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RESISTANCE LOSSES IN NONCIRCULAR FLOOD CONTROL CONDUITS AND SLUICES

by

R. G. Cox

January 1973

Sponsored by Office, Chief of Engineers, U. S. Army

Conducted by U. S. Army Engineer Waterways Experiment Station
Hydraulics Laboratory
Vicksburg, Mississippi

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FOREWORD

The study reported herein was conducted to provide data and background for an Engineer Technical Letter (ETL) to be distributed by the Office, Chief of Engineers, on the effects of cross-section shape on flow resistance in flood control conduits. However, resulting pertinent information was subsequently distributed by revisions to Hydraulic Design Criteria (HDC) Sheets 224-1 and 224-1/1 rather than by an ETL.

The study was accomplished under the Engineering Studies Program, ES 804, "Collection, Analysis and Dissemination of Hydraulic Design Criteria and Procedures for Water Resources Projects," sponsored by the Office, Chief of Engineers, and assigned to the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES). The Hydraulics Laboratory is under the direction of Mr. H. B. Simmons.

The study was made and reported by Mr. R. G. Cox, Chief, Analysis Section, under the supervision of Mr. E. B. Pickett, Chief, Hydraulic Analysis Branch.

COL Ernest D. Peixotto was Director of the WES during the study and preparation of this report. Mr. F. R. Brown was Technical Director.
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CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

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<th>To Obtain</th>
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<tr>
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<td>centimeters</td>
</tr>
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<td>feet</td>
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<tr>
<td>square feet</td>
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<td>square meters</td>
</tr>
<tr>
<td>feet per second</td>
<td>0.3048</td>
<td>meters per second</td>
</tr>
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<td>cubic feet per second</td>
<td>0.028317</td>
<td>cubic meters per second</td>
</tr>
<tr>
<td>Fahrenheit degrees</td>
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<td>Celsius or Kelvin degrees*</td>
</tr>
</tbody>
</table>

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = \frac{5}{9}(F - 32)$. To obtain Kelvin (K) readings, use: $K = \frac{5}{9}(F - 32) + 273.15$. 

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SUMMARY

Two research studies, one on very smooth and one on very rough noncircular conduits, indicated appreciable conduit cross-section shape effect on fluid flow resistance losses. The study reported herein was made to determine comparable shape effects, if any, on conduit shapes normally encountered in Corps of Engineers design of flood control projects. The study showed that the shape effect on resistance losses in these conduits can be neglected for all practical purposes. Also, the concept of equivalent hydraulic diameter can be used with confidence for rectangular conduits having aspect ratios (height to width) between 0.5 and 2.
PART I: CONDUIT SHAPE EFFECTS

General

1. The concept of hydraulic or equivalent diameter has been generally used for the evaluation of resistance losses in noncircular conduits. This concept assumes that resistance losses in a rectangular conduit are the same as those in a circular conduit having an equivalent hydraulic radius and boundary roughness. However, Leutheusser and Malaika report that the effects of shape are appreciable under certain hydraulic and geometric conditions. A study of the effects of conduit shape (within the limits of practical design) on resistance losses is reported herein. Discussion is limited to fully developed turbulent flow.

Background

Circular conduits

2. Resistance losses in smooth and rough circular conduits are principally functions of the conduit diameter, boundary surface roughness, and flow velocity. Hydraulic Design Criteria (HDC) Chart 224-1 summarizes information available on circular concrete conduits and on forming effects. Equations defining the three flow conditions normally used in design problems are also given on the chart. In general, it has been recommended that the smooth-pipe curve be used for computations involving dynamic and momentum forces, and that the suggested surface roughness values be used (depending upon the type of concrete forming to be used, HDC Sheet 224-1) for capacity design. This procedure, in most cases, should result in conservative, economical design.
Noncircular conduits

3. Resistance coefficients from circular conduits have been applied to noncircular conduits by the use of equivalent or hydraulic diameter equal to four times the hydraulic radius of the noncircular conduit. It is assumed that any conduit cross section is adequately described by a circular section of equivalent diameter. Schlichting shows that this assumption appears to be true for smooth boundaries. Exception to this hypothesis has been expressed by several investigators with some justification. The results of experimental studies by Leutheusser on smooth and by Malaika on extremely rough, noncircular conduits are shown in fig. 1 along with other appropriate data.

