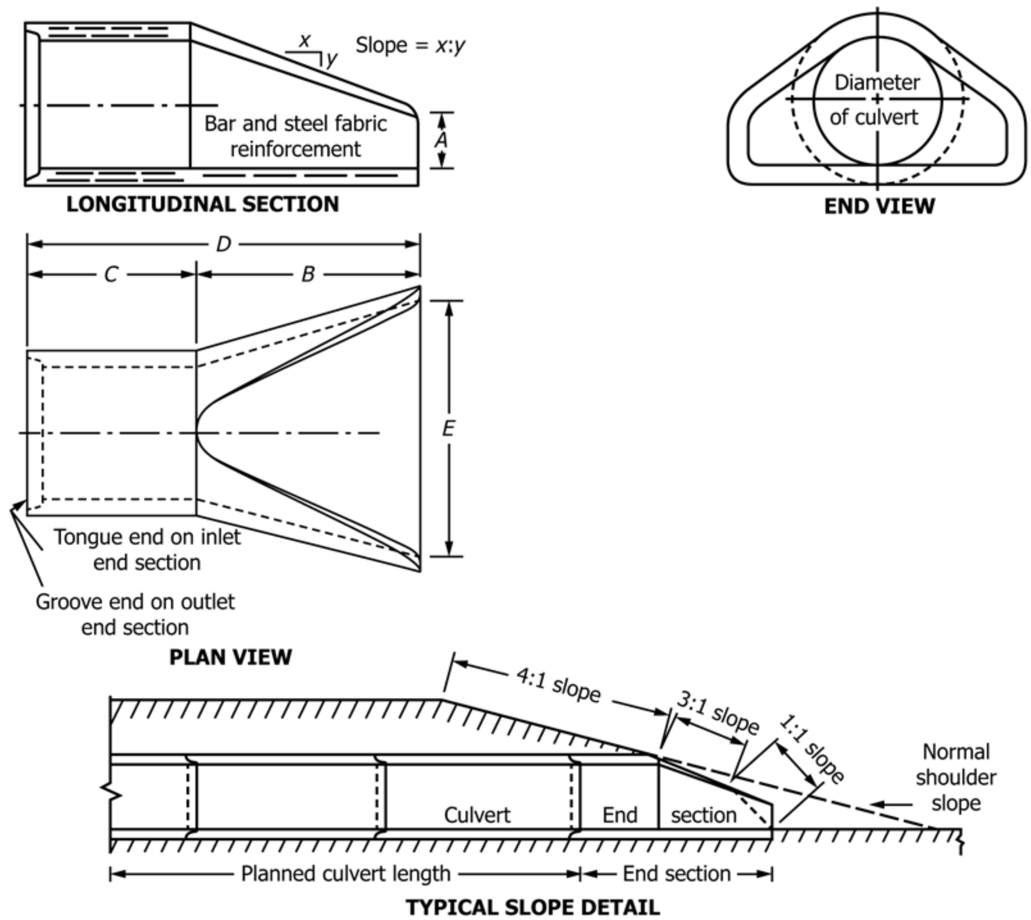


FIG. 4 Approach and Culvert Lengths for Mitered Pipe



Selected dimensions for various diameters of pipe

Diam (in.)	A		B		C		D		E	
	(ft	in.)	(ft	in.)	(ft	in.)	(ft	in.)	(ft	in.)
12	0	4	2	0	4	0⅞	6	0⅞	2	0
15	0	6	2	3	3	10	6	1	2	6
18	0	9	2	3	3	10	6	1	3	0
21	0	9	3	0	3	1½	6	1½	3	6
24*	0	9½	3	7½	2	6	6	1½	4	0
27	0	10½	4	1½	2	0	6	1½	4	6
30*	1	0	4	6	1	7¾	6	1¾	5	0
36	1	3	5	3	2	10¾	8	1¾	6	0
42	1	9	5	3	2	11	8	2	6	6
48	2	0	6	0	2	2	8	2	7	0
54	2	3	5	5	2	9¼	8	2¼	7	6

* Overall length (*D*) of Iowa design is 8 ft 1½ in. for 24 in. and 8 ft 1¾ in. for 30 in.

NOTE 1—Slope 3:1 for all sizes except 54 in. which is 2.4:1.

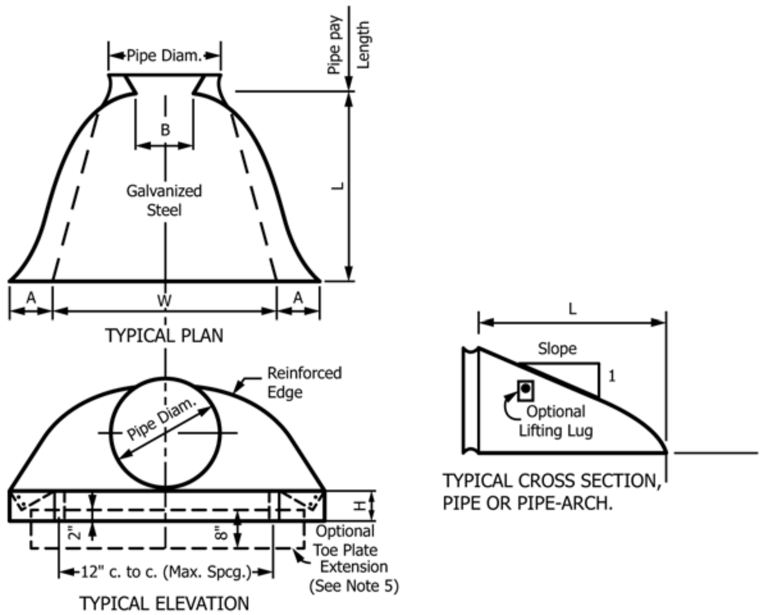
FIG. 5 Dimensions of Flared End Sections for Reinforced Concrete Pipe

first type as a flared entrance and the second as a tapered entrance. If a flared or tapered entrance is present it must be fully measured in the field and dimensioned in the field notes. Record width and shape of the face, elevation of top and bottom of the face, and elevation of breaks in slope of side walls of the end section.

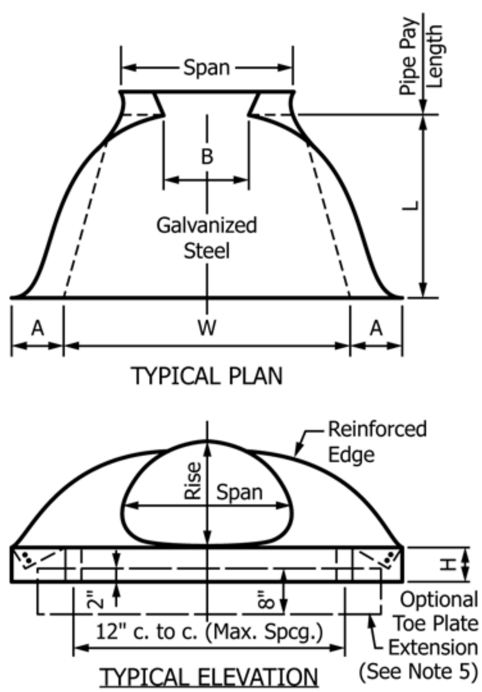
14. Special Conditions

14.1 Hydraulic characteristics of culverts in the field can be greatly different from closely controlled laboratory conditions. Before coefficients and methods derived in the laboratory can be applied to field installations, consider any features that tend to destroy model-prototype similarity.

14.2 *Drift*—Examine drift found lodged at the inlet of a culvert after a rise and evaluate its effect. It is not uncommon for material to float above a culvert at the peak without causing obstruction and then lodge at the bottom when the water subsides. However, if examination shows it to be well compacted in the culvert entrance and probably in the same position as during the peak, measure the obstructed area and deduct it from the total area.



Details of steel end sections for circular steel pipe.



Details of steel end sections for steel pipe-arches.

FIG. 6 Details of End Sections for Steel Pipes and Pipe Arches

14.2.1 *Deposits in Culvert*—Sand and gravel found within a culvert barrel are often deposited after the extreme velocities of peak flow have passed; where this occurs, use the full area of the culvert. Careful judgment must be exercised because, in many places, levels before and after a peak show virtually the same invert elevations even though high velocities occurred. Deposits composed of unconsolidated sand and small gravel generally will not remain in place if the velocity of flow in the

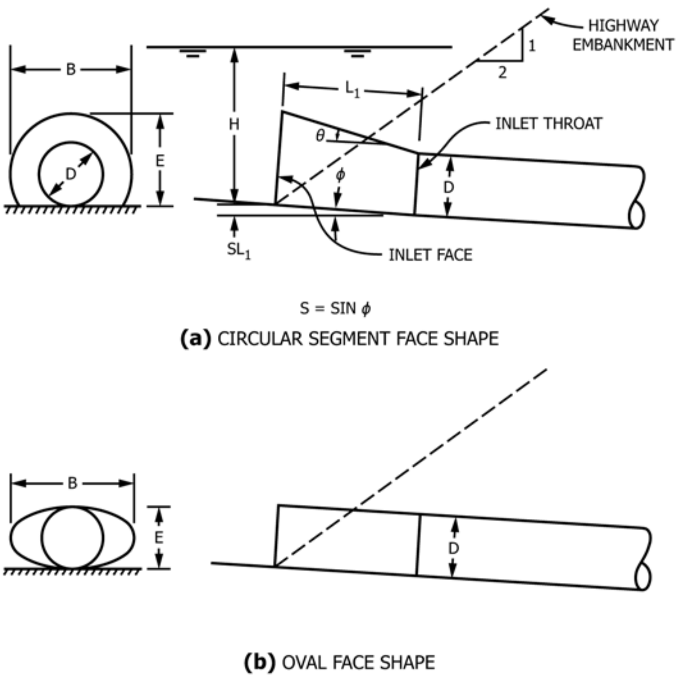


FIG. 7 Details of Typical Tapered Entrances

culvert exceeds about 4 ft/s (1.2 m/s) and may wash out at lower velocities. Consolidated deposits and large cobbles may withstand somewhat higher velocities.

14.2.2 *Ice and Snow*—In certain areas ice and snow may present problems. Ice very often causes backwater partly blocking the culvert entrance. Snow frequently causes the deposition of misleading high-water marks as it melts.

14.3 *Breaks in Slope*—Sometimes culverts are installed with a break in bottom slope. At other times a break in slope will occur as a result of uneven settling in soft fill material. Determine the elevation and location of the invert at each break in slope. A break in slope frequently occurs where a culvert has been lengthened during road reconstruction. In rare cases the size, shape, or material, or all three, of the culvert sections may differ. Measure the length of each section and determine the invert elevation at each change.

14.4 *Streambed Bottoms*—Many culverts, especially small bridge-type structures and multiplate arches, have natural stream-bed bottoms. The irregularity of the bottom may present difficulties in applying these data to the equations for certain types of flow. Take special care in the field to properly define the bottom elevation at each end of the culvert.

15. Roughness Coefficients

15.1 Select roughness coefficients in the field for use in the Manning equation for both the approach reach and the culvert at the time of the field survey.

15.2 *Approach Section*—Assign roughness coefficients selected for the approach reach to the approach section as being typical of the reach. These coefficients will usually be in the range between 0.030 and 0.060 at culverts, because stream channels are usually kept cleared in the vicinity of the culvert entrance. At times the approach roughness coefficient may be lower than 0.030 in sand channels or when the culvert apron and wingwalls extend upstream to, or through, the approach section.

15.2.1 Select points of subdivision of the cross section in the field and assign values of *n* to the various sub-areas. For the computation of a rating where various headwater elevations are used, *n* and the points of subdivision may change. For these sections, note the elevations at which the changes take place.

15.3 *Culvert Sections*—Field inspection is always necessary before *n* values are assigned to any culvert. The condition of the material, the type of joint, and the kind of bottom, whether natural or constructed, all influence the selection of roughness coefficients.

15.3.1 *Corrugated Metal*—A number of laboratory tests have been run to determine the roughness coefficient for corrugated-metal pipes of all sizes.

15.3.2 *Riveted Construction*—The corrugated metal most commonly used in the manufacture of pipes and pipe arches has a 2⅔-in. (67.7 mm) pitch with a rise of ½ in. (12.7 mm). This is frequently referred to as standard corrugated metal. Sections of pipe arc riveted together. According to laboratory tests (**3**), *n* values for full pipe flow vary from 0.0266 for a 1-ft (0.3 m)-diameter pipe to 0.0224 for an 8-ft (2.4-m) diameter pipe for the velocities normally encountered in culverts. The American Iron and Steel Institute (**4**) recommends that a single value of 0.024 be used in deign of both partly-full and full-pipe flow for any size of pipe. This value is also considered satisfactory for most computations of discharge. For more precise computations, take *n* values from Table 2. The *n* values in Table 2 were derived from tables and graphs published by FHWA for culvert design (**5**), and apply to both annular and helical corrugations as noted in the table.

15.3.2.1 Riveted pipes are also made from corrugated metal with a 1-in. (25.4-mm) rise and 3, 5, and 6-in. (76.2, 127, and 152.4-mm) pitch. Experimental data shows a slight lowering of the *n* values as the pitch increases. The *n* values for these three types of corrugation are also shown in Table 2.

15.3.3 *Structural-Plate (Multiplate)* —The metal most commonly used in structural-plate (also called multiplate construction) has much larger corrugations than does standard corrugated metal, and plates are bolted together. Structural-plate construction is used with both steel and aluminum. The steel has a 6-in. (152.4 mm) pitch and a 2-in. (50.8 mm) rise, aluminum has a 9-in. (228.6 mm) pitch and a 2.5 in. (63.1 mm) rise. Tests show *n* values for this construction to be somewhat higher than for riveted-pipe construction. Average *n* values range from 0.035 (steel) and 0.036 (aluminum) for 5-ft (1.52 m) diameter pipes to 0.033 for pipes of 18 ft (5.48 m) or greater diameter. The *n* values for various diameters of pipe are tabulated in Table 2.

15.3.4 *Paved Inverts*— In many instances the bottom parts of corrugated pipe and pipe-arch culverts are paved, usually with a bituminous material. This reduces the roughness coefficient to a value between that normally used and 0.012. The reduction is directly proportional to the percentage of wetted

TABLE 2 Manning's Roughness Coefficients for Corrugated Metal

NOTE 1—*n* values apply to pipes in good conditions. Severe deterioration of metal and misalignment of pipe sections may cause slightly higher values.

NOTE 2—For purposes of metric conversion 1 in. = 25.4 mm.

Pipe Diameter, ft	*n* value for Indicated Corrugation Size					
	Riveted Construction				Structural-Plate Construction	
	Corrugation, Pitch by Rise, in.					
	2⅔ by ½	3 by 1	5 by 1	6 by 1	6 by 2	9 by 2½
	Annular Corrugations					
1	0.027	. . .	. . .	. . .	. . .	. . .
2	0.025	. . .	. . .	. . .	. . .	. . .
3	0.024	0.028	. . .	0.025	. . .	. . .
4	0.024	0.028	0.026	0.025	. . .	. . .
5	0.024	0.028	0.026	0.024	0.035	0.036
6	0.023	0.028	0.026	0.024	0.035	0.035
7	0.023	0.028	0.026	0.024	0.035	0.034
8	0.023	0.028	0.025	0.023	0.034	0.034
9	0.023	0.028	0.025	0.023	0.034	0.034
10	0.022	0.027	0.025	0.023	0.034	0.034
11	0.022 [A]	0.027	0.025	0.022	0.034	0.034
12	. . .	0.027	0.024	0.022	0.034	0.034
16	. . .	0.026 [A]	0.023 [A]	0.021 [A]	. . .	. . .
18	. . .	. . .	. . .	. . .	. . .	0.033
21	. . .	. . .	. . .	. . .	0.033	. . .
	Helical Corrugations					
4	0.020	Use values for annular corrugations for all other corrugation sizes and pipe diameters.				
5	0.022					
6	0.023					
7	0.023					
Range of pipe diameter in feet commonly encountered with indicated corrugation size:	< 9	3 to 13	5 to 13	3 to 13	5 to 25	5 to 25

[A] Extrapolated beyond Federal Highway Administration curves.

perimeter that is paved. The composite value of *n* for standard pipes and pipe-arches may be computed by the following equation:

$$n_c = \frac{0.012P_p + 0.024(P - P_p)}{P}, \quad (13)$$

where:

P_p = length of wetted perimeter that is paved, and
P = total length of wetted perimeter.

15.3.4.1 Eq 13 is for corrugations having a 2⅔-in. (67.7 mm) rise and a ½-in. (12.7 mm) rise. For other corrugations the value of 0.024 must be replaced with the correct value corresponding to the corrugation and size of the pipe.

15.3.4.2 Occasionally the paving material may extend several inches (millimetres) above the corrugations. Where this condition exists, the area and wetted perimeter should be adjusted accordingly.

15.3.5 *Concrete*—The roughness coefficient of concrete is dependent upon the condition of the concrete and the irregularities of the surface resulting from construction. Suggested values of *n* for general use are as follows:

Condition of Concrete	*n*
Very smooth (spun pipe)	0.010
Smooth (cast or tamped pipe)	0.011–0.015
Ordinary field construction	0.012–0.015
Badly spalled	0.015–0.020

15.3.5.1 *Displacement*—At times, sections of concrete pipe became displaced either vertically or laterally, resulting in a much rougher interior surface than normal. When this occurs, increase *n* commensurate with the degree of displacement of the culvert sections. Laboratory tests have shown that the displacement must be considerable before the roughness coefficient is affected very much.

15.3.5.2 *Bends*—Slight bends or changes in alignment of the culvert will not affect the roughness coefficient. However, the effects of fairly sharp bends or angles can be compensated for by raising the *n* value. Russell **(6)** showed that for extremely sharp bends (90°) the head loss may vary from 0.2 to 1.0 times the velocity head, depending on the radius of the bend and the velocity. The lower value applies to velocities of 2 or 3 ft/s (0.6 or 1.0 m/s) and radii of 1 to 8 ft (0.3 to 2.5 m), and the higher value to velocities of 15 to 20 ft/s (5 to 6 m/s) and radii of 40 to 60 ft (12 to 20 m). King **(7)** stated that the losses in a 45° bend may be about ¾ as great as those in a 90° bend, and losses for a 22½ ° bend may be about half as great as those of a 90° bend.

15.3.6 *Other Materials*—Occasionally culverts will be constructed of some material other than concrete or corrugated metal. Manning's coefficients **(7)** for some of these materials are given in Table 3.

15.3.6.1 Culverts made from cement rubble or rock may have roughness coefficients ranging from 0.020 to 0.030, depending on the type of material and the care with which it is laid.

15.3.7 *Natural Bottoms*— Many culverts, especially the large arch type, are constructed with the natural channel as the bottom. The bottom roughness usually weights the composite roughness coefficient quite heavily, especially when the bottom

TABLE 3 Roughness Coefficients for Materials Other Than Corrugated Metal and Concrete

Material	*n*
Welded steel	0.012
Wood stave	0.012
Cast iron	0.013
Vitrified clay	0.013
Riveted steel	0.015

is composed of cobbles and large angular rock. The formula used for paved inverts can be used here if the correct *n* values are substituted therein.

16. Coefficients of Discharge—General

16.1 Coefficients of discharge, C , for all six types of flow have been defined by laboratory studies. They range from 0.39 to 0.98 for average entrances and are functions of the type of flow, degree of channel contraction, and the geometry of the culvert entrance.

16.2 Entrance geometries may require an adjustment to a base coefficient for entrance rounding (k_r) or for beveling or wingwalls (k_w). An adjusted coefficient of 0.98 is the limiting value.

16.3 The coefficients are applicable to skewed culverts and to both single barrel and multi-barrel installations. If the width of the web between barrels at a multi-barrel site is less than 0.1 the width of a single barrel, it should be disregarded when evaluating the entrance geometry. Bevels are considered as such only if they are 0.1 or less of the diameter, depth, or width of a culvert barrel. If greater than 0.1, they are considered to be wingwalls.

16.4 The geometry of the sides determines C for Types 1, 2, and 3 flow, and that for the top and sides determines C for Types 4, 5, and 6 flow.

16.5 Coefficients for the six flow types have been divided into three groups, each group having a discharge equation of the same general form. Thus, Types 1, 2, and 3 are in the first group, Types 4 and 6 in the second, and Type 5 in the third.

16.6 The entrance geometries have been classified in four general categories: flush setting in a vertical headwall, wingwall entrance, projecting entrance, and mitered pipe set flush with sloping embankment.

17. Coefficients of Discharge—Specific

17.1 *Types 1, 2, and 3 Flow:*

17.1.1 *Adjustment for m*—For culverts, the ratio of channel contraction, m , is defined as $(1 - A/A_1)$ where A is the area of flow at the terminal section and A_1 is the area of the approach section. Tests on flow through bridge openings with geometries that approach those of culverts demonstrate that the discharge coefficient varies almost linearly between values of m from 0 to 0.80, and that the coefficient reaches a minimum value at $m = 0.80$. All coefficients given herein are for an m of 0.80. If the contraction ratio is smaller than 0.80, the following equation may be used:

$$C'(\text{adjusted}) = 0.98 - (0.98 - C)m/0.80$$

This equation is expressed graphically in Fig. 8. This adjustment is made as the last step in the computation of the discharge coefficient.

17.1.2 *Flush Setting in Vertical Headwall:*

17.1.2.1 *Square Ended Pipes and Pipe Arches*—The discharge coefficient for square-ended pipes set flush in a vertical headwall is a function of the ratio of the headwater height to the pipe diameter $(h_1 - z)/D$. The coefficient for flow Types 1, 2, and 3 can be determined from Fig. 9.

17.1.2.2 *Pipes and Pipe Arches with Rounded or Beveled Entrances*—If the entrance to the pipe is rounded or beveled, compute the discharge coefficient by multiplying the coefficient for the square-ended pipe by an adjustment factor, k_r or k_w. These adjustment factors are a function of the degree of entrance rounding or beveling and these relations, applicable to flow Types 1, 2, and 3, are defined in Fig. 10 and Fig. 11. Where the degree of rounding or beveling is not the same on both sides, average the coefficients for each side.

17.1.2.3 *Concrete Pipes*—Use a C of 0.95 for all sizes of machine tongue-and-groove concrete pipe and for a bell-mouthed precast concrete pipe for all headwater-pipe diameter ratios in Types 1 through 3 flow.

17.1.2.4 *Standard Corrugated Metal Entrance*—Corrugated-metal pipe generally has a beveled edge with an average w of 0.30 in. (5 mm) ((0.025 ft) (0.005 m)) and a bevel angle of 67°. If the entrance appears to be rounded rather than beveled, the rounding may vary with the gauge of the metal, but it will average slightly less than 0.80 in. (20mm) ((0.067 ft) (0.002 m)) for the weights of metal ordinarily used. The following table shows average values of r/D and w/D for the above values of w, r, and various sizes of standard riveted corrugated-metal pipe (2⅔ in. (67.7 mm) pitch and ½ in. (12.7 mm) rise).

D, in. (m)	*r/D*	*w/D*
24 (0.6)	0.031	0.0125
36 (0.9)	0.021	0.0083
48 (1.2)	0.016	0.0062
60 (1.6)	0.012	0.0050
72 (2.0)	0.010	0.0042

17.1.2.5 *Multiplate Construction*—Because of the longer pitch in multiplate pipe construction, the entrance is nearly always considered to be beveled. The value of w will average about 1.2 in. (30 mm) and θ about 52°. Always measure in the field these factors or the data required to compute them. The average w and θ have not been determined for other sizes of corrugations. These must be measured in the field.

