Computation of Uniform and Nonuniform Flow in Prismatic Conduits

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The methods for hydraulic calculation and the tables of this publication involve an extension of methods devised about 1955 by Mr. Herbert G. Bossy. The procedures were first applied to a determination of headwater requirements for square and circular highway culverts operating with free-surface flow and with control at the outlet by minimum energy conditions. I am much indebted to Mr. Bossy for his review of the text and his suggestions for its arrangement.

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Paul N. Zelensky

Washington, D.C.
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CONTENTS

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LIST OF TABLES

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LIST OF SYMBOLS

A = Area of flow, square feet
A_c = Area of flow at the critical condition, square feet
B = Width or span of conduit, feet
D = Diameter, height or rise of conduit, feet
d = Depth of flow, feet
d_c = Critical depth, feet
d_n = Normal depth, feet
f = Darcy resistance factor
g = Gravitational acceleration = 32.16 ft./second/second
H = Specific head $= d + \frac{\alpha V^2}{2g}$, or total energy measured above the invert, feet
H_c = Specific head at critical flow, feet
h_f = Friction head loss, feet
K_f = Resistance computation factor for Darcy f
K_n = Resistance computation factor for Manning n
L = Length of conduit, feet
ΔL = Incremental length of one step in backwater profile computation, feet
M = Shape factor for rectangular conduits $= \frac{B}{D}$
m = Subscript indicating mean value of the factor
n = Manning resistance factor
P = Wetted perimeter, feet
Q = Discharge or rate of flow, cubic feet/second
Q_c = Discharge at the critical flow, cubic feet/second
R = Hydraulic radius, feet
S_o = Conduit invert slope, feet/foot
S_f = Resistance (friction) slope; slope of total head line, feet/foot
T = Top width of flow, feet
T_c = Top width at critical flow, feet
V = Mean velocity of flow, $\frac{Q}{A}$, feet/second
V_c = Critical velocity, feet/second
α = Kinetic energy correction factor

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I. DESCRIPTION OF THE TABLES

a. Scope

This volume of tables of hydraulic factors for conduits of uniform cross section is intended to facilitate the hydraulic computations essential to engineering design. Conduits of the types included are commonly used for conveyance of storm water flow or for more constant flow conditions as are encountered in irrigation systems or supply of water for power or consumptive uses. The needs of engineers engaged in the design of highway drainage facilities are given prime consideration.

To accomplish these purposes, tables of geometric and hydraulic factors are included for the closed conduit shapes commonly encountered in water conveyance engineering and highway construction practice. The tables provide for the different degrees of resistance to flow resulting from the different materials used for construction of circular and pipe-arch conduits, and include square, rectangular and oval conduits which are usually constructed only of concrete.

b. Table arrangement and types

A single table of geometric properties of a particular shape of conduit is possible only if all available sizes of that shape are geometrically similar. This requires that the relative area, $\frac{A}{BD}$ $\left(\text{or } \frac{A}{D^2}\right)$, wetted perimeter, $\frac{P}{D}$, hydraulic radius, $\frac{R}{D}$, and top width for flow $\frac{T}{B}$, all have the same values for all conduit sizes at each relative depth of flow, $\frac{d}{D}$.

It is known that circular and square conduits meet this test for geometric similarity. However, rectangular cross sections are not geometrically similar unless the ratio of span, B, to height, D, is constant over a range of sizes, a condition not generally met in conduits built with interior dimensions in whole feet. The tables provide a means for overcoming this problem.

Oval concrete pipes are geometrically similar by design. These conduits are sometimes described as ellipitical pipe, although the sections are composed of segments of four circular areas, and thus are not truly elliptical.

Pipe-arch cross sections of the various types of corrugated metal are not geometrically similar. However, as will be shown, a series of geometrically similar sections may be selected, each retaining the clear span and height of a commercial section, such that the actual section varies but little from the stylized series at full flow and at all depths greater than 0.4D. The tables list the geometric and hydraulic properties of two sets of geometrically similar pipe-arch sections, which suffice for design of the five pipe-arch types currently available.

The tables facilitate the rapid completion of design calculations by slide rule or mechanical calculator. In addition, the tables of hydraulic factors may be used to simplify computer operations, especially for nonuniform flow problems, by including the calculation factors of the tables in the computer memory system. This avoids the need to incorporate complex equations for calculating flow area and hydraulic radius in circular, oval, and pipe-arch conduits.

Most calculations for determining a state of flow in a conduit involve either the finding the depth for uniform flow, or the rate of loss of energy by resistance at one or at a number of particular depths of nonuniform flow. In steady, uniform flow the depth, area, and mean velocity of flow are constant, and the rate of loss of energy by resistance equals the rate of slope of the conduit. In nonuniform flow, a state of uniformity is not yet reached, and the rate of loss of energy may be either less or greater than the slope of the conduit. Associated problems, such as a determination of a required conduit size, may also be encountered.

For some conditions of flow in a conduit, it is also necessary to determine the depth of flow at minimum total energy, that is, a critical depth. For this determination, it is necessary to take into account the kinetic energy correction factor, which is needed because the velocity across the flow prism is generally nonuniform, increasing from a small value near the walls to a maximum at the greatest distance from a boundary. The use of a kinetic energy factor will be discussed in detail in a following section.

The tables of this publication are grouped by the shape of the several conduit cross sections. The six groups included are:

IV	circular
V	oval with longer axis horizontal
V	oval with longer axis vertical
VI	corrugated metal pipe-arch of 1/2 in. deep corrugations
VII	structural plate corrugated metal pipe-arches of 2 in., 1 in. and 2 1/2 in. corrugation depth and
VIII	rectangular

For each conduit shape, the first table lists the cross-sectional area of the flow prism, hydraulic radius, surface width, and mean depth, at a series of relative depths of flow at 0.01D intervals, and the discharge rate and minimum specific head for critical depth at these values.

Hydraulic engineers are familiar with tables of this type for circular cross sections.

A second table for each conduit shape includes a base value for velocity head at each relative depth, from which the actual velocity head at any discharge rate may readily be computed, and a resistance computation factor which combined the values representing area, hydraulic radius and flow velocity so that the rate of loss of energy by resistance may be calculated directly in one simple operation. A reverse of this operation is also used to determine normal depth at any discharge rate and slope of the conduit. A table of this type is especially useful for computation of surface profiles for nonuniform flow in prismatic conduits.

In addition, a supplementary table of normally available sizes of each conduit type is included for convenience in use of the main tables.

Rectangular conduits are not included in the dimensional tables, as such conduits are constructed with a great variety of ratios of span-to-height, and in a variety of sizes. A method is given for application of the resistance tables to rectangular conduits of any span-to-height ratio.

c. Kinetic energy factors

Because the velocity of flow across a conduit varies as a result of boundary shear, the total kinetic energy of the flow will not be accurately computed in a cross section normal to the conduit axis by use of the mean velocity, V, which is the rate of flow, Q, divided by the area of flow, A. Therefore, a factor greater than unity, designated the kinetic energy factor, α, is used as a multiplier of mean velocity squared to compute the actual kinetic energy of the flow. The equation is

$$\text{Velocity head } h_v = \frac{\alpha V^2}{2g},$$

where V, is mean velocity and g is the acceleration due to gravity.

The value of α is usually determined by integration of the velocity distribution equation applicable to flow in a given conduit. Accordingly, α increases with roughness of the boundary. The kinetic energy factor varies within narrow limits for conduits of a given material over a range of sizes and depths of flow.

For most design purposes, α may be considered constant for a particular material forming the conduit. On the basis of a broad field of data, α in the following tables has been assigned a value of 1.04 for all relatively smooth conduits such as those of concrete, clay, or fully lined corrugated metal. The limited data available indicate that a value of 1.12 is fairly representative of the velocity distribution conditions in corrugated metal conduits of all types, including 1/2 in. and 2 1/2 in. deep corrugations. To broaden the application of the tables to other similar problems, values of discharge or velocity head are also included for $\alpha = 1.00$.

Deviations of total energy due to small variations from the kinetic energy values of 1.04 and 1.12 used in the tables will not be of significance in design calculations. However, the two values should not be used interchangeably between smooth and corrugated conduits.

Rates of loss of energy by resistance are computed by use of *resistance factors*, such as the Darcy "f" or the Manning "n," used in connection with the flow velocity and hydraulic radius. Because both f and n are determined experimentally through use of the mean velocity of flow, the kinetic energy correction factor α is not used in calculations involving resistance effects.

d. Non-dimensional methods

Hydraulic engineers are familiar with the basic methods for application of non-dimensional units

for computation of uniform flow and for determination of the critical discharge. Tables in many textbooks and handbooks cover various open channels of constant cross section, but usually are limited to circular closed conduits.

The tables for circular sections flowing partly full list the flow area in the form of $\frac{A}{D^2}$, the hydraulic radius as $\frac{R}{D}$, and the surface width of flow, $\frac{T}{D}$, at intervals of relative depth, $\frac{d}{D}$. The discharge ratio, Q_c, when the flow is critical, is usually included for each $0.01D$ in the form $\frac{Q}{D^{2.5}}$. The usual tables for $\frac{Q_c}{D^{2.5}}$ are based upon a kinetic energy factor, α, of unity, and therefore are not directly applicable to critical flow at a conduit outlet.

The advantages in use of these tables are obvious where design applications involve use of a large number of conduit diameters. This publication adds similar tables for the non-circular sections now in general use in highway construction, such as oval concrete pipe and corrugated metal pipe-arches. The area and the critical flow factor are stated in a more general form, such as $\frac{Q}{BD^{1.5}}$, to apply to the non-circular sections. Here, B is the maximum horizontal clear span and D is the maximum height of the cross section.

Hydraulic handbooks usually include tables of discharge rates for flow at normal depth, that is, uniform flow with the water surface and the total head line parallel to the conduit invert. Such tables present some difficulties in their use, because indirect methods are required. The tables included here permit direct determination of normal depth, and in addition provide velocity head and specific head $\left(H=d+\frac{\alpha V^2}{2g}\right)$ at any depth of flow.

A general application of non-dimensional methods to most hydraulic computations is secured by using, for the various types of problems, only one universal discharge factor $\frac{Q}{BD^{1.5}}$, which relates at any depth of flow to the gross dimensions of the conduit. As noted previously, $\frac{Q}{BD^{1.5}}$ is also applicable to critical flow.

In non-dimensional terms, that is, ft. divided by ft., the specific head equation becomes $\frac{H}{D}=\frac{d}{D}+\frac{\alpha V^2}{2gD}$, where H is the specific head or total energy measured above the low point (invert) of a conduit cross section at a particular location. Because the rate of loss of energy by resistance to flow is a function of V^2, similar to velocity head, a general computation system will be aided by expressing velocity head in terms of the discharge function $\frac{Q}{BD^{1.5}}$, and geometric values derived from the conduit shape and the relative depth of flow, $\frac{d}{D}$.

The velocity head as given above is readily converted by substituting $\frac{Q}{A}$ for V and expressing A as $BD\left[\frac{A}{BD}\right]$.

$$\frac{\alpha V^2}{2gD}=\frac{\alpha Q^2}{2gA^2D}=\frac{\alpha Q^2}{2g(BD)^2\left(\frac{A}{BD}\right)^2 D}$$

or

$$\frac{\alpha V^2}{2gD}=\left[\frac{\alpha}{2g\left(\frac{A}{BD}\right)^2}\right]\cdot\left(\frac{Q}{BD^{1.5}}\right)^2$$

The above expression for velocity head retains its non-dimensional feature. The general discharge term $\frac{Q}{BD^{1.5}}$, while not non-dimensional alone, will retain this quality if the gravitational constant g, as shown in the term in brackets, is used in an equation as a numerical value (as specified in the tables). The following sections demonstrate that the discharge term, $\frac{Q}{BD^{1.5}}$, may also be used for computation of resistance losses and minimum energy flow.

II. MINIMUM ENERGY COMPUTATIONS

Computations of depth of flow in closed conduits frequently involve the identification of a cross section of flow at minimum energy and the determination of the depth of flow and specific head at that section.

The case usually considered in textbooks is that for critical depth at a change of conduit slope from mild to steep. Another situation, more commonly encountered in conduit design by the hydraulic engineer, is that of a drop or lateral expansion of the flow, as will for example, occur at the outlet of a conduit into a larger channel, provided critical depth within the conduit is not submerged by the outlet channel flow. A section of flow at minimum energy will occur at the conduit outlet, either with or without a drop of the invert at the plane of the outlet.

It may well be questioned whether the true critical depth occurs at the outlet section in such a case. However, there can be no doubt that a control section of minimum energy of flow will occur here. An assumption of critical depth at the outlet has been demonstrated to suffice for backwater profile calculations in conduits at mild slopes. The author's check computations agreed closely with observed water surface profiles in 24 in. and 36 in. concrete pipes about 200 ft. in length. The data were taken from observations made at the St. Anthony Falls Hydraulic Laboratory in 1959 and 1960.

A definition of critical flow is that state of flow at which the specific energy is a minimum for a given discharge. A free surface must exist, and the kinetic energy factor, α, must be taken into account in determining the kinetic energy, or velocity head. The principles involved are covered in various textbooks of hydraulics, for example: Ven Te Chow, "Open-Channel Hydraulics," 1959, pp. 42–43.

At the critical state of flow, the velocity head is equal to half the hydraulic depth, or mean depth, $\frac{A}{T}$, where T is the surface width of the flow. Thus,

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

or, in non-dimensional terms, the equation appears:

$$\frac{\alpha V_c^2}{2gD}=\frac{A}{2TD}=\frac{A}{BD}\cdot\frac{B}{2T}=\frac{\frac{A}{BD}}{\frac{2T}{B}}$$

One half the mean depth (which is equal to the relative velocity head at critical flow) may be readily determined from the non-dimensional tables of geometric properties of any conduit section.

Such a determination of velocity head at critical depth from the conduit and flow depth dimensions is not useful without a determination of the discharge rate which will occur at the depth under consideration. Since $Q=VA$, the non-dimensional expression for discharge may be determined as follows:

$$\frac{Q_c}{BD}=\frac{V_cA_c}{BD}$$

Squaring each side of this equation and substituting for V_c^2 as derived from the earlier equation for velocity head in the form

$$V_c{}^2=\frac{\frac{A_c}{BD}}{\frac{2T}{B}}\cdot\frac{2gD}{\alpha}$$

an equation for critical discharge is obtained,

$$\left(\frac{Q_c}{BD}\right)^2=\frac{\frac{A_c}{BD}}{\frac{T_c}{B}}\cdot\frac{gD\left(\frac{A_c}{BD}\right)^2}{\alpha}$$

$$\text{and, }\frac{Q_c{}^2}{B^2D^3}=\frac{g}{\alpha}\cdot\frac{\left(\frac{A_c}{BD}\right)^3}{\left(\frac{T_c}{B}\right)}$$

$$\text{or, }\frac{Q_c}{BD^{1.5}}=\frac{g^{0.5}}{\alpha^{0.5}}\cdot\frac{\left(\frac{A_c}{BD}\right)^{1.5}}{\left(\frac{T_c}{B}\right)^{0.5}}$$

The second of the above expressions may be recognized as equivalent to the familiar relation for critical flow

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

Thus, the non-dimensional critical discharge at any particular relative depth of flow at the critical state may be computed from the geometric factors for any conduit cross-sectional form, and applied to each available size of such a conduit.

It will be observed that critical depth may not be readily obtained from the above equation for a given rate of flow and conduit size. A convenient method for obtaining critical depth requires use of tabulation of geometric factors at relative depth intervals of 0.01D for each conduit shape to be considered, with the inclusion of computed values of $\frac{Q_c}{BD^{1.5}}$ for each value of α commonly encountered.

Such tables for five forms of nonrectangular conduits, and one table to apply to all span-height ratios for rectangular conduits, are included in later sections of this publication. To use the tables, compute the value of $\frac{Q_c}{BD^{1.5}}$ for the discharge and conduit size involved, and determine $\frac{d_c}{D}$ by interpolation in the appropriate table. The tables include $\alpha=1.04$ and 1.12 for direct use with the more common types of conduits, and a value of $\frac{Q_c}{BD^{1.5}}$ for $\alpha=1.00$ for convenience of conversion to any value of α by dividing the tabular value of $\frac{Q_c}{BD^{1.5}}$ at $\alpha=1.00$ by $\alpha^{0.5}$.

The equations defining critical depth show that selection of a particular relative depth as the critical depth of flow will result in a fixed value of the relative velocity head and specific head

$$\frac{H_c}{D}=\frac{d_c}{D}+\frac{\alpha V_c^2}{2gD},$$

not varying with the value of α.

Therefore, the tables of geometric properties and critical flow factors for the various conduits contain values of $\frac{\alpha V_c^2}{2gD}$ and $\frac{H_c}{D}$ fixed by the relative critical depth, $\frac{d_c}{D}$. Only the discharge, Q_c, varies with α in such tables.

Use of the tables for determination of critical depth and minimum specific head may be illustrated by the following examples.

Example 1

Discharge of 336 c.f.s. in a 6.5 ft. diameter concrete pipe, for which $\alpha=1.04$. Find critical depth.

From Table 1, $D^{2.5}=107.7$, therefore,

$$\frac{Q_c}{D^{2.5}}=\frac{336.00}{107.70}=3.1198$$

From Table 4, $\alpha=1.04$, it is found,

for $\frac{d_c}{D}=0.76$, $\frac{Q_c}{D^{2.5}}=3.0839$

and $\frac{d_c}{D}=0.77$, $\frac{Q_c}{D^{2.5}}=3.1687$

Thus, by interpolation, it is found that 336 c.f.s. would flow at a relative critical depth $\frac{d_c}{D}=0.764$, or $d_c=4.97$ ft. The relative velocity head $\frac{\alpha V_c^2}{2gD}=0.379$ and the specific head:

$$\frac{H_c}{D}=0.764+0.379=1.143 \text{ or } H_c=7.43 \text{ ft.}$$

This would also be obtained directly by interpolation from Table 4 (for $\frac{Q_c}{D^{2.5}}=3.1198$).

Example 2

a. Discharge of 138 c.f.s. in a 76 in. by 48 in. oval concrete pipe, long axis horizontal, $\alpha=1.06$. Find critical depth and specific head.

From Table 6, actual dimensions in feet:

$$B=6.292, \qquad D=4.014; \qquad \frac{Q_c}{BD^{1.5}}=\frac{138.0}{50.6}=2.727.$$

Since in Table 7 there is no column for $\alpha=1.06$, the $\frac{Q_c}{BD^{1.5}}$ for $\alpha=1.00$ must first be determined.

$$\frac{Q_c}{BD^{1.5}}(\alpha=1.00)=2.727\times\sqrt{1.06}=2.808$$

$$\frac{d_c}{D}=0.71; \qquad \frac{V_c^2}{2gD}=0.3283$$

and

$$\frac{H_c}{D}=0.71+0.328=1.038$$

which is also found directly from the column for $\frac{H_c}{D}$.

$$d_c = 0.71 \times 4.014 = 2.85 \text{ ft.}$$

$$H_c = 1.038 \times 4.014 = 4.17 \text{ ft.}$$

b. Critical depth for the same rate of flow, α, and size of oval pipe with the long axis vertical is found in a similar way.

From Table 9, actual dimensions in feet

$$B = 4.014, \qquad D = 6.292; \qquad \frac{Q_c}{BD^{1.5}} = \frac{138.0}{63.34} = 2.179$$

$$\frac{Q_c}{BD^{1.5}}(\alpha = 1.00) = 2.179 \times \sqrt{1.06} = 2.243$$

From Table 10, by interpolation $\frac{d_c}{D} = 0.629$

$$\frac{V_c^2}{2gD} = 0.2752 \text{ and } \frac{H_c}{D} = 0.629 + 0.275 = 0.904$$

which is also found directly in the column for $\frac{H_c}{D}$

$$d_c = 0.629 \times 6.292 = 3.96 \text{ ft.}$$

$$H_c = 0.904 \times 6.292 = 5.69 \text{ ft.}$$

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III. RESISTANCE LOSS COMPUTATIONS

The rate of energy loss due to flow resistance is a prime factor in all calculations related to free surface flow in channels or closed conduits. This publication provides a means for simplifying and reducing such calculations through elimination of the detailed operations previously required to compute the area of the flow prism, from which the velocity is determined, and the hydraulic radius which is used with area to compute the rate of resistance loss.

Hydraulic engineers are familiar with the use of tables giving the area and hydraulic radius for partly full flow in circular conduits at a series of depth intervals. This paper extends the usefulness of these methods to several other cross-sectional shapes in common use by making additional tables available, and offers a method for combining calculations to obtain the rate of loss of energy by resistance, S_f, without the need to calculate either area or hydraulic radius.

The tables also include factors for direct computation of velcoity head at any discharge rate and any relative depth of flow without first calculating velocity by flow area. Thus, specific head may readily be obtained at any of a series of relative depths, $\frac{d}{D}$. Computation of a backwater profile (or any case of nonuniform flow) requires only the change of specific head between two particular depths of flow, the conduit invert slope, and the resistance slope S_f. With these values, the longitudinal distance between these two section of selected depth may be calculated to derive the nonuniform flow profile.

A general description of non-dimensional methods, including an equation for velocity head, was given in the introductory description of the tables.

The tables contained herein include factors for computation of S_f, the rate of loss of energy by resistance (or the resistance slope), by use of either the *Darcy or the Manning resistance factors,* f *and* n, *respectively.* These factors are commonly encountered in the following equations for mean velocity of flow, for which the hydraulic radius, R, and the slope of the total energy line, S_f, with respect to a horizontal plane, must be known.

$$V = \sqrt{2g}\left(\frac{2R^{1/2}}{f^{1/2}}\right) S_f^{1/2} \qquad \text{Darcy}$$

$$V = \frac{1.486}{n} R^{2/3} S_f^{1/2} \qquad \text{Manning}$$

In the case of uniform flow, S_f is equal to the conduit or channel invert slope, S_o. Because in many cases uniform flow is assumed, the above equations are frequently given with a slope term S, without specifying that the equations will apply only for the case where S equals S_f.

To compute S_f for a known discharge rate and a known depth, the above equations may be rearranged to solve for S_f. Using the Darcy f, the rate of resistance loss in feet per foot is

$$S_f = \frac{f}{4R}\frac{V^2}{2g}.$$

Using the Manning n, the alternative form

$$S_f = \frac{n^2V^2}{(1.486)^2 R^{4/3}}$$

will apply.

As was noted above, the tables included here combine the geometric properties of the conduit cross section with the equations for resistance loss, S_f, to provide a *resistance computation factor* which provides the means to avoid the need for computing V and R as well the arithmetical computations indicated by the resistance loss equations.

The properties of geometrically similar cross sections make it feasible to state the equations for S_f in a form in which the geometric factors, $\frac{A}{BD}$ and $\frac{R}{D}$, at any specific relative depth, $\frac{d}{D}$, are combined with numerical constants, and the discharge rate, Q, is combined into a relation to the area of the rectangle enclosing the cross section of the conduit, that is, BD (or D^2 for a circular section).

Because the hydraulic radius, $R=\left(\frac{R}{D}\right)D$, is included in the equations as well as the area, $A=\left(\frac{A}{BD}\right)BD$, the discharge factor will appear in the form $\frac{Q}{BD^{1.5}}$ or $\frac{Q}{D^{2.5}}$, as will be seen in the following development of the equations for the resistance computation factors of the tables. A relative depth interval of $0.01D$ has been found to be both convenient and adequate for the use of the tables of velocity head and resistance computation factors.

The resistance computation factors are developed from each of the two resistance loss equations by first substituting $\frac{Q}{A}=V$ and then substituting $\left(\frac{R}{D}\right)D=R$ and $\left(\frac{A}{BD}\right)BD=A$, as follows:

Darcy f	Manning n
$S_f=\frac{f}{4R}\frac{V^2}{2g}$	$S_f=\frac{n^2V^2}{2.208R^{1.33}}$
$S_f=\frac{f}{4R2g}\frac{Q^2}{A^2}$	$S_f=\frac{n^2}{2.208R^{1.33}}\frac{Q^2}{A^2}$

$$S_f=\frac{f}{8gD\left(\frac{R}{D}\right)}\frac{Q^2}{B^2D^2\left(\frac{A}{BD}\right)^2};$$

$$S_f=\frac{n^2}{2.208D^{0.333}\left(\frac{R}{D}\right)^{1.33}}\frac{Q^2}{B^2D^2\left(\frac{A}{BD}\right)^2}$$

Then, by combining terms,

$$S_f=\frac{f}{8g\left(\frac{R}{D}\right)\left(\frac{A}{BD}\right)^2}\left(\frac{Q}{BD^{1.5}}\right)^2;$$

$$S_f=\frac{n^2}{2.208D^{0.333}\left(\frac{R}{D}\right)^{1.33}\left(\frac{A}{BD}\right)^2}\cdot\left(\frac{Q}{BD^{1.5}}\right)^2$$

It will be evident that the use of the Darcy resistance factor f results in an equation involving only three components:

f, the resistance factor

a fixed value at any given depth, including $\frac{R}{D}$, $\frac{A}{BD}$ and the constant $8g$

and $\frac{Q}{BD^{1.5}}$, the discharge factor.

For a particular size of a conduit of given shape, the dimensions of B and D, in feet, are used with the rate of flow, Q, in c.f.s., to compute the applicable discharge factor.

If the Manning resistance factor n is used, the hydraulic radius appears in the form $R^{4/3}$, with the result that a similar development of an equation for S_f would produce a discharge factor $\frac{Q}{BD^{5/3}}$. A separate set of tables for $BD^{5/3}$ could be prepared for various sizes of each of the conduit sections, but it was considered more convenient to use only $BD^{1.5}$ for both forms of the equation and to use the additional term $D^{1/3}$ in the equation for S_f where the Manning n is used.

The last step in the derivation of equations for S_f is to use the numerical values of the respective constants and to rearrange, thus:

$$S_f=\frac{0.003887}{\left(\frac{R}{D}\right)\left(\frac{A}{BD}\right)^2}\cdot f\cdot\left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Darcy}$$

and

$$S_f=\frac{0.4529}{\left(\frac{R}{D}\right)^{1.33}\left(\frac{A}{BD}\right)^2}\cdot\frac{n^2}{D^{0.333}}\cdot\left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Manning}$$

The combination of constants with the geometric factors for non-dimensional hydraulic radius and area at each interval of depth is called the *resistance computation factor*, K_f for the Darcy f, and K_n for the Manning n. The equations for the rate of resistance loss then become,

$$S_f=fK_f\left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Darcy}$$

$$S_f=\frac{n^2}{D^{0.333}}K_n\left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Manning}$$

in which

$$K_f=\frac{0.003887}{\left(\frac{R}{D}\right)\left(\frac{A}{BD}\right)^2} \quad \text{and} \quad K_n=\frac{0.4529}{\left(\frac{R}{D}\right)^{1.33}\left(\frac{A}{BD}\right)^2}$$

are the *resistance computation factors.*

Should it be desired to refer to the values of $\frac{R}{D}$ and $\frac{A}{BD}$ in a particular case, these ratios are given in the separate table of Geometric Properties and Critical Flow Factors for each of the conduit shapes included in these tables.

