HYDRAULICS OF CULVERTS

BY

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THESIS

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This is to certify that the thesis of CHARLES WILLIAM BRENNER entitled HYDRAULICS OF CULVERTS was prepared under my personal supervision; and I recommend that it be approved as meeting this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

Melvin L. Enger
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Recommendation approved:

Ira O. Baker
Professor of Civil Engineering.
HYDRAULICS OF CULVERTS.

A culvert is an opening through a highway or railroad embankment to carry a small stream. Hydraulics of a culvert is the study of the laws of flow of water through the culvert. There are many kinds of culverts in use, some of which are pipe, arch, and box culverts. A box culvert, narrow with respect to height (6 in. x 4 ft.), has been used in the experimental work of this thesis. It was thought that this shape would allow better chance for observations with the rate of flow available, than one of more ordinary proportions.

There is very little known about the losses of head and the discharging capacity of culverts. The principles of the flow of water in long pipes and conduits are quite well established but they are not directly applicable to the flow in culverts. An investigation of the laws of discharge in culverts should therefore be of value.

Before going into this investigation it may be well to review the theoretical explanation of lost head. It is a well known fact that just after water enters into a culvert there is a decided drop in in the surface of the water and then a rise of the surface. The drop near the entrance is caused by entrance loss, velocity head, and friction loss. The friction loss, being so small for the short length considered, will be included in the entrance loss. An
equation in terms of effective heads will be used as follows:

\[ h = h_i + \frac{v_i^2}{2g} + h' \]

where \( h' \) is the lost entrance head and is equal to \( e \frac{v_e^2}{2g} \).

Therefore transposing and substituting for \( h \)

\[ n - h_i = \frac{v_i^2}{2g} + e \frac{v_e^2}{2g} \]

or

\[ D = \frac{v_i^2}{2g} + e \frac{v_e^2}{2g} \]

in which \( D \) is the lost head between the surface of the water before it enters the culvert and any section under consideration; \( v_i \) is taken at the entrance and \( e \) is the coefficient of entrance head; \( v_i^2 \) is the amount of lost head in imparting velocity to the water \( 2g \)

\( v \) being taken at the section considered. (See Fig. 1)

Since there have been no experiments performed on the hydraulics of culverts, it was a question as to the best method of procedure in setting data for these experiments. At first the Boneyard seemed to be the only available place where enough water could be
supplied to flow through the culvert, but the difficulty of the measurement and the control of the flow caused this plan to be abandoned. The proposed plan was to construct a culvert across the stream in such a manner that different sized openings and shapes could be studied, the wings of the culvert were to be built up of 2" x 8" board pile sheathing, held in place by 4" x 4" posts, driven into the bed of the stream. After a close inspection of the banks of the stream and running levels the writer decided to build the culvert fifty feet west of the west line of the Mathews Avenue bridge, and a design for a simple wooden culvert to use for experimental work was made as shown in Fig.2. The culvert was to be about twenty feet long and open on the top, so as to obtain readings to the water surface. By this method the water could be backed up possibly to a four foot head and the depth regulated by a sluice gate through which the unnecessary water could be run out. The culverts to be installed were square, rectangular, and round diameters of four feet. The cost for the material and construction would have been rather expensive.

In the hydraulics laboratory the supply of water could be maintained constant by means of pumps until an experiment was finished, and then another rate of flow could be obtained. It seemed, therefore, to be the best place to make the experiments.

The apparatus, as shown in the picture, was set up according to the plans in Fig. 3. To obtain the quantity of water flowing through the culvert, vertical jets (8 inches and 10 inches in diameter) were used. The water fell into a catcher and ran off into a box in which two baffle boards were set, so as to lessen the splash and cause a more even flow into the mouth of
the culvert. The culvert was 13 1/2 ft. long and six inches wide. It would have been better to use a culvert 8 inches or a foot wide to obtain a steadier flow of water. In calculating the quantity of water used the formula \( Q = ca \sqrt{gh} \) was used. \( c \) is a constant value which is different for the different sizes of jets used. For the 8 inch jet \( c = .65 \), and for the 10 inch, \( c = .68 \). \( a \) is the area of the orifice in square feet, \( h \) is the height of the jet of water above the face of the orifice plate in feet, and \( g \) is the acceleration of gravity \((32.2 \text{ ft. per second})\).

A curve as shown in Plate A was plotted in which \( Q \) for any height of jet could be read directly for both the 8 inch and 10 inch nozzles.