17.1.2.6 *Beaded End*—Occasionally a culvert with a beaded or rolled entrance will be found. The radius of rounding of the bead generally is about ⅜ in. (10 mm) ((0.031 ft)). Always make exact measurements in the field.

17.1.2.7 *Square-Ended Box*—The discharge coefficient for box culverts set flush in a vertical headwall is a function of the Froude number. The Froude number for flow Types 1 and 2 is always 1.0, and the corresponding base discharge coefficient is 0.95. Determine the discharge coefficient for Type 3 flow from Fig. 12 after computing the Froude number, $V/\sqrt{gd}$, at the downstream end of the culvert. If necessary, Fig. 12 may be extrapolated with reasonable safety to a Froude number of 0.1.

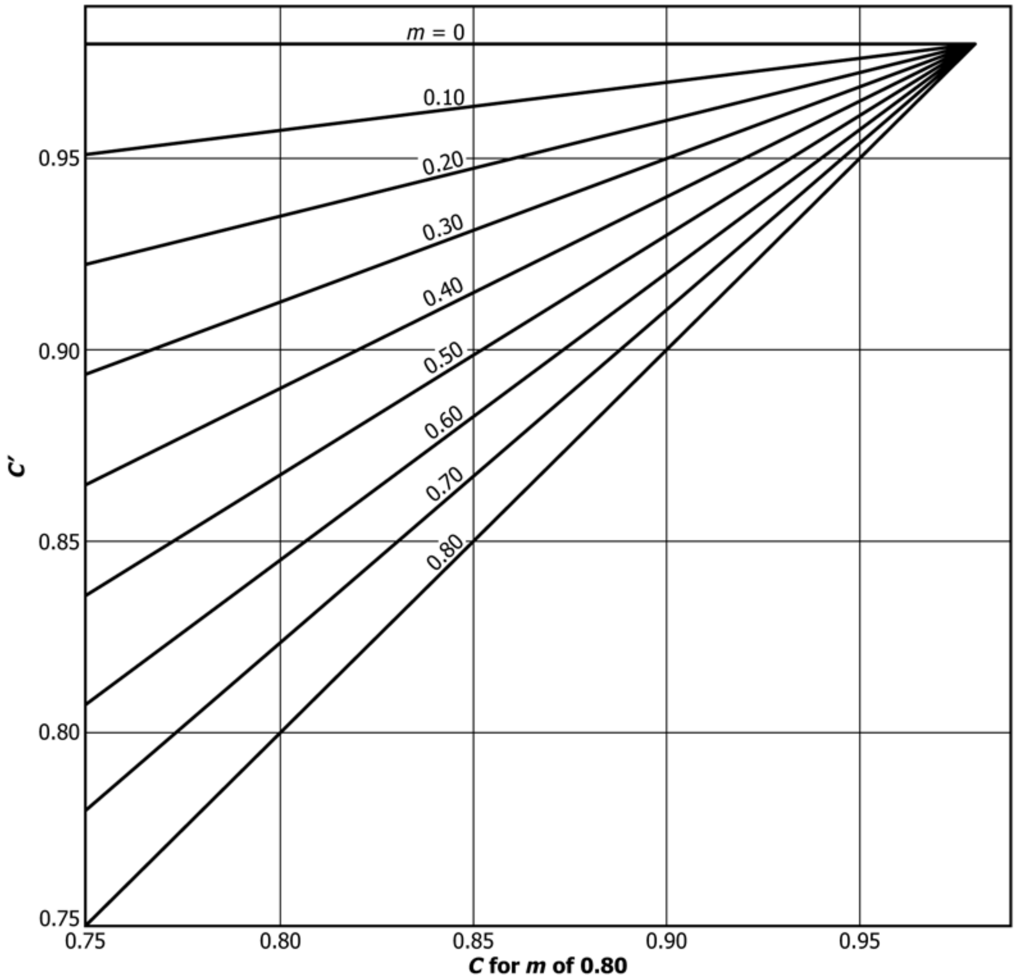


FIG. 8 Adjustment to Discharge Coefficient for Degree of Channel Contraction

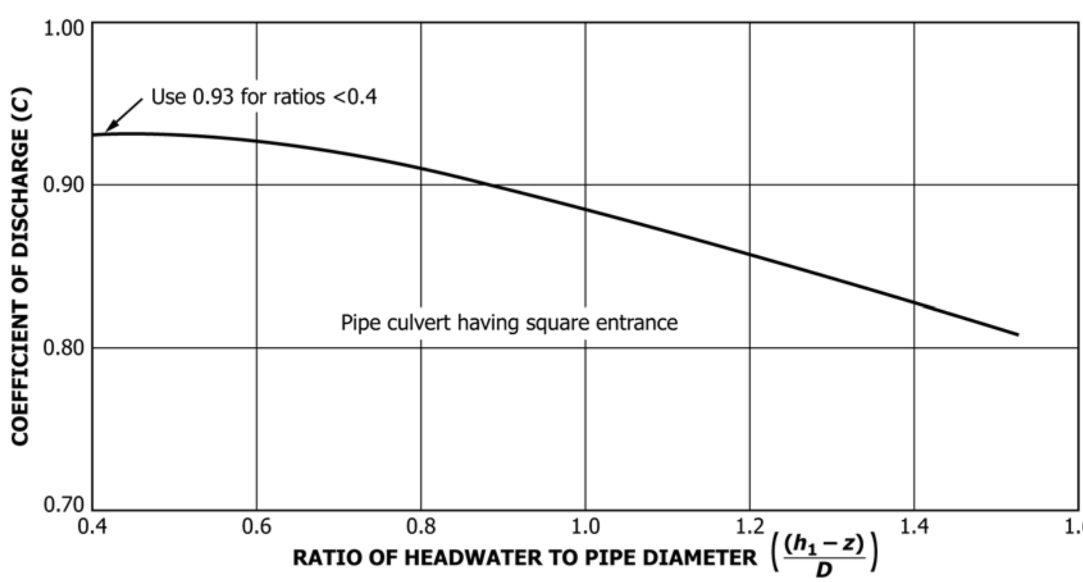


FIG. 9 Base Coefficient of Discharge for Types 1, 2, and 3 Flow in Pipe Culverts with Square Entrance Mounted Flush with Vertical Headwall

17.1.2.8 *Box with Rounded or Beveled Entrance*—If the entrance to the box is rounded or beveled, compute the discharge coefficient by multiplying the coefficient for the square-ended box by an adjustment factor, k_r or k_w. Determine

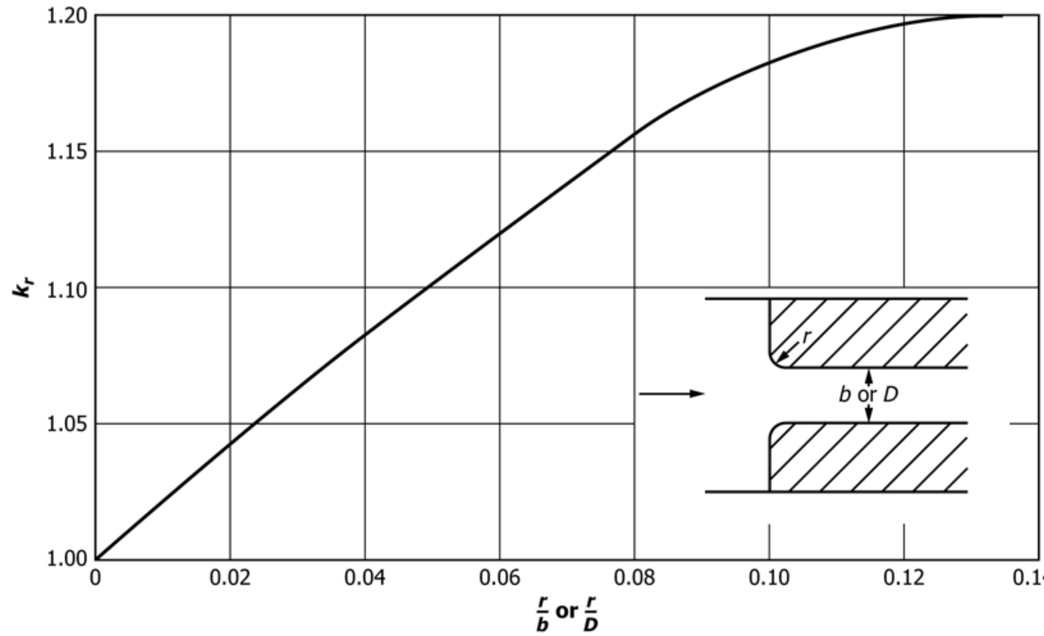


FIG. 10 Variation of the Discharge Coefficient with Entrance Rounding, Types 1, 2, and 3 Flow in Box or Pipe Culverts Set Flush with Vertical Headwall

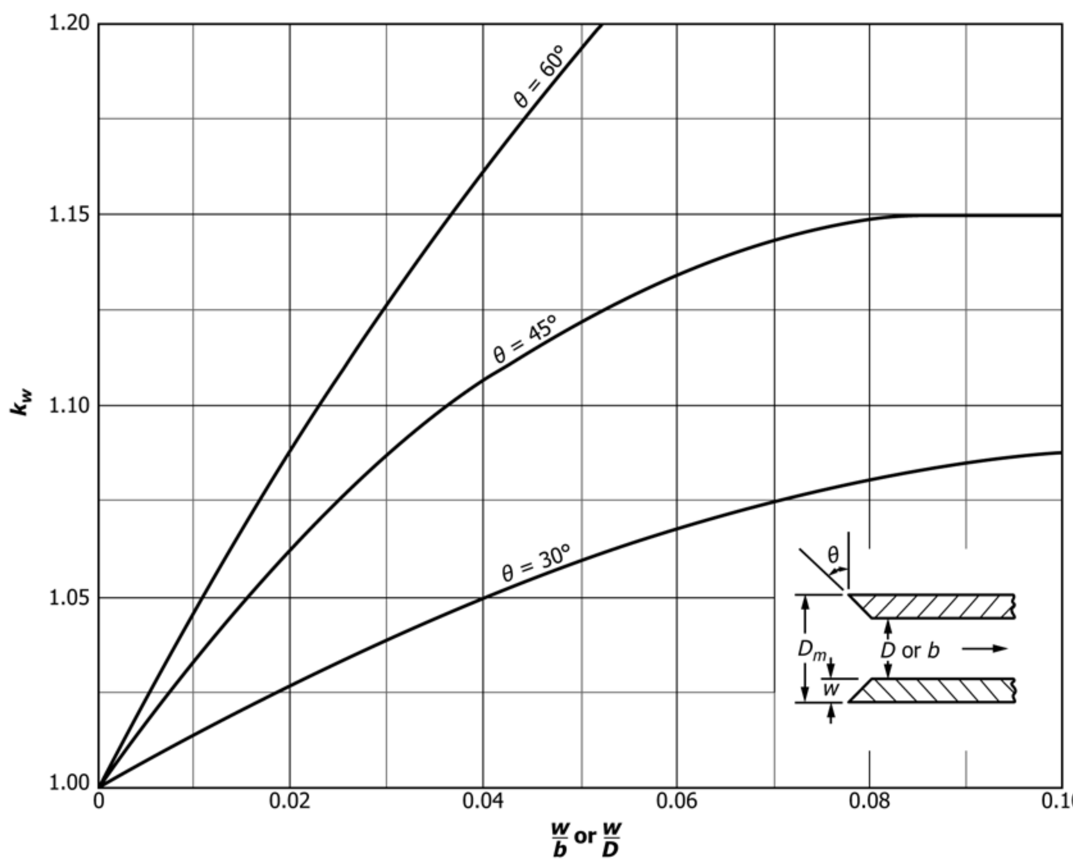


FIG. 11 Variation of the Discharge Coefficient with Entrance Beveling, Types 1, 2, and 3 Flow in Box or Pipe Culverts Set Flush with Vertical Headwall

these adjustment factors, applicable to flow Types 1, 2, and 3, from Fig. 10 or Fig. 11, respectively.

17.1.3 *Wingwall Entrance:*

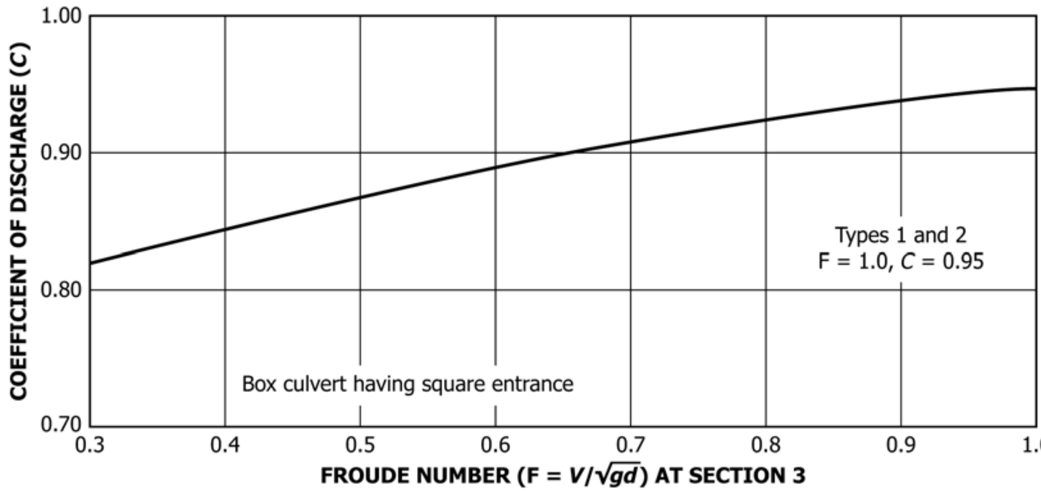


FIG. 12 Base Coefficient of Discharge for Types 1, 2, and 3 Flow in Box Culverts with Square Entrance Mounted Flush in Vertical Headwall

17.1.3.1 *Pipe and Pipe Arches*—The addition of wingwalls to the entrance of pipes or pipe arches set flush in a vertical headwall does not affect the discharge coefficient, that can be determined as explained in 17.1.2.2.

17.1.3.2 *Box Culverts*—Compute the discharge coefficient for box culverts with a wingwall entrance by first selecting a coefficient from Fig. 12 and then multiplying this coefficient by an adjustment factor, k_θ, that can be determined from Fig. 13 on the basis of an angle θ of the wingwall. If the angle of the wingwall is not the same on each side, determine the value of *C* for each side independently and average the results. Where the web between culvert barrels is wide enough (0.1 *b* or greater) to affect the entrance geometry, treat it as a wingwall. Consider a web corner of less than a right angle as a square entrance.

17.1.4 *Projecting Entrance:*

17.1.4.1 *Thin Walls*—Determine the discharge coefficient for pipes and pipe arches that extend beyond a headwall or embankment by first computing a coefficient as outlined for pipes set flush in a vertical headwall and then multiplying the coefficient by an adjustment factor, k_L. The adjustment factor is a function of L_p/D; where L_p is the length by which the culvert projects beyond the headwall or embankment. The adjusted *C* to which k_L is applied must not be greater than 0.98, as this is the limiting value of *C*.

17.1.4.2 *Computation of* L_p—An acceptable method for determining k_L is to weight L_p between invert and headwater elevations for each side of the pipe on the basis of vertical distance and obtain the average L_p before computing k_L. Values of k_L for various values of L_p/D are tabulated in Table 4.

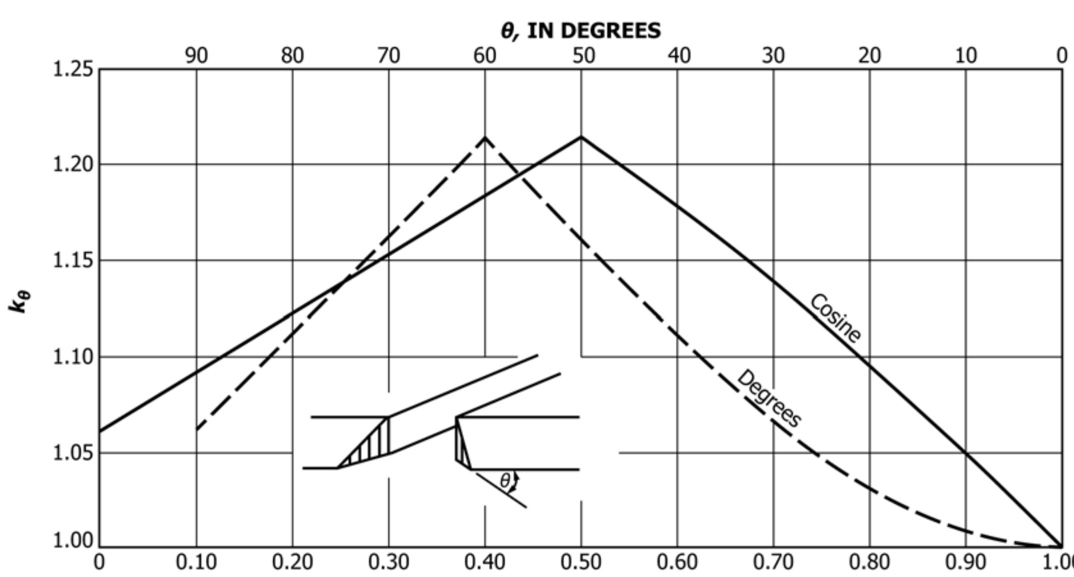


FIG. 13 Variation of Discharge Coefficient with Wingwall Angle, Types 1, 2, and 3 Flow in Box Culverts with Wingwall Set Flush with Sloping Embankment

TABLE 4 Adjustment Factors for Projecting Thin Wall Entrances

L_p/D	k_L	L_p/D	k_L
0.00	1.00	0.0	1.00
0.01	0.99	0.1	0.92
0.02	0.98	0.2	0.92
0.03	0.98	0.3	0.92
0.04	0.97	0.4	0.91
0.05	0.96	0.5	0.91
0.06	0.95	0.6	0.91
0.07	0.94	0.7	0.91
0.08	0.94	0.8	0.90
0.09	0.93	0.9	0.90
0.10	0.92	≥1.0	0.90

17.1.4.3 *Concrete Pipes*—The discharge coefficient for projecting entrances for concrete pipes with a beveled end is the same as for flush entrances.

17.1.5 *Mitered Pipes*—The discharge coefficient for mitered pipes set flush with a sloping embankment is a function of the ratio of headwater height to pipe diameter and can be determined from Fig. 14.

17.1.5.1 *Projecting Miters*—For a projecting mitered pipe with a thin wall (like corrugated metal), determine the base coefficient from Fig. 14 and adjust the coefficient in the same manner as for any other projecting barrels. Do not adjust for rounding or beveling because the bevel of the pipe is removed in the mitering process.

17.1.6 *Flared and Tapered Entrances*—Coefficients of discharge for Types 1, 2, and 3 flow have been determined for only some types of flared entrances, and have not been determined for tapered inlets. Some research is applicable and experience with other types of entrances provides a basis for determining coefficients for those entrances for which the coefficients have not been determined. See 13.9 for the distinction between flared and tapered entrances.

17.1.6.1 *Tapered Entrance*—French (**2**) indicates a coefficient of 0.98 for tapered entrances (Fig. 7) with $(h_1 - z)/D$ ratios in the range from 1.00 to 1.50. Because of the nature of the contraction, it is safe to use a coefficient of 0.98 for all lower head ratios.

17.1.6.2 *Flared Entrances*—Bodhaine (**8**) specifies a coefficient of 0.95 for Types 1, 2, and 3 computations involving the flared entrance of Fig. 5. Using a coefficient of 0.95 for all ratios does not account for the fact that the vertical part of the face should produce a *C* of 0.98 for low stages. It is recommended that 0.98 be used when the upstream water surface is below the top of the vertical part of the entrance, which is represented by *A* in Fig. 5, and 0.95 be used when the upstream water surface is above the vertical part. The height of *A* is generally about 0.4 *D*, but it should always be measured in the field. Coefficients are not specified for the corrugated metal flares of Fig. 6, but they should be similar to those for the concrete flare. The coefficient may depend on the degree to which the sides of the flare extend above the embankment. Lacking better information, a coefficient of 0.95 is recommended for all Types 1, 2, and 3 flow computations through a flared entrance on a corrugated metal pipe. However, if the flare is so constructed that at low headwater elevations water does not spill over sidewalls into the patch of flow, use 0.98 for headwaters in this range.

17.2 *Types 4 and 6 Flow*—Where the sides are rounded or beveled and the top is square, determine the average coefficient for the sides, and multiply the average coefficient by 0.95 for Types 4 and 6 flow. Use the coefficient for the square entrance as the lower limiting value.

17.2.1 *Flush Setting in Vertical Headwall*—Select the discharge coefficient for box or pipe culverts set flush in a vertical headwall from Table 5. This includes square-ended pipes or boxes, corrugated pipes, corrugated pipe-arches, corrugated

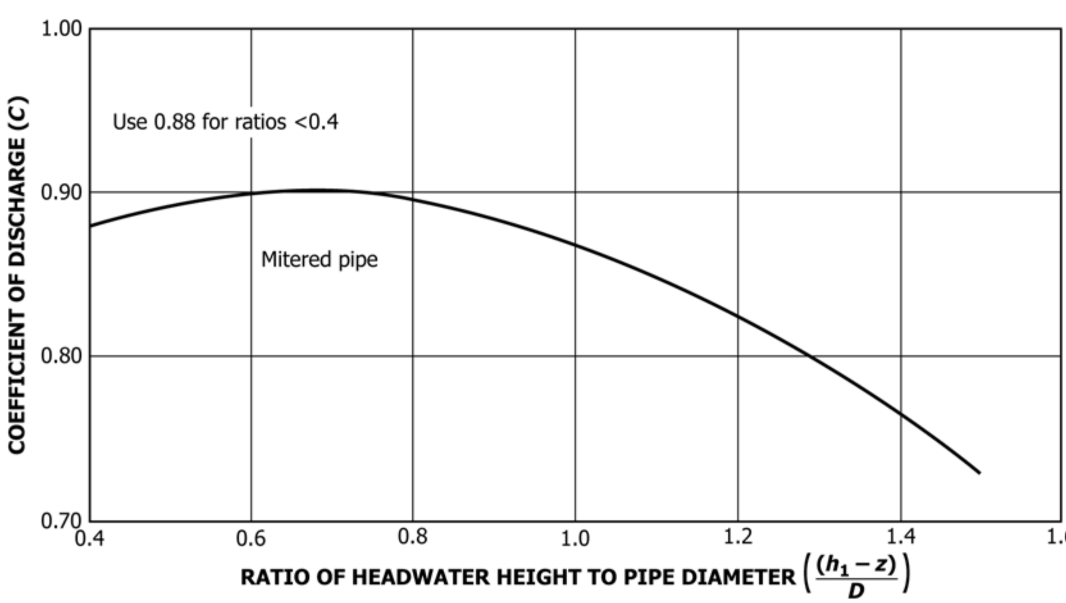


FIG. 14 Variation of Discharge Coefficient with Headwater-Diameter Ratio, Types 1, 2, and 3 Flow in Mitered Pipe Set Flush with Sloping Embankment

TABLE 5 Discharge Coefficients for Box or Pipe Culverts Set Flush in a Vertical Headwall: Types 4 and 6 Flow

r/b, w/b, w/D, or *r/D*	*C*
0.00	0.84
0.02	0.88
0.04	0.91
0.06	0.94
0.08	0.96
0.10	0.97
0.12	0.98

pipes with a standard conical entrance, concrete pipes with a beveled or bellmouthed end, and box culverts with rounded or beveled sides.

