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of the United States Geological Survey

Chapter A3

MEASUREMENT OF PEAK DISCHARGE AT CULVERTS BY INDIRECT METHODS

By G. L. Bodhaine

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SYMBOLS AND UNITS

Symbol	Definition	Unit
A	Area.	ft^2
A_0	Area of culvert barrel.	ft^2
A_c	Area of section of flow at critical depth.	ft^2
b	Width of contracted flow section for box culvert.	ft
C	Coefficient of discharge; also, coefficient for computing various culvert properties; subscripts refer to specific items, as a for area, k for conveyance, m for mean depth, p for wetted perimeter, q for discharge, r for hydraulic radius, and t for top width.	
D	Maximum inside vertical dimension of culvert barrel, or the inside diameter of a circular section. (For corrugated pipes, D is measured as the minimum inside diameter.)	ft
D_m	Maximum inside diameter of pipe culvert at entrance.	ft
d	Depth of flow measured from the lowest point in the cross section for culverts.	ft
d_c	Maximum depth in critical-flow section.	ft
d_m	Mean depth.	ft
$\mathbf{F}$	Froude number.	
g	Gravitational constant (acceleration).	ft/sec^2
H_0	Specific energy.	ft
h	Static or piezometric head above an arbitrary datum.	ft
h_c	d_c+z for type 1 culvert flow.	ft
h_e	Head loss due to entrance contraction.	ft
h_f	Head loss due to friction.	ft
h_v	Velocity head at a section.	ft
K	Conveyance of a section.	ft^3/sec
K_c	Conveyance of critical depth section.	ft^3/sec
K_0	Conveyance of full culvert barrel.	ft^3/sec
k	Adjustment factor; subscripts refer to specific items, as a for skewed abutments with dikes, L for length, r and R for radius, w for length of wingwalls, and θ for wingwall angle.	
L	Length of culvert barrel, bridge abutment, or broad-crested weir in direction of flow.	ft
L_p	Distance a culvert barrel projects beyond a headwall or embankment.	ft
L_w	Distance from approach section to entrance of culvert, upstream side of contraction, or crest of weir.	ft
m	Channel-contraction ratio.	
n	Manning roughness of coefficient.	$ft^{1/6}$
n_c	Composite value of roughness coefficient.	$ft^{1/6}$
P	Wetted perimeter of cross section of flow.	ft
P_p	Wetted perimeter of the paved invert of a culvert.	ft
Q	Total discharge.	ft^3/sec
R	Hydraulic radius.	ft
R_0	Hydraulic radius of a culvert barrel.	ft
r	Radius of entrance rounding.	ft
S	Friction slope.	
S_c	Bed slope of culvert for which the normal depth and the critical depth are equal.	
S_0	Bed slope of culvert barrel.	
T	Width of a section at the water surface.	ft
V	Mean velocity of flow in a section.	ft/sec
V_0	Full culvert velocity.	ft/sec
w	Measure of the length of a wingwall or chamfer.	ft
x	Length of part-full flow.	ft
z	Elevation of a point above a datum.	ft
1,2	Subscripts which denote the location of cross sections or section properties in downstream order.	
α	Velocity-head coefficient.	
θ	Acute angle between a wingwall and plane of contraction or headwall; and the bevel angle.	
$<$	Less than.	
$\leqq$	Equal to or less than.	
$>$	Greater than.	
$\geqq$	Equal to or greater than.	

MEASUREMENT OF PEAK DISCHARGE AT CULVERTS BY INDIRECT METHODS

By G. L. Bodhaine

Abstract

This chapter classifies culvert flow into six types, gives discharge equations based on continuity and energy equations, and describes procedures for measuring peak discharges using culverts in the field. Discharge coefficients for a variety of geometries and flow types are given. Ten examples detail step-by-step computation procedures.

Introduction

The peak discharge through culverts can be determined from high-water marks that define the headwater and tailwater elevations. This indirect method is used extensively to measure flood discharges from small drainage areas.

The head-discharge characteristics of culverts have been studied in laboratory investigations by the U.S. Geological Survey, the Bureau of Public Roads, and many universities. The procedures given in this report are based on the information obtained in these studies and in field studies of the flow through culverts at sites where the discharge was known.