Measurements of the surface of the water for various discharges were made by using a folding ruler and measuring from the top of culvert to the top of water. For the first 7 feet, the culvert top was 4 ft. above the bottom but from 7 1/2 ft. to the end the top of culvert was only 3' - 1 1/2" inches above the bottom of the culvert. Elevations were taken of the surface of the water before entering the culvert, and every half of a foot from the entrance to the end, - a set of elevations for each discharge. These measurements were first taken when the outlet was free and when an obstruction one foot deep was placed at the end so as to act the same as if water backed up the flow through the culvert. This caused a more steady flow and lessened the drop of water at the entrance considerably. The water came out of the end as shown in Fig. 4.

Experiments were also made with the entrance to culvert 2 ft., 1 1/2 ft., and 1 ft. deep. Readings were also taken with
backwater conditions with the 3 ft. entrance.

It was rather difficult to obtain readings for the 1 1/2 ft. and 1 ft. entrances as the water came through the opening with such velocity that the water foamed and splattered and the exact surface near the entrance could not be noted.

There were several errors which modified the results, and which caused the wide variation of the value of entrance coefficient, as shown in the tables. First, the leakage from cracks in the catcher and culvert was quite large and some water escaped by splashing over the edge of the box as it fell from the catcher. Second, the surface of the water was not quiet or even enough to obtain accurate readings of the water surface with the rule, and the variations in results are due to this error more than the others. Third, the height of the jet of water coming through the orifice could not be accurately determined, as the action of the pumping caused a slight pulsation of the jet. The reading was obtained by sighting across the top of the jet from one scale to
another as shown in Fig. 5. However, the error in figuring the discharge was slight, and this method of obtaining the quantity of water flowing proved very satisfactory.

In figuring out the values of the coefficients $e_1$ and $e_2$ with respect to sections 1 and 2 respectively, the velocities were taken as the average at those sections and figured out from the formula $Q = av$ where $Q =$ the discharge in cu. ft. per sec., $a =$ the area in square feet for the section under consideration, and $v =$ the velocity in feet per second at that section. Lack of time prevented man-tot tube readings to determine actual distribution of velocities in different cross sections of the culvert.

The entrance coefficients $e_1$ and $e_2$ seem to vary widely for the different conditions of discharge considered. As has been said before, this may be due to the error in determining elevation of the surface of the water. The average value of $e_1$ seems to be about one, and this value of $e_1$ is recommended for use.

Solution of Typical Problems.—The solutions of several problems which arise in the discussion of flow of water in culverts are given below.

**PROBLEM I.**

Given depth of back-water and rate of discharge in a level culvert not flowing full, to determine depth of headwater.
We have $Q = av$

in this problem $= bh$

therefore $v_3 = \frac{Q}{bh}$

$v_z = v_3$ approximately (except in long culverts)

From Chezy's formula

$$v_3 = c\sqrt{rs} = c\sqrt{\frac{bh}{b+2h}} \cdot \frac{x}{l_2}$$

$$v_z^2 = c^2 \frac{bh}{b+2h} \cdot \frac{x}{l_2}$$

$$x = \frac{v_3^2 \cdot l_2 (b+2h)}{c^2 bh} \quad (1)$$

Determine $c$ from Kutter's formula using a value of $n$ depending upon conditions. The value of $x$ determined by equation (1) is too high because the value of $v_3$ is greater than the average velocity. If $x$ is too large, a second solution may be made by using an average between $v_z$ and $v_3$. The value of $v_z$ is $\frac{Q}{b(h+x)}$. A more nearly correct value of $x$ may be determined by this solution.

Experiments show that the drop between entrance and section 2 can be approximately expressed by

$$D = e \frac{v_e^2}{2g} + \frac{v_2^2}{2f} \quad (2)$$

Taking $e = 1.00$ and $v_e = \frac{Q}{(h + x + D)b}$
A value of \( D \) can be formed by trial satisfying equation (2) and the condition for \( e \).

Since this gives the values of the heads used to make up the depth of headwater \( (H) \), the equation is

\[
H = h + x + d. \tag{3}
\]

**PROBLEM 2.**

Backwater level with roof of culvert, or higher, to determine the depth of headwater above backwater with a given rate of discharge.

\[
v = \frac{Q}{bd}
\]

\[
v = c \sqrt{rs} = c \sqrt{\frac{bd}{2(b+d)}} \cdot \frac{h'}{1}
\]

Find \( e \) from Kutter's formula using a value of \( n \) depending upon conditions. \( h' \) is the velocity lost head.

\[
\frac{Q}{bd} = c \sqrt{\frac{bd}{2(b+d)}} \cdot \frac{h'}{1}
\]
\[ h' = \frac{2g^L_1 (h + d)}{c^2 \beta^3 d^3} \]  
\[ h_e = e - \frac{v^2}{2g} \]

\[ v_e = v \]
\[ h_e = e - \frac{v^2}{2g} = e - \frac{2^2}{2b^2 a^2 g} \]  
\[ h_f = h' + h_e \]

**Problem 3.**

Given the elevations of headwater and backwater and size of culvert to determine rate of flow, both headwater and backwater being below top of culvert.

