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UNDER ARCH BRIDGES

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by

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A) PLAN

B) MILD SLOPE CHANNEL

C) WEIR PLATES

FIGURE 3-1 DEFINITION SKETCH
Fig 2.2 Center Line Surface Profile Near Submerged Constriction

- Y0 = Yn
- Y1
- Y2, Y3
- Y4 = Yn
- M. curve
- Normal Profile
- S < Sₐ
- 3 - Vena Contracta
FIGURE 3-4 - CLASSES OF FLOW IN SUDDEN CONTRACTIONS IN OPEN CHANNELS
Figure 3-6 — Definition sketch for analysis of expanding flow.
Figure 3.7—Graphical Solution of Backwater Due to a Constriction
FIGURE 3-8 — DETAIL OF GRAPHICAL SOLUTION OF BACKWATER DUE TO A CONSTRICION
FIGURE 3-9 — GEOMETRIC PROPERTIES OF SEMI-CIRCULAR AND CIRCULAR SEGMENT ARCHES
FIGURE 3.10 — LIMITING BACKWATER - BOUNDARY BETWEEN FLOWS OF CLASSES I B, II SEMI - CIRCULAR AND CIRCULAR SEGMENT ARCHES
Flow in ADEH = \( Q = V_n B y_n = V_n A_n \)

Flow in BCFG = \( q = V_n A_n \)

Fig 3-11 Definition Sketch for the Channel Opening Ratio
FLOW IN ADEH = \( Q = V_0 B y_0 \)

FLOW IN BCFG = \( q = V_0 b y_0 \)

DEFINITION SKETCH FOR THE DEVELOPMENT OF THE CONTRACTION RATIO

Figure 3-12
FIGURE 3-13 CORRECTION COEFFICIENT FOR THE CHANNEL OPENING RATIO
PRELIMINARY FLUME

FIG. 4-1
A) PLAN

B) MILD SLOPE CHANNEL

C) STEEP SLOPE CHANNEL

D) WEIR PLATES

Effect of Channel Constriction on Water Surface Profile

FIG. 4-2
FIGURE 4-4 SMALL FLUME WITH ARTIFICIAL ROUGHNESS INSTALLED, and MECHANICAL AND ELECTRICAL GAGES
The image includes a graph and equations related to the flow of water over a semicircular weir.

**Graph**

Experimental curves showing $C_d$ as a function of $F_n$ and $M$.

**Equations**

1. \[ Q = C y_i^{3/2} b T \]  
2. \[ C = c_d \sqrt{2g} \left(\frac{1}{17/24} \right) \]
   \[ T = \left[1 - 0.1294 \left(\frac{y_i}{h}\right)^2 - 0.0177 \left(\frac{y_i}{h}\right)^4 \right] \]
3. \[ \frac{y_i}{y_n} = \left(\frac{F_n \sqrt{g}}{C M A} \right)^{2/3} \]

**Definitions**

- $F_n = \frac{V_n}{\sqrt{g y_n}}$
- $M = \frac{b}{B}$

**Fig. 4-5**

Semicircular Weir Tests
Flow in rectangular channels with semi-circular constrictions - Comparison of two and three dimensional cases

**Fig. 4-8**
Fig. 4-8a: Variation of the backwater ratio for segment arches - small flume - rough boundaries.
FLUME CONSTRUCTION

OPERATORS PLATFORM
GUIDE RAIL
L 1 \frac{1}{2} \times 1 \frac{1}{2} \times \frac{1}{4}

\frac{3}{4} STAINLESS STEEL INSTRUMENT CARRIAGE
GUIDE RAILS

L 2 \frac{1}{2} \times 2 \frac{1}{2} \times \frac{3}{4}

\frac{1}{4} \times 2 \frac{1}{2} STUD

L 2 \frac{1}{2} \times 1 \frac{1}{2} \times \frac{3}{8}

\frac{1}{4} STEEL PLATE

\frac{1}{4} STEEL PLATES

L 1 \frac{1}{2} \times 1 \frac{1}{2} \times \frac{3}{4}

\frac{1}{2} \times 5 STUD

6 U 8 2

20I 65.4

TOP OF JACK STAND

SYMMETRICAL
ABOUT

FIGURE 5-1
Fig 5-7 FLOW RATE; CU FT. PER SEC.
FIG 5-8 TOP VIEW OF INSTRUMENT CARRIAGE

FIG 5-9 POINT GAGE AND PRANDTL TUBE
FIGURE 5-10 VELOCITY TRANSDUCER SYSTEM
FIG 5-II Calibration Apparatus for Velocity Transducer System
Fig. 5-12 Typical Calibration Curves for Probe
FIGURE 5-13 $f - Re$ RELATION FOR NORMAL DEPTH TESTS
FIG 5-15 EFFECT OF BARS ON VELOCITY
\[ \frac{c}{\sqrt{g}} = 6.06 \log \frac{y_n}{\alpha} + 3.15 \]

FIG 5-16 VARIATION OF RESISTANCE FUNCTION WITH RELATIVE ROUGHNESS \( \frac{y_n}{\alpha} \)
FIG 5-17 VARIATION OF RESISTANCE FUNCTION WITH RELATIVE ROUGHNESS $y_n/\chi$

$\frac{c}{\sqrt{g}} = 6.06 \log \frac{y_n}{\chi}$
FIGURE 5-18 DIMENSIONLESS VELOCITY PROFILE

Conditions:
\[ \sqrt{\frac{y}{x}} = \sqrt{\frac{y}{x}} \]
\[ X = 0.0126 \text{ ft} \]
\[ Q = 3.714 \text{ cfs} \]
\[ S = 0.0125 \]
\[ n = 0.275 \text{ ft} \]
FIGURE 5-19 GENERAL RESISTANCE DIAGRAM FOR UNIFORM FLOW IN OPEN CHANNELS (SAYRE)
FIGURE 6.1 TEST SELECTION CURVE — LARGE FLUME — SMOOTH BOUNDARIES
FIGURE 6-2 TESTS SELECTION CURVE — LARGE FLUME — ROUGH BOUNDARIES
START