To determine the normal depth of flow, d_n, for any discharge rate and conduit slope, a condition in which S_f is equal to the invert slope S_o, the appropriate equation for S_f is solved to obtain K_f or K_n, with S_f assigned the value of S_o. Then the table of velocity head and resistance computation factors, for the conduit section involved, is used to determine the relative depth, $\frac{d}{D}$, corresponding to the computed value of K_f or K_n using interpolation if desired.

It will be evident that the two equations for S_f will produce identical results if the values of f and n are truly equivalent, By equating the two initial expressions for S_f, a value for n in terms of f will be obtained in the following form:

$$n = 0.0926\, f^{1/2} R^{1/6}$$

Therefore it is clear that specific values of f and n can be equivalent only at a particular value of R in a conduit of given roughness. While it is usually recognized that f varies with R, it has been customary to assume that n is fixed by the conduit wall quality and is invariant with R, and thus with the depth of flow. The above equation shows that such is not the case, although numerical values of n will vary only by small amounts over a range of depths of flow in a conduit of given size.

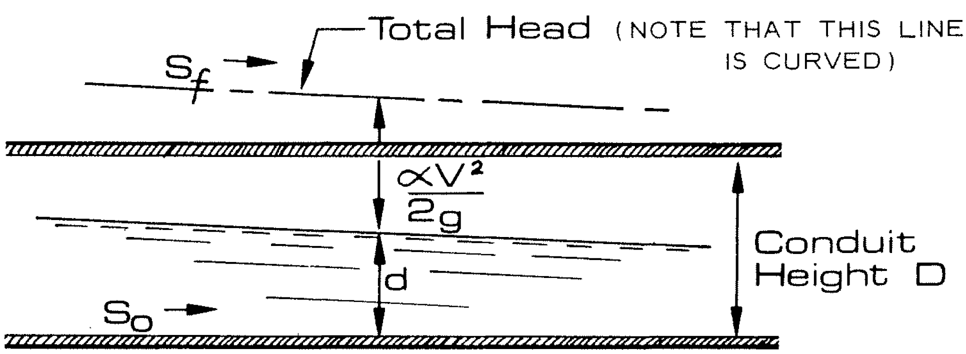
It is not considered necessary to discuss in this publication the details in regarding the various means for estimating either f or n. It is assumed that the user will make use of the most advanced knowledge available.

For use of these tables, it is suggested that a value of f or n applicable to full flow in the size and type of conduit involved can generally be used at all depths of flow with adequate precision. Because R for $\frac{d}{D} = 0.5$ is equal to R at full flow, the degree of error introduced by this simplification is generally acceptable.

An exception to the general rule is desirable for computing flow in structural plate pipe and pipe-arches. The greater roughness of the walls and the considerable range of conduit sizes available make it advisable to introduce resistance factors which vary with the hydraulic radius. The method for introducing a variable resistance factor is explained in the text preceding Example 12, Appendix B.

The following examples illustrate the application of the tables to determine rate of energy loss by resistance at a specific depth of flow, and their use for determining normal depth.

The flow conditions involved are shown in the following diagram:



S_o = conduit invert slope, in feet per foot with reference to the horizontal.
S_f = resistance slope; the local rate of loss of total head at a given location; the tangent of the angle of the resistance slope at that point.

$$\text{Specific Head } \frac{H}{D} = \frac{d}{D} + \frac{\alpha V^2}{2gD}$$

Example 3

Determine (a) the rate of loss of total head with a flow of 78 c.f.s. at a relative depth $\frac{d}{D} = 0.39$, or $d = 1.56$ ft., in a 4-ft. diameter cast-and-vibrated concrete pipe, for which the Darcy f at full flow is 0.0141, and the equivalent Manning n is 0.0110.

Also determine (b) normal depth for this flow rate if the conduit invert slope S_o is 0.0040.

a. The discharge factor $\frac{Q}{D^{2.5}} = \frac{78.0}{32.0} = 2.438$ (for a circular pipe, $B = D$, so that $BD^{1.5} = D^{2.5}$). Assuming the resistance factors remain the same at part-full depths,

From Table 5, using the Darcy f, $K_f = 0.2299$;

$$S_f = 0.0141 \times 0.2299 \times (2.438)^2 = 0.0193$$

Or, by using the Manning n, $K_n = 45.05$;

$$S_f = \frac{0.0110^2}{4.0^{0.333}} \times 45.05 \times (2.438)^2 = 0.0204$$

Since f and n vary differently with hydraulic radius, the calculated S_f values vary by about five percent at $\frac{d}{D} = 0.39$.

b. Normal depth is determined by computing K_f or K_n for the given slope of 0.0040; $S_f = S_0 = 0.0040$

$$K_f = \frac{S_f}{f\left(\frac{Q}{D^{2.5}}\right)^2} = \frac{0.0040}{0.0141 \times (2.438)^2} = 0.0477$$

From Table 5, $\frac{d_n}{D} = 0.642$, and $d_n = 2.57$ ft.

$$K_n = \frac{D^{1/3}S_f}{n^2\left(\frac{Q}{D^{2.5}}\right)^2} = \frac{1.587 \times 0.0040}{0.0110^2 \times 2.438^2} = 8.832$$

From Table 5, $\frac{d_n}{D} = 0.632$, and $d_n = 2.53$ ft.

The difference in depth resulting from the unlike variation of f and n with hydraulic radius is of small significance.

Resistance factors vary with hydraulic radius within a conduit of given wall quality. A simple solution for the problems associated with this fact is to derive and use an expression for f consisting of a constant (fixed by the wall type) times R to a small negative power. This method will avoid errors which would otherwise be introduced by assuming both f and n to be constant for various depths of flow in a given conduit.

It should be recognized that these small errors are due to the values used for f and n. They are not caused by consolidating geometric factors into a single value for simplification of calculations, as is done in this publication.

The next example shows the case with variable f.

Example 4

Determine normal depth for a flow rate of 51 cfs in a 12 ft. 10 in. × 8 ft. 4 in. structural plate co rugated metal pipe-arch, 6 in. × 2 in. corrugatior 18 in. corner radius, for which the Darcy f may b approximated by $\frac{0.1312}{R^{0.474}}$ (see Appendix B, Exampl 12); $\alpha = 1.12$ and the conduit invert slope $S_0 = 0.00$

From Table 15 the actual dimensions are $B = 12.87$ ft., $D = 8.31$ ft., and $BD^{1.5} = 308.3$. Th discharge factor is

$$\frac{Q}{BD^{1.5}} = \frac{510}{308.3} = 1.654.$$

Using the Darcy equation, $S_f = K_f f\left(\frac{Q}{BD^{1.5}}\right)^2$, th resistance computation factor is

$$K_f = \frac{0.006R^{0.474}}{0.1312 \times 2.7357} = 0.0167R^{0.474}.$$

Now, applying the trial and error method, $\frac{d}{D}$ can b found. Try $\frac{d}{D} = 0.70$. From Table 19, $\frac{R}{D} = 0.3531$ an $R = 2.934$; $(2.934)^{0.474} = 1.666$.

From Table 20, $K_f = 00288$, thus

$$K_f = 0.0288 \approx 0.0167 \times 1.666 = 0.0278$$

By comparing the given and computed values fo K_f, it is evident that the assumed $\frac{d}{D} = 0.70$ was low. Try $\frac{d}{D} = 0.72$. From Table 19, $\frac{R}{D} = 0.3553$ and $R = 2.9525$. From Table 20, $K_f = 0.0272$, thus

$$K_f = 0.0272 \approx 0.0167 \times 1.671 = 0.0279.$$

The assumed $\frac{d}{D} = 0.72$ was slightly high. Try $\frac{d}{D} = 0.71$. From Table 16, $\frac{R}{D} = 0.3543$ and $R = 2.944$. From Table 17, $K_f = 0.0280$, thus,

$$K_f = 0.0280 \approx 0.0167 \times 1.668 = 0.0279,$$

which matches best.

$$d_n = 0.71 \times 8.31 = 5.90 \text{ ft.}$$

IV. CIRCULAR CONDUITS

The dimensions of truly circular conduits may be represented in non-dimensional terms as ratios of the diameter, so that the following tables of geometric properties are applicable to each relative depth of flow for all conduit diameters. Therefore, the critical flow factors and the velocity head and resistance computation factors are exact, within the limits of accuracy imposed by the use of four significant figures for the geometric relations.

Many commercially available circular conduits, such as concrete, vitrified clay, corrugated steel, and corrugated aluminum (with 1/2 in. and 1 in. corrugations) are manufactured approximately true to diameters at 1 ft. and 6 in. intervals. Small variations, within the limits of necessary manufacturing tolerances, are to be expected. This fact argues against any expectation of computational exactness beyond that provided by the accompanying tables.

Table 1 provides values of the discharge subfactor, $D^{2.5}$, for the commonly available sizes of conduits manufactured to comply closely to the nominal diameters at 1/2 ft. intervals (3 in. intervals for diameters less than 36 in.).

Circular conduits of the heavier corrugated structural plate, both steel and aluminum, do not conform to the nominal diameters, except for one particular intermediate size in each case, because of manufacturing requirements associated with assembly bolt hole spacing. The several manufacturers have standardized their products to conform to the same actual diameters (within manufacturing tolerances) for each of the nominal diameters commonly used in construction practice. The actual inside diameters, crest-to-crest of corrugations, given in Tables 2 and 3 are derived from data in manufacturer's catalogues. The tabular values for the discharge subfactor $D^{2.5}$, are derived from the actual inside diameter, and are therefore applicable to computations involving Tables 4 and 5.

Methods for use of Tables 4 and 5, in conjunction with Tables 1, 2, or 3, are discussed in Chapters I, II, and III.

Table 1.—$D^{2.5}$ values for various pipe diameters

Actual diameter		$D^{2.5}$	Actual diameter		$D^{2.5}$
Inches	Feet		Inches	Feet	
12	1.0	1.000	66	5.5	70.94
15	1.25	1.747	72	6.0	88.18
18	1.5	2.756	78	6.5	107.72
21	1.75	4.051	84	7.0	129.64
24	2.0	5.657	90	7.5	154.0
27	2.25	7.594	96	8.0	181.0
30	2.5	9.882	102	8.5	210.6
33	2.75	12.54	108	9.0	243.0
			114	9.5	278.2
36	3.0	15.59	120	10.0	316.2
42	3.5	22.92	126	10.5	357.2
48	4.0	32.00	132	11.0	401.3
54	4.5	42.96	138	11.5	448.5
60	5.0	55.90	144	12.0	498.8

Table 2.—Diameter dimensions and $D^{2.5}$ values for structural plate corrugated circular pipe, 6 by 2 in. corrugations (steel)

Diameter (ft.)		$D^{2.5}$	Plates per ring
Nominal	Actual		
5.0	4.93	53.97	4
5.5	5.43	68.71	4
6.0	5.94	85.99	4
6.5	6.45	105.66	4
7.0	6.97	128.26	4
7.5	7.48	153.0	6
8.0	7.98	179.9	6
8.5	8.49	210.0	6
9.0	9.00	243.0	6
9.5	9.51	278.9	6
10.0	10.02	317.8	6
10.5	10.53	359.8	6
11.0	11.03	404.1	8
11.5	11.55	453.4	8
12.0	12.06	505.1	8
12.5	12.57	560.2	8
13.0	13.08	618.8	8
13.5	13.58	679.6	8
14.0	14.09	745.2	8
14.5	14.60	814.5	10
15.0	15.11	887.5	10
15.5	15.62	964.3	10
16.0	16.13	1044.9	10
16.5	16.64	1130.0	10
17.0	17.15	1218.0	10
17.5	17.66	1310.8	10
18.0	18.17	1407.	12
18.5	18.67	1506.	12
19.0	19.18	1611.	12
19.5	19.69	1720.	12
20.0	20.21	1836.	12
20.5	20.72	1954.	12
21.0	21.22	2074.	12

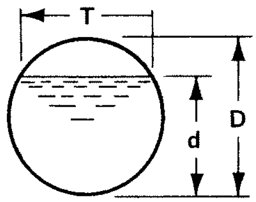
Table 3.—Diameter dimensions and $D^{2.5}$ values for structural plate corrugated circular pipe, 9 by 2½ in. corrugations (aluminum)

Diameter (ft.) Nominal	Diameter (ft.) Actual	$D^{2.5}$	Plates per ring
6.5	6.42	104.4	2
7.0	6.93	126.4	2
7.5	7.44	151.0	3
8.0	7.96	178.8	3
8.5	8.46	208.2	3
9.0	8.97	241.0	3
9.5	9.48	276.7	3
10.0	9.99	315.4	3
10.5	10.50	357.2	3
11.0	11.01	402.2	4
11.5	11.52	450.4	4
12.0	12.04	503.0	4
12.5	12.54	556.9	4
13.0	13.05	615.2	4
13.5	13.57	678.3	4
14.0	14.08	743.9	4
14.5	14.59	813.1	5
15.0	15.10	886.0	5

Table 4.—Geometric properties and critical flow factors for circular conduits flowing full and partly full

d = Depth of flow
d_c = Critical depth
d_m = Mean depth
D = Diameter of pipe
A = Area of flow
R = Hydraulic radius
T = Top width of flow

Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$H_c = d_c + (\alpha V^2)/(2gD)$ (invariant with α)
V_c = Critical velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{T}{D}$	$\frac{d_m}{D}$	$\frac{Q_c}{D^{2.5}}$ α=1.00	$\frac{Q_c}{D^{2.5}}$ α=1.04	$\frac{Q_c}{D^{2.5}}$ α=1.12	$\frac{\alpha V_c^2}{2gD}$ all α	$\frac{H_c}{D}$ all α
1.00	0.7854	0.2500	—	—	—	—	—	—	—
0.99	.7841	.2666	0.1990	—	—	—	—	—	—
.98	.7817	.2735	.2800	—	—	—	—	—	—
.97	.7785	.2787	.3412	2.2817	6.6695	6.5400	6.3021	1.1410	2.1110
.96	.7749	.2829	.3919	1.9773	6.1785	6.0585	5.8381	0.9883	1.9483
.95	.7707	.2865	.4359	1.7681	5.8119	5.6991	5.4917	.8840	1.8340
.94	.7662	.2895	.4750	1.6131	5.5182	5.4111	5.2142	.8063	1.7463
.93	.7612	.2921	.5103	1.4917	5.2727	5.1703	4.9822	.7459	1.6759
.92	.7560	.2944	.5426	1.3933	5.0602	4.9620	4.7814	.6965	1.6165
.91	.7504	.2963	.5724	1.3110	4.8724	4.7778	4.6040	.6555	1.5655
.90	.7445	.2980	.6000	1.2408	4.7033	4.6120	4.4442	.6205	1.5205
.89	.7384	.2995	.6258	1.1799	4.5486	4.4603	4.2980	.5899	1.4799
.88	.7320	.3007	.6499	1.1263	4.4057	4.3202	4.1630	.5633	1.4433
.87	.7254	.3018	.6726	1.0785	4.2722	4.1893	4.0369	.5393	1.4093
.86	.7186	.3026	.6940	1.0354	4.1466	4.0661	3.9182	.5177	1.3777
.85	.7115	.3033	.7142	0.9962	4.0276	3.9494	3.8057	.4982	1.3482
.84	.7043	.3038	.7332	.9606	3.9144	3.8384	3.6988	.4802	1.3202
.83	.6969	.3041	.7513	.9276	3.8062	3.7323	3.5965	.4637	1.2937
.82	.6893	.3043	.7684	.8971	3.7021	3.6302	3.4982	.4484	1.2684
.81	.6815	.3043	.7846	.8686	3.6020	3.5321	3.4036	.4343	1.2443
.80	.6736	.3042	.8000	.8420	3.5051	3.4370	3.3120	.4209	1.2209
.79	.6655	.3039	.8146	.8170	3.4111	3.3449	3.2232	.4084	1.1984
.78	.6573	.3036	.8285	.7934	3.3200	3.2555	3.1371	.3966	1.1766
.77	.6489	.3031	.8417	.7709	3.2314	3.1687	3.0534	.3855	1.1555
.76	.6405	.3024	.8542	.7498	3.1450	3.0839	2.9717	.3749	1.1349

Table 4.—Geometric properties and critical flow factors for circular conduits flowing full and partly full—Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{T}{D}$	$\frac{d_m}{D}$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.00$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.04$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.12$	$\frac{\alpha V_c^2}{2gD}$ all α	$\frac{H_c}{D}$ all α
0.75	0.6319	0.3017	0.8660	0.7297	3.0606	3.0012	2.8920	0.3648	1.1148
.74	.6231	.3008	.8773	.7102	2.9783	2.9205	2.8142	.3552	1.0952
.73	.6143	.2998	.8879	.6919	2.8977	2.8414	2.7381	.3459	1.0759
.72	.6054	.2987	.8980	.6742	2.8188	2.7641	2.6635	.3371	1.0571
.71	.5964	.2975	.9075	.6572	2.7416	2.6884	2.5906	.3285	1.0385
.70	.5872	.2962	.9165	.6407	2.6656	2.6138	2.5188	.3204	1.0204
.69	.5780	.2948	.9250	.6249	2.5912	2.5409	2.4485	.3125	1.0025
.68	.5687	.2933	.9330	.6095	2.5182	2.4693	2.3795	.3048	0.9848
.67	.5594	.2917	.9404	.5949	2.4465	2.3990	2.3117	.2974	.9674
.66	.5499	.2900	.9474	.5804	2.3760	2.3299	2.2451	.2902	.9502
.65	.5404	.2882	.9539	.5665	2.3068	2.2620	2.1797	.2833	.9333
.64	.5308	.2862	.9600	.5529	2.2386	2.1951	2.1153	.2765	.9165
.63	.5212	.2842	.9656	.5398	2.1717	2.1295	2.0521	.2699	.8999
.62	.5115	.2821	.9708	.5269	2.1058	2.0649	1.9898	.2635	.8835
.61	.5018	.2799	.9755	.5144	2.0410	2.0014	1.9286	.2572	.8672
.60	.4920	.2776	.9798	.5021	1.9773	1.9389	1.8684	.2511	.8511
.59	.4822	.2753	.9837	.4902	1.9147	1.8775	1.8092	.2451	.8351
.58	.4724	.2728	.9871	.4786	1.8531	1.8171	1.7510	.2393	.8193
.57	.4625	.2703	.9902	.4671	1.7924	1.7576	1.6937	.2335	.8035
.56	.4526	.2676	.9928	.4559	1.7328	1.6992	1.6373	.2279	.7879
.55	.4426	.2649	.9950	.4448	1.6741	1.6416	1.5819	.2224	.7724
.54	.4327	.2621	.9968	.4341	1.6166	1.5852	1.5275	.2170	.7570
.53	.4227	.2592	.9982	.4235	1.5598	1.5295	1.4739	.2117	.7417
.52	.4127	.2562	.9992	.4130	1.5041	1.4749	1.4212	.2065	.7265
.51	.4027	.2531	.9998	.4028	1.4494	1.4213	1.3696	.2014	.7114
.50	.3927	.2500	1.0000	.3927	1.3956	1.3685	1.3187	.1964	.6964
.49	.3827	.2468	.9998	.3828	1.3427	1.3166	1.2687	.1914	.6814
.48	.3727	.2435	.9992	.3730	1.2908	1.2657	1.2197	.1865	.6665
.47	.3627	.2401	.9982	.3634	1.2400	1.2159	1.1717	.1817	.6517
.46	.3527	.2366	.9968	.3538	1.1900	1.1669	1.1244	.1770	.6370
.45	.3428	.2331	.9950	.3445	1.1410	1.1188	1.0781	.1722	.6222
.44	.3328	.2295	.9928	.3352	1.0929	1.0717	1.0327	.1677	.6077
.43	.3229	.2258	.9902	.3261	1.0459	1.0256	0.9883	.1631	.5931
.42	.3130	.2220	.9871	.3171	0.9997	0.9803	.9446	.1586	.5786
.41	.3032	.2182	.9837	.3082	.9546	.9361	.9020	.1541	.5641
.40	.2934	.2142	.9798	.2994	.9104	.8927	.8602	.1497	.5497
.39	.2836	.2102	.9755	.2907	.8672	.8504	.8194	.1454	.5354
.38	.2739	.2062	.9708	.2821	.8249	.8089	.7795	.1410	.5210
.37	.2642	.2020	.9656	.2736	.7836	.7684	.7404	.1368	.5068
.36	.2546	.1978	.9600	.2652	.7433	.7289	.7024	.1325	.4925
.35	.2450	.1935	.9539	.2568	.7040	.6903	.6652	.1284	.4784
.34	.2355	.1891	.9474	.2486	.6657	.6528	.6290	.1242	.4642
.33	.2260	.1847	.9404	.2403	.6284	.6162	.5938	.1202	.4502
.32	.2167	.1802	.9330	.2323	.5921	.5806	.5595	.1161	.4361
.31	.2074	.1756	.9250	.2242	.5569	.5461	.5262	.1121	.4221
.30	.1982	.1709	.9165	.2163	.5226	.5125	.4938	.1081	.4081
.29	.1890	.1662	.9075	.2083	.4893	.4798	.4623	.1042	.3942
.28	.1800	.1614	.8980	.2004	.4571	.4482	.4319	.1003	.3803
.27	.1711	.1566	.8879	.1927	.4259	.4176	.4024	.0963	.3663
.26	.1623	.1516	.8773	.1850	.3957	.3880	.3739	.0924	.3524
.25	.1535	.1466	.8660	.1773	.3667	.3596	.3465	.0887	.3387
.24	.1449	.1416	.8542	.1696	.3386	.3320	.3199	.0849	.3249
.23	.1365	.1364	.8417	.1622	.3116	.3055	.2944	.0810	.3110
.22	.1281	.1312	.8285	.1546	.2857	.2802	.2700	.0773	.2973
.21	.1199	.1259	.8146	.1472	.2609	.2558	.2465	.0736	.2836

Table 4.—Geometric properties and critical flow factors for circular conduits flowing full and partly full—Continued

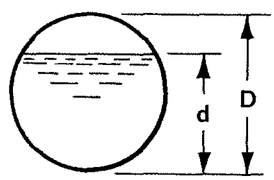
$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{T}{D}$	$\frac{d_m}{D}$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.00$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.04$	$\frac{Q_c}{D^{2.5}}$ $\alpha=1.12$	$\frac{\alpha V_c^2}{2gD}$ all α	$\frac{H_c}{D}$ all α
0.20	0.1118	0.1206	0.8000	0.1397	0.2371	0.2325	0.2240	0.0699	0.2699
.19	.1039	.1152	.7846	.1324	.2144	.2102	.2026	.0662	.2562
.18	.0961	.1097	.7684	.1251	.1928	.1891	.1822	.0626	.2426
.17	.0885	.1042	.7513	.1178	.1724	.1691	.1629	.0590	.2290
.16	.0811	.0985	.7332	.1106	.1530	.1500	.1446	.0553	.2153
.15	.0739	.0929	.7142	.1035	.1347	.1321	.1272	.0516	.2016
.14	.0668	.0871	.6940	.0963	.1176	.1153	.1111	.0482	.1882
.13	.0600	.0813	.6726	.0892	.1016	.0996	.0960	.0446	.1746
.12	.0534	.0755	.6499	.0822	.0868	.0851	.0820	.0411	.1611
.11	.0470	.0695	.6258	.0751	.0731	.0717	.0691	.0376	.1476

Table 5.—Velocity head and resistance computation factors for circular conduits flowing full and partly full

Column A: Relative depth of flow, d/D

Column B: Relative velocity head
$h_v/D=\alpha V^2/2gD$, $\alpha=1.00$, $Q/D^{2.5}=1.0$
V=Mean flow velocity
α=Kinetic energy correction factor
g=Accel. due to gravity=32.16 ft./sec./sec.

Column C: Resistance computation factor (K_n) for the Manning equation, $V=(1.486/n)(R)^{2/3}(S)^{1/2}$
$S_f=Q^2n^2/2.208R^{4/3}A^2=K_n\ (n^2/D^{1/3})\ (Q/D^{2.5})^2$
$K_n=0.4529/(R/D)^{4/3}\ (A/D^2)^2$
A=Flow area in conduit
S_f=Friction slope
R=Hydraulic radius
n=Manning coefficient



Column D: Resistance computation factor (K_f) for the Darcy equation, $h_f=(f)\ (L/4R)\ (V^2/2g)$
$S_f=Q^2f/257.28RA^2=K_f(f)\ (Q/D^{2.5})^2$
$K_f=0.003887/(R/D)\ (A/D^2)^2$
h_f=Friction head loss, ft.
f=Darcy coefficient
L=Length of conduit, ft.

(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/D^{2.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/D^{2.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
1.00	0.02520	4.662	0.02520	0.85	0.03071	4.390	0.02532
0.99	.02529	4.293	.02371	.84	.03134	4.470	.02579
.98	.02544	4.174	.02326	.83	.03201	4.560	.02632
.97	.02565	4.104	.02301	.82	.03272	4.657	.02688
.96	.02589	4.061	.02288	.81	.03348	4.764	.02750
.95	.02618	4.037	.02284	.80	.03426	4.878	.02816
.94	.02648	4.028	.02287	.79	.03510	5.004	.02888
.93	.02683	4.033	.02296	.78	.03598	5.137	.02963
.92	.02720	4.046	.02310	.77	.03692	5.282	.03045
.91	.02761	4.071	.02330	.76	.03790	5.438	.03133
.90	.02805	4.105	.02353	.75	.03894	5.605	.03226
.89	.02852	4.145	.02380	.74	.04004	5.787	.03328
.88	.02902	4.195	.02412	.73	.04120	5.981	.03436
.87	.02955	4.251	.02448	.72	.04242	6.188	.03550
.86	.03011	4.317	.02487	.71	.04371	6.411	.03673

Table 5.—Velocity head and resistance computation factors for circular conduits flowing full and partly full—Continued

(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
0.70	0.04509	6.652	0.03806	.40	.1806	41.05	.2108
.69	.04654	6.909	.03946	.39	.1933	45.05	.2299
.68	.04807	7.185	.04098	.38	.2072	49.55	.2513
.67	.04968	7.481	.04258	.37	.2227	54.74	.2757
.66	.05142	7.802	.04432	.36	.2398	60.62	.3031
.65	.05324	8.146	.04618	.35	.2590	67.41	.3346
.64	.05518	8.522	.04820	.34	.2803	75.23	.3706
.63	.05723	8.922	.05034	.33	.3044	84.29	.4120
.62	.05942	9.356	.05266	.32	.3311	94.75	.4593
.61	.06174	9.823	.05515	.31	.3614	107.1	.5146
.60	.06423	10.33	.05784	.30	.3958	121.6	.5790
.59	.06686	10.88	.06072	.29	.4352	138.7	.6547
.58	.06967	11.47	.06384	.28	.4798	159.0	.7433
.57	.07268	12.11	.06722	.27	.5311	183.3	.8478
.56	.07590	12.82	.07090	.26	.5902	212.7	.9733
.55	.07936	13.59	.07490	.25	.6598	248.6	1.125
.54	.08304	14.42	.07920	.24	.7405	292.2	1.307
.53	.08701	15.34	.08392	.23	.8344	346.2	1.529
.52	.09128	16.34	.08907	.22	.9474	414.0	1.805
.51	.09587	17.44	.09470	.21	1.082	499.2	2.148
.50	.1008	18.65	.1008	.20	1.244	608.1	2.578
.49	.1061	19.97	.1075	.19	1.440	748.4	3.125
.48	.1119	21.44	.1149	.18	1.684	933.8	3.836
.47	.1182	23.07	.1231	.17	1.985	1179.	4.762
.46	.1250	24.88	.1321	.16	2.364	1514.	6.000
.45	.1323	26.86	.1419	.15	2.847	1971.	7.661
.44	.1404	29.10	.1529	.14	3.484	2629.	10.00
.43	.1491	31.59	.1651	.13	4.319	3572.	13.28
.42	.1587	34.39	.1787	.12	5.452	4977.	18.05
.41	.1691	37.50	.1938	.11	7.038	7174.	25.32

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V. OVAL CONDUITS

The oval conduits in common use are constructed of reinforced concrete. The available conduit sections are described in the Concrete Pipe Design Manual, Chapter 5, First Edition, 1970, issued by the American Concrete Pipe Association, 1501 Wilson Boulevard, Arlington, Virginia, 22209. The section numbers used to designate the various sizes and the pipe dimensions used in the following tables are taken from this manual, which designates the conduits as Elliptical Concrete Pipe.

