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BULLETIN 1

FLOW OF WATER THROUGH CULVERTS

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A report of an investigation by the University of Iowa in coöperation with the United States Department of Agriculture Bureau of Public Roads, Thomas H. MacDonald, Chief

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CONTENTS

LIST OF ILLUSTRATIONS

(All plates at back of bulletin)

PLATE

LIST OF TABLES

THE FLOW OF WATER THROUGH CULVERTS

INTRODUCTION

This paper presents the results of 3,301 experiments on the flow of water through short conduits such as pipe and box culverts and sluiceways under levees. The experiments were conducted by the Bureau of Public Roads, U. S. Department of Agriculture, and the State University of Iowa, Iowa City, at the University hydraulic laboratory.

The investigations were undertaken primarily for the purpose of determining:

1. The quantity of water that will flow through culverts or sluiceways under levees of different materials, sizes, and shapes under conditions of actual use.
2. What conditions tend to increase or decrease such quantity.
3. What principles should be followed in design to secure the greatest discharging capacity for the least cost.

The report describes the methods of making the tests and presents the experimental results together with the discharge formulas developed for the various culverts.

SUMMARY AND CONCLUSIONS

The following conclusions are drawn from the results of 1,480 experiments on pipe culverts made of concrete, vitrified-clay, and corrugated-metal, of the following sizes: 12, 18, 24, and 30 inches in diameter; and 1,821 tests on concrete box culverts of the following sizes: 2-ft. by 2-ft., 3-ft. by 3-ft., 4-ft. by 4-ft., 4-ft. by 3-ft., 4-ft. by 2¼-ft., 4-ft. by 2-ft., 4-ft. by 1-ft., and 4-ft. by ½-ft.

Tests were made on the culverts flowing partly full and full, both with a free and submerged outlet. Experiments were also run with various types of entrances.

1 The discharging capacity of a culvert depends primarily upon the cross-section of the culvert and the difference in water level at the two ends of the culvert.

2 To obtain the maximum discharge the culvert must be so laid as to insure the full cross-section of the culvert being filled by the flowing water.

3 If the culvert is laid at too high an elevation with respect to the water levels at the two ends, it will not run full and hence will not attain its maximum capacity.

4 If a culvert is so laid that both its upstream and downstream ends are completely submerged the amount of water which it discharges will be proportional to the square root of the difference in water level at the two ends; and the exact grade at which the culvert is laid has no effect whatever upon its maximum discharging capacity.

5 The difference in water level at the two ends, called hereafter the head on the culvert, is utilized in three ways: first, in overcoming friction around the entrance corner; second, in overcoming friction along the walls throughout the barrel of the culvert; third, in imparting the velocity necessary to the water in entering the culvert. The three portions into which the total head is thus divided are called for convenience, entrance loss, friction loss, and velocity head, respectively.

The following general conclusions numbered from 6 to 25 inclusive are drawn from the results of the tests on the pipe culverts:

6 The coefficient of roughness, n in the Kutter formula for the concrete pipe ranges from 0.012 for the 12-inch size to 0.013 for the 30-inch size.

7 The coefficient of roughness, n, in the Kutter formula, for the vitrified-clay pipe ranges from 0.010 for the 12-inch size to 0.013 for the 30-inch size.

8 The coefficient of roughness, n, in the Kutter formula, for the corrugated-metal pipe ranges from 0.019 for the 12-inch size to 0.023 for the 30-inch size.

9 In concrete, vitrified-clay, and corrugated-metal pipe culverts, 30.6 feet long, with straight endwall entrances:

a. The 12-inch concrete pipe with beveled lip end upstream discharges about 49 per cent more water than the 12-inch metal pipe.

b. The 18-inch concrete pipe with beveled lip end upstream discharges about 40 per cent more water than the 18-inch metal pipe.

c. The 24-inch concrete pipe with beveled lip end upstream discharges about 36 per cent more water than the 24-inch metal pipe.

d. The 30-inch concrete pipe with beveled lip end upstream discharges about 32 per cent more water than the 30-inch metal pipe.

e. The 12-inch clay pipe discharges about 65 per cent more water than the 12-inch metal pipe.

f. The 18-inch clay pipe discharges about 50 per cent more water than the 18-inch metal pipe.

g. The 24-inch clay pipe discharges about 40 per cent more water than the 24-inch metal pipe.

h. The 30-inch clay pipe discharges about 30 per cent more water than the 30-inch metal pipe.

The relative capacities of these culverts may also be expressed in the following terms which are mathematically equivalent to the above.

i. The 12-inch metal pipe has about 67 per cent of the carrying capacity of the 12-inch concrete pipe with beveled lip end upstream.

j. The 18-inch metal pipe has about 71 per cent of the carrying capacity of the 18-inch concrete pipe with beveled lip end upstream.

k. The 24-inch metal pipe has about 74 per cent of the carrying capacity of the 24-inch concrete pipe with beveled lip end upstream.

l. The 30-inch metal pipe has about 76 per cent of the carrying capacity of the 30-inch concrete pipe with beveled lip end upstream.

m. The 12-inch metal pipe has about 61 per cent of the carrying capacity of the 12-inch clay pipe.

n. The 18-inch metal pipe has about 68 per cent of the carrying capacity of the 18-inch clay pipe.

o. The 24-inch metal pipe has about 73 per cent of the carrying capacity of the 24-inch clay pipe.

p. The 30-inch metal pipe has about 78 per cent of the carrying capacity of the 30-inch clay pipe.

10 In concrete pipe culverts, 30.6 feet long, with straight endwall entrances:

a. The 12-inch pipe with beveled lip end upstream discharges about 5 per cent more water than the same pipe with a square cornered entrance.

b. The 18-inch pipe with beveled lip end upstream discharges about 9 per cent more water than the same pipe with a square cornered entrance.

c. The 24-inch pipe with beveled lip end upstream discharges about 12 per cent more water than the same pipe with a square cornered entrance.

d. The 30-inch pipe with beveled lip end upstream discharges about 14 per cent more water than the same pipe with a square cornered entrance.

11 Due to the larger amount of pipe friction in corrugated-metal pipes, a change in culvert length produces a greater change in discharge than with concrete and vitrified-clay pipe culverts.

12 The 45-degree wingwalls used in connection with a corrugated-metal pipe culvert increase the capacity from 1 to 10 per cent over that obtained in a metal pipe culvert with a straight endwall.

13 The 45-degree wingwalls used in connection with a corrugated-metal pipe culvert are more efficient when set flush with the edge of the pipe than when set 6 inches back from the edge of the pipe.

14 The 45-degree wingwalls used in connection with a corrugated-metal pipe culvert are more efficient when built full height to the top of the headwall than when constructed only to the standard height shown in Fig. 6.

15 The 45-degree wingwalls used in connection with a vitrified-clay pipe culvert produce a carrying capacity substantially equal to that with the regular bell end upstream.

16 The U-type wingwalls used in connection with a vitrified-clay pipe culvert produce a carrying capacity slightly less than that with the straight endwall.

17 The beveled lip end at the entrance of a concrete pipe culvert is a great aid in reducing the entrance loss, especially in the larger sizes.

18 The bell end at the entrance of a vitrified-clay pipe culvert by virtue of its shape greatly reduces the entrance loss below that produced by a right-angle corner, especially in the smaller sizes.

19 A 24-inch clay pipe, 38 feet long, with a straight endwall and the regular bell-end upstream carries about 10 per cent more water than the same culvert with a square cornered entrance.

20 Merely rounding the entrance to a 24-inch vitrified-clay

pipe culvert increases the capacity approximately 13 per cent over that obtained with a square cornered entrance.

21 By projecting the pipe through the headwall so as to obtain the effect on the discharge of no headwall, it was found that:

a. In the 12-inch concrete pipe culvert having a square cornered entrance, there is little difference whether the pipe projected 3 inches, 2 feet, or 4 feet beyond the headwall.

b. The discharge is decreased slightly by projecting the pipe through the headwall as compared with the same culvert with a straight endwall entrance.

c. The 18-inch corrugated-metal pipe culvert with a 3-inch projection beyond the headwall carries slightly more water than the same pipe with either a 2-foot or a 4-foot projection.

d. The 18-inch metal pipe culvert with a straight endwall entrance carries more water than the same pipe with any length of projection.

22 By doubling the area of the outlet end of an 18-inch vitrified-clay pipe culvert by attaching a conical section, the sides of which diverge at an angle of about 10 degrees, the discharge of the culvert, when the outlet end is submerged, is increased about 40 per cent over that obtained through the same culvert having a uniform bore throughout.

23 In the formulas for discharge the average exponent of H, the head on the pipe culvert, for tables 22 to 79 inclusive is 0.488. In hydraulics the general practice is to assume that the discharge varies as the square root of the head.

24 New discharge formulas for the flow of water through concrete, vitrified-clay, and corrugated-metal, culvert pipe have been derived from the experimental data in this report. The formulas as derived for culverts 30.6 feet long with straight endwall entrances are as follows:

Concrete pipe with beveled lip end upstream.

$$Q=4.61\ D^{2.18}\ H^{0.50} \quad (1)$$

Concrete pipe with square cornered entrance.

$$Q=4.40\ D^{2.09}\ H^{0.50} \quad (2)$$

Vitrified-clay pipe with bell end upstream.

$$Q=5.07\ D^{2.05}\ H^{0.50} \quad (3)$$

Corrugated-metal pipe.

$$Q=3.10\ D^{2.31}\ H^{0.50} \tag{4}$$

25 The general discharge formulas derived for pipe culverts with straight endwall entrance and of any size and length, when flowing full, are as follows:

Concrete pipe, beveled lip entrance.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1.1+\frac{0.026\ L}{D^{1.2}}}} \tag{13}$$

Concrete pipe, square cornered entrance.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1+0.31\ D^{0.5}+\frac{0.026\ L}{D^{1.2}}}} \tag{14}$$

Vitrified-clay pipe, regular bell end upstream.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1+0.023\ D^{1.9}+\frac{0.022\ L}{D^{1.0}}}} \tag{15}$$

Corrugated-metal pipe.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1+0.16\ D^{0.6}+\frac{0.106\ L}{D^{1.2}}}} \tag{16}$$

In these formulas,

Q=discharge in cubic feet per second.
A=cross-sectional area of pipe in square feet.
D=diameter of pipe in feet.
L=length of culvert in feet.
H=head on pipe in feet or the difference in the water level at the two ends of the culvert.
g=acceleration of gravity.

The following general conclusions numbered from 26 to 33 are drawn from the results of the tests on the concrete box culverts:

26 Concrete box culverts with straight headwalls and rounded lip entrance discharge from 8 to 12 per cent more water than the

same size culvert with square cornered entrance in the sizes tested in this investigation.

27 Concrete box culverts with straight headwalls and beveled lip entrance discharge from 7 to 9 per cent more water than the same size culvert with square cornered entrance in the sizes tested in this investigation.

28 If the outlet end of a 36-foot box culvert with a rounded lip entrance is flared by diverging the sides at an angle of 6° 30′ throughout a distance of 10 to 12 feet from the outlet headwall, thus doubling the area of its cross-section at the outlet, the capacity of the culvert is increased about 60 per cent above the capacity of a similar culvert 36 feet long with the uniform bore extending the entire length of the culvert.

29 The 2-ft. by 2-ft. box culvert, 30 feet long, with a rounded lip entrance and flared on the two sides for its entire length to a 4-ft. by 2-ft. opening at the outlet end will discharge 86 per cent more water than a 2-ft. by 2-ft. by 30-ft. box culvert of uniform bore with a square cornered entrance, when both culverts are flowing full.

30 The 2-ft. by 2-ft. box culvert, 30 feet long, with a rounded lip entrance and flared on the two sides for its entire length to a 4-ft. by 2-ft. opening at the outlet end will discharge the same quantity of water as a 3.61-ft by 2-ft. by 30-ft. box culvert of uniform bore with a square cornered entrance, when both culverts are flowing full.

31 The following general discharge equations have been developed for concrete box culverts with straight endwall entrances when flowing full:

Box culverts with rounded lip entrances.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1.05+\frac{0.0045\ L}{R^{1.25}}}} \qquad (17)$$

Box culverts with square cornered entrances.

$$Q=\frac{A\ \sqrt{2g\ H}}{\sqrt{1+0.4\ R^{0.3}+\frac{0.0045\ L}{R^{1.25}}}} \qquad (18)$$

in which the same symbols are used as in the pipe culvert formulas and the term, R, is the mean hydraulic radius of the culvert in feet.

32 Rectangular concrete box culverts require more head to overcome friction than square concrete box culverts of the same area, and hence have a smaller carrying capacity provided the entrance losses (in head) are the same. The head lost in friction for culverts of the same area varies inversely with the hydraulic radius. The entrance losses, however, on the rectangular culverts tested are less than those on the square culverts of the same area and type of entrance. Since one culvert differs from another in capacity per square foot of area inversely in proportion to the square root of the sum of all head losses involved, it is possible for a rectangular culvert to have a slightly greater capacity than a square culvert, although the reverse is usually the case.

33 The chamfering of the corners of box culverts reduces the discharge of the culvert by an insignificant amount, an amount which is less in per cent than the corresponding reduction in culvert area produced by the chamfering.

A comparison of the results of the tests on the concrete box culverts with the results of the tests on the pipe culverts reveals the following facts:

34 A 24-inch concrete pipe culvert, 30 feet long, with beveled lip end upstream, carries 19 per cent less water than a 2-ft. by 2-ft. by 30-ft. concrete box culvert with square cornered entrance (when the two culverts are flowing full), but the concrete pipe culvert carries about 7 per cent more water per square foot of waterway than the box culvert.

35 A 24-inch corrugated-metal pipe culvert, 30 feet long, carries 57 per cent less water than a 2-ft. by 2-ft. by 30-ft. box culvert with square cornered entrance (when the two culverts are flowing full), and the metal pipe carries about 23 per cent less water per square foot of waterway than the box culvert.

36 A 27-inch vitrified-clay pipe culvert, 30 feet long, (containing approximately the same cross-sectional area as a 2-ft. by 2-ft. box culvert) will carry 7 per cent more water than the 2-ft. by 2-ft. by 30-ft. box culvert with square cornered entrance, when both culverts are flowing full.

37 The value of the entrance loss coefficient for a given type of entrance corner varies with the shape of the cross-section of the

culvert. That cross section having the greatest hydraulic radius for a given culvert area has also the greatest entrance loss coefficient. That is, the entrance loss coefficient is greater for a circular culvert than for one with a square section, and the coefficient for the square section is greater than that for the rectangular section.

38 The results on the various types of entrances and outlets have an important bearing on the design of suction and discharge pipes for drainage and irrigation pumping plants. Sluiceways under levees are hydraulically like road culverts. The data in this report will likewise be found directly applicable to many irrigation structures.

HISTORY

The comparative carrying capacity of culverts under highways is of great importance when the magnitude of the expenditures now being made by both the State and Federal Governments for permanent roads is considered.

The quantity of water that a culvert will discharge is directly proportional to the square root of the head and bears no relation to the grade at which the pipe is laid, if the pipe flows full, as it should at maximum capacity. The water in a culvert under these conditions does not act as does that flowing in an open ditch where the quantity of discharge is dependent upon the slope or grade of the water surface in the ditch, but in a culvert flowing full, the discharge depends upon the water pressure available to force the water through the opening and the culvert. In the case of a culvert, the water pressure which causes discharge is that furnished by the difference between the water levels at entrance and outlet. The depth of submergence of the culvert has no effect on the discharge so long as the difference of the water level at the two ends of the culvert remains the same.

The factors which affect the flow of water through short conduits such as culverts and sluiceways under levees are as follows:

1. The size and shape of the culvert.
2. The smoothness of the culvert walls.
3. The kind, size, and shape of the culvert entrance.
4. The shape of the culvert outlet.

Nearly thirty different formulas have been proposed for use in determining the run-off and waterways required for culverts. In practically all of these formulas the area of the waterway is given direct. Apparently no consideration has been given to the coefficient of roughness in the culvert or to the nature of the culvert entrance. Although it might appear that, since the amount of run-off is known only approximately, there is no necessity for considering these factors in the culvert, yet the great variation in them for culverts of various materials would seem to warrant some consideration. Most formulas contain a variable whose value depends upon the topography of the watershed tributary to the proposed culvert.

Of the various highway departments and railroads, apparently only the Pennsylvania Railroad engineers[1] use the well-known Kutter formula for determining the required area of waterway. They compute the volume of water reaching the site of the proposed culvert in a given time by the Burkli-Ziegler formula.

This formula is

$$q = c\, r \sqrt[4]{\frac{s}{a}}$$

in which q=the water reaching the culvert in cubic feet per second per acre.

r=the average cubic feet of rainfall per second per acre during heaviest rainfall.

s=the general grade of the drainage area in feet per thousand.

a=the area drained in acres.

c=a coefficient. For average areas, c=0.625.

Gilman and Chamberlain[2] state that the Burkli-Ziegler formula was brought to this country by Rudolph Hering in 1881.

Some engineers have not considered the coefficient of roughness in pipes or conduits of short lengths to be of much importance. This was perhaps natural and justifiable so long as the different materials used for culvert pipe did not differ greatly in roughness and hence in their frictional resistance to moving water. In re-

[1] "Determining Sizes of Culverts", O. L. Grover, *Public Roads*, vol. 1, No. 12, April, 1918, p. 39.

[2] "The Principal Formulas Proposed for Determining Run-off and Waterways for Culverts", *Engineering-Contracting*, vol. XXV, March 29, 1911, p. 366.

cent years, however, a new material, corrugated-metal, has come into extensive use for culvert pipe, forming a conduit whose surface obviously causes a greater frictional resistance to the flow of water than the other materials used, such as vitrified-clay, cast iron, concrete, and timber.

The formula most commonly used for computing the velocity of flow in open channels and pipes is

$$V=C\sqrt{Rs}$$

in which V=velocity in feet per second.

R=mean hydraulic radius, or cross-sectional area of flow divided by wetted perimeter, in feet.

s=the grade or slope in feet per foot of length.

C=a coefficient.

This formula was first proposed by a French engineer, Chezy, in 1775. Universal experience shows that the coefficient C varies with the hydraulic radius, the slope, and the amount of frictional resistance offered by the walls of the pipe. The measure of this frictional resistance is commonly called the coefficient of roughness or the roughness factor. Ganguillet and Kutter, two Swiss engineers, in 1869, derived an expression for computing the coefficient C in Chezy's formula based upon experimental data in open channels. Their formula takes into consideration the effect of the slope, the coefficient of roughness, and the hydraulic radius. This formula is so complicated that it is seldom used directly in hydraulic computations. Instead, diagrams and tables based on the formula are used almost exclusively by practicing engineers to obtain numerical results corresponding to the formula. Although numerous other formulas have been proposed, probably most engineers in English-speaking countries still use Kutter's formula.

Many tests have been made for determining the coefficient of roughness in concrete and vitrified-clay as well as in pipes of other materials, but comparatively few have been conducted on corrugated-metal pipe. Probably the first tests[3] on the flow of water in corrugated-metal pipe were made by Cone, Trimble and Jones in 1913. These tests were made on a semi-circular metal flume having

[3] "Frictional Resistance in Artificial Waterways", by V. M. Cone, R. E. Trimble, and P. S. Jones, *Colorado Agricultural Experimental Station Bulletin* No. 194, 1914, p. 9.

an arc length of 132 inches and lineal length of 1,745 feet. The coefficient of roughness *n* for use in Kutter's formula varied from 0.0196 to 0.027 depending upon whether the tests were measured on a tangent or a curve.

In 1917, the Division of Drainage Investigations, Bureau of Public Roads, U. S. Department of Agriculture, conducted at Arlington, Virginia, a series of experiments on the flow of water in two sizes of corrugated-metal pipe, 8 and 10 inches in diameter. The length of pipe tested was 200 feet. The Kutter coefficient of roughness *n* obtained for the pipe flowing full ranged from 0.017 to 0.021. A synopsis of these tests was published[4] in the Engineering News-Record.

In order to supply greatly needed additional data on the flow of water through short conduits such as pipe and box culverts, particularly of the larger diameters in the pipe culverts, the Bureau of Public Roads, U. S. Department of Agriculture and the State University of Iowa, have recently made a large number of tests of the carrying capacity of such conduits. The results of these tests are set forth in this report.

Pipe culverts under 12 inches in diameter are rarely installed, and but few under 15 inches are used. Concrete box culverts are seldom constructed smaller than 2-ft. by 2-ft. in cross-section. Culverts are usually laid at the same depth as the stream bed. To obtain a sufficient quantity of water under an adequate head to test fully sizes of culverts in actual use is beyond the capacity of most hydraulic laboratories, and finally the laboratory of the State University of Iowa was selected as the best available for the purpose. An agreement was entered into by the Bureau of Public Roads and the University to coöperate in the conduct of the tests.

The experiments were conducted by David L. Yarnell, Drainage Engineer, Bureau of Public Roads, and Floyd A. Nagler, Associate Professor of Mechanics and Hydraulics, State University of Iowa, under the direction of E. W. James, Chief, Division of Design, and S. H. McCrory, Chief, Division of Agricultural Engineering, Bureau of Public Roads. Sherman M. Woodward, Professor of Mechanics and Hydraulics, State University of Iowa, acted as consulting engineer for the investigation, making suggestions in the

[4] "The Coefficient of Roughness in Corrugated-Iron Pipe", D. L. Yarnell, *Engineering News-Record,* vol. 88, March 2, 1922, p. 352.

conduct of the experiments and collaborating in the preparation of the data and report.

The baffles, weir, derrick, assembling platform, and the 24-foot length of the 24-inch corrugated-metal pipe (See Pl. 1, A and B) were installed from August 7 to 21, 1922. The tests on the vitrified-clay and corrugated-metal pipe comprising 1139 separate experiments, were run from August 22 to November 4, 1922, or 64 working days. Of this time 21 days were spent in changing pipe and constructing the various types of entrances. The tests on the concrete pipe, 341 in all, were run from April 20 to May 29, 1923. The tables given later in this report contain the results of 1102 of the total number run. The remainder of the tests comprise a series run on the various pipes flowing partly full and are not included in this report.

The tests on the concrete box culverts consisting of 1821 tests were run from September 19, 1923 to December 3, 1924.

The following senior and graduate research assistants of the Department of Mechanics and Hydraulics, State University of Iowa, worked on the project: Edward F. Wilsey, James F. Phillips, Allen C. Rockwood, Verner R. Muth, H. J. Ajwani, W. A. Turner, G. E. Shafer, T. L. Herrick, Glen A. Rick, J. W. Hummer, A. S. Nesheim, J. W. Howe, G. N. Cox, G. H. Hickox, S. W. Hsu, P. Y. Lin, and H. D. Brockman. Professors F. E. Holmes, A. W. Volkmer, and D. D. Curtis also assisted on the project.

County engineers A. F. Fisher and G. M. Griffith, of Johnson County, Iowa, furnished the corrugated-metal pipe used in these tests. The concrete and vitrified-clay pipe were purchased by the Bureau of Public Roads. The concrete box culverts were built in the testing canal and destroyed after being tested.

SCOPE OF THE INVESTIGATION

A total of 1,480 tests on concrete, vitrified-clay, and corrugated-metal pipe culverts and 1,821 tests on concrete box culverts were made with the culverts flowing partly full and full, both with a free and submerged outlet. The sizes of each kind of pipe culvert tested were 12, 18, 24, and 30 inches in diameter. To determine the effect of the length of the culvert on the flow, the 24-inch pipe of the three kinds of material was tested in three lengths: namely, 24, 30, and 36 feet. The other sizes were tested in the 30 foot length only. The concrete box culverts tested consisted of the following sizes: 2-ft. by 2-ft., 3-ft. by 3-ft., 4-ft. by 4-ft., 4-ft. by 3-ft., 4-ft. by 2¼-ft., 4-ft. by 2-ft., 4-ft. by 1-ft., and 4-ft. by ½-ft. The 2-ft. by 2-ft. and 3-ft. by 3-ft. sizes were tested in three lengths, namely, 24, 30, and 36 feet. The other sizes were tested in the 36 foot length only.

Since the highway or drainage engineer is interested principally in the maximum discharge capacity of conduits, only the tests for the pipe culverts flowing full, 1,102 in all, are included in this report. In all, 341 tests were made on the concrete pipe, 668 tests on the vitrified-clay pipe, and 471 tests on the corrugated-metal pipe, of which this report contains the results of 274 tests on the concrete pipe, 479 tests on the vitrified-clay pipe, and 349 tests on the corrugated-metal pipe. A total of 1,248 tests for the concrete box culverts flowing full are also included in this report. So far as the writers know, these are the first hydraulic tests ever made on square and rectangular-shaped conduits.

It has been demonstrated that in conduits of short lengths, the loss of head at the entrance of the conduit is an important factor. Although many tests have been made on small orifices acting under both low and high heads, few tests have been made on large circular or rectangular orifices acting under low heads. In culverts these latter conditions prevail. For the purpose of studying the effect of various types of entrance on reducing the entrance loss several types of entrances were used. These included all of the standard types recommended by the Bureau of Public Roads which consist of the straight end headwall, wingwalls set at 45 degrees to the pipe line, and the U-type wingwall. The effect of varying the height of the wingwall was also tested. In addition to these entrances a study was made of the effect on the flow through pipe culverts constructed without any headwalls. This was accomplished by projecting the entrance end of the pipe for some distance through the headwall.

The concrete box culverts were all tested with the straight end headwall only. However, the effect on discharge of rounding, beveling, or squaring the entrance corner was also investigated for many sizes.

The maximum range of head obtained on the pipe culverts for the different sizes tested varied from 1.05 feet on the 30-inch clay pipe to 3.29 feet on the 12-inch clay pipe. A maximum of 180 cubic feet of water per second was passed through the largest culvert installed in this investigation.

DESCRIPTION OF EXPERIMENTAL PLANT

Hydraulic Laboratory

The hydraulic laboratory of the State University of Iowa[5] is located on the west bank of the Iowa River south of the University dam. The laboratory, built in 1919, consists of three main parts; the testing canal, the basin, and the tail race. The canal (Pl. I), built of concrete, is 130 feet long, 10 feet wide and 10 feet deep. At the upstream end of the canal at the point where it joins with the end of the dam is a wooden gate 10 feet wide by 12 feet deep. This gate is regulated by a hand-operated hoist. Recesses (Pl. I, A) were built in the walls of the canal at intervals of 25 feet for use in building wooden bulkheads when needed in experimental work. Every 10 feet along the canal and 1 foot above its bottom, 2-inch pipes were placed transversely through the east wall for the attachment of piezometer tubes. At the downstream end, the canal joins a basin 22 feet wide by 30 feet long which can be easily subdivided into rectangular forebays for the installation of weirs and other hydraulic apparatus.

Weirs

For use in measuring the amount of water flowing through the culverts, a sharp crested rectangular weir of the suppressed type (Pl. II) was constructed. The weir bulkhead (Fig. 1) was built of nine 6x8-inch timbers of select common Douglas fir. Grooves 7/8 inch wide by 1 3/8 inches deep were plowed on each edge of these timbers, into which 7/8 inch by 2 3/4 inch clear white pine splines were placed as the bulkhead was built. Splines of clear white pine were used for making the joints water-tight because of the great amount of swelling obtained when wood of this nature becomes watersoaked. The timbers were set in the recesses originally built in the walls of the canal, 61 feet from the headgate for the pipe culvert tests. The bottom timber of the bulkhead was secured to the concrete floor of the flume by two 3/4 inch bolts, 12 inches long.

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5 "State University of Iowa's New Hydraulic Laboratory", by Stuart Sims, *Engineering News-Record*, vol. 85, July 15, 1920, p. 124.

Two ¾ inch bolts, 44 inches long, bound the remaining seven timbers to the bottom piece. Two ¾ inch bolts, 10 inches long, held the top timber next to the lower piece. By means of the adjusting nuts on the top of these two bolts the weir crest was maintained level throughout the investigation.

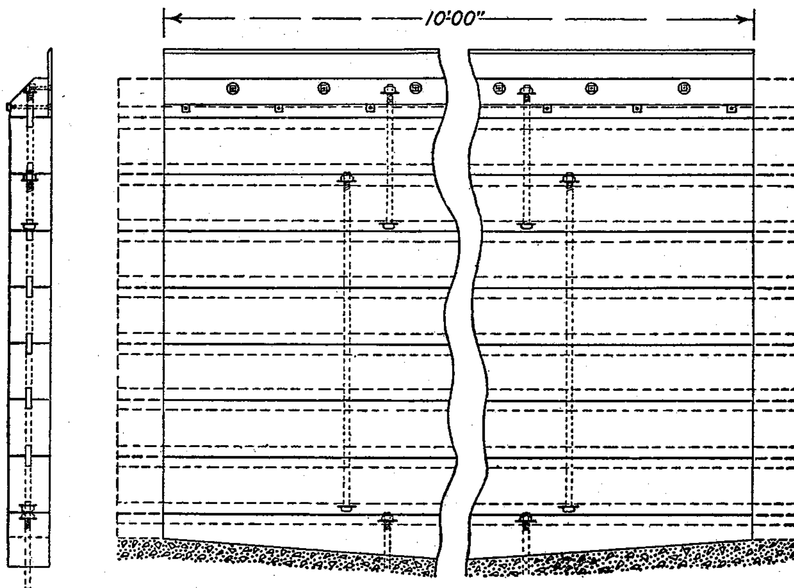


Fig. 1. Details of construction of standard weir used for measuring quantity of flow

For the box culvert tests the weir was located at the outlet gate of the laboratory in order to measure larger quantities of water.

The weir plate (Fig. 2), made of boiler steel, measured 9 inches wide by ⅜ inch thick by 10 feet long. A brass strip, 1 ¼ inches wide, ⅛ inch thick, was inserted along the upper edge of this plate by means of 3/16 by 3/8 inch brass screws with countersunk heads. All cracks in the countersunk holes and slots in screwheads were filled with solder. The back face of the plate and the upper edge of the brass strip were planed and finished true and straight. The downstream edge of the weir crest was planed on a bevel of 35 degrees from the vertical making the lip of the crest entirely of brass 1/16 inch wide. The brass strip was used for a crest since this metal would not corrode easily, thus eliminating possible error

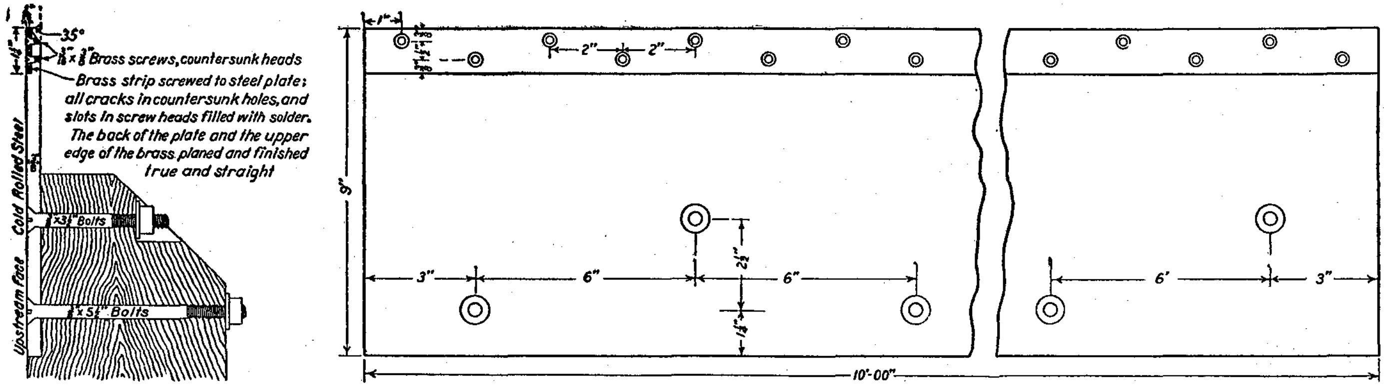


Fig. 2. Details of construction of weir plate

in the weir discharge due to unexpected roughening of the crest. The weir plate was set flush with the upstream face of the timber bulkhead, and fastened to it by means of bolts whose heads were counter sunk in the back of the steel plate. The entire upstream side of the bulkhead was planed and finished smooth so as to offer little resistance to the upward filaments of water flowing over the weir. The crest was set an elevation of 5.33 feet above the bottom of the canal at either side and 5.84 feet above the bottom of the canal at its center for the pipe culvert tests, and the crest was 8.028 feet above the bottom of the turbine pit for the box culvert tests.

The length of the weir crest used in the experiments on the box culverts and the 24 and 30-inch pipe culverts was 10 feet. Since, for the smaller pipe culverts, it was necessary to obtain smaller quantities of water than that secured on the 10-foot weir using the lowest head consistent with accuracy, a false wall was constructed upstream from the weir bulkhead for a distance of 36 feet thus making possible the use of a weir with a crest of 5 feet (Pl. II, A).

The weir plate was so placed that the nappe of the weir cut free and was fully aerated by means of the recesses in the walls of the flume at either end of the crest.

The quantity of water passing over the weir was regulated by raising or lowering the headgate (Pl. I, B) at the upper end of the canal. Since the water entered the canal at a very high velocity, a submerged baffle (Fig. 3) 4 feet high was built immediately below the headgate on the bottom of the canal. This baffle consisted of three 2 by 12-inch planks spaced 6 inches apart. Ten feet below the headgate, a baffle consisting of 2 by 4-inch by 10-foot timbers placed horizontally and spaced ⅝ inch apart, was constructed. One foot from this baffle and immediately below it, another baffle (Fig. 3) consisting of the same size timbers and spacing was built. In this baffle, the timbers were placed vertically. Two feet in front of this second baffle, still another baffle was constructed. This baffle consisted of 1 by 8-inch by 8-foot boards placed in a vertical position and spaced ¼ inch apart. Experience proved that all of these baffles were needed to produce a fairly uniform velocity distribution in the water approaching the weir and a smooth flow over the crest.

To avoid commotion of the water in the canal below the weir as it entered the culvert pipe two baffles were installed (Fig 3) in

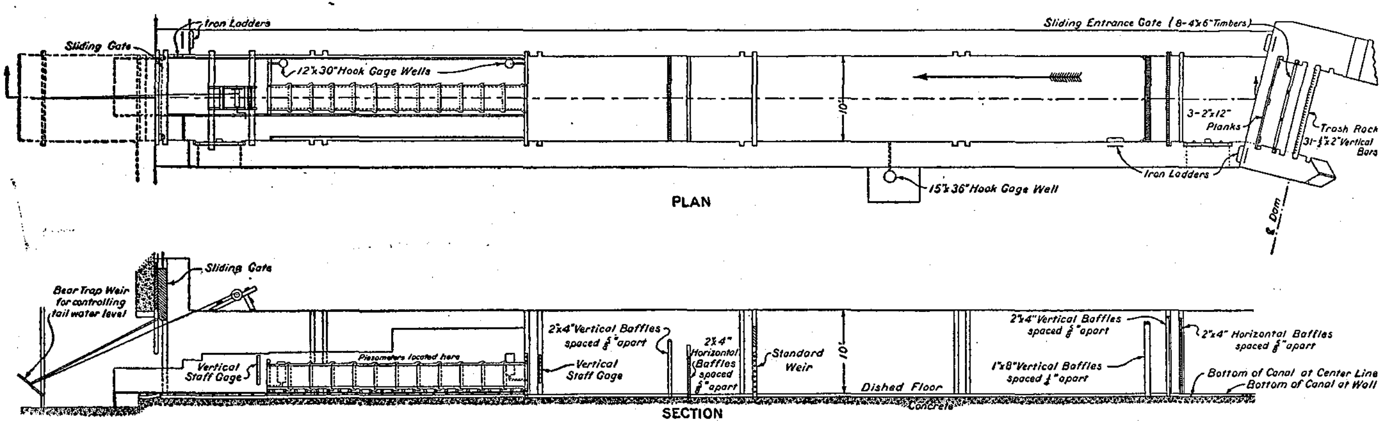


Fig. 3. Plan and section through testing canal showing relative positions of sliding entrance gate used for control of water supply, baffles, standard measuring weir, culvert pipe under test, hook gages, staff gages, and bear trap weir for controlling tail water level.

this section. One baffle located 7.7 feet from the weir consisted of 2 by 4 inch timbers, 10 feet long, placed horizontally. The spacing between the two timbers at the maximum flow level was ⅝ inch, and this spacing was increased by successive amounts of 1/32 inch until at the bottom of the canal the last spacing measured 21/16 inches. The other baffle, located 10 feet from the weir, was built of 2 by 4-inch timbers, 8 feet high. The timbers were placed vertically and spaced ⅝ inch apart. These baffles had the desired effect of stilling the turbulence of the water before it entered the pipe.

For the box culvert tests a wooden partition wall was constructed lengthwise of the turbine pit of the laboratory so as to obtain a weir channel 10 feet wide. Two baffles consisting of 2 by 6 inch timbers with varying spacing were built about 32 feet upstream from the weir.

To determine the discharge over the weir, Bazin's formula

$$Q = \left[0.405 + \frac{0.00984}{H}\right] \left[1 + 0.55 \left(\frac{H}{P+H}\right)^2 \right] b\sqrt{2g}\ H^{1.5}$$

was used in all computations. In this formula, Q=discharge in cubic feet per second, H=head in feet on the weir, b=length in feet of crest, P=height in feet of weir crest above the bottom of the flume, g=acceleration of gravity=32.16 feet per second, per second. The quantity in the first bracket represents a coefficient and the quantity in the second bracket is the correction for the velocity of approach to the weir.

A calibration of the weir for low heads showed that for heads of 0.3 foot, the Bazin formula gave discharges about 3 per cent greater than volumetric measurement; for heads of 0.40 feet the formula gave discharges about 0.8 of one per cent greater; and for higher heads the formula gave discharges in close agreement with volumetric measurement.

A bear-trap weir 4 feet high and located 18 feet down stream from the outlet of the 36-foot culvert, was used to submerge the outlet of the pipe. This weir was hung on hinges and was regulated by means of a block and tackle attached to a windlass mounted on a platform built over the canal.

Hook Gages

Hook gages were used in order to measure with accuracy the total head under which the culvert and weir were discharging. These were of the all-metal Gurley type, with a 45-degree point.

In the pipe culvert tests, hook gage No. 1 (Pl. I, A) was located on the east side of the canal 15.77 feet from the weir. The gage was bolted to a heavy block which was securely fastened to the outer side of the concrete wall of the canal. A 1 ½ inch pipe connected the opening in the wall of the canal, 10 ¾ inches above the bottom, to a 15-inch by 36-inch cylindrical galvanized stilling-tank placed immediately under the hook gage. This opening corresponded quite closely to that used by Bazin in his noted weir experiments; namely 16.35 feet from the weir and 6 inches above the floor of the canal.

Hook gage No. 2 (Pl. IV) was located near the upper end of the pipe line being tested. This gage was used to obtain the elevation of the surface of the water in the canal at the entrance to the pipe. The gage was bolted to a block which was secured to the west wall of the canal. A 1 ½ inch pipe led from the opening in the headwall of the culvert being tested at a point 8 inches from the wall of the canal to another galvanized stilling well placed directly under the gage. A second hook gage, No. 2-A, installed at the culvert entrance, was used to check the readings on the upstream water surface elevation. Its stilling well was connected by means of a 1 ½ inch pipe to an opening in the culvert headwall on the opposite side of the testing canal from Gage No. 2 at a distance of 8 inches from the wall of the canal.

Hook gage No. 3 (Pl. IV) was placed near the bulkhead at the outlet end of the 24-foot length of pipe. It was mounted similarly to gage No. 2. This gage was installed to measure the water level in the canal at the outlet.

Hook gage No. 4 (Pl. IV) was located at the outlet of the 30-foot pipe.

Hook gage No. 5 (Pl. IV) was located at the outlet of the 36-foot pipe.

Staff gages were also set on the canal wall next to the culvert entrance and outlet and opposite the weir hook gage. These were read as checks against possible errors in reading the hook gage scales.

Levels were taken on all hook gages and the weir crest on every day on which tests were made, readings being recorded to the nearest 0.001 foot.