Description of Culvert Flow

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 rather than 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 tranquil, critical, or rapid if the culvert is partly filled, or the culvert may flow full under pressure.

The physical features associated with culvert flow are illustrated in figure 1. They are the approach channel cross section at a distance equivalent to one opening width upstream from

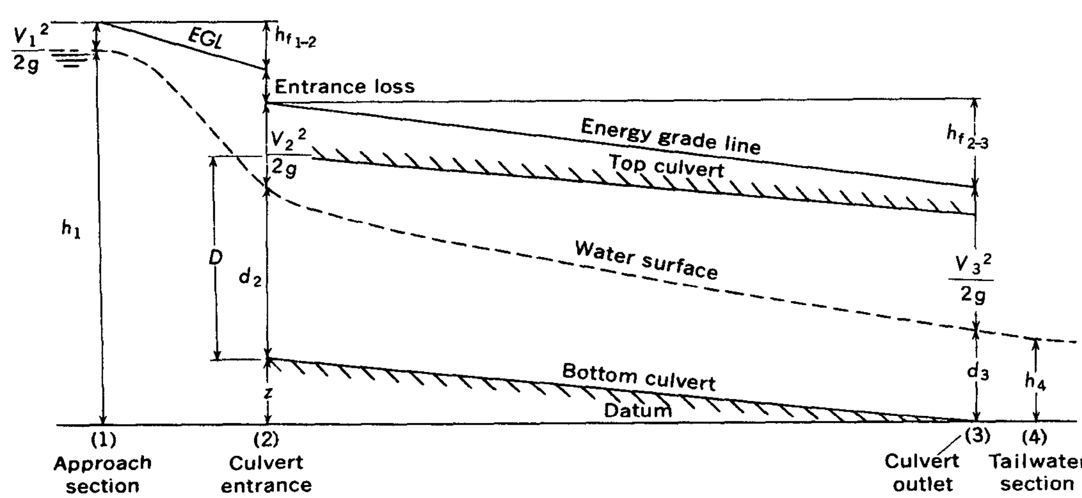

Figure 1.—Definition sketch of culvert flow. Note.—The loss of energy near the entrance is related to the sudden contraction and subsequent expansion of the live stream within the culvert barrel.

the entrance; the culvert entrance; the culvert barrel; the culvert outlet, the farthest downstream section of the barrel; and the tailwater representing the getaway channel.

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 flat slopes. The important features that control the stage-discharge relationship 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.

The peak discharge through a culvert is determined by application of the continuity equation and the energy equation between the approach section and a section within the culvert barrel. The location of the downstream section depends on the state of flow in the culvert barrel. For example, if critical flow occurs at the culvert entrance, the headwater elevation is not a function of either the barrel friction loss or the tailwater elevation, and the terminal section is located at the upstream end of the culvert.

Information obtained in the field survey includes the peak elevation of the water surface upstream and downstream from the culvert and the geometry of the culvert and approach channel. Reliable high-water marks can rarely be found in the culvert barrel; therefore, the type of flow that occurred during the peak flow cannot always be determined directly from field data, and classification becomes a trial-and-error procedure.

General classification of flow

For convenience in computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations. The six types of flow are illustrated in figure 2, and pertinent characteristics of each type are given in table 1. From this information