The concrete pipes are not truly elliptical, as each is composed of four tangent circular arc segments. The radii of the two shorter arcs are equal, as are those of the two longer arcs forming the wider side. A study of the tabular dimensions has revealed that (except for the smallest size, Section 1) the ratio of major axis to minor axis is nearly constant, and the ratio of each arc radius to the axes lengths is also nearly fixed. As would be expected from these conditions, calculations of the geometric properties of area and wetted perimeter at a series of depths of flow relative to the maximum vertical dimension D have shown that the various sizes are geometrically similar. Thus the principles of the calculation methods of this publication may be applied to flow in oval concrete pipe.

The area of flow, the hydraulic radius, and the free-surface width are computed on the basis of the actual inside dimensions of each conduit size (axes lengths) and radii of the forming circular arcs determined from an average value of the ratio of arc radii to axes computed for all sizes, not including Section 1. The geometric properties so determined are, in all cases, within 1 percent of the factors computed for each conduit individually. It is concluded that the generalizations required to formulate Tables 7 and 10 are adequately supported.

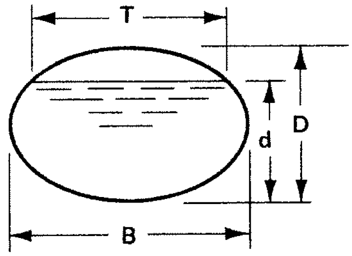
Oval conduits may be installed with either the long axis or the short axis horizontal. The better position must be individually determined for each installation. Therefore, two complete sets of tables are required for hydraulic design of these conduits. One set (Tables 6, 7, and 8) is designated "Long Axis Horizontal"; the second, Tables 9, 10, and 11, is designated "Long Axis Vertical." In each case, letter symbol B designates the maximum horizontal dimension of the conduit and D designates the corresponding vertical dimension. Therefore the value of the factor $BD^{1.5}$ is different for the two positions of each conduit size. Thus the separate tables for long axis horizontal and for long axis vertical are given here in two subchapters. For convenience, the nominal and actual dimensions of the conduits, with $BD^{1.5}$ values, precede the tables for each long axis orientation.

Table 6.—Axes dimensions and $BD^{1.5}$ values for oval concrete pipe, long axis horizontal

Nominal		Actual				$BD^{1.5}$
inches		inches		feet		
B	D	B	D	B	D	
23	14	22.83	14.31	1.902	1.192	2.475
30	19	30.30	19.20	2.525	1.600	5.111
34	22	34.11	21.57	2.843	1.798	6.854
38	24	37.86	23.99	3.155	1.999	8.916
42	27	41.93	26.71	3.494	2.226	11.600
45	29	45.44	28.79	3.787	2.399	14.070
49	32	49.49	31.57	4.124	2.631	17.600
53	34	53.28	34.02	4.440	2.835	21.190
60	38	59.92	38.28	4.993	3.190	28.450
68	43	67.88	43.42	5.657	3.618	38.930
76	48	75.50	48.17	6.292	4.014	50.600
83	53	83.02	53.01	6.918	4.717	64.220
91	58	90.54	57.86	7.545	4.822	79.900
98	63	98.04	62.70	8.170	5.225	97.550
106	68	105.57	67.54	8.797	5.628	117.400
113	72	113.08	72.39	9.423	6.033	139.600
121	77	120.59	77.22	10.05	6.435	164.000
128	82	128.06	82.12	10.67	6.843	191.000
136	87	135.52	87.02	11.29	7.252	220.500
143	92	143.04	91.86	11.92	7.655	252.500
151	97	150.56	96.70	12.55	8.058	278.000
166	106	165.59	106.39	13.80	8.866	364.900
180	116	180.62	116.08	15.05	9.673	452.900

Table 7.—Geometric properties and critical flow factors for oval conduits flowing full and partly full, long axis horizontal

d = Depth of flow
d_c = Critical depth
d_m = Mean depth
D = Height of conduit
B = Width of conduit
A = Area of flow
R = Hydraulic radius
T = Top width of flow
Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$H_c = d_c + (\alpha V_c^2)/(2gD)$ (invariant with α)
V_c = Critical velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



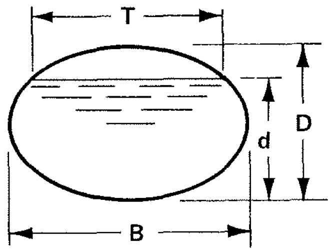
$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.04$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
1.00	0.8108	0.3060	—	—	—	—	—	—
.99	.8094	.3317	0.2096	—	—	—	—	—
.98	.8069	.3430	.2959	—	—	—	—	—
.97	.8036	.3516	.3617	2.222	6.793	6.661	1.1109	2.081
.96	.7997	.3587	.4168	1.918	6.281	6.159	0.9592	1.919
.95	.7953	.3649	.4652	1.710	5.897	5.782	.8548	1.805
.94	.7904	.3704	.5086	1.554	5.588	5.479	.7770	1.717
.93	.7851	.3753	.5483	1.432	5.328	5.224	.7159	1.646
.92	.7794	.3796	.5851	1.332	5.102	5.003	.6661	1.586
.91	.7734	.3835	.6194	1.249	4.901	4.806	.6243	1.534
.90	.7671	.3870	.6516	1.1771	4.720	4.628	.5886	1.489
.89	.7604	.3901	.6808	1.1170	4.557	4.469	.5585	1.448
.88	.7535	.3923	.7068	1.0661	4.412	4.326	.5330	1.413
.87	.7463	.3940	.7297	1.0226	4.280	4.197	.5113	1.381
.86	.7389	.3951	.7504	0.9847	4.158	4.077	.4923	1.352
.85	.7313	.3959	.7692	.9507	4.043	3.965	.4753	1.325
.84	.7235	.3963	.7865	.9199	3.935	3.859	.4600	1.300
.83	.7155	.3964	.8024	.8917	3.832	3.757	.4458	1.276
.82	.7075	.3962	.8173	.8656	3.733	3.660	.4328	1.253
.81	.6992	.3957	.8311	.8413	3.637	3.566	.4207	1.231
.80	.6908	.3950	.8440	.8186	3.544	3.476	.4093	1.209
.79	.6823	.3941	.8560	.7971	3.455	3.388	.3985	1.189
.78	.6737	.3930	.8674	.7767	3.367	3.302	.3884	1.168
.77	.6650	.3917	.8780	.7573	3.282	3.218	.3787	1.149
.76	.6562	.3903	.8881	.7389	3.198	3.136	.3694	1.129
.75	.6472	.3886	.8975	.7211	3.117	3.056	.3606	1.111
.74	.6382	.3868	.9064	.7041	3.037	2.978	.3521	1.092
.73	.6291	.3848	.9147	.6878	2.959	2.901	.3439	1.074
.72	.6199	.3827	.9226	.6719	2.882	2.826	.3360	1.056
.71	.6106	.3805	.9300	.6566	2.806	2.752	.3283	1.038
.70	.6013	.3781	.9369	.6418	2.732	2.679	.3209	1.0209
.69	.5919	.3755	.9434	.6274	2.659	2.607	.3137	1.0037
.68	.5825	.3729	.9495	.6134	2.587	2.537	.3067	.9867
.67	.5729	.3701	.9552	.5998	2.516	2.467	.2999	.9699
.66	.5633	.3672	.9605	.5865	2.447	2.399	.2933	.9533
.65	.5537	.3642	.9655	.5735	2.378	2.332	.2868	.9368
.64	.5440	.3610	.9700	.5608	2.310	2.266	.2804	.9204
.63	.5343	.3577	.9743	.5484	2.244	2.200	.2742	.9042
.62	.5246	.3544	.9782	.5363	2.178	2.136	.2681	.8881
.61	.5147	.3509	.9817	.5243	2.114	2.073	.2622	.8722
.60	.5049	.3473	.9849	.5127	2.050	2.010	.2563	.8563
.59	.4950	.3436	.9878	.5012	1.987	1.949	.2506	.8406
.58	.4852	.3398	.9904	.4899	1.926	1.888	.2449	.8249
.57	.4752	.3359	.9927	.4788	1.865	1.829	.2394	.8094
.56	.4653	.3319	.9946	.4678	1.805	1.770	.2339	.7939

Table 7.—Geometric properties and critical flow factors for oval conduits flowing full and partly full, long axis horizontal—Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.04$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
0.55	0.4554	0.3278	0.9963	0.4571	1.746	1.712	0.2285	0.7785
.54	.4454	.3236	.9976	.4465	1.688	1.655	.2232	.7632
.53	.4354	.3194	.9987	.4360	1.630	1.599	.2180	.7480
.52	.4254	.3150	.9994	.4257	1.574	1.543	.2128	.7328
.51	.4154	.3105	.9998	.4155	1.519	1.489	.2077	.7177
.50	.4054	.3060	1.0000	.4054	1.464	1.435	.2027	.7027
.49	.3954	.3013	.9998	.3955	1.410	1.383	.1977	.6877
.48	.3854	.2966	.9994	.3857	1.357	1.331	.1928	.6728
.47	.3754	.2918	.9987	.3759	1.305	1.280	.1880	.6580
.46	.3655	.2869	.9976	.3663	1.254	1.230	.1832	.6432
.45	.3555	.2819	.9963	.3568	1.204	1.1808	.1784	.6284
.44	.3456	.2768	.9946	.3474	1.155	1.1324	.1737	.6137
.43	.3356	.2716	.9927	.3381	1.107	1.0850	.1690	.5990
.42	.3257	.2664	.9904	.3288	1.059	1.0385	.1644	.5844
.41	.3158	.2611	.9878	.3197	1.013	0.9928	.1598	.5698
.40	.3059	.2557	.9849	.3106	0.9669	.9481	.1553	.5553
.39	.2961	.2502	.9817	.3016	.9221	.9042	.1508	.5408
.38	.2863	.2447	.9782	.2927	.8783	.8613	.1463	.5263
.37	.2765	.2391	.9743	.2838	.8354	.8192	.1419	.5119
.36	.2668	.2334	.9700	.2750	.7935	.7781	.1375	.4975
.35	.2571	.2276	.9655	.2663	.7525	.7379	.1332	.4832
.34	.2475	.2218	.9605	.2577	.7124	.6986	.1288	.4688
.33	.2379	.2159	.9552	.2491	.6733	.6603	.1245	.4545
.32	.2284	.2099	.9495	.2406	.6352	.6229	.1203	.4403
.31	.2189	.2038	.9434	.2321	.5981	.5864	.1160	.4260
.30	.2095	.1977	.9369	.2236	.5619	.5510	.11182	.4118
.29	.2002	.1915	.9300	.2153	.5267	.5165	.10763	.3976
.28	.1909	.1853	.9226	.2070	.4926	.4830	.10347	.3835
.27	.1817	.1790	.9147	.1987	.4594	.4505	.09934	.3693
.26	.1726	.1726	.9064	.1905	.4273	.4190	.09523	.3552
.25	.1636	.1662	.8975	.1823	.3962	.3885	.09115	.3411
.24	.1547	.1597	.8881	.1742	.3661	.3590	.08709	.3271
.23	.1458	.1531	.8780	.1661	.3371	.3306	.08306	.3131
.22	.1371	.1465	.8674	.1581	.3092	.3032	.07905	.2991
.21	.1285	.1398	.8560	.1501	.2824	.2769	.07506	.2851
.20	.12001	.1332	.8440	.1422	.2566	.2517	.07110	.2711
.19	.11163	.1264	.8311	.1343	.2320	.2275	.06716	.2572
.18	.10339	.1196	.8173	.1265	.2085	.2045	.06325	.2433
.17	.09529	.1128	.8024	.1187	.1862	.1826	.05937	.2294
.16	.08734	.1060	.7865	.1111	.1651	.1619	.05553	.2155
.15	.07956	.09909	.7692	.10343	.14511	.14230	.05172	.2017
.14	.07197	.09224	.7504	.09590	.12638	.12393	.04795	.1880
.13	.06456	.08541	.7297	.08847	.10890	.10679	.04424	.1742
.12	.05738	.07864	.7068	.08118	.09271	.09091	.04059	.1606
.11	.05044	.07199	.6808	.07409	.07786	.07634	.03704	.1470

Table 8.—Velocity head and resistance computation factors for oval conduits flowing full and partly full, long axis horizontal

Column A: Relative depth of flow, d/D
Column B: Relative velocity head $h_v/D = \alpha V^2/2gD$, $\alpha = 1.00$, $Q/BD^{1.5} = 1.0$
V = Mean flow velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.
Column C: Resistance computation factor K_n for the Manning equation, $V = (1.486/n)(R)^{2/3}(S)^{1/2}$
$S_f = Q^2n^2/2.208\ R^{4/3}A^2 = K_n(n^2/D^{1/3})(Q/BD^{1.5})^2$
$K_n = 0.4529/(R/D)^{4/3}(A/BD)^2$
A = Area of flow
R = Hydraulic radius
S_f = Friction slope
n = Manning coefficient
Column D: Resistance computation factor K_f for the Darcy equation, $h_f = (f)(L/4R)(V^2/2g)$
$S_f = Q^2f/257.28\ RA^2 = K_f(f)(Q/BD^{1.5})^2$
$K_f = 0.003887/(R/D)(A/BD)^2$
h_f = Friction head loss, ft.
f = Darcy coefficient
L = Length of conduit, ft.



(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
1.00	0.02365	3.341	0.01932	0.60	0.06098	7.276	0.04390
0.99	.02373	3.010	.01788	.59	.06344	7.678	.04616
.98	.02388	2.898	.01741	.58	.06605	8.113	.04860
.97	.02408	2.826	.01712	.57	.06884	8.586	.05123
.96	.02431	2.778	.01694	.56	.07181	9.101	.05409
.95	.02458	2.746	.01684	.55	.07498	9.662	.05718
.94	.02489	2.725	.01680	.54	.07838	10.274	.06054
.93	.02522	2.714	.01680	.53	.08201	10.943	.06420
.92	.02559	2.712	.01685	.52	.08591	11.676	.06819
.91	.02599	2.717	.01694	.51	.09009	12.480	.07254
.90	.02642	2.729	.01707	.50	.09459	13.36	.07729
.89	.02689	2.748	.01724	.49	.09944	14.34	.08251
.88	.02739	2.778	.01745	.48	.10466	15.41	.08823
.87	.02792	2.815	.01772	.47	.11030	16.60	.09452
.86	.02848	2.861	.01802	.46	.11641	17.92	.10146
.85	.02907	2.913	.01836	.45	.1230	19.39	.1091
.84	.02970	2.972	.01874	.44	.1302	21.03	.1176
.83	.03037	3.038	.01915	.43	.1381	22.86	.1271
.82	.03107	3.110	.01961	.42	.1466	24.91	.1376
.81	.03180	3.189	.02009	.41	.1559	27.21	.1493
.80	.03258	3.274	.02062	.40	.1661	29.81	.1624
.79	.03339	3.366	.02118	.39	.1773	32.76	.1772
.78	.03425	3.466	.02179	.38	.1897	36.10	.1938
.77	.03516	3.573	.02244	.37	.2033	39.91	.2126
.76	.03611	3.688	.02313	.36	.2184	44.27	.2340
.75	.03712	3.812	.02388	.35	.2352	49.29	.2583
.74	.03817	3.945	.02467	.34	.2538	55.07	.2861
.73	.03928	4.088	.02552	.33	.2747	61.78	.3181
.72	.04046	4.241	.02643	.32	.2981	69.60	.3550
.71	.04169	4.405	.02740	.31	.3244	78.76	.3979
.70	.04300	4.581	.02843	.30	.3542	89.56	.4478
.69	.04438	4.770	.02954	.29	.3880	102.35	.5064
.68	.04583	4.974	.03073	.28	.4265	117.61	.5755
.67	.04737	5.192	.03200	.27	.4707	135.94	.6575
.66	.04899	5.427	.03336	.26	.5217	158.12	.7557
.65	.05071	5.680	.03481	.25	.5808	185.2	.8739
.64	.05253	5.952	.03638	.24	.6498	218.5	1.0174
.63	.05446	6.246	.03806	.23	.7308	259.9	1.1933
.62	.05650	6.563	.03986	.22	.8268	311.8	1.4109
.61	.05868	6.905	.04181	.21	.9414	377.7	1.6830

Table 8.—Velocity head and resistance computation factors for oval conduits flowing full and partly full, long axis horizontal—Continued

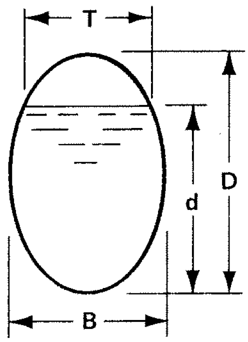
(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.00$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
.20	1.080	462.5	2.027	.15	2.456	1560.	6.196
.19	1.248	572.9	2.468	.14	3.002	2098.	8.137
.18	1.454	718.9	3.040	.13	3.730	2888.	10.918
.17	1.712	915.1	3.795	.12	4.722	4083.	15.013
.16	2.038	1184.0	4.809	.11	6.112	5945.	21.226

Table 9.—Axes dimensions and $BD^{1.5}$ values for oval concrete pipe, long axis vertical

Nominal inches B	Nominal inches D	Actual inches B	Actual inches D	Actual feet B	Actual feet D	$BD^{1.5}$	Nominal inches B	Nominal inches D	Actual inches B	Actual inches D	Actual feet B	Actual feet D	$BD^{1.5}$
14	23	14.31	22.83	1.192	1.902	3.127	58	91	57.86	90.54	4.822	7.545	99.910
19	30	19.20	30.30	1.600	2.525	6.419	63	98	62.70	98.04	5.225	8.170	122.000
22	34	21.57	34.11	1.798	2.843	8.620	68	106	67.54	105.57	5.628	8.797	146.800
24	38	23.99	37.86	1.999	3.155	11.200	72	113	72.39	113.08	6.033	9.423	174.500
27	42	26.71	41.93	2.226	3.494	14.540	77	121	77.22	120.59	6.435	10.05	205.000
29	45	28.79	45.44	2.399	3.787	17.680	82	128	82.12	128.06	6.843	10.67	238.500
32	49	31.57	49.49	2.631	4.124	22.030	87	136	87.02	135.52	7.252	11.29	275.100
34	53	34.02	53.28	2.835	4.440	26.520	92	143	91.86	143.04	7.655	11.92	315.100
38	60	38.28	59.92	3.190	4.993	35.600	97	151	96.70	150.56	8.058	12.55	358.300
43	68	43.42	67.88	3.618	5.657	48.700	106	166	106.39	165.59	8.866	13.80	454.600
48	76	48.17	75.50	4.014	6.292	63.340	116	180	116.08	180.62	9.673	15.05	564.800
53	83	53.01	83.02	4.717	6.918	80.390							

Table 10.—Geometric properties and critical flow factors for oval conduits flowing full and partly full, long axis vertical

d = Depth of flow
d_c = Critical depth
d_m = Mean depth
D = Height of conduit
B = Width of conduit
A = Area of flow
R = Hydraulic radius
T = Top width of flow
Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$H_c = d_c + (\alpha V^2)/(2gD)$ (invariant with α)
V_c = Critical velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.04$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
1.00	0.8108	0.1953	—	—	—	—	—	—
0.99	.8093	.2065	0.2298	—	—	—	—	—
.98	.8065	.2110	.3220	—	—	—	—	—
.97	.8029	.2143	.3906	2.056	6.528	6.402	1.0278	1.998
.96	.7987	.2169	.4467	1.788	6.057	5.940	0.8941	1.854
.95	.7940	.2190	.4944	1.606	5.706	5.596	.8030	1.753
.94	.7889	.2208	.5361	1.471	5.427	5.321	.7357	1.676
.93	.7833	.2222	.5731	1.367	5.193	5.092	.6834	1.613
.92	.7774	.2234	.6062	1.282	4.992	4.896	.6412	1.561
.91	.7712	.2244	.6361	1.212	4.816	4.722	.6062	1.516

Table 10. – Geometric properties and critical flow factors for oval conduits flowing full and partly full, long axis vertical – Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$		$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
					$\alpha = 1.00$	$\alpha = 1.04$		
0.90	0.7647	0.2253	0.6631	1.1532	4.657	4.566	0.5766	1.476
.89	.7579	.2259	.6877	1.1022	4.513	4.425	.5511	1.441
.88	.7510	.2265	.7100	1.0577	4.380	4.295	.5289	1.409
.87	.7437	.2268	.7303	1.0184	4.257	4.174	.5092	1.379
.86	.7364	.2271	.7487	0.9835	4.141	4.061	.4918	1.352
.85	.7288	.2272	.7654	.9521	4.033	3.955	.4761	1.326
.84	.7211	.2273	.7805	.9238	3.930	3.854	.4619	1.302
.83	.7132	.2273	.7946	.8975	3.832	3.757	.4487	1.279
.82	.7052	.2272	.8074	.8734	3.737	3.665	.4367	1.257
.81	.6970	.2270	.8196	.8504	3.645	3.574	.4252	1.235
.80	.6888	.2268	.8315	.8284	3.555	3.486	.4142	1.214
.79	.6804	.2265	.8429	.8072	3.467	3.399	.4036	1.194
.78	.6719	.2262	.8538	.7870	3.380	3.315	.3935	1.174
.77	.6633	.2258	.8643	.7674	3.295	3.231	.3837	1.154
.76	.6546	.2254	.8745	.7486	3.212	3.150	.3743	1.134
.75	.6458	.2249	.8841	.7305	3.130	3.070	.3652	1.115
.74	.6370	.2244	.8934	.7130	3.050	2.991	.3565	1.096
.73	.6280	.2238	.9023	.6960	2.971	2.913	.3480	1.078
.72	.6189	.2231	.9107	.6796	2.893	2.837	.3398	1.060
.71	.6098	.2224	.9188	.6637	2.817	2.762	.3318	1.042
.70	.6005	.2217	.9264	.6482	2.742	2.689	.3241	1.0241
.69	.5912	.2209	.9337	.6332	2.668	2.616	.3166	1.0066
.68	.5819	.2200	.9406	.6186	2.595	2.545	.3093	0.9893
.67	.5724	.2191	.9470	.6044	2.524	2.475	.3022	.9722
.66	.5629	.2181	.9532	.5906	2.453	2.406	.2953	.9553
.65	.5534	.2171	.9589	.5771	2.384	2.338	.2885	.9385
.64	.5438	.2160	.9642	.5639	2.316	2.271	.2820	.9220
.63	.5341	.2149	.9692	.5511	2.248	2.205	.2755	.9055
.62	.5244	.2137	.9738	.5385	2.182	2.140	.2693	.8893
.61	.5146	.2125	.9780	.5262	2.117	2.076	.2631	.8731
.60	.5048	.2112	.9818	.5142	2.053	2.013	.2571	.8571
.59	.4950	.2098	.9853	.5024	1.990	1.951	.2512	.8412
.58	.4851	.2084	.9884	.4908	1.927	1.890	.2454	.8254
.57	.4752	.2070	.9911	.4795	1.866	1.830	.2397	.8097
.56	.4653	.2055	.9935	.4684	1.806	1.771	.2342	.7942
.55	.4553	.2039	.9955	.4574	1.746	1.712	.2287	.7787
.54	.4454	.2023	.9971	.4467	1.688	1.655	.2233	.7633
.53	.4354	.2006	.9984	.4361	1.631	1.599	.2181	.7481
.52	.4254	.1989	.9993	.4257	1.574	1.544	.2129	.7329
.51	.4154	.1971	.9998	.4155	1.519	1.489	.2077	.7177
.50	.4054	.1953	1.0000	.4054	1.464	1.435	.2027	.7027
.49	.3954	.1934	.9998	.3955	1.410	1.383	.1977	.6877
.48	.3854	.1914	.9993	.3857	1.357	1.331	.1929	.6729
.47	.3754	.1894	.9984	.3760	1.306	1.280	.1880	.6580
.46	.3655	.1873	.9971	.3665	1.255	1.230	.1833	.6433
.45	.3555	.1852	.9955	.3571	1.205	1.1813	.1786	.6286
.44	.3456	.1830	.9935	.3478	1.156	1.1332	.1739	.6139
.43	.3356	.1808	.9911	.3386	1.108	1.0861	.1693	.5993
.42	.3257	.1785	.9884	.3296	1.060	1.0398	.1648	.5848
.41	.3159	.1761	.9853	.3206	1.014	0.9945	.1603	.5703
.40	.3060	.1737	.9818	.3117	0.9689	.9501	.1559	.5559
.39	.2962	.1712	.9780	.3029	.9245	.9066	.1514	.5414
.38	.2865	.1686	.9738	.2942	.8811	.8640	.1471	.5271
.37	.2767	.1660	.9692	.2855	.8387	.8224	.1428	.5128
.36	.2671	.1633	.9642	.2770	.7972	.7817	.1385	.4985

Table 10. – Geometric properties and critical flow factors for oval conduits flowing full and partly full, long axis vertical – Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.04$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
0.35	0.2575	0.1606	0.9589	0.2685	0.7566	.7419	.1342	0.4842
.34	.2479	.1577	.9532	.2601	.7170	.7031	.1301	.4701
.33	.2384	.1548	.9470	.2517	.6783	.6652	.1259	.4559
.32	.2290	.1519	.9406	.2434	.6406	.6282	.1217	.4417
.31	.2196	.1488	.9337	.2352	.6039	.5922	.1176	.4276
.30	.2103	.1457	.9264	.2270	.5682	.5572	.11350	.4135
.29	.2011	.1425	.9188	.2188	.5334	.5230	.10942	.3994
.28	.1919	.1392	.9107	.2107	.4996	.4899	.10537	.3854
.27	.1828	.1358	.9023	.2027	.4668	.4577	.10133	.3713
.26	.1739	.1324	.8934	.1946	.4350	.4266	.09731	.3573
.25	.1650	.1288	.8841	.1866	.4042	.3963	.09330	.3433
.24	.1562	.1251	.8745	.1786	.3744	.3671	.08931	.3293
.23	.1475	.1214	.8643	.1706	.3455	.3388	.08532	.3153
.22	.1389	.1175	.8538	.1627	.3177	.3116	.08134	.3013
.21	.1304	.1135	.8429	.1547	.2909	.2853	.07737	.2874
.20	.12205	.10941	.8315	.1468	.2652	.2600	.07339	.2734
.19	.11380	.10517	.8196	.1388	.2405	.2358	.06942	.2594
.18	.10566	.10079	.8074	.1309	.2168	.2126	.06543	.2454
.17	.09765	.09626	.7946	.1229	.1941	.1903	.06144	.2314
.16	.08977	.09158	.7805	.1150	.1727	.1693	.05751	.2175
.15	.08204	.08677	.7654	.10719	.15233	.14937	.05359	.2036
.14	.07447	.08184	.7487	.09947	.13320	.13061	.04973	.1897
.13	.06708	.07678	.7303	.09185	.11528	.11304	.04592	.1759
.12	.05987	.07160	.7100	.08433	.09860	.09668	.04216	.1622
.11	.05288	.06629	.6877	.07690	.08316	.08155	.03845	.1484

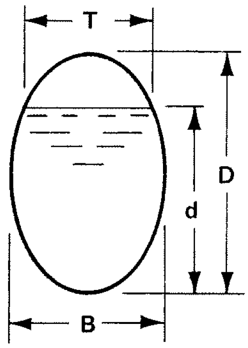
Table 11. – Velocity head and resistance computation factors for oval conduits flowing full and partly full, long axis vertical

Column A: Relative depth of flow, d/D

Column B: Relative velocity head
$h_v/D = \alpha V^2/2gD$, $\alpha = 1.00$, $Q/BD^{1.5} = 1.0$
V = Mean flow velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.