In addition to this check on the measurements of the water stage, a determination of the elevation of the weir crest as compared to the weir hook gage was made as follows: After lowering the water in the canal slightly below the crest of the weir a second hook gage was placed inside the canal about 6 inches from the weir. By means of a level, the readings of this hook gage when the point of the hook was at the elevation of the weir crest was determined. The hook was then lowered and simultaneous readings were made on this hook gage and the weir hook gage outside the canal. This procedure established a relation between the gages and the weir crest. The results of this method checked those obtained with the level within 0.001 feet.

Piezometers and Piezometer Tubes

In order to measure the depth of flow in the culvert when flowing partly full, as well as to secure the hydraulic gradient when the outlet of the pipe was submerged, glass piezometer tubes fastened to enameled graduated staff gages (Pl. IV, A) were placed on the side of the canal and connected to the under side of the culvert pipe. At the mid point of each joint of vitrified-clay pipe a small hole was drilled through the wall and a 1/4 inch iron nipple 3½ inches long, was inserted, care being taken that the tube did not project inside the tile bore. This tube was set in cement (Pl. III, A) and any unevenness on the inside wall of the pipe at the entrance of the tube was removed by coating the surface with a little cement. This method of inserting the tube was proved the best by Hiram F. Mills from a study of the results of some 6,000 observations on various piezometer connections, (Proceedings of the American Academy of Arts and Sciences, New Series, Vol. VI, whole Series Vol. XIV, Boston, 1879, p. 26). Mills found that if the edge of the orifice is in the plane of the side of the conduit, with the bore of the tube normal to this plane, the piezometer column indicates the true height of the water surface in an open conduit, or the static pressure in a closed conduit. Certain exceptions to this conclusion were observed by the writers when investigating the hydraulic gradient near the outlet of culverts discharging freely into the air. When the water in the pipe had sufficient velocity so that the jet filled the entire pipe clear to the outlet end, piezometers connected to the pipe near the outlet indicated the hydraulic gradient at the point of attachment and not necessarily the average gradient for the pipe. When the flow was decreased so that the pipe flowed full for the major portion of its length but a drop-down curve with a free water surface was formed near the outlet, piezometer readings near the outlet were always lower than the water surface in the pipe, the difference being greater the greater the depth to which the piezometer opening was submerged.

Since the vitrified-clay pipe were in lengths of 30 inches, the spacing between the piezometer connections was 30 inches. However, in the upstream length of clay pipe, forming the entrance to the culvert, two piezometer connections (Pl. III, A) were made; one, 24 inches from the piezometer connection in the second clay pipe, and another 12 inches in front of this connection.

The piezometer connections in the concrete pipe were made in a manner similar to that used in the clay pipe.

In making the piezometer connections in the corrugated-metal pipe spacings were used which were as nearly as possible like those of the concrete and clay pipe. Holes were drilled in the surface of the outer corrugation on the outside of the pipe and 1/4 inch iron nipples, 3½ inches long, were inserted through these holes until the nipples were flush with the inside bore of the pipe. The space in the corrugation around the nipple inside the pipe was filled with solder (Pl. III, B) thus forming a plane surface of some extent on all sides of the orifice. This type of piezometer connection was considered the best for obtaining the pressure of the water in corrugated-metal pipe after experiments on several types of piezometer connections in this kind of pipe had been made.

The culvert pipe were turned so as to have the piezometer nipples about 8 inches above the inside bottom of the pipe.

The piezometer connections in the box culverts were made on the side of the culvert along the bottom edge. Steel plates to which nipples were soldered were placed along the edge with the face of the plate forming the inside surface of the culvert. Some 50 such piezometer connections were made in each 30-foot box culverts, 12 of them being in the first 8 feet from the culvert entrance.

Connections were made by rubber tubing to 1-inch glass tubes 3 feet long, attached to white enameled gage staffs secured to the side of the canal. These gage staffs, 3.3 feet long, were graduated with divisions of 0.02 foot, and the markings were such that they could easily be read with little chance of error. With glass tubes of 1-inch bore, the effect of capillarity is negligible and need not be considered.

Construction of the Culverts

The pipes were supported on 4 by 6-inch blocks (Pl. IV, B) resting on a level floor built 14 inches above the bottom of the canal. For the 24-inch clay pipe special cradles which fitted the outer circumference of the pipe were made, but such cradles were found to be no better than straight supporting blocks.

The entrance to the culvert pipe was located 26.8 feet from the weir. The bulkhead or headwall forming the entrance consisted of 4 by 6 inch timbers of select common Douglas fir. Grooves 3/4 inch wide and 7/8 inch deep were plowed on each edge of these timbers, into which 3/4 inch by 1 3/4 inch clear white pine splines were placed as the headwall was built. The timbers were set in the recesses originally built in the walls of the canal. The joints along the ends of the timbers and the wall of the canal were caulked with oakum. The cracks around the circumference of each pipe at its connection with the headwall were caulked with oakum and then coated with melted pine pitch in order to obtain a water-tight connection. After some experience three men in three hours could saw out the required opening for the pipe to be tested and install this headwall. The upstream surfaces of the headwalls for the various pipes tested were generally coated with melted pine pitch. This surface appears to be rough (See Pl. VII, A, B, C and D), but in reality is quite smooth. The rough appearance in the pictures is due to light reflection on the smooth surface exaggerating the high spots and hollows in much the same manner that an automobile headlight shining on a slightly rough road will make the surface look like a washboard.

To secure water-tight joints between adjacent lengths of corrugated-metal pipe strands of oakum were wrapped around the ends of each section in two different corrugations and the collar was attached and drawn up tight with bolts. The joints were then filled with melted pitch which, when solidified, gave a water-tight joint. The seams of the individual pipe were soldered.

The connection with the lower headwall was made similar to that with the upper headwall. The type of construction was identical. Experience showed that the time of 4 men for 3 hours was required to remove this headwall, attach six feet of pipe, and reinstall the bulkhead for testing a longer length of pipe.

The joints of the concrete pipe were made water-tight by placing cement mortar in the joints and allowing it to set.

The joints of the vitrified-clay pipe were made water-tight by tamping two or three strands of oakum in the bell around the circumference of the pipe. The remaining space in the bell was filled with cement mortar. It was necessary to allow the mortar to set over night to obtain sufficient strength to resist the pressure of the water.

In testing the various conical entrances each cone was inserted in the inlet end of the culvert pipe, and a false headwall of 1-inch boards was constructed flush with its upstream end. The various wing walls tested were connected directly to the main headwall at the inlet end of the culvert.

For concrete box culverts the concrete floor of each culvert was built first, reinforcing wire being left projecting up along the edges. A wooden frame whose outside dimensions were the same as the inside dimensions of the culvert to be tested was built and placed on the culvert floor. The outside forms for the walls were then constructed and the concrete was placed in the forms after all piezometer connections had been properly set. After a culvert was tested it was removed in order to permit the construction of a culvert of another size.

The 4-ft. by 4-ft. culvert was built somewhat differently from the 2-ft. by 2-ft. and the 3-ft. by 3-ft. culverts in that the top slab was constructed separate from the walls. This top slab was supported by means of threaded rods from 4 by 6-inch caps resting on the side walls. Any height of a culvert could be obtained by lowering the top slab.

The 2-ft. by 2-ft. and 3-ft. by 3-ft. culverts were also constructed with flared outlets (See Pl. VI, B) in order that the efficiency of this device might be measured. A box culvert, 2-ft. by 2-ft. at the entrance end flared on its two sides to a 4-ft. by 2-ft. opening at its outlet end was built and tested.

Description of Pipe and Box Culverts Used

Although in actual practice the nominal or commercial size of culvert pipe is always used in computing the cross-sectional area, to determine accurately the retardation factors it is essential to know the correct average diameter of all pipe tested. For this purpose two diameters at right angles to each other were measured at each end of every pipe used.

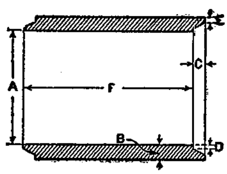


Fig. 4. Longitudinal section of concrete pipe

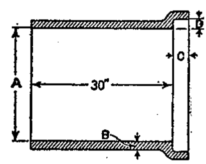


Fig. 5. Longitudinal section of vitrified-clay pipe

Table 1 gives the dimensions and cross-sectional areas of each kind and size of pipe tested. This table shows that the concrete and the corrugated-metal pipe measured practically the nominal or commercial size, while the vitrified-clay pipe generally were a little larger than the nominal size. A longitudinal section of the concrete pipe tested is given in text figure 4, and a longitudinal section of the vitrified-clay pipe tested is given in text figure 5. The dimensions of the beveled lip of the concrete pipe are given in Table 2 and the dimensions of the bell of the clay pipe are given in Table 3.

Table 1—Dimensions and areas of the three kinds of pipe used

1	2	3	4	5	6	7	8	9	10	11	12	13
Kind of pipe	Size of pipe	Number of pieces measured	Average measured diameter	Area computed from column 2	Area computed from column 4	Variation between column 5 and 6	Smallest measured diameter	Diameter normal to diameter column 8	Area* using diameters columns 8 and 9	Largest measured diameter	Diameter normal to diameter in column 11	Area* using diameters in columns 11 and 12
	Inches		Feet	Sq. Ft.	Sq. Ft.	Percent	Feet	Feet	Sq. Ft.	Feet	Feet	Sq. Ft.
Concrete	12	15	0.999	0.785	0.784	—0.13	0.988	0.990	0.768	1.005	1.005	0.793
"	18	15	1.501	1.767	1.770	+0.17	1.495	1.495	1.755	1.520	1.500	1.791
"	24	8	1.993	3.142	3.120	—0.70	1.970	2.000	3.095	2.020	1.990	3.157
"	24	10	1.994	3.142	3.123	—0.60	1.970	2.000	3.095	2.020	1.990	3.157
"	24	12	1.994	3.142	3.123	—0.60	1.960	2.000	3.079	2.020	1.990	3.157
"	30	10	2.495	4.909	4.889	—0.41	2.480	2.495	4.860	2.505	2.495	4.909
Vitrified-Clay	12	12	1.015	0.785	0.809	+3.06	0.980	1.045	0.804	1.050	1.010	0.833
" "	18	12	1.510	1.767	1.791	+1.36	1.480	1.540	1.790	1.540	1.480	1.790
" "	24	10	2.061	3.142	3.336	+6.17	2.010	2.100	3.315	2.100	2.010	3.315
" "	24	12	2.063	3.142	3.343	+6.39	2.010	2.100	3.315	2.100	2.010	3.315
" "	24	15	2.061	3.142	3.336	+6.17	2.010	2.100	3.315	2.100	2.010	3.315
" "	30	12	2.465	4.909	4.772	—2.79	2.420	2.490	4.732	2.500	2.440	4.790
Corrugated-metal	12	4	0.988	0.785	0.767	—2.29	0.962	0.991	0.749	1.012	0.985	0.783
" "	18	3	1.502	1.767	1.772	+0.28	1.492	1.502	1.760	1.515	1.502	1.787
" "	24	2	2.002	3.142	3.148	+0.19	2.000	2.000	3.142	2.010	2.005	3.166
" "	24	3	2.002	3.142	3.148	+0.19	1.995	2.001	3.135	2.010	2.000	3.157
" "	24	4	2.001	3.142	3.144	+0.06	1.965	2.015	3.110	2.030	1.980	3.156
" "	30	3	2.496	4.909	4.893	—0.33	2.482	2.500	4.873	2.505	2.490	4.898

* Computed as an ellipse.

Note: The 12-inch and 18-inch concrete pipe were in 2-foot lengths. The 24-inch and 30-inch concrete pipe were in 3-foot lengths.

The 12, 18, and 30-inch corrugated-metal pipe culvert each consisted of three 8-foot lengths and one 6-foot length. The 24-foot culvert of 24-inch corrugated-metal pipe consisted of three 8-foot lengths. For each successive increase in length a 6-foot section was added. The vitrified-clay pipe were all in 30-inch lengths.

The distance from center to center of corrugations of the corrugated-metal pipe used in these tests was about 2¾ inches and the depth of the corrugations ½ inch.

Although the inside forms for the box culverts were constructed to the desired dimensions of the culvert to be tested, some variation

Table 2—Dimensions of beveled lip of concrete pipe

A Inches	B Feet	C Feet	D Feet	E Feet	F Feet
12	0.167	0.13	0.06	0.05	2.00
18	0.23	0.21	0.06	0.06	2.00
24	0.25	0.21	0.06	0.08	3.00
30	0.29	0.25	0.09	0.10	3.00

Table 3—Dimensions of bells of vitrified clay pipe

A Inches	B Feet	C Feet	D Feet
12	0.09	0.20	0.12
18	0.11	0.24	0.15
24	0.13	0.28	0.18
30	0.20	0.34	0.29

from the true dimensions naturally occurred due to swelling of the forms. Therefore, from four to eight measurements, both horizontal and vertical, were taken at 10-foot intervals lengthwise of the culvert. These readings were averaged in order to obtain the culvert dimensions used in the computations.

The walls for the 2-ft. by 2-ft. culvert were 4 inches thick, for the 3-ft. by 3-ft. culvert, 5 inches thick, for the culverts 4 feet wide, 6 inches thick. The radius of curvature for the rounded lip entrance to the box culverts was the same as the thickness of the culvert walls.

HYDRAULIC ELEMENTS INVOLVED IN DETERMINING CAPACITY OF PIPE CULVERTS

In order to determine the coefficient of roughness in the culvert pipe and the formula for the carrying capacity of a culvert of any length, the magnitude of each hydraulic element involved in the actual discharge of the culvert must be obtained by experiment. The elements to be determined are: (1) the mean velocity of the water in the culvert; (2) the hydraulic gradient showing the friction losses in the culvert; (3) the head lost at the culvert entrance.

Mean Velocity

The quantity of water passing through the culvert per second was measured by means of the weir. The mean velocity of the water flowing through the culvert was obtained by dividing this quantity by the average area of the cross-section of the culvert.

Hydraulic Gradient

The hydraulic gradient was obtained by means of piezometers. Tests were made on the pipe both with a free and with a submerged outlet. When water flows through any culvert, the hydraulic gradient takes the slope required to overcome the retarding effect of the friction acting along the walls of the pipe and between the water filaments.

The Head Lost at the Culvert Entrance

The head lost at the culvert entrance is an important factor in the discharge of a culvert and varies greatly with the type of entrance used. This loss in head was determined by first obtaining the entrance drop, which is the difference between the elevation of the free water surface at the culvert inlet and the elevation of the hydraulic gradient at the upper end of the pipe as determined from piezometer readings. From the entrance drop the velocity head is subtracted to give the loss of head at the entrance.

METHODS OF CONDUCTING TESTS

Tests on each culvert were begun with a head of 0.30 feet of water discharging over the measuring weir, followed by experiments with successive increases of 0.10 feet in head on the weir, until the maximum quantity was obtained which would flow through the pipe without overtopping the bulkhead at the entrance to the culvert. To secure several different tests for each head on the measuring weir the following outflow conditions were imposed by means of the bear-trap weir: (1) outlet discharging freely into air; (2) water surface at outlet raised to the middle of the pipe; (3) water surface at outlet brought up to 6 inches below the top of the pipe; (4) water surface at outlet at top of pipe; (5) water surface at outlet raised above top of pipe by successive increases of 6 inches until the maximum possible submergence was secured.

In obtaining a series of tests for different stages with the outlet submerged and with a constant head on the weir, a set of runs was secured with a uniform discharge and with hydraulic gradients approximately parallel, in which the hydraulic elements previously mentioned should check.

Since, in testing the various entrance attachments, the aim was to obtain data on the efficiency of the different types used, only submerged runs were secured. In this case, the first test was begun with a head of 0.40 feet on the weir and was followed by successive increases of 0.1 foot until the maximum quantity was obtained. For each head, three different depths of submergence were taken.

An electric bell was placed directly over the culvert being tested and was connected with another bell placed on the observation platform at the weir hook gage. The push button for operating these bells was located at hook gage No. 2 at the entrance to the culvert pipe.

To secure the data necessary for determining the hydraulic elements for each kind of pipe tested, five men were required, to act in the following capacities:

1 Observer of piezometers.

2 Observer at hook-gage No. 1 located at the weir.

3 Observer at hook-gage No. 2 located at the culvert entrance.

4 Observer at hook-gage No. 3 located at the culvert outlet.

5 Man for operating headgate and bear-trap weir.

Duties of the Observers—1 The observer of the piezometers, on the signal of starting a test, read a staff gage placed in the entrance chamber to the pipe and then recorded the reading for each piezometer beginning at the entrance of the pipe and working to the outlet. After obtaining one set of readings on the piezometers he went to hook-gage No. 1 at the weir and obtained a single reading on this gage. He then proceeded to hook-gage No. 3 at the culvert outlet and obtained a single reading on this gage. As he returned to the entrance of the culvert he recorded another set of piezometer readings independent of the first set and in the reverse order of the first readings. After completing the second set, he again read the staff gage at the pipe entrance and obtained a single reading on hook-gage No. 2.

2 The observer of hook-gage No. 1 directed the man operating the head-gate to raise or lower the gate until the desired head

on the weir was obtained. He then motioned the man at the head-gate to return to the windlass at the bear-trap weir. He read the gage whenever signals were given.

3 The observer at hook-gage No. 2 read the hook-gage located at the entrance to the pipe culvert and operated the push button for the bells when readings were to be taken. After the head-gate was correctly adjusted, he watched the water stage at the culvert entrance. When the stage of the water had become steady he signalled by means of two bells to all observers to get ready to begin reading. Ten seconds later one bell gave the time to read, and signalled thereafter every 30 seconds until ten consecutive readings had been secured. Three bells denoted the end of a test.

4 The observer at hook-gage No. 3 read the hook-gage located at the outlet of the culvert when signalled by the bell to read. He also secured a reading on a staff gage located in the canal at the pipe outlet in order to obtain a check on the elevation of the tail water surface at the outlet. Whenever the culvert was acting under a high head with the outlet free, the water surface in the pipe at its outlet was somewhat higher than the tail water. Thus, whenever this condition prevailed, this observer recorded the distance of the water surface below the inside top of the pipe at the outlet. He also recorded the temperature of the water. After a test was completed he would direct the man operating the bear-trap weir to raise the weir until the desired stage at the outlet was secured.

5 The man operating the headgate and the bear-trap weir acted as directed by the observer at hook-gage No. 1 whenever the head on the weir was being changed. When the desired head was secured he would return to the windlass of the bear-trap weir under the direction of the observer at hook-gage No. 3 at the culvert outlet.

From start to finish, a single test progressed as follows:

1 The headgate was adjusted to obtain the required head on the weir.

2 The stage of the water surface at the entrance of the culvert was watched to determine when it became steady.

3 The test was then ready to begin. Tests were numbered consecutively. The observer at hook-gage No. 2 gave the time of starting to the observer of hook-gage No. 3 and to the observer

of piezometers, both of whom recorded this time above the number of the test on their log charts. Two short bells announced that a test was to begin.

4 Ten seconds later, one short bell gave the time to take the first reading.

5 One bell every 30 seconds signalled simultaneous readings on all the hook-gages, during which period the piezometers were read.

6 Readings were continued until ten consecutive readings on each hook-gage were secured.

7 Three bells denoted the close of a test.

8 The observer at hook-gage No. 3 directed the operator to raise the bear-trap weir for the next test.

In having the observer of the piezometer secure single readings on all hook gages, a check was obtained on the readings of these gages. Error in reading a gage is much more apt to occur in the reading of the 0.1 foot than in either the 0.01 or the 0.001 foot. No check was necessary on the readings of the piezometers as the observer could not possibly retain all of the readings for the first set (15 to 30 in number depending upon the length of the pipe) in his mind when taking the second set.

For the purpose of determining whether there was a lagging effect in the discharge through the headgate when raising it small amounts, a set of runs was secured with the headgate wide open for the initial test, followed by experiments with successive decreases of about 0.05 of a foot in head on the weir. This series is given in table 45, descending series. The tests in table 44, ascending series, were conducted in the usual manner. The discharge equations, described later, developed from these two sets, see table 7, are practically the same.

METHODS EMPLOYED IN COMPUTATIONS

During a test each observer entered his readings on a loose sheet. Each test was numbered and at the close of a set of runs on a pipe of a certain size, kind, and length, the data sheets of the various observers were collected and fastened together. Another sheet showing the elevation of the inside top of the pipe as compared with the zeros of the piezometers, the spacing of the piezometer connections, as well as the data on the levels taken on the weir and various hook gages, was attached to the collected set of notes. Thus a complete set of runs was made ready for computing.

As soon as possible after the conclusion of each test the average values of all the different readings were plotted on a diagram which was, in effect, a condensed profile of the pipe under test (See Pl. XIX, Figs. 1 to 17). Near the right margin of each diagram is shown the head water level above the entrance to the pipe; at the left margin similarly is shown the tail water level at the outlet of the culvert. Along the pipe in their proper respective positions are shown the elevations of the water in the various piezometer tubes. The diagram shows then at once the amount of submergence of each end of the culvert pipe and the total difference in water level between the bays at the two ends of the pipe.

Through the points representing the water level in the various piezometer tubes an average straight line was drawn, as shown on the diagrams (See Pl. XIX). This line represents the hydraulic gradient in the pipe. The diagrams show strikingly that, while at the outlet end of a submerged pipe the hydraulic gradient nearly meets the tail water level—frequently slightly below it—on the other hand, at the entrance end of the pipe the hydraulic gradient is generally far below the head water level. The slope of the hydraulic gradient indicates the friction loss within the pipe.

The hydraulic elements for each test as well as the number of the test were placed directly on each computation sheet. A sample of a portion of a sheet is shown at the bottom of Plate XIX.

The items included in the table were as follows: (1) the test number; (2) the head on the weir as observed during the test, or H, in feet; (3) the discharge of the weir for this head, or Q, in cubic feet per second; (4) the cross-sectional area of flow in square feet, or A, (equals area of pipe when flowing full); (5) the mean velocity of the water flowing through the pipe, in feet per second, or $V=\frac{Q}{A}$; (6) the velocity head in the pipe, or $\frac{V^2}{2g}$; (7) the total head on the pipe during the test obtained as explained in the next paragraph, in feet; (8) the friction loss; (9) the ratio of friction loss to velocity head; (10) the entrance drop into the pipe, in feet; (11) the head lost at the culvert entrance for the particular type of entrance used, in feet; (12) the ratio of the head lost at the culvert entrance to velocity head; (13) the ratio of the total head to the velocity head; (14) the sum of the entrance loss ratio and the friction loss ratio; (15) the mean hydraulic radius for the pipe, or R, in feet; (16) the hydraulic gradient or slope, s; (17) the coefficient, C, in Chezy's formula; (18) the coefficient, n, for Kutter's formula; (19) the coefficient, n', for Manning's formula; (20) the height of the water surface at the culvert entrance above the top of the pipe at the outlet, in feet; (21) the elevation of the tail water referred to the top of the pipe at the outlet, in feet; (22) the height of the hydraulic gradient above the top of pipe at the outlet, in feet; (23) the elevation of the top of the jet at the outlet of the pipe referred to the top of the pipe, in feet.

As may be seen, the velocity head for the pipe was computed from the mean velocity of flow in the pipe. The total head on the pipe is the difference between the elevation of the water surface at the culvert entrance and the elevation of the hydraulic gradient at the outlet. When the outlet is submerged this is practically equivalent to the difference between the elevations of the water surface at the two ends of the culvert. In some experiments there was evidence of a slight recovery of velocity head in the basin at the outlet end of the culvert, but generally this was so small that it was considered negligible. In field installations the amount of this recovery is usually less than that observed in the laboratory and would vary with local conditions. The friction loss is the difference between the elevations of the hydraulic gradient at the two ends of the pipe. The friction loss coefficient was determined by dividing the friction loss by the velocity head. The entrance drop is the difference between the elevation of the water surface at the culvert entrance and the elevation of the hydraulic gradient at this point. The head lost at the culvert entrance or the entrance loss for the particular entrance used on the pipe was determined by subtracting the velocity head from the entrance drop. The entrance loss coefficient for the type of entrance used was determined by dividing the entrance loss by the velocity head.

For any pipe flowing full, the total head equals the sum of the following factors: The head lost at the culvert entrance, or the entrance loss, plus the friction loss plus the velocity head. Written as an equation it is

$$\text{Total Head} = \text{Entrance Loss} + \text{Friction Loss} + \frac{V^2}{2g}$$

Dividing both sides of the equation by $\frac{V^2}{2g}$, we have

$$\frac{\text{Total Head}}{\frac{V^2}{2g}} = \frac{\text{Entrance Loss}}{\frac{V^2}{2g}} + \frac{\text{Friction Loss}}{\frac{V^2}{2g}} + 1$$

Thus, the sum of the factors as computed in Columns 9 and 12 plus one should equal a quantity consisting of the total head divided by the velocity head (column 13). This serves as a numerical check upon the calculations involved in the preceeding columns.

The hydraulic radius was computed for the pipe tested, and equals $\frac{1}{4}D$ when the pipe is flowing full. The hydraulic grade or slope, s, was determined by dividing the difference between the elevations of the hydraulic grade at the two ends of the pipe by the length of the pipe. The coefficient, C, was computed by solution of the Chezy formula, $V = C\sqrt{R\,s}$. The coefficient, n, for use in Kutter's formula was determined by means of a large scale diagram specially prepared for this investigation. The coefficient, n', for use in Manning's formula, $V = \frac{1.486}{n'} R^{2/3} s^{1/2}$, was computed for each test. The height of the hydraulic gradient above the top of the pipe at the outlet was scaled from the diagram after the grade line was drawn.

Representative computation diagrams for the culvert pipe using an expanding outlet are shown in Plate XX. For these tests a table was used having headings similar to the table shown on Plate XIX except that two columns are added. Column 24 shows the head gained by using an increaser at the outlet end of the culvert. Column 25 gives the ratio of the gain in head over velocity head. The gain in head is the difference between the elevation of the tail water surface and the elevation of the hydraulic gradient line for the section of uniform bore, continued to the outlet end of the pipe. Almost all of this gain in head is produced by an increased static pressure caused by velocity reduction as the water fills the expanding tube. However, a very small portion of the gain in head thus computed is due to the decreased friction loss produced in the enlarged section.

To allay any question as to the effect of the velocity of approach of the water to the culvert entrance in the section of the canal below the measuring weir, mention should be made that this velocity of approach is included when hook gage No. 2 at the culvert entrance is read. The piezometer opening which connected to the stilling well for this hook gage was made in the head wall at some distance from the culvert opening. Since this opening was flush with the headwall it was directed toward the thread of the stream as it flowed toward the culvert, and thus a water level was obtained in the stilling well which was affected by the approaching water to the full extent of its approaching velocity head. To confirm the accuracy of this conclusion, hook gages were installed in the channel approaching the culvert entrance, connected to openings which were flush with the side walls of the channel at some distance above the culvert inlet. The difference between simultaneous readings on these gages and hook gage No. 2 was very slight for normal velocities of flow and generally equal to the head of the velocity in the channel of approach. In many experiments the readings of hook gage No. 2 were checked by reading a similar gage opening in the head wall on the opposite side of the culvert.

The diagrams shown on Plates XIX and XX have been carefully selected from the whole number of 1,102 tests on pipe culverts covered in this report to show not only the general methods of computation used, but also to illustrate some of the interesting and useful comparisons that can be made between the results obtained from different tests.

With a constant head on the measuring weir, and the pipe line submerged at both ends, a series with different amounts of submergence on a pipe of a certain size, kind, and length, will give a set of hydraulic gradients approximately parallel. Thus, certain hydraulic elements should check each other when the data for such a series is compared. Examples of such comparisons are shown in Pl. XIX, Figs. 2 and 10.

It will be noted in these figures that the piezometer readings vary somewhat from the hydraulic gradient. This difference is very slight with low quantities of flow. As the discharge increases the discrepancies increase somewhat. These discrepancies may be due to some defect in the piezometer connections in the culvert. Although equal care was taken in making all the piezometer connections, certain piezometers invariably read either too high or too low. An examination of the connections of these piezometers failed to show any difference from the adjacent connections. These discrepancies are illustrated in Figs. 2 and 3, for example.

In Figs 1 and 2 it can be seen that the readings for the piezometer nearest the entrance are considerably below the slope lines. The amount of the variation of the readings of this piezometer from the hydraulic gradient depends to a great extent upon the amount of stream contraction caused by the entrance. The sharper the inlet corner which the water must turn, the greater the contraction and hence the lower the pressure which will be registered by the piezometer near the entrance. Thus, in tests 700 and 728, Figs. 8 and 9 two different conical entrances were used. In both of these cases, the readings for the first piezometer are higher than with a straight endwall and lie on the hydraulic gradient. In the box culvert tests, these entrance contractions were studied by installing 12 piezometers as close as possible to the inlet.

For certain tests, described later as Group IX, Tables 69 to 71, the shape of the bell end at the pipe entrance was changed by means of cement mortar. The effect of such changes on the piezometer readings is shown in Figs. 14 to 17.

When a short pipe with a free outlet is acting under a comparatively high head, part of the pipe line may be operating under a vacuum and the piezometers will then indicate the hydraulic gradient but not necessarily the elevation of the water surface. An example of this condition is illustrated in Fig. 11. In this case the pipe is discharging full at the outlet while the tail water is 1.25 feet below the top of the pipe. The amount of submergence and the velocity may be such that the entire length of the pipe acts under a vacuum as in Fig. 12.

Representative diagrams of conditions obtained on the 18-inch vitrified-clay pipe with a straight endwall entrance and a submerged conical outlet are shown on Plate XX. Figs. 1, 2, 3, and 4 of this plate show the pipe acting under different heads. These diagrams are strikingly different from those on Pl. XIX in respect to the piezometer readings throughout the conical outlet portion of the pipe. The diagram for test 1,190, Fig. 3, shows part of the pipe acting under a vacuum, while for test 1,192, Fig. 4, the pipe is acting under a vacuum for its entire length. The important feature of this type of outlet is that considerably greater capacity is obtained for a pipe when the outlet is submerged than for a pipe with uniform bore. This expanded outlet has the same effect on the culvert as a draft tube has on a turbine. By converting velocity head into pressure head, greater efficiency is secured. In test 1184 the velocity of the water in the pipe is 7.884 feet per second. The gain in head in this test with an increaser at the outlet is 0.708 feet, which is 73 per cent of the velocity head in the pipe and is 96 per cent of the difference between this velocity head and the head of the mean velocity at the outlet. This increased capacity is not obtained until the outlet end of the pipe is entirely submerged.

This type of outlet has additional merit in that the outlet velocities are greatly reduced and the destructive scour which so often occurs at culvert outlets is avoided.

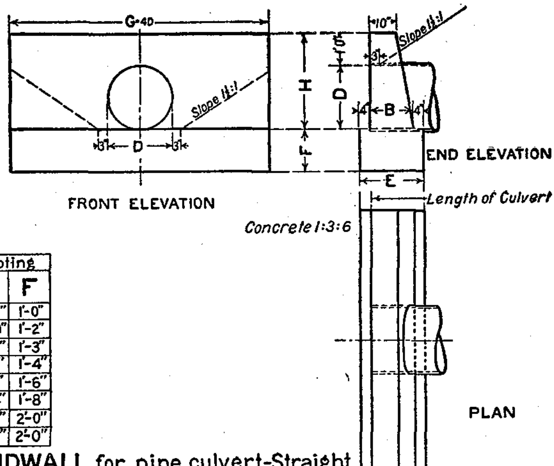
The diagrams and computations for the concrete box culverts are similar to those for the pipe culverts.

DISCUSSION OF EXPERIMENTAL RESULTS

Table 22 to 111 inclusive in the Appendix—pages 103 to 128, give for each of the tests included in this report the most important of the hydraulic elements as explained on pages 41 and 42, and illustrated at the bottom of Pls. XIX and XX. For economy in printing, only the most essential and useful columns are included. By omitting the subsidiary steps necessary to reach the final desired results and averaging consecutive experiments with the same flow passing through the culvert, it has been found possible to condense the tables presented in this report to one-third the number of figures appearing on the original computation sheets.

These printed tables are grouped to show the effect of certain conditions. Group I, consisting of tables 22 to 37 inclusive, shows the effect of size of pipe and material of which it is made. Group II, tables 38 to 45, in connection with the tables of Group I, shows the effect of the length of the pipe. Group III, table 46, shows the effect of a floor placed in front of the entrance and level with the bottom of the pipe. Group IV, tables 47 to 52 shows the effect of special conical entrances. Group V, tables 53 to 55, shows the effect of standard commercial vitrified-clay pipe increasers used as entrances. Group VI, tables 56 to 59, shows the effect of 45-degree wingwalls as entrances without a floor in front of the entrance. Group VII, tables 60 to 64, shows the effect of 45-degree wingwalls as entrances with a floor in front of the entrance. Group VIII, tables 65 to 68, shows the effect of U-type wingwalls as entrances. Group IX, tables 69 to 71, shows the effect of special shaped bells at the pipe entrance. Group X, tables 72 to 78, shows the effect of projecting the entrance end of the pipe beyond the headwall. Group XI, table 79, shows the effect of a conical outlet on the discharge capacity of a pipe culvert. Group XII, tables 80 to 90, shows the tests made on concrete box culverts 2 feet wide. Group XIII, tables 91 to 98, show the tests made on concrete box culverts 3 feet wide. Group XIV, table 99, shows the effect on the discharge capacity, of flaring a box culvert on the two sides only, for its entire length, increasing the size from 2-ft. by 2-ft. at the entrance to 4-ft. by 2-ft. at the outlet. Group XV, tables 100 to 111, shows the tests made on box culverts 4 feet wide. Tables 7 and 8, pages 64 and 68, described in detail later, summarize some of the data and conclusions deduced from tables 22 to 111.

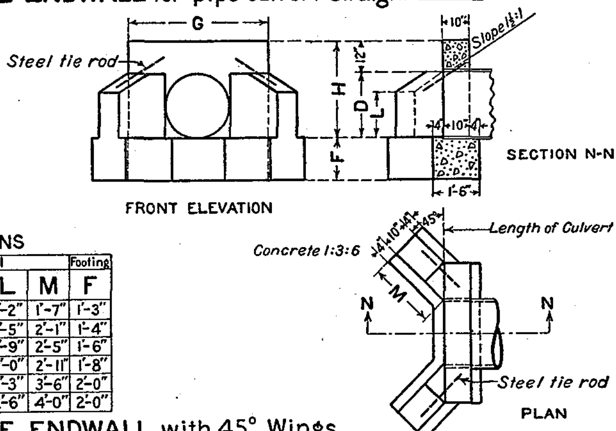
Plates VII to XVI, show the various types of entrances tested. Plate XXI shows the details of the pipe culverts tested and their elevation with respect to the floor of the testing canal. The standard types of pipe culvert entrances used by the Bureau of Public Roads are shown in text figure 6.



DIMENSIONS

Opening		Wall			Footing	
D	Area Sq.Ft.	G	H	B	E	F
12"	0.8	4'-0"	2'-0"	1'-2"	1'-10"	1'-0"
15"	1.2	5'-0"	2'-3"	1'-2"	1'-10"	1'-2"
18"	1.8	6'-0"	2'-6"	1'-3"	1'-11"	1'-3"
24"	3.1	8'-0"	3'-0"	1'-4"	2'-0"	1'-4"
30"	4.9	10'-0"	3'-6"	1'-6"	2'-2"	1'-6"
36"	7.1	12'-0"	4'-0"	1'-8"	2'-4"	1'-8"
42"	9.6	14'-0"	4'-6"	1'-10"	2'-6"	2'-0"
48"	12.6	16'-0"	5'-0"	2'-1"	2'-9"	2'-0"

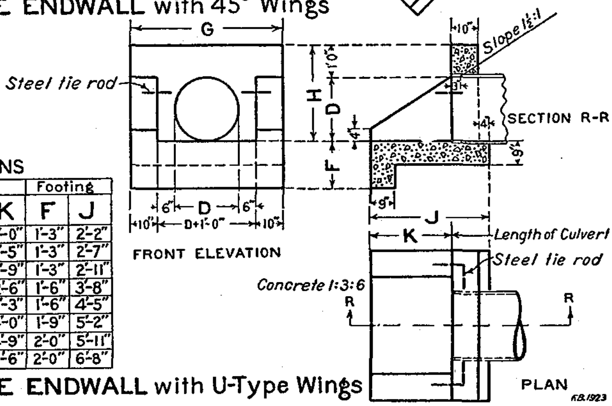
Fig.1. CONCRETE ENDWALL for pipe culvert-Straight



DIMENSIONS

Opening		Wall				Footing
D	Area Sq.Ft.	H	G	L	M	F
18"	1.8	2'-6"	3'-10"	1'-2"	1'-7"	1'-3"
24"	3.1	3'-0"	4'-4"	1'-5"	2'-1"	1'-4"
30"	4.9	3'-6"	4'-10"	1'-9"	2'-5"	1'-6"
36"	7.1	4'-0"	5'-4"	2'-0"	2'-11"	1'-8"
42"	9.6	4'-6"	5'-10"	2'-3"	3'-6"	2'-0"
48"	12.6	5'-0"	6'-4"	2'-6"	4'-0"	2'-0"

Fig.2. CONCRETE ENDWALL with 45° Wings



DIMENSIONS

Opening		Wall			Footing	
D	Area Sq.Ft.	G	H	K	F	J
12"	0.8	3'-8"	2'-0"	1'-0"	1'-3"	2'-2"
15"	1.2	3'-11"	2'-3"	1'-5"	1'-3"	2'-7"
18"	1.8	4'-2"	2'-6"	1'-9"	1'-3"	2'-11"
24"	3.1	4'-8"	3'-0"	2'-6"	1'-6"	3'-8"
30"	4.9	5'-2"	3'-6"	3'-3"	1'-6"	4'-5"
36"	7.1	5'-8"	4'-0"	4'-0"	1'-9"	5'-2"
42"	9.6	6'-2"	4'-6"	4'-9"	2'-0"	5'-11"
48"	12.6	6'-8"	5'-0"	5'-6"	2'-0"	6'-8"

Fig.3. CONCRETE ENDWALL with U-Type Wings

Fig. 6. Standard entrances for pipe culverts used by Bureau of Public Roads

Effect of Depth of Submergence

A study was first made to determine for a culvert submerged at both ends whether the amount of this submergence had any effect on the loss of head at the entrance and the friction loss in the pipe. It was found that these losses are practically independent of the amount of submergence of the culvert. At the same time it was evident that unless the entrance to the pipe was submerged to some extent the pipe would not flow full and thus would not achieve its full discharging capacity.

Relation of Head Losses to Velocity

To determine the relation between the mean velocity in the pipe and the ratios of entrance loss, friction loss, and total head to velocity head for each size and kind of pipe, the mean velocity, mean entrance drop, mean friction loss, and mean total head were determined for each group of tests in which the discharge was approximately the same. The average velocity head was computed from the mean velocity for each group. The entrance loss was obtained by subtracting the new velocity head from the mean entrance drop, and this loss was divided by the new velocity head to determine the average entrance loss ratio. The mean friction loss ratio and mean total head ratio were obtained by dividing the mean friction loss and the mean total head by the new velocity head.

These ratios were plotted with the mean velocity in feet per second as abscissae and the ratios of entrance loss, friction loss and total head to velocity head as ordinates.

A representative example of these diagrams is shown in text figure 7. A study of these diagrams shows that the ratios of the entrance loss, friction loss, and total head to the velocity head are substantially constant, with a slight tendency toward increasing values for higher velocities. For those tests in which the velocity fell below three feet per second the values of the ratios were generally markedly smaller than for the other tests. Since the data for these low velocities does not have the same degree of accuracy as for the higher velocities due to the flat gradients under observation, it cannot definitely be stated whether this apparent tendency indicates a real law or is the result of unavoidable errors in the measurements. If this tendency is a reality, the losses in a pipe are proportional to a power of the velocity slightly greater than its square, and the discharging capacity of a pipe is proportional to a power slightly less than the square root of the head on the pipe. This tendency is supported by most of the final individual pipe equations. However, the fact that these ratios were so nearly constant in each table proves that for any given installation the friction loss, the entrance loss, and the total loss may be considered practically proportional to the square of the velocity of the water flowing through the pipe. In other words the discharging capacity of a pipe is practically proportional to the square root of the head on the pipe.