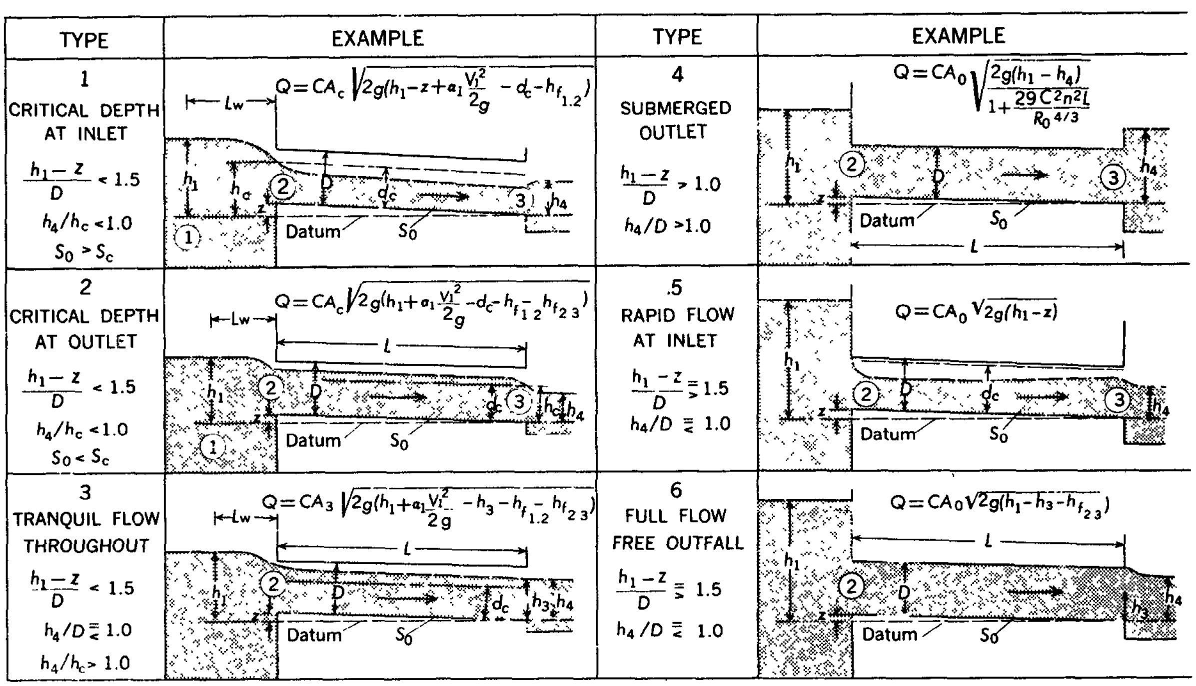

Figure 2.—Classification of culvert flow.

the following general classification of types of flow can be made:

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.
2. If h_4/D is greater than 1.0, only type 4 flow is possible.
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.

Further identification of the type of flow requires a trial-and-error procedure which is described in a subsequent section of this chapter.

Discharge Equations

Discharge equations have been developed for each type of flow by application of the continuity and energy equations between the approach section and the terminal section. The discharge may be computed directly from these equations after the type of flow has been identified. Discharge equations for critical depth at a section are used to identify flow types 1 and 2; thus, these equations are also included in the following sections.

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, and the tailwater elevation. To obtain flow at critical depth, the headwater elevation above the upstream invert must be less than 1.5 times the diameter or height of the culvert. Type 1 flow will occur if the tailwater elevation is lower than the water-surface elevation at critical depth, and if the bed slope of the culvert is greater than the critical slope. Type 2 flow will occur if the bed slope is less than the critical slope.

Critical depth, d_c, is the depth at the point of minimum specific energy for a given discharge and cross section. The relation between specific energy and depth is illustrated in figure 3. The specific energy, H_0, is the height of the energy grade line above the lowest point in the cross section. Thus,

$$H_0=d+\frac{V^2}{2g},$$

where

H_0=specific energy,
d=maximum depth in the section,
V=mean velocity in the section, and
g=acceleration of gravity.

It can be shown that at the point of minimum specific energy and critical depth, d_c,

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

and

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

where

Q=discharge,
A=area of cross section below the water surface,
T=width of the section at the water surface,
d_c=maximum depth of water in the critical-flow section, and
d_m=mean depth in section=A/T.