READ

\[ Q = 1.20 \]
\[ \lambda = 0.03281 \text{ ft/cm} \]
\[ B = 4.955 \text{ ft} \]

\[ 9 = 32.2 \text{ ft/sec}^2 \]

\[ \text{READ} \]
\[ Q = \text{cfs} \]
\[ F_n = \text{cms} \]
\[ y_n = \text{cfs} \]
\[ s_n = \text{cfs} \]

\[ \text{PARAMETER, } \frac{L}{b}, \frac{C_p}{b}, \frac{C_i}{b}, \frac{C_j}{b}, \beta \]

\[ n = \text{READ} \]

\[ \sigma = \frac{2.16 \lambda y_n}{B M} \]
\[ S = \sqrt{\sigma^2} \]
\[ C_m = 0.5 (8 + \Delta) \]
\[ M^* = C_m M \]

\[ \xi = \sqrt{\frac{S \lambda}{F_n}} \]
\[ Q = B \cdot y_n \lambda \xi \]

\[ P = \lambda \beta y_n \]
\[ a_n = \lambda b \cdot y_n \]
\[ z = 2 g \lambda (y_n - y_0)/V^2 \]
\[ \Omega = a_n / A \]
\[ K = 2 g \lambda (w^2 - \Omega^2) \]

\[ V = Q / a_n^2 \]

STOP

PRINT

\[ \text{PARAMETER} \]
\[ M \]
\[ F_n \]
\[ Q \]
\[ y_n \]
\[ s_n \]
\[ M^* \]

\[ D = n_c \left[ \frac{F_n M^*}{2} \right] \]
\[ ZM = (F_n y_n) (M^* / F_n)^2 \]

\[ M^2 / y_n \cdot (y_n - y_0) / y_n \]
\[ (F_n M^2)^2 \]

FIG. 6-3
FOUR VARIABLES GRAPHICAL MULTIPLE CORRELATION

\[ M_1 = 0.75, B_1 = 0.0 \]
\[ M_2 = 0.5, B_2 = 0.3 \]
\[ M_3 = 0.25, B_3 = 0.5 \]

\( y = 0.5, M = 0.25 \)
\( y = 0.3, M = 0.75 \)
\( y = 0.0, M = 0.5 \)
SUPERELEVATION

VS

KINETICITY

○ - M = 5
△ - M = .7
□ - M = 9

FIGURE 7-1-1
**DISCHARGE COEFFICIENT**

**V.S.**

**KINETICITY**

- $\bigcirc$ - $M = 5$
- $\triangle$ - $M = 0.7$
- $\square$ - $M = 0.9$

FIGURE 7-1-2
FIGURE 7-1-4

FRICTION FACTOR VS REYNOLDS NUMBER

\[ f = \frac{8945}{V^2} \]

\[ Re = \frac{V \cdot y}{V} \]

- □ 2.0 CFS
- △ 3.0 CFS
- ● 3.5 CFS
- ○ 4.0 CFS
BACKWATER RATIO

vs

CONTRACTION RATIO

○ - 2 CFS
□ - 3 CFS
△ - 4 CFS

FIGURE 7-1-5
FIGURE 7-1-6 — BACKWATER RATIO VS CHANNEL OPENING RATIO $L/b = 0$ SEMI-CIRC SMOOTH CHANNEL

FIGURE 7-1-7 — DISCHARGE COEF. VS CHANNEL OPENING RATIO $L/b = 0$ SEMI-CIRC SMOOTH CHANNEL
FIGURE 7-1-8 BACKWATER RATIO FOR GEOMETRY 
$I_a$, SMOOTH BOUNDARY $\frac{L}{b} = 0.0$
FIGURE 7-1-9  HEAD LOSS COEFFICIENT, GEOMETRY $I_a$
SMOOTH BOUNDARY $\frac{L}{b} = 0.0$
\[ D = nc \left( \frac{F_{n_1}}{M_i} \right)^{n-1} \]

\[ n = 1.108 \]

\[ C = 0.304 \]

FIGURE 7-110
BACKWATER RATIO COEFFICIENT, GEOMETRY I, SMOOTH BOUNDARY

\[ \frac{L}{b} = 0.0 \]
FIGURE 7-2-1a  BACKWATER RATIO VS CHANNEL OPENING RATIO L/b = 0 SEMI-CIRC.
ROUGH CHANNEL \( y_i/y_n \leq 1.50 \)
FIGURE 7-2-1b BACKWATER RATIO VS CHANNEL OPENING RATIO \( L/b = 0 \) SEMI-CIRC.
ROUGH CHANNEL \( 1.50 \leq \gamma_y/\gamma_n \leq 2.50 \)
FIGURE 7-2-2  DISCHARGE COEF VS CHANNEL OPENING RATIO L/b = 0 SEMI-CIRC. ROUGH CHANNEL
FIGURE 7-2-3a LENGTH TO MAXIMUM BACKWATER

FIGURE 7-2-3b LENGTH OF SURFACE PROFILE BETWEEN $y_1$ and $y_2$
FIG 7.2-4 CORRELATION CURVE OF $F_3$
FIG. 7-2-5a COMPARISON BETWEEN BACKWATER RATIOS IN SMOOTH AND ROUGH CHANNELS

FIG 7-2-5b COMPARISON OF C_d TO F_n FOR THE TWO ROUGHNESS CONDITIONS M=0.7
FIG. 7-2-6a COMPARISON BETWEEN BACKWATER RATIOS FOR BRIDGE LENGTHS-ROUGH CHANNEL