17.2.2 *Flared Entrance*—The discharge coefficient for Type 4 or 6 flow and flared pipe end sections (see 13.9 and 17.1.6) is 0.90 for all diameters and all values of $(h_1 - z)/D$.

17.2.3 *Wingwall Entrance:*

17.2.3.1 *Pipes and Pipe Arches*—The addition of wingwalls to the entrance of pipes or pipe arches set flush with a vertical headwall does not affect the discharge coefficient, that can be determined from Table 5.

17.2.3.2 *Box Culverts*—For box culverts with wingwalls and a square top entrance the discharge coefficient is 0.87 for wingwalls angles, θ, of 30 to 75° and is 0.75 for the special condition whenθ equals 90°. If the top entrance is rounded or beveled, and θ is between 30 and 75°, select a coefficient from Table 5 on the basis of the value of *w/D* or *r/D* for the top entrance, but use 0.87 as the lower limiting value. For the special case when θ equals 90°, if the top entrance is rounded or beveled, multiply the base coefficient (0.75) by k_r or k_w from Fig. 10 or Fig. 11. For angles between 75 and 90°, interpolate between 0.87 and 0.75 to obtain the base coefficient and apply the adjustment for rounding or beveling as described above.

17.2.4 *Mitered Pipes*—The discharge coefficient for pipes and pipe arches set flush with a sloping embankment is 0.74.

17.2.5 *Projecting Entrance:*

17.2.5.1 *Corrugated Pipes*—Determine the discharge coefficient for corrugated-metal pipes and pipe arches that extend past a headwall or embankment by first selecting the coefficient from Table 5 that corresponds to the particular value of *r/D* and then multiplying this coefficient by an adjustment factor k_L from Table 4.

17.2.5.2 *Concrete Pipes*—The discharge coefficient for concrete pipes with a beveled end that have a projecting entrance is the same as for those with a flush entrance and can be determined from Table 5.

17.2.5.3 *Mitered Thin-Walled Pipes and Pipe Arches*—The discharge coefficient for thin-walled pipes mitered and extending from embankment is 0.74 multiplied by k_L from Table 4.

17.2.6 *Tapered Entrances*—Use $C = 0.98$ for all tapered entrances for Type 4 or 6 flow.

17.3 *Type 5 Flow*—Where the sides are rounded or beveled and the top is square, determine the average coefficient for the sides, and multiply the average coefficient by 0.90 for Type 5 flow. Use the coefficient for the square entrance as the lower limiting value.

17.3.1 *Flush Setting in Vertical Headwall*—Determine the discharge coefficient for box or pipe culverts set flush in a vertical headwall from Table 6. This includes square-ended pipe or box, corrugated pipe, corrugated pipe arch, concrete pipe with a beveled end, and box culverts with rounded or beveled sides.

17.3.2 *Wingwall Entrance:*

17.3.2.1 *Pipes and Pipe Arches*—For pipes and pipe arches, the addition of wingwalls to the entrance does not affect the discharge coefficient, which can be determined from Table 6.

17.3.2.2 *Box Culverts*—Determine the discharge coefficient for box culverts with wingwalls and a square top corner from Table 7. If the top is rounded or beveled, select the coefficient from Table 6 on the basis of *w/D* or *r/D* for the top, but use the coefficient from Table 7 as a lower limiting value.

17.3.3 *Mitered Pipes and Pipe Arches*—Determine the discharge coefficient for mitered pipes and pipe arches set flush with a sloping embankment by first selecting a coefficient from Table 7 for a square-ended pipe and then multiplying this coefficient by 0.92.

17.3.4 *Pipes and Arches with Flared Entrance*—Type 5 flow usually cannot be obtained when flared pipe end sections are installed. Only for *L/D* ratios less than six and culvert slopes greater than 0.03 will Type 5 flow occur. Even under these conditions the flow may eventually translate to Type 6 flow. If Type 5 flow is believed to exist, the discharge coefficients in Table 8 are applicable as follows:

17.3.5 *Projecting Entrance:*

17.3.5.1 *Thin-Walled Pipes and Pipe Arches*—Determine the discharge coefficient for thin-walled pipes and pipe arches that extend past a headwall or embankment by first selecting a coefficient from Table 6 and then multiplying by an adjustment factor k_L from Table 4.

17.3.5.2 *Concrete Pipes*—Determine the discharge coefficient for a concrete pipe with either tongue-and-groove or bell-mouth end directly from Table 6.

17.3.5.3 *Mitered Pipes and Pipe Arches*—Determine the discharge coefficient for mitered thin-wall pipes and pipe arches that project from the sloping embankment by first selecting a coefficient from Table 6 for a square-ended pipe and then multiplying this coefficient by 0.92 and by k_L from Table 4.

TABLE 6 Discharge Coefficients for Box or Pipe Culverts Set Flush in a Vertical Headwall with Variation of Head and Entrance Rounding or Beveling; Type 5 Flow

$\frac{h_1 - z}{D}$	*r/b, w/b, r/D*, or *w/D*						
	0	0.02	0.04	0.06	0.08	0.10	0.14
1.4	0.44	0.46	0.49	0.50	0.50	0.51	0.51
1.5	0.46	0.49	0.52	0.53	0.53	0.54	0.54
1.6	0.47	0.51	0.54	0.55	0.55	0.56	0.56
1.7	0.48	0.52	0.55	0.57	0.57	0.57	0.57
1.8	0.49	0.54	0.57	0.58	0.58	0.58	0.58
1.9	0.50	0.55	0.58	0.59	0.60	0.60	0.60
2.0	0.51	0.56	0.59	0.60	0.61	0.61	0.62
2.5	0.54	0.59	0.62	0.64	0.64	0.65	0.66
3.0	0.55	0.61	0.64	0.66	0.67	0.69	0.70
3.5	0.57	0.62	0.65	0.67	0.69	0.70	0.71
4.0	0.58	0.63	0.66	0.68	0.70	0.71	0.72
5.0	0.59	0.64	0.67	0.69	0.71	0.72	0.73

TABLE 7 Discharge Coefficients for Box Culverts with Wingwalls with a Variation of Head and Wingwall Angle, θ; Type 5 Flow

$h_1 - z$	Wingwall, Angle, θ				
D	30°	45°	60°	75°	90°
1.3	0.44	0.44	0.43	0.42	0.39
1.4	0.46	0.46	0.45	0.43	0.41
1.5	0.47	0.47	0.46	0.45	0.42
1.6	0.49	0.49	0.48	0.46	0.43
1.7	0.50	0.50	0.48	0.47	0.44
1.8	0.51	0.51	0.50	0.48	0.45
1.9	0.52	0.52	0.51	0.49	0.46
2.0	0.53	0.53	0.52	0.49	0.46
2.5	0.56	0.56	0.54	0.52	0.49
3.0	0.58	0.58	0.56	0.54	0.50
3.5	0.60	0.60	0.58	0.55	0.52
4.0	0.61	0.61	0.59	0.56	0.53
5.0	0.62	0.62	0.60	0.58	0.54

TABLE 8 Discharge Coefficients for Type 5 Flow in Flared Entrances on Circular Pipes and Pipe Arches

$(h_1 - z)/D$	C	$(h_1 - z)/D$	C
1.4	0.48	2.0	0.57
1.5	0.50	2.5	0.59
1.6	0.52	3.0	0.61
1.7	0.53	3.5	0.63
1.8	0.55	4.0	0.65
1.9	0.56	5.0	0.66

18. Calculation

18.1 *Computation of Discharge*—The peak discharge of a given flood event may be computed manually as described in 18.5 which is tailored after Bodhaine (**8**). However, this computation is time consuming and gives only one discharge. The most efficient computations can now be done by computer. Several headwater elevations for different flow types can be obtained for selected combinations of discharge and tailwater elevations. A stage-discharge relation can be constructed for the average elevations at the approach section. A peak discharge can be determined from this relation using the average elevation of high-water marks at the ends of the approach section. A computer program was developed by the U.S. Geological Survey in 1990 and is presently in use. Other agencies, universities, and consultants have written computer programs to compute discharges through culverts. Exercise care when using any computer program to ensure that it includes the elements of this test method.

18.2 *Water Surface Elevations*—The first step in the computation of discharge is to obtain the proper water surface elevations at the approach and downstream from the culvert. If discharge is being computed for a specific event these elevations are determined from the highwater marks obtained during the field survey (see 13.3). It is also possible to compute the discharge for any assigned combination of water surface elevations.

18.2.1 *Plan View*—Plot a plan view showing the location of the culvert (including all related features such as aprons, wing walls, and headwalls) and the approach section. Include the approximate location of the low water channel as it approaches the culvert. Plot the location of each high-water mark and label the point with the elevation of the mark. Evaluate the location and quality of all marks to determine which ones truly represent the water surface at the approach section and immediately downstream from the culvert. Use only these marks in the computation of water surface elevations.

18.2.2 *Elevation at the Approach*—Using the marks selected above, compute the average water surface at the approach. If the elevations of high-water are all approximately equal and do not indicate a slope in water surface parallel to the direction of flow, determine the water surface elevation by averaging the elevations of individual marks.

18.2.2.1 If the elevations indicate a slope along the direction of flow, determine the water-surface elevation at each end of the approach section from a profile of marks along that bank. Prepare a separate profile for each bank.

18.2.2.2 Prepare the profile by laying off a zero-distance line on the plan upstream from the approach section and the most upstream highwater-mark, measuring the distance from the zero line to each mark, recording that distance and the elevation of the mark, and plotting a profile of distance versus elevation. Read the water surface at the cross section from this profile. Use the average of the elevations for the two sides in the computation of discharge.

18.2.3 *Elevation of Tailwater*—Determine the water surface elevation at the downstream end of the culvert in a manner similar to that used for determining the approach elevation. The elevation used should represent the average of water surface elevations at the stream banks immediately downstream from the culvert.

18.3 *Approach Properties*—After determining the water surface elevations, compute the area (A), convergance (K), and alpha (α) for the approach section at the indicated water surface. These are computed as described. A form similar to Fig. 15 simplifies the computations. If Type 4, 5, or 6 flow is certain, the computation of approach properties can be omitted. Therefore, it may be desirable to delay computation of approach properties until flow type has been determined.

18.3.1 *Area*—Compute the area of the approach cross section by the mean-section method. This method uses partial sections having an area equal to the mean of two adjacent depths multiplied by the horizontal distance between them. See Fig. 16. The summation of the areas for all of the partial sections is the total area of the cross section.

18.3.2 *Wetted Perimeter*—Obtain the wetted perimeter by dividing the channel into increments of width, and computing the hypotenuse of a right triangle with sides equal to the distance between stations and the difference in bed elevations. For example: the wetted perimeter between Stations 5 and 6 in Fig. 16 is the square root of the sum of the squares of ($b_6 - b_5$) and ($d_6 - d_5$). The summation of wetted perimeters for all of the partial sections is the total wetted perimeter for the cross section.

18.3.2.1 It may be more convenient to use a table listing the increase of the slope distance over the horizontal distance to compute the wetted perimeter. In Table 9, for the above example, the width of the partial section is $b_6 - b_5$ and the difference in bottom elevations is $d_6 - d_5$; the increase in slope distance over horizontal distance is read from the table. The

Snake Creek near Connell, WA FLOOD OF February 21, 1956

Approach Section Properties

STA.	DIST.	W. S. ELEV.	ELEV.	DEPTH	MEAN DEPTH	AREA		W. P.		
L. B.										
2	--	13.78	13.8	0	--					
5	3	13.8	13.4	0.4	0.2	0.6		3.0		
10	5		13.2	0.6	0.5	2.5		5.0		r = 11.1/18.0 = 0.62
15	5		13.1	0.7	0.6	3.0		5.0		
20	5		12.6	1.2	1.0	5.0	11.1	5.0	18.0	
22	2		10.7	3.2	2.2	4.4		2.8		
27	5		9.7	4.1	3.6	18.0		5.1		
31	4		9.5	4.3	4.2	16.8		4.0		
35	4		9.3	4.5	4.4	17.6		4.0		
40	5		9.2	4.6	4.6	23.0		5.0		
45	5		9.4	4.4	4.5	22.5		5.0		r = 193/50.1 = 379
50	5		9.7	4.1	4.2	21.0		5.0		
55	5		9.7	4.1	4.1	20.5		5.0		
60	5		9.7	4.1	4.1	20.5		5.0		
64	4		10.5	3.3	3.7	14.8		4.1		
67	3		10.6	3.2	3.2	9.6		3.0		
69	2		12.7	1.1	2.2	4.4	193.1	2.9	50.9	
72	3	13.8	13.4	0.4	0.8	2.4		3.1		r = 2.8/5.1 = 0.55
74	2	13.75	13.8	0.0	0.2	0.4	2.8	2.0	5.1	
RB	72									

Computation of Alpha

Sub Area	n	$\frac{1.486}{n}$	a	r	$r^{2/3}$	$K=\frac{1.486}{n}ar^{2/3}$	K^3/a^2			^{2} α
1	.080	18.6	11.1	.62	.73	150		27	392	
2	.045	33.0	193.0	3.79	2.43	15,480	99	585	991	
3	.045	33.0	2.8	0.55	0.67	60		27	551	
4										
5										
Total		206.6				15,690	99	640	934	
$(\Sigma K)^3 / (\Sigma K)^2$							90	229	354	1.10

FIG. 15 Sample Computation of Approach Properties

wetted perimeter of the partial area is therefore equal to $b_6 - b_5$ plus the value read from Table 9.

18.3.3 *Hydraulic Radius*—The hydraulic radius, R, for the cross section equals the area divided by the wetted perimeter.

18.3.4 *Alpha*—If a cross section includes wide, shallow overbank areas, subdivide the section into subareas. Subdivisions are made at major changes in channel shape, such as where water flows over a bank. Because of the non-uniform velocity distribution, average velocity head in the approach must be adjusted by a multiplication factor alpha (α), that is computed from the following equation:

$$\alpha_1 = \sum \left(K_i^{\,3} / A_i^{\,2} \right) / \left[\left(\sum K_i \right)^3 / \left(\sum A_i \right)^2 \right]$$

where i indicates the conveyance or area of the individual subareas.

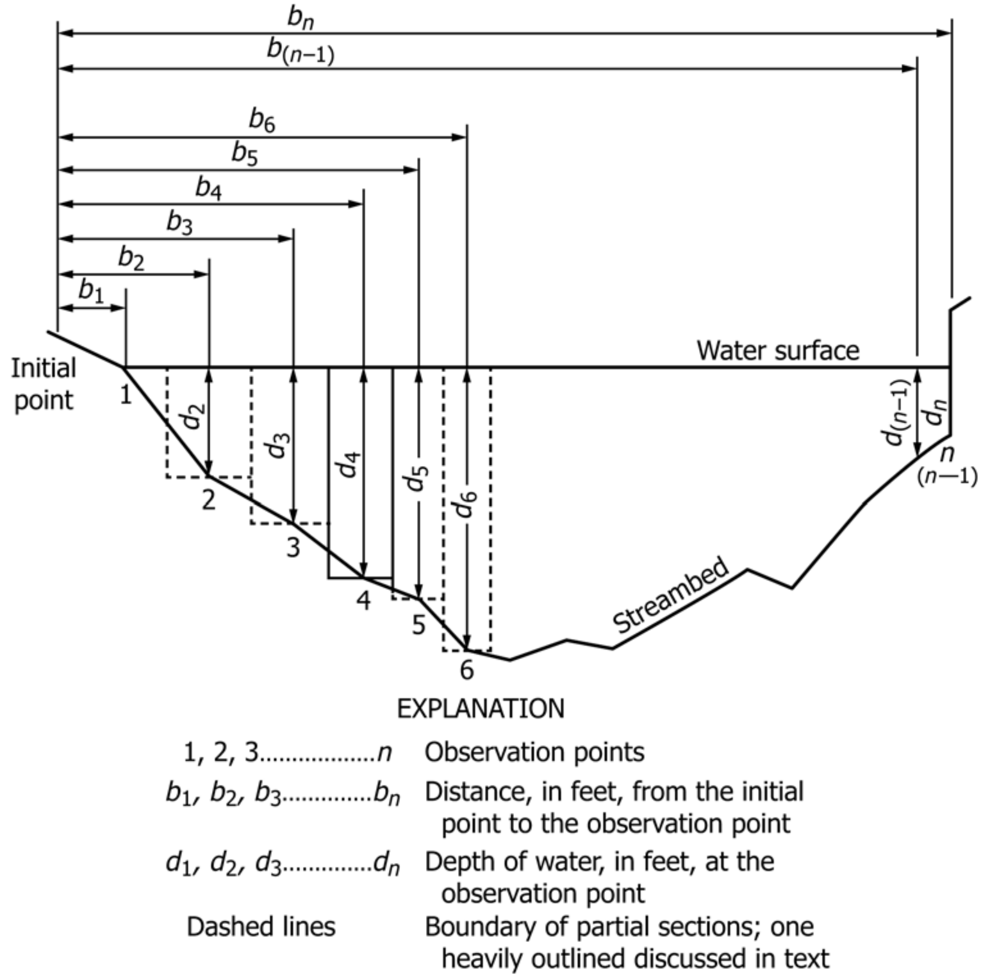


FIG. 16 Definition Sketch of Mean-Section Method of Computing Cross-Section Area

18.4 *Trial Discharges and Culvert Properties*—Compute the discharge at critical depth and the area and conveyance of the culvert barrel from one to several times in each iteration.

18.4.1 *Box Culvert*— Compute discharges and properties for box culverts without fillets or projections from the following equations:

$$Q = 5.67\, bd_c^{\ 3/2}$$

$$A = bd$$

$$WP = b + x(2d)$$

$$R = A/WP$$

$$K = \frac{1.486}{n} A\, R^{2/3}$$

where x is the number of webs in the culvert barrel. If fillets or projections are present, the proper adjustment must be made for these.

18.4.2 *Circular Pipes and Pipe Arches*—Compute discharges and properties from equations given in this subsection. The equations utilize different powers of *D*. These powers can be computed or determined from Table 10. The *C* in each equation is a function of the ratio of depth of flow to the diameter of the culvert (*d/D*). *C* values are given in Table 11 and Table 12:

$$Q = Cq\, D^{5/2}$$

$$A = C_a D^2$$

$$K = C_k \frac{D^{8/3}}{n}$$

$$P = Cp\, D$$

$$R = Cr\, D$$

$$T = C_t D$$

Special attention must be paid to the sizes of arch in Table 12. Each page of the table is for a different sized multiplate arch. The final page of Table 12 is also applicable to all sizes of standard (riveted) corrugated metal arches.

18.4.3 *Irregular Sections*—For irregular sections, compute discharges from Eq 14 or Eq 15.

$$Q = A_c^{\ 3/2} \sqrt{\frac{g}{T}} \tag{14}$$

or:

$$Q = A_c \sqrt{gdm} \tag{15}$$

where:

dm = the mean depth *A/T*.

TABLE 9 Increase of Slope Distance Over Horizontal Distance for Competing Wetted Perimeter

NOTE 1—To obtain vertical perimeter, add value from table to width.

NOTE 2—For purposes of metric conversion 1 in. = 25.4 mm.

Difference in Elevation of Bottom, in Feet	Width of Section, in Feet																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.4	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.5	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.6	0.2	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.7	0.2	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.8	0.3	0.2	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.9	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1.0	0.4	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1.1	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1.2	0.6	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1.3	0.6	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	. . .	. . .	. . .	. . .
1.4	0.7	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	. . .
1.5	0.8	0.5	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.6	0.9	0.6	0.4	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.7	1.0	0.6	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.8	1.1	0.7	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1.9	1.1	0.8	0.6	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2.0	1.2	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2.1	1.3	0.9	0.7	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
2.2	1.4	1.0	0.7	0.6	0.5	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1
2.3	1.5	1.0	0.8	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
2.4	1.6	1.1	0.8	0.7	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
2.5	1.7	1.2	0.9	0.7	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
2.6	1.8	1.3	1.0	0.8	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
2.7	1.9	1.4	1.0	0.8	0.7	0.6	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
2.8	2.0	1.4	1.1	0.9	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
2.9	2.1	1.5	1.2	0.9	0.8	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
3.0	2.2	1.6	1.2	1.0	0.8	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2
3.1	2.3	1.7	1.3	1.1	0.9	0.8	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2
3.2	2.4	1.8	1.4	1.1	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3
3.3	2.4	1.9	1.5	1.2	1.0	0.8	0.7	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
3.4	2.5	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
3.5	2.6	2.0	1.6	1.3	1.1	0.9	0.8	0.7	0.7	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3
3.6	2.7	2.1	1.7	1.4	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
3.7	2.8	2.2	1.8	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3
3.8	2.9	2.3	1.8	1.5	1.3	1.1	1.0	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
3.9	3.0	2.4	1.9	1.6	1.3	1.2	1.0	0.9	0.8	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
4.0	3.1	2.5	2.0	1.7	1.4	1.2	1.1	0.9	0.8	0.8	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4

18.4.3.1 Properties are computed by the procedure used for the approach section and described in 18.2. For a full culvert the wetted perimeter includes the ceiling of the culvert. Compute z as the difference in average bottom elevation at each end of the culvert.

18.4.3.2 For Types 1 through 4 flow it makes no difference whether d and h terms and D are measured from the lowest point in the downstream cross section or from the average bed elevation at that section as long as all such terms are measured from the same point. For Types 5 and 6 flow measure all terms from the average bottom elevation.

18.5 *Classification of Flow*—The first step in the computation of discharge is to determine the type of flow. The procedures for classifying flow are given below and are illustrated in the flow chart of Fig. 17. See special conditions in 18.6.5 for mitered pipes and pipe arches and in 18.9 for irregular cross sections.

18.5.1 Compute h_1, z, and h_4. Compare $h_1 - z$ and h_4 to the height (or diameter) of the culvert (D).

18.5.2 In general, any of three sets of conditions can exist, however in steep culverts a fourth set can exist. These sets of conditions are listed in 10.3, but are repeated here for clarity:

$h_4/D \leq 1.0$ and $(h_1 - z)/D < 1.5$ flow is Type 1, 2, or 3
$h_4/D > 1.0$ and $(h_1 - z)/D > 1.0$ flow is Type 4
$h_4/D \leq 1.0$ and $(h_1 - z)/D > 1.5$ flow is Type 5 or 6
$h_4/D < 1.0$ and $(h_1 - z)/D < 1.0$ flow is Type 1 or 3

18.5.3 If the above comparison indicates Type 1, 2, or 3 flow additional classification is given in 18.5.4 – 18.5.8. The procedure for computing discharge under Type 4 flow is given in 18.7. Procedures for distinguishing between Type 5 and 6 flow and computing discharge for these two types of flow are given in 18.8. If $h_1 - z/D$ ratio is between 1.2 and 1.8, see 18.8.

18.5.4 If Type 1, 2, or 3 flow is indicated, compute C for Type 1 flow and the proper geometry according to Section 17.

18.5.5 Compute a trial value of dc. For box culverts dc is generally taken to be 0.66 $(h_1 - z)$. The factor 0.66 can be refined for ponded flow. The following are factors for various values of C:

C	d_c factor
0.98	0.658
0.97	0.653
0.96	0.648
0.95	0.643

For pipe and pipe arches determine d_c from Fig. 18.