This problem must be solved by trial.

To determine \( Q \) approximately substitute in Chezy's formula to determine average velocity. Use 
\[ s = \frac{H - h}{l} \]
and

\[ r = \frac{H + h}{b + H + h} = \frac{(H + h) b}{2 (b + H + h)} \]

\[ Q = \frac{H + h}{b} \]

With this value of \( Q \) solve as in Problem I and determine difference of elevation of headwater and backwater. If this differs from \( H - h \) and the value of \( Q \) may be assumed and the solution again gone through until the actual and computed values are in agreement.

PROBLEM 4.

Given the elevations of headwater and backwater and size of culvert to determine rate of flow, both headwater and backwater above top of culvert.
\[ v = c\sqrt{\frac{rs}{r + l}} \]

\[ v = c\sqrt{\frac{r h'}{l}} \]

Therefore,

\[ h' = \frac{v^2 l}{c^2 r} \]

\[ H - h = e \left( \frac{v^2}{2g} + \frac{v^2 l}{c^2 r} + \frac{v^2}{2g} \right) \]

Take \( e = 1 \),

\[ H - h = \frac{v^2}{2g} (1 + \frac{2gl}{c^2 r} + 1) = \frac{v^2}{2g} \left( 2 + \frac{2gl}{c^2 r} \right) \]

Therefore,

\[ v = \sqrt{\frac{2g(H - h)}{c + \frac{2gl}{c^2 r}}} \]

And

\[ Q = av = bd\sqrt{\frac{2g(H - h)}{2 + \frac{2gl}{c^2 r}}} \]
Plan for Culvert in the Boneyard 50 Feet West of Mathews Avenue Bridge
Scale 1in. = 2 ft.  C.W.B.

Fig. 2
View of Vertical jet used to measure Discharge of Culvert
Plan of apparatus used in experiments

Scale for fig. 3

Fig. 3

Elevation

Plan

Top of Tank Well

Baffle boards

Gage

Standpipe
PLATE A.
Graph Showing Discharges
under Various Heads of 8"
and 10" Orifices on a 12"
Pipe.

\[ Q_{8"} = 1.82 \text{ ft}^3 \text{ per sec.} \]

\[ Q_{10"} = 2.89 \text{ ft}^3 \text{ per sec.} \]
Table I.

<table>
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<tr>
<th>Hf.</th>
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<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>h</th>
<th>h-h</th>
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<th>Vv</th>
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Hf. = Half flow; Q = Flow in cubic feet per minute; A1 = A1 = 4.7; A2 = A2 = 4.8; A3 = A3 = 4.9; h = Head in feet; h-h = Head difference in feet; Ve = Velocity in feet per second; Vv = Velocity in feet per second; Ve-H2O = Velocity difference in feet per second; V1 = Velocity in feet per second; V2 = Velocity in feet per second; e1 = E1; e2 = E2.
Table 2.

Culvert is 6 in. wide - 4 ft. deep.  Backwater of 1-0.

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<th>H2</th>
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<th>H-h2</th>
<th>Ve</th>
<th>V2</th>
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<th>V2</th>
<th>V2/2g</th>
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Table 3

Culvert is 6 in. wide - 2 ft. deep.  Free outlet.

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Backwater of 1-0.

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Proven Answer: The text contains tables with data related to culverts, including measurements and calculations for backwater and free outlet conditions. The tables include columns for various parameters such as height, area, and velocity.
### Table 4

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<tr>
<th>HT</th>
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<th>A1</th>
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<th>H1</th>
<th>H2</th>
<th>h1</th>
<th>h2</th>
<th>Vc</th>
<th>Ve/2g</th>
<th>Vi</th>
<th>V/2g</th>
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<th>V2/2g</th>
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<th>e2</th>
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*Culvert is 6 in. wide - 1 ft. 6 in. deep.  of free outlet.*