Table 1.—Characteristics of flow types

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

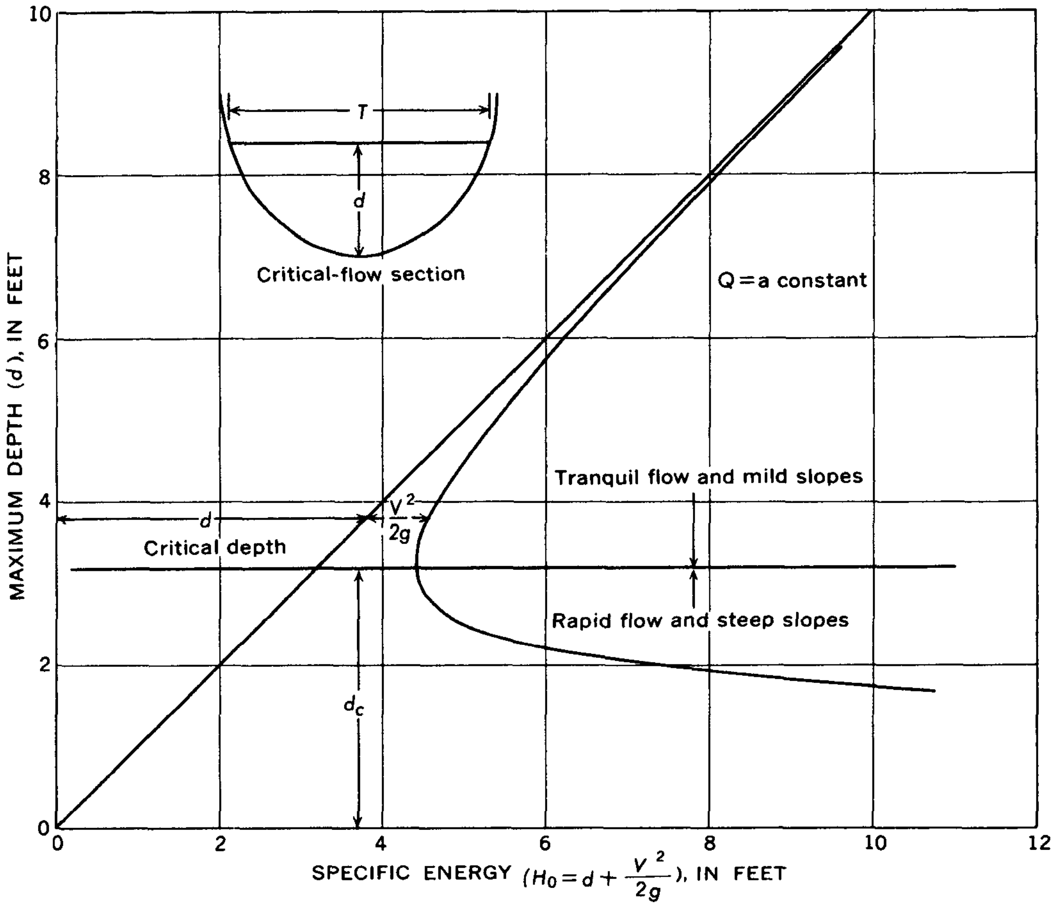

Figure 3.—Relation between specific energy and depth.

For the condition of minimum specific energy and critical depth, the discharge equation for a section of any shape can be written

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

or

$$Q=A_c\sqrt{gd_m}. \qquad (2)$$

The discharge equation can be simplified according to the shape of the sections. Thus, for rectangular sections,

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

and for circular sections,

$$Q=C_qD^{5/2}, \qquad (4)$$

where

b=width of section,
C_q=function of d_c/D,
d_c=maximum depth of water in the critical-flow section, and
D=inside diameter of circular section.

The two types of flow in this classification are 1 and 2.

Type 1 flow

In type 1 flow, as illustrated on figure 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_0, 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_2.

The discharge equation is

$$Q=CA_c\sqrt{2g\left(h_1-z+\frac{\alpha_1V_1^2}{2g}-d_c-h_{f_{1\text{-}2}}\right)}, \qquad (5)$$

where

C=the discharge coefficient,
A_c=the flow area at the control section,
V_1=the mean velocity in the approach section,
α_1=the velocity-head coefficient at the approach section, and
$h_{f_{1-2}}$=the head loss due to friction between the approach section and the inlet $=L_w(Q^2/K_1K_c)$, and
K=conveyance$=(1.486/n)R^{2/3}A$. (6)

Other notation is evident from figure 1 or it has been previously explained. The discharge coefficient, C, is discussed in detail in the section entitled "Coefficients of Discharge."

Type 2 flow

Type 2 flow, as shown on figure 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 is

$$Q=CA_c\sqrt{2g\left(h_1+\frac{\alpha_1V_1^2}{2g}-d_c-h_{f_{1-2}}-h_{f_{2-3}}\right)}, \quad (7)$$

where

$h_{f_{2-3}}$=the head loss due to friction in the culvert barrel$=L(Q^2/K_2K_3)$.

Flow with 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. If the culvert flows partly full, the headwater-diameter ratio is less than 1.5; or if it flows full, both ends of the culvert are completely submerged and the headwater-diameter ratio may be any value greater than 1.0. The two types of flow in this classification are 3 and 4.

