Designation: D 5243 – 92 (Reapproved 1996)

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

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 gage 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:*

D 1129 Terminology Relating to Water [2]

D 2777 Practice for Determination of Precision and Bias of Applicable Methods of Committee D-19 on Water [2]

D 3858 Practice for Open-Channel Flow Measurement of Water by Velocity-Area Method [2]

2.2 *ISO Standards:*

ISO 748 Liquid Flow Measurements in Open Channels-Velocity-Area Methods [3]

ISO 1070 Liquid Flow Measurements in Open Channels-Slope-Area Methods [3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology D 1129.

3.2 *Definitions of Terms Specific to This Standard*—Several of the following terms are illustrated in Fig. 1:

3.2.1 *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.

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

3.2.2.1 *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).

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

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

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

3.2.3.3 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.

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

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

3.2.5.1 *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).

3.2.6 *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.

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[1] This test method is under the jurisdiction of ASTM Committee D-19 on Waterand is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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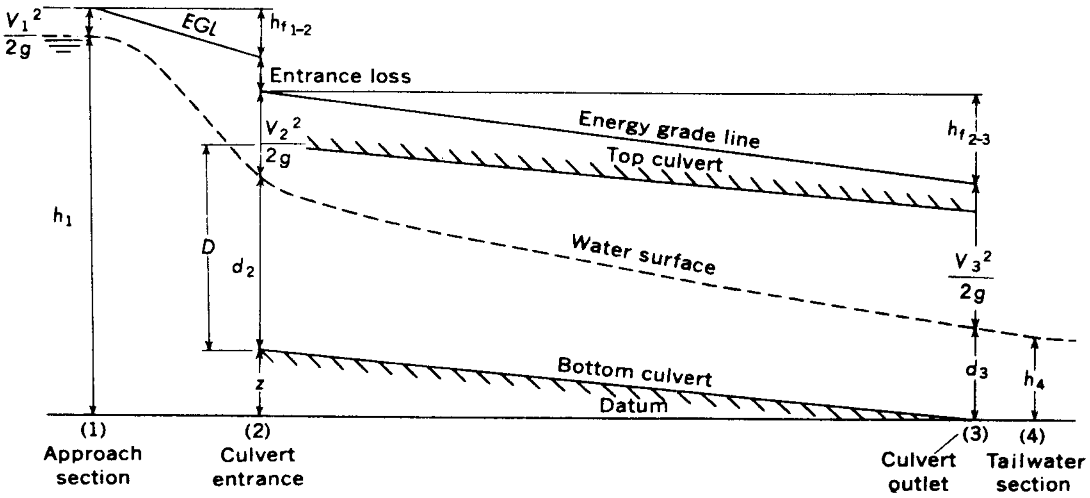
[2] *Annual Book of ASTM Standards*, Vol 11.01.

[3] Available from American National Standards Institute, 11 W. 42 nd Street, 13 th Floor, New York, NY 10036.



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

3.2.6.1 *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}).

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

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

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

3.2.10 *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).

3.2.11 *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 D 3858.

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 D 1129 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.

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:

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

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

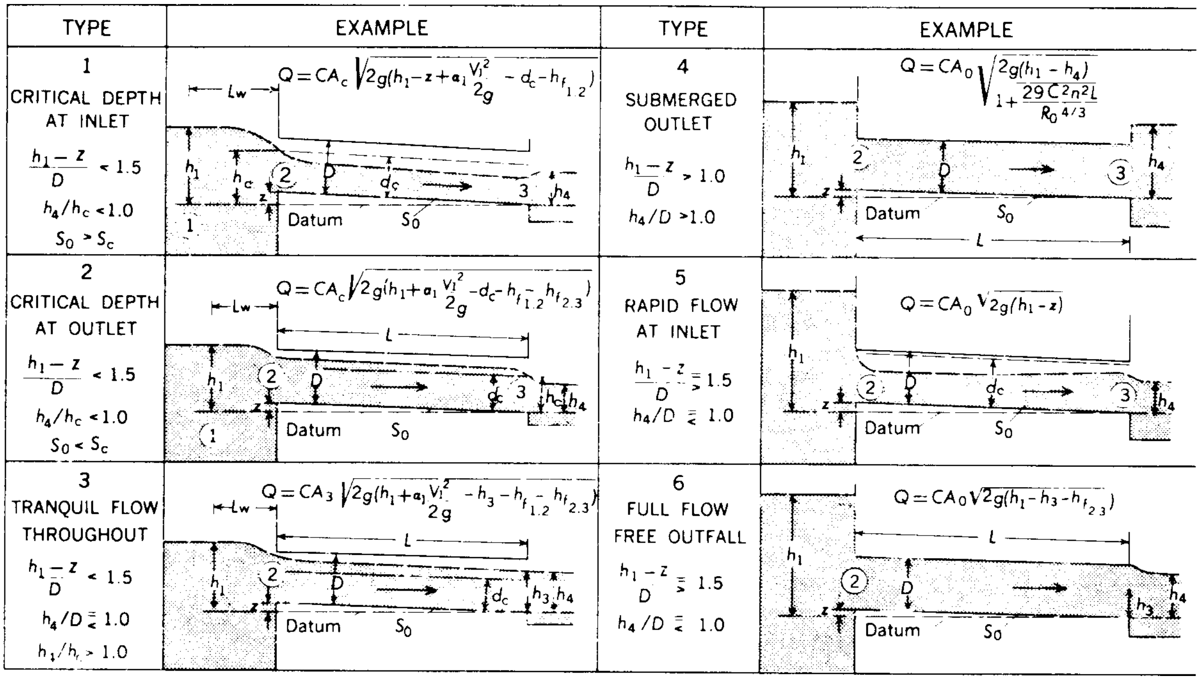


FIG. 2 Classification of Culvert Flow

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	$\leq$1.0
2	do	Outlet	do	Mild	<1.5	<1.0	$\leq$1.0
3	do	do	Backwater	do	<1.5	>1.0	$\leq$1.0
4	Full	do	do	Any	>1.0	. . .	>1.0
5	Partly full	Inlet	Entrance geometry	do	$\geq$1.5	. . .	$\leq$1.0
6	Full	Outlet	Entrance and barrel geometry	do	$\geq$1.5	. . .	$\leq$1.0

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:

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

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

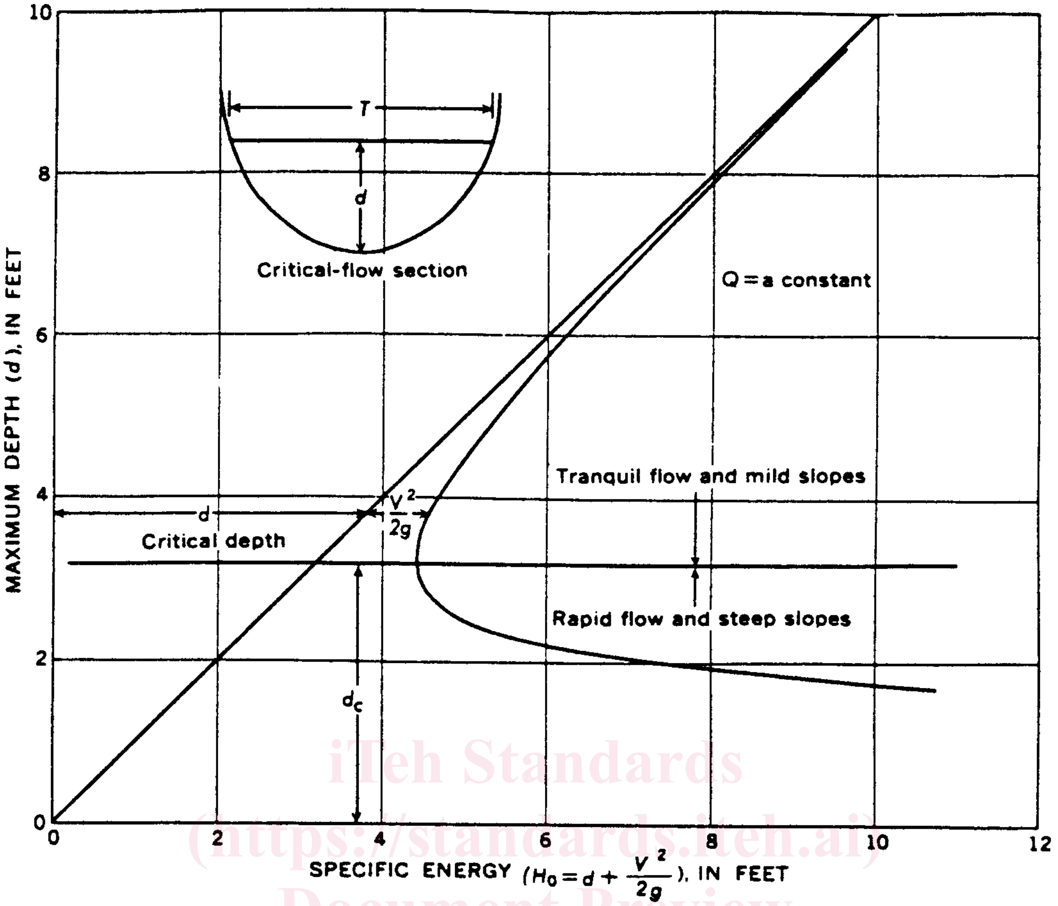


FIG. 3 Relation Between Specific Energy and Depth

minimum specific energy and critical depth, the discharge equation for a section of any shape can be written as follows:

$$Q = A_c^{\,3/2}\sqrt{\frac{g}{T}} \tag{1}$$

or:

$$Q = A_c\sqrt{g d_m} \tag{2}$$

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

$$Q = 5.67 b d_c^{\,3/2} \tag{3}$$

and for circular sections:

$$Q = C_q D^{5/2} \tag{4}$$

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:

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

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:

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

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:

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

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:

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

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:

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

or in terms of Q the equation becomes:

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

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:

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

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:

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

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 gage 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 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