TABLE 10 Properties of Circular Pipes, Rivited Pipe-Arches, and Multiplate Pipe-Arches (8)

Circular pipes

Diam (in.)	Diam D (ft)	Area A_0 (ft²)	D^2	$D^{5/2}$	$D^{8/3}$	Diam (in.)	Diam D (ft)	Area A_0 (ft²)	D^2	$D^{5/2}$	$D^{8/3}$
6	0.500	0.196	0.250	0.177	0.157	60	5.00	19.6	25.0	55.9	73.0
8	0.667	0.349	0.444	0.363	0.339	66	5.00	23.8	30.2	71.0	94.1
10	0.833	0.545	0.694	0.634	0.614	72	6.00	28.3	36.0	88.2	119
12	1.00	0.785	1.00	1.00	1.00	78	6.50	33.2	42.2	108	147
15	1.25	1.23	1.56	1.75	1.81	84	7.00	38.5	49.0	130	179
18	1.50	1.77	2.25	2.76	2.95	96	8.00	50.3	64.0	181	256
21	1.75	2.41	3.06	4.05	4.44	108	9.00	63.6	81.0	243	351
24	2.00	3.14	4.00	5.66	6.34	120	10	78.5	100	316	464
30	2.50	4.91	6.25	9.88	11.5	132	11	95.0	121	401	599
36	3.00	7.07	9.00	15.6	18.7	144	12	113	144	499	755
42	3.50	9.62	12.2	22.9	28.1	156	13	133	169	609	935
48	4.00	12.6	16.0	32.0	40.3	168	14	154	196	733	1140
54	4.50	15.9	20.2	43.0	55.1	180	15	177	225	871	1370

Pipe-arches
(Span (b), maximum width; Rise (D), maximum height)

Nominal dimensions				Span (b)	Rise (D)	Area (A)	D^2	$D^{5/2}$	$D^{8/3}$	Nominal dimensions				Span (b)	Rise (D)	Area (A)	D^2	$D^{5/2}$	$D^{8/3}$
Inches by Inches				Feet		Square feet				Inches by Inches				Feet		Square feet			
Riveted pipe-arches																			
18		11		1.50	0.92	1.07	0.84	0.80	0.79	50	31	4.17	2.58	8.47	6.67	10.7	12.6		
22		13		1.83	1.08	1.48	1.17	1.22	1.24	58		36		4.83	3.00	11.4	9.00	15.6	18.7
29		18		2.42	1.50	2.86	2.25	2.76	2.95	65		40		5.42	3.33	14.1	11.1	20.3	24.8
36		22		3.00	1.83	4.27	3.36	4.55	5.03	72		44		6.00	3.67	17.0	13.4	25.8	32.0
43		27		3.58	2.25	6.43	5.06	7.59	8.69										
Multiplate pipe-arches																			
ft	in. by	ft	in.							ft	in. by	ft	in.						
6 [A]	1	4	7	6.08	4.58	22	20.97	44.89	57.9	11	7	7	5	11.62	7.42	67	55.06	150.0	209
6	4	4	9	6.34	4.76	24	22.66	49.43	64.1	11	10	7	7	11.82	7.61	71	57.91	159.8	224
6	9	4	11	6.76	4.91	26	24.11	53.42	69.6	12	4	7	9	12.32	7.75	74	60.06	167.2	235
7 [A]	0	5	1	7.02	5.09	28	25.91	58.45	76.7	12	6	7	11	12.52	7.93	78	62.88	177.1	250
7	3	5	3	7.24	5.27	31	27.77	63.76	84.1	12	8	8	1	12.70	8.12	81	65.93	187.9	266
7	8	5	5	7.70	5.42	33	29.38	68.39	90.6	12 [A]	10	8	4	12.86	8.31	85	69.06	199.1	283
7	11	5	7	7.94	5.60	35	31.36	74.21	98.9	13	5	8	5	13.40	8.44	89	71.23	206.9	295
8 [A]	2	5	9	8.14	5.78	38	33.41	80.32	108	13	11	8	7	13.94	8.58	93	73.62	215.6	309
8	7	5	11	8.62	5.92	40	35.05	85.27	115	14	1	8	9	14.12	8.77	97	76.91	227.8	327
8	10	6	1	8.84	6.11	43	37.33	92.28	125	14	3	8	11	14.28	8.96	101	80.28	240.3	346
9	4	6	3	9.32	6.26	46	39.19	98.05	133	14	10	9	1	14.82	9.10	105	82.81	249.8	361
9	6	6	5	9.52	6.44	49	41.47	105.2	144	15 [A]	4	9	3	15.34	9.23	109	85.19	258.8	375
9	6	6	7	9.72	6.62	52	43.82	112.8	155	15	6	9	5	15.54	9.42	113	88.74	272.3	396
10	3	6	9	10.22	6.77	55	45.83	119.3	165	15	8	9	7	15.70	9.61	118	92.35	286.3	417
10	8	6	11	10.70	6.91	58	47.75	125.5	173	15	10	9	10	15.86	9.80	122	96.04	300.7	440
10	11	7	1	10.92	7.09	61	50.27	133.8	186	16	5	9	11	16.42	9.93	126	98.61	310.7	456
11 [A]	5	7	3	11.40	7.24	64	52.42	141.0	196	16 [A]	7	10	1	16.58	10.12	130	102.41	325.8	479

[A] Size for which coefficients are provided in Table 12.

TABLE 11 Coefficients for Pipe of Circular Section Flowing Partly Full [A]

d/D [B]	(1)	(2)	(3)	(4)	(5)	(6)	d/D [B]	(1)	(2)	(3)	(4)	(5)	(6)
	$A = C_aD^2$	$P = C_pD$	$R = C_rD$	$K = C_k \frac{D^{8/3}}{n}$	$Q = C_qD^{5/2}$	$T = C_tD$		$A = C_aD^2$	$P = C_pD$	$R = C_rD$	$K = C_k \frac{D^{8/3}}{n}$	$Q = C_qD^{5/2}$	$T = C_tD$
	C_a	C_p	C_r	C_k	C_q	C_t		C_a	C_p	C_r	C_k	C_q	C_t
0.01	0.0013	0.2003	0.0066	0.000068	0.0006	0.199	0.51	0.4027	1.5908	0.2531	0.2394	1.449	1.000
0.02	0.0037	0.2838	0.0132	0.000307	0.0025	0.280	0.52	0.4127	1.6108	0.2562	0.2472	1.504	0.999
0.03	0.0069	0.3482	0.0197	0.000747	0.0055	0.341	0.53	0.4227	1.6308	0.2592	0.2556	1.560	0.998
0.04	0.0105	0.4027	0.0262	0.001376	0.0098	0.392	0.54	0.4327	1.6509	0.2621	0.2630	1.616	0.997
0.05	0.0147	0.4510	0.0325	0.002228	0.0153	0.436	0.55	0.4426	1.6710	0.2649	0.2710	1.674	0.995
0.06	0.0192	0.4949	0.0389	0.00328	0.0220	0.475	0.56	0.4526	1.6911	0.2676	0.2791	1.733	0.993
0.07	0.0242	0.5355	0.0451	0.00457	0.0298	0.510	0.57	0.4625	1.7113	0.2703	0.2873	1.792	0.990
0.08	0.0294	0.5735	0.0513	0.00601	0.0389	0.543	0.58	0.4724	1.7315	0.2728	0.2955	1.853	0.987
0.09	0.0350	0.6094	0.0575	0.00775	0.0491	0.572	0.59	0.4822	1.7518	0.2753	0.3031	1.915	0.984
0.10	0.0409	0.6435	0.0635	0.00966	0.0605	0.600	0.60	0.4920	1.7722	0.2776	0.3115	1.977	0.980
0.11	0.0470	0.6761	0.0695	0.0118	0.0731	0.626	0.61	0.5018	1.7926	0.2799	0.3192	2.041	0.975
0.12	0.0534	0.7075	0.0755	0.0142	0.0868	0.650	0.62	0.5115	1.8132	0.2821	0.3268	2.106	0.971
0.13	0.0600	0.7377	0.0813	0.0168	0.1016	0.673	0.63	0.5212	1.8338	0.2824	0.3346	2.172	0.966
0.14	0.0668	0.7670	0.0871	0.0195	0.1176	0.694	0.64	0.5308	1.8546	0.2862	0.3423	2.239	0.960
0.15	0.0739	0.7954	0.0929	0.0225	0.1347	0.714	0.65	0.5404	1.8755	0.2882	0.3501	2.307	0.954
0.16	0.0811	0.8230	0.0985	0.0257	0.1530	0.733	0.66	0.5499	1.8965	0.2900	0.3579	2.376	0.947
0.17	0.0885	0.8500	0.1042	0.0291	0.1724	0.751	0.67	0.5594	1.9177	0.2917	0.3658	2.446	0.940
0.18	0.0961	0.8763	0.1097	0.0327	0.1928	0.768	0.68	0.5687	1.9391	0.2933	0.3727	2.518	0.933
0.19	0.1039	0.9020	0.1152	0.0366	0.2144	0.785	0.69	0.5780	1.9606	0.2948	0.3805	2.591	0.925
0.20	0.1118	0.9273	0.1206	0.0405	0.2371	0.800	0.70	0.5872	1.9823	0.2962	0.3874	2.666	0.917
0.21	0.1199	0.9521	0.1259	0.0446	0.2609	0.815	0.71	0.5964	2.0042	0.2975	0.3953	2.741	0.908
0.22	0.1281	0.9764	0.1312	0.0491	0.2857	0.828	0.72	0.6054	2.0264	0.2987	0.4021	2.819	0.898
0.23	0.1365	1.0003	0.1364	0.0537	0.3116	0.842	0.73	0.6143	2.0488	0.2998	0.4090	2.898	0.888
0.24	0.1449	1.0239	0.1416	0.0586	0.3386	0.854	0.74	0.6231	2.0714	0.3008	0.4157	2.978	0.877
0.25	0.1535	1.0472	0.1466	0.0634	0.3666	0.866	0.75	0.6319	2.0944	0.3017	0.4226	3.061	0.866
0.26	0.1623	1.0701	0.1516	0.0685	0.3957	0.877	0.76	0.6405	2.1176	0.3024	0.4283	3.145	0.854
0.27	0.1711	1.0928	0.1566	0.0740	0.4259	0.888	0.77	0.6489	2.1412	0.3031	0.4349	3.231	0.842
0.28	0.1800	1.1152	0.1614	0.0792	0.4571	0.898	0.78	0.6573	2.1652	0.3036	0.4415	3.320	0.828
0.29	0.1890	1.1373	0.1662	0.0848	0.4893	0.908	0.79	0.6655	2.1895	0.3039	0.4470	3.411	0.815
0.30	0.1982	1.1593	0.1709	0.0907	0.523	0.917	0.80	0.6736	2.2143	0.3042	0.4524	3.505	0.800
0.31	0.2074	1.1810	0.1756	0.0968	0.557	0.925	0.81	0.6815	2.2395	0.3043	0.4578	3.602	0.785
0.32	0.2167	1.2025	0.1802	0.1027	0.592	0.933	0.82	0.6893	2.2653	0.3043	0.4630	3.702	0.768
0.33	0.2260	1.2239	0.1847	0.1088	0.628	0.940	0.83	0.6969	2.2916	0.3041	0.4681	3.806	0.751
0.34	0.2355	1.2451	0.1891	0.1155	0.666	0.947	0.84	0.7043	2.3186	0.3038	0.4731	3.914	0.733
0.35	0.2450	1.2661	0.1935	0.1220	0.704	0.954	0.85	0.7115	2.3462	0.3033	0.4768	4.028	0.714
0.36	0.2546	1.2870	0.1978	0.1283	0.743	0.960	0.86	0.7186	2.3746	0.3026	0.4816	4.147	0.694
0.37	0.2642	1.3078	0.2020	0.1350	0.784	0.966	0.87	0.7254	2.4038	0.3018	0.4851	4.272	0.673
0.38	0.2739	1.3284	0.2062	0.1421	0.825	0.971	0.88	0.7320	2.4341	0.3007	0.4884	4.406	0.650
0.39	0.2836	1.3490	0.2102	0.1488	0.867	0.975	0.89	0.7384	2.4655	0.2995	0.4916	4.549	0.626
0.40	0.2934	1.3694	0.2142	0.1561	0.910	0.980	0.90	0.7445	2.4981	0.2980	0.4935	4.70	0.600
0.41	0.3032	1.3898	0.2182	0.1631	0.955	0.984	0.91	0.7504	2.5322	0.2963	0.4951	4.87	0.572
0.42	0.3130	1.4101	0.2220	0.1702	1.000	0.987	0.92	0.7560	2.5681	0.2944	0.4966	5.06	0.543
0.43	0.3229	1.4303	0.2258	0.1780	1.046	0.990	0.93	0.7612	2.6061	0.2921	0.4977	5.27	0.510
0.44	0.3328	1.4505	0.2295	0.1854	1.093	0.993	0.94	0.7662	2.6467	0.2895	0.4979	5.52	0.475
0.45	0.3428	1.4706	0.2331	0.1931	1.141	0.995	0.95	0.7707	2.6906	0.2865	0.4970	5.81	0.436
0.46	0.3527	1.4907	0.2366	0.2002	1.190	0.997	0.96	0.7749	2.7389	0.2829	0.4963	6.18	0.392
0.47	0.3627	1.5108	0.2401	0.2080	1.240	0.998	0.97	0.7785	2.7934	0.2787	0.4940	6.67	0.341
0.48	0.3727	1.5308	0.2435	0.2160	1.291	0.999	0.98	0.7817	2.8578	0.2735	0.4902	7.41	0.280
0.49	0.3827	1.5508	0.2468	0.2235	1.343	1.000	0.99	0.7841	2.9412	0.2666	0.4824	8.83	0.199
0.50	0.3927	1.5708	0.2500	0.2317	1.396	1.000	1.00	0.7854	3.1416	0.2500	0.4633	. . .	0.000

[A] Coefficients for (1) area, (2) wetted perimeter, (3) hydraulic radius, (4) conveyance, (5) discharge for critical-depth flow, and (6) top width.
[B] d = maximum depth of water in feet; D = diameter of pipe, in feet.

18.5.6 Compute hc at the inlet; $hc = d_c + z$.

18.5.7 Compare dc (at the outlet) and h_c (at the inlet) to h_4 to further narrow the type of flow according to types of flow described in 12.2. Three possible conditions exist:

$d_c > h_4$ and $hc > h_4$ flow is Type 1 or 2
$d_c < h_4$ and $hc > h_4$ flow is Type 1 or 3
$d_c < h_4$ and $hc < h_4$ flow is Type 3

TABLE 12 Coefficients for Pipe-Arches Flowing Partly Full [A]

d/D [B]	(1) $A = C_a D^2$	(2) $R = C_r D$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_m D$	(5) $Q = C_q D^{5/2}$	d/D [B]	(1) $A = C_a D^2$	(2) $R = C_r D$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_m D$	(5) $Q = C_q D^{5/2}$
	C_a	C_r	C_k	C_m	C_q		C_a	C_r	C_k	C_m	C_q
Nominal sizes 6 ft 1 in. by 4 ft 7 in.											
0.01	0.005	0.016	0.000	0.016	0.003	0.51	0.586	0.289	0.380	0.450	2.23
0.02	0.009	0.019	0.001	0.019	0.007	0.52	0.600	0.292	0.393	0.463	2.32
0.03	0.014	0.025	0.002	0.025	0.012	0.53	0.614	0.296	0.406	0.476	2.41
0.04	0.019	0.029	0.003	0.029	0.018	0.54	0.628	0.300	0.419	0.490	2.50
0.05	0.026	0.036	0.004	0.035	0.028	0.55	0.643	0.304	0.431	0.504	2.59
0.06	0.033	0.042	0.006	0.041	0.038	0.56	0.657	0.307	0.445	0.519	2.69
0.07	0.042	0.048	0.008	0.048	0.052	0.57	0.671	0.311	0.458	0.535	2.79
0.08	0.050	0.054	0.011	0.054	0.066	0.58	0.686	0.314	0.471	0.551	2.89
0.09	0.059	0.061	0.014	0.061	0.082	0.59	0.700	0.318	0.484	0.568	2.99
0.10	0.068	0.067	0.017	0.067	0.099	0.60	0.714	0.321	0.497	0.584	3.10
0.11	0.078	0.075	0.021	0.076	0.122	0.61	0.724	0.321	0.505	0.597	3.17
0.12	0.089	0.082	0.025	0.084	0.145	0.62	0.733	0.322	0.512	0.609	3.25
0.13	0.099	0.089	0.029	0.091	0.170	0.63	0.743	0.322	0.519	0.621	3.32
0.14	0.110	0.096	0.034	0.099	0.195	0.64	0.752	0.323	0.526	0.634	3.40
0.15	0.120	0.102	0.039	0.106	0.221	0.65	0.762	0.323	0.533	0.647	3.48
0.16	0.131	0.109	0.044	0.114	0.251	0.66	0.776	0.327	0.547	0.666	3.59
0.17	0.142	0.115	0.050	0.122	0.282	0.67	0.790	0.330	0.561	0.686	3.71
0.18	0.154	0.121	0.056	0.129	0.314	0.68	0.805	0.334	0.576	0.706	3.84
0.19	0.165	0.127	0.062	0.137	0.346	0.69	0.819	0.337	0.590	0.727	3.96
0.20	0.176	0.132	0.068	0.144	0.380	0.70	0.833	0.341	0.604	0.749	4.09
0.21	0.189	0.139	0.075	0.153	0.418	0.71	0.843	0.341	0.611	0.766	4.19
0.22	0.201	0.145	0.082	0.162	0.458	0.72	0.852	0.341	0.619	0.784	4.28
0.23	0.213	0.151	0.090	0.170	0.499	0.73	0.862	0.342	0.626	0.803	4.38
0.24	0.226	0.157	0.098	0.178	0.541	0.74	0.871	0.342	0.633	0.822	4.48
0.25	0.238	0.163	0.105	0.186	0.583	0.75	0.881	0.342	0.640	0.841	4.58
0.26	0.252	0.170	0.115	0.197	0.635	0.76	0.890	0.343	0.649	0.864	4.70
0.27	0.267	0.177	0.125	0.207	0.688	0.77	0.900	0.345	0.657	0.889	4.81
0.28	0.281	0.184	0.135	0.217	0.742	0.78	0.909	0.346	0.666	0.914	4.93
0.29	0.295	0.191	0.145	0.227	0.797	0.79	0.919	0.347	0.675	0.940	5.06
0.30	0.309	0.197	0.156	0.236	0.854	0.80	0.928	0.349	0.684	0.967	5.18
0.31	0.324	0.203	0.166	0.246	0.912	0.81	0.936	0.347	0.687	0.998	5.31
0.32	0.338	0.209	0.177	0.256	0.972	0.82	0.944	0.345	0.690	1.03	5.43
0.33	0.352	0.215	0.188	0.266	1.03	0.83	0.951	0.344	0.694	1.06	5.57
0.34	0.367	0.221	0.199	0.276	1.09	0.84	0.959	0.342	0.697	1.10	5.70
0.35	0.381	0.227	0.210	0.286	1.16	0.85	0.966	0.341	0.701	1.14	5.85
0.36	0.392	0.231	0.219	0.295	1.21	0.86	0.973	0.338	0.702	1.18	6.01
0.37	0.404	0.234	0.228	0.303	1.26	0.87	0.980	0.336	0.704	1.23	6.18
0.38	0.415	0.238	0.237	0.312	1.32	0.88	0.986	0.334	0.706	1.29	6.35
0.39	0.427	0.241	0.246	0.320	1.37	0.89	0.993	0.332	0.707	1.35	6.54
0.40	0.438	0.245	0.255	0.329	1.42	0.90	1.00	0.330	0.709	1.41	6.74
0.41	0.450	0.249	0.265	0.338	1.49	0.91	1.00	0.326	0.707	1.50	6.98
0.42	0.463	0.252	0.275	0.347	1.55	0.92	1.01	0.323	0.705	1.60	7.23
0.43	0.475	0.256	0.285	0.357	1.61	0.93	1.01	0.319	0.704	1.71	7.52
0.44	0.488	0.260	0.295	0.366	1.67	0.94	1.02	0.316	0.702	1.83	7.82
0.45	0.500	0.263	0.305	0.376	1.74	0.95	1.02	0.313	0.701	2.02	8.25
0.46	0.514	0.268	0.317	0.388	1.82	0.96	1.03	0.304	0.691	. . .	. . .
0.47	0.528	0.272	0.330	0.400	1.90	0.97	1.03	0.296	0.682	. . .	. . .
0.48	0.543	0.276	0.342	0.412	1.98	0.98	1.04	0.288	0.673	. . .	. . .
0.49	0.557	0.281	0.355	0.424	2.06	0.99	1.04	0.281	0.665	. . .	. . .
0.50	0.571	0.285	0.367	0.436	2.14	1.00	1.05	0.274	0.658	. . .	. . .
Nominal size 7 ft 0 in. by 5 ft 1 in.											
0.01	0.006	0.017	0.001	0.017	0.004	0.51	0.594	0.283	0.380	0.447	2.25
0.02	0.012	0.022	0.001	0.022	0.010	0.52	0.609	0.287	0.394	0.462	2.35
0.03	0.016	0.026	0.002	0.026	0.015	0.53	0.625	0.292	0.409	0.476	2.45
0.04	0.021	0.029	0.003	0.029	0.020	0.54	0.640	0.296	0.423	0.491	2.55
0.05	0.028	0.035	0.004	0.035	0.029	0.55	0.656	0.301	0.437	0.506	2.65
0.06	0.035	0.040	0.006	0.039	0.039	0.56	0.667	0.303	0.447	0.518	2.72
0.07	0.044	0.047	0.009	0.047	0.055	0.57	0.679	0.305	0.457	0.530	2.80
0.08	0.054	0.054	0.011	0.054	0.071	0.58	0.690	0.307	0.467	0.542	2.89
0.09	0.064	0.061	0.015	0.061	0.089	0.59	0.702	0.309	0.476	0.555	2.97
0.10	0.073	0.067	0.018	0.067	0.108	0.60	0.714	0.311	0.486	0.568	3.05
0.11	0.085	0.075	0.022	0.076	0.133	0.61	0.725	0.313	0.497	0.582	3.14
0.12	0.096	0.083	0.027	0.084	0.159	0.62	0.737	0.315	0.507	0.597	3.23
0.13	0.108	0.090	0.032	0.092	0.186	0.63	0.748	0.317	0.517	0.613	3.32
0.14	0.120	0.096	0.037	0.100	0.215	0.64	0.760	0.320	0.528	0.628	3.42
0.15	0.131	0.103	0.043	0.107	0.224	0.65	0.771	0.322	0.538	0.644	3.51
0.16	0.141	0.108	0.048	0.114	0.270	0.66	0.784	0.324	0.550	0.662	3.62