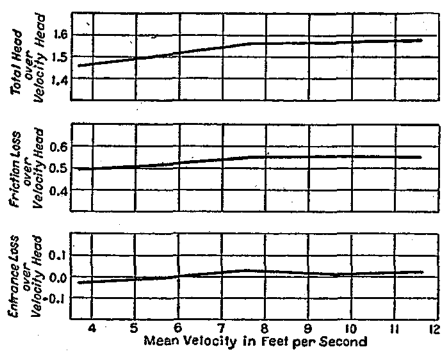


Fig. 7. Diagram showing relation between mean velocity in pipe and the three ratios, entrance loss over velocity head, friction loss over velocity head, and total head over velocity head.

Drop Down in Water Surface at Free Outlet

When the culvert pipe was acting under some head and with a free outlet, it was noted that there was a drop down in the water surface at the outlet of the pipe. (See Pl. XVIII, B). The amount of this drop in the water surface below the top of the pipe at the outlet end varied both with the size of the pipe and the head on the pipe. This drop which was measured in each case is shown in text figure 8. The average pipe velocity in feet per second has been plotted as abscissa against the amount of the drop down at the outlet in per cent of pipe diameter as ordinate. The curves for three sizes of pipe, namely, 12, 18, and 24 inches in diameter are shown.

Methods of Reducing Entrance Losses

Among the many interesting things revealed by a study of tables 22 to 111 is the effect of different types of entrances on the entrance loss. The entrance loss coefficient (Column 12 in Tables 22 to 111) has been averaged for each type of entrance and kind of pipe (See Column 6, Tables 7 and 8), excluding all tests in which the culvert velocity was less than 2.50 feet per second. The reason that velocities less than 2.50 feet per second were ignored in finding averages was that for such low velocities the values are less accurately determined than in the other cases. In a few experiments with low

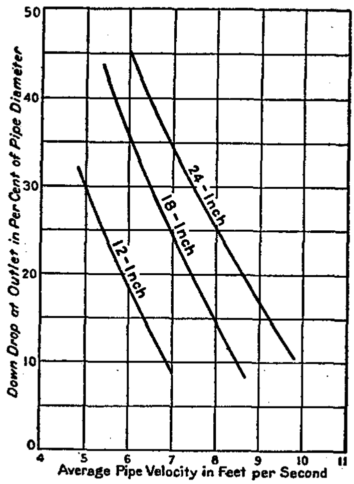


Fig. 8. Curves showing elevation of top of jet at outlets of freely discharging pipes referred to the inside top of pipe

velocities and small contraction effect at the entrance, the entrance loss was evaluated as a negative quantity. While this is theoretically impossible, there is little doubt that other values were estimated correspondingly large, due to the small magnitude of the quantities concerned. Therefore in computing the average entrance loss all positive and negative values were added algebraically. The average shown is a weighted average obtained by dividing the sum of the entrance losses by the sum of the velocity heads.

For the pipe culverts with square cornered entrances (See Tables 26, 27, 28, 29, and 71) the average entrance loss coefficient is 0.393. The tests on the various sizes of box culverts with square corners give values ranging from 0.3 to 0.4. Textbooks on hydraulics give the coefficient for square-cornered entrance as 0.50 but are based mostly on a knife-edge with full contraction on all sides. The corners made in these experiments were as sharp as could be made with concrete, but no doubt had a very small but effective radius. The contraction of the jet was probably not complete, particularly on the bottom edge of the box culverts.

With the concrete pipe having a straight endwall entrance, the beveled lip, shown in text figure 4, page 34, assists greatly in reducing the entrance loss. For this type the average entrance loss coefficient for all sizes and lengths is 0.099 (See Tables 22, 23, 24, 25, 38, and 39).

With a vitrified-clay pipe culvert having a straight endwall entrance the bell-end of the clay pipe, shown in text figure 5, page 34, by virtue of its shape is efficient since the entrance loss is reduced almost to zero. The average entrance loss coefficient for the clay pipe bell (See Tables 30, 31, 32, 33, 40, 41, and 79) is 0.063. By taking sufficient care to make a gradually rounded entrance, this entrance loss can always be reduced practically to zero. When the bell is filled with concrete shaped in the form of an ellipse, this coefficient becomes 0.020 (See Table 70).

Although the entrance loss is greater for a corrugated-metal pipe, the reinforced rounded end of the metal pipe greatly assists in reducing the amount of entrance loss. The average entrance loss coefficient for the corrugated-metal pipe (See Tables 34, 35, 36, 37, 42, 43, 44, and 45) is 0.226.

In general the entrance loss coefficient for a given type of entrance increases with an increase in diameter in the circular culverts. The average values of this coefficient are given in table 4.

While the special conical entrances (See Tables 47, 48, and 49) tested are not as efficient as the bell-end of a clay pipe in reducing the entrance loss, they assist greatly in reducing the entrance loss into a corrugated-metal pipe. The average entrance loss coefficient for the various conical entrances used in connection with the vitrified-clay pipe (See Tables 47, 48, and 49) is 0.088 whereas for the clay pipe this coefficient is 0.063. The average entrance loss coefficient for the various conical entrances used in connection with the corrugated-metal pipe (Tables 50, 51, and 52) is 0.044 whereas for the regular end of a metal pipe this coefficient is 0.226. The difference between the average coefficients for the clay and metal pipe obtained with these conical entrances is partially due to a difference in the types used in each case, and also due to the fact that in the corrugated-metal pipe the cone could be made to end tangent to a corrugation with no corner for the stream to round, whereas with the clay pipe a sharp corner still existed at the junction of the cone and the pipe. There is little difference in the effectiveness of the various types of conical entrances used in reducing the entrance loss, but in general the loss was observed to be smaller for the larger cones and smaller central angles.

Table 4—Average entrance loss coefficients for circular culverts with straight endwalls

Type of entrance	Diameter of pipe Inches			
	12	18	24	30
Square corner	0.276	0.404	0.458	0.493
Beveled lip	.111	.097	.078	.137
Rounded lip			.020	
Clay tile bell end	.010	.038	.091	.120
Corrugated-metal pipe corner	.160	.200	.240	.295

The standard commercial vitrified-clay pipe increasers when used as entrances are not as effective in reducing the entrance loss as the regular bell-end of a clay pipe. The average entrance loss coefficient for the standard vitrified-clay pipe increasers (See Tables 53, 54, and 55) is 0.142 whereas for the regular bell of a vitrified-clay pipe, this coefficient is 0.063.

The 45-degree wingwall used in connection with a corrugated-metal pipe culvert has a slight beneficial effect in reducing the entrance loss below that resulting from the use of the straight endwall. The average entrance loss coefficient for these wingwalls used with corrugated-metal pipe is 0.221 (See Tables 56, 57, 58, and 59). The efficiency of these wingwalls in increasing the discharge in a metal pipe over that obtained with the straight endwall is seen by comparing the discharge equations in Table 7.

The 45-degree wingwall used in connection with a vitrified-clay pipe culvert slightly increases the entrance loss and decreases the discharge as compared to the same pipe with the straight endwall. The average entrance loss coefficient for these wingwalls used in connection with the clay pipe (See Tables 60, 61, 62, and 63) is 0.114 whereas for the straight end wall, it is 0.063.

The U-type wingwalls are inefficient as compared to the straight endwall with vitrified-clay pipe in reducing the entrance loss. These wingwalls will increase the entrance loss (See Pl. XI, B) and consequently decrease the discharge of the culvert. The average entrance loss coefficient for the U-type wingwalls (See Tables 65, 66, 67, and 68) is 0.197 compared with 0.063 obtained for the clay pipe with the straight endwall.

The entrance loss coefficient for the 18-inch corrugated-metal pipe increased consistently with increased amount of projection beyond the headwall, from an average value of 0.200 for no projection to 0.568 with four feet projecting. On the other hand, for the 12-inch concrete pipe it makes very little difference in the entrance loss whether the pipe projects 3 inches, 2 feet, or 4 feet beyond the headwall. In contrast to the sharp edge of the corrugated-metal pipe, the flat end of the concrete pipe has width enough to prevent change in the nature of the contraction and this is responsible for the difference observed. Water in entering the concrete pipe suffered little further contraction than ordinary, due to unchanged direction of the current along the plane of the end regardless of the amount of projection into the water. The contraction of the jet flowing into the metal pipe is considerably increased due to the currents flowing around the sharp corner through an angle of more than 90 degrees. These experiments suggest that the installation of an ordinary pipe flange at the end of inward projecting reservoir outlets and suction pipes such as used in drainage pumping plants, would prove very beneficial in reducing the entrance losses at these points.

The results obtained in Group III were not extensive enough to establish conclusively the effect of the raised floor in front of the entrance.

The carrying capacity of a vitrified-clay pipe culvert with a straight endwall may be increased somewhat by filling the bell with the cement mortar rounding the mortar so as to give an elliptical or circular-shaped entrance corner.

The discharge of any pipe culvert having a square cornered entrance may be increased by setting the pipe back a few inches from the face of the headwall and rounding the concrete in the headwall next to the circumference of the pipe.

The entrance loss coefficient for the box culverts with beveled lip entrances was about 0.10, and with rounded lip entrances about 0.05. For the square cornered entrance to the box culverts, the entrance loss coefficients range from 0.30 to 0.41.

Values of the coefficient of roughness in the Kutter and Manning Formulas for the various culverts

The values of the coefficient of roughness in the Kutter and Manning formulas obtained for the tests are shown in Tables 22 to 111 inclusive. Since for heads of less than 0.40 foot on the weir the Bazin formula used for determining the discharge over sharp-crested rectangular weirs of the suppressed type gives quantities somewhat greater than those obtained by volumetric measurement, the values of the coefficient of roughness for tests with heads of less than 0.40 foot may be a little less than the correct ones. Therefore in obtaining the average values for the coefficient of roughness in Tables 22 to 111 inclusive, all tests with heads of less than 0.40 foot on the weir have been omitted. The average values of the coefficient of roughness in the Kutter and Manning formulas for the various sizes of the three kinds of pipe tested are shown in Table 5.

Table 5—Average values of the coefficient of roughness in concrete, vitrified-clay, and corrugated-metal, culvert pipe

Diameter of pipe	Kutter coefficient			Manning coefficient		
Inches	Concrete	Clay	Metal	Concrete	Clay	Metal
12	0.0117	0.0101	0.0194	0.0119	0.0098	0.0228
18	.0121	.0119	.0217	.0121	.0118	.0248
24	.0130	.0127	.0216	.0130	.0125	.0239
30	.0127.	0131	.0232	.0125	.0131	.0254

This table shows that the coefficient of roughness in the Kutter formula is nearly twice as great for the corrugated-metal pipe as for the concrete and vitrified-clay pipe. The coefficient of roughness increases with an increase in the size of the pipe. The Manning coefficient for the metal pipe is also approximately twice the value for the concrete and clay pipe, and likewise increases with an increase in the size of the pipe.

The average value of the coefficient of roughness in the Kutter formula for all the concrete box culvert tests is 0.0129, for the Manning formula, also 0.0129. Tables 80 to 111 show that the coefficient of roughness increases with an increase in the hydraulic radius, see text figure 9.

The roughness of the concrete pipe used in these tests appeared greater than the surface obtained for the box culverts. Neglecting entrance losses the concrete box culverts had a slightly greater carrying capacity per square foot of area than the pipe of the same hydraulic radius. However the capacity of the circular pipe was greater than that of the box culvert of the same area in spite of the apparent unfavorable difference in roughness.

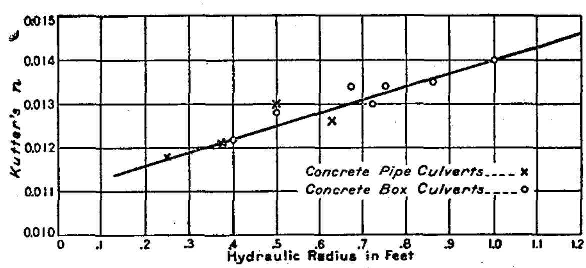


Fig. 9. Variation of Kutter's n with hydraulic radius

The variation in the different values of the Manning coefficients for the same material is about the same or a little less than the variation in the Kutter coefficient, showing that throughout the range covered by these tests and so far as indicated by these results, the Manning coefficient is at least as satisfactory as the Kutter coefficient. For the smoother pipe the Kutter and Manning coefficients are practically the same, as the structure of the formulas indicates they should be. It must be noted, however, that for the rougher pipe the Manning coefficient is definitely higher than the Kutter coefficient, so that for this case it is not safe to use the coefficients as exactly interchangeable. Both coefficients increase for the larger diameter pipes, indicating that neither the Kutter formula nor the Manning formula makes the correct allowance for change in diameter of pipe. The results indicate that in the Manning formula the value, two-thirds, used as the exponent of the hydraulic radius, is too large.

The large roughness factor obtained in the corrugated-metal pipe is undoubtedly due to the corrugations of the wall of the metal pipe. The effect of these corrugations on the flow of the water is readily seen in Plate XVIII, A. Holes were cut in the top of the 24-inch concrete, vitrified-clay, and corrugated-metal pipe and photographs taken of the moving water through the openings.

These views show that in the concrete and vitrified-clay pipe (Pl. XVII, A and B) the filaments of flow are disturbed very little by the joints of the pipe. In the metal pipe, the corrugations show a marked disturbing effect on the flow of the water (Pl. XVIII, A). The retardation effect of the walls of the concrete or clay pipe does not extend to any great distance from the walls. Unlike the clay pipe, the effect of the corrugations of the metal pipe on the flow is so great that the mean velocity of the water is much reduced, the greatest velocity occurring at the center of the pipe. This is well illustrated in the velocity distribution curves obtained by means of a Pitot tube as shown in text figures 12, 13, and 14.

A series of tests using a different crew of observers was run by the University of Iowa a year later on 30 feet of 12-inch vitrified-clay pipe purchased from another manufacturer. These tests gave the same values for the coefficient of roughness as were obtained on the tests in this investigation. The discharge equation developed from the tests was identical with that shown in Table 7.

In pipes as short as standard culverts, the type of entrance has also a decided effect on the effective roughness of the walls of the culvert in retarding the flow by friction. In general, a culvert with an inefficient entrance showed less frictional resistance than the same culvert with a carefully rounded stream line entrance. This is reflected in the higher values of n obtained in culverts with rounded entrances. This is attributed to the difference in velocity distribution caused by the different types of entrances. The square corner concentrates high velocity currents nearer to the center of the culvert, whereas the rounded entrance corner is responsible for a more uniform distribution of velocities hence relatively higher velocities near the roughened wall of the culvert. This causes less skin friction with the walls of the culvert in the case of a square cornered entrance and may also increase the initial kinetic energy to furnish a surplus which may be expended in overcoming friction but not revealed in the hydraulic gradient. Hence, if the culvert is too short to secure a normal distribution of velocities a higher value of the roughness coefficient should be expected with the rounded corner. In general, the shorter, smoother, and larger the culvert, the more pronounced the effect became. This was all too evident in these experiments to be ignored as revealed by the data in table 6.

Table 6—Variation in Kutter's *n* in concrete pipe and box culverts with different types of entrances

Type of culvert	Type of entrance		
	Rounded lip	Beveled lip	Square cornered
12-inch circular		0.0117	0.0119
18-inch circular		.0121	.0121
24-inch circular		.0130	.0130
30-inch circular		.0127	.0125
2-ft. by 2-ft. by 30-ft.	0.0126	.0119	.0116
3-ft. by 3-ft. by 30-ft.	.0136	.0127	.0121
3-ft. by 3-ft. by 24-ft.	.0156		.0134
4-ft. by 4-ft. by 36-ft.	.0145		.0134
4-ft. by 3-ft. by 36-ft.	.0136		.0134
4-ft. by 2¼-ft. by 36-ft.	.0135		.0124
4-ft. by 2-ft. by 36-ft.	.0137		.0132
4-ft. by 1-ft. by 36-ft.	.0124		.0119

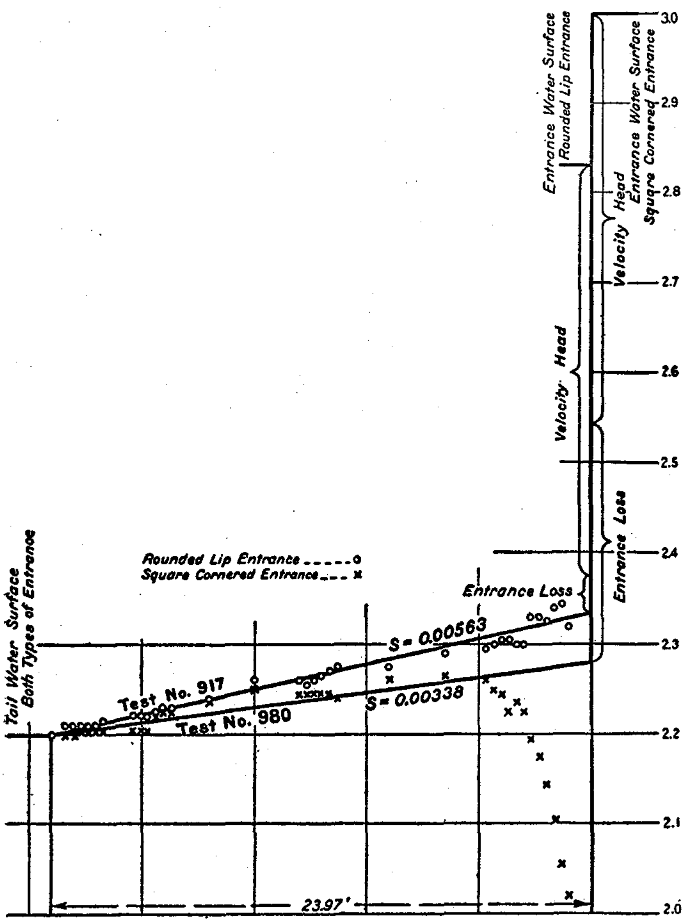


Fig. 10. Variation in friction gradient in the same culvert with different entrances when carrying the same quantity of water

The difference in the friction gradient in the same culvert with different entrances when carrying the same quantity of water is strikingly shown in text figure 10.

The suggestion that the nature of the velocity distribution may be responsible for a considerable variation in *n* is worthy of further investigation.

Investigations of Piezometer Connections in Corrugated-Metal Pipe

There was no precedent to follow in making the piezometer connections in the corrugated-metal pipe. However, it seemed reasonable to extend the piezometric connection in through the outside curved surface, until the edge of the orifice was in the plane of and normal to the inside curved surface, which forms the controlling area of flow through the pipe. The space around the piezometer tube was filled with solder to form a plane surface parallel to the direction of flow (See Pl. III, B).

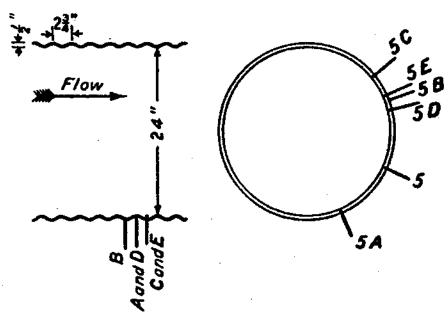


Fig. 11. Piezometer connections in 24-inch corrugated-metal pipe

In order to determine whether this piezometer connection was of the proper type, three other types of connections were tested. Five piezometers were used to represent the three different kinds of connections and were placed about 9 feet from the entrance end of the 24-inch metal culvert so as to be comparable to the standard piezometer placed at this point. These five piezometers were numbered 5-a, 5-b, 5-c, 5-d, 5-e, and were arranged around the conduit as shown in Figure 11.

The standard piezometer, No. 5, was placed 0.68 feet above the bottom of the outside corrugation or 0.635 feet above the invert of the pipe.

The other piezometer connections were as follows:

Piezometer No. 5-a, 0.141 feet above the bottom of the inside corrugation or 0.095 feet above the invert of the pipe and flush with the inside surface of the inner corrugation.

Piezometer No. 5-b, 1.47 feet above the bottom of the outside corrugation or 1.425 feet above the invert of the pipe and flush with the inside surface of the outer corrugation.

Piezometer No. 5-c, 1.72 feet above the bottom of the outside corrugation or 1.675 feet above the invert of the pipe and projecting in ½ inch from the inside surface of the outer corrugation.

Piezometer No. 5-d, 1.34 feet above the bottom of the outside corrugation or 1.295 feet above the invert of the pipe and flush with the inside surface of the inner corrugation.

Piezometer No. 5-e, 1.47 feet above the bottom of the outside corrugation or 1.425 feet above the invert of the pipe and projecting in ½ inch from the inside surface of the outer corrugation.

These five piezometers were used and read along with the others in the usual manner. The results of 91 tests were studied to determine what effect the different connections had. The method of study was as follows: The difference or deviation of the five piezometers from the standard piezometer was tabulated according to the velocity in the pipe for the various tests. These differences were averaged for each velocity and it was found that the average deviation increased with an increase in the velocity. Therefore each velocity head was divided by the corresponding average deviation of the various piezometers from the standard. The quotient obtained was fairly constant. This indicated that the deviation of each of the five piezometers varied as the square of the velocity.

Piezometer 5-a and 5-d read lower than 5 by an amount equal to 0.20 of the velocity head. Piezometer 5-b read higher than 5 by an amount equal to 0.21 of the velocity head. Piezometer 5-c and 5-e read higher by an amount equal to 0.08 of the velocity head. Since piezometers 5-c and 5-e have less deviation and lie between the two extremes, namely, the piezometer 5-b and the two piezometers 5-a and 5-d, this type of connection is presumably more nearly correct. Since the two extremes are equally distant from the standard it would appear that the standard connection adopted was the proper type and records the true pressure in a closed conduit.

The reason piezometer 5-b reads greater than 5-c and 5-e, and both of these types of connections greater than piezometer 5 is due to the outward component of the velocity illustrated in Figure 11. Piezometers 5-a and 5-d read less than piezometer 5 because of the inward component of the velocity which causes a sucking action at the piezometer orifice.

Velocity Distribution in Pipe Culverts

An investigation of the velocity distribution by means of a Pitot tube was made in three of the pipe culverts; namely, an 18-inch corrugated-metal, an 18-inch vitrified-clay, and a 24-inch vitrified-

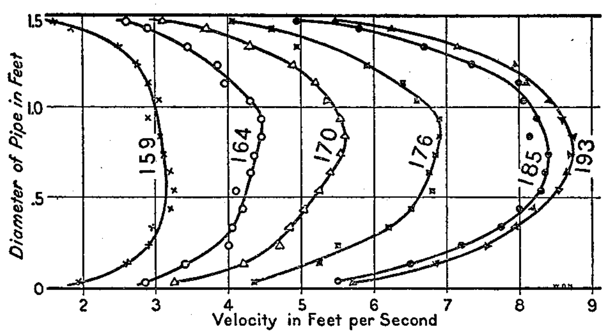


Fig. 12. Velocity curves in 18-inch corrugated-metal pipe

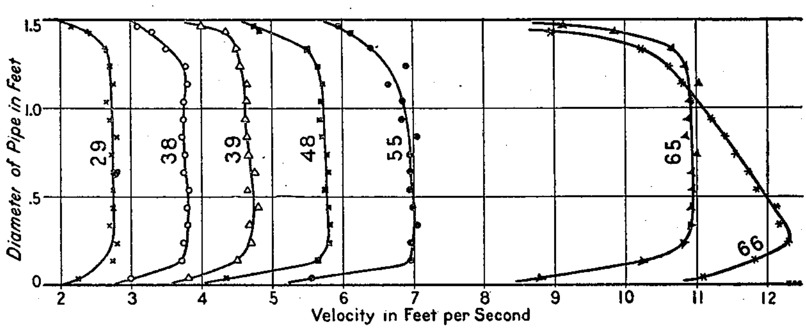


Fig. 13. Velocity curves in 18-inch vitrified-clay pipe

clay pipe. These velocity curves are shown in Figures 12, 13, and 14. It will be noted that the curves for the vitrified-clay pipe are much flatter than those for the metal pipe. The pointed shapes of the velocity curves in the corrugated-metal pipe are probably due to the effect of the corrugation of the walls of the pipe on the flow of the water in the pipe. The filaments of flow in the corrugated-metal pipe are disturbed by the irregularity of the walls and this disturbance extends far towards the center of the pipe. The greater the velocity, the more pronounced is the disturbance. Plate XVIII, A, shows the cross-currents set up in the metal pipe by the corrugations.

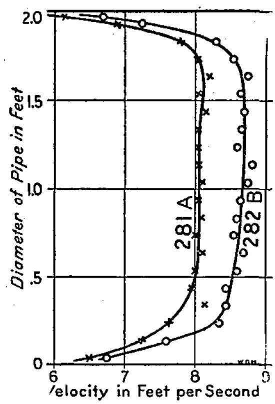


Fig. 14. Velocity curves in 24-inch vitrified-clay pipe

With the exception of test 66 in Figure 13, the velocity curves were taken at a point 5 feet from the outlet end of the culvert. In test 66 the velocity readings were taken at the outlet end of the 18-inch clay pipe culvert. Attention is called to the shape of this curve which shows the greatest velocity near the bottom of the jet. The discharge from the pipe had a free drop similar to that shown in Plate XVIII, B. A readjustment of the velocity distribution in a pipe takes place near the outlet of the pipe if individual stream lines conform to Bernoulli's law, and this test is splendid evidence of this fact.

DEVELOPMENT OF DISCHARGE FORMULAS FOR CULVERTS

A summary sheet giving the more important facts deduced from the tests shown in Tables 22 to 111 has been prepared. This information, Tables 7 and 8, is a condensed summary of the hydraulic elements most useful in making comparisons for the various culverts.

The ratios of velocity head, friction loss, and entrance loss to the total head on the pipe have been tabulated in order to show the relative importance of these factors in determining the capacity of the culvert. These ratios as given in Tables 7 and 8 have been averaged for each kind of culvert for all experiments in which the head on the measuring weir exceeded 0.40 feet. Negative entrance losses were included and added algebracially.

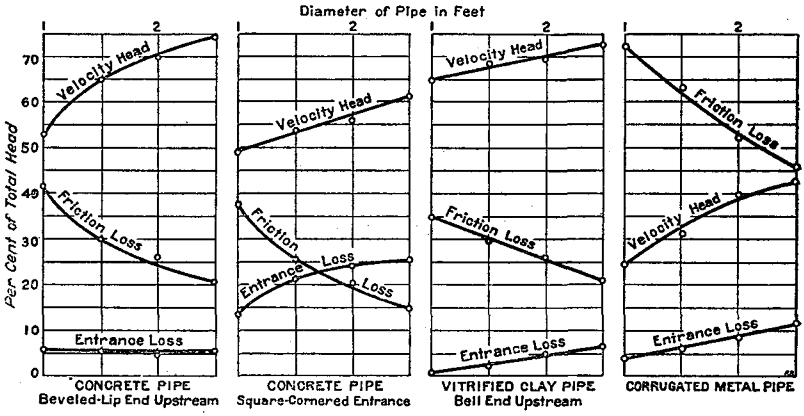


Fig. 15. Losses in pipe culverts with straight endwall entrances

The amount of velocity head, friction loss, and entrance loss expressed in percentage of the total head on the pipe culverts were plotted on rectangular cross-section paper as ordinate against the respective sizes of pipe as abscissa. These curves are shown in text figure 15. These diagrams are of special interest as they show that the percentage of the total head on the pipe consumed in entrance loss and velocity head increases with an increase in the size of the pipe, whereas the percentage required by friction loss decreases with an increase in the size of the pipe. On account of this fact the relative difference in the carrying capacity of a 30-inch vitrified-clay and a 30-inch corrugated-metal pipe culvert under the same head is much less than the relative difference in the carrying capacity of a 12-inch vitrified-clay and a 12-inch corrugated-metal pipe culvert.

Table 7—Summary of results of test data on pipe culverts

1 Table Number	2 Kind	3 Pipe Size Inches	4 Length Feet	5 Remarks	6 Entrance loss co-efficient	7 Ratio of velocity head to total head	8 Ratio of friction loss to total head	9 Ratio of entrance loss to total head	10 Equation
22	Concrete	12	30	Straight endwall entrance. Pipe with beveled lip.	0.111	0.53	0.42	0.05	$Q=4.62\ H^{0.474}$
23	"	18	30	" " " " " " "	.097	.65	.30	.05	$Q=11.42\ H^{0.480}$
24	"	24	30	" " " " " " "	.093	.70	.26	.04	$Q=20.8\ H^{0.470}$
25	"	30	30	" " " " " " "	.137	.74	.21	.05	$Q=33.1\ H^{0.474}$
26	"	12	30	" " " Pipe with square end.	.276	.49	.38	.13	$Q=4.42\ H^{0.486}$
27	"	18	30	" " " " " " "	.404	.54	.25	.21	$Q=10.3\ H^{0.482}$
28	"	24	30	" " " " " " "	.437	.56	.20	.24	$Q=18.65\ H^{0.478}$
29	"	30	30	" " " " " " "	.493	.61	.15	.24	$Q=29.8\ H^{0.467}$
30	Clay	12	30	Straight endwall entrance.	.010	.64	.35	.01	$Q=5.25\ H^{0.482}$
31	"	18	30	" " "	.044	.68	.30	.02	$Q=11.9\ H^{0.505}$
32	"	24	30	" " "	.095	.70	.26	.04	$Q=22.25\ H^{0.481}$
33	"	30	30	" " "	.120	.73	.21	.06	$Q=32.0\ H^{0.485}$
34	Metal	12	30	" " "	.160	.24	.72	.04	$Q=3.0\ H^{0.505}$
35	"	18	30	" " "	.200	.31	.63	.06	$Q=7.86\ H^{0.498}$
36	"	24	30	" " "	.225	.40	.52	.08	$Q=15.8\ H^{0.523}$
37	"	30	30	" " "	.295	.43	.46	.11	$Q=24.9\ H^{0.485}$
38	Concrete	24	24	Straight endwall entrance. Pipe with beveled lip.	.080	.72	.24	.04	$Q=21.0\ H^{0.485}$
39	"	24	36	" " " " " " "	.061	.69	.30	.01	$Q=20.45\ H^{0.485}$
40	Clay	24	25	Straight endwall entrance.	.122	.70	.22	.08	$Q=22.3\ H^{0.496}$
41	"	24	38	" " "	.057	.68	.30	.02	$Q=21.8\ H^{0.489}$
42	Metal	24	24	" " "	.298	.43	.44	.13	$Q=16.5\ H^{0.505}$
43	"	24	36	" " "	.230	.36	.56	.08	$Q=15.1\ H^{0.505}$
44	"	24	36	Straight endwall entrance (Ascending Series).	.212	.36	.57	.07	$Q=15.05\ H^{0.481}$
45	"	24	36	Straight endwall entrance (Descending Series).	.236	.35	.57	.08	$Q=14.8\ H^{0.500}$
46	"	24	36	Straight endwall entrance with floor in front of entrance.	.436	.34	.50	.16	$Q=14.75\ H^{0.512}$
47	Clay	24	38	Conical entrance, 13 degree angle, 10 inches long.	.110	.68	.27	.05	$Q=21.7\ H^{0.477}$
48	"	24	38	Conical entrance, 13 degree angle, 20 inches long.	.027	.69	.30	.01	$Q=21.7\ H^{0.473}$
49	"	24	38	Conical entrance, 45 degree angle, 10 inches long.	.105	.67	.27	.06	$Q=21.8\ H^{0.481}$
50	Metal	24	36	Conical entrance, 13 degree angle, 10 inches long.	.043	.39	.60	.01	$Q=15.65\ H^{0.507}$
51	"	24	36	Conical entrance, 13 degree angle, 20 inches long.	.040	.39	.60	.01	$Q=15.65\ H^{0.503}$
52	"	24	36	Conical entrance, 24°-47′ angle, 10 inches long.	.050	.39	.60	.01	$Q=15.60\ H^{0.504}$

53	Clay	12	30	12-inch to 15-inch standard commercial increaser used as entrance	.128	.61	.32	.07	$Q= 5.10\ H^{0.496}$
54	"	12	30	12-inch to 18-inch standard commercial increaser used as entrance	,083	.61	.34	.05	$Q= 5.10\ H^{0.496}$
55	"	18	30	18-inch to 20-inch standard commercial increaser used as entrance.	.190	.62	.27	.11	$Q=11.30\ H^{0.490}$
56	Metal	24	36	Wingwalls at 45 degrees, full height, set flush with inside edge of pipe, without floor in front of entrance.	.168	.38	.56	.06	$Q=15.50\ H^{0.491}$
57	"	24	36	Wingwalls at 45 degrees, standard height, set flush with inside edge of pipe, without floor.	.243	.37	.54	.09	$Q=15.30\ H^{0.492}$
58	"	24	36	Wingwalls at 45 degrees, full height, set 6-inches from inside edge of pipe, without floor.	.224	.37	.56	.07	$Q=15.25\ H^{0.488}$
59	"	24	36	Wingwalls at 45 degrees, standard height, set 6-inches from inside edge of pipe, without floor.	.269	.37	.54	.09	$Q=15.25\ H^{0.482}$
60	Clay	24	38	Wingwalls at 45 degrees, full height, set flush with inside edge of bell, with floor in front of entrance.	.116	.67	.26	.07	$Q=21.75\ H^{0.475}$
61	"	24	38	Wingwalls at 45 degrees, cut level to top of standard endwall, and set flush with inside edge of bell, with floor in front.	.122	.67	.26	.07	$Q=21.55\ H^{0.476}$
62	"	24	38	Wingwalls at 45 degrees, cut on bevel to top of standard endwall and set flush with inside edge of bell, with floor in front.	.111	.67	.26	.07	$Q=21.55\ H^{0.479}$
63	"	24	38	Wingwalls at 45 degrees, standard height, set flush with inside edge of bell, with floor in front of entrance.	.106	.68	.28	.04	$Q=21.60\ H^{0.479}$
64	Metal	24	36	Wingwalls at 45 degrees, standard height, set flush with inside edge of pipe, with floor in front.	.365	.36	.52	.12	$Q=15.15\ H^{0.486}$
65	Clay	24	38	U-Type wingwalls cut on bevel to top of standard endwall and set flush with inside edge of bell, with floor in front of entrance.	.177	.63	.28	.09	$Q=21.05\ H^{0.483}$
66	"	24	38	U-type wingwalls cut on bevel to top of standard endwall and set 6-inches from inside edge of bell, with floor in front.	.150	.65	.26	.09	$Q=21.35\ H^{0.485}$
67	"	24	38	U-type wingwalls, standard height, set flush with inside edge of bell, with floor in front of entrance.	.291	.59	.27	.14	$Q=20.35\ H^{0.485}$
68	"	24	38	U-type wingwalls, standard height, set 6-inches from inside edge of bell, with floor in front of entrance.	.169	.62	.29	.09	$Q=20.70\ H^{0.476}$
69	"	24	38	Straight endwall with entrance bell filled with concrete and surfaced off straight from inside edge of bell to inside edge of pipe.	.044	.69	.29	.02	$Q=22.05\ H^{0.490}$
70	"	24	38	Straight endwall with entrance bell filled with concrete elliptically shaped with convex surface out.	.020	.70	.29	.01	$Q=22.20\ H^{0.485}$

Table 7—Continued

1 Table Number	2 Kind	3 Pipe Size Inches	4 Length Feet	5 Remarks	6 Entrance loss co-efficient	7 Ratio of velocity head to total head	8 Ratio of friction loss to total head	9 Ratio of entrance loss to total head	10 Equation
71	"	24	38	Straight endwall with entrance bell filled with concrete shaped to give a square cornered entrance.	.478	.55	.21	.24	$Q=19.60\ H^{0.485}$
72	Concrete	12	31	3-inch projection beyond headwall. Pipe with square cornered entrance.	.354	.46	.38	.16	$Q=4.28\ H^{0.477}$
73	"	12	31	24-inch projection beyond headwall. Pipe with square cornered entrance.	.342	.46	.38	.16	$Q=4.32\ H^{0.479}$
74	"	12	33	47-inch projection beyond headwall. Pipe with square cornered entrance.	.361	.45	.38	.17	$Q=4.26\ H^{0.483}$
75	"	12	33	47-inch projection beyond headwall. Pipe with beveled lip.	.092	.50	.45	.05	$Q=4.47\ H^{0.483}$
76	Metal	18	36	3-inch projection beyond headwall.	.314	.27	.65	.08	$Q=7.35\ H^{0.482}$
77	"	18	36	24-inch projection beyond headwall.	.552	.26	.60	.14	$Q=7.18\ H^{0.489}$
78	"	18	36	48-inch projection beyond headwall.	.568	.25	.61	.14	$Q=7.12\ H^{0.485}$
79	Clay	18	30	Straight endwall entrance 18 to 26-inch cone, 60 inches long at outlet end of pipe, length including cone 30-ft.	.032	.64	.33	.03	$Q=16.45\ H^{0.500}$

Exponential formulas for pipe culverts

From the data in Tables 22 to 79, a discharge equation for each table was derived for the various pipe culverts. By plotting on logarithmic paper the total head on the pipe for each test as abscissa against discharge as ordinate, an expression, $Q = K\ H^x$, was obtained in which K is the intercept on the unity vertical axis and x is the slope of the line. These individual discharge equations are given in Table 7 opposite their respective table numbers.

It will be noted from an examination of the individual discharge equations for the pipe culverts that the exponent of H varies from 0.467 to 0.523, eleven being 0.500 or over and forty-seven being less than 0.500. The average of the exponents for all the concrete pipe with beveled lip end upstream is 0.478. The average exponent for the concrete pipe with a square cornered entrance is also 0.478. The average exponent for the vitrified-clay pipe with the bell-end upstream is 0.491. The average exponent for the corrugated-metal pipe is 0.504. These four averages are for the pipe culverts with straight endwall entrances only. The average of the exponents for the 58 tables is 0.488. Since this average is nearly 0.500 and since it is common practice to accept the theory that the discharge varies as the square root of the head, it was decided to adopt the value of 0.500 as the exponent of H for subsequent calculations.

The exponent of H for the individual discharge equations varies somewhat. The value of the intercept for the individual formulas depends upon the slope of the line which is represented by the exponent of H. Changing the slope of the lines representing the formulas for the different pipe to conform to a uniform exponent or slope of 0.500 in general also affects the value of the intercept or coefficient. However, since a head of one foot was close to an average head for most of the experiments and near to the midpoint of the lines drawn over the range of the experimental points, it seemed consistent with the accuracy desired to use the same intercept for the equation with the 0.500 slope as was obtained in the original. Hence in the derivation of the general discharge equations for pipes of varying diameters the only change which was made in the individual formulas as shown in Table 7 was in the value of the exponent of H.