![Diagram](image.png)

**LEGEND**

- MALA IRA
- NIKURADSE
- ENGELUND AND PEDERSEN
- LEUTHEUSser
- WES
- PINE FLAT 1952
- PINE FLAT 1956
- ENID

**NOTE:**

\[ \frac{H}{L} = \frac{\sqrt{\frac{2}{3}}}{\frac{2g}{D}} \]

Leutheusser's and Malaika's investigations were made at opposite ends of the boundary roughness spectrum. Neither extreme actually applies to practical hydraulic design of flood control conduits and sluices. Also included in fig. 1 are appropriate data by Nikuradse, Engelund and

**Fig. 1. Resistance coefficients for rectangular conduits**

Leutheusser's and Malaika's investigations were made at opposite ends of the boundary roughness spectrum. Neither extreme actually applies to practical hydraulic design of flood control conduits and sluices. Also included in fig. 1 are appropriate data by Nikuradse, Engelund and
Pedersen,\textsuperscript{6} and WES.\textsuperscript{7-10} These latter data are used to formulate a design procedure for noncircular conduits. Table 1 summarizes the data shown in fig. 1.

**Smooth Boundaries**

4. It is believed that the smooth pipe curve (HDC Chart 224-1) and the equivalent or hydraulic diameter can be used to define resistance losses in both circular and noncircular smooth conduits having hydraulically smooth boundaries. The trend for the smooth pipe data to plot below the theoretical smooth pipe curve in fig. 1 is attributed to factors other than nonconformity to the concept of equivalent hydraulic diameter. Study of HDC Chart 224-1/1 shows that an appreciable amount of large, smooth steel pipe data in the high Reynolds number range also plot slightly below the smooth pipe curve. This could indicate a fallacy in extrapolating the smooth pipe equation based on low Reynolds number, laboratory data (2- to 4-in.\textsuperscript{*}-diam pipe) to excessively high Reynolds numbers.

**Rough Boundaries**

5. The work of Malaika\textsuperscript{2} on excessively rough conduits indicates a definite conduit shape factor effect. In his study all conduits were sized to have nearly the same hydraulic diameter. Correction of the data to effect common hydraulic diameters of 0.3272 ft had negligible effect on the data locations in fig. 1. Since Malaika used the same boundary material for all conduits, he concluded that conduit shape had the predominant effect on the resistance coefficient. This conclusion is indicated by the range of resistance coefficient and relative roughness values for conduits of different shapes but of the same physical boundary roughness and hydraulic diameter. However, the conduits were made

\* A table of factors for converting British units of measurement to metric units is presented on page vii.
of aluminum tread plate of the type shown in fig. 2. The diamond shape roughness effected a mean physical roughness height of 0.0073 ft and a hydraulic roughness height ranging from 0.035 ft for the circular shape to 0.072 ft for the long rectangular shape (table 1). The shape effects appear to increase rapidly with the geometric aspect ratio. It is possible that the high resistance losses resulted from wake interference flow of the type defined by Morris rather than from normal boundary layer development.

6. Some insight into the shape effect on resistance in square and rectangular conduits relative to that of circular conduits is revealed by study of the Nikuradse and Engelund-Pedersen data and the WES Enid and 1952 Pine Flat data, respectively (fig. 1). The Engelund-Pedersen square conduit hydraulic diameter (0.231 ft) and that of the average of the Nikuradse circular conduits (0.237 ft) are essentially the same. The measured physical roughness heights are also very close (table 1). The average $f$ value of the Nikuradse data is 0.0525 which compares
reasonably well with that of the square conduit (0.0550) or within about 5 percent. In this case the hydraulic diameter seems to adequately define the square of comparable size and boundary roughness. In a similar comparison of Malaika's data there is a 15 percent increase in $f$. This increased resistance possibly can be attributed to the presence of wake interference flow.

7. A comparison of the 1952-1953 Pine Flat and Enid test data is also of interest. In both cases the conduits were formed using longitudinal planking (HDC Sheet 224-1) which resulted in similar physical roughness appearances (figs. 3, 4, and 5). Statistical analysis of boundary surface texture measurements indicated comparable roughness heights (0.0011 and 0.0015 ft, respectively). Since the ratios of the hydraulic diameters and the physical roughness values are comparable (1.71 and 1.36, respectively), it is logical that the measured resistance coefficients should be reasonably comparable (0.0010 and 0.00167). From this comparison, it appears that the hydraulic diameter can also be used to describe a rectangular cross section having an aspect ratio of 0.55 (width to height).
Cast 5
Represents 25 percent of conduit area
\( \varepsilon = 0.0163 \) in.