Column C: Resistance computation factor K_n for the Manning equation, $V = (1.486/n)\ (R)^{2/3}\ (S)^{1/2}$
$S_f = Q^2 n^2 / 2.208\ R^{4/3} A^2 = K_n\ (n^2/D^{1/3})\ (Q/BD^{1.5})^2$
$K_n = 0.4529/(R/D)^{4/3}\ (A/BD)^2$
A = Area of flow S_f = Friction slope
R = Hydraulic radius n = Manning coefficient

Column D: Resistance computation factor K_f for the Darcy equation, $h_f = (f)\ (L/4R)\ (V^2/2g)$
$S_f = Q^2 f / 257.28\ RA^2 = K_f (f)\ (Q/BD^{1.5})^2$
$K_f = 0.003887/(R/D)\ (A/BD)^2$
h_f = Friction head loss, ft.
f = Darcy coefficient
L = Length of conduit, ft.



(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
1.00	0.02365	6.081	0.03028	0.95	0.02466	5.441	0.02815
0.99	.02374	5.666	.02875	.94	.02498	5.454	.02829
.98	.02390	5.543	.02832	.93	.02534	5.483	.02851
.97	.02412	5.478	.02814	.92	.02573	5.526	.02878
.96	.02437	5.447	.02809	.91	.02614	5.582	.02912

Table 11.—Velocity head and resistance computation factors for oval conduits flowing full and partly full, long axis vertical—Continued

(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
0.90	0.02659	5.650	0.02951	0.50	0.09459	24.32	0.1211
.89	.02706	5.729	.02995	.49	.09944	25.90	.1286
.88	.02757	5.818	.03044	.48	.10466	27.64	.1367
.87	.02811	5.918	.03098	.47	.11031	29.54	.1456
.86	.02867	6.028	.03157	.46	.11641	31.63	.1554
.85	.02927	6.148	.03220	.45	.1230	33.94	.1661
.84	.02990	6.279	.03289	.44	.1302	36.50	.1779
.83	.03057	6.420	.03363	.43	.1380	39.33	.1909
.82	.03127	6.570	.03441	.42	.1465	42.48	.2053
.81	.03200	6.731	.03524	.41	.1558	45.98	.2212
.80	.03277	6.902	.03613	.40	.1660	49.90	.2390
.79	.03358	7.084	.03706	.39	.1772	54.30	.2588
.78	.03444	7.278	.03806	.38	.1895	59.23	.2809
.77	.03533	7.484	.03912	.37	.2030	64.81	.3057
.76	.03628	7.704	.04024	.36	.2180	71.11	.3336
.75	.03727	7.938	.04143	.35	.2345	78.28	.3652
.74	.03832	8.187	.04270	.34	.2530	86.46	.4010
.73	.03943	8.453	.04405	.33	.2735	95.83	.4417
.72	.04059	8.736	.04548	.32	.2966	106.61	.4882
.71	.04182	9.038	.04700	.31	.3224	119.08	.5416
.70	.04311	9.360	.04862	.30	.3516	133.6	.6033
.69	.04448	9.704	.05035	.29	.3846	150.5	.6748
.68	.04592	10.071	.05219	.28	.4221	170.4	.7581
.67	.04745	10.464	.05415	.27	.4650	194.0	.8559
.66	.04906	10.885	.05624	.26	.5143	222.1	.9714
.65	.05077	11.34	.05847	.25	.5712	255.8	1.109
.64	.05258	11.82	.06086	.24	.6373	296.6	1.273
.63	.05451	12.34	.06342	.23	.7146	346.4	1.472
.62	.05654	12.89	.06615	.22	.8058	407.8	1.714
.61	.05871	13.49	.06909	.21	.9140	484.3	2.013
.60	.06101	14.13	.07223	.20	1.044	581.0	2.385
.59	.06346	14.82	.07561	.19	1.201	704.4	2.854
.58	.06607	15.57	.07925	.18	1.393	864.8	3.454
.57	.06885	16.38	.08316	.17	1.630	1076.6	4.235
.56	.07182	17.25	.08739	.16	1.929	1361.2	5.266
.55	.07499	18.20	.09194	.15	2.310	1751.	6.655
.54	.07838	19.23	.09687	.14	2.803	2298.	8.564
.53	.08201	20.34	.10221	.13	3.456	3084.	11.252
.52	.08591	21.55	.10799	.12	4.337	4249.	15.145
.51	.09009	22.88	.11428	.11	5.559	6036.	20.968

VI. CORRUGATED METAL PIPE-ARCHES, $2\frac{2}{3}$ BY $\frac{1}{2}$ IN. CORRUGATIONS

Pipe-arch sections with ½ in. deep corrugations are formed by pressure deformation of circular corrugated metal pipes. The sizes commonly available are formed from pipes of diameters ranging from 15 to 72 in.

The basis for preparation of the following table of geometric and hydraulic factors was the "Handbook of Steel Drainage and Highway Construction Products," page 26, Table 1-14, published by the American Iron and Steel Institute (see item 8 in the bibliography).

As the manufacturer's handbook states, the present method of manufacturing pipe-arches with ½ in. corrugations does not permit highly accurate conformance with the nominal dimensions. The assumption of geometric similarity among the various sizes of pipe-arches, which is necessary for compilation of the hydraulic tables, is based on the fact that deformation of circular pipe to the pipe-arch form does not modify the perimeter, at least along the neutral axis of the corrugations. In making up the table, it was assumed that the perimeter measured along the inside crests of the corrugations would therefore remain constant. In addition, an examination of the ratio of the nominal span of the pipe-arch to the diameter of the originating pipe showed a nearly constant relationship. The same was true for the ratio of rise to diameter, as shown in Table 12. Taking the mean ratio of span to pipe diameter as 1.197, and of rise to diameter as 0.745 for the ten largest sections, one obtains the modified values for the span and rise.

A computer program based upon the relative radii of the arcs comprising the boundary (fixed perimeter) and modified values of span and rise was used to determine the area, wetted perimeter, and top width. Then these factors were used to compute the critical flow factors and the velocity head and resistance computation factors of the following tables. The mean values of all these factors for the ten largest sections were computed at relative depth intervals of $0.01D$, as given in Tables 13 and 14.

In the range of $\frac{d}{D} = 1.00$ to $\frac{d}{D} = 0.40$, the error for the ten largest sections in the most unfavorable case did not exceed 2.5 percent. Sections No. 1 and No. 2, the smallest sizes, did not conform as closely to these mean values for the geometric and hydraulic factors. However, the highest error for section No. 2 did not exceed six percent. Only section No. 1 showed a deviation which was as high as 19 percent, at worst. For a diagram (No. 1) to correct this error, see Appendix A.

Tables 12, 13, and 14 are intended for all computations related to steady flow in pipe-arches with $2\frac{2}{3}$ by ½ in. corrugations.

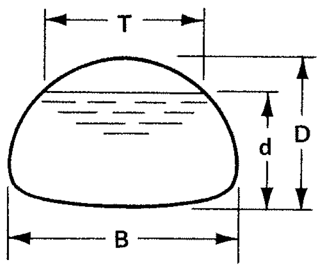
Corrugated metal pipe-arches are also manufactured with 3 by 1 in. corrugations by methods similar to those for the ½ in. deep corrugations. The geometric factors for these sections are not identical to and cannot be used for those in the tables for ½ in. corrugation pipe arches. However, since the tables for structural plate pipe-arch geometry are fairly similar to those for the 3 by 1 in. corrugation pipe arches, these may be applied for hydraulic computation purposes.

Table 12.—Span and rise dimensions and $BD^{1.5}$ values for corrugated metal pipe-arches, 2⅔ by ½ in. corrugations

Sec. No.	Diameter of circ. pipe used to form pipe-arch (in.)	Dimensions: Nominal: Handbook data: Span (in.)	Handbook data: Rise (in.)	In refer. to circ. pipe: Span B	In refer. to circ. pipe: Rise D	Modified values for design: Span (in.)	Rise (in.)	Span (ft.)	Rise (ft.)	Design values $BD^{1.5}$
1	15	18	11	1.200	0.733	17.95	11.17	1.496	0.931	1.344
2	18	22	13	1.222	0.722	21.55	13.41	1.796	1.117	2.121
3	21	25	16	1.190	0.762	25.14	15.64	2.095	1.303	3.115
4	24	29	18	1.208	0.750	28.73	17.88	2.394	1.490	4.355
5	30	36	22	1.200	0.733	35.91	22.35	2.992	1.862	7.603
6	36	43	27	1.194	0.750	43.09	26.82	3.591	2.235	12.000
7	42	50	31	1.190	0.738	50.27	31.29	4.189	2.607	17.630
8	48	58	36	1.208	0.750	57.46	35.76	4.788	2.980	24.63
9	54	65	40	1.204	0.741	64.64	40.23	5.387	3.352	33.06
10	60	72	44	1.200	0.733	71.82	44.70	5.985	3.725	43.03
11	66	79	49	1.197	0.742	79.00	49.17	6.583	4.097	54.59
12	72	85	54	1.181	0.750	86.18	53.64	7.182	4.470	67.88
		Average		1.197	0.745					

Table 13.—Geometric properties and critical flow factors for corrugated metal pipe-arches, 2⅔ by ½ in. corrugations, flowing full and partly full

d = Depth of flow
d_c = Critical depth
d_m = Mean depth
D = Rise of conduit
B = Span of conduit
A = Area of flow
R = Hydraulic radius
T = Top width of flow
Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$H_c = d_c + (\alpha V_c^2)/(2gD)$ (invariant with α)
V_c = Critical velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.12$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
1.00	0.7879	0.2991	–	–	–	–	–	–
.99	.7869	.3179	.1580	–	–	–	–	–
.98	.7850	.3258	.2228	–	–	–	–	–
.97	.7825	.3317	.2720	2.877	7.527	7.112	1.439	2.409
.96	.7796	.3366	.3131	2.490	6.976	6.592	1.245	2.205
.95	.7762	.3408	.3489	2.225	6.566	6.204	1.1124	2.062
.94	.7726	.3444	.3810	2.028	6.239	5.895	1.0139	1.954
.93	.7686	.3475	.4102	1.874	5.967	5.638	.9369	1.867
.92	.7644	.3503	.4371	1.749	5.732	5.417	.8744	1.794
.91	.7599	.3527	.4621	1.644	5.526	5.222	.8222	1.732
.90	.7552	.3549	.4855	1.555	5.341	5.047	.7777	1.678
.89	.7502	.3568	.5075	1.478	5.172	4.887	.7391	1.629
.88	.7450	.3585	.5283	1.410	5.017	4.741	.7051	1.585
.87	.7396	.3599	.5481	1.350	4.873	4.604	.6747	1.545
.86	.7341	.3612	.5669	1.295	4.737	4.476	.6475	1.507

Table 13.—Geometric properties and critical flow factors for corrugated metal pipe-arches 2⅔ by ½ in. corrugations, flowing full and partly full—Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha = 1.12$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
0.85	0.7283	0.3622	0.5848	1.245	4.609	4.355	0.6227	1.473
.84	.7224	.3631	.6019	1.200	4.488	4.240	.6001	1.440
.83	.7162	.3638	.6183	1.158	4.372	4.131	.5792	1.409
.82	.7100	.3644	.6340	1.120	4.261	4.026	.5599	1.380
.81	.7036	.3647	.6491	1.084	4.154	3.925	.5419	1.352
.80	.6970	.3649	.6637	1.0503	4.051	3.828	.5251	1.325
.79	.6903	.3650	.6776	1.0187	3.951	3.733	.5093	1.299
.78	.6835	.3649	.6911	0.9889	3.854	3.642	.4945	1.274
.77	.6765	.3647	.7041	.9607	3.760	3.553	.4804	1.250
.76	.6694	.3644	.7167	.9340	3.669	3.466	.4670	1.227
.75	.6621	.3639	.7288	.9085	3.579	3.382	.4543	1.204
.74	.6548	.3632	.7405	.8842	3.492	3.299	.4421	1.182
.73	.6473	.3625	.7519	.8610	3.406	3.219	.4305	1.160
.72	.6398	.3616	.7628	.8387	3.323	3.140	.4193	1.139
.71	.6321	.3606	.7734	.8173	3.240	3.062	.4086	1.119
.70	.6243	.3595	.7837	.7966	3.160	2.986	.3983	1.098
.69	.6164	.3582	.7936	.7767	3.081	2.911	.3883	1.078
.68	.6084	.3568	.8033	.7575	3.003	2.838	.3787	1.059
.67	.6003	.3553	.8126	.7388	2.926	2.765	.3694	1.039
.66	.5922	.3537	.8216	.7208	2.851	2.694	.3604	1.020
.65	.5839	.3520	.8303	.7033	2.777	2.624	.3516	1.0016
.64	.5756	.3501	.8388	.6862	2.704	2.555	.3431	0.9831
.63	.5671	.3481	.8470	.6696	2.632	2.487	.3348	.9648
.62	.5586	.3461	.8549	.6535	2.561	2.420	.3267	.9467
.61	.5500	.3438	.8626	.6377	2.491	2.354	.3188	.9288
.60	.5414	.3415	.8700	.6223	2.422	2.288	.3111	.9111
.59	.5326	.3391	.8772	.6072	2.354	2.224	.3036	.8936
.58	.5238	.3365	.8842	.5925	2.287	2.161	.2962	.8762
.57	.5150	.3339	.8909	.5780	2.220	2.098	.2890	.8590
.56	.5060	.3311	.8974	.5639	2.155	2.036	.2819	.8419
.55	.4970	.3282	.9037	.5500	2.090	1.975	.2750	.8250
.54	.4880	.3252	.9098	.5364	2.027	1.915	.2682	.8082
.53	.4788	.3220	.9156	.5229	1.964	1.855	.2615	.7915
.52	.4696	.3188	.9213	.5098	1.901	1.797	.2549	.7749
.51	.4604	.3154	.9268	.4968	1.840	1.739	.2484	.7584
.50	.4511	.3120	.9320	.4840	1.780	1.682	.2420	.7420
.49	.4417	.3084	.9371	.4714	1.720	1.625	.2357	.7257
.48	.4324	.3046	.9420	.4590	1.661	1.570	.2295	.7095
.47	.4229	.3008	.9467	.4468	1.603	1.515	.2234	.6934
.46	.4134	.2969	.9512	.4347	1.546	1.461	.2173	.6773
.45	.4039	.2928	.9555	.4227	1.489	1.407	.2114	.6614
.44	.3943	.2886	.9597	.4109	1.433	1.354	.2055	.6455
.43	.3847	.2843	.9636	.3993	1.378	1.303	.1996	.6296
.42	.3751	.2798	.9674	.3877	1.324	1.251	.1939	.6138
.41	.3653	.2752	.9710	.3763	1.271	1.201	.1881	.5981
.40	.3556	.2705	.9755	.3646	1.218	1.1506	.1823	.5823
.39	.3458	.2657	.9788	.3534	1.166	1.1017	.1767	.5667
.38	.3361	.2607	.9818	.3423	1.115	1.0535	.1711	.5511
.37	.3262	.2556	.9846	.3314	1.065	1.0062	.1657	.5357
.36	.3164	.2504	.9865	.3207	1.016	0.9600	.1604	.5204
.35	.3065	.2451	.9889	.3100	0.9676	.9143	.1550	.5050
.34	.2966	.2396	.9910	.2993	.9201	.8694	.1496	.4896
.33	.2867	.2339	.9930	.2887	.8735	.8254	.1443	.4743
.32	.2767	.2282	.9947	.2782	.8278	.7822	.1391	.4591
.31	.2668	.2223	.9955	.2680	.7832	.7400	.1340	.4440

Table 13. – Geometric properties and critical flow factors for corrugated metal pipe-arches 2⅔ by ½ in. corrugations, flowing full and partly full – Continued

$\frac{d}{D}$ or $\frac{d}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$		$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
					$\alpha = 1.00$	$\alpha = 1.12$		
0.30	0.2568	0.2162	0.9967	0.2577	0.7393	0.6986	.1288	.4288
.29	.2468	.2100	.9991	.2470	.6960	.6574	.1235	.4135
.28	.2369	.2037	.9979	.2373	.6544	.6183	.1187	.3987
.27	.2269	.1972	.9984	.2272	.6133	.5795	.1136	.3836
.26	.2169	.1906	.9978	.2173	.5735	.5419	.1087	.3687
.25	.2069	.1839	.9967	.2076	.5347	.5052	.10380	.3538
.24	.1970	.1770	.9949	.1979	.4970	.4696	.09898	.3390
.23	.1870	.1700	.9925	.1884	.4604	.4350	.09421	.3242
.22	.1771	.1629	.9895	.1790	.4249	.4015	.08949	.3095
.21	.1672	.1557	.9859	.1696	.3906	.3691	.08482	.2948
.20	.1574	.1484	.9815	.1603	.3574	.3378	.08018	.2802
.19	.1476	.1409	.9764	.1511	.3255	.3075	.07559	.2656
.18	.1379	.1334	.9706	.1420	.2947	.2785	.07103	.2510
.17	.1282	.1258	.9639	.1330	.2651	.2505	.06650	.2365
.16	.1186	.1180	.9563	.1240	.2369	.2238	.06201	.2220
.15	.10908	.11022	.9477	.11505	.2098	.1983	.05755	.2075
.14	.09965	.10232	.9380	.10619	.1842	.1740	.05312	.1931
.13	.09032	.09436	.9269	.09740	.1599	.1511	.04872	.1787
.12	.08111	.08634	.9143	.08867	.1370	.1295	.04436	.1644
.11	.07204	.07828	.8998	.08002	.1156	.1092	.04003	.1500

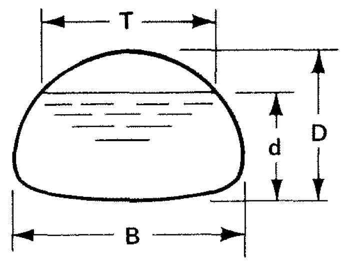
Table 14. – Velocity head and resistance computation factors for corrugated metal pipe-arches, 2⅔ by ½ in. corrugations, flowing full and partly full

Column A: Relative depth of flow, d/D

Column B: Relative velocity head
$h_v/D = \alpha V^2/2gD$, $\alpha = 1.00$, $Q/BD^{1.5} = 1.0$
V = Mean flow velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.

Column C: Resistance computation factor K_n for the Manning equation, $V = (1.486/n)\ (R)^{2/3}\ (S)^{1/2}$
$S_f = Q^2n^2/2.208\ R^{4/3}A^2 = K_n(n^2/D^{1/3})\ (Q/BD^{1.5})^2$
$K_n = 0.4529/(R/D)^{4/3}(A/BD)^2$
A = Area of flow
R = Hydraulic radius
S_f = Friction slope
n = Manning coefficient

Column D: Resistance computation factor K_f for the Darcy equation, $h_f = (f)\ (L/4R)\ (V^2/2g)$
$S_f = Q^2f/257.28\ RA^2 = K_f(f)\ (Q/BD^{1.5})^2$
$K_f = 0.003887/(R/D)\ (A/BD)^2$
h_f = Friction head loss, ft.
f = Darcy coefficient
L = Length of conduit, ft.



(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
1.00	0.02504	3.646	0.02093	0.90	0.02726	3.160	0.01921
0.99	.02511	3.372	.01975	.89	.02763	3.180	.01936
.98	.02523	3.279	.01940	.88	.02801	3.204	.01954
.97	.02539	3.221	.01914	.87	.02842	3.233	.01974
.96	.02558	3.183	.01900	.86	.02885	3.267	.01997
.95	.02580	3.158	.01893	.85	.02931	3.306	.02023
.94	.02605	3.143	.01891	.84	.02980	3.350	.02052
.93	.02632	3.137	.01893	.83	.03031	3.399	.02083
.92	.02661	3.139	.01899	.82	.03084	3.452	.02116
.91	.02692	3.147	.01908	.81	.03141	3.511	.02153

Table 14—Velocity head and resistance computation factors for corrugated metal pipe-arches 2⅔ by ½ in. corrugations, flowing full and partly full—Continued

(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha = 1.00$ $Q/BD^{1.5} = 1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
0.80	0.03200	3.574	0.02192	0.45	0.09531	14.28	0.08138
.79	.03263	3.643	.02235	.44	.09999	15.27	.08663
.78	.03328	3.718	.02280	.43	.10505	16.37	.09240
.77	.03397	3.798	.02329	.42	.11053	17.59	.09876
.76	.03470	3.884	.02381	.41	.11647	18.95	.10580
.75	.03546	3.976	.02437	.40	.1229	20.46	.1136
.74	.03626	4.075	.02496	.39	.1300	22.16	.1223
.73	.03710	4.181	.02559	.38	.1377	24.07	.1320
.72	.03799	4.295	.02626	.37	.1461	26.23	.1429
.71	.03891	4.416	.02698	.36	.1553	28.67	.1551
.70	.03989	4.546	.02775	.35	.1655	31.44	.1689
.69	.04092	4.685	.02856	.34	.1767	34.60	.1845
.68	.04200	4.834	.02943	.33	.1892	38.23	.2022
.67	.04314	4.993	.03035	.32	.2030	42.42	.2225
.66	.04434	5.163	.03134	.31	.2185	47.26	.2457
.65	.04560	5.345	.03239	.30	.2357	52.91	.2726
.64	.04693	5.540	.03351	.29	.2552	59.53	.3037
.63	.04834	5.749	.03471	.28	.2771	67.35	.3401
.62	.04982	5.973	.03599	.27	.3021	76.63	.3829
.61	.05139	6.214	.03736	.26	.3305	87.74	.4334
.60	.05305	6.472	.03883	.25	.3631	101.1	.4937
.59	.05480	6.751	.04040	.24	.4008	117.4	.5660
.58	.05666	7.050	.04209	.23	.4445	137.4	.6535
.57	.05863	7.373	.04390	.22	.4956	162.2	.7605
.56	.06072	7.722	.04585	.21	.5559	193.3	.8926
.55	.06294	8.098	.04795	.20	.6276	232.7	1.057
.54	.06530	8.506	.05021	.19	.7136	283.4	1.266
.53	.06781	8.948	.05264	.18	.8179	349.5	1.533
.52	.07049	9.428	.05528	.17	.9460	437.3	1.881
.51	.07335	9.950	.05813	.16	1.1054	556.1	2.341
.50	.07640	10.52	.06123	.15	1.307	720.3	2.964
.49	.07967	11.14	.06459	.14	1.566	953.0	3.826
.48	.08317	11.82	.06826	.13	1.906	1292.2	5.049
.47	.08692	12.56	.07225	.12	2.363	1803.7	6.843
.46	.09096	13.38	.07661	.11	2.996	2605.9	9.568

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VII. STRUCTURAL PLATE CORRUGATED METAL PIPE-ARCHES, 6 BY 2 IN. CORRUGATIONS

Unlike pipe-arches of $2^2/_3$ by $1/2$ in. and 3 by 1 in. corrugations, which are formed from circular pipes, structural plate pipe-arch sections are field assembled using bolts and nuts. There are 34 sections of 18 in. corner radius and 24 sections of 31-in. corner radius structural plate pipe-arches. Their tables of dimensions appear in the 1967 "Handbook of Steel Drainage and Highway Construction Products," page 31, Table 1-19 and page 32, Table 1-20. (See item 8 in the bibliography.)

The sections of the two groups, taken either separately or together, are not geometrically similar, but there is no significant difference in the dimensionless geometric and hydraulic factors. Thus, one table which contains mean values of geometric and hydraulic factors for all the 58 sections was computed and can be used with a high degree of approximation. Three sections, No. 1, 3, and 23, with 18 in. corner radius, showed the greatest deviation from mean factor values. They were separated and combined with pipe-arch Section No. 6 of 3 by 1 in. corrugation size. A diagram (No. 2) for error correction for these four sections appears in Appendix A.

Using the diagram and, for the remaining 55 sections, taking the most unfavorable combination of section and factor in the range of relative depths from $\frac{d}{D} = 1.00$ to $\frac{d}{D} = 0.40$, computation shows maximum error up to 9 percent in one case (section No. 13, factor K_n at $\frac{d}{D} = 0.40$), declining to zero error gradually. Whether such accuracy is acceptable is a decision left to the designer, and should be based upon design requirements. However, in most cases, errors of less than 10 percent are well within the accuracy required for hydraulic and hydrologic estimates.