Type 3 flow

Type 3 flow is tranquil throughout the length of the culvert, as indicated on figure 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 terminal section.

The lower limit of tailwater must be such that (1) 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 must be at an elevation higher than the elevation of critical depth at the inlet; and (2) if the culvert slope is mild enough that under free-fall conditions critical depth at the outlet would result from a given elevation of headwater, then the tailwater must be at an elevation higher than the elevation of critical depth at the outlet.

The discharge equation for this type of flow is

$$Q=CA_3\sqrt{2g\left(h_1+\frac{\alpha_1V_1^2}{2g}-h_3-h_{f_{1-2}}-h_{f_{2-3}}\right)} \quad (8)$$

Type 4 flow

In this classification the culvert is submerged by both headwater and tailwater, as is shown in figure 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 discharge may be computed directly from the energy equation between sections 1 and 4. Thus,

$$[h_1+h_{v_1}=h_4+h_{v_4}+h_{f_{1-2}}+h_e$$
$$+h_{f_{2-3}}+h_{f_{3-4}}+(h_{v_3}-h_{v_4})],$$

where

h_e=head loss due to entrance contraction.

In the derivation of the discharge formula 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,

$$h_1=h_4+h_e+h_{f_{2-3}}+h_{v_3},$$

or

$$Q=CA_0\sqrt{\frac{2g(h_1-h_4)}{1+\frac{29C^2n^2L}{R_0^{4/3}}}}. \quad (9)$$

Flow under high head

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. This is an approximate criterion. The two types of flow under this category are 5 and 6.

As shown in figure 2, part-full flow under a high head is classified as type 5. The flow pattern is similar to that downstream from a sluice gate with rapid flow near the entrance. The occurrence of type 5 flow requires a relatively square entrance that will cause contraction of the area of live flow to 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. Under these conditions, the headwater surface drops, indicating a more efficient use of the culvert barrel.

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 predicted from a knowledge of entrance geometry and length, culvert slope, and roughness of the culvert barrel.

Type 5 flow

Type 5 flow is rapid at the inlet. The headwater-diameter ratio exceeds 1.5 as shown on figure 2, 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 is

$$Q=CA_0\sqrt{2g(h_1-z)}. \qquad (10)$$

Type 6 flow

In type 6 flow the culvert is full under pressure with free outfall as shown in figure 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

$$Q=CA_0\sqrt{2g(h_1-h_3-h_{f_{2-3}})}. \qquad (11)$$

A straightforward application of equation 11 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. 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 their use is explained on page 31.

Field Data

Make a transit survey of floodmarks and accurately measure the culvert geometry as soon after the flood as possible. Use the methods of surveying previously described; read elevations of highwater marks, hubs, reference marks, and culvert features to hundredths of a foot and ground elevations to tenths. Obtain high-water profiles as well as a complete description of the culvert geometry.

Describe entrance and getaway conditions if not evident from other data. Choose roughness coefficients (values of n) for the culvert as well as for the approach section, and obtain stereophotographs documenting pertinent features. Describe any unusual conditions at the site. Appraise the possibility of entrance or barrel obstruction at the time of the peak; document evidence obtained from observers.

Determine the elevation of the low point of the crown of the road over the culvert or make note that there is a high fill. If there is a possibility that water flowed across the roadway, define a profile along the crown or high point of the road.

High-water profiles

Obtain high-water profiles which adequately define the headwater and tailwater elevations in much the same manner as those for a slope-area or contracted-opening survey described in Benson and Dalrymple (1967). If high-water marks are available within a culvert, locate and level to them for use in checking computed elevations.

Headwater

Obtain the location and elevation of flood-marks along the embankment and upstream from the culvert. For a definite approach channel, obtain marks along the banks from the culvert entrance upstream for a distance of at least two culvert diameters. Where ponded conditions exist, determine the headwater elevation from marks along the banks or upstream from the opening where there is little or no velocity. In doubtful cases of ponding, conditions approximating ponding can be assumed if high-water marks along the embankments approach a level surface away from the culvert opening.