Cast 6
Represents 25 percent of conduit area
\( \varepsilon = 0.0037 \) in.

Cast 7
Represents 25 percent of conduit area
\( \varepsilon = 0.0089 \) in.

Cast 8
Represents 25 percent of conduit area
\( \varepsilon = 0.0058 \) in.

Note: \( \varepsilon \) is the physical roughness height resulting from statistical analysis of several hundred measurements of absolute surface roughness heights on each cast.

Fig. 4. Enid Dam outlet tunnel, actual size roughness casts from conduit.
Fig. 5. Pine Flat sluice No. 20, August 1953
General

8. From the foregoing, it can be concluded that for practical design of square and rectangular conduits the only problem involved is selection of an appropriate or effective roughness value for the type of concrete forming to be used. The tables of experimental values for different types of forming given in HDC Sheet 224-1 can be used as a guide for this purpose.

Capacity

9. The following hydraulic roughness values are recommended for capacity design of all conduits where boundary surface deterioration will not occur.

<table>
<thead>
<tr>
<th>Type of Forming</th>
<th>Design Hydraulic $K$, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal planking</td>
<td>0.002</td>
</tr>
<tr>
<td>Plywood or steel sheeting</td>
<td>0.001</td>
</tr>
</tbody>
</table>

If spalling of the conduit surface is anticipated because of freezing-and-thawing, chemical reaction, or poor quality control, a more conservative hydraulic design $K$ (0.003) should be assumed.

Velocity

10. The smooth-pipe curve in HDC Chart 224-1 has been recommended for computing conduit flow velocity for the design of energy dissipators and for estimating critical low pressures in transitions, etc. This curve is adequate for conduits having large hydraulic diameters (usually circular, Denison, Oahe, etc.\textsuperscript{10}) but can impose stringent design conditions on those with small hydraulic diameters. Fig. 6 and table 2
Fig. 6. Relative roughness effects show how the flow velocity and discharge are affected by changes in relative roughness for a range of diameters. Discharges for the rectangular conduits listed in table 2 were computed using the actual conduit area. Fig. 6 illustrates the percent change in velocity as a function of conduit diameter for a constant energy head with a boundary roughness change from 0.0000001 ft (smooth pipe) to 0.003 ft and from 0.0001 to 0.003 ft. Study of fig. 6 and table 2 indicates that the percentage velocity change in small conduits may be twice the change occurring in large conduits between smooth-pipe flow and capacity design flow based on a design K value of 0.003 ft. It is therefore recommended that a minimum roughness value of 0.0001 ft be assumed in place of the smooth-pipe curve for velocity design if the smooth-pipe curve results in a velocity exceeding 120 percent of the capacity design velocity. The 0.0001-ft value is appreciably less than the concrete experimental hydraulic K values listed in HDC Sheet 224-1 except for Oahe and Ontario.
conduits where exceptionally fine finishing conditions were specially obtained. The likelihood of obtaining a concrete surface finish hydraulically smoother than 0.0001 ft is remote.

Sample Computations for Unsubmerged Exit Portals

**Sluice design**

11. Sluice sizes have been fairly well standardized at 5 ft wide by 9 ft high. Thus, a direct solution can be used for developing a rating curve which, in turn, can be used to determine the number of sluices required to pass the design flow or meet evacuation requirements. Sluices are normally not operated at pools exceeding the spillway crest elevation. The following computations illustrate the solution procedure for full conduit flow.

a. **Given.**

\[ K = 0.002 \text{ ft} \]

Sluice size = 5 ft by 9 ft

Exit portal elevation = 1575 ft msl

Sluice length \((L) = 250 \text{ ft}\)

Spillway crest elevation = 1675 ft msl

Sluice design flow = 20,000 cfs

Water temperature = 60 F

b. **Computation for capacity design.**

1. Area \((A) = 5 \times 9 = 45 \text{ ft}^2\)
2. Wetted perimeter \((WP) = 2(5 + 9) = 28 \text{ ft}\)
3. Hydraulic radius \((R) = \frac{A}{WP} = \frac{45}{28} = 1.61 \text{ ft}\)
4. Hydraulic diameter \((D_h) = 4R = 6.44 \text{ ft}\)
5. Relative roughness \(D_h/K = 6.44/0.002 = 3220\)
6. Design head \((H_e) = \text{spillway crest elevation} - \text{sluice exit portal elevation}\)
   \[ = 1675 - 1575 = 100 \text{ ft}\]
7. Assume sluice discharge \((Q) = 2700 \text{ cfs}\)
8. Sluice velocity \((V) = \frac{Q}{A} = 2700/45 = 60 \text{ fps}\)
9. Velocity head \((H_v) = \frac{V^2}{2g} = 55.9 \text{ ft}\)
(10) Reynolds number \( (Re) = \frac{VD}{\nu} \) (For water = 60 F, \( \nu = 1.21 \times 10^{-5} \), from HDC Chart 001-1)