FIG. 7-2-6b COMPARISON BETWEEN DISCHARGE COEFFICIENTS FOR BRIDGE LENGTHS - ROUGH CHANNEL - $M' = 0.7$
FIGURE 7-2-7 SURFACE TOPOGRAPHY  \( Q = 1 \text{ CFS}, \)
\( S = 0.000584, \ M = 0.5, \ L/b = 0 \)
FIG 7-2-8 VELOCITY PROFILES AT MAXIMUM BACKWATER $Q = 1$ CFS, $S = 0.0003$ ft/s$^2$, $M = 0.5$, $L/b$
FIG 7-2-9 ISOVEL DIAGRAMS IN FPS Q=1CFS,
S=0000584, M=0.5, L/b=0
FIGURE 7-2-10 GENERALIZED BACKWATER RATIO

\[
\frac{y}{y_n} = 1 + 0.47 \left( \frac{F_n}{M'} \right)^{2/3} 3.39
\]
FIGURE 7-2-11 BACKWATER RATIO FOR GEOMETRY $I_a$, ROUGH BOUNDARY $\frac{L}{b} = 0.0$
FIGURE 7-2-12 BACKWATER RATIO FOR GEOMETRY I_b, ROUGH BOUNDARY \( \frac{L}{b} = 0.5 \)
FIGURE 7-2-13 BACKWATER RATIO FOR GEOMETRY $I_b$
ROUGH BOUNDARY $\frac{L}{b} = 1.0$
FIGURE 7-2-14 SUMMARY OF BACKWATER RATIO, GEOMETRY I, ROUGH & SMOOTH BOUNDARIES

\[
\frac{h_i}{y_n} = 0.403 \left( \frac{F_n}{M_i} \right)^2 1.08 \text{ ALL DATA GEOM. I}
\]
FIGURE 7-2-15 HEAD LOSS COEFFICIENT, GEOMETRY Iₐ
ROUGH BOUNDARY, $\frac{L}{B} = 0.00$
FIGURE 7-2-16 HEAD LOSS COEFFICIENT, GEOMETRY I₀
ROUGH BOUNDARY $\frac{L}{b} = 0.5$
FIGURE 7-2-17 HEAD LOSS COEFFICIENT, GEOMETRY $I_b$
ROUGH BOUNDARY $\frac{L}{b} = 1.0$
FIGURE 7-2-18 SUMMARY OF HEAD LOSS COEFFICIENTS
GEOMETRY Ia & Ib, ROUGH BOUNDARY
\[ D = n C \left( \frac{F_n}{M'} \right)^2 \]^{n-1}

\[ n = 1.108 \]
\[ C = 0.403 \]

**Figure 7-2-19** Backwater Ratio Coefficient, Geometry Ia
Rough Boundary \( \frac{L}{b} = 0.00 \)
\[ D = n \cdot C \left( \frac{F_n}{M'} \right)^{2} 
\]

\[ n = 1.108 \]

\[ C = 0.304 \]

**FIGURE 7-2-20** BACKWATER RATIO COEFFICIENT, GEOMETRY Ib, ROUGH BOUNDARY \( \frac{L}{b} = 0.5 \)
\[ D = n c \left( \frac{F_n}{M^1} \right)^2 n-1 \]

\[ n = 1.108 \]

\[ c = 0.403 \]

**FIGURE 7-2-21** BACKWATER RATIO COEFFICIENT, GEOMETRY I_b
ROUGH BOUNDARY \( \frac{L}{b} = 1.0 \)
MEASURED WATER SURFACE PROFILES ALONG THE CENTERLINE FOR THREE DIMENSIONAL DUAL PARALLEL ARCH BRIDGE MODELS

FIG. 7-3-0
FIG 7-3-1 BACKWATER RATIO FOR DUAL PARALLEL BRIDGES

$F_n = 0.10$, AND 0.15
FIG. 7-3-2 BACKWATER RATIO FOR DUAL PARALLEL BRIDGES

\[ F_n = 0.20 \]
FIG. 7-3-3 BACKWATER RATIO FOR DUAL PARALLEL BRIDGES

$F_n = 0.25$
FIG 7-3-4 BACKWATER RATIO FOR DUAL PARALLEL BRIDGES

$F_n = 0.30$
FIG. 7-3-5 BACKWATER RATIO FOR DUAL PARALLEL BRIDGES

\[ F_n = 0.40 \]
\[ \frac{y_i}{y_n} = c + a \left[ \left( \frac{F_n}{M'} \right)^{2/3} \right]^e \]

<table>
<thead>
<tr>
<th>( \frac{bL_d}{An_2} )</th>
<th>c</th>
<th>a</th>
<th>e</th>
</tr>
</thead>
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<tr>
<td>0</td>
<td>0.93</td>
<td>0.67</td>
<td>2.40</td>
</tr>
<tr>
<td>10</td>
<td>0.93</td>
<td>0.83</td>
<td>2.51</td>
</tr>
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<td>20</td>
<td>0.93</td>
<td>0.92</td>
<td>2.53</td>
</tr>
<tr>
<td>30</td>
<td>0.93</td>
<td>0.97</td>
<td>2.57</td>
</tr>
</tbody>
</table>

**FIG. 7-3-7 - GENERALIZED BACKWATER RATIO FOR DUAL PARALLEL BRIDGES**
FIGURE 7-3-8 BACKWATER RATIO, GEOMETRY II
ROUGH BOUNDARY $\frac{L_{db}}{A_{n2}} = 0.00$

\[
\frac{h_i}{y_n} = 0.462 \left( \frac{F_n}{M_i} \right)^{0.976}
\]
\[ \frac{h_i}{y_n} = 0.542 \left( \frac{F_n}{M^*} \right)^{1.111} \]

**Figure 7-3-9** Backwater Ratio for Geometry II

Rough Boundary  \( 0 < \frac{L_d b}{A n^2} \leq 7.5 \)
\[ \frac{\frac{h_l}{y_n}}{F_n^2} = 0.618 \left[ \left( \frac{F_n}{M'} \right)^{2.1025} \right] \]