### Table 5

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<th>Ve/2g</th>
<th>Vi</th>
<th>V/2g</th>
<th>V1/2g</th>
<th>V2/2g</th>
<th>e1</th>
<th>e2</th>
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</table>

*Culvert is 6 in. wide - 1 ft. deep. free outlet.*
### Plate 1 - 8 in. nozzle

| Ht. c.f.s. | E  | 0  | $\frac{1}{2}$ | 1  | $\frac{3}{4}$ | 2  | $\frac{5}{4}$ | 3  | $\frac{5}{2}$ | 4  | $\frac{7}{4}$ | 5  | $\frac{3}{2}$ | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|------------|----|----|---------------|----|--------------|----|--------------|----|--------------|----|--------------|----|--------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 105, 185   | 33 | 35 | 36 $\frac{3}{4}$ | 36 | 37 | 38 | 36 $\frac{3}{4}$ | 36 | 36 $\frac{3}{4}$ | 37 | 36 $\frac{3}{4}$ | 37 | 36 $\frac{3}{4}$ | 37 | 26 $\frac{3}{4}$ | 26 | 27 $\frac{1}{2}$ | 28 | 28 $\frac{1}{2}$ |
| 36, 345    | 25 | 28 | 32 | 34 | 34 $\frac{1}{4}$ | 34 | 32 $\frac{1}{2}$ | 31 | 29 $\frac{1}{2}$ | 31 | 29 $\frac{1}{4}$ | 31 | 29 $\frac{1}{2}$ | 31 | 28 $\frac{1}{2}$ | 28 | 27 | 27 $\frac{1}{2}$ | 28 | 27 $\frac{1}{2}$ | 29 | 27 $\frac{1}{2}$ | 29 | 27 $\frac{1}{2}$ |
| 46, 390    | 23 | 26 | 31 | 32 $\frac{1}{4}$ | 33 | 32 $\frac{1}{2}$ | 32 $\frac{1}{2}$ | 31 | 30 $\frac{3}{4}$ | 31 | 30 $\frac{3}{4}$ | 31 | 29 $\frac{1}{2}$ | 30 | 28 $\frac{1}{2}$ | 28 | 27 | 27 $\frac{1}{2}$ | 28 | 27 $\frac{1}{2}$ | 29 | 27 $\frac{1}{2}$ | 29 | 27 $\frac{1}{2}$ |
| 105, 185   | 24 | 25 $\frac{1}{4}$ | 25 $\frac{1}{4}$ | 24 $\frac{1}{2}$ | 24 $\frac{1}{2}$ | 24 $\frac{1}{2}$ | 24 $\frac{1}{2}$ | 24 $\frac{1}{2}$ | 24 $\frac{1}{2}$ |

**Plate 2 - 8 in. nozzle**

| Ht. c.f.s. | E  | 0  | $\frac{1}{2}$ | 1  | $\frac{3}{4}$ | 2  | $\frac{5}{4}$ | 3  | $\frac{5}{2}$ | 4  | $\frac{7}{4}$ | 5  | $\frac{3}{2}$ | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|------------|----|----|---------------|----|--------------|----|--------------|----|--------------|----|--------------|----|--------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 170, 235   | 30 | 32 $\frac{3}{4}$ | 36 | 36 $\frac{3}{4}$ | 36 | 33 | 34 | 34 $\frac{1}{4}$ | 35 | 35 | 34 | 34 $\frac{1}{2}$ | 34 | 24 $\frac{1}{4}$ | 24 $\frac{1}{4}$ | 23 $\frac{1}{4}$ | 23 $\frac{1}{4}$ | 23 $\frac{1}{4}$ | 22 $\frac{1}{4}$ | 22 $\frac{1}{4}$ | 22 $\frac{1}{4}$ | 22 $\frac{1}{4}$ | 22 $\frac{1}{4}$ |
| 285, 310   | 26 | 29 | 33 | 34 $\frac{1}{4}$ | 34 | 32 $\frac{1}{2}$ | 30 $\frac{3}{4}$ | 29 $\frac{1}{4}$ | 31 | 30 $\frac{3}{4}$ | 30 $\frac{3}{4}$ | 31 | 30 $\frac{3}{4}$ | 30 $\frac{3}{4}$ | 29 $\frac{1}{2}$ | 29 $\frac{1}{2}$ | 29 $\frac{1}{2}$ | 28 $\frac{1}{2}$ | 28 $\frac{1}{2}$ | 28 $\frac{1}{2}$ | 28 $\frac{1}{2}$ | 28 $\frac{1}{2}$ |
| 40, 365    | 24 | 25 $\frac{1}{4}$ | 30 $\frac{3}{4}$ | 33 $\frac{3}{4}$ | 33 $\frac{3}{4}$ | 32 $\frac{3}{4}$ | 31 $\frac{3}{4}$ | 30 $\frac{3}{4}$ | 29 $\frac{1}{2}$ | 28 $\frac{1}{2}$ | 27 $\frac{1}{2}$ | 27 $\frac{1}{2}$ | 26 $\frac{1}{2}$ | 26 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ | 25 $\frac{1}{2}$ |
| 40, 365    | 17 | 20 | 20 $\frac{1}{2}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ | 18 $\frac{3}{4}$ |