TABLE 12 *Continued*

d/D [B]	(1) $A = C_aD^2$	(2) $R = C_rD$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_mD$	(5) $Q = C_qD^{5/2}$	d/D [B]	(1) $A = C_aD^2$	(2) $R = C_rD$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_mD$	(5) $Q = C_qD^{5/2}$
	C_a	C_r	C_k	C_m	C_q		C_a	C_r	C_k	C_m	C_q
0.17	0.151	0.114	0.053	0.120	0.298	0.67	0.798	0.326	0.562	0.681	3.74
0.18	0.161	0.119	0.058	0.127	0.326	0.68	0.811	0.329	0.574	0.701	3.85
0.19	0.171	0.124	0.063	0.133	0.354	0.69	0.824	0.331	0.586	0.721	3.97
0.20	0.181	0.128	0.068	0.139	0.383	0.70	0.837	0.333	0.597	0.741	4.09
0.21	0.194	0.135	0.076	0.147	0.422	0.71	0.848	0.335	0.608	0.761	4.20
0.22	0.206	0.141	0.083	0.156	0.461	0.72	0.860	0.337	0.619	0.781	4.31
0.23	0.218	0.147	0.090	0.164	0.502	0.73	0.872	0.339	0.629	0.801	4.43
0.24	0.231	0.153	0.098	0.172	0.544	0.74	0.883	0.341	0.640	0.822	4.54
0.25	0.243	0.159	0.106	0.181	0.586	0.75	0.895	0.343	0.651	0.844	4.66
0.26	0.258	0.166	0.115	0.191	0.639	0.76	0.905	0.343	0.659	0.868	4.78
0.27	0.272	0.172	0.125	0.201	0.693	0.77	0.915	0.344	0.667	0.892	4.90
0.28	0.287	0.179	0.135	0.211	0.749	0.78	0.925	0.345	0.676	0.918	5.03
0.29	0.302	0.185	0.146	0.222	0.806	0.79	0.935	0.345	0.684	0.945	5.16
0.30	0.316	0.192	0.156	0.232	0.864	0.80	0.945	0.346	0.692	0.972	5.29
0.31	0.330	0.198	0.167	0.242	0.921	0.81	0.956	0.346	0.700	1.01	5.45
0.32	0.344	0.204	0.177	0.251	0.979	0.82	0.968	0.346	0.709	1.04	5.61
0.33	0.358	0.209	0.188	0.261	1.04	0.83	0.980	0.345	0.717	1.08	5.78
0.34	0.372	0.215	0.198	0.271	1.10	0.84	0.991	0.345	0.725	1.12	5.95
0.35	0.386	0.221	0.209	0.281	1.16	0.85	1.003	0.345	0.733	1.16	6.13
0.36	0.401	0.226	0.221	0.292	1.23	0.86	1.009	0.342	0.734	1.21	6.30
0.37	0.417	0.232	0.234	0.304	1.30	0.87	1.015	0.340	0.735	1.26	6.47
0.38	0.432	0.238	0.246	0.316	1.38	0.88	1.021	0.338	0.736	1.32	6.65
0.39	0.447	0.243	0.259	0.327	1.45	0.89	1.027	0.335	0.737	1.38	6.84
0.40	0.463	0.248	0.272	0.339	1.53	0.90	1.034	0.333	0.738	1.44	7.04
0.41	0.474	0.252	0.281	0.348	1.59	0.91	1.039	0.330	0.737	1.52	7.28
0.42	0.486	0.255	0.290	0.357	1.65	0.92	1.044	0.327	0.736	1.61	7.52
0.43	0.498	0.259	0.300	0.366	1.71	0.93	1.050	0.324	0.735	1.72	7.82
0.44	0.509	0.262	0.310	0.375	1.77	0.94	1.055	0.321	0.734	1.85	8.15
0.45	0.521	0.265	0.319	0.384	1.83	0.95	1.061	0.318	0.734	2.04	8.59
0.46	0.532	0.268	0.329	0.394	1.90	0.96	1.064	0.310	0.724	. . .	. . .
0.47	0.544	0.270	0.338	0.404	1.96	0.97	1.068	0.302	0.715	. . .	. . .
0.48	0.555	0.273	0.347	0.413	2.03	0.98	1.072	0.295	0.706	. . .	. . .
0.49	0.567	0.275	0.357	0.423	2.09	0.99	1.076	0.288	0.698	. . .	. . .
0.50	0.579	0.278	0.366	0.433	2.16	1.00	1.081	0.282	0.691	. . .	. . .
Nominal size 8 ft 2 in. by 5 ft 9 in.											
0.01	0.007	0.015	0.001	0.015	0.005	0.51	0.658	0.304	0.442	0.497	2.63
0.02	0.013	0.021	0.002	0.021	0.011	0.52	0.673	0.308	0.456	0.511	2.73
0.03	0.020	0.026	0.003	0.026	0.019	0.53	0.688	0.312	0.470	0.525	2.83
0.04	0.027	0.030	0.004	0.030	0.026	0.54	0.703	0.315	0.484	0.539	2.93
0.05	0.036	0.037	0.006	0.036	0.039	0.55	0.718	0.319	0.498	0.553	3.03
0.06	0.045	0.044	0.008	0.042	0.052	0.56	0.730	0.322	0.509	0.566	3.11
0.07	0.063	0.057	0.014	0.056	0.085	0.57	0.742	0.324	0.520	0.578	3.20
0.08	0.081	0.070	0.020	0.070	0.121	0.58	0.754	0.326	0.531	0.590	3.29
0.09	0.087	0.073	0.023	0.073	0.133	0.59	0.765	0.328	0.541	0.603	3.37
0.10	0.093	0.077	0.025	0.077	0.146	0.60	0.777	0.331	0.552	0.616	3.46
0.11	0.106	0.085	0.030	0.086	0.177	0.61	0.789	0.333	0.563	0.613	3.56
0.12	0.119	0.094	0.036	0.096	0.209	0.62	0.801	0.335	0.574	0.645	3.65
0.13	0.132	0.101	0.043	0.105	0.243	0.63	0.813	0.337	0.585	0.661	3.75
0.14	0.145	0.109	0.049	0.114	0.279	0.64	0.825	0.339	0.596	0.676	3.85
0.15	0.158	0.116	0.056	0.123	0.315	0.65	0.837	0.341	0.607	0.692	3.95
0.16	0.172	0.123	0.063	0.132	0.354	0.66	0.849	0.342	0.618	0.708	4.05
0.17	0.185	0.131	0.071	0.141	0.394	0.67	0.861	0.344	0.628	0.724	4.16
0.18	0.198	0.138	0.078	0.149	0.434	0.68	0.873	0.345	0.639	0.740	4.26
0.19	0.211	0.144	0.086	0.158	0.476	0.69	0.885	0.347	0.649	0.757	4.37
0.20	0.224	0.151	0.094	0.166	0.519	0.70	0.897	0.348	0.660	0.774	4.48
0.21	0.239	0.159	0.104	0.176	0.570	0.71	0.909	0.350	0.671	0.796	4.60
0.22	0.254	0.166	0.114	0.186	0.622	0.72	0.921	0.352	0.682	0.819	4.73
0.23	0.269	0.174	0.124	0.196	0.676	0.73	0.933	0.354	0.693	0.843	4.86
0.24	0.284	0.181	0.135	0.205	0.731	0.74	0.945	0.355	0.704	0.867	4.99
0.25	0.299	0.188	0.146	0.215	0.786	0.75	0.957	0.357	0.716	0.892	5.13
0.26	0.314	0.194	0.157	0.225	0.845	0.76	0.966	0.357	0.722	0.916	5.24
0.27	0.329	0.201	0.168	0.235	0.905	0.77	0.975	0.357	0.729	0.940	5.36
0.28	0.344	0.207	0.179	0.245	0.966	0.78	0.984	0.357	0.736	0.964	5.48
0.29	0.359	0.213	0.190	0.255	1.03	0.79	0.993	0.357	0.743	0.990	5.61
0.30	0.374	0.218	0.201	0.265	1.09	0.80	1.002	0.358	0.750	1.02	5.73
0.31	0.386	0.223	0.211	0.273	1.14	0.81	1.011	0.357	0.756	1.03	5.83
0.32	0.398	0.227	0.220	0.282	1.20	0.82	1.020	0.356	0.761	1.05	5.93
0.33	0.410	0.231	0.229	0.290	1.25	0.83	1.029	0.335	0.767	1.07	6.03

TABLE 12 *Continued*

d/D [B]	(1) $A = C_aD^2$	(2) $R = C_rD$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_mD$	(5) $Q = C_qD^{5/2}$	d/D [B]	(1) $A = C_aD^2$	(2) $R = C_rD$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_mD$	(5) $Q = C_qD^{5/2}$
	C_a	C_r	C_k	C_m	C_q		C_a	C_r	C_k	C_m	C_q
0.34	0.422	0.235	0.239	0.299	1.31	0.84	1.038	0.355	0.772	1.08	6.13
0.35	0.434	0.239	0.248	0.308	1.36	0.85	1.047	0.354	0.778	1.10	6.23
0.36	0.449	0.244	0.260	0.319	1.44	0.86	1.054	0.352	0.780	1.17	6.46
0.37	0.463	0.250	0.273	0.330	1.51	0.87	1.062	0.349	0.783	1.24	6.71
0.38	0.478	0.255	0.286	0.342	1.59	0.88	1.070	0.347	0.785	1.32	6.97
0.39	0.493	0.260	0.299	0.354	1.66	0.89	1.078	0.345	0.788	1.41	7.26
0.40	0.508	0.265	0.312	0.365	1.74	0.90	1.085	0.343	0.790	1.51	7.58
0.41	0.521	0.268	0.322	0.376	1.81	0.91	1.091	0.339	0.789	1.60	7.83
0.42	0.535	0.272	0.333	0.387	1.89	0.92	1.097	0.336	0.788	1.69	8.10
0.43	0.548	0.275	0.344	0.398	1.96	0.93	1.103	0.332	0.787	1.82	7.45
0.44	0.561	0.278	0.355	0.409	2.04	0.94	1.109	0.329	0.786	1.97	8.85
0.45	0.574	0.281	0.366	0.420	2.11	0.95	1.115	0.326	0.785	2.17	9.32
0.46	0.588	0.285	0.378	0.433	2.19	0.96	1.119	0.318	0.775	. . .	. . .
0.47	0.602	0.289	0.391	0.445	2.28	0.97	1.123	0.311	0.765	. . .	. . .
0.48	0.615	0.293	0.403	0.457	2.36	0.98	1.127	0.304	0.756	. . .	. . .
0.49	0.629	0.296	0.415	0.470	2.45	0.99	1.130	0.297	0.748	. . .	. . .
0.50	0.643	0.300	0.428	0.483	2.54	1.00	1.137	0.291	0.739	. . .	. . .
Nominal sizes 11 ft 5 in. by 7 ft 3 in. and 12 ft 10 in. by 8 ft 4 in.											
0.01	0.007	0.014	0.001	0.014	0.004	0.51	0.710	0.311	0.484	0.488	2.81
0.02	0.013	0.021	0.002	0.021	0.011	0.52	0.724	0.315	0.498	0.501	2.91
0.03	0.020	0.027	0.003	0.027	0.019	0.53	0.739	0.318	0.512	0.514	3.01
0.04	0.027	0.032	0.004	0.032	0.028	0.54	0.754	0.321	0.526	0.527	3.11
0.05	0.037	0.038	0.006	0.038	0.041	0.55	0.769	0.324	0.539	0.541	3.21
0.06	0.046	0.044	0.009	0.043	0.054	0.56	0.783	0.327	0.553	0.555	3.31
0.07	0.057	0.050	0.012	0.050	0.072	0.57	0.797	0.330	0.566	0.569	3.41
0.08	0.068	0.056	0.015	0.056	0.091	0.58	0.811	0.333	0.580	0.584	3.52
0.09	0.079	0.063	0.019	0.063	0.113	0.59	0.825	0.336	0.593	0.599	3.63
0.10	0.091	0.069	0.023	0.069	0.136	0.60	0.840	0.339	0.607	0.614	3.73
0.11	0.104	0.078	0.028	0.078	0.165	0.61	0.854	0.342	0.620	0.630	3.85
0.12	0.117	0.085	0.034	0.086	0.196	0.62	0.867	0.344	0.633	0.647	3.96
0.13	0.131	0.093	0.040	0.094	0.228	0.63	0.881	0.347	0.646	0.664	4.08
0.14	0.144	0.100	0.046	0.101	0.261	0.64	0.895	0.349	0.659	0.682	4.20
0.15	0.158	0.107	0.053	0.109	0.296	0.65	0.909	0.351	0.673	0.700	4.32
0.16	0.173	0.115	0.061	0.118	0.337	0.66	0.921	0.352	0.683	0.716	4.42
0.17	0.188	0.123	0.069	0.127	0.380	0.67	0.934	0.354	0.694	0.733	4.53
0.18	0.203	0.130	0.077	0.136	0.424	0.68	0.946	0.355	0.704	0.750	4.65
0.19	0.218	0.137	0.086	0.144	0.470	0.69	0.958	0.356	0.715	0.767	4.76
0.20	0.233	0.144	0.095	0.153	0.517	0.70	0.970	0.357	0.725	0.785	4.88
0.21	0.248	0.151	0.105	0.162	0.569	0.71	0.982	0.358	0.735	0.806	5.00
0.22	0.264	0.159	0.115	0.172	0.622	0.72	0.994	0.359	0.746	0.827	5.13
0.23	0.280	0.166	0.126	0.181	0.676	0.73	1.005	0.360	0.756	0.848	5.26
0.24	0.295	0.173	0.136	0.191	0.732	0.74	1.017	0.361	0.766	0.871	5.39
0.25	0.311	0.180	0.147	0.200	0.789	0.75	1.029	0.362	0.776	0.894	5.52
0.26	0.328	0.188	0.160	0.211	0.856	0.76	1.039	0.361	0.783	0.918	5.65
0.27	0.345	0.195	0.173	0.222	0.924	0.77	1.048	0.361	0.790	0.944	5.78
0.28	0.363	0.203	0.186	0.233	0.994	0.78	1.058	0.361	0.796	0.971	5.92
0.29	0.380	0.210	0.199	0.244	1.07	0.79	1.068	0.360	0.803	0.999	6.05
0.30	0.397	0.217	0.213	0.255	1.14	0.80	1.077	0.360	0.810	1.03	6.20
0.31	0.411	0.222	0.224	0.264	1.20	0.81	1.086	0.359	0.815	1.06	6.35
0.32	0.425	0.227	0.235	0.274	1.26	0.82	1.096	0.358	0.821	1.10	6.51
0.33	0.440	0.232	0.247	0.283	1.33	0.83	1.105	0.357	0.827	1.13	6.68
0.34	0.454	0.237	0.258	0.293	1.39	0.84	1.114	0.357	0.832	1.17	6.85
0.35	0.468	0.241	0.269	0.302	1.46	0.85	1.123	0.356	0.838	1.22	7.03
0.36	0.484	0.247	0.283	0.313	1.54	0.86	1.132	0.354	0.842	1.27	7.24
0.37	0.499	0.252	0.296	0.324	1.61	0.87	1.140	0.353	0.846	1.33	7.46
0.38	0.515	0.257	0.309	0.335	1.69	0.88	1.149	0.352	0.851	1.39	7.69
0.39	0.530	0.262	0.323	0.346	1.77	0.89	1.158	0.350	0.855	1.46	7.93
0.40	0.546	0.267	0.337	0.357	1.84	0.90	1.167	0.349	0.859	1.53	8.19
0.41	0.561	0.272	0.349	0.369	1.93	0.91	1.173	0.346	0.858	1.62	8.46
0.42	0.576	0.276	0.362	0.380	2.01	0.92	1.179	0.342	0.857	1.71	8.75
0.43	0.591	0.280	0.376	0.391	2.10	0.93	1.185	0.339	0.856	1.85	9.14
0.44	0.605	0.284	0.389	0.403	2.18	0.94	1.191	0.336	0.855	2.00	9.57
0.45	0.620	0.288	0.402	0.415	2.27	0.95	1.197	0.332	0.854	2.22	10.1
0.46	0.635	0.292	0.416	0.427	2.35	0.96	1.203	0.324	0.844	. . .	. . .
0.47	0.650	0.296	0.429	0.439	2.44	0.97	1.209	0.317	0.835	. . .	. . .
0.48	0.665	0.300	0.443	0.451	2.53	0.98	1.215	0.310	0.826	. . .	. . .
0.49	0.680	0.304	0.457	0.463	2.63	0.99	1.220	0.303	0.818	. . .	. . .
0.50	0.695	0.308	0.471	0.476	2.72	1.00	1.226	0.297	0.810	. . .	. . .

TABLE 12 *Continued*

d/D [B]	(1) $A = C_a D^2$	(2) $R = C_r D$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_m D$	(5) $Q = C_q D^{5/2}$	d/D [B]	(1) $A = C_a D^2$	(2) $R = C_r D$	(3) $K = C_k \frac{D^{8/3}}{n}$	(4) $d_m = C_m D$	(5) $Q = C_q D^{5/2}$
	C_a	C_r	C_k	C_m	C_q		C_a	C_r	C_k	C_m	C_q
Nominal sizes 16 ft 7 in. by 10 ft 1 in. and 15 ft 4 in. by 9 ft 3 in., and all riveted pipe-arches											
0.01	0.013	0.031	0.002	0.031	0.013	0.51	0.747	0.318	0.517	0.494	2.98
0.02	0.027	0.043	0.005	0.043	0.031	0.52	0.761	0.321	0.531	0.506	3.07
0.03	0.040	0.053	0.008	0.053	0.052	0.53	0.775	0.324	0.544	0.518	3.17
0.04	0.053	0.060	0.012	0.060	0.073	0.54	0.789	0.327	0.557	0.531	3.26
0.05	0.066	0.069	0.017	0.069	0.098	0.55	0.804	0.330	0.571	0.544	3.36
0.06	0.080	0.076	0.021	0.075	0.124	0.56	0.819	0.333	0.585	0.558	3.47
0.07	0.093	0.082	0.026	0.082	0.150	0.57	0.834	0.336	0.599	0.573	3.58
0.08	0.106	0.087	0.031	0.087	0.177	0.58	0.849	0.339	0.613	0.587	3.69
0.09	0.119	0.093	0.036	0.093	0.205	0.59	0.864	0.342	0.627	0.602	3.80
0.10	0.131	0.098	0.042	0.098	0.234	0.60	0.879	0.343	0.642	0.617	3.92
0.11	0.144	0.105	0.048	0.105	0.265	0.61	0.892	0.343	0.651	0.632	4.03
0.12	0.157	0.110	0.054	0.111	0.296	0.62	0.905	0.344	0.659	0.648	4.14
0.13	0.169	0.116	0.060	0.117	0.329	0.63	0.919	0.344	0.668	0.663	4.25
0.14	0.182	0.121	0.066	0.122	0.362	0.64	0.932	0.344	0.677	0.679	4.36
0.15	0.195	0.126	0.073	0.128	0.395	0.65	0.945	0.345	0.686	0.696	4.47
0.16	0.209	0.132	0.081	0.135	0.437	0.66	0.959	0.345	0.701	0.714	4.60
0.17	0.223	0.139	0.089	0.143	0.480	0.67	0.972	0.349	0.716	0.732	4.72
0.18	0.238	0.145	0.097	0.151	0.523	0.68	0.985	0.353	0.731	0.751	4.85
0.19	0.252	0.150	0.106	0.158	0.568	0.69	0.998	0.357	0.746	0.771	4.97
0.20	0.266	0.156	0.114	0.165	0.614	0.70	1.012	0.361	0.762	0.791	5.11
0.21	0.280	0.162	0.124	0.173	0.661	0.71	1.024	0.362	0.772	0.811	5.23
0.22	0.294	0.168	0.133	0.181	0.709	0.72	1.036	0.362	0.783	0.832	5.37
0.23	0.308	0.173	0.142	0.188	0.758	0.73	1.049	0.363	0.793	0.854	5.50
0.24	0.322	0.179	0.152	0.196	0.808	0.74	1.061	0.364	0.803	0.876	5.64
0.25	0.335	0.185	0.162	0.204	0.859	0.75	1.073	0.365	0.814	0.899	5.77
0.26	0.351	0.191	0.173	0.213	0.919	0.76	1.084	0.364	0.821	0.925	5.91
0.27	0.366	0.197	0.184	0.223	0.981	0.77	1.094	0.364	0.829	0.952	6.06
0.28	0.382	0.203	0.196	0.232	1.04	0.78	1.105	0.364	0.837	0.979	6.21
0.29	0.397	0.209	0.208	0.242	1.11	0.79	1.116	0.364	0.845	1.01	6.36
0.30	0.413	0.215	0.220	0.251	1.17	0.80	1.126	0.363	0.852	1.04	6.51
0.31	0.430	0.222	0.234	0.262	1.25	0.81	1.136	0.362	0.858	1.07	6.68
0.32	0.447	0.229	0.248	0.273	1.33	0.82	1.147	0.361	0.864	1.11	6.86
0.33	0.464	0.235	0.262	0.284	1.40	0.83	1.157	0.361	0.871	1.15	7.04
0.34	0.481	0.241	0.277	0.296	1.48	0.84	1.167	0.360	0.877	1.19	7.23
0.35	0.498	0.247	0.292	0.307	1.57	0.85	1.177	0.359	0.883	1.24	7.43
0.36	0.513	0.252	0.305	0.318	1.64	0.86	1.186	0.357	0.886	1.29	7.65
0.37	0.529	0.257	0.318	0.328	1.72	0.87	1.195	0.355	0.890	1.35	7.88
0.38	0.544	0.262	0.331	0.339	1.80	0.88	1.204	0.353	0.894	1.41	8.12
0.39	0.560	0.267	0.345	0.350	1.88	0.89	1.213	0.352	0.898	1.48	8.37
0.40	0.575	0.272	0.358	0.361	1.96	0.90	1.222	0.350	0.902	1.55	8.64
0.41	0.591	0.277	0.373	0.372	2.05	0.91	1.228	0.346	0.900	1.64	8.93
0.42	0.607	0.282	0.388	0.384	2.14	0.92	1.235	0.343	0.899	1.74	9.25
0.43	0.623	0.286	0.402	0.396	2.23	0.93	1.241	0.340	0.898	1.87	9.64
0.44	0.639	0.291	0.417	0.408	2.32	0.94	1.247	0.336	0.897	2.02	10.0
0.45	0.655	0.296	0.432	0.420	2.41	0.95	1.254	0.333	0.896	2.22	10.1
0.46	0.671	0.300	0.446	0.432	2.50	0.96	1.259	0.326	0.886	. . .	. . .
0.47	0.686	0.304	0.461	0.444	2.59	0.97	1.264	0.319	0.876	. . .	. . .
0.48	0.702	0.308	0.475	0.456	2.69	0.98	1.268	0.312	0.867	. . .	. . .
0.49	0.717	0.311	0.489	0.469	2.79	0.99	1.273	0.306	0.859	. . .	. . .
0.50	0.732	0.315	0.504	0.481	2.88	1.00	1.280	0.300	0.848	. . .	. . .

[A]Coefficients for (1) area, (2) wetted perimeter, (3) hydraulic radius, (4) conveyance, (5) discharge for critical-depth flow, and (6) top width.
[B]d = maximum depth of water in feet; D = diameter of pipe, in feet.

If more than 1 Type of flow is possible (combinations *a* and *b*) further classification is needed as shown in 18.5.8. If the comparison indicates that only Type 3 flow is possible (Condition *c*), no further classification is needed. The procedure for computing discharge under Type 3 flow is given in 18.6.3.

18.5.8 Compare culvert slope (S_o) and critical slope (S_c) as follows:

$$S_o = Iz$$

$$S_c = \left(\frac{Q}{K_c}\right)^2$$

where:

K_c = conveyance at critical depth.