FIGURE 7-3-10 BACKWATER RATIO, GEOMETRY II
ROUGH BOUNDARY \( \frac{L_{db}}{An^2} = 7.5 - 15 \)
FIGURE 7-3-II BACKWATER RATIO, GEOMETRY II
ROUGH BOUNDARY $\frac{L_d b}{A_{n2}} = 15 - 25$

\[ h_1^* \frac{y_n}{y_n} = 0.98 \left( \frac{F_n}{M} \right)^2 ]^{1.57} \]
FIGURE 7-3-12 BACKWATER RATIO, GEOMETRY II
ROUGH BOUNDARY \( \frac{L_{db}}{A_{n2}} = 25 - 30 \)
FIGURE 7-3-13 SUMMARY OF BACKWATER RATIO, GEOMETRY II ROUGH BOUNDARY
FIGURE 7-3-14
HEAD LOSS COEFFICIENT, GEOMETRY II
ROUGH BOUNDARY $\frac{L_d b}{A_n^2} = 0.00$
FIGURE 7-3-15 HEAD LOSS COEFFICIENT, GEOMETRY II
ROUGH BOUNDARY $\frac{L_{db}}{A_{n2}} > 0 \leq 7.5$

$K = 2.15 - 2.06 M'$
**FIGURE 7-3-16** HEAD LOSS COEFFICIENT, GEOMETRY II
ROUGH BOUNDARY $\frac{L_{db}}{A_{n2}} = 7.5 - 15$
\[ K = 2.79 - 2.87 M' \]

FIGURE 7-3-17 HEAD LOSS COEFFICIENT, GEOMETRY II
ROUGH BOUNDARY \( \frac{L_{db}}{A_{n2}} = 15 - 25 \)
FIGURE 7-3-18  HEAD LOSS COEFFICIENT, GEOMETRY II
ROUGH BOUNDARY $\frac{L_{db}}{A_{n2}} = 25 - 30$
FIGURE 7-3-19 SUMMARY OF HEAD LOSS COEFFICIENTS, GEOMETRY II, ROUGH BOUNDARIES
\[ D = n \left( \frac{F_n}{M'} \right)^{n-1} \]

FIGURE 7.3-20 BACKWATER RATIO COEFFICIENT GEOMETRY II

ROUGH BOUNDARY
FIG. 7-4-1 BACKWATER RATIO FOR ARCH BRIDGES WITH WINGWALLS $\Phi_i = 30^\circ$
FIG. 7-4-2 BACKWATER RATIO FOR ARCH BRIDGES WITH WINGWALLS $\Phi_i=45^\circ$
FIG. 7-4-3 BACKWATER RATIO FOR ARCH BRIDGES WITH WINGWALLS $\Phi_i = 60^\circ$
FIG. 7-4 BACKWATER RATIO FOR ARCH BRIDGES
WITH WINGWALLS $\phi_1 = 90^\circ$
FIG. 7-4-5 BACKWATER RATIO FOR ARCH BRIDGES WITH WINGWALLS
\[
\frac{Y_i}{Y_n} = c + a \left[ \left( \frac{F_n}{M'} \right)^{2/3} \right] e
\]

<table>
<thead>
<tr>
<th>(\phi_i)</th>
<th>c</th>
<th>a</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>1.00</td>
<td>0.45</td>
<td>3.42</td>
</tr>
<tr>
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<tr>
<td>60°</td>
<td>1.00</td>
<td>0.52</td>
<td>3.40</td>
</tr>
<tr>
<td>90°</td>
<td>1.00</td>
<td>0.55</td>
<td>3.40</td>
</tr>
</tbody>
</table>

**Fig. 7-4-6 - Generalized Backwater Ratio for Arch Bridges with Wingwalls**
\[ \frac{h_i^*}{y_n} = 0.27 \left( \frac{F_n}{M'} \right)^{1.07} \]

**Figure 7-4-7** Backwater Ratio, Geometry III
Rough Boundary $\Phi_I = 30^\circ$
\[ \frac{h_1^*}{y_n} = 0.29 \left[ \frac{(F_n^2)}{M^2} \right]^{0.03} \]

**Figure 7-4-8** Backwater Ratio, Geometry III

Rough Boundary \( \Phi_1 = 45^\circ \)
\[
\frac{h^*_{1}}{y_{n}} = 0.42 \left[ \left( \frac{F_{n}}{M'} \right)^2 \right]^{1.08}
\]

**FIGURE 7-4-9** BACKWATER RATIO, GEOMETRY III
ROUGH BOUNDARY \( \Phi_{1} = 60^\circ \)
FIGURE 7-4-10 BACKWATER RATIO, GEOMETRY III
ROUGH BOUNDARY $\Phi_i = 90^\circ$

\[ \frac{h_i^*}{y_n} = 0.45 \left( \frac{F_n}{M'} \right)^{1.068} \]
FIGURE 7-4-II  SUMMARY OF BACKWATER RATIO, GEOMETRY III, ROUGH BOUNDARY
FIGURE 7-4-12  HEAD LOSS COEFFICIENT, GEOMETRY III
ROUGH BOUNDARY $\Phi_1 = 30^\circ$
FIGURE 7-4-13  HEAD LOSS COEFFICIENT, GEMETRY III  
ROUGH BOUNDARY  $\phi_1 = 45^\circ$
FIGURE 7-4-14 HEAD LOSS COEFFICIENT, GEOMETRY III
ROUGHBOUNDARY $\Phi = 60^\circ$

$K = 1.751 - 1.750 M'$
FIGURE 7-4-15 HEAD LOSS COEFFICIENT, GEOMETRY III
ROUGH BOUNDARY $\Phi_1 = 90^\circ$

$K = 1.85 - 1.70 M'$
FIGURE 7-4-16 SUMMARY OF HEAD LOSS COEFFICIENTS
GEOMETRY III, ROUGH BOUNDARIES
$D = n C \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1}$