\[
Re = \frac{60 (6.44)}{1.2 \times 10^{-5}} = 3.0 \times 10^7
\]

(11) From HDC Chart 224-1 for \( D_n/K = 3200 \) and \( Re = 3.0 \times 10^7, f = 0.0153 \)

(12) From HDC Chart 221-1, \( K_e = 0.16 \) for single sluice entrance

(13) Required energy head \( (He) = (K_e + K_f + 1.0)H_v \)

\[
K_f = f \left( \frac{L}{D_n} \right) = 0.0153 \left( \frac{250}{6.44} \right) = 0.594
\]

\[
He = (0.160 + 0.594 + 1.00) 55.9 = 98.04 \text{ ft}
\]

(14) Repeat computations for other assumed discharges and plot rating curve. Read \( Q \) from rating curve for pool at spillway crest or other design elevation, and divide design flow by \( Q \) to obtain required number of sluices. Round off number of sluices to next higher figure. Check evacuation requirements. Increase number of sluices if required.


(1) Assume design velocity = 68 fps for smooth conduit

(2) For water at 60 F, \( \nu = 1.21 \times 10^{-5} \) (from HDC Chart 001-1)

\[
Re = \frac{VD_n}{\nu} = \frac{68}{1.21 \times 10^{-5}} = \frac{3.60}{5.30} \times 10^7
\]

\[
0.0067
\]

(4) \( f = 0.0064 \) (from HDC Chart 224-1, smooth-pipe curve)
(5) \( H_v = \frac{68 \times 68}{64.4} = 71.8 \)

(6) \( K_f = 0.0067 \left( \frac{250}{6.44} \right) = 0.260 \)

(7) \( H_e = (K_e + K_f + 1.0)H_v \)
\[ = (0.26 + 0.24 + 1.0) \frac{71.8}{155} \]
\[ = 101.9 \sim 100 \text{ (satisfactory)} \]
\[ = 217 > 100 \text{ (not satisfactory)} \]

(8) \( \frac{V_{\text{smooth}}}{V_{\text{design}}} = \frac{68}{60} = 1.13 < 1.20 \text{ (satisfactory)} \)

(9) If \( \frac{V_{\text{smooth}}}{V_{\text{design}}} \) exceeds 1.20, a \( K \) value of 0.0001 ft should be assumed to compute the required velocity for stilling basin design in the following manner.

(a) For \( K = 0.0001 \) ft

\[ \frac{D_n}{K} = \frac{6.44}{0.0001} = 64,400 \]

(b) Assume \( R = 3.0 \times 10^7 \)
\[ f = 0.0087 \text{ (from HDC Chart 224-1)} \]
\[ V = \frac{R e v}{D_n} = \frac{3.5 \times 10^7 (1.21 \times 10^5)}{6.44} = 65.5 \text{ fps} \]
\[ H_v = \frac{(65.5)^2}{64.4} = 66.6 \]

(c) \( K_f = 0.0087 \left( \frac{250}{6.44} \right) = 0.330 \)
Conduit design

12. For larger circular conduits, the design is approached indirectly using a cut-and-try method for conduit sizing until the design discharge can be passed by the design head. The following computation illustrates the procedure.

a. Given.
K = 0.002 ft
Design flow \( Q \) = 20,000 cfs
Conduit length \( L \) = 1080 ft
Design pool elevation = 1260 ft msl
Conduit exit portal invert = 1054.0 ft msl
Two-barrel intake
One horizontal bend 60 deg, radius \( r \) = 150 ft

b. Computation for capacity design.