The same tables can be used with adequate accuracy for corrugated metal pipe-arches having 3 by 1 in. corrugations, of which there are 10 sections. The table of dimensions is also contained in the "Handbook of Steel Drainage and Highway Construction Products," page 26, Table 1-15.

To determine the modified geometric and hydraulic factors for these pipe-arches, the same method was used as for the pipe-arches having $2^2/_3$ by $1/2$ in. corrugations—that is, reference was made to the diameter of the circular pipe forming the pipe-arch. After comparison of the modified values obtained in this manner with the mean values from 6 by 2 in. corrugated pipe-arches, it was found that section No. 6 deviated the most. Since the character and the magnitude of error of No. 6 were very similar to those of sections Nos. 1, 3 and 28 (18 in. corner radius), these four were combined into one group. A diagram (No. 2) for error correction was formulated for these sections. Using the diagram and taking the most unfavorable cases the highest error found was 9 percent in one case. Then error rapidly declined and finally reached zero percent.

The same table can also be used for structural plate corrugated aluminum pipe-arches with 9 by $2^1/_2$ in. corrugations and 28.8 in. corner radius. There are 33 sections of this type of pipe-arch. The table of dimensions is given on page 9 of the Kaiser Aluminum Manual (see item 10 in the bibliography). The actual dimensions were obtained using the method suggested by the Kaiser Aluminum Co.

After comparison of given factors, values with mean values for 6 by 2 in. corrugations, the 8 smallest sections (Nos. 1, 2, 3, 4, 5, 6, 7, 8), and 10, showed a considerable deviation from the mean values. A diagram (No. 3) for error correction for these sections appears in Appendix A.

Using the diagram and taking the most unfavorable cases from the remaining 24 sections, the highest error was slightly greater than 10 percent at three points (section 10, K_f and K_n at $\frac{d}{D} = 0.40$

and Section 1, K_n at $\frac{d}{D} = 0.40$). Then, declining gradually, it finally reached zero percent.

Tables Nos. 15, 16, 17, and 18 contain nominal and modified dimensions for all the aforementioned pipe-arches.

Table 15.—Span and rise dimensions and $BD^{1.5}$ values for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, 18 in. corner radius

Section No.	Size: Nominal Span B x Rise D ft.-in. ft.-in.	Actual Span B ft.	Actual Rise D ft.	Plates per ring	$BD^{1.5}$	Section No.	Size: Nominal Span B x Rise D ft.-in. ft.-in.	Actual Span B ft.	Actual Rise D ft.	Plates per ring	$BD^{1.5}$
1	6- 1 x 4- 7	6.08	4.58	5	59.60	18	11- 7 x 7- 5	11.62	7.42	8	234.80
2	6- 4 x 4- 9	6.33	4.76	5	65.77	19	11-10 x 7- 7	11.82	7.61	8	248.10
3	6- 9 x 4-11	6.77	4.91	5	73.66	20	12- 4 x 7- 9	12.32	7.75	8	265.80
4	7- 0 x 5- 1	7.02	5.09	5	80.59	21	12- 6 x 7-11	12.52	7.93	8	279.60
						22	12- 8 x 8- 1	12.70	8.12	8	293.90
5	7- 3 x 5- 3	7.25	5.27	6	87.72	23	12-10 x 8- 4	12.87	8.31	8	308.30
6	7- 8 x 5- 5	7.70	5.42	6	97.17						
7	7-11 x 5- 7	7.93	5.60	6	105.07	24	13- 5 x 8- 5	13.40	8.44	9	328.60
8	8- 2 x 5- 9	8.15	5.78	6	113.28	25	13-11 x 8- 7	13.93	8.58	9	350.10
						26	14- 1 x 8- 9	14.12	8.77	9	366.70
9	8- 7 x 5-11	8.62	5.92	7	124.10	27	14- 3 x 8-11	14.28	8.96	9	383.00
10	8-10 x 6- 1	8.83	6.11	7	133.30	28	14-10 x 9- 1	14.82	9.10	9	406.80
11	9- 4 x 6- 3	9.32	6.26	7	146.00	29	15- 4 x 9- 3	15.33	9.23	9	429.80
12	9- 6 x 6- 5	9.52	6.44	7	155.60						
						30	15- 6 x 9- 5	15.53	9.42	10	449.00
13	9- 9 x 6- 7	9.72	6.62	7	165.50	31	15- 8 x 9- 7	15.70	9.61	10	467.70
14	10- 3 x 6- 9	10.22	6.77	7	180.00	32	15-10 x 9-10	15.87	9.80	10	486.40
15	10- 8 x 6-11	10.70	6.91	7	194.30	33	16- 5 x 9-11	16.42	9.93	10	513.80
16	10-11 x 7- 1	10.92	7.09	7	206.20	34	16- 7 x 10- 1	16.58	10.12	10	533.70
17	11- 5 x 7- 3	11.40	7.24	7	222.10						

Table 16.—Span and rise dimensions and $BD^{1.5}$ values for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, 31 in. corner radius

Section No.	Size: Nominal Span B x Rise D ft.-in. ft.-in.	Actual Span B ft.	Actual Rise D ft.	Plates per ring	$BD^{1.5}$	Section No.	Size: Nominal Span B x Rise D ft.-in. ft.-in.	Actual Span B ft.	Actual Rise D ft.	Plates per ring	$BD^{1.5}$
1	13- 3 x 9- 4	13.28	9.36	8	380.3	14	17- 5 x 11- 6	17.40	11.54	10	682.1
2	13- 6 x 9- 6	13.52	9.53	8	397.8	15	17-11 x 11- 8	17.88	11.69	10	714.7
3	14- 0 x 9- 8	13.97	9.68	8	420.8	16	18- 1 x 11-10	18.10	11.87	10	740.3
4	14- 2 x 9-10	14.22	9.87	8	441.0	17	18- 7 x 12- 0	18.58	12.01	10	772.9
5	14- 5 x 10- 0	14.40	10.04	8	458.1	18	18- 9 x 12- 2	18.78	12.20	10	800.2
						19	19- 3 x 12- 4	19.28	12.34	10	835.8
6	14-11 x 10- 2	14.88	10.19	9	484.0						
7	15- 4 x 10- 4	15.35	10.34	9	510.4	20	19- 6 x 12- 6	19.50	12.52	11	863.8
						21	19- 8 x 12- 8	19.70	12.71	11	892.6
8	15- 7 x 10- 6	15.58	10.52	10	531.6	22	19-11 x 12-10	19.88	12.89	11	920.0
9	15-10 x 10- 8	15.80	10.71	10	553.8						
10	16- 3 x 10-10	16.28	10.85	10	581.8	23	20- 5 x 13- 0	20.40	13.03	12	959.4
11	16- 6 x 11- 0	16.50	11.03	10	604.4	24	20- 7 x 13- 2	20.58	13.22	12	989.3
12	17- 0 x 11- 2	16.97	11.18	10	634.3						
13	17- 2 x 11- 4	17.18	11.36	10	657.8						

Table 17.—Span and rise dimensions and $BD^{1.5}$ values for corrugated metal pipe-arches, 3 by 1 in. corrugations

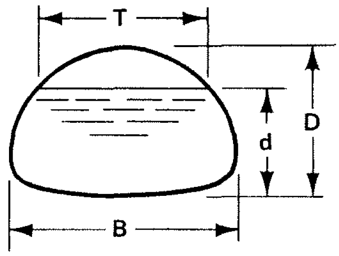
Sec. No.	Diameter of circ. pipe used to form pipe-arch (in.)	Dimensions: Nominal: Handbook data Span (in.)	Handbook data Rise (in.)	In refer. to circ. pipe Span B	In refer. to circ. pipe Rise D	Modified values for design: Span (in.)	Rise (in.)	Span (ft.)	Rise (ft.)	Design values $BD^{1.5}$
1	36	43	27	1.194	0.750	43.16	26.71	3.567	2.226	11.85
2	42	50	31	1.190	.738	50.36	31.16	4.197	2.597	17.56
3	48	58	36	1.208	.750	57.55	35.62	4.796	2.968	24.52
4	54	65	40	1.204	.740	64.75	40.07	5.396	3.339	32.92
5	60	72	44	1.200	.733	71.94	44.52	5.995	3.710	42.84
		Average		1.199	0.742					
6	66	73	55	1.106	0.833	74.18	53.39	6.182	4.449	58.01
7	72	81	59	1.125	.819	80.93	58.25	6.744	4.854	72.12
8	78	87	63	1.115	.808	87.67	63.10	7.306	5.258	88.09
9	84	95	67	1.131	.798	94.42	67.96	7.868	5.663	106.00
10	90	103	71	1.144	.789	101.16	72.81	8.430	6.067	126.00
		Average		1.124	0.809					

Table 18.—Span and rise dimensions and $BD^{1.5}$ values for structural plate corrugated metal pipe-arches, 9 by 2½ in. corrugations, 28.8 in. corner radius

Section No.	Size: Nominal Span B x Rise D ft.-in. ft.-in.	Size: Actual Span B ft.	Actual Rise D ft.	Plates per ring	$BD^{1.5}$
1	5-11 x 5- 4	5.91	5.32	2	72.52
2	6- 3 x 5- 5	6.28	5.48	2	80.57
3	6- 8 x 5- 7	6.65	5.60	2	88.11
4	6-11 x 5- 9	6.96	5.76	2	96.19
5	7- 4 x 5-11	7.34	5.91	2	105.48
6	7- 8 x 6- 1	7.65	6.08	2	114.67
7	8- 0 x 6- 2	8.04	6.19	3	123.80
8	8- 4 x 6- 4	8.33	6.34	3	132.90
9	8- 7 x 6- 6	8.64	6.54	3	144.50
10	9- 0 x 6- 8	9.04	6.64	3	154.70
11	9- 4 x 6-10	9.32	6.82	3	166.00
12	9- 9 x 6-11	9.73	6.94	3	177.90
13	10- 0 x 7- 1	10.03	7.11	3	190.20
14	10- 5 x 7- 3	10.45	7.24	3	203.60
15	10- 9 x 7- 5	10.73	7.41	3	216.40
16	11- 2 x 7- 6	11.15	7.54	3	230.80
17	11- 5 x 7- 8	11.44	7.71	3	244.90
18	11- 8 x 7-10	11.69	7.84	3	256.60
19	12- 2 x 8- 0	12.15	8.01	3	275.40
20	12- 5 x 8- 2	12.40	8.15	3	288.50
21	12-10 x 8- 3	12.91	8.39	4	313.70
22	13- 1 x 8- 5	13.09	8.41	4	319.30
23	13- 7 x 8- 7	13.57	8.58	4	341.00
24	13-10 x 8- 9	13.81	8.73	4	356.20
25	14- 3 x 8-10	14.28	8.88	4	377.80
26	14- 6 x 9- 0	14.55	9.06	4	396.80
27	14- 9 x 9- 2	14.77	9.16	4	409.40
28	15- 3 x 9- 4	15.20	9.26	4	428.30
29	15- 6 x 9- 6	15.52	9.52	4	455.80
30	16- 0 x 9- 7	15.97	9.64	4	478.00
31	16- 2 x 9- 9	16.22	9.81	4	498.40
32	16- 8 x 9-11	16.70	9.92	4	521.70
33	16-11 x 10- 1	16.90	10.05	4	538.40

Table 19.—Geometric properties and critical flow factors for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, with 18 in. & 31 in. radius corner plates, flowing full and partly full

d = Depth of flow
d_c = Critical depth
d_m = Mean depth
D = Rise of conduit
B = Span of conduit
A = Area of flow
R = Hydraulic radius
T = Top width of flow
Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$H_c = d_c + (\alpha V_c^2)/(2gD)$ (invariant with α)
V_c = Critical velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



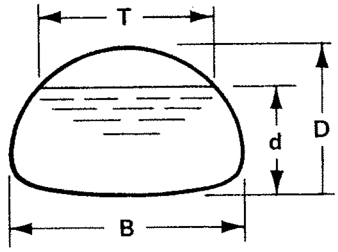
$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$		$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
					α=1.00	α=1.12		
1.00	0.7857	0.2936	—	—	—	—	—	—
0.99	.7846	.3123	0.1626	—	—	—	—	—
.98	.7826	.3201	.2291	—	—	—	—	—
.97	.7801	.3261	.2797	2.790	7.388	6.981	1.394	2.364
.96	.7770	.3309	.3219	2.415	6.847	6.470	1.207	2.167
.95	.7736	.3350	.3586	2.158	6.444	6.089	1.0785	2.029
.94	.7699	.3386	.3915	1.967	6.122	5.785	0.9832	1.923
.93	.7658	.3417	.4215	1.818	5.854	5.532	.9085	1.839
.92	.7615	.3445	.4490	1.697	5.624	5.314	.8480	1.768
.91	.7568	.3469	.4746	1.596	5.420	5.122	.7974	1.707
.90	.7520	.3491	.4985	1.509	5.238	4.949	.7543	1.654
.89	.7469	.3509	.5210	1.434	5.071	4.792	.7168	1.607
.88	.7416	.3526	.5422	1.368	4.918	4.647	.6838	1.564
.87	.7360	.3540	.5623	1.309	4.775	4.512	.6545	1.524
.86	.7303	.3552	.5814	1.257	4.642	4.386	.6280	1.488
.85	.7244	.3563	.5997	1.209	4.515	4.267	.6040	1.454
.84	.7183	.3571	.6171	1.165	4.395	4.153	.5821	1.422
.83	.7121	.3578	.6337	1.124	4.281	4.045	.5618	1.392
.82	.7057	.3583	.6496	1.087	4.171	3.941	.5431	1.363
.81	.6991	.3586	.6649	1.052	4.065	3.841	.5257	1.336
.80	.6924	.3588	.6796	1.0191	3.963	3.745	.5094	1.309
.79	.6855	.3589	.6938	0.9884	3.864	3.651	.4940	1.284
.78	.6785	.3588	.7074	.9595	3.769	3.561	.4796	1.260
.77	.6713	.3585	.7205	.9321	3.675	3.473	.4659	1.236
.76	.6641	.3582	.7331	.9062	3.584	3.387	.4529	1.213
.75	.6567	.3576	.7453	.8814	3.496	3.303	.4405	1.191
.74	.6492	.3570	.7571	.8578	3.409	3.221	.4288	1.169
.73	.6415	.3562	.7684	.8352	3.324	3.241	.4175	1.147
.72	.6338	.3553	.7794	.8135	3.241	3.063	.4066	1.127
.71	.6260	.3543	.7899	.7927	3.160	2.986	.3962	1.106
.70	.6180	.3531	.8002	.7726	3.080	2.910	.3862	1.086
.69	.6100	.3518	.8100	.7532	3.002	2.836	.3765	1.066
.68	.6018	.3504	.8196	.7345	2.924	2.763	.3671	1.047
.67	.5936	.3489	.8288	.7164	2.849	2.692	.3581	1.028
.66	.5852	.3473	.8377	.6988	2.774	2.621	.3493	1.009
.65	.5768	.3455	.8463	.6818	2.700	2.552	.3408	0.9908
.64	.5683	.3436	.8547	.6652	2.628	2.483	.3325	.9725
.63	.5597	.3416	.8627	.6490	2.557	2.416	.3244	.9544
.62	.5511	.3395	.8704	.6333	2.486	2.350	.3165	.9365
.61	.5423	.3373	.8779	.6179	2.417	2.284	.3089	.9189

Table 19.—Geometric properties and critical flow factors for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, with 18 in. & 31 in. radius corner plates, flowing full and partly full—Continued

$\frac{d}{D}$ or $\frac{d_c}{D}$	$\frac{A}{BD}$	$\frac{R}{D}$	$\frac{T}{B}$	$\frac{d_m}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.12$	$\frac{\alpha V_c^2}{2gD}$	$\frac{H_c}{D}$
0.60	0.5335	0.3350	0.8852	0.6029	2.349	2.219	0.3014	0.9014
.59	.5246	.3325	.8921	.5882	2.281	2.156	.2940	.8840
.58	.5157	.3299	.8989	.5738	2.215	2.093	.2868	.8668
.57	.5066	.3272	.9053	.5597	2.149	2.031	.2798	.8498
.56	.4976	.3244	.9116	.5459	2.085	1.970	.2729	.8329
.55	.4884	.3215	.9176	.5324	2.021	1.910	.2661	.8161
.54	.4792	.3185	.9234	.5191	1.958	1.850	.2595	.7995
.53	.4699	.3153	.9289	.5060	1.896	1.791	.2529	.7829
.52	.4606	.3121	.9343	.4931	1.834	1.733	.2465	.7665
.51	.4512	.3087	.9394	.4805	1.774	1.676	.2402	.7502
.50	.4418	.3052	.9443	.4680	1.714	1.620	.2340	.7340
.49	.4324	.3016	.9490	.4557	1.655	1.564	.2278	.7178
.48	.4229	.2979	.9535	.4436	1.597	1.509	.2218	.7018
.47	.4133	.2940	.9577	.4316	1.540	1.455	.2158	.6858
.46	.4037	.2900	.9618	.4198	1.483	1.402	.2099	.6699
.45	.3941	.2859	.9657	.4081	1.428	1.349	.2040	.6540
.44	.3844	.2817	.9694	.3966	1.373	1.297	.1983	.6383
.43	.3747	.2774	.9728	.3852	1.319	1.246	.1926	.6226
.42	.3649	.2729	.9761	.3739	1.265	1.196	.1869	.6070
.41	.3552	.2684	.9792	.3628	1.213	1.146	.1813	.5913
.40	.3454	.2637	.9821	.3517	1.1614	1.0974	.1758	.5758
.39	.3355	.2588	.9848	.3407	1.1106	1.0494	.1703	.5603
.38	.3257	.2538	.9872	.3299	1.0607	1.0023	.1649	.5449
.37	.3158	.2487	.9895	.3191	1.0116	0.9559	.1596	.5296
.36	.3059	.2435	.9916	.3085	0.9634	.9103	.1542	.5142
.35	.2959	.2381	.9934	.2979	.9160	.8655	.1489	.4989
.34	.2860	.2327	.9949	.2875	.8696	.8217	.1437	.4837
.33	.2760	.2270	.9961	.2771	.8241	.7787	.1386	.4686
.32	.2661	.2212	.9970	.2669	.7795	.7366	.1334	.4534
.31	.2561	.2153	.9974	.2568	.7359	.6954	.1284	.4384
.30	.2461	.2093	.9975	.2468	.6933	.6552	.1234	.4234
.29	.2362	.2031	.9970	.2368	.6518	.6159	.1184	.4084
.28	.2262	.1968	.9961	.2271	.6113	.5776	.1135	.3935
.27	.2162	.1903	.9946	.2174	.5718	.5403	.1087	.3787
.26	.2063	.1838	.9925	.2078	.5334	.5040	.1039	.3639
.25	.1964	.1771	.9898	.1984	.4961	.4687	.09920	.3492
.24	.1865	.1703	.9865	.1890	.4599	.4346	.09453	.3345
.23	.1767	.1634	.9825	.1798	.4248	.4014	.08990	.3199
.22	.1669	.1563	.9778	.1706	.3909	.3694	.08533	.3053
.21	.1571	.1492	.9723	.1615	.3581	.3384	.08079	.2908
.20	.1474	.1420	.9660	.1526	.3266	.3086	.07630	.2763
.19	.1378	.1347	.9589	.1437	.2962	.2799	.07185	.2618
.18	.1282	.1273	.9508	.1349	.2671	.2524	.06744	.2474
.17	.1188	.1198	.9416	.1261	.2392	.2260	.06307	.2331
.16	.1094	.1123	.9313	.1175	.2127	.2010	.05874	.2187
.15	.10016	.10465	.9196	.10888	.1874	.17711	.05445	.2044
.14	.09102	.09702	.9063	.10041	.1636	.15458	.05022	.1902
.13	.08204	.08939	.8909	.09206	.1412	.13340	.04604	.1760
.12	.07323	.08182	.8712	.08402	.1204	.11376	.04203	.1620
.11	.06462	.07438	.8489	.07609	.1011	.09554	.03806	.1481

Table 20.—Velocity head and resistance computation factors for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, with 18 in. & 31 in. radius corner plates, flowing full and partly full

Column A: Relative depth of flow, d/D
Column B: Relative velocity head
$h_v/D=\alpha V^2/2gD$, $\alpha=1.00$, $Q/BD^{1.5}=1.0$
V= Mean flow velocity
α= Kinetic energy correction factor
g= Acceleration due to gravity = 32.16 ft./sec./sec.
Column C: Resistance computation factor K_n for the Manning equation, $V=(1.486/n)(R)^{2/3}(S)^{1/2}$
$S_f=Q^2n^2/2.208R^{4/3}A^2=K_n(n^2/D^{1/3})(Q/BD^{1.5})^2$
$K_n=0.4529/(R/D)^{4/3}(A/BD)^2$
A= Area of flow
R= Hydraulic radius
S_f= Friction slope
n= Manning coefficient
Column D: Resistance computation factor K_f for the Darcy equation, $h_f=(f)(L/4R)(V^2/2g)$
$S_f=Q^2f/257.28\ RA^2=K_f(f)(Q/BD^{1.5})^2$
$K_f=0.003887/(R/D)(A/BD)^2$
h_f= Friction head loss, ft. L= Length of conduit, ft.
f= Darcy coefficient



(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
1.00	0.02519	3.759	0.02145	0.60	0.05463	6.840	0.04077
0.99	.02526	3.472	.02022	.59	.05649	7.143	.04248
.98	.02538	3.376	.01982	.58	.05847	7.471	.04431
.97	.02555	3.316	.01959	.57	.06057	7.824	.04628
.96	.02575	3.277	.01945	.56	.06280	8.206	.04840
.95	.02598	3.252	.01938	.55	.06518	8.619	.05068
.94	.02623	3.237	.01937	.54	.06771	9.067	.05315
.93	.02651	3.232	.01939	.53	.07040	9.554	.05581
.92	.02681	3.234	.01946	.52	.07328	10.083	.05870
.91	.02714	3.243	.01956	.51	.07635	10.660	.06183
.90	.02749	3.258	.01969	.50	.07964	11.29	.06524
.89	.02787	3.279	.01985	.49	.08317	11.98	.06894
.88	.02827	3.306	.02005	.48	.08695	12.73	.07298
.87	.02870	3.338	.02027	.47	.09102	13.56	.07740
.86	.02915	3.375	.02052	.46	.09540	14.47	.08223
.85	.02963	3.417	.02079	.45	.1001	15.48	.08754
.84	.03013	3.464	.02109	.44	.1052	16.59	.09337
.83	.03066	3.516	.02143	.43	.1107	17.83	.09981
.82	.03122	3.574	.02179	.42	.1167	19.21	.10693
.81	.03181	3.637	.02218	.41	.1233	20.74	.11483
.80	.03243	3.705	.02260	.40	.1304	22.46	.1236
.79	.03309	3.779	.02305	.39	.1381	24.39	.1334
.78	.03377	3.859	.02354	.38	.1466	26.57	.1444
.77	.03449	3.945	.02405	.37	.1559	29.03	.1567
.76	.03526	4.037	.02461	.36	.1662	31.83	.1706
.75	.03605	4.137	.02520	.35	.1775	35.03	.1864
.74	.03689	4.243	.02584	.34	.1901	38.69	.2043
.73	.03777	4.358	.02651	.33	.2040	42.92	.2247
.72	.03870	4.480	.02723	.32	.2196	47.81	.2482
.71	.03968	4.611	.02800	.31	.2370	53.50	.2752
.70	.04071	4.751	.02882	.30	.2566	60.17	.3066
.69	.04179	4.901	.02970	.29	.2788	68.02	.3432
.68	.04293	5.061	.03063	.28	.3039	77.34	.3861
.67	.04413	5.233	.03162	.27	.3325	88.46	.4368
.66	.04539	5.417	.03268	.26	.3653	101.85	.4970
.65	.04673	5.614	.03381	.25	.4031	118.1	.5691
.64	.04814	5.826	.03502	.24	.4470	137.9	.6563
.63	.04963	6.053	.03632	.23	.4982	162.5	.7624
.62	.05120	6.296	.03770	.22	.5584	193.1	.8931
.61	.05286	6.558	.03918	.21	.6299	231.8	1.0555

Table 20.—Velocity head and resistance computation factors for structural plate corrugated metal pipe-arches, 6 by 2 in. corrugations, with 18 in. & 31 in. radius corner plates, flowing full and partly full—Continued

(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f	(A) Relative depth d/D	(B) Relative velocity head $\alpha V^2/2gD$ $\alpha=1.00$ $Q/BD^{1.5}=1.0$	(C) Manning Eq. resistance computation factor K_n	(D) Darcy Eq. resistance computation factor K_f
0.20	0.7154	281.4	1.260	0.15	1.550	915.4	3.703
.19	.8189	345.6	1.520	.14	1.876	1226.0	4.835
.18	.9454	430.2	1.857	.13	2.310	1683.7	6.462
.17	1.1020	543.6	2.300	.12	2.899	2377.4	8.859
.16	1.2988	698.7	2.893	.11	3.723	3466.9	12.514

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VIII. RECTANGULAR CONDUITS

Rectangular conduits present hydraulic computation problems significantly different from the previously discussed methods applicable to conduits with curved cross sections.

Similarity is essential to the general use of the computation system presented by this publication, in which the geometric properties are generalized in non-dimensional forms and combined with the constants of the hydraulic equations involved to produce factors useful for rapid calculation. Among rectangular conduits, only square ones are geometrically similar.

Rectangular conduits are usually constructed of reinforced concrete. The general practice is to use widths and heights not involving fractions of a foot. Hence the various sizes are not geometrically similar. For example, a conduit with span $B=7$ ft. by height $D=6$ *ft.* $\left(\frac{B}{D}=1.167\right)$ is not similar to a smaller 6 ft. by 5 ft. $\left(\frac{B}{D}=1.200\right)$.

Because all square cross section conduits are geometrically similar, the type of hydraulic factors used in the tables for circular and other commercial conduits may also be used for them. These factors include: critical flow discharge rates, velocity head, and resistance computation factors, each for relative depths of flow, $\frac{d}{D}$.

a. Computation Factors Common to Square and Rectangular Conduits

In non-dimensional terms, only relative hydraulic radius and hence the resistance computation factor depends on conduit shape $\left(\frac{B}{D}\right)$. The other hydraulic parameters may be presented in the usual form employed in this publication.

Unlike the situation for circular and other conduits formed with curved boundaries, the tables for rectangular conduits may be simplified to a degree because the geometric factors which determine area, top width and the mean depth of flow, are readily computed from conduit height and the depth of flow. Therefore the tables for rectangular conduits are simplified by omission of the non-dimensional geometric factors from the tables of Critical Flow Factors. Because $A=Bd$, $T=B$ and $d_m=d$, the non-dimensional geometric factors may be readily determined, as follows:

$$\frac{A}{BD}=\frac{Bd}{BD}=\frac{d}{D};\ \frac{T}{B}=1.0;\ \frac{d_m}{D}=\frac{d_c}{D},$$

and hence are all adequately represented in the table by the relative depth of flow, $\frac{d}{D}$.