$n = 1.07$

$C = 0.27$

**Figure 7-4-17** Backwater Ratio Coefficient, Geometry III, Rough Boundary $\Phi_1 = 30^\circ$
\[ D = n \cdot c \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1} \]

\[ n = 1.03 \]

\[ c = 0.29 \]

**Figure 7-4-18** Backwater Ratio Coefficient, Geometry III Rough Boundary \( \Phi_1 = 45^\circ \)
\[ D = n c \left( \frac{F_n}{M'} \right)^2 \]^{n-1} \\
\[ n = 1.08 \] \\
\[ c = 0.42 \] 

**Figure 7-4-19** Backwater Ratio Coefficient, Geometry III, Rough Boundary \( \Phi_1 = 60^\circ \)
\[ D = nc \left( \frac{F_n}{M^l} \right)^{n-1} \]

where:
- \( D \) is a dimensionless parameter
- \( n = 1.068 \)
- \( c = 0.450 \)

Figure 7-4-20 Backwater Ratio Coefficient, Geometry III, Rough Boundary \( \phi_l = 90^\circ \)
FIG. 7-5-1 BACKWATER RATIO FOR ECCENTRIC ARCH BRIDGES

\[ e = 1 - \frac{c}{a} \]

\( e = 0 \)
\[ e = 1 - \frac{c}{a} \]

**Fig. 7-5-2 - Backwater Ratio for Eccentric Arch Bridges**

\[ e = 0.80 \]
\[ e = 1 - \frac{c}{a} \]

FIG. 7-5-3 - BACKWATER RATIO FOR ECCENTRIC ARCH BRIDGES

\( e = .85 \)
FIG. 7-5-4 BACKWATER RATIO FOR ECCENTRIC ARCH BRIDGES

\( e = 0.90 \)
FIG. 7-5-5 - BACKWATER RATIO FOR ECCENTRIC ARCH BRIDGES

\[ e = 0.95 \]
FIG. 7-5-6 - BACKWATER RATIO FOR ECCENTRIC ARCH BRIDGES

\[ e = 1 - \frac{c}{a} \]
FIG. 7-5-7 - GENERALIZED BACKWATER RATIO
FOR ECCENTRIC ARCH BRIDGE

\[ \frac{y_i}{y_n} = 1 + 0.64 \left[ \frac{(F_n)^{2/3}}{M^*} \right]^{3.31} \]

for \( e \leq 0.9 \)

\[ \frac{y_i}{y_n} = 1 + 0.73 \left[ \frac{(F_n)^{2/3}}{M^*} \right]^{3.31} \]

for \( e = 1.00 \)
\[ \frac{h^*}{y_n} = 0.556 \left( \frac{F_n}{M^*} \right)^2 \]

**FIGURE 7-5-8** BACKWATER RATIO, GEOMETRY IV
ROUGH BOUNDARY \( e = 0.0 \)
\[ \frac{h_i}{y_n} = 0.62 \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{0.992} \]

**Figure 7-5-9: Backwater Ratio, Geometry IV**

Rough Boundary \( e = 0.8 \)
\[
\frac{h_i^*}{y_n} = 0.57 \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{0.993}
\]

**FIGURE 7-5-10** BACKWATER RATIO GEOMETRY IV
ROUGH BOUNDARY \( e = 0.85 \)
FIGURE 7-5-11 BACKWATER RATIO, GEOMETRY IV
ROUGH BOUNDARY \( e = 0.9 \)

\[
\frac{h_*}{y_n} = 0.624 \left[ \left( \frac{F_n}{M} \right)^2 \right]^{0.975}
\]
FIGURE 7-5-12 BACKWATER RATIO GEOMETRY IV

ROUGH BOUNDARY \( e = 0.95 \)
\[
\frac{h_i}{y_n} = 0.612 \left( \frac{F_n}{M'} \right)^{0.972}
\]

**FIGURE 7-5-13** BACKWATER RATIO, GEOMETRY IV
ROUGH BOUNDARY \( e = 1.0 \)
FIGURE 7-5-14 SUMMARY OF BACKWATER RATIO
GEOMETRY IV ROUGH BOUNDARY
FIGURE 7-5-15 HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY $e = 0.00$
FIGURE 7-5-16  HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY  $e = 0.8$
FIGURE 7-5-17  HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY  e = 0.85
FIGURE 7-5-18 HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY $e = 0.9$
FIGURE 7-5-19  HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY  $e = 0.95$
FIGURE 7-5-20 HEAD LOSS COEFFICIENT, GEOMETRY IV
ROUGH BOUNDARY $e = 1.0$
FIGURE 7-5-21 SUMMARY OF HEAD LOSS COEFFICIENTS
GEOMETRY IV ROUGH BOUNDARY
\[ D = n c \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1} \]

\[ n = 0.994 \]

\[ c = 0.556 \]

**Figure 7-5-22** Backwater Ratio Coefficient, Geometry IV, Rough Boundary \( e = 0.0 \)
\[ D = n c \left( \frac{F_n}{M_T} \right)^2 n - 1 \]

\[ n = 0.972 \]

\[ c = 0.612 \]

**Figure 7-5-23** Backwater Ratio Coefficient, Geometry IV Rough Boundary \( e = 0.8 \)
\[
D = n c \left( \frac{F_n^2}{M'} \right)^{n-1}
\]

\[
n = 0.993
\]

\[
c = 0.57
\]

**Figure 7-5-24** Backwater Ratio Coefficient

Geometric IV  Rough Boundary  \( e = 0.85 \)
\[ D = n c \left( \frac{F_n}{M'} \right)^2 \left( \frac{h_i}{y_n} \right) {\left( \frac{M'}{F_n} \right)}^2 n^{-1} \]

\[ n = 0.975 \]

\[ c = 0.624 \]