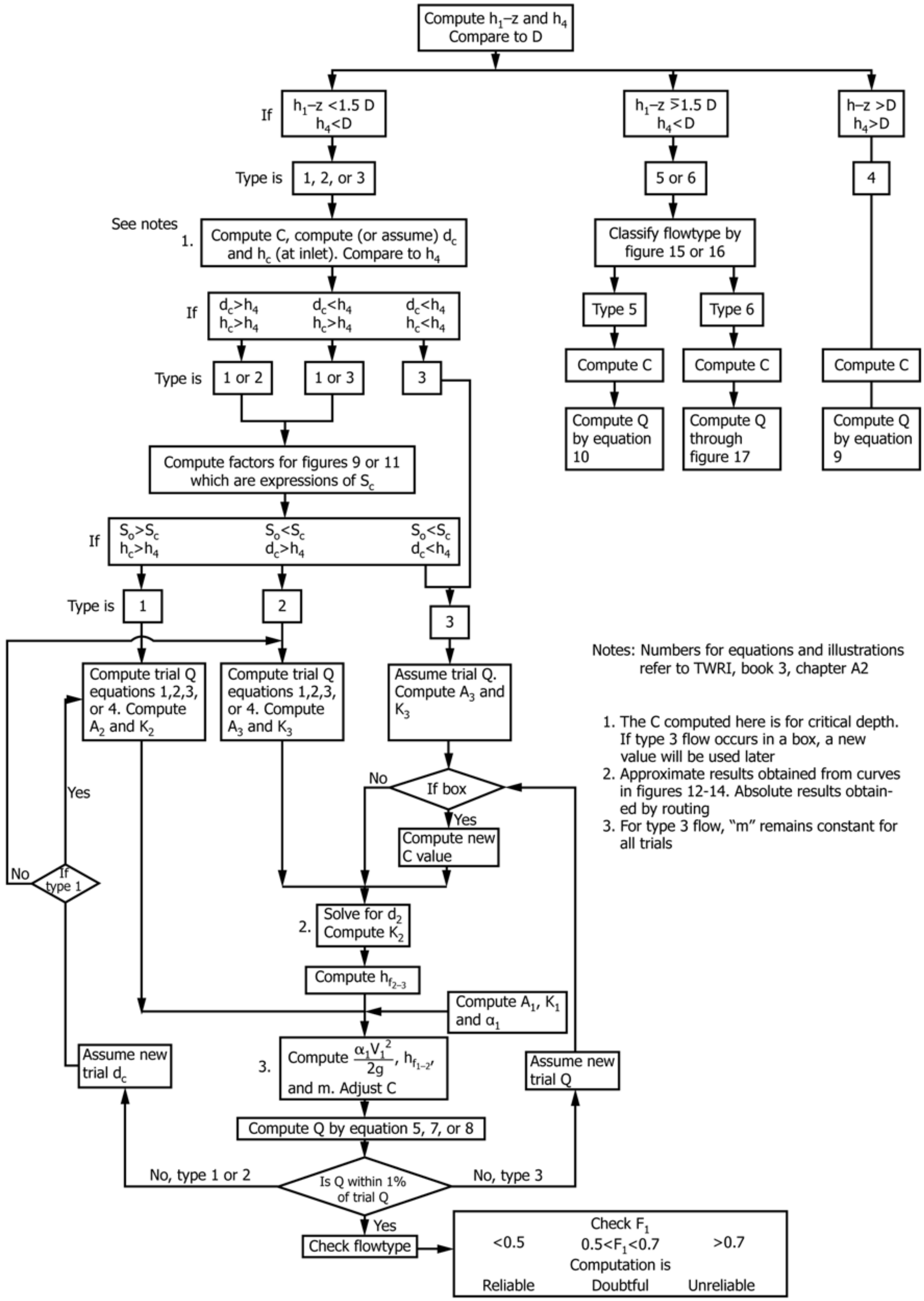


FIG. 17 Computation of Discharge in Culverts

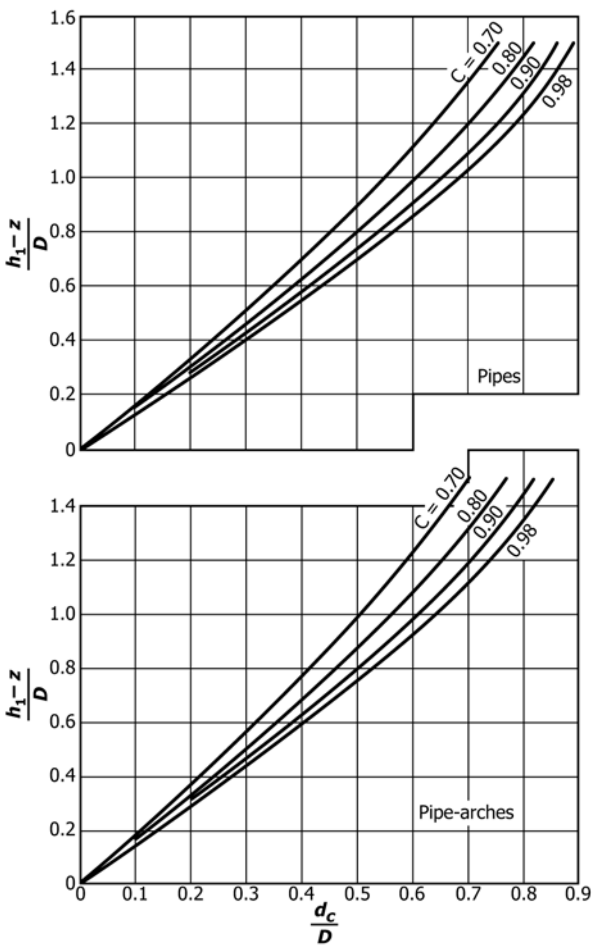


FIG. 18 Relation Between Head and Critical Depth in Pipe and Pipe-Arch Culverts

It is necessary to refer back to the comparison h_c and d_c with h_4. Three possible combinations exist:

$S_o > S_c$ and $hc > h_4$ flow is Type 1
$S_o < S_c$ and $hc > h_4$ flow is Type 2
$S_o < S_c$ and $hc < h_4$ flow is Type 3

18.5.8.1 The comparison of S_o and S_c can be made without computing K_c and S_c by using Fig. 19 for pipe or pipe arch culverts and Fig. 20 for box culverts.

18.5.8.2 If a point defined by coordinates of the abscissa and ordinate scales plots to the right of the curve for a given type of culvert, S_o is greater than S_c, and flow is Type 1. If the point plots to the left, S_o is less than S_c and flow is Type 2.

18.6 *Computation of Low Head Flows*—The type of flow determined in 18.5.7 or 18.5.8 is a trial type that must be checked after the computation of discharge is completed. Fig. 17 indicates similar but slightly different paths for computing discharge under each type of flow as well as different discharge equations. Therefore, a complete procedure is given here for each type of flow. The computation of approach properties used in the computations is discussed in 18.2.

18.6.1 *Type 1 Flow:*

18.6.1.1 Select the applicable Eq 14, Eq 15, Eq 16, or Eq 17 for the shape of the culvert and compute the discharge (Q) that corresponds to dc. For the first iteration dc is the one computed in 18.5.4. For subsequent iterations dc is the one assumed in 18.6.1.6.

18.6.1.2 Compute area (A_c) and conveyance (K_c) corresponding to dc. The control is at the culvert entrance, therefore $A_c = A_2$ and $K_c = K_2$.

18.6.1.3 Adjust C for m as described in 17.1.1. The starting C value for m 0.80 was computed in 18.5.3.

18.6.1.4 Using approach properties previously computed (see 18.3), compute:

$$h_{f_{1-2}} = \frac{Q^2 L_w}{K_1 K_2} \quad (16)$$

and:

$$\frac{\alpha_1 V_1^2}{2g} \quad (17)$$

18.6.1.5 Enter the values from 18.6.1.3 and 18.6.1.4 into Eq 18 and compute the discharge:

$$Q = CA_c \sqrt{2g\left(h_z - z + \frac{\alpha_1 V_1^2}{2g} - dc - h_{f_{1-2}}\right)} \quad (18)$$

18.6.1.6 If the discharge computed in 18.6.1.5 differs by more than 1 % from that of 18.6.1.1, assume a new dc and repeat 18.6.1.1 – 18.6.1.5 until agreement is reached. One good method of assuming dc is to substitute the following for h_1 and use the same procedure as was used in 18.5.5.

$$h_1 + \frac{\alpha_1 V_1^2}{2g} - h_{f_{1-2}}$$

18.6.1.7 When agreement is reached, proceed to 18.6.4.

18.6.2 *Type 2 Flow:*

18.6.2.1 Multiply dc from 18.5.5 by 0.95.

18.6.2.2 Compute discharge corresponding to dc.

18.6.2.3 Compute A_c and K_c corresponding to ddc. The control is at the downstream end of the culvert; therefore $A_c = A_3$ and $K_c = K_3$.

18.6.2.4 Assume d_2. A close approximation of d_2 can be obtained by using Fig. 21 for circular pipes, Fig. 22 for pipe arches, and Fig. 23 for box culverts. Using these curves can produce an error in discharge if $h_{f_{2-3}}$ is large. Section 18.6.3 discusses the applicability of these curves and presents an alternate, and more accurate procedure for computing d_2. Use of these curves can cause convergence problems in computer programs. Therefore, computer programs generally revert to the alternate method of determining d_2 given in 18.6.3.

18.6.2.5 To use Fig. 21 or Fig. 22 enter the ordinate with $h_1 - z/D$ and move horizontally to intersect the curve for the computed value of the following:

$$\frac{Q^2}{2gC^2(h_1 - z)D^4}$$

and read dc/D on the abscissa. To use Fig. 23 enter the abscissa with the computed value of the following:

$$\frac{Q^2}{2g(h_1 - z)^3 b^2 C^2}$$

and read $dc/h_1 - z$ on the ordinate.

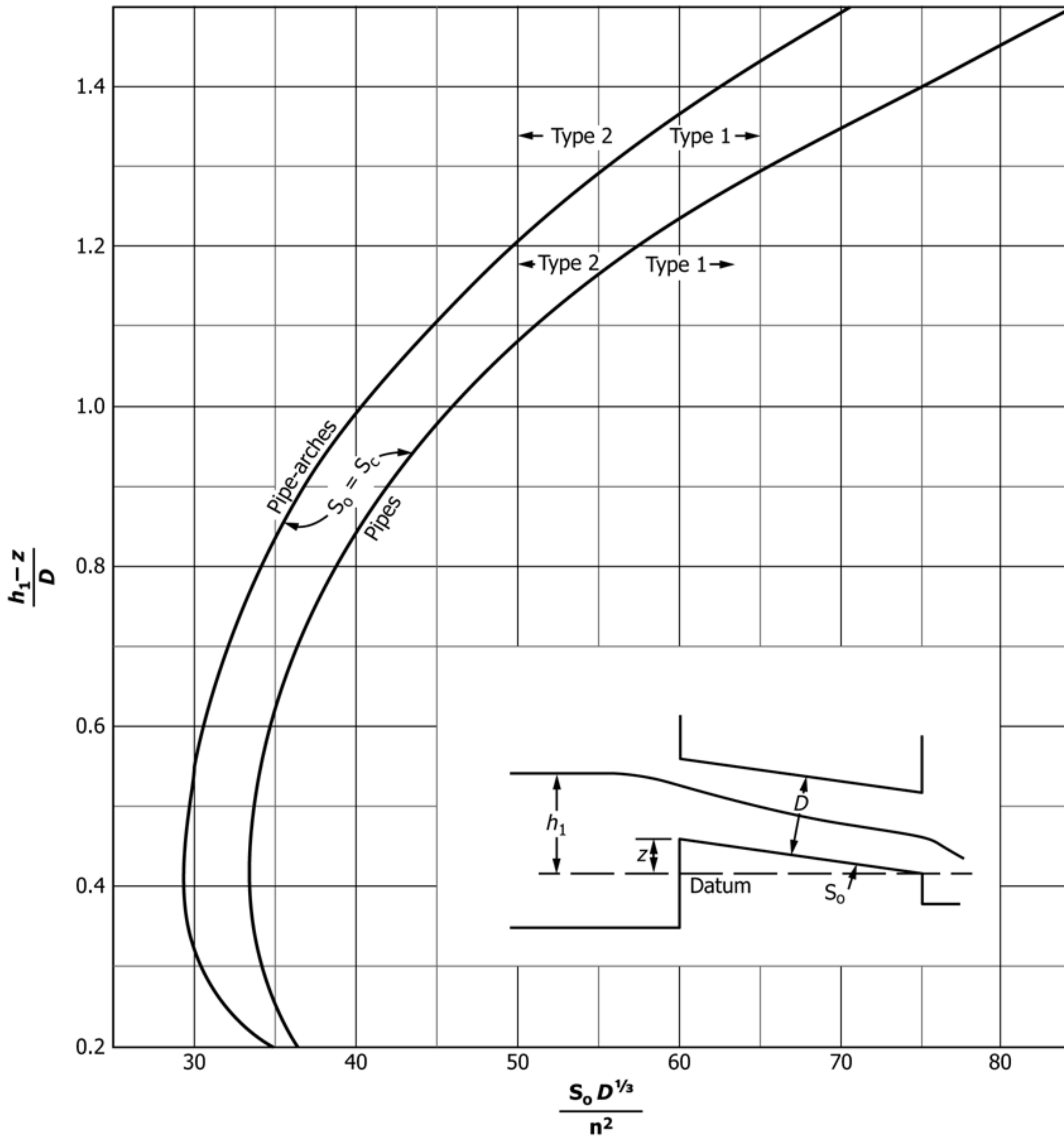


FIG. 19 Critical Slope as a Function of Head for Pipe and Pipe-Arch Culverts, with Free Outfall

18.6.2.6 At times the $h_1 - z/D$ line will not intersect the computed parameter curve of Fig. 21 or Fig. 22, or the computed parameter may be beyond the limit of the curve in Fig. 23. This can be due to one or more of the following reasons.

(a) Assumed discharge is too large. Assume a smaller *dc* and restart the computation at 18.6.2.2.

(b) Flow is not Type 2. Compute discharge by Type 1 procedure.

(c) Velocity of approach is great enough to be included.

The h_1 term should be replaced by $h_1 + \frac{\alpha_1 V_1^2}{2g}$ in ordinate scales and computed parameters.

18.6.2.7 Compute K_2 for the assumed d_2.

18.6.2.8 Compute

$$h_{f_{2-3}} = \frac{Q^2 L}{K_2 K_3}$$

:

$$h_{f_{1-2}} = \frac{Q^2 Lw}{K_1 K_2}$$

and:

$$\frac{\alpha V_1^2}{2g}$$

The curves may indicate a full culvert at the upstream end. In that case, use the procedure in 18.6.3.

18.6.2.9 At this point some authors, for example Bodhaine on p. 29 of Ref (**9**), recommend an adjustment of h_1 by adding velocity head and subtracting friction losses. The equation used is as follows:

$$H = h_1 + \frac{\alpha V_1^2}{2g} - h_{f_{1-2}} - h_{f_{2-3}}$$

H is then substituted for h_{1_1} and the above procedures are repeated. This mid-course adjustment is not required. Under some conditions the adjustment reduces the spread between the

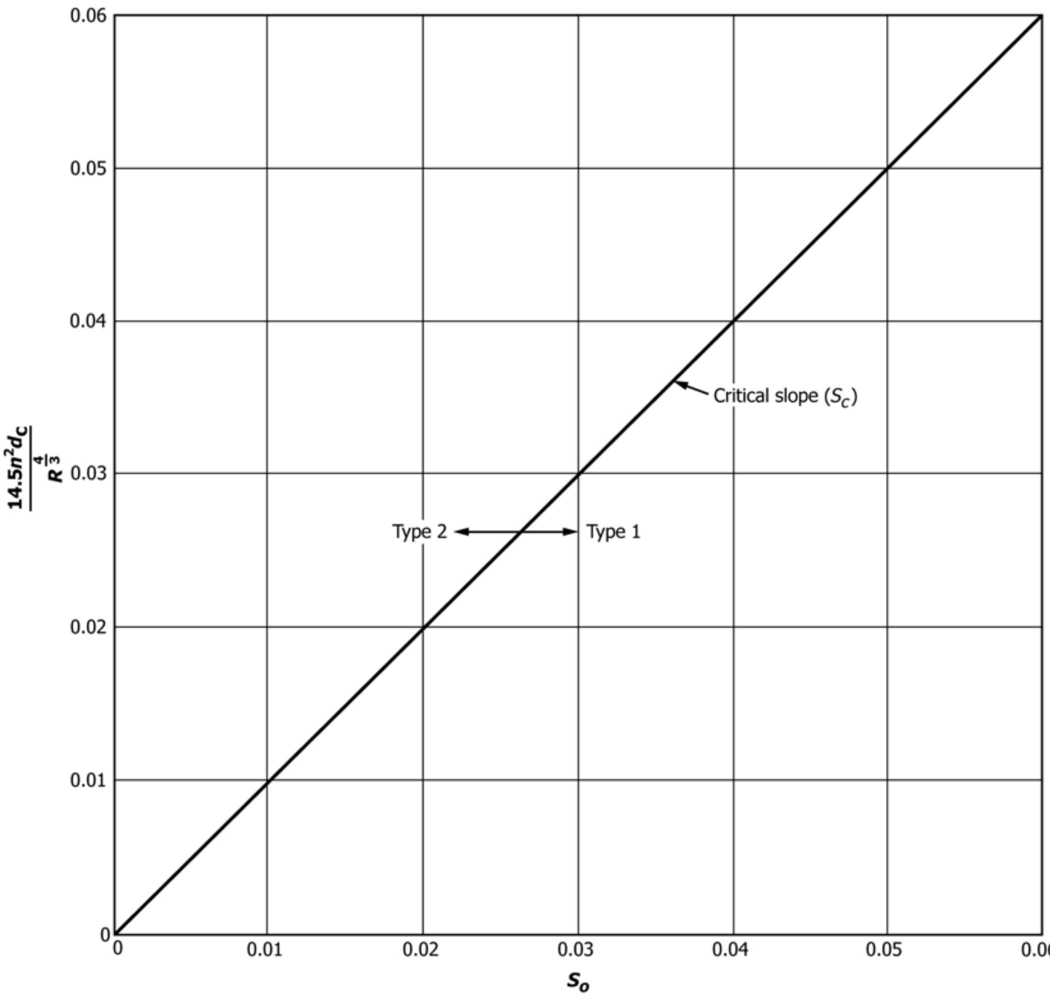


FIG. 20 Critical Slope for Culverts of Rectangular Section, with Free Outfall

trial discharge of 18.6.2.2 and the computed discharge of 18.6.2.11; however under other conditions it may increase the spread. The adjustment is not used in this test method.

18.6.2.10 Adjust *C* for degree of contraction *m*. The starting *C* for $m = 0.80$ was computed in 18.5.4. The area used in the computation of *m* is A_c computed in 18.5.4.

18.6.2.11 Substitute values from 18.6.2.9 and 18.6.2.10 in Eq 19 and compute discharge as follows:

$$Q = CA_c \sqrt{2g\left(h_1 + \frac{\alpha_1 V_1^2}{2g}\right) - dc - h_{f_{1-2}} - h_{f_{2-3}}} \quad (19)$$

18.6.2.12 If the discharge computed in 18.6.2.11 differs by more than 1 % from that computed in 18.6.2.2, assume a new *dc* and repeat 18.6.2.2 – 18.6.2.11 until agreement is reached. A good method of assuming *dc* is to substitute the following for h_1 and determine *dc* directly from Fig. 17. When agreement is reached go to 18.6.6:

$$h_1 + \frac{\alpha_1 V_1^2}{2g} - h_{f_{1-2}} - h_{f_{2-3}}$$

18.6.3 *Alternate Method for Determining* d_2—Curves in Figs. 21-23 are based on the assumption that $V_2 = V_3$. This assumption is greatly in error if the friction loss in the culvert barrel, $h_{f_{2-3}}$, is large. For a friction loss of 0.5 ft (150 mm) the error in discharge can be about 5 or 6 %. If friction loss is much greater than 0.5 ft, compute d_2 by trial from the following procedure:

18.6.3.1 d_2—is selected from Fig. 21, Fig. 22, or Fig. 23, or is assumed outright.

18.6.3.2 After having a trial d_2, compute A_2, K_2, $\frac{V_2^2}{2g}$, $\frac{V_3^2}{2g}$, and $h_{f_{2-3}}$.

18.6.3.3 Compute a new value of d_2 from the following equation:

$$d_2 = dc + \frac{V_3^2}{2g} + h_{f_{2-3}} - \frac{V_2^2}{2g} - z$$

If the computed d_2 of 18.6.3.3 differs by more than 0.1 ft (.3 m) from the value used in 18.6.3.1, assume a new d_2 and repeat 18.6.3.2 and 18.6.3.3 until agreement is reached. Use the value of $h_{f_{2-3}}$ from the last computation of d_2 in the discharge equation.