Tailwater

Obtain tailwater elevations along the embankment or the channel close to the outlet, but not to represent the elevation of the issuing jet, which may be higher than the tailwater pool. If marks cannot be found in the immediate vicinity of the culvert, extend the profile upstream to the outlet on the basis of the existing profiles.

Approach section

An approach section usually is necessary, but if the area of the approach channel is estimated as equal to or greater than five times the area of the culvert barrel, zero approach velocity in the approach section may be assumed, and an approach section is not required. To avoid the possibility of the approach section being within the drawdown region, locate it one culvert width upstream from the culvert entrance; or where wingwalls exist, a distance upstream from the end of the wingwalls equal to the width between wingwalls at their upstream end. If the wingwalls do not cause a significant contraction, the approach section may be closer than this, but not closer than one culvert width. Take the cross section at right angles to the channel. If high-water marks cannot be found at the location specified for the approach section, take the approach section where high-water marks can be found. Drive stakes at the ends of the cross section.

One culvert width at a multiple culvert installation may be considered as the sum of the widths of the individual culverts.

Select values of *n* and points of subdivision, if any, and record them clearly in the field notes.

Culvert geometry

Obtain complete details of culvert dimensions (measured by steel tape) including projections, wingwall angles, size of fillets and chamfers, degree of entrance rounding, size and shape of opening, type of entrance, and length. Describe the material of which the culvert is made (concrete, corrugated metal, iron, or other) as well as its condition (new, fair, poor, or other). Record the value of *n* for the culvert. (See section below on roughness coefficients.)

If dimensions of corrugated pipes, riveted pipe-arches, and multiplate pipe-arches differ significantly from design dimensions, the tabulated property coefficients listed in the tables may not be directly applicable. For this reason check in the field the pertinent dimensions of every culvert used.

In referring to culvert dimensions the usual practice of highway engineers of specifying the horizontal or width dimension first generally should be followed. For example, a 12- × 10-foot culvert has a barrel 12 feet wide and 10 feet high.

Normal culverts

Where the culvert opening is normal to the axis of the culvert, measure the elevation of the invert at the opening or headwall. For corrugated pipes, measure the invert elevation at the top of the first full corrugation and for concrete pipes, at the point of minimum diameter (not down in the bell). For rectangular shapes, obtain invert elevations usually at the center and edges, except in very wide sections where they should be obtained every 2 or 3 feet across the width. Elevations may be needed at closer intervals for irregular sections. The elevation of the downstream invert is determined similarly. Always obtain the elevation of the crown at both ends of the culvert. Also determine the elevations of the ends of the culvert aprons.

Locate the positions of the culvert, wingwalls, aprons, and other features. Measure the length of the culvert and length of aprons with a tape.

Skewed culverts

A skewed culvert is one in which the headwall is not normal to the centerline of the culvert or, in the event of no headwall, the end is not cut off squarely. Pipes and pipe-arches as well as box culverts are sometimes skewed. Where this occurs, measure the wingwall angle as for a normal culvert, as the acute angle at which the wingwall and headwall join.

Measure the invert elevation for a skewed culvert on a line normal to the axis of the culvert and at the point where the full section of the culvert begins (minimum section).

Measure the approach length, L_w, to the invert line described above. Measure the length of the culvert, L, between invert lines, the shortest length of the culvert.

Mitered culverts

Many pipes and pipe-arches are mitered to be flush with the highway embankment. Determine the invert elevations at the extreme ends of the pipe. Often, the first section of a mitered pipe is laid on a different slope from the rest of the culvert; therefore, obtain also the elevation of the invert at full pipe. Determine the elevation of the crown at both ends of the full pipe section. Measure the total length of the culvert to determine the slope (z is measured at ends of the invert). Also determine the short length (the full section of the culvert) and the length of miter.

For headwater-diameter ratios less than 1.0 measure the approach length from section 1 to the point where the headwater elevation intersects the miter, figure 4. For ratios greater than 1.0, L_w is the distance from section 1 to the beginning of the full section of the culvert. For outlet control, measure the length, L, to the point where d_c or h_3 intersects the downstream miter, or for a culvert flowing full, to the end of the full section.