**Figure 7-5-25 Backwater Ratio Coefficient, Geometry IV Rough Boundary e = 0.9**
\[ D = n \cdot c \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1} \]

\( n = 0.983 \)
\( c = 0.575 \)

**Figure 7-5-26** BACKWATER RATIO COEFFICIENT

**Geometry IV** ROUGH BOUNDARY  \( e = 0.95 \)
FIG. 7-6-1 BACKWATER RATIO FOR SKEW ARCH BRIDGES
$\phi_2 = 0^\circ$
FIG. 7-6-2 - BACKWATER RATIO FOR SKEW ARCH BRIDGES

\[ \Phi_2 = 15^\circ \]
FIG. 7-6-3 - BACKWATER RATIO FOR SKEW ARCH BRIDGES

\[ \Phi_2 = 30° \]
FIG. 7-6-4—BACKWATER RATIO FOR SKEW ARCH BRIDGES

$\phi_2 = 45^\circ$
FIG. 7-6-5 - BACKWATER RATIO FOR SKEW ARCH BRIDGE
FIG. 7-6-6 - GENERALIZED BACKWATER RATIO
FOR SKEW ARCH BRIDGE

\[
\frac{Y_i}{Y_n} = c + a \left[ \left( \frac{F_n}{M'} \right)^{2/3} \right]^e
\]

<table>
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<tr>
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<th>e</th>
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<tr>
<td>45°</td>
<td>1.00</td>
<td>0.42</td>
<td>3.28</td>
</tr>
</tbody>
</table>
\[
\frac{h_i^*}{y_n} = 0.563 \left( \frac{F_n}{M} \right)^{1.038}
\]

**Figure 7-6-7** Backwater Ratio, Geometry $V_a$

Rough Boundary $\Phi_2 = 0.00$
FIGURE 7-6-8  BACKWATER RATIO, GEOMETRY $V_a$
ROUGH BOUNDARY $\Phi_2 = 15^\circ$

\[
\frac{h^*_l}{y_n} = 0.565\left[\left(\frac{F_n}{M_L}\right)^2\right]^{1.113}
\]
\[ \frac{h_1}{y_n} = 0.5 \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{0.628} \]

**FIGURE 7-6-9 BACKWATER RATIO, GEOMETRY \( V_a \)**

**ROUGH BOUNDARY \( \Phi_2 = 30^\circ \)**
FIGURE 7-6-10 BACKWATER RATIO, GEOMETRY $V_o$

ROUGH BOUNDARY $\Phi_2 = 45^\circ$

$\frac{h_i}{y_n} = 0.394 \left[ \left( \frac{F_n}{M} \right)^2 \right]^{1.0889}$
FIGURE 7-6-11 SUMMARY OF BACKWATER RATIO
GEOMETRY $V_0$ ROUGH BOUNDARY
FIGURE 7-6-12 HEAD LOSS COEFFICIENT, GEOMETRY \( V_a \)
ROUGH BOUNDARY \( \phi_2 = 0.0^\circ \)

\[ K = 2.34 - 2.37 M' \]
FIGURE 7-6-13 HEAD LOSS COEFFICIENT, GEOMETRY $V_d$
ROUGH BOUNDARY $\phi_2 = 15^\circ$

\[ K = 2.23 - 2.29 M' \]
FIGURE 7-6-14 HEAD LOSS COEFFICIENT, GEOMETRY $\xi_0$
ROUGH BOUNDARY $\Phi_2 = 30^\circ$

$K = 1.77 - 1.75 M'$
FIGURE 7-6-15 HEAD LOSS COEFFICIENT, GEOMETRY $\Sigma_a$
ROUGH BOUNDARY $\phi_2 = 45^\circ$

\[ K = 1.51 - 1.58 M' \]
FIGURE 7-6-16 SUMMARY OF HEAD LOSS COEFFICIENTS
GEOMETRY $\varphi_0$. ROUGH BOUNDARIES
\[ D = n \cdot C \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1} \]

- \( n = 1.038 \)
- \( C = 0.563 \)

**Figure 7-6-17** Backwater Ratio Coefficient, Geometry \( \nu_a \) Rough Boundary \( \Phi_2 = 0.0 \)
D = n C \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1}

n = 1.113
C = 0.565

**Figure 7-6-18 Backwater Ratio Coefficient, Geometry \( \mathbf{V}_a \) Rough Boundary \( \Phi_2 = 15^\circ \)**
\[ D = n c \left( \frac{F_n}{M^2} \right)^{n-1} \]

\( n = 1.0889 \)

\( c = 0.394 \)

**FIGURE 7-6-20** BACKWATER RATIO COEFFICIENT, GEOMETRY \( V_a \) ROUGH BOUNDARY \( \Phi_2 = 45^\circ \)
FIGURE 7-7-1  BACKWATER RATIO, GEOMETRY $V_d$
ROUGH BOUNDARY $\Phi_2 = 15^\circ$
FIGURE 7-7-2 BACKWATER RATIO, GEOMETRY $V_b$
ROUGH BOUNDARY $\Phi_2 = 30^\circ$
FIGURE 7-7-3 SUMMARY OF BACKWATER RATIO, GEOMETRY $\nu_b$ ROUGH BOUNDARY
\[
\frac{h_i}{y_n} = 0.754 \left( \frac{F_n}{M} \right)^{0.931}
\]

**FIGURE 7-8-I** BACKWATER RATIO, GEOMETRY VI
ROUGH BOUNDARY
FIGURE 7-8-2 HEAD LOSS COEFFICIENT, GEOMETRY VI
ROUGH BOUNDARY

\[ K = 3.58 - 3.20 M' \]
\[ D = n \cdot c \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{n-1} \]

\[ n = 0.931 \]

\[ c = 0.754 \]