Table 8—Summary of results of test data on concrete box culverts

1 Table Number	2 Culvert Size in Feet	3 Length in Feet	4 Remarks	5 Entrance loss co-efficient	6 Ratio of velocity head to total head	7 Ratio of friction loss to total head	8 Ratio of entrance loss to total head	9 Equation
80	2 by 2	24	Straight end wall entrance with square corners.	0.411	0.62	0.12	0.26	$Q=25.4\ H^{0.503}$
81	2 by 2	30	” ” ” ” ” ” ”	.394	.60	.17	.23	$Q=24.8\ H^{0.496}$
82	2 by 2	36	” ” ” ” ” ” ”	.370	.58	.21	.21	$Q=24.5\ H^{0.500}$
83	2 by 2	30	Straight end wall entrance with beveled lip corners.	.134	.69	.21	.10	$Q=26.7\ H^{0.488}$
84	2 by 2	30	Straight end wall entrance with rounded lip corners.	.055	.72	.24	.04	$Q=27.2\ H^{0.498}$
85	2 by 2	30	Straight end wall entrance with rounded lip corners. Upper two corners of culvert chamfered 2-inches by 2-inches.	.048	.70	.26	.04	$Q=26.8\ H^{0.498}$
86	2 by 2	30	Straight end wall entrance with rounded lip corners. Outlet 2-ft. by 2-ft. to 4-ft. by 2-ft., 6-ft. long, flared on two sides only	.058	.70	.27	.03	$Q=34.8\ H^{0.492}$
87	2 by 2	30	Straight end wall entrance with rounded lip corners. Outlet 2-ft. by 2-ft. to 3.12-ft. by 2.56-ft., 6-ft. long, flared on two sides and bottom.	.045	.69	.28	.03	$Q=36.2\ H^{0.480}$
88	2 by 2	30	Straight end wall entrance with rounded lip corners. Outlet 2-ft. by 2-ft. to 3.12-ft. by 2.00-ft., 6-ft. long, flared on two sides only.	.053	.69	.27	.04	$Q=34.6\ H^{0.485}$
89	2 by 2	30	Straight end wall entrance with rounded lip corners. Outlet 2-ft. by 2-ft. to 4-ft. by 2-ft., 6-ft. long, sides flared on hyperbolic curve.	.057	.69	.28	.03	$Q=35.0\ H^{0.499}$
90	2 by 2	30	Straight end wall entrance with rounded lip corners. Outlet 2-ft. by 2-ft., to 4-ft. by 2-ft., 10-ft. long, flared on two sides only.	.063	.69	.27	.04	$Q=38.7\ H^{0.484}$
91	3 by 3	36	Straight end wall entrance with square corners.	.397	.62	.15	.23	$Q=55.5\ H^{0.488}$
92	3 by 3	30	” ” ” ” ” ” ”	.342	.67	.11	.22	$Q=58.2\ H^{0.490}$
93	3 by 3	30	Straight end wall entrance with beveled lip corners.	.081	.79	.15	.06	$Q=62.9\ H^{0.495}$
94	3 by 3	30	Straight end wall entrance with rounded lip corners.	.000	.81	.19	.00	$Q=63.2\ H^{0.470}$
95	3 by 3	30	Straight end wall entrance with rounded lip corners. Upper two corners of culvert chamfered 4-inches by 4-inches.	.000	.84	.16	.00	$Q=64.0\ H^{0.490}$
96	3 by 3	24	Straight end wall entrance with square corners.	.407	.65	.11	.24	$Q=56.1\ H^{0.466}$
97	3 by 3	36	Straight end wall entrance with rounded lip corners. Outlet 3-ft. by 3-ft. to 6-ft. by 3-ft., 12-ft. long, flared on two sides only.	.000	.76	.24	.00	$Q=88.5\ H^{0.468}$
98	3 by 3	24	Straight end wall entrance with rounded lip corners	.000	.80	.20	.00	$Q=62.4\ H^{0.448}$

99	2 by 2 to 4 by 2	30	Straight end wall entrance with rounded corners on two sides; culvert flared on two sides for entire length.					$Q=46.0\ H^{0.485}$
100	4 by 4	36	Straight end wall entrance with rounded lip corners.	.000	.82	.18	.00	$Q=116.0\ H^{0.497}$
101	4 by 4	36	Straight end wall entrance with square corners.	.400	.65	.12	.23	$Q=103.0\ H^{0.490}$
102	4 by 3	36	" " " " " " "	.386	.64	.14	.22	$Q=77.5\ H^{0.488}$
103	4 by 3	36	Straight end wall entrance with rounded lip corners.	.000	.82	.18	.00	$Q=87.0\ H^{0.477}$
104	4 by 2¼	36	Straight end wall entrance with rounded lip corners.	.000	.78	.22	.00	$Q=64.2\ H^{0.489}$
105	4 by 2¼	36	Straight end wall entrance with square corners.	.361	.64	.15	.21	$Q=58.2\ H^{0.487}$
106	4 by 2	36	" " " " " " "	.325	.63	.20	.17	$Q=51.2\ H^{0.489}$
107	4 by 2	36	Straight end wall entrance with rounded lip corners.	.000	.75	.25	.00	$Q=56.0\ H^{0.491}$
108	4 by 1	36	Straight end wall entrance with square corners.	.297	.56	.28	.16	$Q=23.7\ H^{0.513}$
109	4 by 1	36	Straight end wall entrance with rounded lip on top side of culvert only.	.027	.65	.34	.01	$Q=25.9\ H^{0.492}$
110	4 by 1	36	Straight end wall entrance with rounded lip corners.	.000	.65	.35	.00	$Q=26.2\ H^{0.493}$
111	4 by ½	36	Straight end wall entrance with rounded lip corners.	.024	.51	.48	.01	$Q=11.5\ H^{0.500}$

It was found that in laying the pipe culverts, the average length was approximately 30.6 feet so this figure was adopted as a base. Therefore, for the purpose of obtaining a comparison of the carrying capacities of various sizes of concrete, vitrified-clay, and corrugated-metal pipe culverts of this length, discharge equations have been derived from the data in Tables 22 to 37.

These general discharge equations for pipe culverts, 30.6 feet long with straight endwall entrances are as follows:

Concrete pipe with beveled lip end upstream.

$$Q = 4.61\ D^{2.18}\ H^{0.50} \quad (1)$$

Concrete pipe with square-cornered entrance.

$$Q = 4.40\ D^{2.09}\ H^{0.50} \quad (2)$$

Vitrified-clay pipe with regular bell-end upstream.

$$Q = 5.07\ D^{2.05}\ H^{0.50} \quad (3)$$

Corrugated-metal pipe.

$$Q = 3.10\ D^{2.31}\ H^{0.50} \quad (4)$$

in which Q = discharge in cubic feet per second.
D = diameter of pipe in feet.
H = Total head on pipe or the difference in the water level at the two ends of the pipe.

These formulas apply to pipes with diameters of 12 to 30 inches and may be extended with comparatively little error up to 48-inch pipes.

General formulas for pipe culverts

After a study of the experimental values of the entrance loss coefficients for the pipe culverts given in Table 7 which is a summary of the results of the test data on pipe culverts, it was decided to develop a formula of the usual type for flow in pipes. This formula is as follows:

$$Q = \frac{A\sqrt{2gH}}{\left[1 + K_e + \frac{fl}{D^x}\right]^{1/2}} \quad (5)$$

in which Q = discharge in cubic feet per second.
H = head on the pipe in feet.
A = area of pipe in square feet.
D = diameter of pipe in feet.

L = length of pipe in feet.
K_e = entrance loss coefficient.
f = friction loss coefficient.
g = acceleration of gravity.

The total head acting on a culvert may be expressed by the following equation:

$$H=\left(1+K_e+\frac{fl}{D^x}\right)\frac{V^2}{2g} \qquad (6)$$

Since $Q=A\ V$, then $V=\frac{Q}{A}$

Substituting in equation 6, the value of V, we get

$$H=\left(1+K_e+\frac{fl}{D^x}\right)\frac{Q^2}{2gA^2} \qquad (7)$$

Transposing and rearranging equation 7, we get

$$\frac{2g\ A^2H}{Q^2}-(1+K_e)=\frac{fl}{D^x} \qquad (8)$$

But the individual pipe culvert equations as given in Table 7 are of the form

$$Q=K\ H^{0.50} \qquad (9)$$

Substituting in equation 8, the values of Q as given in equation 9, we get

$$\frac{2g\ A^2}{K^2}-(1+K_e)=\frac{fl}{D^x} \qquad (10)$$

The values of K and K_e obtained for each pipe were taken from Table 7 and substituted in equation 10. Thus the quantity $\frac{f}{D^x}$ was computed directly. Since the symbol f is the friction constant for a given pipe, it may be obtained by another method. In the tables giving the results of the experimental data, (Tables 22 to 37) the summation of the friction losses for all tests in any one table was divided by the summation of the velocity heads for that table. These quotients were divided in each case by the length of the culvert and a value of $\frac{f}{D^x}$ was obtained which should check with that obtained by equation 10.

It will be noted in the tables giving the results of the experimental data that the entrance loss coefficient for any given size of pipe is fairly constant but varies somewhat with the different sizes of the same pipe. Therefore, in order to introduce the effect of the diameter, the values of the entrance loss coefficient, K_e, may be plotted as ordinate against the respective diameters of the pipe as abscissa on logarithmic paper, and an equation of the form

$$K_e = K' D^x \qquad (11)$$

would be obtained in which K' is the intercept on the unity vertical axis and the exponent x is the slope of the line.

Likewise, the friction factors were plotted as ordinate against their respective diameters as abscissa on logarithmic paper and the equation

$$F = f/D^x \qquad (12)$$

was obtained. It was noted that the exponent x for the various pipe culverts was as follows:

Concrete pipe culvert, beveled lip entrance	1.18
Concrete pipe culvert, square cornered entrance	1.29
Vitrified-clay pipe	0.60
Corrugated-metal pipe	1.18

The exponent for the vitrified-clay pipe culvert, 0.60, is lower than might be expected. For the other culverts, 1.2 is about an average value. It was decided to adopt unity as the exponent of D for the vitrified-clay pipe and 1.2 as the exponent of D for the other pipe culverts. Using these adopted slopes, the lines were redrawn and new intercepts determined.

The equations finally obtained for pipe culverts with straight endwall entrances are as follows:

Concrete pipe, beveled lip entrance

$$Q = \frac{A\sqrt{2g\,H}}{\sqrt{1.1 + \dfrac{0.026\,L}{D^{1.2}}}} \qquad (13)$$

Concrete pipe, square cornered entrance

$$Q = \frac{A\sqrt{2g\,H}}{\sqrt{1 + 0.31\,D^{0.5} + \dfrac{0.026\,L}{D^{1.2}}}} \qquad (14)$$

Vitrified-clay pipe, regular bell-end upstream

$$Q = \frac{A\ \sqrt{2g\ H}}{\sqrt{1 + 0.023\ D^{1.9} + \frac{0.022\ L}{D^{1.0}}}} \tag{15}$$

Corrugated-metal pipe

$$Q = \frac{A\ \sqrt{2g\ H}}{\sqrt{1 + 0.16\ D^{0.6} + \frac{0.106\ L}{D^{1.2}}}} \tag{16}$$

Formulas 13 to 16 apply to pipe culverts of any size and length with straight endwall entrances.

Exponential formulas for box culverts

From the data in Tables 80 to 111, a discharge equation for each table was derived for the various concrete box culverts. By plotting on logarithmic paper the total head on the box culvert for each test as abscissa against discharge as ordinate, an expression, $Q = K\ H^x$ was obtained in which K is the intercept on the unity vertical axis and x is the slope of the line. These individual discharge equations for the box culverts are given in Table 8 opposite their respective table numbers.

An examination of the individual discharge equations for the box culverts shows that the exponent of H varies from 0.448 to 0.513, five being either 0.500 or above and twenty-eight being less than 0.500. The average of the exponents 0.500 and over is 0.505 and the average of the exponents under 0.500 is 0.486. The average for all the box-culvert equations is 0.489.

General formulas for box culverts

The general formulas for the box culverts were derived in the same manner as the general formulas for the pipe culverts. However, it was necessary to use the mean hydraulic radius as a variable instead of the diameter so the formulas would be more convenient.

A study of Tables 80 to 111 as well as Table 8 will show that for box culverts with square-cornered entrances the entrance loss coefficient increases with an increase in the hydraulic radius. The entrance loss coefficient for the box culverts with rounded lip entrances is very small and may be considered practically constant for all sizes with a value of about 0.05. Some of the entrance loss coefficients for the box culverts with rounded lip entrances are negative. This coefficient can never be negative but the amount of entrance loss with this type of entrance is so small that it is difficult to determine accurately. The friction loss factors were determined by equation 10. Although the friction loss in a box culvert varies with the type of entrance (See Table 6), there was insufficient data on the different shapes of culverts of various sizes and types of entrances to evaluate for the general formula a friction factor for each shape of culvert and type of entrance. Therefore a general equation for the friction loss was obtained from all the data on box culverts.

Plotting the data for the box culvert tests, we obtain the following general equations for concrete box culverts with straight end wall entrances, and of any size and length:

Box culverts with rounded lip entrance:

$$Q = \frac{A\sqrt{2g\,H}}{\sqrt{1.05 + \dfrac{0.0045\,L}{R^{1.25}}}} \tag{17}$$

Box culverts with square cornered entrance:

$$Q = \frac{A\sqrt{2g\,H}}{\sqrt{1 + 0.40\,R^{0.3} + \dfrac{0.0045\,L}{R^{1.25}}}} \tag{18}$$

Formulas for box culverts flowing partly full

In a study of the results of the tests on the box culverts flowing partly full it was found that the hydraulics of the flow through the culvert varies for different downstream water surface elevations, and no one formula could apply to all of the different conditions encountered. If the water discharged freely into air, that is, the outlet water was not of sufficient height to retard the flow, the conditions were not unlike that of water discharging over a broad-crested weir as long as the width of the culvert and with a crest breadth equal to the length of the culvert. For such conditions it is comparatively easy to compute the discharge of a box culvert knowing the width of the culvert and the height of the entrance water above the floor of the culvert at its entrance.

For those tests in which a free outlet existed, the height of the head water, H, above the culvert floor was plotted as abscissa against the discharge, Q, as ordinate on logarithmic paper and the following equations were obtained:

Box culverts with square-cornered entrances:

2-ft. by 2-ft.	$Q = 2.66\ L\ H^{1.5}$	(19)
3-ft. by 3-ft.	$Q = 2.77\ L\ H^{1.5}$	(20)
4-ft. by 4-ft.	$Q = 2.61\ L\ H^{1.5}$	(21)

Box culverts with rounded lip entrances:

2-ft. by 2-ft.	$Q = 2.85\ L\ H^{1.5}$	(22)
3-ft. by 3-ft.	$Q = 2.93\ L\ H^{1.5}$	(23)
4-ft. by 4-ft.	$Q = 2.71\ L\ H^{1.5}$	(24)

In these formulas Q = discharge in cubic feet per second
L = width of culvert in feet
H = height of entrance water above culvert floor

These formulas are very similar to the formula for the broad-crested weir, the difference being in the coefficient.

Averaging the coefficients for each type of entrance we have for box culverts flowing partly full and with a free outlet,

Box culverts with square cornered entrance:

$$Q = 2.70\ L\ H^{1.5} \qquad (25)$$

Box culverts with rounded lip entrance:

$$Q = 2.85\ L\ H^{1.5} \qquad (26)$$

These formulas do not apply when the water level at the entrance of the culvert is above the inside top of the culvert at the entrance.

When the outlet water is high enough to retard the flow in a box culvert flowing partly full, different conditions exist for different types of flow and many attempts were made to adapt the results in the form of a simple formula, but with little success. The formula finally adopted was

$$Q = K\ A\ \sqrt{2g\ H} \qquad (27)$$

in which Q = discharge in cubic feet per second
K = a coefficient
A = average cross-sectional area of flow in culvert
H = difference in elevation of water level between entrance and outlet of the culvert

Table 9—Capacities in cubic feet per second of concrete pipe culverts, straight endwall entrance, length 30.6 feet, beveled lip end upstream

Head on Pipe-Feet	12-inch	* 15-inch	18-inch	* 21-inch	24-inch	30-inch	* 36-inch	* 42-inch	* 48-inch
.01	0.46	0.75	1.12	1.56	2.09	3.40	5.06	7.08	9.47
.02	0.65	1.06	1.58	2.21	2.95	4.80	7.15	10.0	13.4
.03	0.80	1.30	1.93	2.70	3.62	5.89	8.76	12.3	16.4
.04	0.92	1.50	2.23	3.12	4.18	6.80	10.1	14.2	18.9
.05	1.03	1.68	2.49	3.49	4.67	7.60	11.3	15.8	21.2
.06	1.13	1.84	2.73	3.83	5.12	8.32	12.4	17.3	23.2
.07	1.22	1.98	2.95	4.13	5.53	8.99	13.4	18.7	25.1
.08	1.30	2.12	3.16	4.42	5.91	9.61	14.3	20.0	26.8
.09	1.38	2.25	3.35	4.68	6.27	10.2	15.2	21.2	28.4
.1	1.46	2.37	3.53	4.94	6.61	10.7	16.0	22.4	29.9
.2	2.06	3.35	4.99	6.98	9.34	15.2	22.6	31.6	42.3
.3	2.52	4.11	6.11	8.55	11.4	18.6	27.7	38.8	51.9
.4	2.92	4.74	7.06	9.88	13.2	21.5	32.0	44.8	59.9
.5	3.26	5.30	7.89	11.0	14.8	24.0	35.8	50.0	66.9
.6	3.57	5.81	8.64	12.1	16.2	26.3	39.2	54.8	73.3
.7	3.86	6.27	9.34	13.1	17.5	28.4	42.3	59.2	79.2
.8	4.12	6.71	9.98	14.0	18.7	30.4	45.2	63.3	84.7
.9	4.37	7.11	10.6	14.8	19.8	32.2	48.0	67.1	89.8
1.0	4.61	7.50	11.2	15.6	20.9	34.0	50.6	70.8	94.7
1.2	5.05	8.21	12.2	17.1	22.9	37.2	55.4	77.5	104
1.4	5.45	8.87	13.2	18.5	24.7	40.2	59.8	83.7	112
1.6	5.83	9.48	14.1	19.8	26.4	43.0	64.0	89.5	120
1.8	6.18	10.1	15.0	21.0	28.0	45.6	67.8	94.9	127
2.0	6.52	10.6	15.8	22.1	29.5	48.1	71.5	100	134
2.2	6.84	11.1	16.6	23.2	31.0	50.4	75.0	105	140
2.4	7.14	11.6	17.3	24.2	32.4	52.6	78.3	110	147
2.6	7.43	12.1	18.0	25.2	33.7	54.8	81.5	114	153
2.8	7.71	12.6	18.7	26.1	35.0	56.9	84.6	118	158
3.0	7.98	13.0	19.3	27.1	36.2	58.9	87.6	123	164
3.2	8.25	13.4	20.0	27.9	37.4	60.8	90.5	127	169
3.4	8.50	13.8	20.6	28.8	38.5	62.7	93.2	130	175
3.5	8.62	14.0	20.9	29.2	39.1	63.6	94.6	132	177

Note: This table is based on the Formula $Q=4.61\ D^{2.18} H^{0.50}$ in which Q=Discharge in Cubic feet per second, D=Diameter of Pipe in feet, and H=Head on Pipe in feet.
* No experiments were made on these sizes.

The coefficient, *K*, varied greatly for the various tests for the different culverts ranging from 0.82 to 1.18, the average value for a great many tests being 0.90. It was evident that no reliable degree of accuracy could be obtained with a formula having a coefficient varying so widely.

COMPARISON OF CARRYING CAPACITY OF CONCRETE, VITRIFIED-CLAY, AND CORRUGATED-METAL PIPE CULVERTS

Discharge tables have been computed from the general exponential equations 1, 2, 3, and 4 for concrete, vitrified-clay, and corrugated-metal pipe culverts for heads from 0.01 to 3.5 feet for the following sizes of pipe, 12, 15, 18, 21, 24, 30, 36, 42, and 48 inches in diameter. These capacities are shown in Tables 9, 10, 11, and 12.

Table 10—Capacities in cubic feet per second of concrete pipe culverts, straight endwall entrance, length 30.6 feet, square cornered entrance

Head on Pipe feet	12-inch	* 15.inch	18-inch	* 21-inch	24-inch	30-inch	* 36-inch	* 42-inch	* 48-inch
.01	0.44	0.70	1.03	1.42	1.87	2.99	4.37	6.03	7.98
.02	0.62	0.99	1.45	2.00	2.65	4.22	6.18	8.53	11.3
.03	0.76	1.21	1.78	2.45	3.24	5.17	7.57	10.4	13.8
.04	0.88	1.40	2.05	2.83	3.75	5.97	8.74	12.1	16.0
.05	0.98	1.57	2.30	3.17	4.19	6.68	9.77	13.5	17.8
.06	1.08	1.72	2.52	3.47	4.59	7.32	10.7	14.8	19.5
.07	1.16	1.86	2.72	3.75	4.96	7.90	11.6	16.0	21.1
.08	1.24	1.98	2.90	4.01	5.30	8.45	12.4	17.1	22.6
.09	1.32	2.10	3.08	4.25	5.62	8.96	13.1	18.1	23.9
.1	1.39	2.22	3.25	4.48	5.92	9.44	13.8	19.1	25.2
.2	1.97	3.14	4.59	6.34	8.38	13.4	19.6	27.0	35.7
.3	2.41	3.84	5.62	7.76	10.3	16.4	23.9	33.0	43.7
.4	2.78	4.44	6.49	8.96	11.9	18.9	27.7	38.2	50.4
.5	3.11	4.96	7.26	10.0	13.3	21.1	30.9	42.7	56.4
.6	3.41	5.43	7.95	11.0	14.5	23.1	33.9	46.7	61.8
.7	3.68	5.87	8.59	11.9	15.7	25.0	36.6	50.5	66.7
.8	3.94	6.27	9.18	12.7	16.8	26.7	39.1	54.0	71.3
.9	4.17	6.65	9.74	13.4	17.8	28.3	41.5	57.2	75.7
1.0	4.40	7.01	10.3	14.2	18.7	29.9	43.7	60.3	79.8
1.2	4.82	7.68	11.3	15.5	20.5	32.7	48.0	66.1	87.4
1.4	5.21	8.30	12.2	16.8	22.2	35.3	51.7	71.4	94.4
1.6	5.57	8.87	13.0	17.9	23.7	37.8	55.3	76.3	101
1.8	5.90	9.41	13.8	19.0	25.1	40.1	58.6	80.9	107
2.0	6.22	9.92	14.5	20.0	26.5	42.2	61.8	85.3	113
2.2	6.53	10.4	15.2	21.0	27.8	44.3	64.8	89.5	118
2.4	6.82	10.9	15.9	21.9	29.0	46.3	67.7	93.5	124
2.6	7.10	11.3	16.6	22.9	30.2	48.2	70.5	97.3	129
2.8	7.36	11.7	17.2	23.7	31.4	50.0	73.2	101	133
3.0	7.62	12.2	17.7	24.5	32.5	51.7	75.7	105	138
3.2	7.87	12.6	18.4	25.3	33.5	53.4	78.2	108	143
3.4	8.11	12.9	18.9	26.1	34.5	55.1	80.6	111	147
3.5	8.23	13.1	19.2	26.5	35.1	55.9	81.8	113	149

Note: This table is based on the Formula $Q=4.40\ D^{2.09} H^{0.50}$ in which Q=Discharge in Cubic feet per second, D=Diameter of Pipe in feet, and H=Head on Pipe in feet.
* No experiments were made on these sizes.

From the data in Tables 9, 10, 11, and 12, discharge curves have been plotted using total head on the culvert in feet as the abscissa and discharge in cubic feet per second as the ordinate. These curves are shown in figures 16, 17, 18, and 19. The individual test observations have also been plotted on these diagrams.

In order to determine the carrying capacities of pipe culverts longer than 30 feet, discharge tables have been prepared for the various pipe culverts using formulas 13 to 16 for the following lengths, 100, 200, 300, 400, and 500 feet. These capacities are given in Tables 13, 14, 15, and 16. In these longer pipes, the metal culvert has a much smaller capacity in comparison with the others than in the standard 30-foot lengths.

Table 11—Capacities in cubic feet per second of vitrified-clay pipe culverts, straight endwall entrance, length 30.6 feet, regular bell end upstream

Head on Pipe-Feet	12-inch	* 15.inch	18-inch	* 21-inch	24-inch	30-inch	* 36-inch	* 42-inch	* 48-inch
.01	0.51	0.80	1.16	1.60	2.10	3.32	4.82	6.61	8.69
.02	0.72	1.13	1.65	2.26	2.97	4.69	6.82	9.35	12.3
.03	0.88	1.39	2.02	2.77	3.64	5.75	8.35	11.5	15.1
.04	1.01	1.60	2.33	3.19	4.20	6.63	9.64	13.2	17.4
.05	1.13	1.79	2.60	3.57	4.69	7.42	10.8	14.8	19.4
.06	1.24	1.96	2.85	3.91	5.14	8.13	11.8	16.2	21.3
.07	1.34	2.12	3.08	4.22	5.56	8.78	12.8	17.5	23.0
.08	1.43	2.27	3.29	4.52	5.94	9.38	13.6	18.7	24.6
.09	1.52	2.40	3.49	4.79	6.30	9.95	14.5	19.8	26.1
.1	1.60	2.53	3.68	5.05	6.64	10.5	15.2	20.9	27.5
.2	2.27	3.58	5.21	7.14	9.39	14.8	21.6	29.6	38.9
.3	2.78	4.39	6.38	8.75	11.5	18.2	26.4	36.2	47.6
.4	3.21	5.07	7.36	10.1	13.3	21.0	30.5	41.8	55.0
.5	3.58	5.66	8.23	11.3	14.9	23.5	34.1	46.8	61.5
.6	3.93	6.21	9.02	12.4	16.3	25.7	37.3	51.2	67.4
.7	4.24	6.70	9.74	13.4	17.6	27.8	40.3	55.3	72.7
.8	4.53	7.16	10.4	14.3	18.8	29.7	43.1	59.1	77.8
.9	4.81	7.60	11.0	15.2	19.9	31.5	45.7	62.7	82.5
1.0	5.07	8.01	11.6	16.0	21.0	33.2	48.2	66.1	86.9
1.2	5.55	8.78	12.8	17.5	23.0	36.3	52.8	72.4	95.3
1.4	6.00	9.48	13.8	18.9	24.8	39.3	57.0	78.2	103
1.6	6.41	10.1	14.7	20.2	26.6	42.0	61.0	83.6	110
1.8	6.80	10.8	15.6	21.4	28.2	44.5	64.7	88.7	117
2.0	7.17	11.3	16.5	22.6	29.7	46.9	68.2	93.5	123
2.2	7.52	11.9	17.3	23.7	31.1	49.2	71.5	98.1	129
2.4	7.85	12.4	18.0	24.7	32.5	51.4	74.7	102	135
2.6	8.18	12.9	18.8	25.8	33.9	53.5	77.7	107	140
2.8	8.48	13.4	19.5	26.7	35.1	55.5	80.7	111	145
3.0	8.78	13.9	20.2	27.7	36.4	57.5	83.5	115	151
3.2	9.07	14.3	20.8	28.6	37.6	59.3	86.2	118	156
3.4	9.35	14.8	21.5	29.4	38.7	61.2	88.9	122	160
3.5	9.48	15.0	21.8	29.9	39.3	62.1	90.2	124	163

Note: This table is based on the Formula $Q=5.07\ D^{2.05}H^{0.50}$ in which Q=Discharge in Cubic feet per second, D=Diameter of Pipe in feet, and H=Head on Pipe in feet.
* No experiments were made on these sizes.

Table 12—Capacities in cubic feet per second of corrugated-metal pipe culverts, straight endwall entrance, length 30.6 feet

Head on Pipe-Feet	12-inch	* 15-inch	18-inch	* 21-inch	24-inch	30-inch	* 36-inch	* 42-inch	* 48-inch
.01	0.31	0.52	0.79	1.13	1.54	2.57	3.92	5.60	7.62
.02	0.44	0.73	1.12	1.60	2.17	3.64	5.55	7.92	10.8
.03	0.54	0.90	1.37	1.96	2.66	4.46	6.79	9.70	13.2
.04	0.62	1.04	1.58	2.26	3.07	5.15	7.84	11.2	15.3
.05	0.69	1.16	1.77	2.52	3.44	5.76	8.77	12.5	17.0
.06	0.76	1.27	1.94	2.77	3.77	6.31	9.61	13.7	18.7
.07	0.82	1.37	2.09	2.99	4.07	6.81	10.4	14.8	20.2
.08	0.88	1.47	2.24	3.19	4.35	7.28	11.1	15.8	21.6
.09	0.93	1.56	2.37	3.39	4.61	7.72	11.8	16.8	22.9
.1	0.98	1.64	2.50	3.57	4.86	8.14	12.4	17.7	24.1
.2	1.39	2.32	3.54	5.05	6.87	11.5	17.5	25.0	34.1
.3	1.70	2.84	4.33	6.18	8.42	14.1	21.5	30.7	41.8
.4	1.96	3.28	5.00	7.14	9.72	16.3	24.8	35.4	48.2
.5	2.19	3.67	5.59	7.98	10.9	18.2	27.7	39.6	53.9
.6	2.40	4.02	6.13	8.75	11.9	19.9	30.4	43.4	59.1
.7	2.59	4.34	6.62	9.45	12.9	21.5	32.8	46.9	63.8
.8	2.77	4.64	7.07	10.1	13.8	23.0	35.1	50.1	68.2
.9	2.94	4.92	7.50	10.7	14.6	24.4	37.2	53.1	72.3
1.0	3.10	5.19	7.91	11.3	15.4	25.7	39.2	56.0	76.2
1.2	3.40	5.69	8.66	12.4	16.8	28.2	43.0	61.3	83.5
1.4	3.67	6.14	9.36	13.4	18.2	30.5	46.4	66.3	90.2
1.6	3.92	6.57	10.0	14.3	19.4	32.6	49.6	70.8	96.4
1.8	4.16	6.96	10.6	15.2	20.6	34.5	52.6	75.1	102
2.0	4.38	7.34	11.2	16.0	21.7	36.4	55.5	79.2	108
2.2	4.60	7.70	11.7	16.8	22.8	38.2	58.2	83.0	113
2.4	4.80	8.04	12.3	17.5	23.8	39.9	60.8	86.8	118
2.6	5.00	8.37	12.8	18.2	24.8	41.5	63.2	90.3	123
2.8	5.19	8.69	13.2	18.9	25.7	43.1	65.6	93.7	128
3.0	5.37	8.99	13.7	19.6	26.6	44.6	67.9	97.0	132
3.2	5.55	9.29	14.2	20.2	27.5	46.1	70.2	100	136
3.4	5.72	9.57	14.6	20.8	28.4	47.5	72.3	103	141
3.5	5.80	9.71	14.8	21.1	28.8	48.2	73.4	105	143

Note: This table is based on the Formula $Q=3.10\ D^{2.31}H^{0.50}$ in which Q=Discharge in Cubic feet per second, D=Diameter of Pipe in feet, and H=Head on Pipe in feet.
* No experiments were made on these sizes.

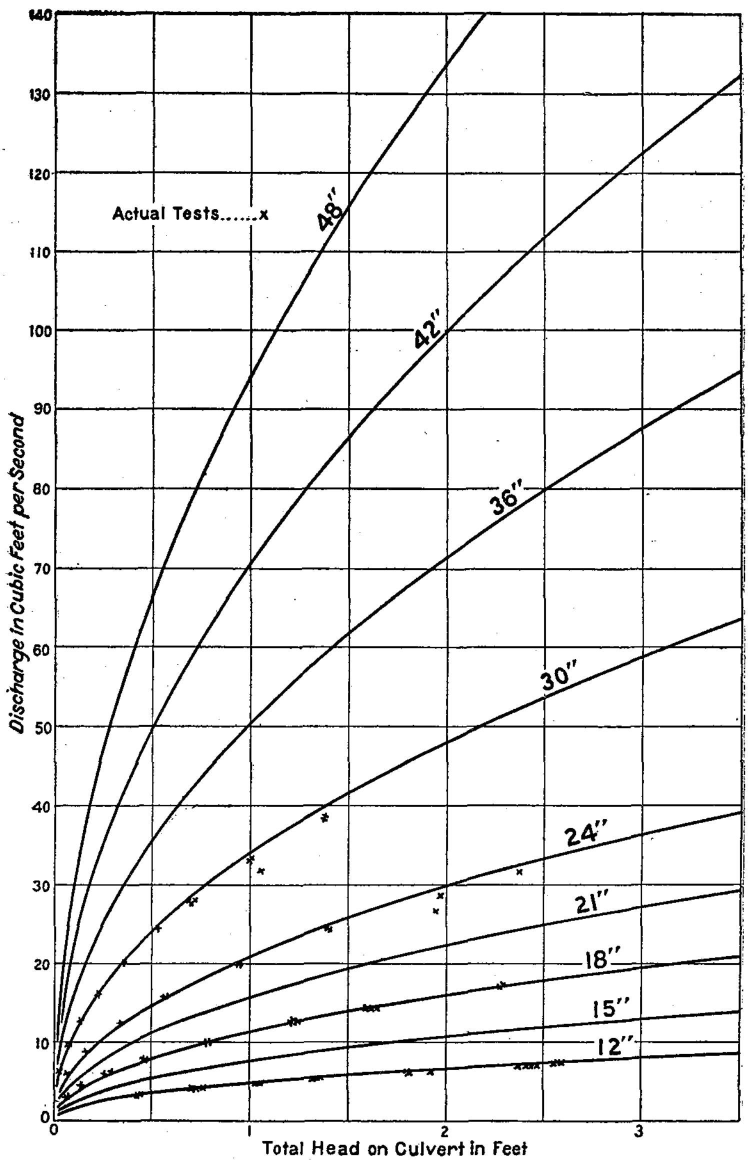


Fig. 16. DISCHARGE CURVES FOR CONCRETE PIPE CULVERTS

Straight endwall entrance. Length, 30.6 feet. Beveled-lip end upstream. Based on the formula, $Q = 4.61 D^{2.18} H^{0.50}$ in which: Q = discharge in cubic feet per second; D = diameter of pipe in feet; H = head on pipe in feet.

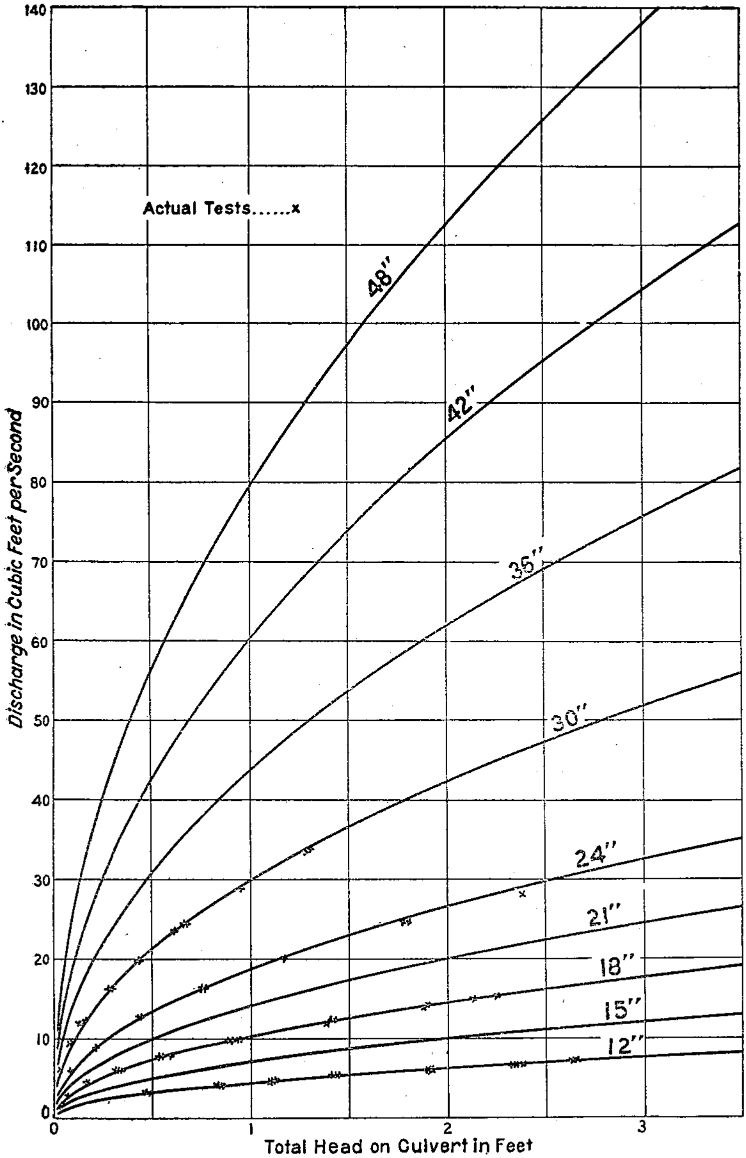


Fig. 17. DISCHARGE CURVES FOR CONCRETE PIPE CULVERTS

Straight endwall entrance. Length, 30.6 feet. Square-cornered entrance. Based on the formula, $Q = 4.40\ D^{2.09}\ H^{0.50}$ in which: Q = discharge in cubic feet per second; D = diameter of pipe in feet; H = head on pipe in feet.

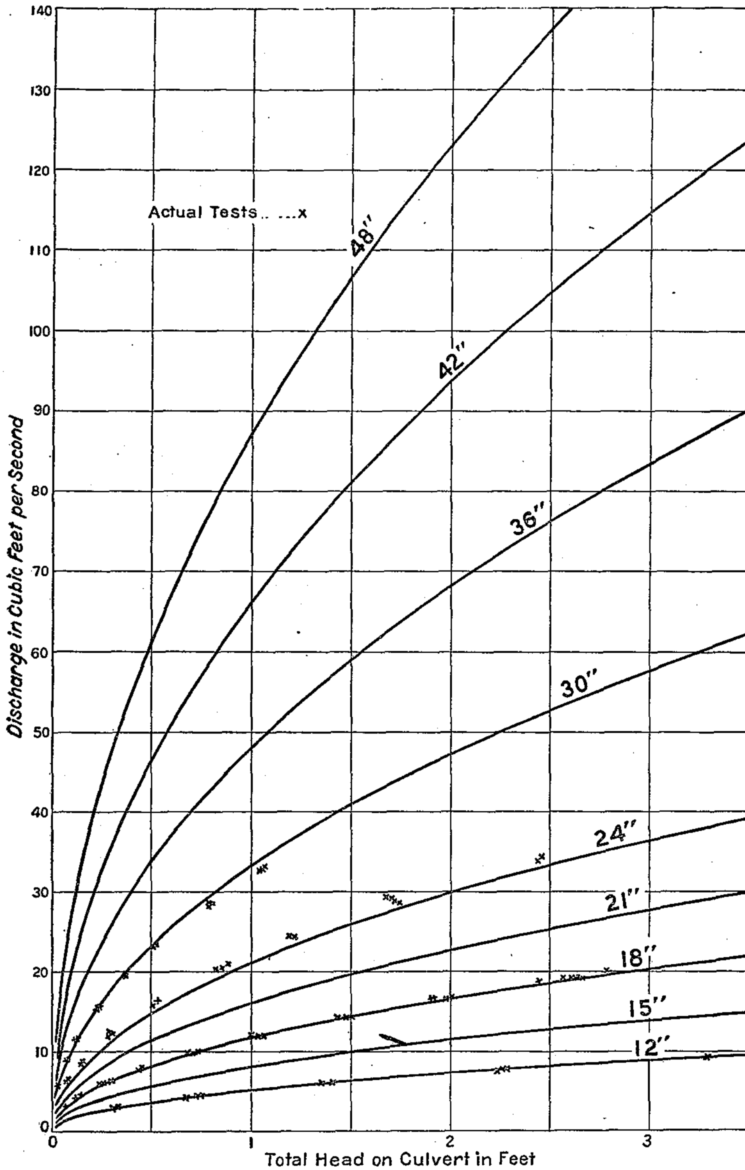


Fig. 18. DISCHARGE CURVES FOR VITRIFIED-CLAY PIPE CULVERTS

Straight endwall entrance. Length, 30.6 feet. Regular bell end upstream. Based on the formula, $Q = 5.07\ D^{2.05}\ H^{0.50}$ in which: Q = discharge in cubic feet per second; D = diameter of pipe in feet; H = head on pipe in feet.