The critical flow factor, $\frac{Q_c}{BD^{1.5}}$, may be developed directly from the velocity head at critical flow

$$\frac{\alpha V_c^2}{2gD}=\frac{d_m}{2D}=\frac{d_c}{2D}$$

Substituting $\frac{Q_c}{Bd_c}$ for V_c, and dividing D^2,

$$\frac{\alpha Q_c^2}{2gD^3B^2d_c^2}=\frac{d_c}{2D^3},$$

which results in the relation

$$\frac{Q_c}{BD^{1.5}}=\left(\frac{g}{\alpha}\right)^{0.5}\cdot\left(\frac{d_c}{D}\right)^{1.5}.$$

Therefore, the critical flow discharge rate varies directly with the relative critical depth and inversely with the square root of the kinetic energy factor, α. Because the discharge factor includes conduit width, B, and B is not involved elsewhere, the equation applies for all values of the shape ratio, $\frac{B}{D}$.

The table of Critical Flow Factors includes discharge rates for $\alpha=1.00$ and 1.04, the latter applicable to the usual concrete box conduits. The value for $\alpha=1.00$ permits a ready determination of critical flow rates for other values of α.

Hydraulic radii values are not included in this table. These depend upon the conduit shape ratio,

$\frac{B}{D}$, as is evident from the relative hydraulic radius equation.

$$\frac{R}{D}=\frac{A}{PD}=\frac{Bd}{(B+2d)D}$$

The table of Velocity Head and Resistance Computation Factors, is divided into two tables in this case, one for f and one for n, to provide for the greater number of columns required. The two tables contain common values for $\frac{\alpha V^2}{2gD}$, the relative velocity head at various depths of flow, applicable to all $\frac{B}{D}$ ratios.

That the velocity head factor of the tables is in fact independent of the $\frac{B}{D}$ ratio is shown by the following development:

$$\frac{\alpha V^2}{2gD}=\frac{\alpha Q^2}{2gDB^2d^2}=\frac{D^2}{D^2}\cdot\frac{\alpha Q^2}{2gDB^2d^2}$$

$$=\frac{Q^2}{B^2D^3}\cdot\frac{\alpha}{2g}\cdot\left(\frac{D}{d}\right)^2$$

Therefore $$\frac{\alpha V^2}{2gD}\div\alpha\left(\frac{Q}{BD^{1.5}}\right)^2=\frac{1}{2g\left(\frac{d}{D}\right)^2},$$

and the tabulated values of relative velocity head apply for all conduit shapes, requiring only the multiplication of the tabular values at any value of $\frac{d}{D}$ by the α and $\left(\frac{Q}{BD^{1.5}}\right)^2$, as is the case for tables presented for other conduit forms.

b. Resistance computation factors

Resistance to flow in a conduit varies inversely with the hydraulic radius of the flow cross-section. Therefore a resistance computation factor (Chapter III) for application to full or partly-full flow will have values dependent to a degree upon the shape of the rectangular conduit. In the following development of equations for the resistance computation factors, for either the Darcy f or the Manning n, use will be made of the shape factor, $\frac{B}{D}$, or as given here, for convenience,

$$M=\frac{B}{D}\text{ or }B=MD.$$

In the basic expression for hydraulic radius (repeated below),

$$\frac{R}{D}=\frac{Bd}{D(B+2d)}$$

MD may be substituted for B to yield the equatior

$$\frac{R}{D}=\frac{MDd}{D(MD+2d)}=\frac{d}{D}\left[\frac{MD}{MD+2d}\right]$$

$$=\frac{d}{D}\left[\frac{M}{M+2\frac{d}{D}}\right]$$

The latter form of the equation for the relative hydraulic radius of partly-full flow in a rectangular conduit, involving the shape ratio M together with the relative area of flow, $\frac{A}{BD}=\frac{d}{D}$, may be incorporated in the general equations for rate of resistance loss given in Chapter III, that is,

$$S_f=\frac{f}{8g\left(\frac{R}{D}\right)\left(\frac{A}{BD}\right)^2}\left(\frac{Q}{BD^{1.5}}\right)^2\qquad\text{Darcy}$$

$$\text{or }S_f=\frac{n^2}{2.208D^{0.333}\left(\frac{}{D}\right)^{1.33}\left(\frac{A}{BD}\right)^2}\left(\frac{Q}{BD^{1.5}}\right)^2\qquad\text{Manning}$$

Using the Darcy f, the following will result:

$$S_f=\frac{0.003887}{\frac{d}{D}\left[\frac{M}{M+2\frac{d}{D}}\right]\left(\frac{d}{D}\right)^2}\cdot f\cdot\left(\frac{Q}{BD^{1.5}}\right)^2$$

Representing the first part of this equation by K_f, the final equation for the rate of loxs of energy becomes

$$S_f=f\cdot K_f\cdot\left(\frac{Q}{BD^{1.5}}\right)^2$$

as in Chapter III, and

$$K_f=\frac{0.003887}{\left(\frac{d}{D}\right)^3}\cdot\left[\frac{M+2\frac{d}{D}}{M}\right]$$

for rectangular conduits, for which $M=\frac{B}{D}$.

Using the Manning n resistance factor,

$$S_f = \frac{0.4529}{\left(\frac{d}{D}\right)^{1.33}\left[\frac{M}{M+2\frac{d}{D}}\right]^{1.33}\left(\frac{d}{D}\right)^2} \cdot \frac{n^2}{D^{0.333}} \cdot \left(\frac{Q}{BD^{1.5}}\right)^2$$

The reduced form of the equation is

$$S_f = K_n \frac{n^2}{D^{0.333}} \left(\frac{Q}{BD^{1.5}}\right)^2$$

in which

$$K_n = \frac{0.4529}{\left(\frac{d}{D}\right)^2} \left[\frac{M+2\frac{d}{D}}{M\frac{d}{D}}\right]^{4/3}$$

For the case of a square conduit, $M = 1$, the resistance computation factors are reduced to

$$K_f = \frac{0.003887}{\left(\frac{d}{D}\right)^3}\left[1+2\left(\frac{d}{D}\right)\right] \qquad \text{Darcy}$$

$$K_n = \frac{0.4529}{\left(\frac{d}{D}\right)^2}\left[\frac{1+2\frac{d}{D}}{\frac{d}{D}}\right]^{4/3} \qquad \text{Manning}$$

It will be evident that the resistance computation factor, K_f or K_n, as the case may be, for a rectangular conduit is related to K_f or K_n for a square conduit through the relative values of the bracketed terms of the general equation involving M and the more simple bracketed terms for the case of $M=1$.

c. Direct calculation of resistance to flow in rectangular conduits

The preceding paragraphs and equations demonstrate that rectangular conduits of shapes other than square will create difficulties in the use of tables of hydraulic factors for determining loss of energy by resistance, as is required when seeking normal depth or computing a nonuniform flow profile. For direct use of the methods employed for other conduits it would be necessary to compute and tabulate resistance computation factors for a great number of rectangular shape ratios. Because of the simplicity of direct computation methods, this procedure appears unnecessary.

The simple geometry of a rectangle for which flow area is expressed as $\frac{A}{BD}=\frac{d}{D}$, and hydraulic radius appears as $\frac{R}{D}=\frac{Bd}{D(B+2d)}$, will produce readily solvable equations for rate of loss of energy, or friction slope, as follows:

$$S_f = \frac{0.003887f}{\frac{R}{D}\left(\frac{d}{D}\right)^2} \cdot \left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Darcy}$$

and

$$S_f = \frac{0.4529n^2}{D^{0.333}\left(\frac{R}{D}\right)^{4/3}\left(\frac{d}{D}\right)^2} \cdot \left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Manning}$$

The equations retain the rate of flow factor and the relative area and hydraulic radius to eliminate the need for calculation of flow area and velocity. Moreover, the equation for rate of resistance loss in this form is in the form particularly adaptable to making a series of trial calculations. Trial solutions for normal depth of flow are made by selection of $\frac{d}{D}$ and the computation of S_f. Trial depths are used until S_f corresponds closely to the conduit invert slope, S_o.

Where a nonuniform flow profile is required, as for a backwater curve upstream from critical depth, critical depth would first be determined by use of the critical flow table, and a series of greater relative depths selected at 0.01 or 0.02 intervals. Then the resistance slope at each depth would be determined by one of the above equations. With these data, a backwater profile may be calculated by the step method, as explained in Chapter IX and as illustrated by examples in Appendix B.

The trial method for determination of normal depth in a rectangular conduit by direct use of the simplified form of the resistance loss equations is illustrated in the following example.

Example 5

A 7 ft. by 5 ft. conduit at a slope of 0.0140 conveys 360 cfs. For a Manning resistance factor $n=0.012$, determine normal depth of flow.

For such cases, a first trial with $\frac{d}{D} = 0.50$ is usually a useful guide to subsequent trials. Applying the fixed values of this example to the resistance equation, i.e.,

$$\frac{Q}{BD^{1.5}} = \frac{360}{7\times 5^{1.5}} = \frac{360}{78.26} = 4.600, \qquad \text{(Table 21)}$$

$D^{0.333} = 5^{0.333} = 1.710$, and $n^2 = 0.000144$,

the equation becomes

$$S_f = \frac{0.4529 \times 0.000144 \times 4.600^2}{1.710 \left[\frac{7 \times d}{5(7+2d)}\right]^{4/3} \left(\frac{d}{D}\right)^2}$$

$$= \frac{0.000807}{\left[\frac{7 \times d}{5(7+2d)}\right]^{4/3} \left(\frac{d}{D}\right)^2}$$

Then trial depths are selected to obtain $S_f =$ 0.0140

$\frac{d}{D}$	0.50	0.55	0.533
d, ft.	2.50	2.75	2.665
$\frac{R}{D}$	0.2920	0.3080	0.3026
$\left(\frac{R}{D}\right)^{4/3}$	0.1940	0.2080	0.2032
S_f	0.0167	0.0128	0.0140
Relation, S_f to S_o	high	low	exact

Therefore, normal depth is 2.66 ft.

d. Direct use of K_f or K_n for square conduits in resistance computations for rectangular conduits

An alternative and simple method for determination of normal depth of flow or for calculation of nonuniform flow profiles in nonsquare rectangular conduits permits use of the resistance computation factors for square conduits ($M = 1.0$), as given in the tables. This may be done only within certain limiting depths of flow.

The procedure is to treat the rectangular conduit as a square conduit with a height equal to its width B, as sketched:

Obviously, the calculations for resistance losses are valid only in the range where the depth of flow does not exceed the physical limits. For the wide conduit $M > 1$, the depth must not exceed about $0.99D$, or just clear of the top slab of the actual conduit. For the narrow conduit, $M < 1$, a limiting depth of $0.99B$ is imposed by the tables, which do not include greater relative depths.

The discharge factor $\frac{Q}{BD^{1.5}}$ must be computed for the assumed square conduit. Therefore it is computed as $\frac{Q}{B^{2.5}}$. This procedure maintains the rate of flow per unit width, and will not modify the flow velocity. The only additional change of normal procedures as used for a square conduit is that relative depths of flow are $\frac{d}{B}$, which may later be converted to $\frac{d}{D}$ if desired.

The following example illustrates this method:

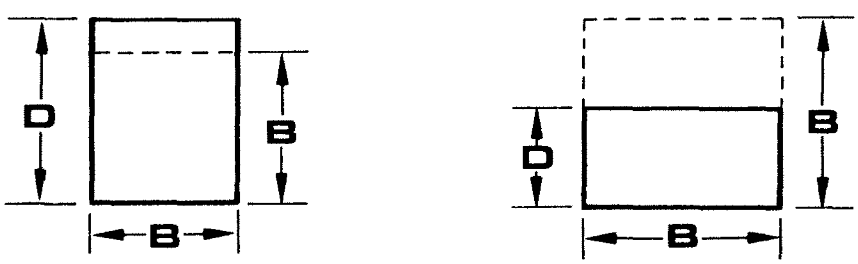
Example 6

Given: A discharge rate of 360 cfs entering a 7 ft. by 5 ft. concrete box conduit at a steep slope ($S = 0.0140$). For a Manning n of 0.012, and $\alpha = 1.04$, what depth will be approached at a distant downstream point (normal depth)? In this case $M > 1$. Consider the conduit to be 7 ft. × 7 ft.

$$BD^{1.5} = B^{2.5} = 129.64 \qquad \text{(Table 21)}$$

$$\frac{Q}{BD^{1.5}} = \frac{360}{129.64} = 2.777$$

$$S_f = K_n \times \frac{n^2}{D^{0.333}} \times \left(\frac{Q}{BD^{1.5}}\right)^2 = K_n \times \frac{0.000144 \times 2.777^2}{7^{0.333}}$$



M < 1 M > 1

For $S_f = S_o$ (normal depth)

$$K_n = \frac{0.0140 \times 1.913}{0.00111} = 24.13$$

Then from Table 23, in Col. D, $M = 1.0$,

$$\frac{d_n}{B} = 0.380$$

Therefore, normal depth

$$d_n = 0.38 \times 7 \text{ ft.} = 2.66 \text{ ft.}$$

The result obtained is the same as that of trial solutions in the preceding example.

For a discharge rate $\frac{Q_c}{BD^{1.5}} = 2.78$ in the 7 ft. × 7 ft. conduit, Table 22 gives a relative critical depth $\frac{d_c}{B} = 0.63$, indicating that the flow is supercritical at normal depth of 0.38 B. Therefore, the assumption of an upstream control and accelerating flow is correct. The normal depth of 2.66 ft. is within the scope of this method, since it does not exceed the actual conduit height of 5 ft.

Example 7

Given: A discharge rate of 230 cfs entering a 6-ft. by 10-ft. concrete box conduit with slope $S_o = 0.006$, and $\alpha = 1.04$. For a Manning n of 0.012, find normal depth. In this case, $M < 1$. Consider the conduit to be 6 ft. × 6 ft.

$$BD^{1.5} = B^{2.5} = 6.0^{2.5} = 88.18 \quad \text{(Table 21)}$$

$$\frac{Q}{B^{2.5}} = \frac{230.0}{88.18} = 2.61$$

$$S_f = K_n \frac{n^2}{D^{0.333}} \left(\frac{Q}{B^{2.5}}\right)^2$$

$$K_n = \frac{0.006 \times 6.0^{0.333}}{0.012^2 \times 2.61^2} = 11.113.$$

Then from Table 23, Col. D, $M = 1.0$,

$$\frac{d_n}{B} = 0.506; \; d_n = 3.04 \text{ ft. and } \frac{d_n}{D} = 0.304.$$

Critical depth for this rate of flow, from Table 22,

$$\frac{d_c}{B} = 0.604 \text{ or } d_c = 3.62 \text{ ft.}$$

Since $M = \frac{6.0}{10.0} = 0.6$, the results can be checked using the table for $M = 0.6$:

$$BD^{1.5} = 6.0 \times 10.0^{1.5} = 189.72$$

$$\frac{Q}{BD^{1.5}} = \frac{230.0}{189.72} = 1.212$$

$$K_n = \frac{0.006 \times 10.0^{0.333}}{0.012^2 \times 1.212^2} = 60.99$$

From Table 23, Col. D, $M = 0.6$:

$$\frac{d_n}{D} = 0.304, \qquad d_n = 3.04 \text{ ft.}$$

Critical depth (Table 22):

$$\frac{d_c}{D} = 0.362 \qquad d_c = 3.62 \text{ ft.}$$

The results obtained are the same as those in the preceding solution.

e. Method for transforming K_f and K_n for square conduits to values for any shape

In a preceding section, equations for resistance computation factors for square and for rectangular conduits were presented in a form that used the conduit shape factor, $M = \frac{B}{D}$, as a determinant of the hydraulic radius in partly full flow. The equations of that section made it evident that K_f and K_n for rectangular conduits were related to those for square conduits through the terms involving M, and that at equal relative depths of flow, other terms of the equation were not modified by the conduit shape.

Therefore, it is feasible to compute values for K_f or K_n at an entire series of relative depths for any particular relation of conduit width to height (the M factor) by conversion from the base values for a square conduit ($M = 1.0$) given in Tables 23 and 24.

The methods previously presented for determining normal depth in a rectangular conduit suffice for most design problems. To provide a procedure for eventual frequent use of rectangular conduits of a particular B to D ratio (other than square), and to complete the exposition of computation methods, the following procedure is presented for conversion of K_f or K_n for square conduits to values for any ratio $\frac{B}{D}$.

For this purpose, the tables for rectangular conduits presented herein give the values for K_n (Table 23) and for K_f (Table 24) for a square conduit in a column identified by $M=1.0$. The tables also include, in Column C, the value of the bracketed term of the K_n or K_f equations of a previous section, as applied to a square conduit.

A value of the resistance computation factor for a rectangular conduit of any shape, i.e., $M<1.0$ or $M>1.0$, will be obtained from the tabulated value for $M=1.0$ by the following procedure.

1. First, compute the value of the bracketed term of the general equation for K_f or K_n for the conduit shape factor M involved, at the relative depth of flow, or for a series of depths, i.e.,

$$\left[\frac{M+2\frac{d}{D}}{M}\right] \qquad \text{Darcy}$$

$$\left[\frac{M+2\frac{d}{D}}{M\frac{d}{D}}\right]^{4/3} \qquad \text{Manning}$$

Observe that the 4/3 power of the term must be computed if the Manning n is to be used.

2. Second, take the corresponding value of the bracketed term for a square conduit from Column C of the table, and divide the value obtained in step one by this value.

3. Third, multiply the tabulated value of K_f or K_n for $M=1.0$ in Column D of the table by the ratio obtained in Step 2.

Example 8

The resistance computation factor for an 8 ft. by 5 ft. rectangular conduit $(M=\frac{B}{D}=1.60)$ may be computed from the tabulated value of either K_f or K_n for a square conduit, $M=1.0$. Consider a depth of flow of 3.5 ft., or $\frac{d}{D}=0.70$.

	Darcy	Manning
Step 1.	$\left[\frac{M+2\frac{d}{D}}{M}\right]$	$\left[\frac{M+2\frac{d}{D}}{M\left(\frac{d}{D}\right)}\right]^{4/3}$
	$\frac{1.60+1.40}{1.60}=1.875$	$\left[\frac{1.60+1.40}{1.60\times 0.70}\right]^{4/3}=3.720$
Step 2.	$\frac{1.875}{2.40}=0.7812$	$\frac{3.720}{5.170}=0.7196$
Step 3.	$K_f=0.7812\times 0.0272=0.02125$	$K_n=0.7196\times 4.778=3.438$

The values obtained for K_f and K_n by this conversion procedure will correspond to those given in the following tables, for $M=1.6$ in Column D. The tabulated values were computed directly by use of the basic equations.

In addition to the tabulated values for K_f and K_n for square conduits, which should be of frequent usefulness, the tables include similar values for rectangular conduits with $M=0.6$ and $M=1.6$. These values will aid in evaluating the general level of reliability of values computed for any rectangle from the tabulated values for $M=1.0$, to help avoid gross errors. The direct use of the values of K_f and K_n for $M=0.6$ and $M=1.6$ should be infrequent in common design problems.

The method described for conversion of resistance computation factors for partly full flow in square conduits to such factors for rectangular conduits at equal $\frac{d}{D}$ value is not applicable to full flow conditions, that is: $\frac{d}{D}=1.00$. A less complex method will apply.

In full flow, the hydraulic radius is reduced because the flow is in contact with the top slab of the conduit. For this stage of flow

$$\frac{R}{D}=\frac{BD}{D(2B+2D)}$$

and substituting $B=MD$,

$$\frac{R}{D}=\frac{MD^2}{D(2MD+2D)}=\frac{M}{2(M+1)}.$$

With $\frac{A}{BD}=1.0$, the equations for resistance slope at full flow become

$$S_f=\frac{f}{8g\left[\frac{M}{2(M+1)}\right]}\left(\frac{Q}{BD^{1.5}}\right)^2 \qquad \text{Darcy}$$

$$S_f = \frac{n^2}{2.208 D^{0.33}\left[\frac{M}{2(M+1)}\right]^{1.33}} \left(\frac{Q}{BD^{1.5}}\right)^2. \quad \text{Manning}$$

From the above:

$$K_f = 0.003887 \left[\frac{2(M+1)}{M}\right]. \quad \text{Darcy}$$

$$K_n = 0.4529 \left[\frac{2(M+1)}{M}\right]^{4/3}. \quad \text{Manning}$$

Therefore K_f and K_n values for *full flow* in rectangular conduits may be obtained directly from the above equations, with the shape factor $M = \frac{B}{D}$, without conversion from the tabulated values for $\frac{d}{D} = 1.0$ for square conduits.

Values of $BD^{1.5}$ for various sizes of square and rectangular conduits are given in Table 21.

Table 21.—$BD^{1.5}$ Values for various square and rectangular conduits

$B \times D$ ft.	$BD^{1.5}$	$B \times D$ ft.	$BD^{1.5}$	$B \times D$ ft.	$BD^{1.5}$	$B \times D$ ft.	$BD^{1.5}$	$B \times D$ ft.	$BD^{1.5}$	$B \times D$ ft.	$BD^{1.5}$
2 x 1.5	3.674	6 x 3	31.18	8 x 5	89.44	8 x 7	148.2	6 x 9	162.0	14 x 10	442.7
3 x 1.5	5.511	7 x 3	36.37	9 x 5	100.6	9 x 7	166.7	7 x 9	189.0	16 x 10	506.0
				10 x 5	111.8	10 x 7	185.2	8 x 9	216.0	18 x 10	569.2
2 x 2	5.657	3 x 4	24.00			12 x 7	222.2	9 x 9	243.0	20 x 10	632.4
3 x 2	8.485	4 x 4	32.00	4 x 6	58.79	14 x 7	259.3	10 x 9	270.0		
4 x 2	11.31	5 x 4	40.00	5 x 6	73.48			12 x 9	324.0	9 x 11	328.3
5 x 2	14.14	6 x 4	48.00	6 x 6	88.18	5 x 8	113.1	14 x 9	378.0	11 x 11	401.3
		7 x 4	56.00	7 x 6	102.9	6 x 8	135.8	16 x 9	432.0	15 x 11	547.2
4 x 2.5	15.81	8 x 4	64.00	8 x 6	117.6	7 x 8	158.4	18 x 9	486.0		
5 x 2.5	19.76	9 x 4	72.00	9 x 6	132.3	8 x 8	181.0			10 x 12	415.7
6 x 2.5	23.72			10 x 6	147.0	9 x 8	203.6	6 x 10	189.7	12 x 12	498.8
		3 x 5	33.54	12 x 6	176.4	10 x 8	226.3	7 x 10	221.4	14 x 12	582.0
2 x 3	10.39	4 x 5	44.72			12 x 8	271.5	8 x 10	253.0	16 x 12	665.1
3 x 3	15.59	5 x 5	55.90	5 x 7	92.60	14 x 8	316.8	9 x 10	284.6	18 x 12	748.2
4 x 3	20.78	6 x 5	67.08	6 x 7	111.1	16 x 8	362.0	10 x 10	316.2	20 x 12	831.4
5 x 3	25.98	7 x 5	78.26	7 x 7	129.6	18 x 8	407.3	12 x 10	379.5	22 x 12	914.5

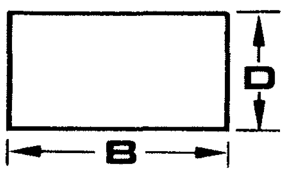
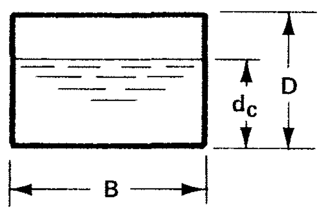


Table 22.—Critical flow factors for rectangular conduits flowing partly full

D = Height of conduit
B = Width of conduit
d_c = Critical depth
Q_c = Discharge at a critical flow condition
H_c = Specific head at critical flow
$\frac{H_c}{D} = \frac{d_c}{D} + \frac{\alpha V_c^2}{2gD} = \frac{3}{2}\frac{d_c}{D}$ (invariant with α)
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.



$\frac{d_c}{D}$	$\frac{Q_c}{BD^{1.5}}$		$\frac{H_c}{D}$	$\frac{d_c}{D}$	$\frac{Q_c}{BD^{1.5}}$		$\frac{H_c}{D}$
	$\alpha = 1.00$	$\alpha = 1.04$			$\alpha = 1.00$	$\alpha = 1.04$	
1.00	—	—	—	0.95	5.251	5.149	1.425
0.99	5.586	5.478	1.485	.94	5.168	5.068	1.410
.98	5.502	5.395	1.470	.93	5.086	4.987	1.395
.97	5.418	5.313	1.455	.92	5.004	4.907	1.380
.96	5.334	5.231	1.440	.91	4.923	4.827	1.365

Table 22.—Critical flow factors for rectangular conduits flowing partly full—Continued

$\frac{d_c}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.04$	$\frac{H_c}{D}$	$\frac{d_c}{D}$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.00$	$\frac{Q_c}{BD^{1.5}}$ $\alpha=1.04$	$\frac{H_c}{D}$
0.90	4.842	4.748	1.350	0.50	2.005	1.966	0.750
.89	4.761	4.669	1.335	.49	1.945	1.907	.735
.88	4.681	4.591	1.320	.48	1.886	1.849	.720
.87	4.602	4.513	1.305	.47	1.827	1.792	.705
.86	4.523	4.435	1.290	.46	1.769	1.735	.690
.85	4.444	4.358	1.275	.45	1.712	1.679	.675
.84	4.366	4.281	1.260	.44	1.655	1.623	.660
.83	4.288	4.205	1.245	.43	1.599	1.568	.645
.82	4.211	4.129	1.230	.42	1.544	1.514	.630
.81	4.134	4.054	1.215	.41	1.489	1.460	.615
.80	4.058	3.979	1.200	.40	1.435	1.407	.600
.79	3.982	3.905	1.185	.39	1.381	1.354	.585
.78	3.907	3.831	1.170	.38	1.328	1.303	.570
.77	3.832	3.758	1.155	.37	1.276	1.252	.555
.76	3.757	3.684	1.140	.36	1.225	1.201	.540
.75	3.683	3.612	1.125	.35	1.1742	1.1514	.525
.74	3.610	3.540	1.110	.34	1.1243	1.1024	.510
.73	3.537	3.468	1.095	.33	1.0750	1.0542	.495
.72	3.465	3.397	1.080	.32	1.0266	1.0066	.480
.71	3.393	3.327	1.065	.31	0.9788	0.9598	.465
.70	3.321	3.257	1.050	.30	.9319	.9138	.450
.69	3.250	3.187	1.035	.29	.8856	.8684	.435
.68	3.180	3.118	1.020	.28	.8402	.8239	.420
.67	3.110	3.050	1.005	.27	.7956	.7802	.405
.66	3.041	2.982	0.990	.26	.7518	.7372	.390
.65	2.972	2.914	.975	.25	.7089	.6951	.375
.64	2.904	2.847	.960	.24	.6668	.6538	.360
.63	2.836	2.781	.945	.23	.6255	.6134	.345
.62	2.769	2.715	.930	.22	.5852	.5738	.330
.61	2.702	2.649	.915	.21	.5457	.5351	.315
.60	2.636	2.584	.900	.20	.5072	.4974	.300
.59	2.570	2.520	.885	.19	.4697	.4606	.285
.58	2.505	2.456	.870	.18	.4331	.4247	.270
.57	2.440	2.393	.855	.17	.3975	.3898	.255
.56	2.377	2.330	.840	.16	.3629	.3559	.240
.55	2.313	2.268	.825	.15	.3294	.3230	.225
.54	2.250	2.207	.810	.14	.2970	.2913	.210
.53	2.188	2.146	.795	.13	.2658	.2606	.195
.52	2.127	2.085	.780	.12	.2069	.2029	.180
.51	2.065	2.025	.765	.11	.1793	.1758	.165

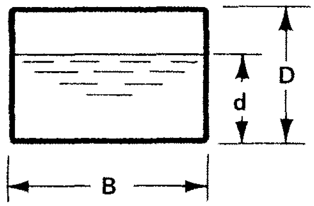
Table 23. – Velocity head and resistance computation factor (Manning Equation) for rectangular conduits flowing full and partly full

Column A: Relative depth of flow, $\frac{d}{D}$

Column B: Relative velocity head
$h_v/D=\alpha V^2/2gD$, $\alpha=1.00$, $Q/BD^{1.5}=1.0$
V = Mean flow velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.