**Figure 7-8-3** Backwater Ratio Coefficient, Geometry VI Rough Boundary
FIGURE 7-9-1  BACKWATER RATIO, GEOMETRY VII
ROUGH BOUNDARY  $\beta = 0.00$

\[ \frac{h_i}{y_n} = 0.563 \left( \frac{F_n}{M'} \right)^{1.088} \]
FIGURE 7-9-2 BACKWATER RATIO, GEOMETRY VII
ROUGH BOUNDARY $\beta = 0.3$

\[ \frac{h_i^*}{y_n} = 0.525 \left[ \left( \frac{F_n}{M'} \right)^2 \right]^{0.954} \]
\[
\frac{h_i}{y_n} = 0.563 \left( \frac{F_n}{M'} \right)^{0.962}
\]

FIGURE 7-9-3 BACKWATER RATIO, GEOMETRY VII
ROUGH BOUNDARIES \( \beta = 0.5 \)
Figure 7-9-4 Summary of Backwater Ratio, Geometry VII, Rough Boundaries
FIGURE 7-9-5  HEAD LOSS COEFFICIENT, GEOMETRY VII
ROUGH BOUNDARY, $\beta = 0.00$

\[ K = 2.49 - 2.67 M' \]
FIGURE 7-9-6 HEAD LOSS COEFFICIENT, GEOMETRY VII
ROUGH BOUNDARY, $\beta = 0.3$
FIGURE 7-9-7 HEAD LOSS COEFFICIENT, GEOMETRY VII
ROUGH BOUNDARY, $\beta = 0.5$

$K = 1.53 - 1.27 M'$
FIGURE 7-9-8 SUMMARY OF HEAD LOSS COEFFICIENT

GEOMETRY VII ROUGH BOUNDARY
\( D = n \cdot c \left[ \left( \frac{F_n}{M^i} \right)^2 \right]^{n-1} \)

\( n = 1.088 \)

\( c = 0.563 \)

**FIGURE 7-9-9 BACKWATER RATIO COEFFICIENT, GEOMETRY VII ROUGH BOUNDARY \( \beta = 0.0 \)**
\[ D = n \cdot c \left[ \left( \frac{F_n}{M_i} \right)^2 \right]^{n-1} \]

\[ n = 0.954 \]

\[ c = 0.525 \]

**FIGURE 7-9-10 BACKWATER RATIO COEFFICIENT, GEOMETRY VII ROUGH BOUNDARY \( \beta = 0.3 \)**
\[ D = n \cdot c \left( \frac{F_n}{M^*} \right)^{2n-1} \]

\[ n = 0.962 \]
\[ c = 0.560 \]

**FIGURE 7-9-11** BACKWATER RATIO COEFFICIENT, GEOMETRY VII ROUGH BOUNDARY \( \beta = 0.5 \)
FIG 8.3-2 ISOVELOCITY CURVES AT VENA CONTRACTA
FIG. 8-3 ISOVELOCITY CURVES FOR CROSS SECTION AT VENA CONTRACTA
FIG. 8-3-5 GENERALIZED BACKWATER RATIO FOR SUBMERGED INLET GEOMETRY Iα
Fig. 8-3-7 Discharge coefficient for free & submerged discharge & partly submerged jet. Geometry $I_0$.
FIG. 8-5-1 DIMENSIONLESS CURVES FOR GEOMETRIES Ia AND Ib. ROUGH BOUNDARIES
Fig 8-5-2a Spiral Motion in Barrel Section Downstream of Vena Contracta

Fig 8-5-2b Typical Flow Condition Through Constriction
FIG 8-5-3  SLUG FLOW AT BARREL EXIT

FIG 8-5-4  FREE DISCHARGE JET
FIG. 8-5-5 Comparison of Dimensionless Curves for Geometry Ia for Smooth and Rough Boundaries
FIG. 8-7-1 DIMENSIONLESS CURVES FOR GEOMETRY VI USING $\text{IF}_n$ AS PARAMETER. ROUGH BOUNDARIES
FIG. 8-8-1 Dimensionless Curves for Geometry VII Rough Boundaries
FIG. 8.9-1 HEAD LOSS COEFFICIENT FOR GEOMETRY

In smooth boundaries, $\frac{L}{b} = 0.0$

The graph shows a linear relationship between $K$ and $M'$ with the equation $K = 2.70 - 2.967 M'$. The plot includes data points for various values of $K$ and $M'$.
K = 2.40 - 3.00 M'

FIG. 8-9-2 HEAD LOSS COEFFICIENT FOR GEOMETRY

Ib SMOOTH BOUNDARIES, \( \frac{L}{b} = 0.25 \)
FIG. 8-9-3 HEAD LOSS COEFFICIENT FOR GEOMETRY

I_b SMOOTH BOUNDARIES, $\frac{L}{b} = 0.50$

$k = 2.061 - 3.248 M'$
FIG 8-9-4 HEAD LOSS COEFFICIENT FOR GEOMETRY

I_b SMOOTH BOUNDARIES, \( \frac{L}{b} = 0.75 \)
FIG. 8-9-5 HEAD LOSS COEFFICIENT FOR GEOMETRY

\[ K = 1.969 - 4.695 M^I \]

Points Not Considered:
Outlet Not Sufficiently Submerged

\[ \frac{L}{b} = 1.00 \]
FIG 8-9-6 SUMMARY OF HEAD LOSS COEFFICIENT CURVES FOR GEOMETRIES I_a, & I_b , SMOOTH BOUNDARIES
FIG. 8-9-7 HEAD LOSS COEFFICIENT CURVES FOR GEOMETRIES $I_a$, $I_b$, ROUGH BOUNDARIES
φ, ϕ, Δ: Points Not Considered, Outlet Not Sufficiently Submerged.