1. Assume \( D = 22 \) ft, \( A = 380.13 \) ft\(^2\)

2. \( V = \frac{Q}{A} = \frac{20,000}{380.13} = 52.6 \) fps

3. Exit portal Froude No. \( F = \frac{V}{\sqrt{gD}} \), for
   conduit diameter \( D \)

\[
F = \frac{78.6}{78.6} \frac{3.27}{18} = 1.98
\]

Conduit design

\[
(d) \quad h_e = (0.16 + 0.33 + 1.0) h_v
\]

\[
1.49 \quad 99.2 \quad \sim 100 \text{ (satisfactory)}
\]

\[
= 1.5 \quad h_v = 75 \text{ ft} < 100 \text{ (unsatisfactory)}
\]

\[
(e) \quad \frac{V(K = 0.0001)}{V(K = 0.002)} = \frac{65.5}{60.0} = 1.09 < 1.20 \text{ (satisfactory)}
\]
(4) From HDC Chart 225-1, \( \frac{y_p}{D} = 0.59 \)
\[
y_p = 0.67 (\varphi) = 14.7 \text{ ft}
\]
(5) \( H_e = \text{pool elevation} - (\text{invert elevation} + y_p) \)
\[= 1260 - \left(1054 + \frac{10.6}{14.7}\right) = 191.3 \text{ ft} \]
(6) \( H_v = \frac{78.6}{64.4} = 95.9 \text{ ft} \)
(7) \( R_e = \frac{V_D}{V} = \frac{78.6}{1.21 \times 10^{-5}} = 1.17 \times 10^8 \)
(8) \( D = \frac{2200}{0.002} = 9,000 \)
(9) For \( R_e = 1.17 \times 10^8 \) and \( \frac{D}{K} = 9,000 \)
\[f = 0.0115 \text{ (from HDC Chart 224-1)}\]
(10) \( H_e = (K_e + K_b + K_f + 1.0)H_v \)
\[K_e = 0.25 \text{ (from HDC Chart 221-1)} \]
\[K_b = 0.07 \text{ (from HDC Chart 228-1)} \]
\[K_f = f \left(\frac{I}{D}\right) = 0.012 \left(\frac{1080}{18}\right) = 0.720 \]
\[H_e = (0.25 + 0.07 + 0.564 + 1.0) 43.2 \]
\[H_e = 2.040 (43.2) \]
\[= 88.4 \text{ ft} \]
(11) Check conduit's ability to meet evacuation requirements. If not adequate, redesign as necessary.

(1) Assume \( R_e = \frac{1.30}{1.4} \times 10^8 \)

(2) From HDC Chart 224-1, \( f = 0.0057 \)

(3) \( V = \frac{R_e V}{D} = \frac{1.30}{1.4} \times 10^8 (1.21 \times 10^{-5}) = 87.4 \text{ fps} \)

(4) \( H_v = \frac{137.4}{18} \text{ ft} \)

(5) \( K_f = 0.0057 \left( \frac{1080}{18} \right) = 0.345 \)

\( f = 0.0057 \) (from HDC Chart 224-1)

(6) \( F = \frac{V}{\sqrt{gD}} = \frac{87.4}{5.67 (4.25)} = 3.63 \text{ ft} \)

(7) \( y_p = 0.585 \) (from HDC Chart 225-1)

\( y_p = \frac{10.5}{10.4} \text{ ft} \)

(9) \( H_e = (K_e + K_f + K_b + 1.0)H_v \)

\( = (0.25 + 0.345 + 0.07 + 1.0) \frac{118.6}{137.4} \)

\( = 1.665 118.6 \approx 197.5 \) (\( R_e \) satisfactory)

(10) Since \( V_{smooth}/V_{capacity} = \frac{87.4}{78.6} = 111\% < 120\% \)

design is acceptable.

d. Computation for rating curve. Computations for developing a rating curve for pools effecting full conduit flow follow the direct procedure outlined for sluices. A conduit discharge is assumed, and the required pool elevation is computed taking into account the flow energy losses and velocity head.


7. U. S. Army Engineer Waterways Experiment Station, CE, "The Effects of Artificial Stimulation of the Turbulent Boundary Layer in Rectangular Conduits," Miscellaneous Paper No. 2-160, Mar 1956, Vicksburg, Miss.


9. Guyton, B., "Vibration, Pressure and Air-Demand Tests in Flood-Control Sluice, Pine Flat Dam, Kings River, California," Miscellaneous Paper No. 2-75, Feb 1954, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.