Column C: Factor $\left[\left(M+2\frac{d}{D}\right)\Big/\left(M\frac{d}{D}\right)\right]^{4/3}$ for $M=1.0$, Square Conduit
$M=B/D$, the conduit shape factor

Column D: Resistance computation factor K_n for the Manning equation, $V=(1.486/n)R^{2/3}S^{1/2}$
$S_f=Q^2n^2/2.208R^{4/3}A^2=K_n(^2/D^{1/3})(Q/BD^{1.5})^2$
$K_n=0.4529/(R/D)^{4/3}(A/BD)^2=$
$=0.4529/(d/D)^2[(M+2d/D)/(Md/D)]^{4/3}$
A = Area of flow $\quad$ S_f = Friction slope
R = Hydraulic radius $\quad$ n = Manning coefficient



(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$, $\alpha=1.00$, $\frac{Q}{BD^{1.5}}=1.0$	(C) Square conduit $M=1.0$ $\left[\frac{1+2\frac{d}{D}}{\frac{d}{D}}\right]^{4/3}$	(D) Resistance computation factor K_n for Manning equation		
			$M=1.0$	$M=0.6$	$M=1.6$
1.00	0.01555	–	2.876	4.220	2.180
0.99	.01587	4.346	2.008	3.274	1.371
.98	.01619	4.366	2.059	3.352	1.407
.97	.01653	4.386	2.111	3.433	1.445
.96	.01687	4.407	2.166	3.516	1.485
.95	.01723	4.428	2.222	3.602	1.526
.94	.01760	4.450	2.281	3.692	1.568
.93	.01798	4.472	2.342	3.785	1.613
.92	.01837	4.495	2.405	3.881	1.659
.91	.01878	4.518	2.471	3.982	1.707
.90	.01920	4.542	2.539	4.085	1.758
.89	.01963	4.566	2.610	4.193	1.810
.88	.02008	4.591	2.685	4.306	1.865
.87	.02054	4.616	2.762	4.422	1.922
.86	.02102	4.643	2.843	4.544	1.981
.85	.02152	4.669	2.927	4.670	2.044
.84	.02204	4.697	3.015	4.802	2.109
.83	.02257	4.725	3.106	4.939	2.177
.82	.02313	4.754	3.202	5.082	2.248
.81	.02370	4.784	3.302	5.231	2.323
.80	.02430	4.814	3.406	5.387	2.401
.79	.02492	4.845	3.516	5.550	2.483
.78	.02556	4.878	3.631	5.720	2.569
.77	.02623	4.910	3.751	5.898	2.659
.76	.02692	4.944	3.877	6.084	2.754
.75	.02764	4.979	4.009	6.278	2.854
.74	.02840	5.015	4.148	6.483	2.959
.73	.02918	5.052	4.293	6.696	3.069
.72	.03000	5.090	4.447	6.921	3.186
.71	.03085	5.129	4.608	7.157	3.308
.70	.03173	5.170	4.778	7.404	3.438
.69	.03266	5.212	4.957	7.665	3.575
.68	.03363	5.255	5.146	7.939	3.720
.67	.03464	5.299	5.346	8.227	3.873
.66	.03570	5.345	5.557	8.531	4.035
0.65	0.03680	5.392	5.780	8.852	4.207
.64	.03796	5.441	6.016	9.191	4.389
.63	.03918	5.491	6.266	9.549	4.583
.62	.04045	5.544	6.531	9.928	4.789
.61	.04179	5.598	6.813	10.330	5.008
.60	.04319	5.654	7.112	10.76	5.242
.59	.04467	5.712	7.431	11.21	5.492
.58	.04622	5.772	7.771	11.69	5.758
.57	.04786	5.835	8.133	12.20	6.043
.56	.04959	5.900	8.520	12.74	6.348
.55	.05140	5.968	8.934	13.32	6.674
.54	.05333	6.038	9.377	13.94	7.025
.53	.05536	6.111	9.852	14.60	7.403
.52	.05751	6.187	10.362	15.31	7.809
.51	.05978	6.267	10.911	16.06	8.247
.50	.06220	6.350	11.50	16.88	8.720
.49	.06476	6.436	12.14	17.75	9.232
.48	.06749	6.527	12.83	18.70	9.787
.47	.07039	6.621	13.57	19.71	10.389
.46	.07349	6.720	14.38	20.81	11.044
.45	.07679	6.824	15.26	22.00	11.76
.44	.08032	6.933	16.22	23.30	12.54
.43	.08410	7.048	17.26	24.70	13.39
.42	.08815	7.168	18.40	26.23	14.33
.41	.09250	7.295	19.65	27.90	15.36
.40	.09719	7.429	21.03	29.72	16.49
.39	.10224	7.571	22.54	31.72	17.74
.38	.10769	7.720	24.21	33.93	19.13
.37	.11359	7.879	26.06	36.35	20.67
.36	.11998	8.047	28.12	39.04	22.39
.35	.1269	8.226	30.41	42.02	24.32
.34	.1345	8.416	32.97	45.34	26.47
.33	.1428	8.619	35.84	49.04	28.90
.32	.1519	8.836	39.08	53.19	31.64
.31	.1618	9.069	42.73	57.86	34.76

Table 23.—Velocity head and resistance computation factor (Manning Equation) for rectangular conduits flowing full and partly full—Continued

(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$ $\alpha = 1.00$ $\frac{Q}{BD^{1.5}} = 1.0$	(C) Square conduit $M = 1.0$ $\left[\frac{1+2\frac{d}{D}}{\frac{d}{D}}\right]^{4/3}$	(D) Resistance computation factor K_n for Manning equation $M = 1.0$	$M = 0.6$	$M = 1.6$	(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$ $\alpha = 1.00$ $\frac{Q}{BD^{1.5}} = 1.0$	(C) Square conduit $M = 1.0$ $\left[\frac{1+2\frac{d}{D}}{\frac{d}{D}}\right]^{4/3}$	(D) Resistance computation facto K_n for Manning equation $M = 1.0$	$M = 0.6$	$M = 1.($
0.30	0.1728	9.318	46.89	63.13	38.31	0.20	0.3887	13.39	151.6	191.3	130.3
.29	.1849	9.587	51.62	69.12	42.37	.19	.4307	14.07	176.5	220.9	152.6
.28	.1983	9.877	57.05	75.95	47.05	.18	.4799	14.83	207.2	257.4	180.3
.27	.2133	10.191	63.31	83.77	52.46	.17	.5381	15.69	245.8	302.8	215.1
.26	.2300	10.532	70.55	92.78	58.75	.16	.6074	16.67	294.9	360.1	259.7
.25	.2488	10.90	79.00	103.2	66.11						
.24	.2700	11.31	88.91	115.4	74.79						
.23	.2940	11.75	100.62	129.7	85.09						
.22	.3213	12.24	114.56	146.7	97.40						
.21	.3526	12.79	131.31	166.9	112.26						

Table 24.—Velocity head and resistance computation factors (Darcy equation) for rectangular conduits flowing full and partly full

Column A: Relative depth of flow, $\frac{d}{D}$

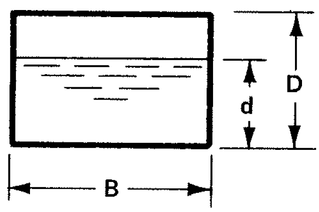
Column B: Relative velocity head
$h_v/D = \alpha V^2/2gD$, $\alpha = 1.00$, $Q/BD^{1.5} = 1.0$
V = Mean flow velocity
α = Kinetic energy correction factor
g = Acceleration due to gravity = 32.16 ft./sec./sec.

Column C: $\frac{d}{D} \div \frac{R}{D} = \frac{M+2d/D}{M} = 1+2\frac{d}{D}$, for $M = 1$
$M = B/D$, the conduit shape factor

Column D: Resistance computation factor K_f for the Darcy equation, $h_f = (f)(L/4R)(V^2/2g)$
$S_f = Q^2 f/257.28\ RA^2 = K_f(f)(Q/BD^{1.5})^2$

$$K_f = 0.003887/(R/D)(A/BD)^2 = 0.003887/(d/D)^3\left[\left(M+2\frac{d}{D}\right)/M\right]$$

A = Area of flow
R = Hydraulic radius
S_f = Friction slope
h_f = Friction head loss, ft.
f = Darcy coefficient
L = Length of conduit, ft.



(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$ $\alpha = 1.00$ $\frac{Q}{BD^{1.5}} = 1.0$	(C) Square conduit $M = 1$ $\frac{d}{D} \div \frac{R}{D}$ $= 1+2\frac{d}{D}$	(D) Resistance computation factor K_f for Darcy equation $M = 1.0$	$M = 0.6$	$M = 1.6$	(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$ $\alpha = 1.00$ $\frac{Q}{BD^{1.5}} = 1.0$	(C) Square conduit $M = 1$ $\frac{d}{D} \div \frac{R}{D}$ $= 1+2\frac{d}{D}$	(D) Resistance computation factor K_f for Darcy equation $M = 1.0$	$M = 0.6$	$M = 1.6$
1.00	0.01555	—	0.01555	0.02073	0.012633	0.95	0.01723	2.90	0.01315	0.01889	0.00992
0.99	.01587	2.98	.01194	.01723	.008963	.94	.01760	2.88	.01348	.01934	.01018
.98	.01619	2.96	.01222	.01762	.009189	.93	.01798	2.86	.01382	.01981	.01045
.97	.01653	2.94	.01252	.01803	.009423	.92	.01837	2.84	.01418	.02030	.01073
.96	.01687	2.92	.01283	.01845	.009665	.91	.01878	2.82	.01455	.02080	.01103

Table 24.—Velocity head and resistance computation factors (Darcy equation) for rectangular conduits flowing full and partly full—Continued

(A) Relative depth $\frac{d}{D}$	(B) Relative velocity head $\frac{\alpha V^2}{2gD}$, $\alpha = 1.00$, $\frac{Q}{BD^{1.5}} = 1.0$	(C) Square conduit $M = 1$, $\frac{d}{D} \div \frac{R}{D} = 1 + 2\frac{d}{D}$	(D) Resistance computation factor K_f for Darcy equation		
			$M = 1.0$	$M = 0.6$	$M = 1.6$
0.90	0.01920	2.80	0.01493	0.02133	0.01133
.89	.01963	2.78	.01533	.02187	.01165
.88	.02008	2.76	.01574	.02244	.01198
.87	.02054	2.74	.01617	.02302	.01232
.86	.02102	2.72	.01662	.02363	.01268
.85	.02152	2.70	.01709	.02426	.01305
.84	.02204	2.68	.01758	.02492	.01344
.83	.02257	2.66	.01808	.02561	.01385
.82	.02313	2.64	.01861	.02632	.01428
.81	.02370	2.62	.01916	.02706	.01472
.80	.02430	2.60	.01974	.02784	.01518
.79	.02492	2.58	.02034	.02864	.01567
.78	.02556	2.56	.02097	.02949	.01618
.77	.02623	2.54	.02163	.03037	.01671
.76	.02692	2.52	.02231	.03129	.01727
.75	.02764	2.50	.02303	.03225	.01785
.74	.02840	2.48	.02379	.03325	.01847
.73	.02918	2.46	.02458	.03431	.01911
.72	.03000	2.44	.02541	.03541	.01979
.71	.03085	2.42	.02628	.03656	.02050
.70	.03173	2.40	.02720	.03777	.02125
.69	.03266	2.38	.02816	.03905	.02204
.68	.03363	2.36	.02917	.04038	.02287
.67	.03464	2.34	.03024	.04179	.02375
.66	.03570	2.32	.03137	.04326	.02468
.65	.03680	2.30	.03255	.04482	.02565
.64	.03796	2.28	.03381	.04646	.02669
.63	.03918	2.26	.03513	.04819	.02779
.62	.04045	2.24	.03653	.05002	.02895
.61	.04179	2.22	.03802	.05195	.03018
.60	.04319	2.20	.03959	.05399	.03149
.59	.04467	2.18	.04126	.05615	.03288
.58	.04622	2.16	.04303	.05844	.03437
.57	.04786	2.14	.04492	.06087	.03594
.56	.04959	2.12	.04692	.06345	.03763
.55	.05140	2.10	.04906	.06619	.03942
.54	.05333	2.08	.05135	.06912	.04135
.53	.05536	2.06	.05378	.07223	.04341
.52	.05751	2.04	.05639	.07556	.04561
.51	.05978	2.02	.05919	.07912	.04798
0.50	0.06220	2.00	0.06219	0.08292	0.05053
.49	.06476	1.98	.06541	.08700	.05328
.48	.06749	1.96	.06889	.09138	.05624
.47	.07039	1.94	.07263	.09609	.05943
.46	.07349	1.92	.07667	.10117	.06290
.45	.07679	1.90	.08104	.1066	.06665
.44	.08032	1.88	.08579	.1126	.07073
.43	.08410	1.86	.09094	.1190	.07517
.42	.08815	1.84	.09653	.1259	.08001
.41	.09250	1.82	.10264	.1335	.08530
.40	.09719	1.80	.1093	.1417	.09110
.39	.10224	1.78	.1166	.1507	.09747
.38	.10769	1.76	.1247	.1606	.10450
.37	.11359	1.74	.1335	.1714	.11223
.36	.11998	1.72	.1433	.1833	.12080
.35	.1269	1.70	.1541	.1964	.1303
.34	.1345	1.68	.1661	.2110	.1409
.33	.1428	1.66	.1795	.2271	.1528
.32	.1519	1.64	.1945	.2452	.1661
.31	.1618	1.62	.2114	.2653	.1810
.30	.1728	1.60	.2303	.2879	.1979
.29	.1849	1.58	.2518	.3134	.2171
.28	.1983	1.56	.2762	.3423	.2390
.27	.2133	1.54	.3041	.3752	.2641
.26	.2300	1.52	.3361	.4128	.2930
.25	.2488	1.50	.3731	.4561	.3265
.24	.2700	1.48	.4162	.5061	.3655
.23	.2940	1.46	.4664	.5644	.4113
.22	.3213	1.44	.5256	.6327	.4654
.21	.3526	1.42	.5960	.7135	.5299
.20	.3887	1.40	.6802	.8098	.6073
.19	.4307	1.38	.7820	.9256	.7013
.18	.4799	1.36	.9064	1.0664	.8165
.17	.5381	1.34	1.0602	1.2395	.9593
.16	.6074	1.32	1.2527	1.4551	1.1388

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IX. NONUNIFORM FLOW COMPUTATION

The tables in this report will facilitate the computation of nonuniform flow in prismatic conduits of constant cross section. For reliable results it is essential that the air space in the conduit above the free-surface flow be at a uniform pressure. In general, this requires the maintenance of atmospheric pressure. Under these conditions, the closed conduit acts as an open channel.

Flow profiles may be computed by application of the standard step method, working with suitably small increments of depth of flow. Because the cross section is uniform, it is not necessary to select particular locations in the channel and to make trial computations, as the step method usually requires. Instead, channel lengths between successive selected depths of flow are computed directly and summed to determine the flow depth profile over a sufficient length to cover or exceed the conduit length involved. A simple interpolation will determine the depth at any specific length. Because the tables are prepared with depth intervals of $0.01D$, frequently interpolation will not be necessary.

The standard step method for computation of depths of flow in a conduit is applicable to both subcritical and supercritical flow. It is necessary to observe the restriction that supercritical flow cannot be transformed to flow at subcritical depths without the formation of a hydraulic jump. Where the conduit slope is adverse—that is, the conduit slopes upward in the direction of flow—the invert rise must be properly taken into account in formulating the equation relating total heads at two successive locations.

The tables provide velocity head factors at any relative depth for a discharge rate of $1.00\ BD^{1.5}$, with a kinetic energy factor $\alpha = 1.00$. Therefore, the velocity head is determined by multiplying the tabular value by α and by $\left(\frac{Q}{BD^{1.5}}\right)^2$ as was explained previously. Depth of flow is added to velocity head to obtain the specific head at the location of each selected depth of flow. Determination of total head, in each case, requires addition of the invert height above a datum.

In application of the step method, it is convenient to use the invert of the lower of the two stations in the conduit involved in each step computation as a datum. This procedure avoids the need for involving invert elevations above a common datum applicable to the entire length of the conduit.

Whether the conduit invert falls or rises in the direction of flow, to avoid mistakes in the flow profile calculations, stick to the principle that the total head above a common datum must always decrease along the direction of flow.

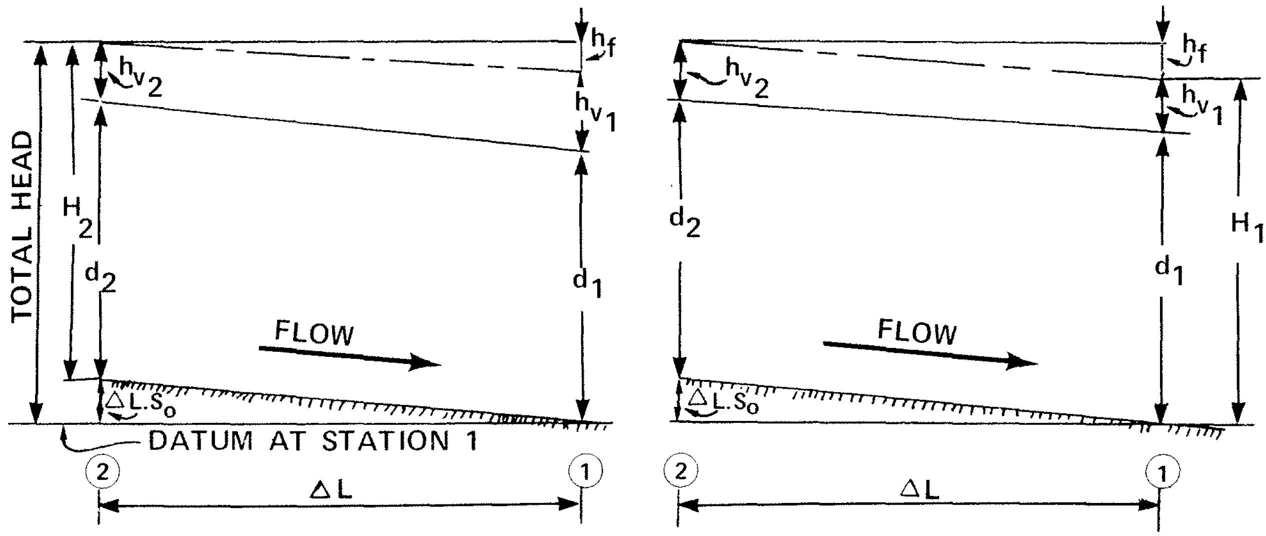
The tables, which involve only the geometry of the flow prism and the methods through which it is applied to the hydraulic calculations, may be applied with the assumption that the Darcy resistance factor f, or the Manning n, do not vary with the hydraulic radius, and therefore are constant over a range of varying depths. This is the current (1971) practice of most engineers. With more nearly correct methods involving resistance factors which vary with hydraulic radius in a conduit with uniform wall roughness, the tables in their present form may also be applied.

Nonuniform flow profile and specific and total head lines are illustrated in the sketches on p. 54. The method for application of the tables of Velocity Head and Resistance Computation Factors is also demonstrated.

With subcritical flow, computation of the surface profile must begin at a known downstream depth and proceed upstream. The difference of total heads (above a common horizontal datum) is equal to the loss of energy by resistance to flow over the distance between sections, viz. $h_f = \Delta L \times S_f$.

With a known rate of flow, $\frac{Q}{BD^{1.5}}$, and a known relative depth $\frac{d_1}{D}$ at Station 1, the velocity head $\frac{h_v}{D} = \frac{\alpha V_1^2}{2gD}$ may be obtained from the table, of velocity head factors for the conduit shape involved, viz.

Specific head and total head in steady, nonuniform, subcritical flow



A. Accelerating flow as for flow approaching critical depth.

B. Decelerating flow as for flow approaching a weir.

$$\frac{\alpha V_1^2}{2gD} = {}^*\left(\frac{\alpha V_1^2}{2gD}\right) \times \alpha \times \left(\frac{Q}{BD^{1.5}}\right)^2$$

Then the relative specific head,

$$\frac{H_1}{D} = \frac{d_1}{D} + \frac{\alpha V_1^2}{2gD} \text{ at Station 1.}$$

For Case A, slightly greater depth d_2 at an upstream Station 2 is then selected. Depths at $0.01D$ or $0.02D$ intervals are convenient for use of the tables. Then the specific head at Station 2 is similarly determined,

$$\frac{H_2}{D} = \frac{d_2}{D} + \frac{\alpha V_2^2}{2gD} \text{ at Station 2}$$

Taking into account the loss of energy by resistance, and the difference of conduit invert elevations, $\Delta L \times S_0$, both over the conduit length interval ΔL between the two stations, the total heads are related by the equation:

$$\frac{H_2}{D} + \frac{\Delta L.S_0}{D} = \frac{H_1}{D} + \frac{\Delta L S_f}{D}$$

The equation may be rearranged to solve for the unknown length between the stations with the two selected depths of flow.

$$\frac{\Delta L}{D} = \left[\frac{H_2}{D} - \frac{H_1}{D}\right] \div (S_f - S_0)$$

For cases A and B, as illustrated, the length increment ΔL obtained will always be measured in an upstream direction from the downstream Station 1.

For more reliable results, the resistance loss h_f over the length ΔL should be computed for the mean of the resistance loss rates S_{f_1} and S_{f_2} at the two locations of known depths d_1 and d_2. The geometric mean, rather than the arithmetic mean, is a more nearly true representation of the mean rate of resistance loss, S_{f_m} That is

$$S_{f_m} = (S_{f_1} \times S_{f_2})^{1/2}$$

The mean value, S_{f_m}, is to be used in the above equation for $\frac{\Delta L}{D}$.

Either the Darcy K_f or the Manning K_n resistance computation factor may be used for determination of rate of resistance loss at each of the two stations of known depth. Either factor may be obtained directly from the table of Resistance Computa-

*Tabular value for $\alpha = 1.00$ and $\left(\frac{Q}{BD^{1.5}}\right) = 1.00$

tion Factors for the particular conduit shape involved. These rates of resistance loss are the local slope of the total head line at each station, with reference to the horizontal. Therefore, the mean rate, S_{f_m}, is the mean slope over the length ΔL between the two stations.

To reduce the calculations required, it is preferable to compute the mean of the two values of K_f (or K_n) and then to compute

$$S_{f_m} = K_{f_m} f \left(\frac{Q}{BD^{1.5}}\right)^2$$

The example below will illustrate the method for determining the location of a greater depth d_2 upstream from an initial depth d_1 in a conduit sloping in the direction of the flow, with a gradual decrease of depth as the flow approaches the conduit outlet, where critical depth occurs.

Example 9

Flow rate 80 cfs in a 4.0-ft. diameter circular concrete conduit ($f=0.0141$, or $n=0.0110$) with an invert slope 0.0020 ft. per foot. Determine the distance ΔL from a depth of 3.00 ft. to an upstream depth of 3.08 ft; $\alpha=1.04$. The discharge factor is

$$\frac{Q}{D^{2.5}} = \frac{80}{32.0} = 2.50;$$

Therefore $\frac{d_c}{D} = 0.684$ (Tables 1 and 4) and the flow is subcritical. $\frac{d_1}{D} = 0.75$ and $\frac{d_2}{D} = 0.77$, then velocity heads (Table 5) are

$$\frac{V_1^2}{2gD} = 0.03894 \times 1.04 \times 6.25 = 0.2531;$$

and

$$\frac{V_2^2}{2gD} = 0.03692 \times 1.04 \times 6.25 = 0.2400.$$

Therefore $\frac{H_1}{D} = 1.0030$ and $\frac{H_2}{D} = 1.0100$

$$K_{f_1} = 0.03226 \text{ and } K_{f_2} = 0.03045 \text{ (Table 5)}$$

$$K_{f_m} = 0.03134$$

$$S_{f_m} = 0.03134 \times 0.0141 \times 6.25 = 0.00276.$$

Then compute $\frac{\Delta L}{D}$

$$\frac{\Delta L}{D} = \left[\frac{H_2}{D} - \frac{H_1}{D}\right] \div (S_{f_m} - S_0)$$

$$\frac{\Delta L}{D} = \frac{1.0100 - 1.0030}{0.00276 - 0.00200} = 9.21$$

Therefore $\Delta L = 9.21 \times 4.0 = 36.8$ ft. from Station 1 to Station 2.

Examples of application of the step method and the tables to the computation of a complete flow profile over the length of a conduit are included in Appendix B.

These methods are also applicable to computation of headwater depths for culverts on mild slopes flowing under outlet control conditions.

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APPENDIX A
DIAGRAMS FOR ERROR CORRECTION

This Appendix includes three diagrams for error correction for some particular sections and factors. The mean values of these factors, which are in Tables 13, 14, 19 and 20, show a considerable deviation from their true values. The factors were grouped according to the similarity of their errors, and curves of percent of error versus relative depth, $\frac{d}{D}$, were plotted.

A correction value is obtained by multiplying the tabulated value of a factor by the percent of error, which is derived from the diagram, using the appropriate curve and the given relative depth, $\frac{d}{D}$. The function signs in the legend of the diagrams dictate whether the correction value should be added to the tabulated value or subtracted from it. A negative sign means that the tabulated value of function is lower than the true value; therefore, the correction value must be added to the tabulated value. Conversely, when the sign is positive, the correction must be subtracted from the tabulated value.