18.6.4 *Culvert Flowing Full Part Way*—If the curves of Fig. 21, Fig. 22, or Fig. 23 or the assumed depth of 18.6.3 indicate a full culvert at the upstream end, compute the friction loss for the length that is flowing full ($L - x$) and for the length that is flowing part full (x). The sum of the two replaces $h_{f_{2-3}}$ in Eq 19 or Eq 22. Obtain the length *x* by solving *x* in Eq 20:

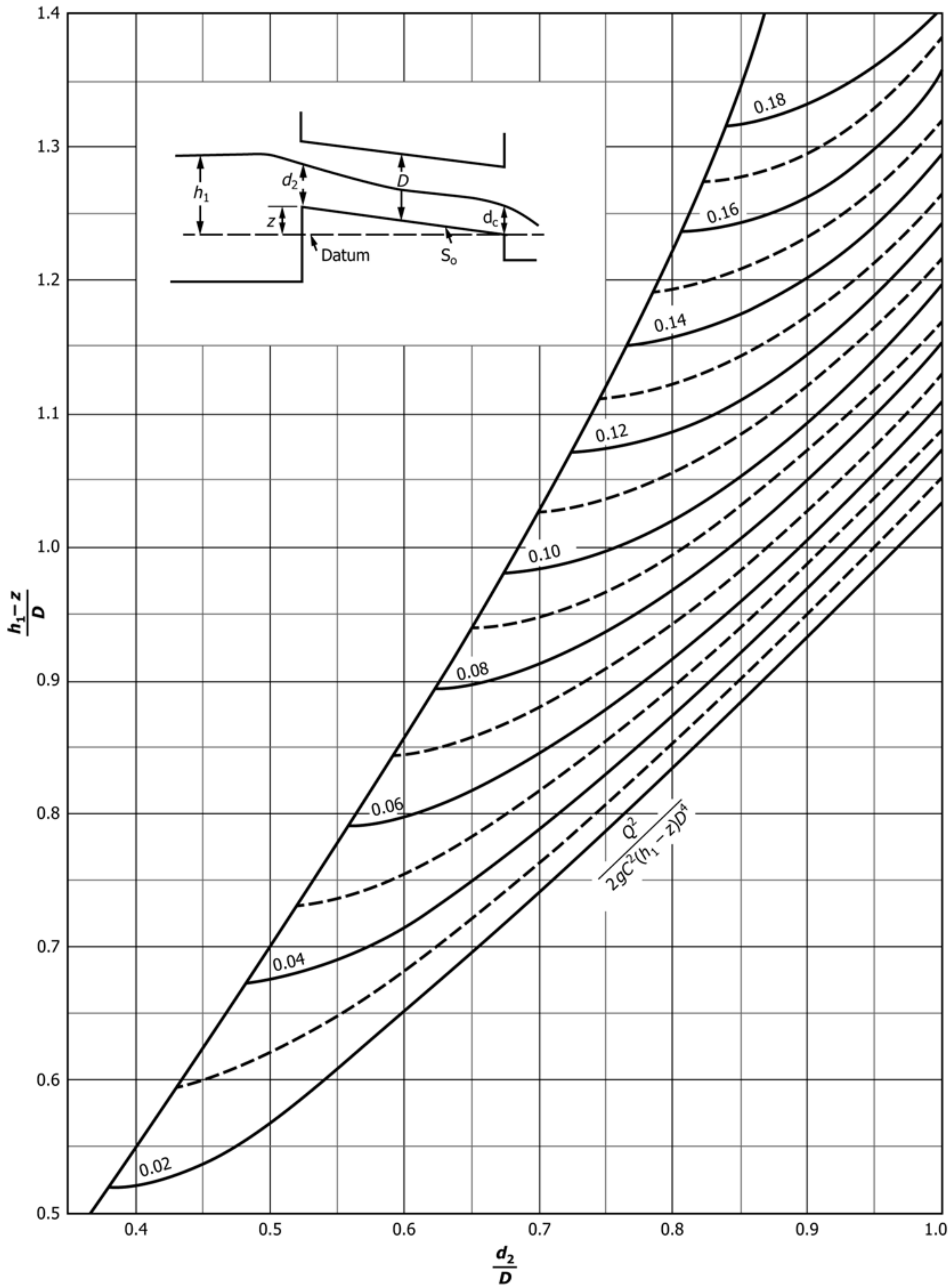


FIG. 21 Relation Between Head and Depth of Water at Inlet with Critical Depth at Outlet for Culverts of Circular Section

$$D + S_o x = d_3 + Q^2 x / K_o K_3 + \frac{V_3^2}{2g} - \frac{V_o^2}{2g} \quad (20)$$

Then compute $h_{f_{2-3}}$ from:

$$h_{f_{2-3}} = h_{fx} + h_{f_{L-x}} = \frac{Q^2(L-x)}{K_o^2} + \frac{Q^2 x}{K_o K_3} \quad (21)$$

18.6.5 *Type 3 Flow:*

18.6.5.1 Assume a discharge. One way to assume the discharge is to use the following equation:

$$Q = (J)(C)(8.02)(A_3)(h_1 - h_4)^{0.5}$$

where C is the discharge coefficient, and J varies with the type of culvert. It ranges from slightly over 1.0 for short concrete culverts where $h_1 - h_4$ is low and velocity of

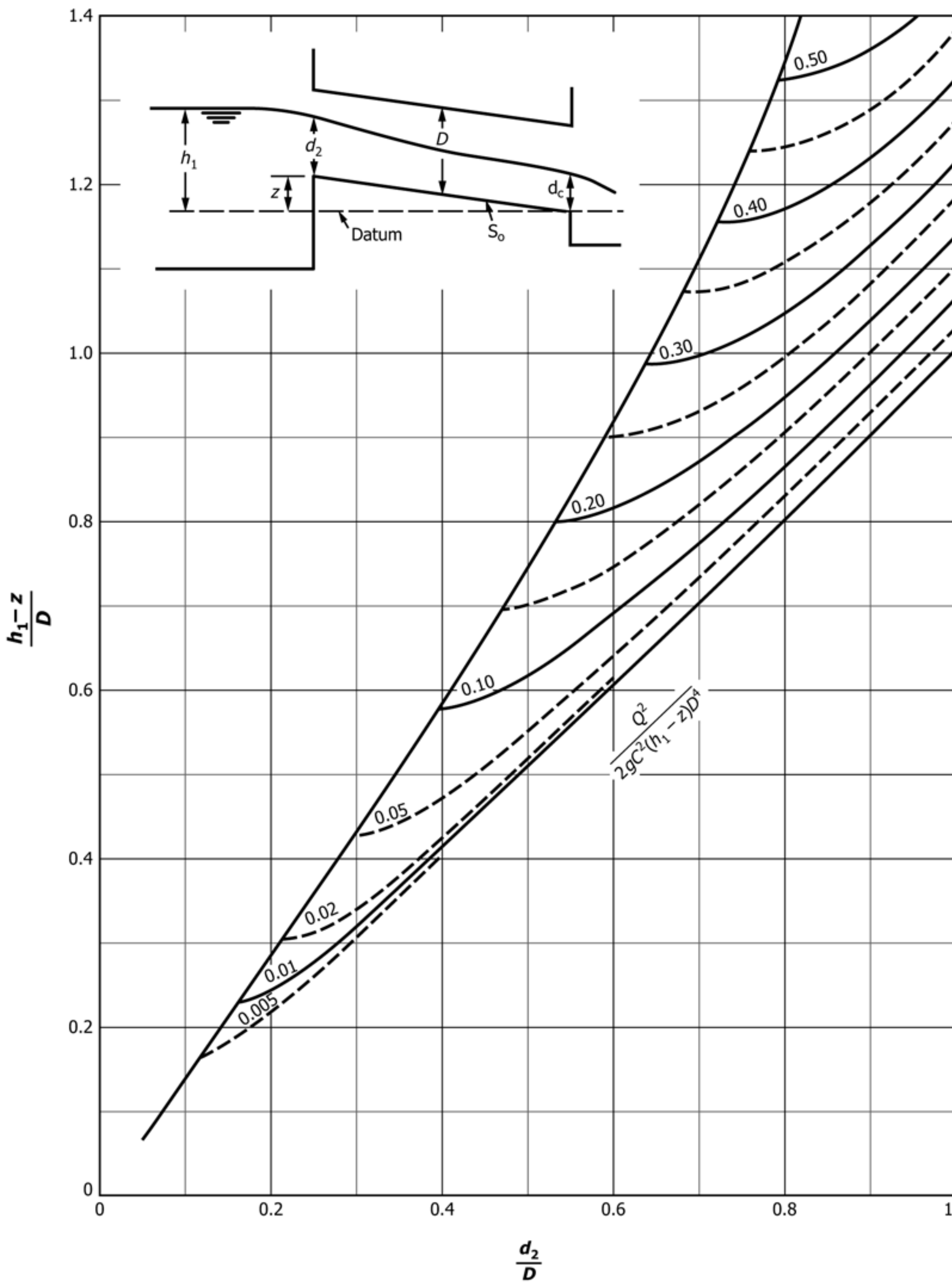


FIG. 22 Relation Between Head and Depth of Water at Inlet with Critical Depth at Outlet for Pipe-Arch Culverts

approach is high to about 0.70 for long corrugated pipes and arches where $h_1 - h_4$ approaches 30 % of h_4 and approach is ponded. For circular pipes J is usually used as 0.90 or 0.95. The C for a box culvert with Type 3 flow is a function of the Froude number in 3.3.6. It must be estimated at this stage. It may range from 0.80 for a very low value of $h_1 - h_4$ to 0.98, and generally is about 0.90 to 0.95. For a box culvert generally combine C and J into one estimate. A combined value of 0.90 is usually a reasonable starting point. The combined value could be as low as 0.80 if $h_1 - h_4$ is less than 0.15 h_4 or culvert is long and rough. A more simple method is to assume that $Q = 7.5A_3$ $(h_1 - h_4)^{0.5}$. Regardless of the values used, there is little reason to carry the trial discharge to a higher level of refinement than two significant figures.

18.6.5.2 Compute A_3 and K_3 for the measured d_3.

18.6.5.3 If culvert is of circular or pipe arch shape the C computed in 18.5.4 remains in effect. Proceed to 18.6.5.4. For a box culvert compute a new C value by computing F_3 for the trial Q of 18.6.5.1 and determining C from Fig. 12.

18.6.5.4 Assume d_2. Determine an approximate value of d_2 by using Fig. 21 for circular pipes, Fig. 22 for pipe arches, and Fig. 23 for box culverts. The use of these curves is described in

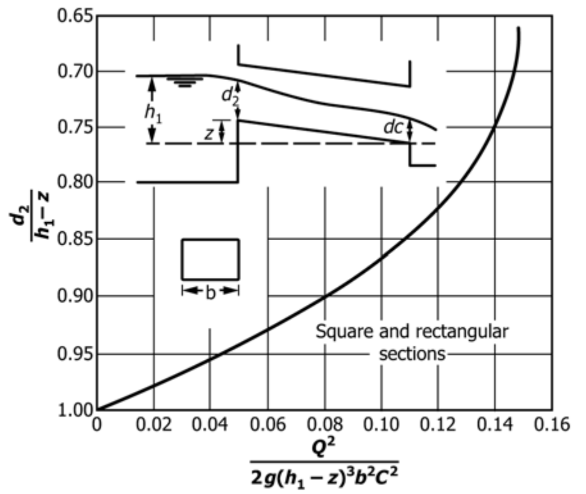


FIG. 23 Relation Between Head and Depth of Water at Inlet with Critical Depth at Outlet for Culverts of Rectangular Section

18.6.2.4. It can produce an error in the computed discharge if $h_{f_{2-3}}$ is large. Subsection 18.6.3 discusses the applicability of the curves and an alternate procedure for computing d_2. Subsection 18.6.4 discusses a culvert flowing full part way. These subsections also apply to Type 3 flow.

18.6.5.5 Compute K_2 as follows:

$$h_{f_{2-3}} = \frac{Q^2 L}{K_2 K_3}$$

$$h_{f_{1-2}} = \frac{Q^2 L_w}{K_2 K_3}$$

and:

$$\frac{\alpha_1 V_1^2}{2g}$$

18.6.5.6 Adjust C for degree of contraction as discussed in Section 17 of this test method.

18.6.5.7 Compute discharge from Eq 22:

$$Q = CA_3 \sqrt{2g\left(h_{11} + \frac{\alpha_1 V_1^2}{2g} - h_3 - h_{f_{1-2}} - h_{f_{2-3}}\right)} \quad (22)$$

18.6.5.8 If the discharge computed in 18.6.5.7 differs by more than 1 % from that assumed in 18.6.5.1, assume a new Q and repeat 18.6.5.2 – 18.6.5.8 until agreement is reached.

18.6.5.9 When agreement is reached go to 18.6.6.

18.6.6 *Validation of Computed Discharge:*

18.6.6.1 If discharge was computed by Type 1, 2, or 3 methods, check the type of flow for the final discharge to see that the proper flow type was used. Compute S_c for the final value of d_c and Q. Repeat all comparisons from 18.8. If type does not agree with that used, recompute discharge using the type of flow indicated. The magnitude of the discharge will not change by much.

18.6.6.2 Compute the Froude number at the approach from the following:

$$F_1 = \frac{V_1}{\sqrt{dm_1}}$$

where:

V_1 = Q/A_1,
dm = A_1/T_1, and
T_1 = width of the approach section at the elevation of the water surface.

If F_1 is less than 0.5 the computation provides a reliable discharge. If F_1 is between 0.5 and 0.7 the computation should be used with caution and may be unreliable for some shapes and conditions of the approach section. If F_1 is greater than 0.7 the computation is most likely unreliable and should not be used.

18.6.7 *Special Conditions for Mitered Pipes:*

18.6.7.1 For headwater-diameter ratios less than 1.0 on mitered pipes and pipe arches, length (L_w) is the distance between the approach section (Section 1) and the point on the miter at the elevation of the headwater (see Fig. 4). For ratios greater than 1.0, the approach length is the distance from Section 1 to the beginning of the full pipe. For Type 1 flow, assume critical depth to occur at the point to which the approach length is measured. For Type 2 or 3 flow, measure the culvert length from the point where headwater intersects the upstream miter to the point on the downstream miter at the elevation of critical depth for Type 2 or the tailwater for Type 3. The length of a culvert flowing full under Type 4 flow is the length of the full pipe section.

18.6.7.2 Computer programs may not have the above refinements incorporated in them. When using a computer program it may be necessary to compute the discharge for two combinations of approach length, culvert length, and invert elevations. Discharge is determined by interpolating between computations with the following equation:

$$Q = Q_1 + (Q_2 - Q_1)\frac{E_{ws} - E_1}{E_c - E_1}$$

where:

Q_1 = discharge computed at the given upstream water surface for the length and invert elevations measured to or at the extreme ends of the culvert,
Q_2 = discharge computed at the same water surface elevation for the lengths and invert elevations measured to or at the points where the full culvert section begins and ends,
E_1 = elevation of the extreme upstream end of the culvert,
E_c = elevation of crown at beginning of full culvert system, and
E_{ws} = elevation of water surface at the approach.

18.6.8 *Breaks in Slope:*

18.6.8.1 If breaks in slope, changes in culvert roughness, or changes in barrel size are present, the type of flow must be determined for each section of culvert. Without backwater, if all sections are steep enough to support critical flow, the control is at the inlet, and discharge is computed as for any Type 1 flow. If all sections are too flat to support critical flow, the control is at the outlet, and $h_{f_{2-3}}$ in Eq 19 is replaced by the sum of friction losses in the various parts of the culvert. If roughness or size changes at a break, two sets of culvert properties are used. One set applies to the part downstream from the break, and the other applies to the part upstream from the break. Depth at each break must be computed by the method described in 18.6.3.

18.6.8.2 If some sections will support critical flow and others will not, locate the control at the upstream end of the most upstream length of culvert that will support critical flow. Route the flow from that section to the entrance and compute flow by Eq 19, replacing $h_{f_{2-3}}$ with the sum of friction losses between the control section and the inlet.

18.6.8.3 A check must be made that parts of the culvert downstream from the break will not cause backwater at the control. This is done by routing the computed discharge from the most downstream section where critical flow could occur to the control section used in 18.6.8.2. If the depth of flow below the break is less than critical depth at the break, the computed flow is correct.

18.6.8.4 If culvert is flowing under backwater an assumed discharge is routed from the outlet to the inlet. The $h_{f_{2-3}}$ term in Eq 22 is replaced with the sum of the friction losses in the various parts of the culvert as described in 18.6.8.3.

18.7 *Type 4 Flow:*

18.7.1 The following procedure is used if Type 4 flow was identified in 18.5:

18.7.1.1 Determine C for Type 4 flow from Table 5.

18.7.1.2 Compute A_o and $R_o{}^{4/3}$ for the full culvert section. For a circular pipe or pipe arch section $R_o = C_r D$, where C_r is determined from Table 10 or Table 11. For a box culvert:

$$R = \frac{bd}{2(b+d)}$$

unless webs are present, in which case d is multiplied by the number of webs present before being used in the above equation.

18.7.1.3 Compute discharge from Eq 23:

$$Q = CA_o \sqrt{\frac{2g(h_1 - h_4)}{\frac{29\,C^2 n^2 L}{R_o{}^{4/3}}}} \tag{23}$$

18.7.2 *Breaks in Slope and Changes in Material or Size*—Eq 23 applies equally well to a culvert with breaks in slope as long as n and culvert size remain constant throughout the length of the culvert. The equation does not apply where n or culvert size varies within the culvert. In that case, the discharge must be computed by routing.

18.8 *High-Head Flow*—The following procedure is used if Type 5 or 6 flow was indicated in 18.5:

18.8.1 *Classification of High-Head Flow*—The first step in a manual computation of discharge is to determine which type of flow existed. Some computer programs, the USGS one for example, do not determine the type of flow. The user must do that by using the procedure discussed after discharge is computed for both types.

18.8.1.1 As stated in 12.5.1 the occurrence of Type 5 or 6 flow depends on several aspects of culvert geometry and approach conditions. The effects of approach conditions other than the height of water above the culvert cannot be measured. Therefore, the Type 5 and 6 flow are distinguished on the basis of items that were measurable in the laboratory. The best fit curves of laboratory data are presented in Fig. 24 and Fig. 25. Although the curves of Fig. 24 and Fig. 25 are used as absolute dividing lines, they are highly approximate.

18.8.1.2 Fig. 24 is for concrete and other smooth materials such as cast iron. Fig. 25 is for corrugated metal and other rough barrels. The dividing line for smooth or rough material is somewhat indeterminate but appears to be at an n value near 0.020. This varies with length and size of culvert and can best be determined on the basis of the factor of Fig. 25, that is:

$$\frac{29n^2(h_1 - z)}{R_o{}^{2/3}}$$

If that value is less than 0.05 use Fig. 24. If that value is greater than 0.05 use Fig. 25 with extrapolations discussed in 18.8.4.3.

18.8.2 *Concrete and Other Smooth Materials*—Fig. 24 may be used to classify Type 5 or 6 flow in culvert barrels made of concrete or other smooth materials. Use the following procedure:

18.8.2.1 Compute the ratios *L/D*, *r/D*, or *w/D*, and S_o.

18.8.2.2 Select the curve of Fig. 24 corresponding to *r/D* or *w/D* for the culvert. Sketch in an interpolated curve for the given *r/D* or *w/D*, if necessary.

18.8.2.3 Plot the point defined by S_o and *L/D* for the culvert.

18.8.2.4 If the point lies to the right of the curve selected or sketched in 18.8.2.2, the flow was Type 6; if the point lies to the left, the flow was Type 5.

18.8.2.5 The use of Fig. 24 is restricted to square, rounded, or beveled entrances, either with or without wingwalls. Wingwalls do not affect the flow classification, as the rounding effect they provide is offset by a tendency to produce vortexes that supply air to the culvert entrance. For box culverts with wingwalls, use the geometry of only the top side of the entrance in computing the effective radius of rounding, r, or the effective bevel, w, in using Fig. 24.

18.8.3 *Corrugated Metal and Other Rough Materials*—Fig. 25 may be used to classify Type 5 or 6 flow in rough pipes, both circular and pipe-arch sections, mounted flush with a vertical headwall, either with or without wingwalls, as outlined below, or for projecting entrances.

18.8.3.1 Determine the ratio *r/D* for the pipe.

18.8.3.2 From Fig. 25, select the graph corresponding to the value of *r/D* for the culvert. Fig. 25(*a*) should be used in classifying the flow if a thin wall projects from a headwall or embankment.

18.8.3.3 Compute the ratio $29n^2(h_1 - z)/R_o{}^{4/3}$ and select the corresponding curve on the graph selected in 18.8.3.2. Sketch in an interpolated curve for the computed ratio, if necessary.

18.8.3.4 Plot the point defined by S_o and *L/D* for the culvert under study.

18.8.3.5 If the point plots to the right of the curve selected in 18.8.3.3, the flow was Type 6; if the point plots to the left of the curve, the flow was Type 5.

18.8.4 *Extrapolation of* Fig. 25—The parameter of Fig. 25 may at times be greater than 0.30 (for small culverts under heads greater than 4D) or less than 0.10 (for large culverts under heads of about 1.5 D). It will be necessary to extrapolate the curves only if the point defined by S_o and *L/D* also falls outside the defined curves. Reasonable upward extrapolation

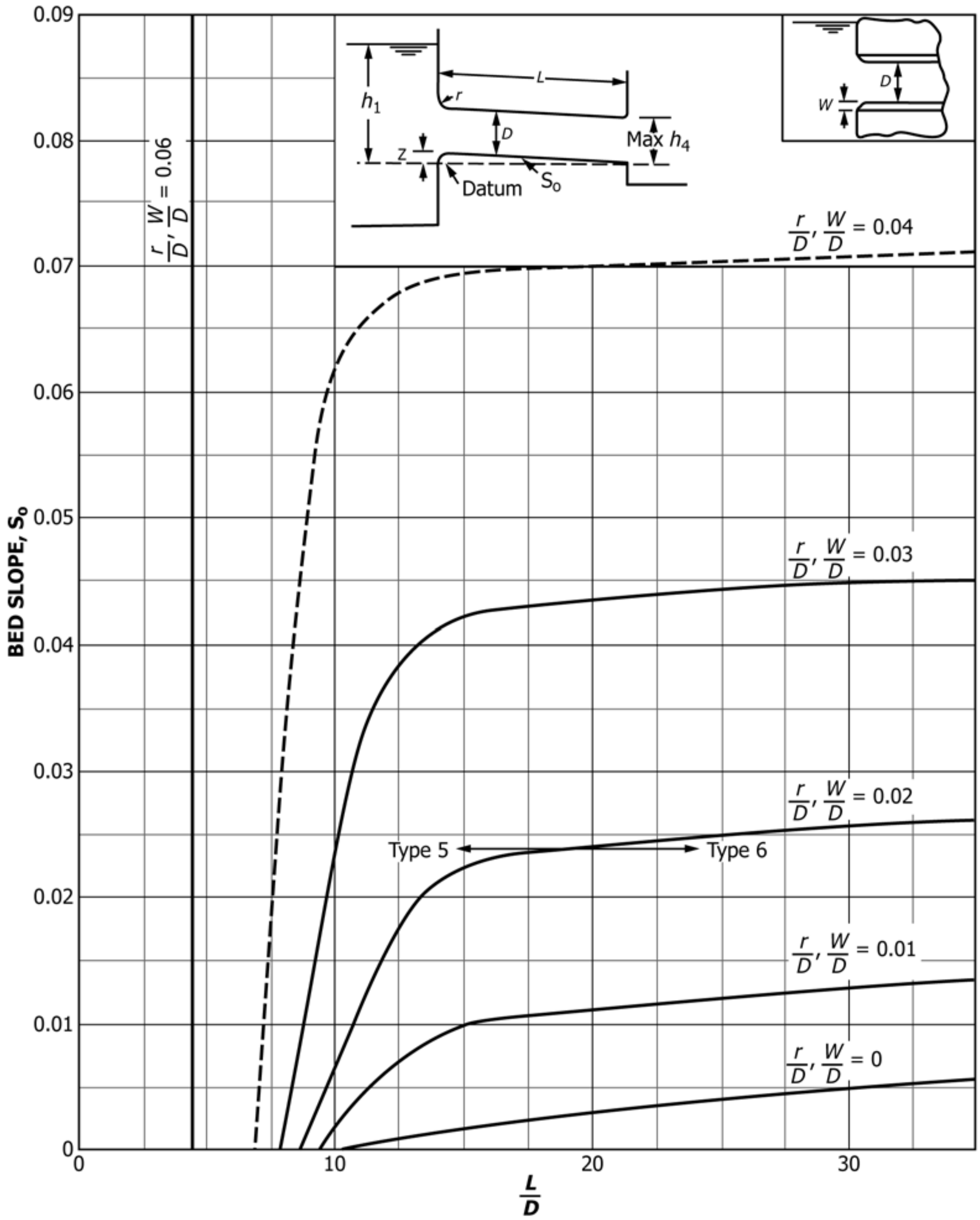


FIG. 24 Criterion for Classifying Types 5 and 6 Flow in Box or Pipe Culverts with Concrete Barrels and Square, Rounded, or Beveled Entrances, Either with or without Wingwalls

can be made by sketching in additional curves. The spacing for each 0.05 increase in the parameter should be equal to the spacing between the line for 0.25 and 0.30. The downward extrapolation below 0.10 is more difficult. A fairly reasonable extrapolation can be made in Fig. 25(*a*) and (*b*) by putting a 0.05 line half way between the 0.10 line and the *x*-axis. A similar extrapolation in Fig. 25(*c*) and (*d*) causes a much wider spacing between the 0.05 and 0.10 lines than between the 0.10 and 0.15 lines. On the latter two diagrams, it is recommended that the extrapolation be made by placing the 0.05 line the same distance from the 0.10 line as the 0.10 line is from the 0.15 line.

18.8.5 *Computation of Discharge—High Head Flow:*

18.8.5.1 *Type 5*—Type 5 flow is computed directly from Eq 24:

$$Q = CA_o\sqrt{h_1 - z} \quad (24)$$

18.8.5.2 *Type 6*—Subsection 12.5.3 discusses alternate functional relations for computation of Type 6 flow. The relations expressed in Fig. 26 are used to compute the discharge for Type 6 flow.