<table>
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<th>Project or Investigator</th>
<th>Reference No.</th>
<th>Conduit Shape</th>
<th>Height, ft</th>
<th>Width, ft</th>
<th>Hydraulic Diameter, ft</th>
<th>Reynolds No.</th>
<th>Resistance Factor, f</th>
<th>Roughness Height, K</th>
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<td>0.3272</td>
<td>$3 \times 10^4$-$4 \times 10^5$</td>
<td>0.101 to 0.117</td>
<td>0.035</td>
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<td>0.326</td>
<td>0.334</td>
<td>0.3330</td>
<td>$6 \times 10^4$-$3 \times 10^5$</td>
<td>0.111 to 0.122</td>
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<td>0.2205</td>
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<td>$6 \times 10^4$-$3 \times 10^5$</td>
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<td>0.196</td>
<td>1.168</td>
<td>0.3444</td>
<td>$4 \times 10^4$-$3 \times 10^5$</td>
<td>0.144 to 0.163</td>
<td>0.072</td>
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<td>0.158</td>
<td>$3 \times 10^5$-$1 \times 10^7$</td>
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<td>0.0053</td>
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<td>--</td>
<td>0.316</td>
<td>$5 \times 10^4$-$1 \times 10^5$</td>
<td>0.045</td>
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<td>$1 \times 10^4$-$1 \times 10^5$</td>
<td>0.027 to 0.018</td>
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<td>0.250</td>
<td>0.750</td>
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<td>$1 \times 10^4$-$1 \times 10^5$</td>
<td>0.027 to 0.018</td>
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<td>8</td>
<td>Circ</td>
<td>--</td>
<td>--</td>
<td>11.00</td>
<td>$3 \times 10^7$</td>
<td>0.013</td>
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<td>0.0015</td>
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### Table 2
Comparison of Results