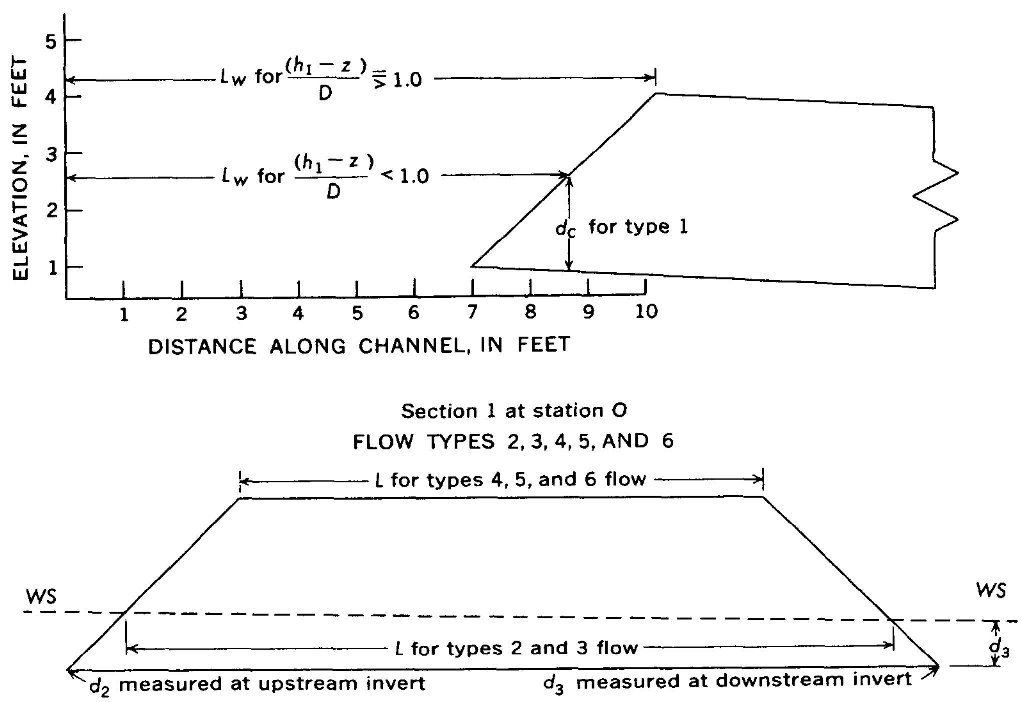

Figure 4.—Approach and culvert lengths for mitered pipe.

For type 1 flow, d_c is assumed to occur at the point where the headwater intersects the mitered entrance.

Photographs

Obtain stereophotographs showing culvert details and all pertinent conditions upstream and downstream from the culvert. These pictures are extremely important and may often avert a return trip to the site if certain data are unintentionally omitted during the field survey. Good photographs are a required part of the data necessary before computations can be completely reviewed.

General views of the relationship of the culvert to the approach channel, to crest-stage gages if they exist, and to the getaway conditions are useful. Take at least one closeup of the culvert entrance to show entrance detail. A level rod standing at the entrance furnishes a permanent record of culvert height and is a good reference for other details. Where road overflow occurs, include a view showing the entire overflow section.

Special conditions

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.

Debris

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. Sand and gravel found within a culvert barrel is 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.

Where discharge will be computed many times through a culvert that has a shifting bottom (natural bottom or deposited material), a cross section should be run after any severe flood, or at least once a year, and a record kept to evaluate the effect.

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.

Break 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 the break.

A break in slope frequently occurs where a culvert is lengthened during road reconstruction. In rare cases the size and shape of the culvert may be changed at this time.

Natural bottom

Many culverts, especially small bridge-type structures and multiplate arches, have natural stream bottoms. The irregularity of the bottom may present difficulties in applying these data to the formulas for certain types of flow. Compute slope using average bottom elevations. The determination of depth to the minimum elevation (definition of d) in the cross section or to the average elevation has no effect in flow types 1, 2, and 3 so long as h_1, d_c, and h_3 are measured at the same points. For flow types 5 and 6, use the average bottom elevation to determine h_1.

Because natural bottoms in culverts usually cause nonuniformity in cross-sectional areas, special treatment must be given when the culvert is flowing full. An example is in type 4, where the standard formula is not applicable and the routing method of computing discharge should be used.

Roughness Coefficients

Roughness coefficients for use in the Manning equation should be selected in the field for both the approach section and the culvert at the time of the field survey.