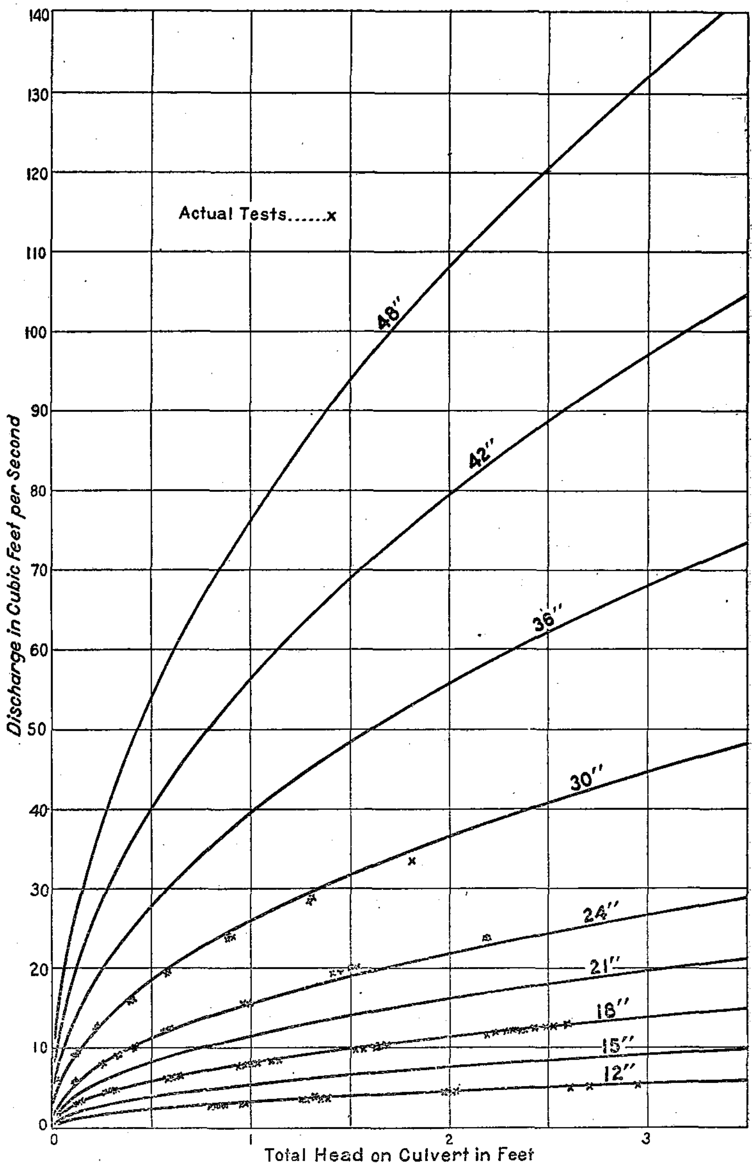


Fig. 19. DISCHARGE CURVES FOR CORRUGATED-METAL PIPE CULVERTS

Straight endwall entrance. Length 30.6 feet. Based on the formula $Q = 3.10\ D^{2.31}\ H^{0.50}$ in which: Q = discharge in cubic feet per second; D = diameter of pipe in feet; H = head on pipe in feet.

Table 13—Capacities in cubic feet per second of concrete pipe culverts, straight endwall entrance, beveled lip end upstream

Diameter of Pipe-Inches	Head on culvert in feet															
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
	Length = 100 feet															
12	1.03	1.46	1.79	2.07	2.31	2.53	2.74	2.92	3.10	3.27	3.99	4.61	5.17	5.66	6.54	7.32
15	1.77	2.50	3.07	3.54	3.96	4.34	4.69	5.01	5.31	5.60	6.86	7.92	8.85	9.70	11.2	12.5
18	2.72	3.85	4.72	5.45	6.10	6.68	7.21	7.71	8.18	8.62	10.6	12.2	13.6	14.9	17.2	19.3
24	5.34	7.55	9.26	10.7	11.9	13.1	14.1	15.1	16.0	16.9	20.7	23.9	26.7	29.2	33.8	37.8
30	8.88	12.6	15.4	17.8	19.9	21.8	23.5	25.1	26.6	28.1	34.4	39.7	44.4	48.6	56.2	62.8
36	13.4	18.9	23.2	26.7	29.9	32.8	35.4	37.8	40.1	42.3	51.8	59.8	66.9	73.3	84.6	94.6
48	25.2	35.7	43.8	50.5	56.5	61.9	66.8	71.4	75.8	79.9	97.9	113.0	126.0	138.0	160.0	179.0
	Length = 200 feet															
12	0.79	1.12	1.37	1.59	1.77	1.94	2.10	2.24	2.38	2.51	3.08	3.55	3.97	4.35	5.02	5.61
15	1.38	1.95	2.39	2.76	3.09	3.38	3.66	3.91	4.15	4.37	5.35	6.18	6.91	7.56	8.74	9.77
18	2.16	3.06	3.75	4.33	4.84	5.30	5.72	6.12	6.49	6.84	8.38	9.67	10.8	11.8	13.7	15.3
24	4.33	6.13	7.50	8.66	9.69	10.6	11.5	12.2	13.0	13.7	16.7	19.4	21.6	23.7	27.4	30.6
30	7.40	10.5	12.8	14.8	16.5	18.1	19.6	20.9	22.2	23.4	28.7	33.1	37.0	40.5	46.8	52.3
36	11.4	16.0	19.7	22.7	25.4	27.8	30.0	32.1	34.1	35.9	44.0	50.8	56.8	62.2	71.8	80.3
48	22.1	31.2	38.2	44.1	49.4	54.1	58.4	62.4	66.2	69.8	85.5	98.7	110.0	121.0	140.0	156.0
	Length = 300 feet															
12	0.67	0.94	1.16	1.33	1.49	1.64	1.76	1.89	2.00	2.11	2.58	2.98	3.33	3.65	4.22	4.72
15	1.17	1.65	2.03	2.34	2.62	2.87	3.10	3.31	3.51	3.70	4.53	5.23	5.85	6.41	7.40	8.27
18	1.85	2.61	3.20	3.69	4.13	4.52	4.89	5.22	5.54	5.84	7.15	8.26	9.23	10.1	11.7	13.1
24	3.76	5.32	6.52	7.53	8.41	9.22	9.96	10.6	11.3	11.9	14.6	16.8	18.8	20.6	23.8	26.6
30	6.48	9.17	11.2	13.0	14.5	15.9	17.2	18.3	19.4	20.5	25.1	29.0	32.4	35.5	41.0	45.8
36	10.0	14.2	17.4	20.1	22.5	24.6	26.6	28.4	30.2	31.8	39.0	45.0	50.3	55.1	63.6	71.1
48	19.9	28.1	34.4	39.7	44.4	48.6	52.5	56.1	59.6	62.8	76.9	88.8	99.3	109.0	126.0	140.0
	Length = 400 feet															
12	0.59	0.83	1.02	1.18	1.32	1.44	1.56	1.66	1.76	1.86	2.28	2.63	2.94	3.22	3.72	4.16
15	1.03	1.46	1.79	2.07	2.31	2.53	2.74	2.92	3.10	3.27	4.01	4.61	5.17	5.66	6.54	7.31
18	1.64	2.32	2.84	3.28	3.66	4.01	4.34	4.63	4.92	5.18	6.35	7.32	8.19	8.97	10.4	11.6
24	3.35	4.74	5.81	6.70	7.50	8.21	8.87	9.48	10.1	10.6	13.0	15.0	16.8	18.4	21.2	23.7
30	5.82	8.23	10.1	11.6	13.0	14.2	15.4	16.4	17.5	18.4	22.5	26.0	29.1	31.8	36.8	41.1
36	9.11	12.9	15.8	18.2	20.4	22.3	24.1	25.7	27.3	28.8	35.3	40.7	45.5	49.9	57.6	64.5
48	18.2	25.7	31.5	36.4	40.7	44.5	48.1	51.4	54.5	57.5	70.5	81.3	90.9	99.6	115.0	129.0

Length = 500 feet																
12	0.53	0.75	0.92	1.06	1.19	1.30	1.41	1.50	1.59	1.68	2.06	2.38	2.66	2.91	3.36	3.76
15	0.93	1.32	1.62	1.87	2.09	2.29	2.48	2.65	2.81	2.96	3.62	4.18	4.68	5.12	5.92	6.62
18	1.49	2.10	2.58	2.97	3.32	3.64	3.93	4.20	4.46	4.70	5.75	6.65	7.43	8.14	9.40	10.5
24	3.06	4.33	5.31	6.13	6.85	7.51	8.11	8.66	9.19	9.69	11.9	13.7	15.3	16.8	19.4	21.7
30	5.34	7.55	9.26	10.7	12.0	13.1	14.1	15.1	16.0	16.9	20.7	23.9	26.7	29.2	33.8	37.8
36	8.38	11.8	14.5	16.8	18.7	20.5	22.2	23.7	25.1	26.5	32.5	37.5	41.9	45.9	53.0	59.2
48	16.9	23.9	29.2	33.8	37.8	41.4	44.7	47.7	50.7	53.4	65.4	75.5	84.4	92.5	107.0	119.0

This table is based on the formula $Q = \frac{A\sqrt{2gH}}{\sqrt{1.1 + \frac{0.0260\,L}{D^{1.2}}}}$ in which Q = Discharge in cubic feet per second; A = Cross sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; D = Diameter of culvert pipe in feet.

Table 14—Capacities in cubic feet per second of concrete pipe culverts, straight endwall entrance, square corners

Diameter of Pipe-Inches	Head on culvert in feet 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
							Length = 100 feet									
12	1.01	1.43	1.75	2.02	2.26	2.47	2.67	2.85	3.03	3.19	3.89	4.50	5.04	5.52	6.38	7.14
15	1.70	2.41	2.95	3.41	3.81	4.18	4.51	4.82	5.12	5.39	6.58	7.60	8.52	9.32	10.8	12.1
18	2.59	3.67	4.50	5.19	5.80	6.36	6.87	7.34	7.79	8.21	10.0	11.6	13.0	14.2	16.4	18.4
24	4.96	7.02	8.60	9.92	11.1	12.2	13.1	14.0	14.9	15.7	19.2	22.1	24.8	27.2	31.4	35.2
30	8.09	11.4	14.0	16.2	18.1	19.8	21.4	22.9	24.3	25.6	31.2	36.1	40.4	44.3	51.2	57.3
36	12.0	16.9	20.8	24.0	26.8	29.4	31.7	33.9	36.0	37.9	46.2	53.4	59.9	65.6	75.8	84.9
48	21.9	31.0	38.0	43.8	49.0	53.7	58.0	62.0	65.8	69.3	84.5	97.7	109.0	120.0	139.0	155.0
							Length = 200 feet									
12	0.78	1.10	1.35	1.56	1.75	1.91	2.07	2.21	2.34	2.47	3.01	3.48	3.90	4.27	4.94	5.53
15	1.35	1.90	2.33	2.69	3.01	3.30	3.57	3.81	4.04	4.26	5.20	6.01	6.73	7.37	8.52	9.54
18	2.09	2.96	3.63	4.18	4.68	5.13	5.54	5.92	6.28	6.62	8.08	9.33	10.5	11.5	13.2	14.8
24	4.14	5.86	7.18	8.28	9.26	10.2	11.0	11.7	12.4	13.1	16.0	18.5	20.7	22.7	26.2	29.3
30	6.92	9.79	12.0	13.8	15.5	17.0	18.3	19.6	20.8	21.9	26.7	30.9	34.6	37.9	43.8	49.1
36	10.5	14.8	18.1	20.9	23.4	25.6	27.7	29.6	31.4	33.1	40.4	46.7	52.3	57.3	66.2	74.1
48	19.8	27.9	34.2	39.5	44.2	48.4	52.3	55.9	59.3	62.5	76.2	88.1	98.8	108.0	125.0	140.0
							Length = 300 feet									
12	0.66	0.93	1.15	1.32	1.48	1.62	1.75	1.87	1.98	2.09	2.55	2.95	3.30	3.62	4.18	4.68
15	1.15	1.63	1.99	2.30	2.57	2.82	3.05	3.25	3.45	3.64	4.44	5.13	5.75	6.30	7.28	8.15
18	1.80	2.55	3.12	3.60	4.03	4.42	4.77	5.10	5.41	5.70	6.95	8.04	9.01	9.86	11.4	12.8
24	3.63	5.14	6.30	7.27	8.13	8.91	9.63	10.3	10.9	11.5	14.0	16.2	18.2	19.9	23.0	25.8
30	6.16	8.72	10.7	12.3	13.8	15.1	16.3	17.4	18.5	19.5	23.8	27.5	30.8	33.7	39.0	43.7
36	9.42	13.3	16.3	18.8	21.1	23.1	24.9	26.6	28.3	29.8	36.4	42.0	47.1	51.6	59.6	66.8
48	18.1	25.6	31.4	36.2	40.5	44.4	48.0	51.2	54.4	57.3	69.9	80.8	90.5	99.1	115.0	128.0
							Length = 400 feet									
12	0.58	0.82	1.01	1.16	1.30	1.43	1.54	1.64	1.75	1.84	2.24	2.59	2.91	3.18	3.68	4.12
15	1.02	1.44	1.77	2.04	2.28	2.50	2.70	2.89	3.06	3.23	3.94	4.55	5.10	5.59	6.46	7.23
18	1.61	2.27	2.78	3.21	3.59	3.94	4.25	4.54	4.82	5.08	6.20	7.16	8.03	8.79	10.2	11.4
24	3.26	4.60	5.64	6.51	7.28	7.98	8.62	9.21	9.77	10.3	12.6	14.5	16.3	17.8	20.6	23.1
30	5.59	7.91	9.70	11.2	12.5	13.7	14.8	15.8	16.8	17.7	21.6	25.0	28.0	30.6	35.4	39.6
36	8.63	12.2	15.0	17.3	19.3	21.2	22.9	24.4	25.9	27.3	33.3	38.5	43.1	47.2	54.6	61.2
48	16.8	23.8	29.2	33.6	37.6	41.2	44.5	47.6	50.5	53.2	64.9	75.0	84.1	92.0	106.0	119.0

Length = 500 feet

12	0.53	0.75	0.92	1.06	1.18	1.29	1.40	1.49	1.58	1.67	2.04	2.35	2.64	2.89	3.34	3.74
15	0.93	1.31	1.61	1.85	2.07	2.27	2.45	2.62	2.78	2.93	3.58	4.13	4.63	5.07	5.86	6.56
18	1.46	2.07	2.54	2.93	3.27	3.59	3.88	4.14	4.39	4.63	5.65	6.53	7.31	8.01	9.26	10.4
24	2.99	4.23	5.18	5.98	6.69	7.33	7.92	8.46	8.98	9.46	11.5	13.3	15.0	16.4	18.9	21.2
30	5.15	7.29	8.93	10.3	11.5	12.6	13.6	14.6	15.5	16.3	19.9	23.0	25.8	28.2	32.6	36.5
36	8.00	11.3	13.9	16.0	17.9	19.6	21.2	22.6	24.0	25.3	30.9	35.7	40.0	43.8	50.6	56.7
48	15.8	22.3	27.3	31.5	35.3	38.7	41.8	44.6	47.4	49.9	60.9	70.3	78.8	86.3	99.8	112.0

This table is based on the formula $Q = \dfrac{A\sqrt{2gH}}{\sqrt{1 + 0.31\ D^{0.50} + \dfrac{0.0260\ L}{D^{1.2}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; D = Diameter of culvert pipe in feet,

Table 15—Capacities in cubic feet per second of vitrified-clay pipe culverts, straight endwall entrance, bell end upstream

Diameter of Pipe-Inches	Head on culvert in feet 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
Length = 100 feet																
12	1.11	1.57	1.92	2.22	2.48	2.72	2.94	3.14	3.33	3.51	4.30	4.96	5.55	6.08	7.02	7.85
15	1.86	2.63	3.22	3.72	4.16	4.56	4.92	5.26	5.58	5.88	7.21	8.32	9.30	10.2	11.8	13.2
18	2.82	4.00	4.89	5.65	6.32	6.92	7.48	7.99	8.46	8.93	10.9	12.6	14.1	15.5	17.9	20.0
24	5.39	7.62	9.33	10.8	12.0	13.2	14.2	15.2	16.2	17.0	20.9	24.1	26.9	29.5	34.1	38.1
30	8.78	12.4	15.2	17.6	19.6	21.5	23.2	24.8	26.3	27.8	34.0	39.2	43.9	48.1	55.5	62.1
36	12.9	18.3	22.4	25.9	28.9	31.7	34.2	36.6	38.8	40.9	50.1	57.8	64.7	70.8	81.8	91.5
48	23.3	33.0	40.4	46.6	52.1	57.1	61.7	65.9	69.9	73.7	90.3	104.	116.	128.	147.	165.
Length = 200 feet																
12	0.86	1.21	1.48	1.71	1.91	2.09	2.26	2.42	2.57	2.70	3.31	3.82	4.27	4.68	5.41	6.04
15	1.46	2.06	2.53	2.92	3.26	3.57	3.86	4.12	4.37	4.61	5.65	6.52	7.29	7.99	9.22	10.3
18	2.24	3.17	3.89	4.49	5.02	5.50	5.94	6.35	6.73	7.10	8.70	10.0	11.2	12.3	14.2	15.9
24	4.40	6.22	7.61	8.79	9.83	10.8	11.6	12.4	13.2	13.9	17.0	19.6	22.0	24.1	27.8	31.1
30	7.32	10.4	12.7	14.6	16.4	17.9	19.4	20.7	22.0	23.2	28.4	32.8	36.6	40.1	46.3	51.8
36	11.0	15.6	19.1	22.0	24.6	27.0	29.1	31.1	33.0	34.8	42.7	49.2	55.0	60.3	69.6	77.8
48	20.5	29.0	35.5	41.0	45.8	50.2	54.2	57.9	61.5	64.8	79.4	91.6	102.	112.	130.	145.
Length = 300 feet																
12	0.72	1.02	1.25	1.44	1.61	1.77	1.91	2.04	2.16	2.28	2.79	3.22	3.61	3.95	4.56	5.10
15	1.24	1.75	2.14	2.48	2.77	3.03	3.28	3.50	3.72	3.92	4.80	5.52	6.19	6.78	7.83	8.75
18	1.92	2.71	3.32	3.84	4.29	4.70	5.08	5.43	5.76	6.07	7.43	8.56	9.59	10.5	12.1	13.6
24	3.80	5.38	6.59	7.61	8.50	9.32	10.1	10.8	11.4	12.0	14.7	17.0	19.0	20.8	24.1	26.9
30	6.41	9.06	11.1	12.8	14.3	15.7	17.0	18.1	19.2	20.3	24.8	28.7	32.0	35.1	40.5	45.3
36	9.74	13.8	16.9	19.5	21.8	23.9	25.8	27.5	29.2	30.8	37.7	43.6	48.7	53.3	61.6	68.9
48	18.5	26.2	32.0	37.0	41.4	45.3	49.0	52.3	55.5	58.5	71.7	82.7	92.5	101	117.	131.
Length = 400 feet																
12	0.64	0.90	1.10	1.27	1.42	1.56	1.68	1.80	1.91	2.01	2.46	2.84	3.18	3.48	4.02	4.49
15	1.10	1.55	1.90	2.19	2.45	2.68	2.90	3.10	3.28	3.46	4.24	4.90	5.47	6.00	6.92	7.74
18	1.70	2.41	2.95	3.41	3.81	4.17	4.51	4.82	5.11	5.39	6.60	7.62	8.52	9.33	10.8	12.0
24	3.40	4.81	5.89	6.81	7.61	8.33	9.00	9.62	10.2	10.8	13.2	15.2	17.0	18.6	21.5	24.1
30	5.77	8.16	10.0	11.5	12.9	14.1	15.3	16.3	17.3	18.2	22.4	25.8	28.8	31.6	36.5	40.8
36	8.83	12.5	15.3	17.7	19.7	21.6	23.4	25.0	26.5	27.9	34.2	39.5	44.2	48.4	55.9	62.4
48	17.0	24.0	29.4	34.0	38.0	41.6	45.0	48.1	51.0	53.7	65.8	76.0	85.0	93.1	107.	120.

Length = 500 feet																
12	0.57	0.81	1.00	1.15	1.28	1.41	1.52	1.62	1.72	1.82	2.22	2.57	2.87	3.15	3.63	4.06
15	0.99	1.40	1.72	1.98	2.22	2.43	2.63	2.81	2.98	3.14	3.84	4.44	4.96	5.44	6.28	7.02
18	1.55	2.19	2.68	3.10	3.46	3.79	4.09	4.38	4.64	4.89	5.99	6.92	7.74	8.47	9.79	10.9
24	3.10	4.39	5.38	6.21	6.94	7.61	8.22	8.78	9.32	9.82	12.0	13.9	15.5	17.0	19.6	22.0
30	5.30	7.49	9.17	10.6	11.8	13.0	14.0	15.0	15.9	16.8	20.5	23.7	26.5	29.0	33.5	37.4
36	8.14	11.5	14.1	16.3	18.2	19.9	21.5	23.0	24.4	25.7	31.5	36.4	40.7	44.6	51.5	57.6
48	15.8	22.4	27.3	31.6	35.3	38.7	41.8	44.7	47.4	50.0	61.2	70.7	79.0	86.6	100.	112.

This table is based on the formula $Q = \frac{A\sqrt{2gH}}{\sqrt{1 + 0.023\,D^{1.9} + \frac{0.022\,L}{D^{1.0}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; D = Diameter of culvert pipe in feet.

Table 16—Capacities in cubic feet per second of corrugated-metal pipe culverts, straight endwall entrance

Diameter of Pipe-Inches	Head on culvert in feet															
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
Length = 100 feet																
12	0.58	0.82	1.01	1.16	1.30	1.43	1.54	1.64	1.75	1.84	2.24	2.59	2.91	3.18	3.68	4.12
15	1.02	1.44	1.77	2.04	2.28	2.50	2.70	2.89	3.07	3.23	3.94	4.55	5.10	5.59	6.46	7.23
18	1.61	2.28	2.79	3.22	3.61	3.95	4.27	4.56	4.84	5.10	6.22	7.19	8.06	8.82	10.2	11.4
24	3.29	4.65	5.70	6.57	7.35	8.06	8.70	9.30	9.87	10.4	12.7	14.7	16.4	18.0	20.8	23.3
30	5.69	8.05	9.86	11.4	12.7	14.0	15.1	16.1	17.1	18.0	22.0	25.4	28.4	31.1	36.0	40.3
36	8.78	12.4	15.2	17.6	19.7	21.5	23.3	24.8	26.4	27.8	33.9	39.2	43.9	48.1	55.6	62.3
48	17.4	24.5	30.1	34.7	38.8	42.5	46.0	49.1	52.1	54.9	67.0	77.4	86.7	95.0	110.0	123.0
Length = 200 feet																
12	0.42	0.59	0.73	0.84	0.94	1.03	1.11	1.19	1.26	1.33	1.62	1.88	2.10	2.30	2.66	2.98
15	0.75	1.05	1.29	1.49	1.67	1.83	1.98	2.11	2.24	2.36	2.88	3.33	3.73	4.08	4.72	5.29
18	1.19	1.68	2.06	2.38	2.66	2.91	3.15	3.36	3.57	3.76	4.59	5.30	5.94	6.50	7.52	8.42
24	2.46	3.48	4.27	4.92	5.51	6.04	6.52	6.96	7.39	7.79	9.50	11.0	12.3	13.5	15.6	17.4
30	4.30	6.08	7.45	8.60	9.62	10.5	11.4	12.2	12.9	13.6	16.6	19.2	21.5	23.5	27.2	30.5
36	6.76	9.57	11.7	13.5	15.1	16.6	17.9	19.1	20.3	21.4	26.1	30.2	33.8	37.0	42.8	47.9
48	13.7	19.4	23.8	27.4	30.7	33.6	36.3	38.8	41.2	43.4	52.9	61.2	68.6	75.1	86.8	97.2
Length = 300 feet																
12	0.35	0.49	0.60	0.70	0.78	0.85	0.92	0.98	1.04	1.10	1.34	1.55	1.74	1.90	2.20	2.46
15	0.62	0.87	1.07	1.23	1.38	1.51	1.63	1.74	1.85	1.95	2.38	2.75	3.08	3.37	3.90	4.37
18	0.98	1.39	1.70	1.97	2.20	2.41	2.60	2.78	2.95	3.11	3.79	4.38	4.91	5.38	6.22	6.97
24	2.05	2.90	3.56	4.10	4.59	5.03	5.43	5.80	6.16	6.49	7.92	9.15	10.3	11.2	13.0	14.5
30	3.60	5.10	6.25	7.20	8.06	8.84	9.54	10.2	10.8	11.4	13.9	16.1	18.0	19.7	22.8	25.5
36	5.72	8.09	9.92	11.4	12.8	14.0	15.2	16.2	17.2	18.1	22.1	25.5	28.6	31.3	36.2	40.5
48	11.7	16.6	20.3	23.4	26.2	28.8	31.0	33.2	35.2	37.1	45.3	52.3	58.6	64.2	74.2	83.1
Length = 400 feet																
12	0.30	0.43	0.52	0.60	0.67	0.74	0.80	0.85	0.90	0.95	1.16	1.35	1.51	1.65	1.91	2.14
15	0.54	0.76	0.93	1.07	1.20	1.32	1.42	1.52	1.61	1.70	2.07	2.40	2.69	2.94	3.40	3.81
18	0.86	1.21	1.48	1.71	1.92	2.10	2.27	2.42	2.57	2.71	3.31	3.82	4.28	4.69	5.42	6.07
24	1.79	2.54	3.11	3.59	4.02	4.40	4.75	5.08	5.39	5.68	6.93	8.01	8.97	9.83	11.4	12.7
30	3.16	4.47	5.48	6.32	7.07	7.75	8.37	8.94	9.49	10.0	12.2	14.1	15.8	17.3	20.0	22.4
36	5.02	7.11	8.71	10.0	11.2	12.3	13.3	14.2	15.1	15.9	19.4	22.4	25.1	27.5	31.8	35.6
48	10.4	14.7	18.0	20.8	23.3	25.5	27.5	29.4	31.2	32.9	40.1	46.4	52.0	56.9	65.8	73.7

Length = 500 feet																
12	**0.27**	**0.38**	0.47	**0.54**	**0.60**	0.66	0.72	0.76	0.81	0.86	1.04	1.21	1.35	1.48	1.71	1.92
15	**0.48**	**0.68**	0.83	0.96	1.07	1.18	1.27	1.36	1.44	1.52	1.85	2.14	2.40	2.63	3.04	3.40
18	**0.77**	1.09	1.34	1.54	1.73	1.89	2.04	2.18	2.32	2.44	2.98	3.44	3.86	4.22	4.88	5.47
24	**1.62**	2.28	2.80	3.23	3.61	3.96	4.28	4.57	4.85	5.11	6.23	7.20	8.07	8.84	10.2	11.4
30	2.86	4.05	4.96	5.72	6.40	7.01	7.58	8.09	8.59	9.05	11.0	12.8	14.3	15.7	18.1	20.3
36	**4.55**	**6.44**	7.89	9.10	10.2	11.2	12.1	12.9	13.7	14.4	17.6	20.3	22.8	24.9	28.8	32.3
48	**9.42**	**13.3**	16.3	18.8	21.1	23.1	24.9	26.6	28.3	29.8	36.4	42.0	47.1	51.6	59.6	66.8

This table is based on the formula $Q = \dfrac{A\sqrt{2gH}}{\sqrt{1 + 0.16\ D^{0.6} + \dfrac{0.106\ L}{D^{1.2}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-**sectional area of culvert in square feet;** H = **Head on culvert in feet;** L = Length of culvert in feet; D = Diameter of culvert pipe in feet.

Table 17—Head in feet required on culverts of different types to discharge various quantities of water

Discharge Cu. ft. per sec.	Concrete pipe, straight endwall, beveled lip entrance	Concrete pipe, straight endwall, square cornered entrance	Vitrified-clay pipe, straight endwall, bell end entrance	Corrugated-metal pipe, straight endwall
		12-inch diameter		
1	0.05	0.05	0.04	0.10
2	.19	.21	.16	.42
3	.42	.46	.35	.94
4	.75	.83	.62	1.66
5	1.18	1.29	.97	2.60
6	1.69	1.86	1.40	3.75
7	2.31	2.53	1.91	5.10
8	3.01	3.30	2.49	6.66
		24-inch diameter		
5	0.06	0.07	0.06	0.11
10	.23	.28	.23	.42
15	.52	.64	.51	.95
20	.92	1.14	.91	1.69
25	1.43	1.78	1.42	2.64
30	2.06	2.56	2.04	3.81
35	2.81	3.49	2.78	5.18
		36-inch diameter		
5	0.01	0.01	0.01	0.02
10	.04	.05	.04	.07
20	.16	.21	.17	.26
30	.35	.47	.39	.59
40	.63	.84	.69	1.04
50	.98	1.31	1.08	1.63
60	1.41	1.88	1.55	2.34
70	1.92	2.56	2.11	3.19
80	2.50	3.35	2.75	4.16
		48-inch diameter		
10	0.01	0.02	0.01	0.02
20	.04	.06	.05	.07
30	.10	.14	.12	.15
40	.18	.25	.21	.28
50	.28	.39	.33	.43
60	.40	.57	.48	.62
70	.55	.77	.65	.84
80	.71	1.01	.85	1.10
90	.90	1.27	1.07	1.39
100	1.12	1.57	1.32	1.72
125	1.74	2.46	2.07	2.69

For the purpose of enabling the highway engineer to determine the size of a pipe culvert of a certain kind when the quantity to be carried, the head on the pipe, and the length of the culvert are known, Plate XXII has been compiled from the discharge formulas from the test data. This diagram is useful since no computations are required to obtain the desired information. Discharge in cubic feet per second for any head on the culvert is plotted at the bottom of the diagram. Diagonal lines are drawn to represent the head on the culvert. Along the top of the diagram and to the left, the length of the culvert in feet is given. Various diagonal curved

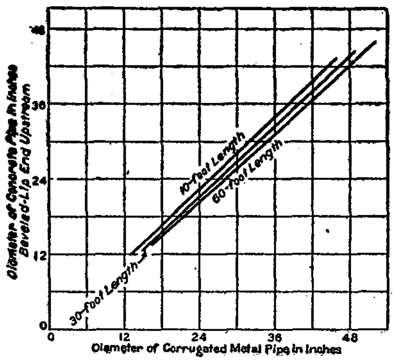


Fig. 20. Diagram for concrete pipe culverts with beveled-lip end upstream and corrugated-metal pipe culverts showing equivalent sizes when discharging the same quantity. Straight endwall entrance.

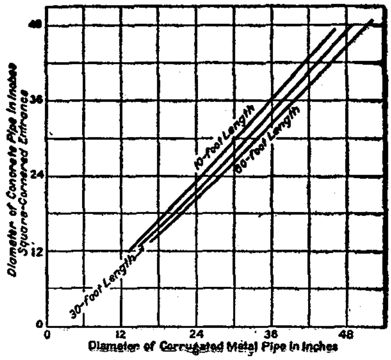


Fig. 21. Diagram for concrete pipe culverts with square-cornered entrance and corrugated-metal pipe culverts showing equivalent sizes when discharging the same quantity. Straight endwall entrance

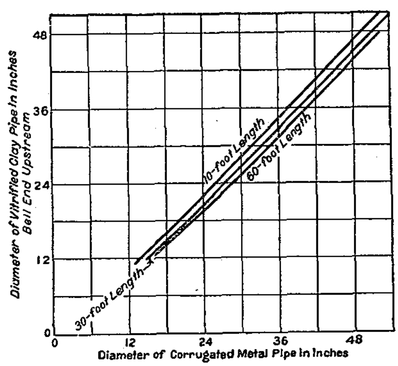


Fig. 22. Diagram for vitrified-clay pipe culverts with bell end upstream and corrugated metal pipe culverts showing equivalent sizes when discharging the same quantity. Straight endwall entrance.

lines on the left of the diagram represent the various sizes of culverts.

This diagram is used as follows: Let us assume it is desired to determine the size of a vitrified-clay pipe culvert 40 feet long when 113 second feet is to be carried by the culvert. From the highway construction data it is determined that 3 feet is the maximum safe head to use on the culvert. Find 113 second feet on the abscissa scale. Run up the diagram on a vertical above 113 second feet to

Table 18—Capacities in cubic feet per second of concrete box culverts, straight endwall entrance, length 30.6 feet, rounded lip entrance

Head on Culvert feet	Size of culvert in feet 2 by 2	3 by 3	4 by 4	4 by 3
.01	2.74	6.47	11.8	8.73
.02	3.87	9.14	16.7	12.3
.03	4.74	11.2	20.4	15.1
.04	5.47	12.9	23.6	17.5
.05	6.11	14.5	26.3	19.5
.06	6.70	15.8	28.8	21.4
.07	7.23	17.1	31.2	23.1
.08	7.73	18.3	33.3	24.7
.09	8.20	19.4	35.3	26.2
.1	8.64	20.4	37.2	27.6
.2	12.2	28.9	52.6	39.0
.3	15.0	35.4	64.5	47.8
.4	17.3	40.9	74.5	55.2
.5	19.3	45.7	83.3	61.7
.6	21.2	50.1	91.2	67.6
.7	22.9	54.1	98.6	73.0
.8	24.4	57.8	105.	78.1
.9	25.9	61.4	112.	82.8
1.0	27.4	64.7	118.	87.3
1.2	29.9	70.8	129.	95.6
1.4	32.3	76.5	139.	103.
1.6	34.6	81.8	149.	110.
1.8	36.7	86.8	158.	117.
2.0	38.7	91.4	167.	123.
2.2	40.5	95.9	175.	129.
2.4	42.3	100.	182.	135.
2,6	44.1	104.	190.	140.
2.8	45.7	108.	197.	146.
3.0	47.4	112.	204.	151.
3.2	48.9	116.	211.	156.
3.4	50.4	119.	217.	161.
3.5	51.2	121.	220.	164.

This table is based on the formula $Q = \dfrac{A\sqrt{2gH}}{\sqrt{1.05 + \dfrac{0.0045\ L}{R^{1.25}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; R = Hydraulic radius in feet.

the diagonal line representing a head of 3 feet. From this point run a horizontal line over to the vertical line through the length of the culvert to be used. It is found that a 42-inch clay pipe is required to discharge the required capacity.

Text Figures 20, 21, and 22 have been compiled for the purpose of showing the size of metal pipe which will carry the same quantity of water as that carried by concrete and clay pipes. Table 17 shows for each kind of pipe the head required on culverts of various types to discharge various quantities of water.

COMPARISON OF CARRYING CAPACITIES OF CONCRETE BOX CULVERTS

Discharge tables have been computed from the general equations 17 and 18 for concrete box culverts, 30.6 feet long, for the same heads as used in Tables 9 to 12 inclusive, and for the following sizes

Table 19—Capacities in cubic feet per second of concrete box culverts, straight endwall entrance, length 30.6 feet, square cornered entrance

Head on Culvert Feet	Size of culvert in feet			
	2 by 2	3 by 3	4 by 4	4 by 3
.01	2.49	5.77	10.4	7.73
.02	3.53	8.16	14.6	10.9
.03	4.32	10.0	17.9	13.4
.04	4.99	11.5	20.7	15.5
.05	5.58	12.9	23.1	17.3
.06	6.11	14.1	25.3	18.9
.07	6.60	15.3	27.4	20.5
.08	7.05	16.3	29.3	21.9
.09	7.48	17.3	31.0	23.2
.1	7.89	18.2	32.7	24.4
.2	11.2	25.8	46.3	34.6
.3	13.7	31.6	56.7	42.3
.4	15.8	36.5	65.5	48.9
.5	17.6	40.8	73.2	54.7
.6	19.3	44.7	80.2	59.9
.7	20.9	48.3	86.6	64.7
.8	22.3	51.6	92.6	69.1
.9	23.7	54.7	98.2	73.3
1.0	24.9	57.7	104.	77.3
1.2	27.3	63.2	113.	84.6
1.4	29.5	68.3	122.	91.4
1.6	31.5	73.0	131.	97.8
1.8	33.5	77.4	139.	104.
2.0	35.3	81.6	146.	109.
2.2	37.0	85.6	153.	115.
2.4	38.6	89.4	160.	120.
2.6	40.2	93.0	167.	125.
2.8	41.7	96.5	173.	129.
3.0	43.2	100.	179.	134.
3.2	44.6	103.	185.	138.
3.4	46.0	106.	191.	143.
3.5	46.7	108.	194.	145.

This table is based on the formula $Q = \dfrac{A\sqrt{2gH}}{\sqrt{1 + 0.4\,R^{0.30} + \dfrac{0.0045\,L}{R^{1.25}}}}$ in which

Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; R = Hydraulic radius in feet.

of box culvert, 2-ft. by 2-ft., 3-ft. by 3-ft., 4-ft. by 4-ft., and 4-ft. by 3-ft. These capacities are shown in Tables 18 and 19. Likewise, to determine the carrying capacities of box culverts longer than 30 feet, discharge tables have been prepared for the same sizes of culverts used in Tables 18 and 19, and for the following lengths: 100, 200, 300, 400, and 500 feet. These capacities are given in Tables 20 and 21.

In order to enable the highway engineer to determine the size of a box culvert when the quantity to be carried, the head on the culvert, and the length of the culvert are known, Plate XXIII has been compiled from discharge formulas 17 and 18. This diagram was prepared in the same manner as Plate XXII for pipe culverts and is used in the same manner to get the size of culvert. It is useful since no computations are required to obtain the desired information.

Table 20—Capacities in cubic feet per second of concrete box culverts, straight endwall entrance with rounded lip

Size of culvert Feet	Head on culvert in feet 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
								Length = 100 feet.								
2 by 2	6.97	9.85	12.1	13.9	15.6	17.1	18.4	19.7	20.9	22.0	27.0	31.1	34.8	38.2	44.1	49.3
3 by 3	17.5	24.8	30.4	35.1	39.2	42.9	46.4	49.6	52.6	55.4	67.9	78.4	87.7	96.0	111.0	124.0
4 by 4	33.1	46.8	57.3	66.2	74.0	81.1	87.6	93.6	99.3	105.0	128.0	148.0	166.0	181.0	209.0	234.0
4 by 3	24.1	34.1	41.7	48.2	53.9	59.0	63.8	68.2	72.3	76.2	93.3	108.0	120.0	132.0	152.0	170.0
								Length = 200 feet.								
2 by 2	5.68	8.03	9.84	11.4	12.7	13.9	15.0	16.1	17.0	18.0	22.0	25.4	28.4	31.1	35.9	40.2
3 by 3	14.9	21.1	25.8	29.8	33.4	36.5	39.5	42.2	44.7	47.2	57.8	66.7	74.6	81.7	94.3	105.0
4 by 4	29.1	41.1	50.3	58.1	65.0	71.2	76.9	82.2	87.2	91.9	113.0	130.0	145.0	159.0	184.0	205.0
4 by 3	20.8	29.4	36.0	41.6	46.5	51.0	55.0	58.8	62.4	65.8	80.6	93.0	104.0	114.0	132.0	147.0
								Length = 300 feet.								
2 by 2	4.91	6.95	8.51	9.83	11.0	12.0	13.0	13.9	14.7	15.5	19.0	22.0	24.6	26.9	31.1	34.7
3 by 3	13.2	18.7	22.9	26.4	29.5	32.4	35.0	37.4	39.6	41.8	51.2	59.1	66.1	72.4	83.6	93.4
4 by 4	26.2	37.0	45.4	52.4	58.5	64.1	69.4	74.1	78.5	82.8	102.0	117.0	131.0	143.0	166.0	185.0
4 by 3	18.6	26.3	32.2	37.1	41.5	45.5	49.1	52.5	55.7	58.7	71.9	83.0	92.8	102.0	117.0	131.0
								Length = 400 feet.								
2 by 2	4.39	6.21	7.61	8.79	9.82	10.8	11.6	12.4	13.2	13.9	17.0	19.6	22.0	24.1	27.8	31.1
3 by 3	12.0	16.9	20.8	24.0	26.8	29.3	31.7	33.9	35.9	37.9	46.4	53.6	59.9	65.6	75.8	84.7
4 by 4	24.0	34.0	41.6	48.1	53.7	58.9	63.6	68.0	72.1	76.0	93.1	107.0	120.0	132.0	152.0	170.0
4 by 3	16.9	23.9	29.3	33.9	37.8	41.5	44.8	47.9	50.8	53.5	65.6	75.7	84.6	92.7	107.0	120.0
								Length = 500 feet.								
2 by 2	4.01	5.67	6.95	8.02	8.97	9.82	10.6	11.3	12.0	12.7	15.5	17.9	20.0	22.0	25.4	28.4
3 by 3	11.0	15.6	19.1	22.1	24.7	27.0	29.2	31.2	33.1	34.9	42.8	49.3	55.2	60.4	69.8	78.0
4 by 4	22.3	31.6	38.7	44.7	49.9	54.7	59.1	63.2	67.0	70.6	86.5	99.8	112.0	122.0	141.0	158.0
4 by 3	15.7	22.1	27.1	31.3	35.0	38.3	41.4	44.3	47.0	49.5	60.6	70.0	78.3	85.7	99.0	111.0

This table is based on the formula $Q = \dfrac{A\sqrt{2gH}}{\sqrt{1.05 + \dfrac{0.0045\ L}{R^{1.25}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; R = Hydraulic radius in feet.