Points

ϕ₂

Δ  22.5°  
○  30°  
○  15°  

\[ K = 0.895 - 2.942 M' \]

FIG 8-9-8 HEAD LOSS COEFFICIENT CURVE FOR GEOMETRY \( V_b \), ROUGH BOUNDARIES
\[ K = 0.227 - 0.753 M' \]

**FIG. 8-9-9** HEAD LOSS COEFFICIENT CURVE FOR GEOMETRY VI, ROUGH BOUNDARIES
\[ \beta = 0.3 \]
\[ K = 3.767 - 1.774 M' \]

\[ \beta = 0.5 \]
\[ K = 2.128 - 0.668 M' \]

FIG. 8-9-10 HEAD LOSS COEFFICIENT CURVES FOR GEOMETRY VII, ROUGH BOUNDARIES
FIG. 8-10-IGENERALIZED BACKWATER RATIO GEOMETRY
IG, SMOOTH BOUNDARIES, \( \frac{L}{b} = 0.0 \)

\[
\frac{h_i^*}{y_n} = 1.08 \left( \frac{F_n}{M'} \right)^{0.74}
\]
FIG. 8-10-2 GENERALIZED BACKWATER RATIO GEOMETRY

Ib, SMOOTH BOUNDARIES, $\frac{L}{b} = 0.25$

\[ \frac{h_i^*}{Y} = 0.964 \left( \frac{F_n}{M_t} \right)^{2.205} \]
FIG 8-10-3 GENERALIZED BACKWATER RATIO GEOMETRY

Ib, SMOOTH BOUNDARIES, \( \frac{L}{b} = 0.50 \)

\[ \frac{h_i^*}{Y_n} = 0.807 \left( \frac{F_n}{M_i} \right)^{2.280} \]
FIG. 8-10-4 GENERALIZED BACKWATER RATIO GEOMETRY

Ib, SMOOTH BOUNDARIES, \( \frac{L}{b} = 0.75 \)
FIG. 8-10-5 GENERALIZED BACKWATER RATIO GEOMETRY

Ib, SMOOTH BOUNDARIES, $\frac{L}{b} = 1.0$

$h^* \over Y_n = 0.646 \left( \frac{F_n}{M} \right)^{2.436}$
FIG. 8-10-6 SUMMARY OF BACKWATER RATIO CURVES FOR GEOMETRIES Ia AND Ib, SMOOTH BOUNDARIES
FIG. 8-10-7 GENERALIZED BACKWATER RATIO GEOMETRIES Ia AND Ib, ROUGH BOUNDARIES
FIG 8-10-8 GENERALIZED BACKWATER RATIO GEOMETRY Vb, ROUGH BOUNDARIES
FIG. 8-10-9 GENERALIZED BACKWATER RATIO GEOMETRY VI, ROUGH BOUNDARIES
FIG. 8-10-10 GENERALIZED BACKWATER RATIO GEOMETRY

VII, ROUGH BOUNDARIES
POGUES RUN
OLNEY STREET BRIDGE
INDIANAPOLIS
UPSTREAM FACE

SCALES: AS NOTED

FIG. 9-1-2

NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION.

DISTANCE IN FEET
NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION
NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION
FIG 9-6-5

Scales as noted

INDIANA FLOOD CONTROL AND WATER RESOURCES COMMISSION

ELEVATION (M S L, 1932 AD)

NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION

PLEASANT RUN, INDIANAPOLIS NATURAL CROSS-SECTION

RIVER MILE 351

NEGATIVE GS 63

WS 7.5.63

0.000 FOR BRIDGE CROSS-SECTION

0.000 FOR NATURAL CROSS-SECTION

BRIDGE
NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION

HURRICANE CREEK
EAST JEFFERSON STREET BRIDGE
FRANKLIN
DOWNSTREAM SIDE
RIVER MILE 0.30
SCALES: AS NOTED

FIG. 9-8-3

INDIANA FLOOD CONTROL AND WATER RESOURCES COMMISSION
NOTE: ALL SECTIONS ARE PLOTTED LOOKING IN DOWNSTREAM DIRECTION

DEAN ROAD BRIDGE, INDIANAPOLIS
DOWNSTREAM SIDE

SCALES: AS NOTED

FIG 9-10-3
\( \Delta y_E \)

- Pursue Data, Small Flume - Segment Tests - Rough Boundaries
- Pursue Data, Large Flume - Semicircular - Smooth Boundaries
- Pursue Data, Large Flume - Semicircular - Rough Boundaries
- Colorado Data, Simple Normal Crossing - Vertical Board Model
- Indiana Streams

Relation of maximum backwater effect to velocity head

FIG. 9-11-1
Bridge Number 2A
Olney Street and Pogue's Run
Aerial Photograph Numbers 48 (166-167)
Scale: one inch represents fifty feet
July 1963

FIG. 9-1-6
Bridge Number 8A
South Belmont and Little Buck Creek
Aerial Photographs 48(57-8)
Scale: one inch represents 50 feet
July 1963

FIG. 9-4-6
Bridge Number 13
State Road 100 to Williams Creek
Marion County
Aerial Photographs 48 (163-163)
July 1963
Bridge Number 15A

Pleasant Run to Villa

Aerial Photographs 48 (72-3)

Scale: one inch represents 50 feet

FIG. 9-6-6  July 1963
Bridge Number 15B
Pleasant Run and Linden
Indianapolis
Aerial Photographs 48 (74-5)
Scale: one inch represents 50 feet
July 1963

FIG. 9-7-6
Bridge Number 51
East Jefferson Street and Hurricane Creek
Franklin, Indiana
Aerial Photographs 148 (155-156)
Scale: One inch represents 50 feet
FIG-9-8-6
Bridge Number 59A
Plainfield–White Lick Creek and 267
Aerial Photographs 48(59-60)
Scale: one inch represents 50 feet
FIG 9-9-6
July 1963
Bridge Number 66A
Dean Road to Howland Ditch
Aerial Photographs 145 (164-5)
Scale: 1 inch represents 50 feet
July 1963
FIG. 9-10-6