Example 10

Using the error correction diagrams, find true values for:

a) Factor K_n at $\frac{d}{D}=0.45$, Section No. 1 of Corrugated Metal Pipe-Arch 2⅔ by ½ in. corrugation;

From Table 14, $K_n = 14.28$;
From Diagram 1, correction Value $= 14.28 \times 0.17 = 2.43$;
The function sign is (−), then $K_n' = 14.28 + 2.43 = 16.71$;
The actual value obtained by computer is $K_{n_{act.}} = 16.80$,

hence

$$\text{Error} = \frac{0.09}{16.80} = -0.5 \text{ percent.}$$

b) Factor K_f at $\frac{d}{D}=0.42$, Section No. 23 of Structural Plate Pipe-Arch 6 by 2 in. corrugation, 18 in. corner radius;

From Table 20, $K_f = 0.10693$;
From Diagram 2, correction value $= 0.1063 \times 0.103 = 0.01101$;
The function sign is (+), then $K_f' = 0.10693 - 0.01101 = 0.09592$;
The actual value obtained by computer is $K_{f_{act.}} = 0.09678$,

hence

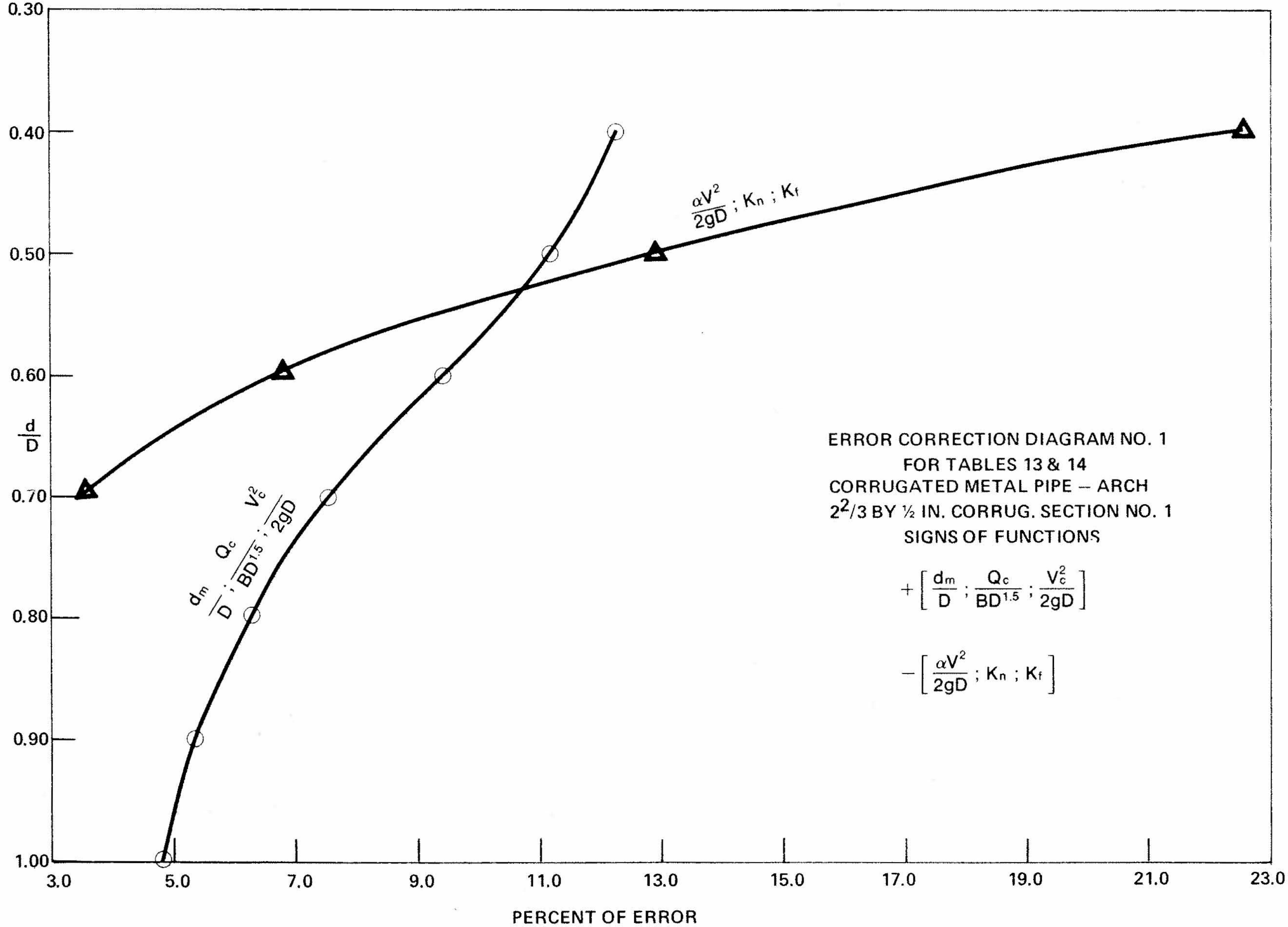
$$\text{Error} = \frac{0.00086}{0.09678} = -0.9 \text{ percent}$$

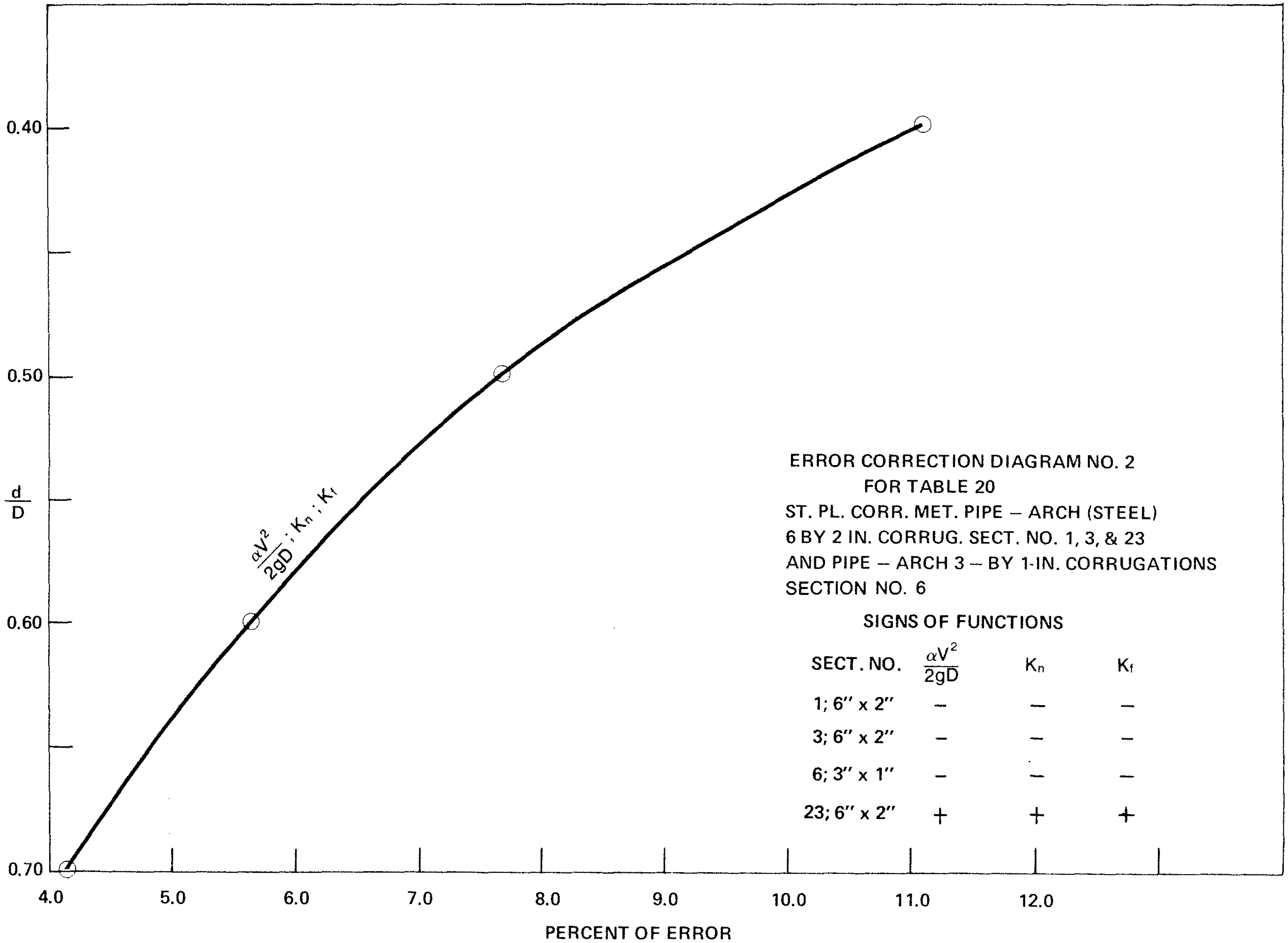
c) Factor $\frac{R}{D}$ at $\frac{d}{D}=0.44$, Section No. 2 Structural Plate Aluminum Pipe-Arch 9 by 2½ in. corrugation, 28.8 in. corner radius.

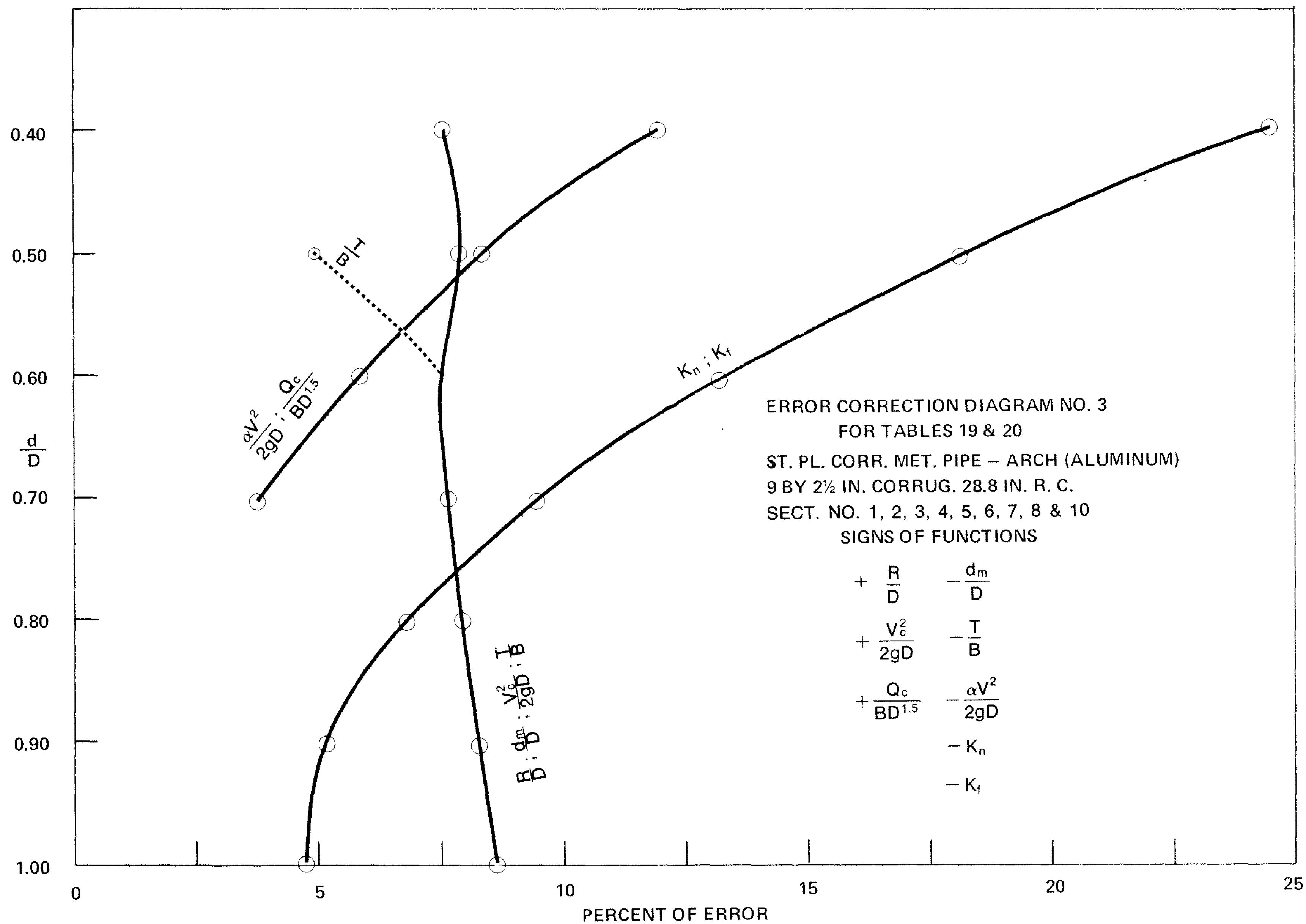
From Table 19, $\frac{R}{D} = 0.2817$;
From Diagram 3, correction value $= 0.2817 \times 0.078 = 0.0220$.
The function sign is (+), then $\left(\frac{R}{D}\right)' = 0.2817 - 0.0220 = 0.2597$;
The actual value obtained by computer is $\left(\frac{R}{D}\right)_{act.} = 0.2531$,

hence

$$\text{Error} = \frac{0.0066}{0.2531} = +2.6 \text{ percent.}$$


0.30
0.40
0.50
0.60
d/D
0.70
0.80
0.90
1.00
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
23.0
PERCENT OF ERROR
$\frac{\alpha V^2}{2gD}$; K_n ; K_f
$\frac{d_m}{D}$; $\frac{Q_c}{BD^{1.5}}$; $\frac{V_c^2}{2gD}$
ERROR CORRECTION DIAGRAM NO. 1
FOR TABLES 13 & 14
CORRUGATED METAL PIPE – ARCH
$2^2/3$ BY ½ IN. CORRUG. SECTION NO. 1
SIGNS OF FUNCTIONS
$+\left[\frac{d_m}{D} ; \frac{Q_c}{BD^{1.5}} ; \frac{V_c^2}{2gD}\right]$
$-\left[\frac{\alpha V^2}{2gD} ; K_n ; K_f\right]$


0.40
0.50
0.60
0.70
$\frac{d}{D}$
$\frac{\alpha V^2}{2gD}$; K_n ; K_f
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
PERCENT OF ERROR
ERROR CORRECTION DIAGRAM NO. 2
FOR TABLE 20
ST. PL. CORR. MET. PIPE – ARCH (STEEL)
6 BY 2 IN. CORRUG. SECT. NO. 1, 3, & 23
AND PIPE – ARCH 3 – BY 1-IN. CORRUGATIONS
SECTION NO. 6
SIGNS OF FUNCTIONS
SECT. NO. $\frac{\alpha V^2}{2gD}$ K_n K_f
1; 6″ x 2″ – – –
3; 6″ x 2″ – – –
6; 3″ x 1″ – – –
23; 6″ x 2″ + + +


ERROR CORRECTION DIAGRAM NO. 3
FOR TABLES 19 & 20
ST. PL. CORR. MET. PIPE – ARCH (ALUMINUM)
9 BY 2½ IN. CORRUG. 28.8 IN. R. C.
SECT. NO. 1, 2, 3, 4, 5, 6, 7, 8 & 10
SIGNS OF FUNCTIONS
$+ \frac{R}{D}$ $- \frac{d_m}{D}$
$+ \frac{V_c^2}{2gD}$ $- \frac{T}{B}$
$+ \frac{Q_c}{BD^{1.5}}$ $- \frac{\alpha V^2}{2gD}$
$- K_n$
$- K_f$
$\frac{\alpha V^2}{2gD}$; $\frac{Q_c}{BD^{1.5}}$
$\frac{T}{B}$
K_n ; K_f
$\frac{R}{D}$; $\frac{d_m}{D}$; $\frac{V_c^2}{2gD}$; $\frac{T}{B}$
$\frac{d}{D}$
0.40
0.50
0.60
0.70
0.80
0.90
1.00
0
5
10
15
20
25
PERCENT OF ERROR

APPENDIX B
BACKWATER PROFILE COMPUTATION

Example 11

Given: Square box storm drain conduit flowing with outlet control, because of critical depth at the outlet,

$$D = 4.0 \text{ ft.};\ L = 240 \text{ ft.};\ S_0 = 0.002 \text{ ft/ft};$$

$$Q = 125 \text{ cfs};\ n = 0.012;\ \alpha = 1.04.$$

Compute a backwater profile from the outlet to the point at which the depth reaches the crown, and find the specific head in the conduit at the entrance.

$$\frac{Q}{BD^{1.5}} = \frac{125.0}{4.0 \times 4.0^{1.5}} = 3.906;\quad \frac{L}{D} = \frac{240}{4.0} = 60$$

$$\frac{d_c}{D} = 0.790 \text{ (Table 22)}$$

$$\frac{\alpha V^2}{2gD} = \text{tabulated value} \times \alpha \times \left(\frac{Q}{BD^{1.5}}\right)^2$$

$$\text{t.v.} \times 1.04 \times 3.906^2 = 15.867 \times \text{t.v.}$$

$$\frac{\Delta H}{D} = \frac{H_2}{D} - \frac{H_1}{D}$$ (downstream specific head subtracted from upstream specific head)

$$S_{fm} = K_{n_m} \frac{n^2}{D^{0.333}}\left(\frac{Q}{BD^{1.5}}\right)^2$$

$$= K_{n_m} \frac{0.012^2}{4.0^{0.333}}(3.906)^2 = 0.001384\, K_{n_m}$$

See Table 25 for tabulated computation.

Thus, the length of the backwater curve; i.e., distance from the point of critical depth of flow to the point at which the depth of flow reaches the crown, is equal to $\frac{L_2}{D} = 46.25$ (See Table No. 25). Then the length of the conduit with full flow is $\frac{L_1}{D} = \frac{L}{D} - \frac{L_2}{D} = 60 - 46.25 = 13.75$ (See sketch on p. 62.)

Resistance slope for the full flow is

$$S_{f\text{full}} = K_{n\text{full}} \frac{n^2}{D^{0.333}}\left(\frac{Q}{BD^{1.5}}\right)^2$$

$$= 2.876 \frac{0.012^2}{4.D^{0.333}} 3.906^2 = 0.00398$$

Specific head in the conduit at the entrance,

$$\frac{H}{D} = \frac{H}{D}_{\text{full}} + (S_{f\text{full}} - S_0)\frac{L_1}{D}$$

$$= 1.2467 + 0.00398 \times 13.75 = 1.3014$$

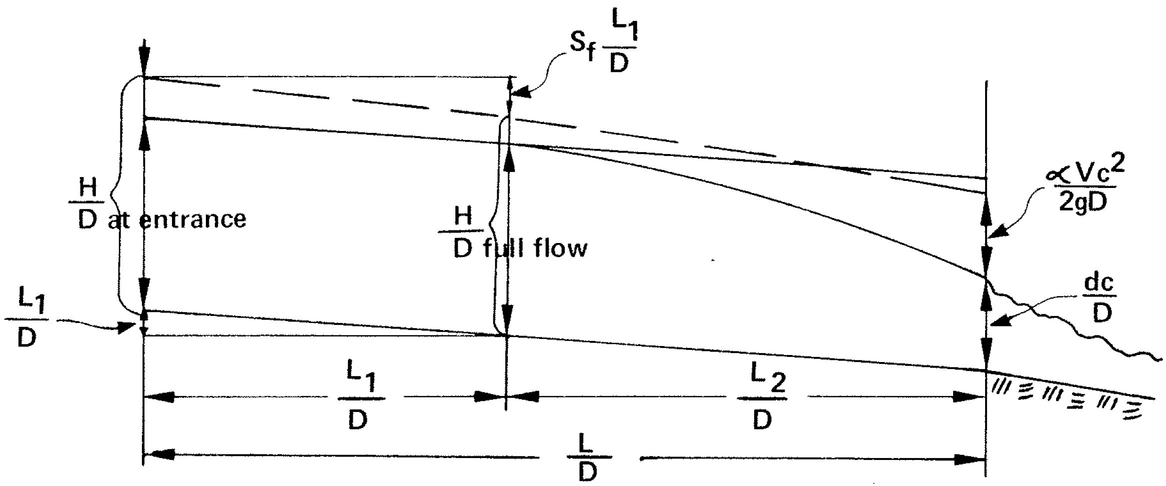
$$H = 1.3014 \times 4.0 = 5.21 \text{ ft.}$$

Note that to determine headwater depth, entrance losses must be considered.

It has been found that the resistance factor, f, for structural plate corrugated metal pipes usually

Table No. 25.—Backwater profile computation (Example 11)

$\frac{d}{D}$	$\frac{\alpha V^2}{2gD}$ Table 23	$\frac{H}{D}$ $\frac{d}{D} + \frac{\alpha V^2}{2gD}$	$\frac{\Delta H}{D}$	K_n Table 23	$K_{n_{mean}}$	$S_{f_{mean}}$	$S_{fm} - S_0$	$\frac{\Delta L_2}{D}$	$\frac{L_2}{D}$
0.79	0.3954	1.1854	—	3.516	—	—	—	—	0.00
.80	.3856	1.1856	0.0002	3.406	3.461	0.00479	0.00279	0.0717	.07
.82	.3670	1.1870	.0014	3.202	3.302	.00457	.00257	.5447	.62
.84	.3497	1.1897	.0027	3.015	3.107	.00430	.00230	1.1739	1.79
.86	.3335	1.1935	.0038	2.843	2.928	.00405	.00205	1.8537	3.64
.88	.3186	1.1986	.0051	2.685	2.763	.00382	.00182	2.8022	6.45
.90	.3046	1.2046	.0060	2.539	2.611	.00361	.00161	3.7267	10.17
.92	.2915	1.2115	.0069	2.405	2.471	.00342	.00142	4.8592	15.03
.94	.2793	1.2193	.0078	2.281	2.342	.00324	.00124	6.2903	21.32
.96	.2677	1.2277	.0084	2.166	2.223	.00308	.00108	7.7778	29.10
.98	.2569	1.2369	.0092	2.059	2.112	.00292	.00092	10.0000	39.10
1.00	.2467	1.2467	.0098	2.876	2.433	.00337	.00137	7.1533	46.25



varies with hydraulic radius. One such possible relationship is presented in the following example.

Example 12

Given a structural plate corrugated metal pipe 2 by 6 in. corrugation, outlet control; $D = 5.0$ ft.; actual diameter $D_{act.} = 4.93$ ft.; $Q = 108.0$ cfs; $L = 200$ ft.; $F = \frac{0.13114}{R^{0.474}}$; $S_0 = 0.004$ ft/ft. $\alpha = 1.12$; Find the specific head of flow in the conduit at the entrance.

$$\frac{Q}{D^{2.5}} = \frac{108.0}{(4.93)^{2.5}} = 2.00 \text{ (Table 2)}$$

$$\frac{d_c}{D} = 0.622 \text{ (Table 4)}$$

$$S_{f_m} = K_{f_m} f\left(\frac{Q}{D^{2.5}}\right)^2 = K_{f_m} \frac{0.13114}{R^{0.474}} \times 4.0$$

$$= 0.52456 \frac{K_{f_m}}{R^{0.474}}$$

$$\frac{K_{f_m}}{R^{0.474}} = \left[\frac{K_{f_1}}{R_1^{0.474}} \times \frac{K_{f_2}}{R_2^{0.474}}\right]^{1/2}$$

See table 26 for tabulated computation.

From the computed backwater profile shown in Table 26, it is found that the length of free surface flow $\frac{L_2}{D} = 30.19$. Then, the length of the conduit flowing full is

$$\frac{L}{D} = \frac{200}{4.93} = 40.57; \frac{L_1}{D} = \frac{L}{D} - \frac{L_2}{D} = 40.57 - 30.19 = 10.38.$$

The resistance slope for full flow in this conduit is

$$S_{f_{full}} = K_{f_{full}} \cdot f \cdot \left(\frac{Q}{D^{2.5}}\right)^2 = 0.0252 \frac{0.13114}{(1.2325)^{0.474}} 4.0$$

$$= 0.01197$$

$$\frac{H}{D} = 1.1129 + 10.38\ (0.01197 - 0.004) = 1.1956$$

$$H = 1.1956 \times 4.93 = 5.89 \text{ ft.}$$

Table No. 26.—Backwater profile computation (Example 12)

$\frac{d}{D}$	$\frac{\alpha V^2}{2gD}$ Table 5	$\frac{H}{D}$ $\frac{d}{D}+\frac{\alpha V^2}{2gD}$	$\frac{\Delta H}{D}$	K_f Table 5	$\frac{R}{D}$ Table 4	$\frac{K_f}{R^{0.474}}$	$\frac{K_{f\,mean}}{R^{0.474}}$	$S_{fm}-S_o$	$\frac{\Delta L_2}{D}$	$\frac{L_2}{D}$
0.622	0.26424	0.88624	—	0.05220	0.2825	0.04462	—	—	—	—
.64	.24721	.88721	0.00097	.04820	.2862	.04094	0.04275	0.01842	0.0527	0.05
.66	.23036	.89036	.00315	.04432	.2900	.03741	.03914	.01653	.1906	.24
.68	.21535	.89535	.00499	.04098	.2933	.03441	.03588	.01482	.3367	.58
.70	.20200	.90200	.00665	.03806	.2962	.03181	.03308	.01335	.4981	1.08
.72	.19004	.91004	.00804	.03550	.2987	.02955	.03066	.01208	.6656	1.74
.74	.17938	.91938	.00934	.03328	.3008	.02761	.02856	.01098	.8506	2.59
.76	.16979	.92979	.01041	.03133	.3024	.02593	.02676	.01004	1.0369	3.63
.78	.16119	.94119	.01140	.02963	.3036	.02448	.02519	.00921	1.2378	4.87
.80	.15348	.95348	.01229	.02816	.3042	.02324	.02385	.00851	1.4442	6.31
.82	.14659	.96659	.01311	.02688	.3043	.02218	.02270	.00791	1.6574	7.97
.84	.14040	.98040	.01381	.02579	.3038	.02130	.02174	.00740	1.8662	9.84
.86	.13489	.99489	.01449	.02487	.3026	.02057	.02093	.00698	2.0759	11.91
.88	.13001	1.01001	.01512	.02412	.3007	.02001	.02029	.00664	2.2771	14.19
.90	.12566	1.02566	.01565	.02353	.2980	.01961	.01981	.00639	2.4491	16.64
.92	.12186	1.04186	.01620	.02310	.2944	.01936	.01948	.00622	2.6045	19.24
.94	.11863	1.05863	.01677	.02287	.2895	.01932	.01934	.00614	2.7313	21.97
.96	.11599	1.07599	.01736	.02288	.2829	.01954	.01943	.00619	2.8045	24.78
.98	.11397	1.09397	.01798	.02326	.2735	.02019	.01986	.00642	2.8006	27.58
1.00	.11290	1.11290	.01893	.02520	.2500	.02280	.02146	.00726	2.6074	30.19

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APPENDIX C
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