Table 21—Capacities in cubic feet per second of concrete box culverts, straight endwall entrance with square corners

Size of culvert Feet	Head on culvert in feet 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5	3.0	4.0	5.0
Length = 100 feet.																
2 by 2	6.55	9.27	11.3	13.1	14.7	16.0	17.3	18.5	19.7	20.7	25.4	29.3	32.8	35.9	41.4	46.3
3 by 3	16.1	22.8	27.9	32.2	36.0	39.4	42.6	45.5	48.3	50.9	62.4	72.0	80.5	88.2	102.0	114.0
4 by 4	29.8	42.2	51.7	59.7	66.7	73.1	78.9	84.4	89.5	94.3	116.0	133.0	149.0	163.0	189.0	211.0
4 by 3	21.9	31.0	38.0	43.8	49.0	53.7	58.0	62.0	65.7	69.3	84.9	98.0	110.0	120.0	139.0	155.0
Length = 200 feet.																
2 by 2	5.45	7.70	9.46	10.9	12.2	13.4	14.4	15.4	16.3	17.2	21.1	24.4	27.2	29.8	34.5	38.5
3 by 3	14.0	19.8	24.3	28.0	31.3	34.3	37.1	39.6	42.0	44.3	54.2	62.6	70.0	76.7	88.6	99.0
4 by 4	26.7	37.8	46.3	53.5	59.8	65.5	70.8	75.6	80.2	84.6	104.0	120.0	134.0	146.0	169.0	189.0
4 by 3	19.3	27.4	33.5	38.7	43.3	47.4	51.2	54.7	58.0	61.2	74.9	86.5	96.7	106.0	122.0	137.0
Length = 300 feet.																
2 by 2	4.76	6.73	8.25	9.52	10.6	11.7	12.6	13.5	14.3	15.1	18.4	21.3	23.8	26.1	30.1	33.7
3 by 3	12.6	17.8	21.8	25.1	28.1	30.8	33.2	35.5	37.7	39.7	48.7	56.2	62.8	68.8	79.5	88.8
4 by 4	24.5	34.6	42.4	48.9	54.7	59.9	64.7	69.2	73.4	77.4	94.7	109.0	122.0	134.0	155.0	173.0
4 by 3	17.5	24.8	30.3	35.0	39.2	42.9	46.3	49.5	52.5	55.4	67.8	78.3	87.5	95.9	111.0	124.0
Length = 400 feet.																
2 by 2	4.28	6.06	7.42	8.57	9.58	10.5	11.3	12.1	12.9	13.6	16.6	19.2	21.4	23.5	27.1	30.3
3 by 3	11.5	16.2	19.9	23.0	25.7	28.1	30.4	32.5	34.5	36.3	44.5	51.4	57.4	62.9	72.7	81.2
4 by 4	22.7	32.1	39.3	45.4	50.7	55.6	60.0	64.1	68.0	71.7	87.8	101.0	113.0	124.0	143.0	160.0
4 by 3	16.1	22.8	27.9	32.2	36.0	39.5	42.7	45.6	48.4	51.0	62.4	72.1	80.6	88.3	102.0	114.0
Length = 500 feet.																
2 by 2	3.93	5.56	6.80	7.86	8.78	9.62	10.4	11.1	11.8	12.4	15.2	17.6	19.6	21.5	24.8	27.8
3 by 3	10.6	15.1	18.4	21.3	23.8	26.1	28.2	30.1	31.9	33.7	41.2	47.6	53.2	58.3	67.3	75.3
4 by 4	21.2	30.0	36.8	42.5	47.5	52.0	56.2	60.1	63.7	67.2	82.3	95.0	106.0	116.0	134.0	150.0
4 by 3	15.0	21.2	26.0	30.0	33.6	36.8	39.7	42.5	45.0	47.5	58.2	67.1	75.1	82.2	95.0	106.0

This table is based on the formula $Q = \frac{A\sqrt{2gH}}{\sqrt{1 + 0.4\,R^{0.3} + \frac{0.0045\,L}{R^{1.25}}}}$ in which Q = Discharge in cubic feet per second; A = Cross-sectional area of culvert in square feet; H = Head on culvert in feet; L = Length of culvert in feet; R = Hydraulic radius in feet.

SIGNIFICANCE OF THE HYDRAULIC CAPACITY OF CULVERTS IN CARING FOR FLOOD RUNOFF

A culvert of proper size will be taxed to capacity only during intense storms. It should be so installed that under these conditions it will flow entirely full, and under some head. The maximum head under which a culvert should operate will depend upon the height and character of the fill, the amount of land flooded by the heading up of the water, and the maximum permissable velocity of outflow at the downstream end of the culvert. Inspection of Table 17 shows that the amount of heading up of the water on the upstream side of the culvert when discharging a given quantity of water differs considerably for the different types of culverts, and therein is demonstrated the importance of culvert *water* capacity in design. Flows which will give an average velocity in the culvert of about 10 feet per second seem to be the maximum upon which most culvert waterway formulas are based. With this velocity the amount of backwater caused by a 24-inch corrugated metal culvert 30 feet long is 86 per cent more than that produced by this same velocity of flow through a 24-inch clay pipe of the same length.

If, during an intense storm, water has been ponded in the channel or over the low land upstream from a culvert, the time required to discharge this stored water from the flooded area is inversely proportional to the hydraulic capacity of the culvert installed. Thus, a field behind an 18-inch clay pipe culvert would be under water nearly twice as long as it would be had a 24-inch culvert of the same type been installed to discharge the same amount of water off the field. Furthermore, due to the smaller capacity of the 18-inch pipe culvert more water will be ponded behind this culvert during a storm of a given magnitude. Hence, the 24-inch culvert will prove slightly more effective in ridding the land of its flood water derived from a given storm than the ratio of the discharging capacities of the two culverts would indicate. These facts drawn specifically for the 18-inch and 24-inch pipe culverts apply as well to any culvert installations of different hydraulic capacity.

In this report considerable experimentation is described to determine the increased capacity which can be realized if the outlet end of a culvert is gradually expanded to a larger cross-sectional area. In order to realize this additional capacity, however, the culvert must be operating with its outlet submerged. The water will reach this stage during the intense storms for which the culvert is designed if the culvert is properly installed. The additional capacity produced by this expanded outlet will then come into service at just the critical time, like a safety valve, so to speak, to take care of the excess rate of discharge occurring during the peak of the flood, and to prevent serious heading up of the water on the upstream side of the culvert. The following practical example has been selected in order to compare the operation of a culvert having such an increaser with the performance of the standard culvert.

It was assumed that a box culvert with a 3-ft. by 3-ft. section, 36 feet long, with rounded entrance corners is installed underneath a highway to carry the flood discharge coming down a stream channel about 2 feet wide on the bottom with 1 to 1 side slopes, a roughness coefficient of $n = 0.040$, and a slope of 5 feet per thousand.

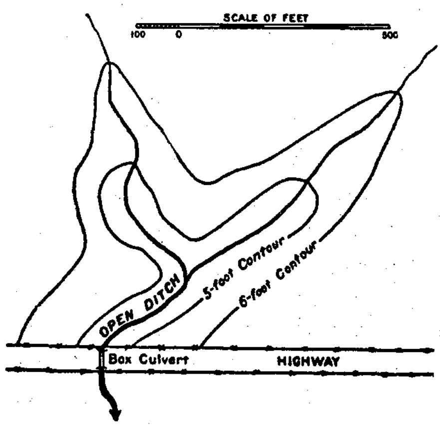


Fig. 23. Site of 3-ft. by 3-ft. by 36-ft. box culvert.

If the culvert is properly installed so that the bottom of the culvert is at the bottom of the ditch, the outlet end of the culvert is submerged for all discharges greater than 51 cubic feet per second. If the outlet end is properly expanded, the culvert capacity, for greater discharges than this, can be increased 50 per cent, but for smaller discharges the culvert with the increaser has the same capacity as the culvert with the uniform bore throughout its entire length.

The topography of the culvert site has been assumed as shown in figure 23. The ditch upstream from the culvert is four feet deep, and when the culvert fails to care for the storm water as fast as it comes, the ditch is overtopped and the flooding of some valuable land takes place.

The water surface elevation at the upstream end of the culvert which will cause a discharge of a given amount through the culvert is shown in figure 24. Curve 1 applies to a culvert of uniform bore, and curve 2 has been computed for a culvert of the same bore, with the outlet end properly enlarged. The discharge equations for the two culverts are as follows:

3-ft by 3-ft. by 36-ft. concrete box culvert with rounded lip entrance:

$$Q = 59.0\ H^{0.488}$$

3-ft by 3-ft. by 36-ft. concrete box culvert with rounded lip entrance and expanded outlet

$$Q = 88.5\ H^{0.468}$$

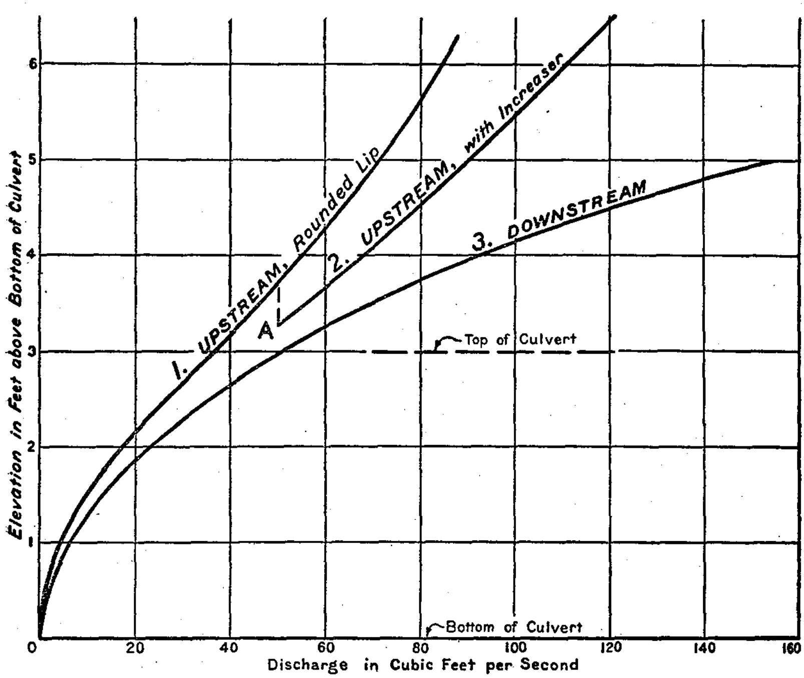


Fig. 24. Curves showing water surface elevations upstream and downstream from box culvert, 3-ft. by 3-ft. by 36-ft. with and without increaser

The head required to discharge a given quantity of water through the standard culvert is more than double that required to pass this same water through a culvert of the same size with the expanded outlet submerged. It will be noted in the figure, that the expanded outlet begins to function at point A, when the water level at the downstream end of the culvert (Curve 3) rises to the top of the culvert opening. A culvert of this type may be brought into operation at its increased capacity sooner if the the culvert were designed with a change in grade lowering the downstream end. In this problem it was assumed to have the same elevation as the standard culvert.

A heavy storm producing a twelve hour run off at the rates indicated by curve 1 in figure 25 has been assumed. If 100 acres is tributary to this culvert, which conforms to a reasonable standard for a culvert of this size in slightly rolling or flat country, this rate of runoff which increases to 100 cubic feet per second in two hours, and decreases to zero at the end of the twelfth hour, is equivalent to a total runoff of six inches from this watershed.

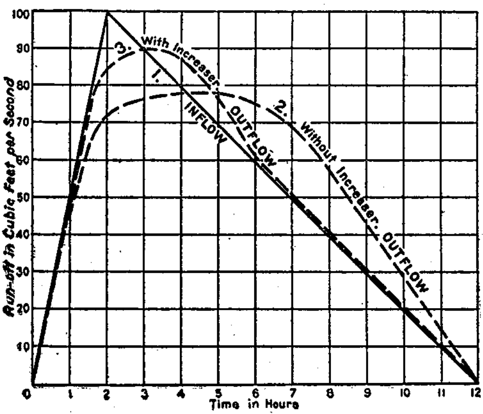


Fig. 25. Inflow and outflow hydrographs for 3-ft. by 3-ft. by 36-ft. box culvert with and without increaser

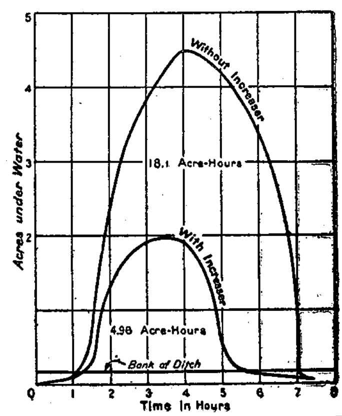


Fig. 26. Curves showing area and time during which land upstream from culvert is flooded, 3-ft. by 3-ft. by 36-ft. box culvert with and without increaser

This same figure shows how the inflow is modified by the standard culvert to produce the outflow rates shown by curve 2. The same culvert with the increaser handles the flood more nearly as it comes and discharges it at the rates shown in curve 3. However, the real importance of water capacity is revealed in the amount of land which was necessarily flooded in each case, in order to store the flood water until the culvert could handle it, thus backing the head water up to a level which discharges more through the culvert. These facts are shown in figure 26. Thus a maximum of 4.5 acres is flooded with the standard culvert installation whereas only about 2 acres come under water if the culvert is provided with the expanding outlet.

It is also of significance to note in the case of the standard culvert installation, that, not only is a greater area submerged, but this land is held under water for a much longer period of time. If the magnitude of damage in each case be measured by the number of acre-hours of submergence, the 3-ft. by 3-ft. culvert with the increaser produced only $\frac{4.96}{18.1}=\frac{1}{3.6}$ of the damage caused by the standard culvert, yet the culvert with the expanded outlet had only 50 per cent greater capacity than the standard culvert.

Various modifications of conditions may be considered, yet the comparison between the two types of culverts will result substantially as indicated in the above example. In fact, this illustration computed for a standard 3-ft. by 3-ft. culvert and the same culvert with an enlarged outlet, will apply as well to illustrate the difference in operation between the standard 3-ft. by 3-ft. culvert and any other culvert which has 50 per cent greater capacity, such as a 4.42-ft by 3-ft. culvert. Similarly, any two culverts which differ in capacity by 50 per cent, such as the 18-inch by 36-foot corrugated metal culvert as compared with the 18-inch clay culvert of the same length, would produce comparative results similar to those illustrated in the above example.

It is certain, therefore, that differences in hydraulic capacity must be multiplied several times if one is to measure in practical results the comparative effectiveness of different culverts. Culverts are installed for no other purpose than to carry water, and the amount of water which they are designed for or may be called upon to carry may not be ascertainable within 200 per cent; but the fact remains that when the flood comes which taxes the culvert to capacity, which may be once in five years or only once in twenty-five years, as between culverts of different capacities, the danger of the water heading up and overtopping the highway will be in proportion to the square of the *capacity of the culvert;* the danger of erosion at the downstream end of the culvert will be in a proportion greater than the first power of the capacity of the culvert, and the flood damage from the water which is held up at the upstream end of the culvert will also be in a proportion greater than the capacity of the culvert.

APPENDIX

Tables of Experimental Results

Tables 22 to 111 inclusive, give the results of the experimental data. For economy in printing, these tables have been condensed considerably by averaging the various factors for all tests having the same discharge. The test numbers are not consecutive. All tests in which the velocity was below 2.5 feet per second were omitted.

In Group I, the effect of the size of the pipe culvert and the material of which it is made is shown. Group II in connection with the tables in Group I shows the effect of the length of the pipe. Groups III to IX, inclusive, show the effect of the various types of entrances used on pipe culverts. Group X shows the effect of projecting the entrance end of the pipe beyond the headwall. Group XI shows the effect of a conical outlet on the discharge of a pipe culvert. Groups XII, XIII, XIV, and XV show the tests on the concrete box culverts.

GROUP I—Tables 22 to 37 showing the effect of size of pipe and material of which it is made. Standard straight endwall entrance, no floor in front of pipe

22—12-inch concrete pipe with beveled lip entrance, 30-foot length
23—18-inch concrete pipe with beveled lip entrance, 30-foot length
24—24-inch concrete pipe with beveled lip entrance, 30-foot length
25—30-inch concrete pipe with beveled lip entrance, 30-foot length
26—12-inch concrete pipe with square cornered entrance, 30-foot lnegth
27—18-inch concrete pipe with square cornered entrance, 30-foot length
28—24-inch concrete pipe with square cornered entrance, 30-foot length
29—30-inch concrete pipe with square cornered entrance, 30-foot length
30—12-inch vitrified clay pipe with bell end entrance, 30-foot length
31—18-inch vitrified-clay pipe with bell end entrance, 30-foot length
32—24-inch vitrified-clay pipe with bell end entrance, 30-foot length
33—30-inch vitrified-clay pipe with bell end entrance, 30-foot length
34—12-inch corrugated-metal pipe, 30-foot length
35—18-inch corrugated-metal pipe, 30-foot length
36—24-inch corrugated-metal pipe, 30-foot length
37—30-inch corrugated-metal pipe, 30-foot length

GROUP II—Tables 38 to 45, in connection with Tables 22 to 37 of Group I, showing the effect of length of pipe. Standard straight endwall entrance, no floor in front of pipe

38—24-inch concrete pipe with beveled lip entrance, 24-foot length
39—24-inch concrete pipe with beveled lip entrance, 36-foot length
40—24-inch vitrified-clay pipe with bell end entrance, 24-foot length
41—24-inch vitrified-clay pipe with bell end entrance, 38-foot length
42—24-inch corrugated-metal pipe, 24-foot length
43—24-inch corrugated-metal pipe, 36-foot length

44—24-inch corrugated-metal pipe, 36-foot length (Ascending series)
45—24-inch corrugated-metal pipe, 36-foot length (Descending series)

GROUP III—Table 46, in connection with Tables 22 to 37 of Group I and Tables 38 to 45 of Group II, showing the effect of a floor in front of entrance. Standard straight endwall entrance

46—24-inch corrugated-metal pipe, 36-foot length

GROUP IV—Tables 47 to 52 showing the effect of special conical entrances, no floor in front of pipe

47—13-degree angle, 10-inch length to 24-inch vitrified-clay pipe, 38-foot length
48—13-degree angle, 20-inch length to 24-inch vitrified-clay pipe, 38-foot length
49—45-degree angle, 10-inch length, to 24-inch vitrified-clay pipe, 38-foot length
50—13-degree angle, 10-inch length to 24-inch corrugated-metal pipe, 36-foot length
51—13-degree angle, 20-inch length to 24-inch corrugated-metal pipe, 36-foot length
52—24°-47′ angle, 10-inch length to 24-inch corrugated-metal pipe, 36-foot length

GROUP V—Tables 53 to 55 showing the effect of standard commercial vitrified-clay pipe increasers as entrances. Standard straight endwall entrance, no floor in front of pipe

53—12-inch to 15-inch increaser to 12-inch vitrified-clay pipe, 30-foot length
54—12-inch to 18-inch increaser to 12-inch vitrified-clay pipe, 30-foot length
55—18-inch to 20-inch increaser to 18-inch vitrified-clay pipe, 30-foot length

GROUP VI—Tables 56 to 59 showing effect of 45-degree wingwall at entrance without floor in front of pipe

56—Wingwalls, full height, set flush with inside edge of 24-inch corrugated-metal pipe, 36-foot length
57—Wingwalls, standard height, set flush with inside edge of 24-inch corrugated-metal pipe, 36-foot length
58—Wingwalls, full height, set 6 inches from inside edge of 24-inch corrumetal pipe, 36-foot length
59—Wingwalls, standard height, set 6 inches from inside edge of 24-inch corrugated-metal pipe, 36-foot length.

GROUP VII—Tables 60 to 64 showing effect of 45-degree wingwall at entrance with floor in front of pipe

60—Wingwalls, full height, set flush with inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length
61—Wingwalls cut level with top of standard endwall and set flush with inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length
62—Wingwalls cut on bevel to top of standard endwall and set flush with inside edge of bell of 24-inch vitrified-clay pipe, 38-foot length

63—Wingwalls, standard height, set flush with inside edge of 24-inch vitrified-clay pipe, 38-foot length
64—Wingwalls, standard height, set flush with inside edge of 24-inch corrugated-metal pipe, 36-foot length

GROUP VIII—Tables 65 to 68 showing effect of U-type wingwalls at entrance with floor in front of pipe

65—Wingwalls cut on bevel to top of standard endwall and set flush with inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length
66—Wingwalls cut on bevel to top of standard endwall and set 6 inches from inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length
67—Wingwalls, standard height, set flush with inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length
68—Wingwalls, standard height, set 6 inches from inside edge of bell to 24-inch vitrified-clay pipe, 38-foot length

GROUP IX—Tables 69 to 71 showing effect of special shaped bells at entrance, no floor in front of pipe

69—Bell of 24-inch vitrified-clay pipe, 38-foot length, filled with concrete and beveled off straight from inside edge of pipe to inside edge of bell
70—Bell of 24-inch vitrified-clay pipe, 38-foot length, filled with concrete elliptically shaped with convex side out
71—Bell of 24-inch vitrified-clay pipe, 38-foot length, filled with concrete and shaped to give a square cornered entrance

GROUP X—Tables 72 to 78 showing effect of projecting entrance end of pipe beyond the headwall

72—12-inch concrete pipe with 3-inch projection. Entrance end of pipe with square corner
73—12-inch concrete pipe with 24-inch projection. Entrance end of pipe with square corner
74—12-inch concrete pipe with 47-inch projection. Entrance end of pipe with square corner
75—12-inch concrete pipe with 47-inch projection. Entrance end of pipe with beveled lip
76—18-inch corrugated-metal pipe with 3-inch projection
77—18-inch corrugated-metal pipe with 24-inch projection
78—18-inch corrugated-metal pipe with 48-inch projection

GROUP XI—Table 79 showing the effect of a cone placed at the outlet end of a pipe culvert

79—18-inch vitrified-clay pipe, with straight endwall entrance and without floor in front of pipe; cone, 60 inches long increasing from 18 inches in diameter to 26 inches in diameter; total length of culvert including cone, 30 feet

GROUP XII—Tables 80 to 90 showing the tests on concrete box culverts 2 feet wide. Standard straight endwall entrance

80—2-ft. by 2-ft. box culvert with square cornered entrance, 24-foot length
81—2-ft. by 2-ft. box culvert with square cornered entrance, 30-foot length
82—2-ft. by 2-ft. box culvert with square cornered entrance, 36-foot length
83—2-ft. by 2-ft. box culvert with beveled lip entrance, 30-foot length
84—2-ft. by 2-ft. box culvert with rounded lip entrance, 30-foot length
85—2-ft. by 2-ft. box culvert with rounded lip entrance, 30-foot length, upper two corners of culvert chamfered 2 inches by 2 inches

86—2-ft. by 2-ft. box culvert with rounded lip entrance; outlet end 2-ft. by 2-ft. to 4-ft. by 2-ft., 6 feet long, flared on two sides only; total length including flared outlet, 30 feet
87—2-ft. by 2-ft. box culvert with rounded lip entrance; outlet end 2-ft. by 2-ft. to 3.12-ft. by 2.56-ft., 6 feet long, flared on sides and bottom; total length including flared outlet, 30 feet
88—2-ft. by 2-ft. box culvert with rounded lip entrance, outlet end 2-ft. by 2-ft. to 3.12-ft. by 2-ft., 6 feet long, flared on two sides only; total length including flared outlet, 30 feet
89—2-ft. by 2-ft. box culvert with rounded lip entrance; outlet end 2-ft. by 2-ft to 4-ft. by 2-ft., 6 feet long, two sides flared on hyperbolic curve; total length including flared outlet, 30 feet
90—2-ft. by 2-ft. box culvert with rounded lip entrance; outlet end 2-ft. by 2-ft. to 4-ft. by 2-ft., 10 feet long, flared on two sides only; total length including flared outlet, 30 feet

GROUP XIII—Tables 91 to 98 showing the tests on concrete box culverts, 3 feet wide. Standard straight endwall entrance

91—3-ft. by 3-ft. box culvert with square cornered entrance, 36-foot length
92—3-ft. by 3-ft. box culvert with square cornered entrance, 30-foot length
93—3-ft. by 3-ft. box culvert with beveled lip entrance, 30-foot length
94—3-ft. by 3-ft. box culvert with rounded lip entrance, 30-foot length
95—3-ft. by 3-ft. box culvert with rounded lip entrance, 30-foot length; upper two corners chamfered 4 inches by 4 inches
96—3-ft. by 3-ft. box culvert with square cornered entrance, 24-foot length
97—3-ft. by 3-ft. box culvert with rounded lip entrance; outlet end 3-ft. by 3-ft. to 6-ft. by 3-ft., 12 feet long, flared on two sides only; total length of culvert including flared outlet, 36 feet
98—3-ft. by 3-ft. box culvert with rounded lip entrance, 24-foot length

GROUP XIV—Table 99 showing the effect on the discharge capacity of flaring a box culvert on the two sides only, for its entire length

99—2-ft. by 2-ft. box culvert, with rounded lip entrance and flared on the two sides for its entire length to a 4-ft. by 2-ft. opening at the outlet end, 30-foot length. Entrance end rounded on the two sides with 1-foot radius curves

GROUP XV—Tables 100 to 111 showing the tests on concrete box culverts 4 feet wide. Standard straight endwall entrance

100—4-ft. by 4-ft. box culvert with rounded lip entrance, 36-foot length
101—4-ft. by 4-ft. box culvert with square cornered entrance, 36-foot length
102—4-ft. by 3-ft. box culvert with square cornered entrance, 36-foot length
103—4-ft. by 3-ft. box culvert with rounded lip entrance, 36-foot length
104—4-ft by 2¼-ft. box culvert with rounded lip entrance, 36-foot length
105—4-ft. by 2¼-ft. box culvert with square cornered entrance, 36-foot length
106—4-ft. by 2-ft. box culvert with square cornered entrance, 36-foot length
107—4-ft. by 2-ft. box culvert with rounded lip entrance, 36-foot length
108—4-ft. by 1-ft. box culvert with square cornered entrance, 36-foot length
109—4-ft. by 1-ft. box culvert with entrance end rounded on top edge only, 36-foot length
110—4-ft by 1-ft. box culvert with entrance end rounded on top and sides, 36-foot length
111—4-ft. by ½-ft. box culvert with rounded lip entrance, 36-foot length

GROUP I—TABLES 22 TO 37 SHOWING THE EFFECT OF SIZE OF PIPE AND THE KIND OF MATERIAL. STANDARD STRAIGHT ENDWALL ENTRANCE, NO FLOOR IN FRONT OF PIPE

Table 22—12-inch concrete pipe, beveled lip entrance. Length, 29.48 feet; area of cross-section, 0.7843 square feet; mean hydraulic radius, 0.2498 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1-4	3.129	3.990	0.248	0.437	0.184	0.005	0.021	0.00624	101.1	0.0115	0.0117
5-8	4.029	5.137	0.410	0.728	0.290	0.028	0.069	.00982	103.9	.0113	.0114
9-12	4.732	6.035	0.566	1.039	0.427	0.046	0.081	.01450	100.3	.0116	.0118
13-16	5.254	6.699	0.698	1.334	0.558	0.078	0.112	.01892	97.5	.0119	.0121
17-20	6.086	7.760	0.936	1.835	0.765	0.134	0.143	.02594	96.4	.0120	.0122
21-24	6.972	8.890	1.228	2.419	1.032	0.159	0.129	.03501	95.1	.0121	.0124
25-28	7.260	9.257	1.332	2.568	1.085	0.151	0.113	.03680	96.6	.0120	.0122

Table 23—18-inch concrete pipe, beveled lip entrance. Length, 29.8 feet; area of cross-section, 1.770 square feet; mean hydraulic radius, 0.3752 feet

Test numbers	Q	V	$\frac{V^2}{2g}$	Total head	Friction loss	Entrance loss	Entrance loss coefficient	s	C	n	n'
32-34	4.389	2.480	0.095	0.133	0.039	-0.002	-0.017	0.001321	111.8	0.0114	0.0113
35-37	5.971	3.373	0.177	0.266	0.078	0.011	0.061	.002619	107.9	.0118	.0117
38-41	7.790	4.401	0.302	0.465	0.128	0.035	0.116	.004310	109.7	.0116	.0115
42-46	9.961	5.628	0.493	0.784	0.237	0.054	0.108	.007972	103.1	.0123	.0123
47-51	12.48	7.051	0.773	1.214	0.364	0.077	0.100	.01222	104.3	.0122	.0121
52-56	14.34	8.098	1.020	1.618	0.501	0.097	0.095	.01683	102.1	.0124	.0124
57-58	17.07	9.644	1.446	2.277	0.707	0.124	0.086	.02374	102.2	.0124	.0124

Table 24—24-inch concrete pipe beveled lip entrance. Length, 30.6 feet; area of cross-section, 3.123 square feet; mean hydraulic radius, 0.4985 feet (See Plate VII-A)

Test numbers	Q	V	$\frac{V^2}{2g}$	Total head	Friction loss	Entrance loss	Entrance loss coefficient	s	C	n	n'
62-64	8.769	2.808	0.123	0.156	0.038	-0.005	-0.043	0.001254	112.4	0.0119	0.0118
65-67	12.165	3.895	0.236	0.330	0.090	0.004	0.017	.002934	102.6	.0130	.0130
68-70	15.73	5.036	0.394	0.559	0.129	0.009	0.024	.004209	110.0	.0122	.0120
71-73	19.80	6.341	0.625	0.936	0.249	0.061	0.097	.007916	101.2	.0131	.0131
74-75	24.18	7.741	0.932	1.391	0.379	0.081	0.086	.01240	98.6	.0134	.0134
76-77	27.60	8.838	1.215	1.951	0.538	0.197	0.166	.01760	94.4	.0140	.0140
78	31.49	10.083	1.580	2.365	0.612	0.173	0.109	.02002	100.9	.0131	.0131

Table 25—30-inch concrete pipe, beveled lip entrance. Length 30.3 feet; area of cross-section, 4.889 square feet; mean hydraulic radius, 0.6238 feet

Test numbers	Q	V	$\frac{V^2}{2g}$	Total head	Friction loss	Entrance loss	Entrance loss coefficient	s	C	n	n'
82-84	9.386	1.920	0.057	0.068	0.019	-0.008	-0.140	0.000627	97.7	0.0139	0.0141
85-87	12.67	2.591	0.105	0.135	0.029	0.001	0.010	.000968	105.9	.0131	.0130
88-90	16.00	3.273	0.167	0.227	0.047	0.013	0.076	.001563	105.7	.0131	.0131
91-93	19.90	4.070	0.257	0.355	0.072	0.026	0.100	.002388	105.5	.0132	.0130
94-96	24.21	4.952	0.381	0.515	0.094	0.040	0.104	.003103	112.7	.0124	.0128
97-99	27.77	5.680	0.502	0.699	0.119	0.077	0.154	.003940	115.2	.0122	.0119
100-102	32.60	6.668	0.692	1.018	0.187	0.139	0.205	.006163	107.7	.0130	.0128
103-104	38.33	7.840	0.956	1.370	0.292	0.121	0.126	.009656	101.0	.0137	.0136

Table 26—12-inch concrete pipe, square cornered entrance. Length, 29.48 feet; area of cross-section, 0.7843 square feet; mean hydraulic radius, 0.2498 feet

Test numbers	Q	V	$\frac{V^2}{2g}$	Total head	Friction loss	Entrance loss	Entrance loss coefficient	s	C	n	n'
105-107	3.126	3.986	0.247	0.478	0.175	0.056	0.228	0.00592	103.6	0.0113	0.0114
108-112	4.072	5.192	0.419	0.841	0.315	0.107	0.255	.01069	100.6	.0116	.0117
113-117	4.656	5.936	0.548	1.113	0.424	0.141	0.258	.01438	99.1	.0117	.0119
118-122	5.270	6.720	0.702	1.428	0.536	0.190	0.271	.01817	99.9	.0117	.0118
123-127	6.045	7.707	0.923	1.898	0.710	0.265	0.287	.02408	99.4	.0117	.0119
128-131	6.694	8.535	1.132	2.347	0.879	0.336	0.296	.02982	98.9	.0117	.0119
132-133	7.132	9.094	1.286	2.642	0.996	0.360	0.280	.03380	99.0	.0118	.0119

Table 27—18-inch concrete pipe, square cornered entrance. Length, 29.8 feet; area of cross-section, 1.770 square feet; mean hydraulic radius, 0.3752 feet

Test numbers	Q	V	$\frac{V^2}{2g}$	Total head	Friction loss	Entrance loss	Entrance loss coefficient	s	C	n	n'
137-140	4.392	2.482	0.096	0.168	0.045	0.028	0.298	0.001502	105.0	0.0120	0.0120
141-144	6.025	3.404	0.180	0.324	0.070	0.074	0.413	.00236	115.3	.0112	.0110
145-148	7.732	4.369	0.297	0.559	0.136	0.126	0.425	.00457	105.8	.0120	.0119
149-152	9.820	5.548	0.478	0.908	0.226	0.203	0.425	.00758	104.2	.0122	.0121
153-156	12.13	6.853	0.730	1.409	0.377	0.302	0.414	.01265	99.7	.0127	.0127

GROUP I—CONTINUED

Table 27—Continued

Test numbers	Q Dis-charge Cu. ft. per sec.	V Veloc-ity Feet per sec.	$\frac{V^2}{2g}$ Veloc-ity head Feet	Total head on pipe Feet	Fric-tion loss Feet	En-trance loss Feet	En-trance loss coeffi-cient	s Slope	C Chezy coeffi-cient	n Kutter coeffi-cient	n' Man-ning coeffi-cient
157-158	14.04	7.932	0.978	1.886	0.506	0.400	0.410	.01701	99.4	.0126	.0127
159	14.77	8,345	1.083	2.133	0.656	0.394	0.364	.02203	91.8	.0135	.0137
160	15.33	8.661	1.166	2.253	0.638	0.449	0.385	.02142	96.6	.0130	.0131

Table 28—24-inch concrete pipe, square cornered entrance. Length, 30.6 feet; area of cross-section, 3.123 square feet; mean hydraulic radius, 0.4985 feet (see Plate VII-C)

163-164	8.927	2.858	0.127	0.212	0.036	0.048	0.380	0.00118	119.3	0.0114	0.0116
165-166	12.51	4.006	0.249	0.436	0.076	0.112	0.448	.00249	113.8	.0119	.0116
167-168	16.19	5.184	0.418	0.759	0.152	0.188	0.451	.00498	104.0	.0128	.0127
169-170	20.02	6.411	0.639	1.172	0.264	0.268	0.420	.00864	97.7	.0135	.0136
171-172	24.46	7.832	0.954	1.786	0.398	0.433	0.454	.01304	98.0	.0136	.0136
173-	28.11	9.001	1.260	2.379	0.581	0.538	0.427	.01901	92.5	.0141	.0143

Table 29—30-inch concrete pipe, square cornered entrance. Length, 30.3 feet; area of cross-section, 4.889 square feet; mean hydraulic radius, 0.6238 feet

177-179	9.321	1.907	0.057	0.084	0.014	0.013	0.236	0.000451	113.8	0.0121	0.0121
180-182	12.02	2.460	0.094	0.142	0.023	0.025	0.262	.000770	115.0	.0122	.0121
183-185	16.10	3.294	0.168	0.284	0.046	0.070	0.414	.001508	107.9	.0129	.0128
186-188	19.73	4.037	0.253	0.427	0.061	0.113	0.446	.002003	114.2	.0123	.0120
189-191	24.12	4.933	0.378	0.651	0.086	0.186	0.492	.002850	117.1	.0121	.0117
192-193	28.96	5.924	0.546	0.950	0.120	0.284	0.521	.003946	119.6	.0118	.0115
194-195	33.60	6.874	0.734	1.290	0.170	0.386	0.526	.005596	117.3	.0121	.0118

Table 30—12-inch vitrified-clay pipe, bell end entrance. Length, 30.6 feet; area of cross-section, 0.8091 square feet; mean hydraulic radius, 0.2538 feet

196-199	2.975	3,678	0.210	0.306	0.104	−0.009	−0.043	0.003404	125.2	0.0097	0.0094
200-202	4.389	5.425	0.458	0.674	0.219	−0.003	−0.007	.007161	127.3	.0097	.0093
203-205	4.490	5.549	0.479	0.732	0.261	−0.008	−0.016	.008510	119.4	.0101	.0099
206-208	6.034	7.457	0.865	1.359	0.469	0.026	0.030	.01530	119.8	.0101	.0099
209-212	6.142	7.592	0.896	1.394	0.488	0.009	0.010	.01595	119.4	.0102	.0099
213-217	7.784	9.620	1.439	2.256	0.800	0.018	0.012	.02610	118.2	.0102	.0100
218	9.380	11.590	2.088	3.289	1.153	0.048	0.023	.03764	118.6	.0102	.0100

Table 31—18-inch vitrified-clay pipe, bell end entrance. Length, 30.8 feet; area of cross-section, 1.791 square feet; mean hydraulic radius, 0.3775 feet

225-228	4.526	2.527	0.100	0.141	0.048	−0.006	−0.062	0.00156	104.9	0.0120	0.0121
229-233	6.018	3.360	0.175	0.253	0.081	−0.004	−0.021	.00264	106.7	.0119	.0118
234-238	7.948	4.438	0.306	0.446	0.120	0.020	0.065	.00390	116.0	.0112	.0111
239-243	9.958	5.560	0.481	0.708	0.209	0.018	0.038	.00679	109.9	.0117	.0115
244-246	11.98	6.691	0.696	1.029	0.309	0.025	0.035	.01003	109.5	.0118	.0116
247-250	11.99	6.695	0.697	1.042	0.314	0.031	0.044	.01020	107.9	.0119	.0117
251-254	14.30	7.986	0.992	1.462	0.417	0.054	0.054	.01358	111.7	.0115	.0114
255-257	16.56	9.246	1.329	1.930	0.544	0.058	0.043	.01767	113.5	.0114	.0112
258-262	18.59	10.382	1.679	2.461	0.703	0.079	0.048	.02284	112.4	.0115	.0113
263-266	19.20	10.722	1.788	2.609	0.737	0.085	0.047	.02395	112.8	.0114	.0112
267	20.04	11.190	1.947	2.785	0.760	0.078	0.040	.02470	115.9	.0112	.0109

Table 32—24-inch vitrified-clay pipe, bell end entrance. Length, 30.7 feet; area of cross-section, 3.343 square feet; mean hydraulic radius, 0.5158 feet (See Plate VII-D)

271-273	8.663	2.591	0.104	0.144	0.041	−0.002	−0.019	0.00135	99.8	0.0134	0.0135
274-276	12.15	3.635	0.205	0.288	0.074	0.009	0.042	.00241	103.2	.0130	.0129
277-279	16.08	4,809	0.359	0.513	0.140	0.014	0.039	.00456	99.2	.0134	.0134
280-282	20.53	6.141	0.586	0.849	0.218	0.045	0.077	.00710	101.5	.0132	.0131
283-285	24.41	7.301	0.829	1.196	0.285	0.082	0.098	.00929	105.6	.0128	.0126
286-289	28.86	8.632	1.158	1.706	0.424	0.124	0.106	.01382	103.3	.0131	.0130
290-291	34.12	10.204	1.619	2.438	0.618	0.202	0.124	.02012	100.2	.0134	.0133

GROUP I—CONTINUED

Table 33—30-inch vitrified-clay pipe, bell end entrance. Length, 30.5 feet; area of cross-section, 4.772 square feet; mean hydraulic radius, 0.6162 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
296-299	8.761	1.836	0.052	0.067	0.014	0.001	0.019	0.000450	110.5	0.0124	0.0124
300-303	11.699	2.452	0.093	0.122	0.023	0.006	0.064	.000754	118.5	.0120	.0119
304-307	15.47	3.242	0.164	0.225	0.052	0.010	0.061	.00169	101.7	.0136	.0136
308-311	19.49	4.084	0.260	0.366	0.080	0.027	0.105	.00260	102.2	.0135	.0134
312-315	23.09	4.840	0.364	0.517	0.108	0.045	0.124	.00352	104.0	.0133	.0132
316-319	28.44	5.960	0.552	0.793	0.167	0.074	0.133	.00548	102.8	.0134	.0134
320-323	32.82	6.877	0.736	1.056	0.228	0.093	0.126	.00746	101.6	.0136	.0135

Table 34—12-inch corrugated-metal pipe. Length, 30.6 feet; area of cross-section, 0.7667 square feet; mean hydraulic radius, 0.2470 feet