Approach section

Select roughness coefficients for the approach section as outlined in the discussion of "Field Data." 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 when the culvert apron and wingwalls extend upstream to, or through, the approach section.

Select points of subdivision of the cross section in the field and assign values of n to the various parts. For crest-stage gages 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.

Culvert

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.

Corrugated metal

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

Standard riveted section

The corrugated metal used in the manufacture of standard pipes and pipe-arches has a 2⅔-inch pitch with a rise of ½ inch. According to laboratory tests (Neill, 1962), n values for full pipe flow vary from 0.0266 for a 1-foot-diameter pipe to 0.0224 for an 8-foot-diameter pipe for the velocities normally encountered in culverts. Tests indicate that n is slightly smaller for pipes flowing part full than for full pipe flow. The following are the results of tests by Neill (1962), and these values may be used:

Pipe diameter (feet)	n
1	0.027
2	.025
3–4	.024
5–7	.023
8	.022

A single value of 0.024 is considered satisfactory for both partly full and full pipe flow for most computations. This applies to all riveted pipes and pipe-arches of standard sizes.

Multiplate section

In multiplate construction the corrugations are much larger, having a 6-inch pitch with a 2-inch rise. Tests show n values to be somewhat higher than for riveted-pipe construction. Average n values from various experiments range from 0.034 for a 5-foot-diameter pipe to 0.027 for a 22-foot pipe. A straight line relationship of n values is assumed to exist for diameters between 5 and 22 feet. Use the following roughness coefficients:

Pipe diameter (feet)	n
5–6	0.034
7–8	.033
9–11	.032
12–13	.031
14–15	.030
16–18	.029
19–20	.028
21–22	.027

A corrugated pipe with corrugations half the size of those in multiplate construction, 3-inch pitch with a 1-inch rise, is being made in both standard and multiplate sections. Until actual tests are run to obtain n values, use average roughness coefficients between equal sizes of standard and multiplate sections—for example, use an n value of 0.028 for a 7-foot diameter pipe.

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 amount of paved surface area in contact with the water, or wetted perimeter. The composite value of n for standard pipes and pipe-arches may be computed by the equation,

$$n_c=\frac{0.012P_p+0.024(P-P_p)}{P}, \qquad (12)$$

where

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

For multiplate construction the value of 0.024 must be replaced with the correct value corresponding to the size of the pipe.

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:

Condition of concrete	n
Very smooth (spun pipe)	0.010
Smooth (cast or tamped pipe)	.011–0.015
Ordinary field construction	.012– .015
Badly spalled	.015– .020

At times, sections of concrete pipe become displaced either vertically or laterally, resulting in a much rougher interior surface than normal. Where 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 very much affected.

Slight bends or changes in alinement 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, as is done in slope-area measurements. Russell (1935) showed that for extremely sharp bends (90°) the head loss may vary from 0.2 to 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 feet per second and radii of 1–8 feet, and the higher value to velocities of 15–20 feet per second and radii of 40–60 feet. King (1954) stated that the losses in a 45° bend may be about ¾ as great, and for a 22½° bend about ½ as great as those of a 90° bend.

Other materials

Occasionally culverts will be constructed of some material other than concrete or corrugated metal. Manning's coefficients (King, 1954) for some of these materials are:

Material	n
Welded steel	0.012
Wood stave	.012
Cast iron	.013
Vitrified clay	.013
Riveted steel	.015

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.

Natural bottom

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.

Computation of Discharge

The first step in the computation of discharge is to determine the type of flow. Under low heads, headwater-diameter ratios less than 1.5, type 3 flow will occur if the elevation of the downstream water surface is higher than the water-surface elevation at critical depth. If the tailwater elevation is lower than the water-surface elevation at critical depth, type 1 flow will occur with the bed slope of the culvert greater than the critical slope, or type 2 flow will occur with the bed slope less than the critical slope. Type 5 or 6 flow will occur with high heads, headwater-diameter ratios greater than 1.5, depending on the steepness of the culvert and the entrance conditions.

Discharge coefficients are a vital part of each culvert computation. These are discussed in detail on pages 37–45.

Tables 2–4 have information that applies to circular sections, riveted pipe-arches, and multiplate pipe-arches. Figures 5–8 are graphs