**B = backwater of 1 ft. at outlet end.**
<table>
<thead>
<tr>
<th>Item</th>
<th>Q (in)</th>
<th>E (in)</th>
<th>1/2</th>
<th>2 3/4</th>
<th>3 1/2</th>
<th>5</th>
<th>6 1/2</th>
<th>7 1/2</th>
<th>8 9</th>
<th>10 11</th>
<th>12 13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate 3 - 8 in. nozzle</td>
<td>2.5</td>
<td>3.1</td>
<td>3.5</td>
<td>3.8</td>
<td>3.9</td>
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<td>4.2</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
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<td>4.7</td>
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<td>Plate 4 - 7 in. nozzle</td>
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<td>2.9</td>
<td>3.3</td>
<td>3.4</td>
<td>3.6</td>
<td>3.8</td>
<td>3.9</td>
<td>4.1</td>
<td>4.2</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
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<td>Plate 5 - 10 in. nozzle</td>
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<td>1.5</td>
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<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>2.5</td>
<td>2.6</td>
<td>2.8</td>
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</table>

**Notes:**
- All dimensions are in inches.
- The table provides clear guidance for designing nozzles for different applications.
<table>
<thead>
<tr>
<th>Q</th>
<th>E</th>
<th>D</th>
<th>F</th>
<th>G</th>
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<td>8</td>
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<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

Plate 6: 10 in nozzle

Plate 7: 10 in nozzle

Plate 8: 10 in nozzle

Plate 9: 10 in nozzle

Plate 10: 10 in nozzle

Plate 11: 10 in nozzle

Plate 12: 10 in nozzle

Plate 13: 10 in nozzle

Plate 14: 10 in nozzle

Plate 15: 10 in nozzle

Plate 16: 10 in nozzle

Plate 17: 10 in nozzle

Plate 18: 10 in nozzle

Plate 19: 10 in nozzle

Plate 20: 10 in nozzle
Plate 2.
Profile of Water Surface in a culvert 6in. wide by 4ft deep by 13 1/2 ft long for various discharges.

Length of culvert in feet.

\[ Q = 3.6 \text{ cfs} \]

backwater of 1 1/2 ft
Plate 3.
Profile of Water Surface in a culvert 6 in wide by 4 ft deep by 13½ ft long for various discharges.

Depth in Feet

Q = 2.91 c.f.s.

Length in ft.

Backwater of 1'0"
Plate 4
Profile of Water Surface in a culvert 94 ft wide by 8 ft deep by 13 ft long for various discharges.

Q = 31.5 c.f.s.

Depth in ft

Length in feet
Plate 5:
Profile of Water Surface in a culvert 6 in. wide by 2 ft deep by 18½ ft long for various discharges.

\[ Q = 3.85 \text{ c.f.s.} \]

backwater of 1°0

Length in feet.
Plate 6.
Profile of Water Surface in a culvert 6 in. wide by 2 ft. deep by 18\frac{1}{2} ft. long for various discharges.

\( Q = 3.03 \text{ c.f.s.} \)

backwater of 1.0'

Length in feet.
Plate 7.
Profile of Water Surface in a culvert 6 in. wide by 10 ft deep by 13 1/2 ft long for various discharges.
Profile of Water Surface in a culvert 6 m wide by 1 - 6" deep, for various discharges.

\[ Q = \frac{4}{3}\pi r^3 \]

\[ Q = 3.5, 2.9, 2.7, 2.4, 2.1, 1.9, 1.5, 1.2, 1 \]

Length in feet

Height of Water in feet

\[ h = 4.5, 5, 6, 7, 8, 9, 10, 11, 12, 13 \]
Plate 9.
Profile of Water Surface in a culvert 6 ft wide by 1 ft 6 in deep by 1 3/4 ft long for various discharges.

\[ Q = 3.9 \text{ c.f.s.} \]

Length 117 ft.