(a) Compute the ratio h_1/D. Select the discharge coefficient, *C*, applicable to the culvert geometry as described in Section 17.

(b) From the lower part of Fig. 26, determine the value of $Q/A_o\sqrt{D}$ corresponding to $29n^2\ L/R_o^{4/3} = 1$.

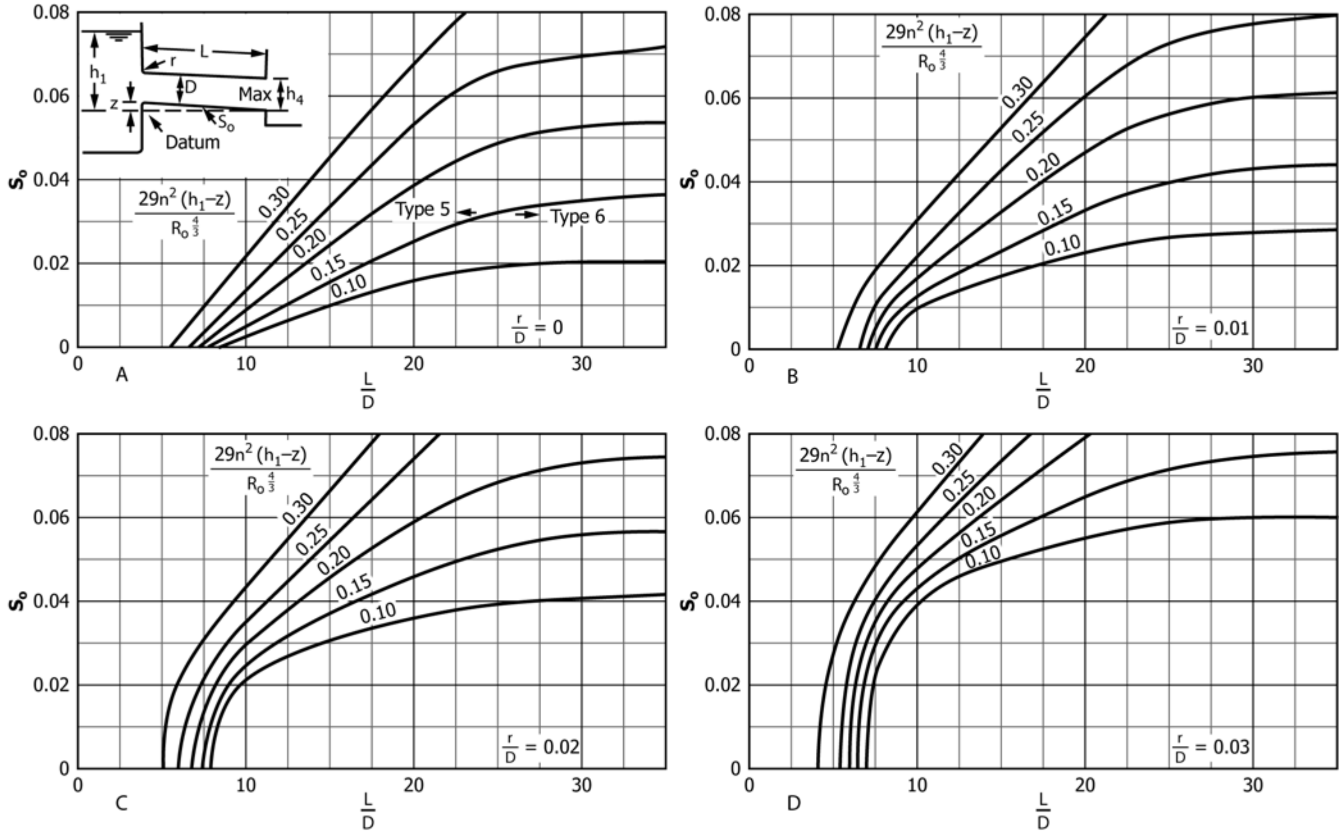


FIG. 25 Criterion for Classifying Types 5 and 6 Flow in Pipe Culverts with Rough Barrels

(c) Compute the ratio 29 $n^2L/R_o^{4/3}$ for the culvert under study.

(d) From the upper part of Fig. 26, using the computed ratio $29n^2L/R_o^{4/3}$ and the coefficient C, find the correction factor, k_f.

(e) Multiply the ratio determined in (*b*) above by k_f.

(f) Determine the value of Q by multiplying the adjusted ratio from (*e*) above by $A_o\sqrt{D}$.

18.8.5.3 *Flow in Culverts with Varying Geometries*—Where a culvert is composed of multiple lengths having different slope, roughness, or size, it is difficult to determine if flow is Type 5 or 6. If the carrying capacity of the culvert increases in a downstream direction, that is, slope steepens, roughness decreases or size increases at each break in slope, base the flow type on the first length of culvert. If that length indicates Type 5 flow, compute by the standard Type 5 procedure. If that length indicates Type 6 flow, compute Type 6 flow in that length and assume that the more downstream length will carry the water. For any other condition where the flow condition is unknown, a range in discharge can be obtained by computing Type 5 in the standard way and Type 6 through the entire culvert by routing the flow as described in 18.9.

18.9 *Special Procedure for Irregular Sections*—Many culverts do not fit the standard geometries described in this test method. These include semi-circular arches, pipes that have been badly deformed, and culverts with natural bottoms. Natural bottoms frequently cause nonuniformity in cross-sectional areas. Special treatment must be given to such culverts because standard equations are not applicable. The routing method of computing discharge should be used whenever the culvert shape is other than box, circular, or pipe arch, or wherever there is an appreciable variation within the culvert of slope, shape, area, conveyance, or roughness. Routing is done by using Eq 8 of 12.3 with $h_{f_{3-4}}$ and $(h_{v_3} - h_{v_4})$ equal to zero for Types 1, 2, and 3 flow, and Eq 9 of the same section for Type 4 flow.

18.9.1 For Type 6 flow, the same procedure is followed except that the starting point for the piezometric head (h_3) must be estimated in some manner.

18.9.1.1 For box culverts the line of piezometric head at the outlet may be considered to lie slightly below the centerline for high Froude numbers, gradually increasing to a level about halfway between centerline and top of barrel for a Froude number approaching unity. An average h_3 of 0.65D may be used for the range of Froude numbers ordinarily encountered in culvert flow in the field.

18.9.1.2 For pipe culverts of circular section it is known that the piezometric head usually lies between 0.5D and 1.0D. An average h_3 of 0.75D may be used for the range of Froude numbers ordinarily encountered under field conditions. A more exact value may be obtained from Fig. 27.

18.10 *Transitional Flow:*

18.10.1 The computational procedures outlined in 18.9 use the $h_1 - z/D$ ratio of 1.5 as a distinct dividing line between low-head and high-head flow. The dividing line is not that sharp in either the field or laboratory. Laboratory data show an

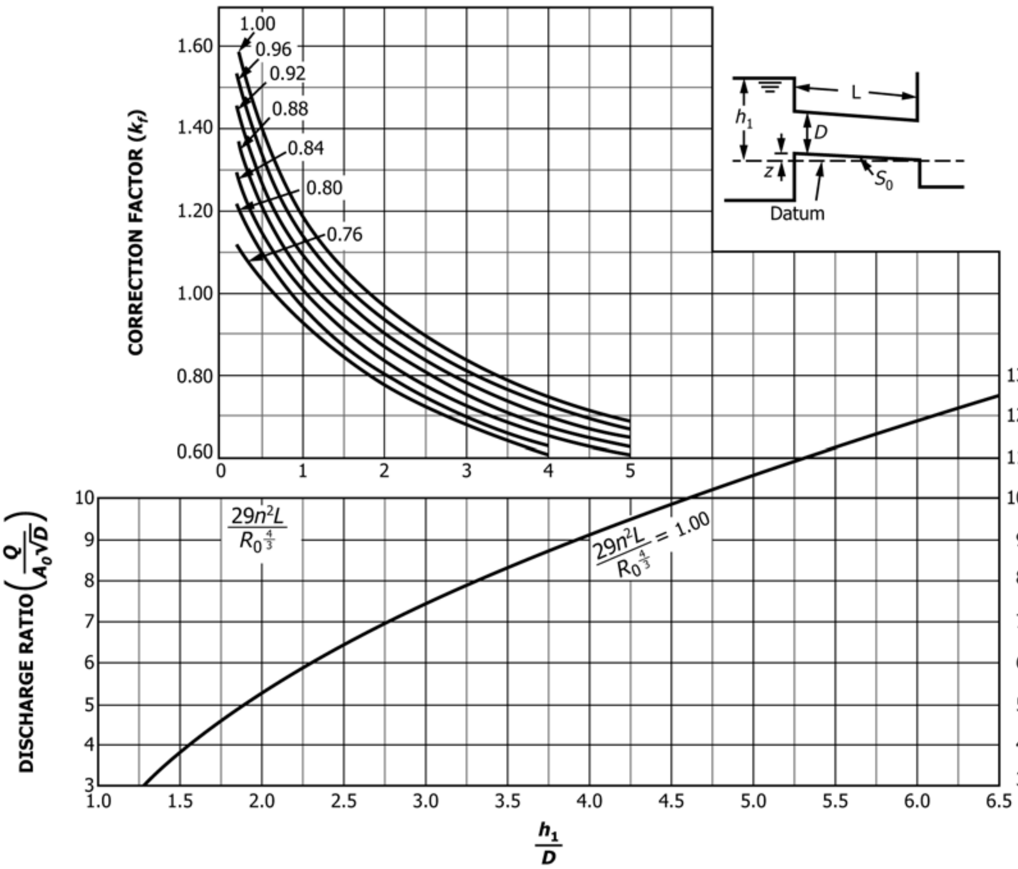


FIG. 26 Relation Between Head and Discharge for Type 6 Flow

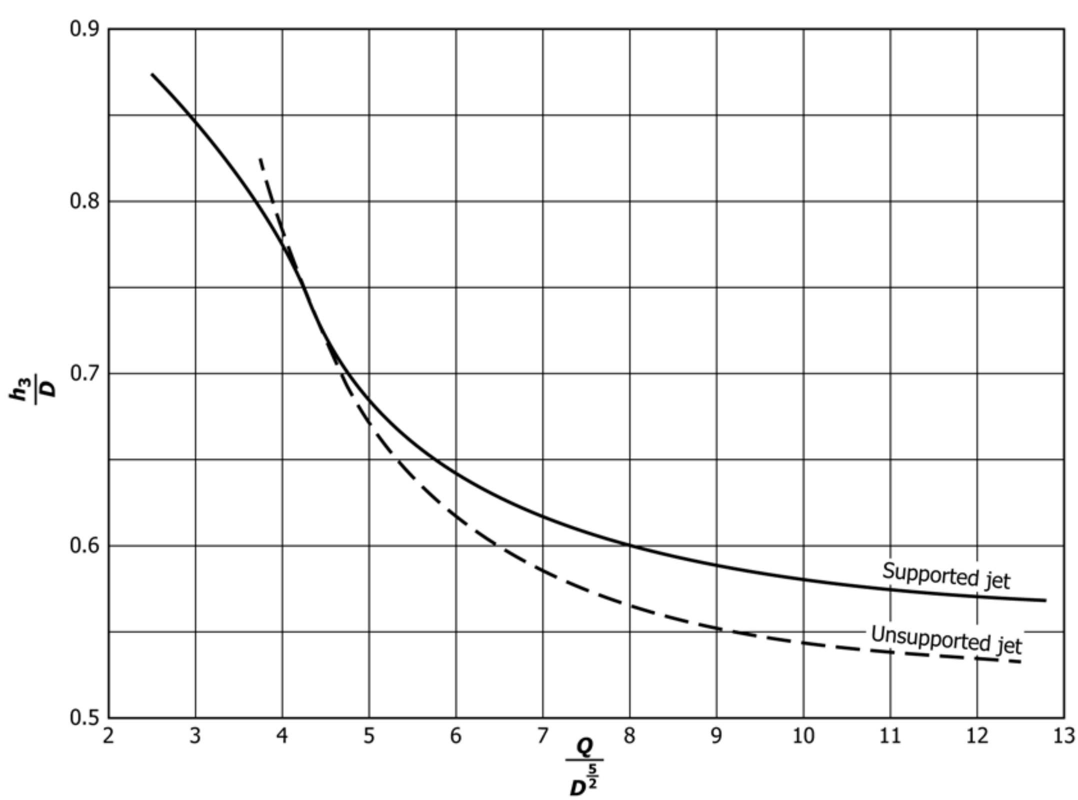


FIG. 27 Relation Between Outlet Pressure Lines and Discharge for Type 6 Flow Through Culverts of Circular Section (10)

unstable condition at ratios between 1.2 and 1.5. In this range slug flow may occur with headwater fluctuating up and down as the flow passing through the culvert varies with the degree of aeration in the culvert. If culvert geometry is such that Type 6 flow should occur, the unstable condition may extend to a ratio greater than 1.5. Bodhaine's solution for this problem is reasonable and is therefore made a part of this test method.

18.10.2 The procedure for transition from Type 1 to Type 5 is as follows:

18.10.2.1 Compute the discharge as Type 1 flow at an $h_1 - z/D$ ratio of 1.2.

18.10.2.2 Compute the discharge as Type 5 flow at a ratio of 1.5.

18.10.2.3 For ratios between 1.2 and 1.5 determine Q from a straight line interpolation between the two computed discharges.

18.10.3 The procedure for transition from Type 2 to Type 6 is as follows:

18.10.3.1 Compute discharge Type 2 at $h_1 - z/D$ ratio of 1.25.

18.10.3.2 Compute discharge as Type 6 at a ratio of 1.75.

18.10.3.3 For ratios between 1.25 and 1.75 determine Q from a straight line interpolation between the two computed discharges.

19. Precision and Bias

19.1 Except as otherwise explained, this test method and equations presented here are precise, but this does not ensure that bias is equitable to this precision. The bias with which a discharge can be computed for a given set of conditions may be a function of many variables, including but not limited to the measurement of water surface elevations and culvert geometry, the amount of drop in water surface through the culvert (Δh), type of flow, ratio of headwater height ($h_1 - z$) to height of culvert (D), amount of contraction from approach into culvert, a user's ability to assign n values for the approach section and non-standard culverts, and the degree of match between the field installation and the standard conditions for which coefficients have been developed.

19.2 For inlet control and relatively small approach velocity and friction, and for completely submerged flow (Type 4) it is relatively easy to do an error analysis. For outlet control and Type 3 flow, the effect of any one variable is strongly related to the relative magnitude of Δh, $\frac{\alpha V_1^2}{2g}$ and h_f. It is impossible to do a finite analysis of errors without making a sensitivity study for the individual culvert. However, the error analysis for inlet control can be used as an indication of errors in other types of flow.

19.3 *Water Surface Elevations:*

19.3.1 The water surface elevations used in the computations are determined from high water marks located in the field. The elevations of selected marks should be measured precisely to the nearest 0.01 ft (2 mm), but accuracy depends on how well the person in the field selects marks, and how well these marks represent the average water surface elevations in the channel upstream and downstream from the culvert.

19.3.2 In selecting marks, there is more tendency to select marks that are too low than to select marks that are too high, because water may not remain at the maximum elevation long enough for it to leave good marks, and false marks may be left as stage recedes. An experienced person exercising reasonable care should be able to select marks that are within 0.1 or 0.2 ft (30 or 50 mm) of the true elevation.

19.3.3 Water surface elevations may vary considerably with position of the mark relative to the flow lines of the stream as described in 13.3. Careful selection of marks that represent the effective water surface is essential. Errors from improper location of marks will be very small in ponded flow where the stream is parallel to the culvert, but can become very significant if stream approaches the culvert on a curve or at high velocity. Errors can be significant if water surface elevation is determined from a gauge reading at a single point.

19.3.3.1 *Upstream Elevation*—For inlet control and ponded conditions, it can be shown that discharge is a function of head to the "$^3\!/_2$" power. The ratio of the computed discharge to the discharge for the true water surface is equal to $\left(\frac{measured\ head}{true\ head}\right)^{3/2}$. Therefore, a 4 % error in the measured head causes a 6 % error in discharge. For Type 4 flow, discharge is a function of $\Delta h^{1/2}$; therefore, the ratio of computed discharge to the discharge for the correct elevation is equal to $\left(\frac{measured\ \Delta h}{true\ \Delta h}\right)^{1/2}$. In Type 3 flow, the error becomes a function of the relative magnitude of fall in relation to velocity head and friction loss.

19.3.3.2 *Downstream Water Surface*—In critical flow (Types 1 and 2), and high head flow (Types 5 and 6) the downstream elevation is used only in determining the type of flow. As long as the elevation accurately indicates the type of flow, errors have no impact on the computed discharge.

19.3.3.3 In computations of discharge under backwater (Types 3 and 4), the downstream elevation enters directly into the computation of effective fall. The impact of an error in h_4 Type 4 flow is the same as that of a similar error in the upstream elevation. In Type 3 flow, an error in tailwater elevation produces a corresponding error in A_3. An error in tailwater elevation produces too much fall and too little area, or vice versa, and the net effect is much smaller than the error in the measurement of h_4. The true error must be determined by a sensitivity analysis in which only h_4 is varied.

19.4 *Manning's Roughness Coefficient:*

19.4.1 Friction loss in the culvert $h_{f_{2-3}}$ is a function of $n_o{}^2$, and the loss in the approach ($h_{f_{1-2}}$) is a function of the product of $n_i\, n_o$ where n_i is the roughness coefficient for the approach section and n_o is roughness coefficient in the culvert. The value of n_o is quite well fixed by the type of culvert material. Because $h_{f_{1-2}}$ is generally small in relation to the other parts of the energy equation, fairly large errors in n_1 cause only minor error in computed discharge. The $h_{f_{2-3}}$ term does not enter into the Types 1 and 5 equations. As long as n_o is close enough to indicate the proper flow type, errors in n_o have no effect on the computed discharge for this type of flow.

19.4.2 Equations for Types 2, 3, 4 and 6 flow include $h_{f_{2-3}}$ or n_o. Errors in n_o usually have a very minor effect on the computed discharge except in long rough culverts and where $h_{f_{2-3}}$ is large in relation to Δh. Under conditions normally encountered, errors in n_o will generally cause an error of less than 2 % in discharge. Maximum error for the worst conditions will generally be less than 8 %.

19.5 *Approach and Culvert Geometry:*

19.5.1 It is assumed that the approach and culvert geometry can be and are measured quite accurately and therefore errors in the items are not considered. Any error that occurs in these are random human errors and are not systematic.

19.5.2 Coefficients and methods are well defined for most entrance types on pipes, pipe arches, and for box culverts of moderate width. Unknown uncertainties may be introduced by non-standard culvert shapes and certain approach problems and conditions. Approach problems are most prevalent at low discharges, and may include those that result from steep gradients, narrow sections, poor distribution of flow among barrels of multiple-barrel culverts, and control sections between the culvert and the approach. Non-standard culvert geometries include, but are not limited to, natural bottoms, wide multi-barreled skewed culverts, and culverts with arch tops (other than shapes designated as pipe arch). The arch may sit on the streambed, a concrete floor, or on vertical walls. Procedures given in this test method can be adopted to compute flow in these culverts, but the discharge coefficients are uncertain.

19.6 *Classification of Flow Types:*

19.6.1 The procedure given in this test method assumes that criteria for classifying flow are absolute. This is true of Types 1 through 4 flow throughout most of the range over which these computations are used. However, at the points where flow types change, different flow types may produce different discharges. For changes between certain pairs of flow types it is necessary to compute the flow for each type.

19.6.2 The impact of various changes are as follows:

19.6.2.1 *Between Types 1 and 2*—At the change-over point, discharge by either flow type will be the same and type of flow used does not matter.

19.6.2.2 *Between Types 1 or 2, and Type 3*—Under some conditions, a Type 3 computation will indicate more discharge than a Type 1 or 2 computation. The discharge computed by Type 1 or 2 flow is the maximum and should be used. A Type 3 computation may produce a discharge that is up to 5 % too large.

19.6.2.3 *Between Types 3 and 4*—In a Type 3 computation for a pipe or arch culvert, the wetted perimeter of the culvert gradually approaches that of a full culvert and results are essentially the same for either Type 3 or Type 4 flow. In the computations for a box culvert, the Type 3 computation assumes that the ceiling of the culvert is not wetted. A Type 4 computation assumes that the ceiling is wetted. As a result, friction losses are greater on Type 4 than Type 3 and at the change-over a Type 4 computation will give a few percent less water. The difference is usually small, unless the culvert is long and rough or is quite wide. This difference is eliminated by using the procedure described in 18.6.4.

19.6.2.4 *Between Types 5 and 6*—The uncertainties in classification of high head flow are given in 12.5 and 18.8.1. The difference in discharges from the two computations is a function of z, $h_{f_{2-3}}$, and the discharge coefficient. This difference can be quite large, and can be determined only by making a computation for each type of flow. Computer programs can easily be designed to produce a rating for each type of flow. The percentage difference can be computed for any given headwater elevation.

19.6.2.5 *Between Low Head (Types 1 or 2) and High Head (Types 5 or 6)*—The uncertainties at the change between low and high head flow are discussed in 18.10, which describes a method for computing flow through the transition. This test method minimizes the error.

19.7 *Discharge Coefficients—*The discharge coefficients used herein were derived by Carter **(10)** and are based on his laboratory studies and those by several previous researchers. Carter did not present his experimental data or standard errors for these data. A measure of the accuracy of coefficients was obtained by comparing results obtained by using these coefficients with those from independent research by French **(2)**, who presented all of his experimental results. For most types of entrances and headwater/diameter ratios, discharges computed using the Carter **(10)** coefficients differ from the experimental results obtained by French **(2)** by less than 3 %. Of the computations for pipes, only those for headwater/diameter ratios less than 0.5 or greater than 6 differed by more than 6 %. For the very low heads, the Carter **(10)** coefficients for pipes with a vertical entrance face could have a slight bias (less than 10 %) toward the low side. However, other researchers also differ from French in the like direction and magnitude.

19.8 Numerous field verification measurements have been made under Type 1, 2, or 3 flow and good approach conditions. Discharges from these measurements generally differ by less than 5 % from those computed with the coefficients given here, thus indicating that coefficients are reliable. Few verification measurements are available for Types 4 through 6 flow.

19.8.1 *Effect of Headwater/Diameter Ratio*—Nearly all research on culvert flow has been done at headwater diameter ratios between 0.4 and 5.0. Coefficients have been well determined in this range, but are extrapolations outside these ranges. Little field verification is available in the extrapolated ranges.

19.8.2 *Prototype Model Scales—*The error produced by scale differences is not readily computable, but scale does not seem to be a problem. Much of the research on culvert flow has been done with field size culverts up to 36 in. (0.91 mm) in diameter. Results from the full-size pipes agree with tests on small models. Also, the field verifications referred to above indicate that scale-ratio is not a problem.

19.8.3 *Degree of Contraction*—Coefficients were developed for a contraction ratio of 0.80. A small unknown uncertainty may be introduced for lesser degrees of contraction, especially if m is less than 0.50. For very low degrees of contraction, the control may move to the approach section and methods described in this practice become invalid.

19.9 In accordance with 1.6 of Practice D2777, an exemption to the precision and bias statement required by Practice D2777 was recommended by the results advisor and concurred with the Technical Operations Section of the Executive Subcommittee on June 24, 1992.

20. Keywords

20.1 floods; open-channel flow water discharge

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