324-327	2.752	3.589	0.200	0.812	0.592	0.020	0.102	0.0193	52.0	0.0193	0.0226
328-330	2.825	3.684	0.211	0.849	0.613	0.025	0.120	.0200	52.4	.0192	.0225
331-332	2,944	3,840	0.230	0.965	0.716	0.020	0.085	.0234	50.5	.0198	.0233
333-336	3.380	4.408	0.302	1.279	0.913	0.064	0.212	.0298	51.4	.0196	.0230
337-339	3,500	4.565	0.324	1.354	0.965	0.065	0.200	.0315	51.7	.0194	.0228
340-343	4.278	5.579	0.484	2.008	1.459	0.066	0.136	.0476	51.4	.0194	.0229
344-346	4.290	5.595	0.487	2.005	1.448	0.069	0.142	.0473	51.8	.0194	.0228
347-348	4.926	6.424	0.642	2.662	1.898	0.123	0.191	.0620	51.9	.0193	.0227
349	5.166	6.738	0.706	2.954	2.095	0.153	0.217	.0685	51.8	.0194	.0227

Table 35—18-inch corrugated-metal pipe. Length, 30.4 feet; area of cross-section, 1.771 square feet; mean hydraulic radius, 0.3754 feet

354-355	4.314	2.436	0.092	0.274	0.172	0.010	0.108	0.00566	52.8	0.0210	0.0239
356-358	4.453	2.514	0.098	0.301	0.186	0.017	0.169	.00610	52.5	.0210	.0240
361-363	6.10	3.444	0.184	0.600	0.380	0.036	0.195	.0125	50.4	.0218	.0251
359, 360, and 364	6.28	3.547	0.196	0.628	0.401	0.032	0.162	.0132	50.4	.0218	.0250
365-368	7.78	4.396	0.301	0.987	0.626	0.060	0.201	.0206	50.0	.0220	.0252
369-370	8.31	4.692	0.342	1.121	0.705	0.074	0.216	.0232	50.4	.0218	.0251
371-374	9.86	5.564	0.482	1.589	1.018	0.089	0.186	.0334	49.7	.0221	.0254
375-378	10.18	5.745	0.514	1.660	1.044	0.102	0.199	.0343	50.6	.0218	.0250
379-383	11.94	6.740	0.706	2.298	1.454	0.137	0.194	.0477	50.4	.0219	.0251
384-387	12.14	6.855	0.731	2.407	1.519	0.157	0.214	.0499	50.1	.0220	.0252
388-389	12.65	7.143	0.794	2.558	1.596	0.170	0.214	.0524	50.9	.0217	.0248

Table 36—24-inch corrugated-metal pipe. Length 30.6 feet; area of cross-section, 3.147 square feet; mean hydraulic radius, 0.5004 feet (See Plate VII-B)

394-395	8.382	2.664	0.111	0.298	0.166	0.021	0.194	0.00544	51.3	0.0230	0.0258
392-393	9.916	3.151	0.154	0.407	0.215	0.038	0.242	.00704	53.2	.0222	.0249
396-399	12.16	3.862	0.232	0.576	0.314	0.030	0.131	.0103	53.8	.0221	.0246
400-402	15.57	4.946	0.380	0.968	0.514	0.074	0.194	.0168	53.5	.0221	.0246
403-406	19.67	6.250	0.608	1.480	0.716	0.157	0.258	.0234	57.8	.0208	.0229
407-408	23.79	7.560	0.889	2.206	1.096	0.221	0.248	.0359	56.4	.0212	.0235

Table 37—30-inch corrugated-metal pipe. Length, 30.3 feet; area of cross-section, 4.893 square feet; mean hydraulic radius, 0.6240 feet

413-416	9.110	1.862	0.054	0.111	0.048	0.010	0.185	0.00156	59.9	0.0212	0.0230
417-420	12.46	2.546	0.100	0.228	0.101	0.026	0.264	.00331	56.0	.0226	.0245
421-424	15.89	3.248	0.164	0.397	0.186	0.048	0.292	.00608	52.8	.0236	.0260
425-428	19.20	3.924	0.240	0.582	0.269	0.074	0.307	.00881	52.9	.0236	.0259
429-432	23.75	4.853	0.366	0.898	0.423	0.108	0.296	.01385	52.2	.0239	.0263
433-436	28.58	5.842	0.530	1.302	0.608	0.164	0.308	.01992	52.4	.0238	.0262
437	33.28	6.802	0.719	1.811	0.907	0.185	0.257	.02970	50.0	.0247	.0275

GROUP II—TABLES 38 TO 45 IN CONNECTION WITH TABLES 22 TO 37 OF GROUP I SHOWING THE EFFECT OF LENGTH OF PIPE. STANDARD STRAIGHT ENDWALL ENTRANCE, NO FLOOR IN FRONT OF PIPE

Table 38—24-inch concrete pipe, beveled lip entrance. Length, 24.4 feet; area of cross-section, 3.120 square feet; mean hydraulic radius, 0.4983 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
441-443	8.800	2.821	0.124	0.162	0.041	−0.003	−0.021	0.00168	97.6	0.0135	0.0136
444-446	12.19	3.908	0.237	0.328	0.081	0.009	0.038	.00333	95.9	.0137	.0138
447-449	15.67	5.021	0.392	0.546	0.115	0.038	0.098	.00472	104.4	.0128	.0128
450-452	19.76	6.333	0.624	0.891	0.216	0.051	0.082	.00885	95.5	.0138	.0139
453-455	23.95	7.676	0.917	1.308	0.311	0.080	0.088	.01272	96.4	.0136	.0137
456	28.77	9.221	1.322	1.897	0.449	0.126	0.095	.01839	96.3	.0137	.0137

Table 39—24-inch concrete pipe, beveled lip entrance: Length, 36.7 feet; area of cross-section, 3.123 square feet; mean hydraulic radius, 0.4985 feet

460-462	8.642	2.767	0.119	0.152	0.049	−0.016	−0.135	0.00134	107.6	0.0124	0.0123
463-465	12.06	3.861	0.232	0.335	0.102	0.002	0.009	.00277	104.1	.0128	.0127
466-468	15.78	5.053	0.397	0.594	0.179	0.018	0.045	.00488	102.6	.0129	.0129
469-471	20.36	6.519	0.661	1.003	0.301	0.041	0.063	.00821	101.5	.0131	.0131
472-473	24.24	7.762	0.937	1.444	0.436	0.070	0.076	.01189	100.8	.0132	.0131
474	28.49	9.123	1.294	2.008	0.569	0.145	0.112	.01550	103.8	.0129	.0127
475	30.17	9.661	1.451	2.270	0.700	0.119	0.082	.01906	99.1	.0134	.0134

Table 40—24-inch vitrified-clay pipe, bell end entrance. Length, 25.6 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet

479-481	8.895	2.666	0.111	0.153	0.034	0.009	0.078	0.00133	103.1	0.0129	0.0130
482-484	11.933	3.577	0.199	0.283	0.062	0.022	0.110	.00244	101.0	.0131	.0132
485-487	15.39	4.612	0.331	0.474	0.108	0.035	0.109	.00421	99.0	.0134	.0134
488-490	19.48	5.838	0.530	0.764	0.165	0.068	0.129	.00647	101.5	.0132	.0131
491-493	23.82	7.140	0.793	1.144	0.256	0.095	0.119	.01001	99.5	.0134	.0134
494-496	25.35	7.600	0.898	1.292	0.274	0.120	0.133	.01073	102.3	.0130	.0130

Table 41—24-inch vitrified-clay pipe, bell end entrance. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet

500-502	9.236	2.769	0.119	0.161	0.048	−0.006	−0.049	0.00125	110.6	0.0122	0.0121
503-505	12.58	2.771	0.221	0.319	0.101	−0.003	−0.014	.00263	102.5	.0130	.0130
506-508	16.01	4.800	0.358	0.517	0.150	0.009	0.024	.00393	106.8	.0126	.0124
509-511	21.14	6.337	0.624	0.930	0.283	0.023	0.036	.00740	102.7	.0130	.0130
512-514	24.93	7.473	0.868	1.318	0.395	0.055	0.063	.01033	102.5	.0131	.0130
515-517	28.65	8.588	1.147	1.751	0.497	0.107	0.093	.01299	105.1	.0128	.0126
518	32.93	9.871	1.515	2.309	0.685	0.109	0.072	.01790	102.8	.0130	.0129

Table 42—24-inch corrugated-metal pipe. Length, 24.4 feet; area of cross-section, 3.147 square feet; mean hydraulic radius, 0.500 feet

521	8.453	2.686	0.112	0.265	0.124	0.029	0.259	0.0051	53.2	0.0222	0.0249
519-520	9.376	2.980	0.138	0.316	0.141	0.037	0.268	.0058	55.4	.0216	.0240
523-524	11.612	3.690	0.212	0.515	0.208	0.096	0.455	.0085	56.6	.0212	.0234
522	12.26	3.896	0.236	0.540	0.255	0.049	0.208	.0105	53.7	.0222	.0246
525-528	16.32	5.186	0.418	0.971	0.440	0.114	0.272	.0180	54.6	.0218	.0242
529-532	18.95	6.022	0.564	1.312	0.605	0.143	0.254	.0248	54.2	.0220	.0245
533-535	21.20	6.736	0.705	1.643	0.702	0.236	0.334	.0286	56.1	.0214	.0235
536	24.20	7.690	0.919	2.091	0.860	0.312	0.340	.0353	57.9	.0208	.0229

GROUP II—CONTINUED

Table 43—24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
540-541	8.537	2.717	0.115	0.308	0.174	0.020	0.172	0.0047	55.9	0.0215	0.0237
543-546	11.699	3.723	0.215	0.600	0.338	0.047	0.217	.0092	54.9	.0217	.0241
547-551	15.12	4.812	0.360	1.001	0.562	0.079	0.219	.0153	55.0	.0218	.0241
552-556	19.10	6.079	0.574	1.590	0.874	0.142	0.246	.0238	55.7	.0215	.0238
557 559	21.55	6.859	0.731	2.019	1.118	0.169	0.231	.0305	55.6	.0216	.0238

Table 44—24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (Ascending series)

563-565	7.473	2.378	0.088	0.219	0.116	0.016	0.178	0.00315	60.0	0.0201	0.0221
566-568	8.800	2.801	0.122	0.326	0.183	0.021	0.170	.00499	56.1	.0213	.0236
569-571	9,604	3.057	0.145	0.396	0.223	0.028	0.191	.00607	55.5	.0216	.0239
572-574	10.668	3.395	0.179	0.487	0.270	0.038	0.214	.00735	56.1	.0214	.0236
575-577	11.442	3.642	0.206	0.571	0.330	0.035	0.171	.00898	54.4	.0219	.0243
578-580	12.27	3.905	0.237	0.656	0.367	0.051	0.216	.00999	55.3	.0217	.0240
581-583	13.27	4.223	0.277	0.772	0.438	0.057	0.206	.0119	54.8	.0218	.0242
584-586	14.26	4.538	0.320	0.898	0.511	0.067	0.210	.0139	54.4	.0220	.0243
587-589	15.24	4.849	0.365	1.036	0.608	0.063	0.171	.0166	53.3	.0223	.0248
590-592	16.52	5.258	0.430	1.211	0.691	0.091	0.211	.0188	54.2	.0220	.0244
593 595	17.60	5.601	0.488	1.374	0.776	0.110	0.226	.0211	54.5	.0219	.0243
596-597	18.97	6.006	0.560	1.602	0.901	0.140	0.250	.0246	54.2	.0220	.0244
598-599	19.90	6.335	0.624	1.808	1.033	0.152	0.243	.0282	53.4	.0222	.0248

Table 45—24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (Descending series)

600-601	19.93	6.343	0.626	1.792	1.014	0.152	0.243	0.0276	54.0	0.0220	0.0245
602-604	18.41	5.860	0.534	1.539	0.861	0.144	0.271	.0234	54.2	.0220	.0245
605-607	16.64	5.297	0.437	1.270	0.735	0.098	0.225	.0200	53.0	.0224	.0250
608-610	15.51	4.936	0.379	1.092	0.626	0.087	0.229	.0171	53.4	.0222	.0248
611-613	13.91	4.428	0.305	0.880	0.504	0.072	0.237	.0137	53.5	.0223	.0248
614-616	12.43	3.955	0.243	0.705	0.402	0.059	.0242	.0109	53.5	.0222	.0247
617-619	10.904	3.470	0.187	0.540	0.312	0.041	0.218	.00850	53.2	.0223	.0249
620-622	9.637	3.067	0.146	0.420	0.242	0.032	0.222	.00658	53.5	.0222	.0247
623-625	8.463	2.693	0.112	0.313	0.183	0.018	0.163	.00498	53.7	.0220	.0245
626-628	7.594	2.417	0.091	0.254	0.145	0.018	0.201	.00395	54.4	.0219	.0243

GROUP III—TABLE 46 IN CONNECTION WITH TABLES 22 TO 37 OF GROUP I AND TABLES 38 TO 45 OF GROUP II SHOWING THE EFFECT OF FLOOR IN FRONT OF ENTRANCE. STANDARD STRAIGHT ENDWALL ENTRANCE

Table 46—24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (See Plate VIII—A)

634-635	8.879	2.826	0.124	0.384	0.173	0.086	0.691	0.00472	58.2	0.0206	0.0228
636-637	11.874	3.780	0.222	0.646	0.334	0.091	0.410	.00908	56.2	.0214	.0236
638-639	15.88	5.054	0.397	1.170	0.598	0.175	0.440	.0168	56.1	.0214	.0236
640-642	19.59	6.235	0.604	1.750	0.882	0.264	0.436	.0240	56.6	.0212	.0233
643-644	21.44	6.826	0.724	2.099	1.086	0.288	0.398	.0296	56.1	.0214	.0236

GROUP IV—TABLES 47 TO 52 SHOWING THE EFFECT OF SPECIAL CONICAL ENTRANCES, NO FLOOR IN FRONT OF PIPE

Table 47—Conical entrance, 13-degree angle, 10 inches long, attached to 24-inch vitrified-clay pipe. Length 38.3 feet; area of cross-section, 3.336 square feet: mean hydraulic radius, 0.5152 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
645-647	8.653	2.594	0.105	0.141	0.035	0.001	0.0092	0.000915	121.7	0.0113	0.0111
648-650	12.20	3.656	0.208	0.295	0.077	0.010	0.0497	.00200	115.0	.0118	.0118
651-653	15.99	4.792	0.357	0.523	0.130	0.036	0.100	.00341	114.5	.0119	.0116
654-656	19.39	5.813	0.526	0.798	0.217	0.055	0.104	.00568	107.5	.0126	.0124
657-659	23.69	7.100	0.784	1.199	0.334	0.082	0.105	.00872	106.1	.0127	.0126
660-661	28.08	8.418	1.102	1.740	0.498	0.140	0.126	.01303	103.4	.0130	.0129
662-663	32.06	9.608	1.436	2.254	0.628	0.190	0.133	.01642	104.5	.0128	.0127

Table 48—Conical entrance, 13-degree angle, 20 inches long, attached to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate VII-E)

664-666	8.195	2.457	0.094	0.121	0.033	−0.005	−0.057	0.000862	120.3	0.0115	0.0113
667-669	11.945	3.581	0.199	0.285	0.095	−0.010	−0.050	.00249	99.9	.0134	.0133
670-672	15.94	4.778	0.355	0.528	0.158	0.015	0.041	.00414	103.7	.0129	.0129
673-675	19.16	5.743	0.513	0.759	0.231	0.015	0.030	.00605	103.0	.0130	.0129
676-678	23.78	7.128	0.790	1.210	0.491	0.029	0.037	.01022	98.5	.0135	.0135

Table 49—Conical entrance, 45-degree angle, 10 inches long, attached to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate VIII-B)

679-681	8.716	2.613	0.106	0.151	0.042	0.003	0.026	0.00110	110.4	0.0122	0.0121
682-684	12.41	3.719	0.215	0.313	0.082	0.015	0.070	.00215	111.8	.0121	.0119
685-687	15.44	4.629	0.333	0.490	0.128	0.029	0.087	.00335	111.7	.0121	.0119
688-690	19.31	5.789	0.521	0.788	0.220	0.046	0.089	.00576	106.3	.0127	.0125
691-693	24.47	7.334	0.837	1.283	0.340	0.107	0.128	.00888	108.8	.0124	.0122
694-696	29.06	8.711	1.180	1.829	0.485	0.164	0.139	.01269	107.8	.0126	.0124
697	30.81	9.235	1.326	1.991	0.609	0.056	0.042	.01592	102.0	.0131	.0130

Table 50—Conical entrance, 13-degree angle, 10 inches long, attached to 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (See Plate VII-F)

700-701	8.752	2.786	0.120	0.310	0.190	−0.0005	−0.004	0.00518	54.8	0.0218	0.0242
702-703	12.32	3.921	0.239	0.632	0.378	0.016	0.067	.01030	54.6	.0217	.0242
704-705	15.70	4.998	0.388	1.015	0.620	0.006	0.016	.0169	54.4	.0220	.0244
706-707	19.44	6.188	0.596	1.546	0.922	0.028	0.047	.0251	55.2	.0217	.0240
708-709	21.49	6.840	0.728	1.876	1.110	0.039	0.054	.0302	55.7	.0214	.0238

Table 51—Conical entrance, 13-degree angle, 20 inches long, attached to 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet

712-713	9.022	2.871	0.128	0.329	0.197	0.004	0.031	0.00536	55.5	0.0216	0.0238
714-715	11.506	3.662	0.208	0.556	0.336	0.012	0.060	.00914	54.2	.0220	.0244
716-717	15.48	4.926	0.378	0.988	0.594	0.016	0.042	.0162	54.8	.0218	.0242
718-721	18.60	5.918	0.545	1.415	0.861	0.010	0.018	.0234	54.7	.0219	.0242
722-724	22.63	7.203	0.807	2.077	1.224	0.044	0.057	.0333	55.8	.0214	.0237

Table 52—Conical entrance, 24° - 47′ angle, 10 inches long, attached to 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet

727-729	8.800	2.801	0.122	0.306	0.184	0.0003	0.002	0.0050	55.9	0.0215	0.0237
730-731	12.07	3.841	0.229	0.596	0.365	0.002	0.011	.0099	54.6	.0219	.0242
732-733	15.61	4.968	0.384	1.026	0.625	0.017	0.044	.0170	53.8	.0222	.0246
734-735	19.98	6.357	0.628	1.648	1.010	0.010	0.016	.0275	54.2	.0220	.0244
736-737	23.02	7.326	0.834	2.174	1.258	0.082	0.098	.0342	56.0	.0213	.0236

GROUP V—TABLES 53 TO 55 SHOWING THE EFFECT OF STANDARD COMMERCIAL VITRIFIED-CLAY PIPE INCREASERS AS ENTRANCES, NO FLOOR IN FRONT OF ENTRANCE

Table 53—12-inch to 15-inch increaser attached to 12-inch vitrified-clay pipe. Length, 30.6 feet; area of cross-section, 0.8091 square feet; mean hydraulic radius, 0.2538 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
738-740	2.981	3.685	0.211	0.327	0.100	0.015	0.072	0.003275	128.0	0.0096	0.0092
741-743	4.511	5.575	0.483	0.777	0.247	0.047	0.097	.008075	123.2	.0099	.0096
744-746	5.984	7.396	0.850	1.390	0.437	0.103	0.121	.01428	123.1	.0099	.0096
747-749	7.63	9.434	1.384	2.278	0.709	0.185	0.134	.02315	123.1	.0099	.0096
750-751	9.12	11.27	1.975	3.261	1.058	0.228	0.116	.03454	120.4	.0100	.0098

Table 54—12-inch to 18-inch increaser attached to 12-inch vitrified-clay pipe. Length, 30.6 feet; area of cross-section, 0.8091 square feet; mean hydraulic radius, 0.2538 feet

752-754	2.967	3.667	0.209	0.317	0.107	0.001	0.005	0.00348	123.5	0.0098	0.0096
755-757	4.337	5.360	0.447	0.728	0.248	0.034	0.075	.00809	118.3	.0102	.0100
758-760	6.44	7.960	0.985	1.603	0.539	0.079	0.080	.0176	119.1	.0101	.0099
761-763	8.00	9.884	1.519	2.498	0.838	0.142	0.093	.0273	118.7	.0102	.0099
764	9.16	11.32	1.992	3.284	1.108	0.184	0.092	.0362	118.1	.0102	.0100

Table 55—18-inch to 20-inch increaser attached to 18-inch vitrified-clay pipe. Length, 30.8 feet; area of cross-section, 1.791 square feet; mean hydraulic radius, 0.3775 feet (See Plate X-A)

765-767	4.411	2.463	0.095	0.146	0.041	0.010	0.109	0.00132	110.6	0.0116	0.0114
768-770	6.06	3.384	0.178	0.280	0.075	0.027	0.150	.00244	113.4	.0114	.0113
771-773	7.93	4.428	0.305	0.484	0.133	0.046	0.151	.00433	109.6	.0117	.0115
774-776	9.84	5.494	0.469	0.747	0.194	0.084	0.179	.00632	112.5	.0115	.0112
777-779	12.08	6.747	0.708	1.165	0.345	0.113	0.159	.01120	103.9	.0123	.0122
780-783	14.14	7.898	0.970	1.588	0.423	0.196	0.202	.01375	109.6	.0117	.0115
784-786	17.14	9.572	1.424	2.348	0.624	0.300	0.210	.02030	109.4	.0117	.0115
787	18.51	10.340	1.663	2.743	0.759	0.321	0.193	.02468	107.2	.0119	.0118

GROUP VI—TABLES 56 TO 59 SHOWING THE EFFECT OF 45-DEGREE WINGWALLS AT ENTRANCE, NO FLOOR IN FRONT OF PIPE

Table 56—Wingwalls, full height, set flush with inside edge of 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0,5000 feet (See Plate VIII-E)

791-793	9.225	2.936	0.134	0.346	0.197	0.015	0.109	0.00536	56.8	0.0212	0.0233
794-796	12.21	3.885	0.235	0.621	0.349	0.037	0.156	.00951	56.4	.0213	.0235
797-799	16.14	5.138	0.411	1.107	0.629	0.067	0.163	.0171	55.5	.0216	.0238
800-803	19.79	6.299	0.617	1.656	0.922	0.116	0.189	.0251	56.3	.0213	.0235
804-805	22.64	7.207	0.808	2.160	1.223	0.128	0.159	.0334	55.8	.0215	.0238

Table 57—Wingwalls, standard height, set flush with inside edge of 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (See Plate VIII-C)

808-809	8.611	2.740	0.117	0.302	0.156	0.028	0.244	0.00426	59.4	0.0203	0.0223
810-811	12.36	3.935	0.241	0.652	0.364	0.047	0.196	.00971	56.0	.0214	.0236
812-813	15.40	4.901	0.373	1.014	0.554	0.088	0.235	.0152	56.4	.0212	.0234
814-817	19.88	6.326	0.622	1.697	0.917	0.158	0.253	.0250	56.7	.0212	.0234
818-819	22.36	7.114	0.787	2.146	1.166	0.194	0.246	.0318	56.5	.0212	.0234

GROUP VI—CONTINUED

Table 58—Wingwalls, full height, set 6 inches from inside edge of 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (See Plate VIII-F)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
822-823	8.927	2.841	0.125	0.329	0.180	0.024	0.192	0.00490	57.4	0.0210	0.0231
824-825	12.20	3.883	0.234	0.636	0.358	0.044	0.186	.00972	55.7	.0216	.0238
826-827	15.84	5.042	0.395	1.078	0.590	0.093	0.236	.0160	56.3	.0214	.0235
828-831	19.04	6.061	0.571	1.600	0.896	0.132	0.232	.0244	54.9	.0218	.0241
832-833	21.54	6.854	0.730	2.014	1.119	0.164	0.224	.0304	55.6	.0216	.0238

Table 59—Wingwalls, standard height, set 6 inches from inside edge of 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section, 3.142 square feet; mean hydraulic radius, 0.5000 feet (See Plate VIII-D)

836-837	8.832	2.811	0.123	0.317	0.175	0.019	0.154	0.00476	57.6	0.0208	0.0230
838-839	12.10	3.851	0.231	0.624	0.350	0.042	0.183	.00953	55.8	.0214	.0238
840-841	15.68	4.992	0.388	1.048	0.564	0.096	0.249	.0154	57.0	.0212	.0232
842-844	19.72	6.275	0.612	1.684	0.885	0.187	0.305	.0231	57.2	.0211	.0231
845	21.81	6.941	0.749	2.111	1.145	0.217	0.290	.0312	55.6	.0217	.0238

GROUP VII—TABLES 60 TO 64 SHOWING THE EFFECT OF 45-DEGREE WINGWALLS AT ENTRANCE WITH FLOOR IN FRONT OF PIPE

Table 60—Wingwalls, full height, set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate IX-C)

846-848	8.705	2.609	0.106	0.157	0.043	0.007	0.069	0.001132	109.1	0.0124	0.0123
849-851	12.06	3.615	0.203	0.294	0.072	0.019	0.094	.001891	116.1	.0117	.0115
852-854	15.65	4,692	0.342	0.500	0.120	0.038	0.110	.003145	116.6	.0117	.0115
855-857	19.15	5.740	0.512	0.766	0.193	0.061	0.118	.005036	112.9	.0120	.0118
858-860	23.94	7.176	0.801	1.219	0.310	0.108	0.135	.008102	111.2	.0122	.0120
861-862	28.32	8.489	1.120	1.736	0.488	0.128	0.114	.01274	104.8	.0128	.0127
863	32.88	9.856	1.510	2.418	0.741	0.167	0.111	.01937	98.7	.0134	.0135

Table 61—Wingwalls, cut level with top of standard endwall and set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate IX-B)

864-866	8.621	2.584	0.104	0.146	0.037	0.005	0.048	0.00096	118.8	0.0116	0.0114
867-869	11.629	3.486	0.189	0.278	0.074	0.014	0.076	.00194	111.7	.0122	.0120
870-872	15.31	4.589	0.328	0.487	0.126	0.033	0.102	.00328	112.8	.0121	.0119
873-875	19.08	5.718	0.508	0.761	0.185	0.068	0.133	.00484	114.6	.0119	.0116
876-878	23.84	7.145	0.794	1.221	0.320	0.107	0.134	.00837	108.8	.0124	.0122
879-880	28.11	8.426	1.104	1.750	0.504	0.142	0.128	.01319	102.2	.0131	.0130
881	32.43	9.721	1.469	2.331	0.669	0.193	0.131	.01749	102.4	.0131	.0130

Table 62—Wingwalls cut on bevel to top of standard endwall and set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius. 0.5152 feet (See Plate IX-A)

882-884	8.421	2.524	0.099	0.139	0.028	0.012	0.118	0.000732	132.4	0.0105	0.0102
885-887	12.16	3.646	0.207	0.305	0.078	0.020	0.095	.00205	112.3	.0121	.0118
888-890	15.67	4.696	0.343	0.503	0.132	0.028	0.082	.00344	112.0	.0121	.0119
891-893	19.44	5.826	0.528	0.806	0.221	0.058	0.109	.00577	107.0	.0126	.0124
894-896	24.21	7.257	0.819	1.252	0.342	0.091	0.112	.00894	107.2	.0126	.0125
897-898	28.66	8.590	1.147	1.808	0.515	0.146	0.126	.01346	103.2	.0130	.0129
899	32.48	9.736	1.474	2.361	0.717	0.170	0.115	.01874	99.1	.0134	.0134

GROUP VII—CONTINUED

Table 63—Wingwalls, standard height, set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
900-902	8.632	2.587	0.104	0.145	0.044	–0.003	–0.026	0.001142	107.2	0.0125	0.0124
903-905	11.933	3.577	0.199	0.284	0.077	0.008	0.040	.00201	111.2	.0122	.0122
906-908	15.39	4.613	0.331	0.486	0.139	0.016	0.049	.00362	106.8	.0126	.0125
909-911	19.45	5.831	0.529	0.799	0.217	0.053	0.101	.00568	107.8	.0125	.0124
912-914	24.25	7.270	0.822	1.245	0.324	0.099	0.120	.00848	110.1	.0123	.0121
915-916	28.70	8.603	1.150	1.827	0.516	0.160	0.140	.01348	103.2	.0130	.0129
917 -	30.02	8.999	1.259	1.961	0.538	0.164	0.130	.01406	105.7	.0128	.0126

Table 64—Wingwalls, standard height, set flush with inside edge of 24-inch corrugated-metal pipe. Length, 36.7 feet; area of cross-section 3.142 square feet; mean hydraulic radius, 0.5000 feet

920-921	8.532	2.716	0.114	0.301	0.146	0.040	0.350	0.00399	60.8	0.0200	0.0218
922-923	11.878	3.781	0.222	0.628	0.335	0.070	0.318	.00912	56.0	.0214	.0236
924-925	15.48	4.927	0.377	1.089	0.592	0.120	0.318	.0161	54.9	.0218	.0241
926-929	19.42	6.181	0.594	1.689	0.868	0.227	0.382	.0236	56.9	.0211	.0233
930-931	21.83	6.948	0.750	2.122	1.089	0.283	0.377	.0297	57.2	.0211	.0232

GROUP VIII—TABLES 65 TO 68 SHOWING THE EFFECT OF U-TYPE WINGWALLS AT ENTRANCE WITH FLOOR IN FRONT OF PIPE

Table 65—Wingwalls cut on bevel to top of standard endwall and set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate IX-F)

932-934	8.432	2.527	0.099	0.151	0.048	0.003	0.034	0.00126	99.9	0.0133	0.0133
935-937	11.327	3.395	0.179	0.276	0.076	0.021	0.115	.00199	106.1	.0126	.0125
938-940	15.81	4.738	0.349	0.549	0.137	0.064	0.184	.00357	110.7	.0123	.0120
941-943	20.22	6.060	0.571	0.919	0.246	0.102	0.179	.00643	105.3	.0128	.0127
944-946	23.51	7.047	0.772	1.255	0.348	0.135	0.175	.00909	103.0	.0130	.0129
947-948	28.89	8.660	1.166	1.922	0.530	0.226	0.194	.01384	102.6	.0130	.0130
949	30.96	9.281	1.339	2.244	0.640	0.265	0.198	.01673	100.0	.0133	.0133

Table 66—Wingwalls cut on bevel to top of standard endwall and set 6 inches from inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate IX-D)

950-952	8.600	2.578	0.104	0.151	0.035	0.013	0.122	0.000915	118.9	0.0114	0.0112
953-955	11.910	3.570	0.198	0.302	0.074	0.030	0.151	.00193	113.3	.0120	.0118
956-958	15.70	4.707	0.344	0.523	0.134	0.045	0.132	.00348	111.1	.0122	.0120
959-961	19.45	5.829	0.528	0.817	0.211	0.077	0.146	.00552	109.3	.0124	.0122
962-964	23.73	7.112	0.786	1.235	0.340	0.109	0.138	.00890	105.1	.0128	.0127
965-966	28.20	8.454	1.112	1.790	0.497	0.182	0.164	.01299	103.4	.0130	.0129
967	29.44	8.825	1.211	1.921	0.502	0.208	0.172	.01312	107.3	.0126	.0124

Table 67—Wingwalls, standard height, set flush with inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate IX-E)

968-970	8.516	2.553	0.101	0.167	0.050	0.016	0.155	0.00130	98.6	0.0134	0.0135
971-973	12.11	3.629	0.205	0.344	0.101	0.038	0.187	.00263	98.9	.0135	.0135
974-976	15.53	4.654	0.337	0.565	0.151	0.076	0.228	.00394	104.2	.0129	.0128
977-979	19.31	5.789	0.521	0.896	0.217	0.158	0.304	.00567	107.6	.0126	.0124
980-982	24.12	7.231	0.813	1.441	0.418	0.210	0.259	.01093	98.1	.0137	.0137
983-984	28.20	8.454	1.112	1.955	0.440	0.404	0.364	.01148	110.3	.0123	.0121
985	29.68	8.897	1.231	2.154	0.494	0.429	0.348	.01291	109.1	.0124	.0122

GROUP VIII—CONTINUED

Table 68—Wingwalls, standard height, set 6 inches from inside edge of bell to 24-inch vitrified-clay pipe. Length, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
986-988	8.421	2.524	0.099	0.149	0.043	0.007	0.071	0.00113	104.6	0.0128	0.0127
989-991	12.06	3.615	0.203	0.319	0.092	0.024	0.116	.00242	102.3	.0130	.0130
992-994	15.27	4.578	0.326	0.520	0.142	0.052	0.159	.00373	104.7	.0128	.0127
995-997	19.31	5.789	0.521	0.863	0.247	0.095	0.182	.00646	100.4	.0133	.0133
998-1000	23.55	7.060	0.775	1.313	0.423	0.116	0.149	.01104	94.0	.0141	.0142
1001-1002	28.54	8.555	1.138	1.946	0.586	0.222	0.195	.01532	96.3	.0138	.0138
1003	30.42	9.119	1.293	2.243	0.693	0.257	0.199	.01811	94.4	.0140	.0141

GROUP IX—TABLES 69 TO 71 SHOWING THE EFFECT OF SPECIAL SHAPED BELLS AT ENTRANCE, NO FLOOR IN FRONT OF PIPE

Table 69—Bell of 24-inch vitrified-clay pipe filled with concrete and beveled off straight from inside edge of pipe to inside edge of bell. Length of pipe, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate X-C)

1004-1006	9.376	2.810	0.123	0.175	0.054	−0.001	−0.012	0.00141	104.5	0.0128	0.0127
1007-1009	12.20	3.656	0.208	0.295	0.088	−0.001	−0.003	.00231	106.3	.0127	.0125
1010-1012	16.37	4.906	0.374	0.539	0.153	0.012	0.032	.00399	108.4	.0125	.0123
1013-1015	19.46	5.834	0.529	0.777	0.217	0.031	0.059	.00566	108.0	.0125	.0123
1016-1018	24.42	7.320	0.833	1.222	0.337	0.052	0.063	.00880	108.8	.0125	.0122
1019-1021	28.95	8.677	1.171	1.741	0.516	0.054	0.047	.01348	104.2	.0129	.0128
1022	30.46	9.131	1.296	1.951	0.608	0.047	0.036	.01589	100.9	.0133	.0132

Table 70—Bell of 24-inch vitrified-clay pipe filled with concrete elliptically shaped with convex side out. Length, of pipe, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate X-D)

1023-1025	8.306	2.550	0.101	0.140	0.040	−0.001	−0.011	0.00105	109.9	0.0122	0.0121
1026-1028	11.454	3.433	0.183	0.256	0.075	−0.002	−0.011	.00196	108.1	.0124	.0123
1029-1031	15.95	4.781	0.355	0.509	0.140	0.014	0.038	.00365	110.3	.0123	.0124
1032-1034	18.87	5.657	0.497	0.717	0.211	0.008	0.016	.00552	106.1	.0127	.0125
1035-1037	24.45	7.328	0.835	1.209	0.352	0.022	0.027	.00920	106.4	.0127	.0125
1038-1040	28.38	8.507	1.125	1.646	0.486	0.035	0.032	.01269	105.2	.0128	.0127
1041	34.24	10.264	1.638	2.432	0.803	−0.009	−0.005	.02099	98.7	.0135	.0135

Table 71—Bell of 24-inch vitrified-clay pipe filled with concrete and shaped to give a square cornered entrance. Length of pipe, 38.3 feet; area of cross-section, 3.336 square feet; mean hydraulic radius, 0.5152 feet (See Plate X-B)

1042-1044	8.779	2.632	0.108	0.190	0.040	0.042	0.394	0.00106	114.4	0.0119	0 0117
1045-1047	11.536	3.458	0.186	0.331	0.076	0.070	0.375	.00199	108.3	.0124	.0123
1048-1050	15.36	4.605	0.330	0.603	0.120	0.153	0.463	.00314	114.8	.0119	.0116
1051-1053	19.44	5.827	0.528	0.985	0.196	0.260	0.493	.00513	114.1	.0120	.0117
1054-1056	24.13	7.234	0.814	1.515	0.288	0.413	0.508	.00752	116.3	.0118	.0114
1057	27.92	8.369	1.089	2.093	0.480	0.524	0.481	.01255	104.1	.0129	.0128

GROUP X—TABLES 72 TO 78 SHOWING THE EFFECT OF PROJECTING THE ENTRANCE END OF THE PIPE BEYOND THE HEADWALL

Table 72—12-inch concrete pipe with 3-inch projection. Entrance end of pipe with square end. Length of pipe, 31.5 feet; area of cross-section, 0.7841 square feet; mean hydraulic radius, 0.2498 feet (See Plate XII-A)

1058-1060	3.092	3.944	0.242	0.500	0.185	0.074	0.305	0.00587	103.1	0.0114	0.0114
1061-1063	4.010	5.114	0.407	0.868	0.326	0.134	0.330	.01036	100.6	.0116	.0117
1064-1066	4.580	5.841	0.530	1.153	0.443	0.180	0.340	.01406	98.6	.0118	.0120
1067-1069	5.311	6.774	0.714	1.560	0.578	0.269	0.377	.01835	100.1	.0116	.0118
1070-1071	5.955	7.595	0.897	1.987	0.772	0.318	0.354	.02452	97.0	.0120	.0122
1072-1073	6.982	8.906	1.234	2.762	1.072	0.457	0.371	.03406	96.7	.0120	.0122

GROUP X—CONTINUED

Table 73—12-inch concrete pipe with 24-inch projection. Entrance end of pipe with square end. Length of pipe, 31.5 feet; area of cross-section, 0.7841 square feet; mean hydraulic radius, 0.2498 feet (See Plate XII-B)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1074-1076	3.340	4.260	0.282	0.586	0.220	0.084	0.298	0.00700	102.0	0.0114	0.0116
1077-1079	4.041	5.154	0.413	0.868	0.331	0.124	0.300	.01051	100.6	.0116	.0117
1080-1083	4.692	5.984	0.557	1.188	0.444	0.187	0.336	.01410	100.8	.0116	.0117
1084-1086	5.044	6.434	0.644	1.383	0.521	0.219	0.340	.01654	100.1	.0116	.0118
1087-1089	6.116	7.801	0.946	2.064	0.783	0.335	0.355	.02488	99.0	.0118	.0119
1090-1091	6.945	8.857	1.220	2.716	1.041	0.454	0.372	.03307	97.4	.0120	.0121

Table 74—12-inch concrete pipe with 47-inch projection. Entrance end of pipe with square end. Length of pipe, 33.4 feet; area of cross-section, 0.7838 square feet; mean hydraulic radius, 0.2498 feet (See Plate XII-C)

1092-1094	3.154	4.024	0.252	0.526	0.195	0.079	0.312	0.00585	105.3	0.0111	0.0112
1095-1097	4.174	5.325	0.441	0.958	0.365	0.152	0.345	.01094	101.9	.0115	.0116
1098-1100	4.667	5.954	0.552	1.214	0.473	0.190	0.344	.01415	100.2	.0116	.0118
1101-1103	5.351	6.827	0.724	1.598	0.622	0.252	0.347	.01861	100.2	.0116	.0118
1104-1106	6.780	8.650	1.163	2.501	0.980	0.458	0.394	.02935	101.0	.0116	.0117

Table 75—12-inch concrete pipe with 47-inch projection. Entrance end of pipe with beveled lip end. Length of pipe, 33.4 feet, area of cross-section, 0.7838 square feet, mean hydraulic radius, 0.2498 feet

1107-1109	3.559	4.541	0.321	0.616	0.277	0.018	0.057	0.00829	99.8	0.0117	0.0118
1110-1112	3.782	4.825	0.362	0.701	0.321	0.017	0.048	.00962	98.4	.0118	.0119
1113-1114	4.599	5.868	0.536	1.072	0.485	0.052	0.096	.01452	97.4	.0119	.0121
1115-1117	5.435	6.934	0.748	1.492	0.673	0.071	0.095	.02014	97.8	.0119	.0120
1118-1120	6.090	7.770	0.939	1.880	0.848	0.094	0.100	.02538	97.6	.0119	.0121
1121	7.300	9.314	1.349	2.740	1.222	0.169	0.125	.03659	97.4	.0119	.0121

Table 76—18-inch corrugated-metal pipe with 3-inch projection. Length of pipe, 36.4 feet; area of cross-section, 1.771 square feet; mean hydraulic radius, 0.3754 feet (See Plate XII-D)