| Conduit Size, ft | Area, ft² | Hydraulic Radius, ft | Diameter, ft | \( K \) ft | \( D \) ft | Length, ft | \( r \) | \( V \), fps | \( H_e \), ft | \( B_e \) | \( Q \) | \( V \) | \( f \) | \( K \) or \( D \) | % Difference* |
|-----------------|-----------|---------------------|-------------|----------|--------|-----------|------|----------|----------|------|------|------|------|--------|----------------|---------------|
| 2.0D            | 3.14      | 0.50                | 2.0         | Smooth** | 20,000,000 | 1600 | 0.0089   | 28.8    | 105     | 5.2 \( \times 10^6 \) | 90.7 | 0     | 0     | 100.0 |
|                 |           |                     |             | 0.000004 | 50,000   |      | 0.0169   | 28.3    | 105     | 5.2 \( \times 10^6 \) | 85.8 | 5.2   | +13.1 | 98.7  |
|                 |           |                     |             | 0.00100  | 2,000    |      | 0.0168   | 21.6    | 3.9     | 67.9    | 25.0 | +88.8 | 66.6 |
|                 |           |                     |             | 0.00200  | 1,000    |      | 0.0197   | 20.1    | 3.7     | 63.0    | 30.2 | +121.3 | 33.3 |
|                 |           |                     |             | 0.00300  | 666      |      | 0.0218   | 19.2    | 3.5     | 60.2    | 33.3 | +164.9 | 0    |
|                 |           |                     |             | 0.00500  | 20,000   |      | 0.0112   | 26.1    | 4.7     | 81.9    | 9.5  | +25.8  | 96.7 |
| 4.0D            | 12.6      | 1.00                | 4.0         | Smooth** | 40,000,000 | 1600 | 0.0077   | 40.8    | 105     | 1.5 \( \times 10^7 \) | 512.5 | 0     | 0     | 100.0 |
|                 |           |                     |             | 0.00004  | 100,000  |      | 0.0088   | 38.7    | 1.4     | 486.5   | 5.1  | +14.3  | 98.7 |
|                 |           |                     |             | 0.00100  | 40,000   |      | 0.0098   | 37.1    | 1.3     | 446.8   | 9.1  | +29.7  | 97.6 |
|                 |           |                     |             | 0.00200  | 4,000    |      | 0.0145   | 31.6    | 1.1     | 396.7   | 49.5 | +48.3  | 66.6 |
|                 |           |                     |             | 0.00300  | 1,333    |      | 0.0184   | 28.3    | 1.0     | 376.4   | 79.7 | +138.2 | 33.3 |
|                 |           |                     |             | 0.00500  | 1,333    |      | 0.0184   | 28.3    | 1.0     | 376.4   | 79.7 | +138.2 | 33.3 |
| 5 by 9          | 45.0      | 1.61                | 6.4         | Smooth** | 64,000,000 | 1000 | 0.0097   | 5.06    | 1       | 3.0 \( \times 10^6 \) | 227.7 | 0     | 0     | 100.0 |
|                 |           |                     |             | 0.00004  | 160,000  |      | 0.0100   | 5.01    | 2.9     | 225.5   | 1.0  | +3.1   | 98.7 |
|                 |           |                     |             | 0.00100  | 64,000   |      | 0.0104   | 4.95    | 2.9     | 222.8   | 1.0  | +4.2   | 98.7 |
|                 |           |                     |             | 0.00200  | 6,000    |      | 0.0135   | 4.96    | 2.7     | 205.2   | 9.9  | +43.9  | 66.6 |
|                 |           |                     |             | 0.00300  | 2,133    |      | 0.0153   | 4.36    | 2.5     | 196.2   | 13.8 | +57.7  | 33.3 |
|                 |           |                     |             | 0.00500  | 2,133    |      | 0.0167   | 4.23    | 2.5     | 190.4   | 16.4 | +72.1  | 0    |
| 10 by 15        | 150       | 3.00                | 12.0        | Smooth** | 120,000,000 | 1000 | 0.0063   | 57.0    | 77      | 6.2 \( \times 10^7 \) | 8,550 | 0     | 0     | 100.0 |
|                 |           |                     |             | 0.00004  | 300,000  |      | 0.0073   | 55.5    | 6.0     | 8,325   | 4.6  | +43.9  | 96.7 |
|                 |           |                     |             | 0.00100  | 120,000  |      | 0.0081   | 54.3    | 5.9     | 8,175   | 4.4  | +28.6  | 96.7 |
|                 |           |                     |             | 0.00200  | 12,000   |      | 0.0116   | 50.2    | 5.5     | 7,530   | 11.9 | +49.4  | 66.6 |
|                 |           |                     |             | 0.00300  | 6,000    |      | 0.0132   | 48.5    | 5.3     | 7,275   | 14.9 | +103.5 | 33.3 |
|                 |           |                     |             | 0.00500  | 4,000    |      | 0.0143   | 47.5    | 5.2     | 7,125   | 16.7 | +126.9 | 0    |
| 2.0D            | 314.2     | 5.00                | 20          | Smooth   | 200,000,000 | 1600 | 0.0063   | 68.0    | 105     | 1.2 \( \times 10^8 \) | 21,357 | 0     | 0     | 100.0 |
|                 |           |                     |             | 0.00004  | 500,000  |      | 0.0077   | 66.3    | 1.2     | 20,834  | 8.2  | +6.3   | 98.7 |
|                 |           |                     |             | 0.00100  | 200,000  |      | 0.0074   | 65.1    | 1.2     | 20,453  | 4.3  | +17.4  | 96.7 |
|                 |           |                     |             | 0.00200  | 100,000  |      | 0.0130   | 60.5    | 1.1     | 19,014  | 11.0 | +106.3 | 66.6 |
|                 |           |                     |             | 0.00300  | 50,000   |      | 0.0150   | 58.7    | 1.1     | 18,154  | 13.0 | +128.1 | 33.0 |
|                 |           |                     |             | 0.00500  | 2,666    |      | 0.0184   | 57.6    | 1.0     | 18,096  | 15.3 | +150.3 | 0    |

* Assumed to be 0.0000001 ft.

** \( \frac{V_s - V}{V_s} \times 100 \), \( \frac{f_s - f}{f} \times 100 \), \( \frac{K_0,003 - K_0}{K_0,003} \). Basic equations: \( Q = AV \), \( Re = \frac{VD}{v} \), \( f = \frac{h_f}{2g} \), \( \frac{1}{\sqrt{q}} = -2 \log_{10} \left( \frac{K_e}{D} + 2.51 \right) \frac{1}{R_e} \sqrt{q} \).
Two research studies, one on very smooth and one on very rough noncircular conduits, indicated appreciable conduit cross-section shape effect on fluid flow resistance losses. The study reported herein was made to determine comparable shape effects, if any, on conduit shapes normally encountered in Corps of Engineers design of flood control projects. The study showed that the shape effect on resistance losses in these conduits can be neglected for all practical purposes. Also, the concept of equivalent hydraulic diameter can be used with confidence for rectangular conduits having aspect ratios (height to width) between 0.5 and 2.
<table>
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