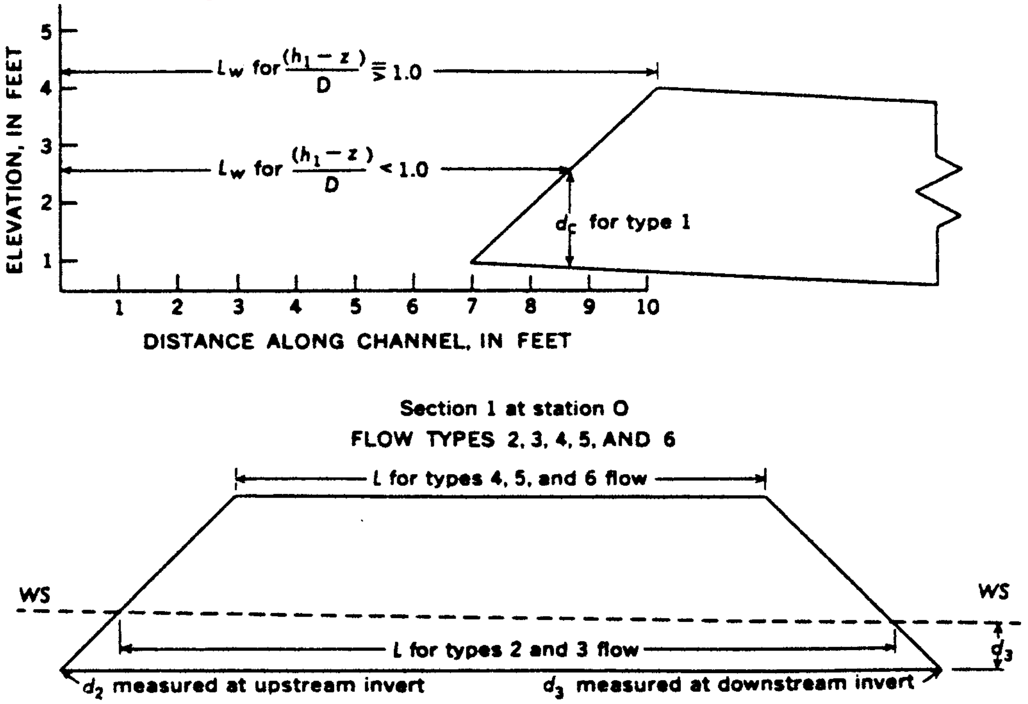
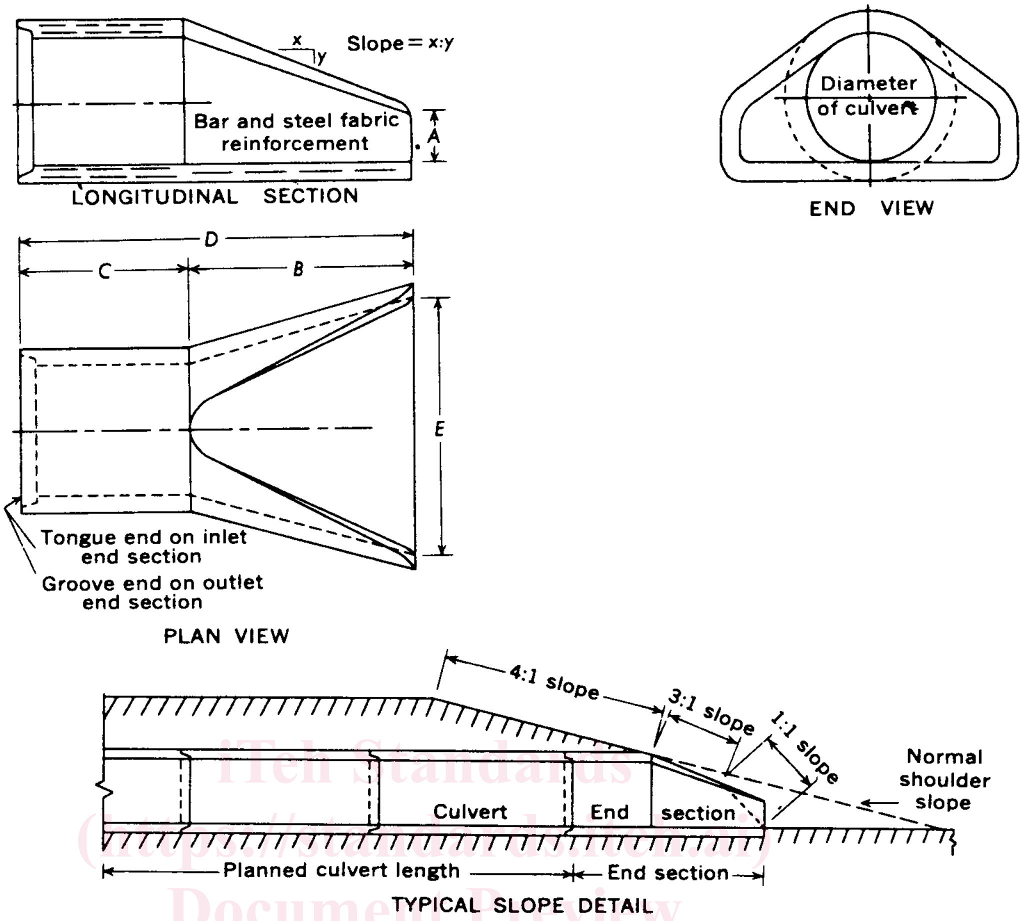


FIG. 4 Approach and Culvert Lengths for Mitered Pipe



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	7 3/4	6	1 3/4	5	0
36	1	3	5	3	2	10 3/4	8	1 3/4	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	9 1/4	8	2 1/4	7	6

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

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

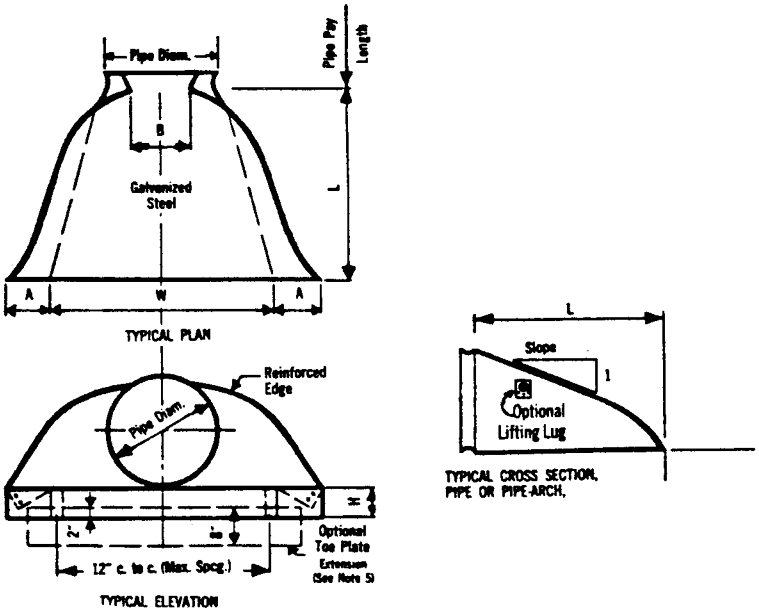
FIG. 5 Dimensions of Flared End Sections for Reinforced Concrete Pipe

position as during the peak, measure the obstructed area and deduct it from the total area.

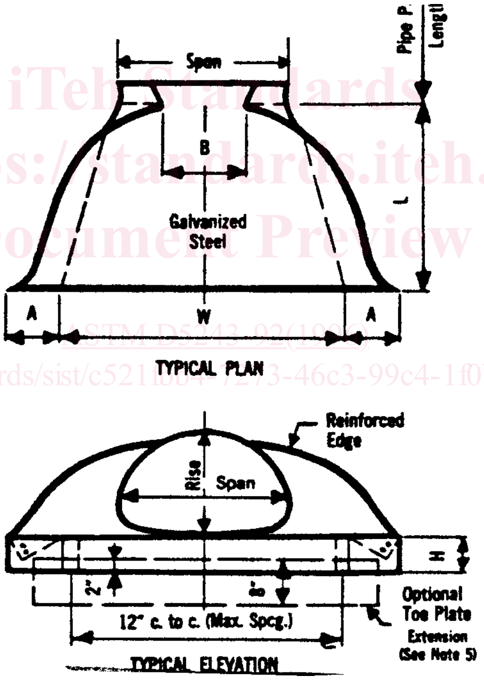
14.2.1 *Deposits in Culvert*—Sand and gravel found within a culvert barrel are often deposited after the extreme velocities of peak flow have passed; where this occurs, use the full area of the culvert. Careful judgment must be exercised because, in many places, levels before and after a peak show virtually 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 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



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

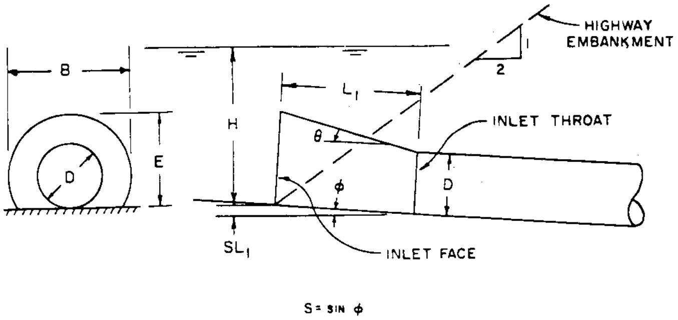
been lengthened during road reconstruction. In rare cases the size, shape, or material, or all three, of the culvert sections may differ. Measure the length of each section and determine the invert elevation at each change.

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.

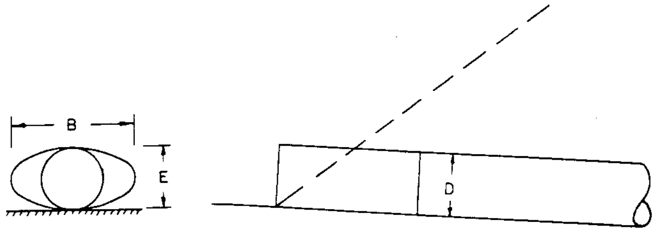
15. Roughness Coefficients

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



a) CIRCULAR SEGMENT FACE SHAPE



b) OVAL FACE SHAPE

FIG. 7 Details of Typical Tapered Entrances

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 ½in. (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

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.					
	2 2/3 by 1/2	3 by 1	5 by 1	6 by 1	6 by 2	9 by 2 1/2
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.

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

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

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 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

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