1125-1127	4.515	2.550	0.101	0.361	0.231	0.029	0.286	0.00634	52.3	0.0212	0.0242
1128-1130	5.588	3.155	0.155	0.579	0.377	0.047	0.303	.01038	50.6	.0218	.0249
1131-1133	6.052	3.417	0.182	0.670	0.433	0.056	0.308	.01189	51.2	.0215	.0247
1134-1136	10.093	5.699	0.505	1.911	1.242	0.164	0.325	.03414	50.4	.0219	.0250

Table 77—18-inch corrugated-metal pipe with 24-inch projection. Length of pipe, 36.4 feet; area of cross-section, 1.771 square feet; mean hydraulic radius, 0.3754 feet (See Plate XII-E)

1140-1142	4.432	2.503	0.097	0.364	0.215	0.052	0.536	0.00590	53.2	0.0208	0.0237
1143-1145	5.955	3.362	0.176	0.683	0.413	0.094	0.534	.01134	51.5	.0214	.0245
1146-1148	7.822	4.417	0.303	1.186	0.712	0.171	0.564	.01957	51.5	.0214	.0245
1149-1151	9.453	5.338	0.444	1.763	1.074	0.246	0.554	.02952	50.7	.0218	.0249

Table 78—18-inch corrugated-metal pipe with 48-inch projection. Length of pipe, 36.4 feet; area of cross-section, 1.771 square feet; mean hydraulic radius, 0.3754 feet (See Plate XII-F)

1155-1157	4.268	2.410	0.091	0.336	0.197	0.048	0.533	0.00541	53.5	0.0207	0.0236
1158-1160	6.117	3.454	0.185	0.736	0.441	0.109	0.590	.01212	51.2	.0215	.0247
1161-1163	7.560	4.269	0.284	1.166	0.725	0.157	0.554	.01994	49.4	.0222	.0256
1164-1166	9.873	5.575	0.483	1.960	1.202	0.275	0.569	.03305	50.1	.0219	.0252

GROUP XI—TABLE 79 SHOWING THE EFFECT OF A CONE PLACED AT THE OUTLET END OF A PIPE CULVERT

Table 79—18-inch vitrified-clay pipe, with straight endwall entrance and without floor in front of pipe; cone, 60 inches long increasing from 18-inches in diameter to 26 inches in diameter, total length of pipe including cone, 30 feet. Area of cross-section, 1.791 square feet; mean hydraulic radius, 0.3775 (See Plate XI-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
1167-1169	4.321	2.143	0.071	0.143	0.061	0.011	0.151	0.00199	78.5	0.0153	0.0162	0.07	0.074	1.047
1170-1172	6.02	3.361	0.176	0.264	0.090	−0.002	−0.011	.00292	101.3	.0124	.0125	0.14	0.128	0.729
1173-1175	8.02	4.478	0.312	0.455	0.133	0.010	0.031	.00435	110.9	.0116	.0114	0.24	0.214	0.686
1176-1178	10.05	5.609	0.489	0.747	0.244	0.013	0.027	.00775	103.8	.0122	.0122	0.38	0.363	0.742
1179-1181	12.14	6.778	0.714	1.069	0.339	0.016	0.023	.01104	105.2	.0121	.0120	0.55	0.519	0.726
1182-1184	14.16	7.908	0.972	1.481	0.470	0.039	0.040	.01534	104.2	.0122	.0122	0.74	0.740	0.761
1185-1187	16.50	9.213	1.319	2.011	0.652	0.039	0.030	.02128	103.3	.0123	.0123	1.00	1.015	0.769
1188-1190	18.96	10.59	1.743	2.667	0.876	0.049	0.028	.02856	102.4	.0124	.0124	1.32	1.353	0.777
1191-1192	21.84	12.20	2.312	3.538	1.118	0.108	0.046	.03647	104.0	.0122	.0122	1.76	1.786	0.772

GROUP XII—TABLES 80 TO 90 SHOWING THE TESTS ON CONCRETE BOX CULVERTS 2 FEET WIDE, STANDARD STRAIGHT ENDWALL ENTRANCE

Table 80—2-ft. by 2-ft. box culvert with square cornered entrance. Length, 24.02 feet; area of cross-section, 4.010 square feet; mean hydraulic radius, 0.5006 feet (See Plate XIII-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
20-24	8.781	2.190	0.074	0.122	0.015	0.034	0.454	0.00061	126.2	0.0113	0.0105
32-36	12.15	3.029	0.143	0.234	0.027	0.064	0.452	.00114	127.1	.0108	.0104
44-48	15.73	3.924	0.239	0.383	0.048	0.096	0.402	.00200	124.4	.0110	.0107
54-58	19.74	4.922	0.377	0.603	0.070	0.156	0.415	.00290	129.5	.0107	.0102
63-67	24.16	6.025	0.564	0.909	0.115	0.230	0.407	.00479	123.1	.0111	.0108
72-76	28.78	7.177	0.801	1.302	0.169	0.333	0.415	.00703	121.6	.0113	.0109
79-83	33.80	8.429	1.105	1.784	0.236	0.443	0.401	.00983	120.6	.0114	.0110
84-85	38.88	9.698	1.462	2.326	0.248	0.616	0.422	.01030	135.0	.0103	.0098

Table 81—2-ft. by 2-ft. box culvert with square cornered entrance. Length, 30.06 feet; area of cross-section, 4,012 square feet; mean hydraulic radius, 0.5007 feet (See Plate XIII-A)

105-109	8.947	2.225	0.077	0.127	0.022	0.028	0.370	0.00074	116.2	0.0116	0.0114
117-121	12.14	3.025	0.142	0.239	0.037	0.060	0.420	.00122	122.7	.0111	.0108
129-133	16.01	3.990	0.248	0.409	0.066	0.095	0.385	.00218	120.8	.0113	.0110
139-143	19.97	4.978	0.385	0.643	0.108	0.149	0.388	.00359	117.5	.0116	.0113
149-153	24.29	6.055	0.570	0.966	0.159	0.237	0.415	.00530	117.9	.0116	.0113
158-162	28.80	7.178	0.801	1.346	0.236	0.309	0.386	.00783	114.7	.0119	.0115
169-172	33.96	8.464	1.114	1.888	0.333	0.432	0.388	.01141	112.0	.0121	.0118

Table 82—2-ft. by 2-ft. box culvert with square cornered entrance. Length, 36.12 feet; area of cross-section, 4.012 square feet; mean hydraulic radius, 0.5007 feet

183-187	8.636	2.152	0.072	0.128	0.036	0.020	0.275	0.00101	97.2	0.0136	0.0138
190-194	12.14	3.027	0.142	0.244	0.057	0.045	0.315	.00158	108.1	.0124	.0123
197-201	15.78	3.934	0.241	0.410	0.085	0.084	0.350	.00234	114.5	.0118	.0116
204-208	19.91	4.965	0.383	0.661	0.135	0.143	0.373	.00375	114.6	.0118	.0116
211-215	23.84	5.943	0.549	0.943	0.196	0.197	0.359	.00543	114.0	.0119	.0116
218-223	28.74	7.162	0.798	1.384	0.284	0.303	0.380	.00785	114.2	.0119	.0116
225	33.68	8.395	1.096	1.886	0.345	0.445	0.406	.00955	121.4	.0113	.0109

Table 83—2-ft. by 2-ft. box culvert with beveled lip entrance. Length, 30.06 feet; area of cross-section, 4.012 square feet; mean hydraulic radius, 0.5007 feet (See Plate XIII-C)

232-235	8.658	2.158	0.072	0.107	0.022	0.013	0.184	0.00074	113.3	0.0118	0.0118
236-239	11.63	2.898	0.131	0.186	0.034	0.021	0.162	.00114	121.7	.0112	.0109
240-243	16.03	3.996	0.248	0.352	0.065	0.038	0.155	.00216	121.6	.0112	.0109
244-247	19.91	4.962	0.383	0.551	0.121	0.048	0.124	.00402	110.6	.0122	.0120
248-251	24.09	6.006	0.561	0.808	0.161	0.086	0.154	.00536	115.9	.0118	.0114
252-255	28.35	7.066	0.776	1.125	0.250	0.099	0.127	.00833	109.5	.0123	.0121
256-259	32.94	8.211	1.048	1.532	0.340	0.144	0.138	.01131	109.1	.0124	.0122
260-262	39.42	9.825	1.503	2.219	0.534	0.182	0.122	.01775	104.7	.0128	.0127

Table 84—2-ft. by 2-ft. box culvert with rounded lip entrance. Length, 30.06 feet; area of cross-section, 4.012 square feet; mean hydraulic radius, 0.5007 feet (See Plate XIII-B)

267-270	8.658	2.158	0.072	0.102	0.025	0.004	0.058	0.00082	106.4	0.0124	0.0124
271-274	12.09	3.014	0.141	0.194	0.046	0.006	0.046	.00154	108.7	.0123	.0122
275-278	15.95	3.976	0.246	0.341	0.081	0.014	0.058	.00270	108.3	.0124	.0122
279-282	19.53	4.868	0.368	0.514	0.123	0.022	0.061	.00408	107.8	.0124	.0123
283-286	24.58	6.126	0.584	0.804	0.190	0.031	0.053	.00631	109.0	.0123	.0122
287-290	28.56	7.119	0.788	1.102	0.272	0.042	0.053	.00905	105.8	.0127	.0125
291-294	33.42	8.330	1.078	1.516	0.380	0.058	0.054	.01266	104.6	.0128	.0126
295-298	37.41	9.324	1.352	1.925	0.499	0.074	0.054	.01660	102.7	.0130	.0129

Table 85—2-ft. by 2-ft. box culvert with rounded lip entrance. Upper two corners on inside of culvert chamfered 2 inches by 2 inches. Length, 30.06 feet; area of cross-section 3.984 square feet; mean hydraulic radius, 0.5096 feet

308-310	8.884	2.229	0.077	0.114	0.029	0.009	0.113	0.00095	101.5	0.0130	0.0131
311-313	11.58	2.907	0.132	0.192	0.051	0.009	0.069	.00170	99.1	.0134	.0134
314-316	16.16	4.055	0.256	0.362	0.095	0.011	0.042	.00317	100.9	.0132	.0132
317-319	19.43	4.877	0.370	0.526	0.145	0.011	0.031	.00481	98.7	.0135	.0135
320-322	24.31	6.102	0.579	0.822	0.218	0.026	0.044	.00724	100.5	.0132	.0132
323-325	28.77	7.221	0.811	1.142	0.278	0.053	0.065	.00925	105.3	.0128	.0126
326-330	34.39	8.632	1.158	1.638	0.428	0.051	0.044	.01424	101.4	.0132	.0131

GROUP XII—CONTINUED

Table 86—2-ft. by 2-ft. box culvert with rounded lip entrance. Outlet end 2-ft. by 2-ft. to 4-ft. by 2-ft. 6 feet long, flared on two sides only, total length including flared outlet, 30.06 feet; area of cross-section, 4.010 square feet; mean hydraulic radius, 0.5006 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
348-351	8.587	2.141	0.071	0.110	0.033	0.006	0.084	0.00109	94.2	0.0140	0.0144	0.058	0.052	0.729
352-355	12.49	3.116	0.150	0.220	0.066	0.003	0.022	.00220	94.7	.0139	.0141	0.122	0.098	0.652
356-359	15.82	3.945	0.242	0.353	0.094	0.017	0.069	.00314	99.6	.0132	.0133	0.203	0.150	0.621
360-363	19.64	4.897	0.373	0.532	0.137	0.022	0.060	.00456	103.0	.0129	.0129	0.307	0.226	0.605
364-367	24.12	6.014	0.562	0.802	0.207	0.032	0.058	.00688	102.8	.0130	.0129	0.474	0.327	0.582
368-372	28.07	7.011	0.764	1.102	0.285	0.052	0.068	.00949	102.2	.0131	.0130	0.649	0.453	0.592
373-376	32.87	8.196	1.044	1.513	0.401	0.068	0.065	.01333	100.4	.0132	.0132	0.892	0.620	0.594
377-380	40.52	10.105	1.588	2.249	0.585	0.077	0.048	.01946	102.4	.0130	.0130	1.351	0.898	0.566

Table 87—2-ft. by 2-ft. box culvert with rounded lip entrance. Outlet end 2-ft. by 2-ft. to 3.12 feet. by 2.56 ft., 6 feet long flared on sides and bottom, total length including flared outlet 30.08 feet; area of cross-section, 4.010 square feet; mean hydraulic radius, 0.5006 feet

390-393	9.006	2.246	0.078	0.122	0.041	0.003	0.035	0.00136	86.0	0.0150	0.0154	0.057	0.066	0.834
394-397	12.06	3.007	0.140	0.208	0.060	0.008	0.054	.00200	95.4	.0138	.0139	0.102	0.106	0.756
398-401	15.80	3.940	0.242	0.347	0.097	0.009	0.036	.00322	98.4	.0134	.0135	0.177	0.170	0.704
402-405	19.78	4.933	0.378	0.538	0.149	0.010	0.027	.00495	99.4	.0134	.0134	0.280	0.257	0.680
406-409	24.24	6.045	0.568	0.819	0.238	0.013	0.023	.00792	96.0	.0137	.0138	0.433	0.386	0.680
410-413	29.11	7.252	0.818	1.196	0.341	0.038	0.046	.01144	96.4	.0137	.0138	0.650	0.546	0.668
414-417	34.04	8.489	1.120	1.622	0.433	0.069	0.062	.01440	100.0	.0133	.0132	0.892	0.731	0.652

Table 88—2-ft. by 2-ft. box culvert with rounded lip entrance. Outlet end 2-ft. by 2-ft. to 3.12 ft. by 2.00 ft., 6 feet long, flared on two sides only, total length including flared outlet 30.08 feet; area of cross-section, 4,010 square feet; mean hydraulic radius, 0.5006 feet

423-426	9.069	2.262	0.080	0.128	0.039	0.009	0.110	0.00130	88.6	0.0145	0.0150	0.066	0.062	0.774
427-430	11.813	2.946	0.135	0.198	0.055	0.008	0.057	.00183	97.4	.0135	.0136	0.110	0.088	0.651
431-434	15.68	3.912	0.238	0.338	0.090	0.010	0.040	.00300	101.0	.0131	.0131	0.194	0.144	0.604
435-438	19.55	4.875	0.369	0.526	0.144	0.013	0.036	.00478	99.7	.0133	.0133	0.304	0.222	0.600
439-442	24.24	6.045	0.568	0.828	0.226	0.033	0.058	.00753	98.5	.0134	.0134	0.483	0.344	0.606
443-446	28.66	7.146	0.794	1.159	0.321	0.044	0.056	.01067	97.8	.0136	.0136	0.681	0.478	0.602
447-450	32.98	8.224	1.052	1.534	0.422	0.060	0.056	.01404	98.1	.0136	.0135	0.913	0.620	0.590

Table 89—2-ft. by 2-ft. box culvert with rounded lip entrance. Outlet end 2-ft. by 2-ft. to 4-ft. by 2-ft. 6 feet long, two sides flared on hyperbolic curve, total length including flared outlet 30.11 feet; area of cross-section, 4.010 square feet; mean hydraulic radius, 0.5006 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
456-459	8.958	2.234	0.078	0.116	0.033	0.005	0.061	00.00110	95.1	0.0138	0.0140	0.066	0.050	0.644
460-463	12.61	3.145	0.154	0.224	0.062	0.008	0.055	.00206	98.1	.0134	.0135	0.128	0.096	0.622
464-467	16.00	3.991	0.248	0.365	0.111	0.007	0.027	.00368	93.0	.0141	.0142	0.210	0.155	0.625
468-471	19.61	4.890	0.372	0.530	0.144	0.016	0.042	.00476	100.6	.0132	.0132	0.312	0.219	0.589
472-475	23.64	5.894	0.540	0.780	0.214	0.026	0.049	.00709	99.0	.0134	.0134	0.464	0.316	0.585
477-480	28.52	7.112	0.787	1.126	0.288	0.051	0.065	.00956	102.9	.0130	.0129	0.670	0.456	0.579
481-484	32.62	8.134	1.029	1.508	0.409	0.070	0.068	.01359	98.6	.0134	.0135	0.880	0.628	0.610

Table 90—2-ft. by 2-ft. box culvert with rounded lip entrance. Outlet end 2-ft. by 2-ft to 4-ft. by 2-ft., 10 feet long, flared on two sides only. Total length including flared outlet, 30.15 feet; area of cross-section, 4.010 square feet; mean hydraulic radius, 0.5006 feet

492-495	8.926	2.226	0.077	0.130	0.045	0.008	0.110	0.00149	83.4	0.0155	0.0162	0.049	0.081	1.056
496-499	11.89	2.965	0.137	0.192	0.042	0.013	0.097	.00139	114.6	.0119	.0117	0.088	0.104	0.761
500-503	16.14	4.024	0.252	0.364	0.100	0.012	0.049	.00332	98.9	.0134	.0134	0.165	0.199	0.792
504-507	20.50	5.112	0.406	0.636	0.220	0.009	0.023	.00730	88.4	.0150	.0154	0.275	0.361	0.887
508-511	24.26	6.050	0.569	0.824	0.219	0.036	0.062	.00726	101.0	.0132	.0132	0.393	0.430	0.756
513-516	28.77	7.175	0.800	1.146	0.299	0.047	0.059	.00992	102.4	.0130	.0130	0.551	0.595	0.744
517-520	33.42	8.333	1.080	1.570	0.417	0.073	0.067	.01384	100.4	.0133	.0132	0.737	0.832	0.771
521-522	38.04	9.485	1.398	2.048	0.532	0.117	0.084	.01765	101.0	.0132	.0131	0.968	1.080	0.772

GROUP XIII—TABLES 91 TO 98 SHOWING THE TESTS ON CONCRETE BOX CULVERTS 3 FEET WIDE, STANDARD STRAIGHT ENDWALL ENTRANCE

Table 91—3-ft. by 3-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 9.021 square feet; mean hydraulic radius, 0.7509 feet (See Plate XIV-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
536-539	8.903	0.987	0.015	0.020	0.004	0.001	0.067	0.00010	112.7	0.0120	0.0126
542-545	11.786	1.306	0.026	0.037	0.008	0.003	0.104	.00021	105.2	.0132	.0135
548-551	16.34	1.812	0.051	0.076	0.011	0.014	0.270	.00030	122.2	.0117	.0116
554-557	19.28	2.137	0.071	0.111	0.018	0.022	0.317	.00049	111.2	.0128	.0128
560-563	23.28	2.580	0.104	0.164	0.026	0.034	0.324	.00074	109.6	.0130	.0130
566-567 and 574-575	28.66	3.178	0.157	0.254	0.031	0.066	0.417	.00086	124.8	.0117	.0114
578-581	33.17	3.677	0.210	0.344	0.048	0.086	0.411	.00132	117.1	.0124	.0121
570-573	40.89	4.533	0.320	0.530	0.082	0.129	0.402	.00227	109.9	.0131	.0129

Table 92—3-ft. by 3-ft. box culvert with square cornered entrance. Length, 30.00 feet; area of cross-section, 9.021 square feet; mean hydraulic radius, 0.7509 feet

589-592	8.595	0.953	0.014	0.017	0.003	0.000	0.000	0.00010	110.0	0.0122	0.0129
595-598	12.33	1.367	0.029	0.039	0.006	0.003	0.103	.00022	107.7	.0130	.0132
601-604	16.11	1.786	0.050	0.072	0.010	0.012	0.246	.00035	111.0	.0128	.0128
607-610	19.85	2.200	0.075	0.110	0.013	0.022	0.292	.00040	128.4	.0114	.0111
613-616	23.97	2.658	0.110	0.162	0.016	0.035	0.318	.00055	131.5	.0111	.0108
619-622	29.14	3.230	0.162	0.245	0.028	0.055	0.338	.00094	121.6	.0120	.0116
625-627	34.89	3.907	0.233	0.358	0.041	0.084	0.361	.00137	121.6	.0120	.0117

Table 93—3-ft. by 3-ft. box culvert with beveled lip entrance. Length, 30.00 feet; area of cross-section, 9.021 square feet; mean hydraulic radius, 0.7509 feet, (See Plate XIV-C)

632-635	9.093	1.008	0.016	0.018	0.003	−0.001	−0.062	0.00011	112.7	0.0121	0.0126
636-639	11.962	1.326	0.027	0.031	0.006	−0.002	−0.074	.00020	108.6	.0128	.0131
640-643	15.46	1.714	0.046	0.056	0.011	−0.001	−0.016	.00036	105.9	.0134	.0136
644-647	19.58	2.171	0.073	0.092	0.016	0.003	0.038	.00054	108.2	.0132	.0131
648-651	23.62	2.619	0.106	0.134	0.022	0.006	0.054	.00074	111.5	.0129	.0127
652-655	27.90	3.093	0.149	0.189	0.025	0.015	0.101	.00084	123.3	.0118	.0115
656-659	32.86	3.642	0.206	0.264	0.041	0.016	0.080	.00137	113.8	.0127	.0124

Table 94—3-ft. by 3-ft. box culvert with rounded lip entrance. Length, 30.00 feet; area of cross-section, 9.021 square feet; mean hydraulic radius, 0.7509 feet, (See Plate XIV-B)

680-683	8.367	0.928	0.013	0.010	0.004	−0.006	−0.500	0.00013	93.8	0.0143	0.0151
684-687	12.53	1.389	0.030	0.028	0.008	−0.009	−0.300	.00025	101.5	.0137	.0140
688-691	15.95	1.768	0.049	0.050	0.011	−0.010	−0.215	.00035	109.3	.0129	.0130
692-695	19.74	2.188	0.074	0.080	0.016	−0.010	−0.134	.00053	109.6	.0130	.0130
696-699	24.29	2.692	0.113	0.138	0.030	−0.005	−0.042	.00098	103.8	.0138	.0137
700-703	28.37	3.145	0.154	0.183	0.038	−0.009	−0.058	.00126	102.4	.0139	.0138
704-706	33.08	3.667	0.209	0.251	0.049	−0.007	−0.032	.00163	104.8	.0136	.0135

Table 95—3.ft. by 3-ft. box culvert with rounded lip entrance. Upper two corners on inside of culvert chamfered 4 inches by 4 inches. Length, 30.00 feet; area of cross-section, 8.910 square feet; mean hydraulic radius, 0.7675 feet

723-726	8.848	0.993	0.015	0.010	0.003	−0.009	−0.592	0.00011	109.9	0.0124	0.0130
727-730	12.07	1.354	0.028	0.027	0.006	−0.007	−0.244	.00018	116.4	.0122	.0124
731-734	15.77	1.770	0.049	0.049	0.008	−0.008	−0.166	.00028	121.0	.0118	.0118
735-738	20.09	2.254	0.079	0.092	0.018	−0.006	−0.067	.00062	103.7	.0137	.0137
739-742	24.15	2.710	0.114	0.135	0.026	−0.006	−0.047	.00087	105.6	.0136	.0135
743-746	29.13	3.269	0.166	0.198	0.033	−0.001	−0.007	.00110	112.8	.0128	.0126
747-750	33.02	3.705	0.214	0.257	0.042	0.001	0.005	.00141	112.9	.0128	.0126
751-754	38.02	4.267	0.283	0.340	0.052	0.034	0.017	.00174	116.8	.0125	.0122

GROUP XIII—CONTINUED

Table 97—3-ft. by 3-ft. box culvert with rounded lip entrance. Outlet end 3-ft. by 3-ft. to 6-ft. by 3-ft., 12 feet long, flared on two sides only. Total length including flared outlet, 36.06 feet; area of cross-section, 9.027 square feet; mean hydraulic radius, 0.7511 feet (See Plate VI-B)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
802-804	8.842	0.979	0.015	0.020	0.004	0.0003	0.022	0.00012	103.4	0.0131	0.0137	0.007	0.013	0.844
805-807	12.07	1.337	0.028	0.033	0.008	−0.002	−0.083	.00021	106.3	.0130	.0133	0.015	0.018	0.643
808-810	15.33	1.699	0.045	0.056	0.013	−0.002	−0.037	.00035	105.0	.0134	.0135	0.024	0.032	0.718
811-813	19.40	2.150	0.072	0.086	0.019	−0.006	−0.079	.00054	106.9	.0133	.0133	0.041	0.045	0.620
814-816	23.58	2.613	0.106	0.141	0.033	0.001	0.012	.00091	99.9	.0142	.0142	0.063	0.078	0.730
835-838	28.58	3.166	0.156	0.178	0.042	−0.021	−0.133	.00117	109.1	.0134	.0132	0.084	0.094	0.599
817-819	29.73	3.293	0.169	0.219	0.052	−0.002	−0.010	.00143	100.6	.0141	.0141	0.097	0.122	0.721
839-843	33.58	3.720	0.215	0.280	0.079	−0.015	−0.070	.00220	91.4	.0155	.0155	0.125	0.154	0.717
826-828	34.06	3.773	0.221	0.290	0.070	−0.001	−0.006	.00195	98.5	.0144	.0144	0.127	0.163	0.736
846-849	38.09	4.220	0.277	0.357	0.085	−0.005	−0.018	.00236	100.3	.0145	.0141	0.162	0.194	0.702
823-825	39.07	4.328	0.291	0.385	0.094	0.000	0.000	.00261	97.8	.0145	.0145	0.174	0.211	0.725
853-855	43.42	4.810	0.359	0.510	0.142	0.009	0.026	.00393	88.9	.0159	.0160	0.218	0.293	0.814
820-822	45.49	5.039	0.394	0.538	0.132	0.012	0.031	.00365	96.2	.0147	.0147	0.245	0.293	0.743
860-862	49.44	5.477	0.467	0.630	0.151	0.013	0.028	.00419	97.7	.0145	.0145	0.288	0.343	0.734
867-869	55.07	6.101	0.579	0.780	0.182	0.019	0.033	.00505	99.2	.0144	.0143	0.359	0.421	0.728

GROUP XIII—CONTINUED

Table 96—3-ft. by 3-ft. box culvert with square cornered entrance. Length, 23.97 feet; area of cross-section, 9.027 square feet; mean hydraulic radius, 0.7511 feet (See Plate XIV-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
766-769	8.484	0.940	0.014	0.018	0.003	0.001	0.089	0.000125	97.0	0.0138	0.0146
772-775	11.725	1.299	0.026	0.034	0.006	0.002	0.086	.000260	93.6	.0147	.0152
778-781	15.48	1.714	0.046	0.062	0.010	0.006	0.120	.000417	97.1	.0144	.0146
791-793	18.17	2.013	0.063	0.090	0.014	0.013	0.206	.000598	95.2	.0147	.0149
790	19.84	2.198	0.075	0.100	0.015	0.010	0.133	.000626	101.4	.0139	.0140
784-787	24.03	2.662	0.110	0.164	0.020	0.033	0.300	.00086	105.2	.0135	.0135
797-798	27.45	3.040	0.144	0.220	0.030	0.047	0.328	.00125	99.2	.0143	.0143
954-957	28.45	3.152	0.154	0.230	0.021	0.055	0.358	.00087	125.9	.0117	.0114
796	28.91	3.203	0.160	0.230	0.027	0.043	0.269	.00113	110.1	.0130	.0129
799-801	31.25	3.461	0.186	0.282	0.035	0.061	0.327	.00145	105.9	.0136	.0135
961-964	33.41	3.701	0.213	0.326	0.026	0.086	0.404	.00110	131.2	.0113	.0110
968-971	38.74	4.292	0.286	0.448	0.054	0.108	0.375	.00224	105.8	.0137	.0135
975-978	43.20	4.786	0.356	0.564	0.056	0.151	0.423	.00236	114.0	.0128	.0126
979-982	49.77	5.513	0.473	0.787	0.076	0.238	0.506	.00318	113.4	.0128	.0125

Table 98—3-ft. by 3-ft. box culvert with rounded lip entrance. Length, 23.97 feet; area of cross-section, 9.027 square feet, mean hydraulic radius, 0.7511 feet (See Plate XIV-B)

918-920	8.617	0.955	0.014	0.011	0.004	−0.008	−0.548	0.00018	82.9	0.0163	0.0173
921-923	12.24	1.356	0.029	0.022	0.005	−0.012	−0.421	.00021	108.0	.0128	.0131
924-926	15.74	1.744	0.047	0.041	0.010	−0.017	−0.352	.00043	96.8	.0144	.0146
927-929	20.13	2.231	0.077	0.078	0.020	−0.020	−0.256	.00083	89.4	.0157	.0159
930-932	24.33	2.695	0.113	0.120	0.028	−0.021	−0.183	.00118	90.4	.0155	.0157
882-885	28.78	3.188	0.158	0.186	0.052	−0.024	−0.154	.00219	78.8	.0176	.0180
889-892	33.06	3.662	0.208	0.249	0.054	−0.013	−0.062	.00223	89.5	.0157	.0158
896-899	39.12	4.333	0.292	0.365	0.072	0.001	0.004	.00302	91.3	.0155	.0156
903-906	44.58	4.938	0.379	0.474	0.090	0.004	0.012	.00375	93.0	.0152	.0152
915-917	49.74	5.510	0.472	0.602	0.124	0.006	0.014	.00510	88.4	.0159	.0161
910-912	52.40	5.801	0.523	0.691	0.131	0.037	0.070	.00545	90.7	.0156	.0156

GROUP XIV—TABLE 99 SHOWING THE EFFECT ON THE DISCHARGE CAPACITY OF FLARING A BOX CULVERT ON THE TWO SIDES ONLY FOR ITS ENTIRE LENGTH

Table 99—2-ft. by 2-ft. box culvert, with rounded lip entrance and flared on the two sides for its entire length to a 4-ft. by 2-ft. opening at the outlet end. Length, 30.00 feet

Test numbers	Q Discharge Cu. ft. per sec.	Difference in elevation of water surface between entrance and outlet Feet
995-998	8.633	0.035
999-1002	11.75	0.058
1003-1006	16.15	0.116
1007-1010	18.57	0.173
1011-1014	23.51	0.244
1015-1018	28.45	0.383
1019-1022	33.42	0.518
1023-1026	38.82	0.700
1027-1030	43.62	0.877
1031-1034	49.08	1.135

GROUP XV—TABLES 100 TO 111 SHOWING THE TESTS ON CONCRETE BOX CULVERTS 4 FEET WIDE, STANDARD STRAIGHT ENDWALL ENTRANCE

Table 100—4-ft. by 4-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 15.994 square feet; mean hydraulic radius, 0.998 feet (See Plate XV-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1128-1131	28.33	1.771	0.049	0.064	0.012	0.003	0.060	0.000326	99.6	0.0148	0.0150
1121-1123	32.89	2.057	0.066	0.082	0.014	0.002	0.031	.000388	104.7	.0142	.0142
1124-1127	37.94	2.372	0.088	0.109	0.018	0.004	0.044	.000485	109.6	.0138	.0137
1077-1080	43.85	2.741	0.117	0.142	0.026	−0.001	−0.008	.000728	102.1	.0146	.0146
1081-1084	49.24	3.078	0.148	0.176	0.032	−0.003	−0.020	.000873	104.4	.0144	.0142
1085-1088	54.44	3.404	0.180	0.218	0.040	−0.003	−0.017	.001123	101.7	.0147	.0146
1089-1092	60.16	3.762	0.220	0.266	0.049	−0.003	−0.012	.001352	102.6	.0146	.0145
1093-1096	66.21	4.140	0.266	0.321	0.059	−0.004	−0.015	.001636	102.6	.0146	.0145
1097-1100	72.98	4.563	0.324	0.396	0.064	0.007	0.022	.001781	108.5	.0139	.0137
1101-1104	79.72	4.984	0.386	0.472	0.081	0.005	0.013	.002238	105.5	.0143	.0141
1105-1108	86.42	5.404	0.454	0.555	0.104	−0.004	−0.008	.002882	100.8	.0149	.0148
1109-1112	93.40	5.840	0.530	0.643	0.110	0.002	0.004	.003056	105.9	.0143	.0140
1113-1116	100.46	6.281	0.613	0.741	0.138	−0.010	−0.016	.003818	101.8	.0148	.0146
1117-1120	107.59	6.727	0.704	0.860	0.155	0.002	0.002	.004303	102.8	.0146	.0144
1199-1202	142.34	8.900	1.231	1.507	0.261	0.015	0.012	.007234	103.5	.0146	.0142

Table 101—4-ft. by 4-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 15.994 square feet; mean hydraulic radius, 0.998 feet (See Plate XV-B)

1213-1216	28.73	1.796	0.050	0.074	0.011	0.013	0.258	0.000305	103.4	0.0142	0.0144
1217-1220	33.74	2.110	0.070	0.109	0.018	0.021	0.305	.000513	97.2	.0155	.0157
1221-1224	39.94	2.498	0.097	0.149	0.024	0.028	0.283	.000672	99.3	.0152	.0153
1226-1228	43.85	2.742	0.117	0.179	0.024	0.038	0.322	.000665	106.4	.0140	.0139
1229-1232	48.80	3.051	0.145	0.221	0.033	0.043	0.297	.000922	100.6	.0148	.0148
1233-1236	53.98	3.375	0.177	0.268	0.038	0.052	0.293	.001067	103.5	.0145	.0144
1237-1240	60.03	3.753	0.219	0.334	0.035	0.080	0.368	.000970	125.6	.0124	.0122
1241-1244	66.98	4.188	0.273	0.406	0.047	0.086	0.315	.001302	116.1	.0130	.0128
1245-1248	73.00	4.564	0.324	0.490	0.063	0.104	0.321	.001739	113.0	.0136	.0134
1249-1252	79.56	4.974	0.385	0.579	0.076	0.118	0.307	.002100	109.0	.0139	.0136
1253-1256	86.46	5.406	0.454	0.690	0.084	0.151	0.332	.002335	112.4	.0136	.0132
1257-1260	93.40	5.839	0.530	0.802	0.094	0.177	0.335	.002620	114.4	.0134	.0130
1261-1264	102.04	6.380	0.633	0.972	0.124	0.215	0.340	.003430	109.4	.0139	.0136
1269-1272, and 1343	108.37	6.776	0.714	1.074	0.120	0.240	0.336	.003321	118.2	.0130	.0126
1265-1268, and 1344	110.09	6.884	0.737	1.131	0.136	0.258	0.350	.003759	112.7	.0135	.0132
1273-1276	117.28	7.333	0.836	1.290	0.121	0.333	0.398	.003347	127.2	.0121	.0117
1277-1280	124.24	7.767	0.938	1.488	0.144	0.406	0.432	.003991	123.9	.0124	.0120
1281-1283	131.73	8.237	1.055	1.668	0.136	0.477	0.452	.003779	134.2	.0115	.0111
1331-1333	140.03	8.756	1.192	1.910	0.176	0.541	0.454	.004887	125.6	.0122	.0119
1334-1336	147.80	9.241	1.328	2.126	0.193	0.605	0.456	.005359	126.6	.0121	.0118
1337-1339	157.20	9.828	1.502	2.397	0.201	0.693	0.462	.005581	131.8	.0117	.0113
1340-1342	163.57	10.226	1.627	2.618	0.257	0.734	0.452	.007114	122.1	.0126	.0122
1209-1212	170.01	10.630	1.758	2.780	0.282	0.741	0.422	.007817	121.6	.0127	.0125

Table 102—4-ft. by 3-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 12.067 square feet; mean hydraulic radius, 0.8592 feet

1367-1370	19.38	1.606	0.040	0.058	0.012	0.006	0.149	0.000326	99.5	0.0146	0.0149
1371-1374	24.32	2.016	0.063	0.097	0.020	0.014	0.224	.000540	95.5	.0151	.0154
1375-1378	28.96	2.400	0.090	0.133	0.028	0.016	0.174	.000776	93.4	.0154	.0156
1379-1382	33.10	2.742	0.117	0.181	0.027	0.037	0.316	.000755	108.1	.0135	.0134
1383-1386	38.17	3.164	0.154	0.231	0.041	0.035	0.226	.001136	101.5	.0144	.0143
1387-1390	43.96	3.643	0.206	0.314	0.052	0.056	0.268	.001455	103.6	.0141	.0140
1391-1394	49.61	4.112	0.263	0.404	0.069	0.072	0.275	.001906	102.1	.0143	.0142
1395-1398	54.57	4.522	0.318	0.493	0.070	0.105	0.329	.001947	111.5	.0132	.0131
1399-1402	60.48	5.013	0.391	0.606	0.085	0.130	0.334	.002349	112.8	.0132	.0129
1403-1406	66.40	5.503	0.471	0.722	0.088	0.164	0.348	.002432	120.8	.0124	.0120

GROUP XV—CONTINUED

Table 102—Continued

Test number	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1407-1410	73.15	6.062	0.571	0.886	0.129	0.186	0.325	.003576	110.2	.0135	.0132
1411-1413	79.30	6.571	0.671	1.031	0.127	0.233	0.347	.003511	119.6	.0125	.0121
1414-1416	86.44	7.163	0.798	1.217	0.143	0.276	0.346	.003973	122.7	.0122	.0118
1417-1419	93.24	7.727	0.928	1.419	0.183	0.308	0.332	.005072	117.1	.0127	.0124
1420-1422	99.23	8.223	1.051	1.641	0.189	0.401	0.381	.005229	122.9	.0122	.0118
1348-1351	109.98	9.114	1.292	2.082	0.289	0.502	0.389	.008010	110.7	.0134	.0131
1352-1355	116.85	9.684	1.458	2.352	0.280	0.614	0.420	.007760	119.5	.0126	.0122
1356-1359	124.64	10.33	1.659	2.705	0.342	0.704	0.424	.009486	114.7	.0129	.0126
1360-1363	132.58	10.99	1.878	3.017	0.344	0.795	0.424	.009521	121.6	.0123	.0119
1364-1366	139.13	11.53	2.067	3.314	0.374	0.873	0.422	.010366	123.1	.0122	.0118
1345-1347	147.00	12.18	2.309	3.714	0.493	0.912	0.395	.013655	113.0	.0131	.0129

Table 103—4-ft. by 3-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 12.067 square feet; mean hydraulic radius, 0.8592 feet

1423-1426	20.11	1.667	0.043	0.046	0.011	–0.008	–0.172	0.000305	103.7	0.0139	0.0140
1427-1430	24.11	1.998	0.062	0.069	0.018	–0.011	–0.172	.000492	98.3	.0147	.0149
1431-1434	28.53	2.364	0.087	0.105	0.020	–0.002	–0.027	.000561	108.1	.0135	.0134
1435-1438	33.20	2.751	0.118	0.138	0.035	–0.015	–0.124	.000977	95.8	.0151	.0152
1439-1442	38.49	3.190	0.158	0.191	0.032	0.001	0.008	.000880	118.6	.0126	.0124
1443-1446	43.23	3.583	0.200	0.242	0.055	–0.012	–0.060	.001518	99.2	.0147	.0146
1447-1450	49.06	4.066	0.257	0.311	0.064	–0.011	–0.043	.001788	104.7	.0141	.0140
1451-1454	56.04	4.644	0.335	0.397	0.061	0.001	0.002	.001691	122.6	.0122	.0118
1455-1458	59.91	4.965	0.383	0.455	0.081	–0.009	–0.024	.002238	113.2	.0130	.0128
1459-1462	66.16	5.483	0.468	0.562	0.115	–0.007	–0.016	.002820	111.6	.0132	.0130
1463-1466	72.90	6.042	0.568	0.689	0.125	–0.004	–0.006	.003464	110.8	.0133	.0131
1467-1470	80.02	6.632	0.684	0.821	0.121	0.016	0.024	.003347	124.8	.0121	.0117
1471-1474	86.28	7.150	0.795	0.955	0.162	–0.002	–0.002	.004490	116.2	.0128	.0126
1475-1478	93.12	7.718	0.926	1.126	0.197	0.003	0.004	.005467	113.4	.0132	.0128
1479-1482	100.97	8.368	1.089	1.309	0.218	0.003	0.002	.006028	118.0	.0127	.0124
1483-1486	108.92	9.027	1.267	1.584	0.304	0.014	0.012	.008412	106.2	.0138	.0136
1487-1490	116.36	9.644	1.446	1.796	0.326	0.023	0.016	.009050	110.1	.0135	.0132
1491-1493	125.65	10.413	1.686	2.153	0.408	0.059	0.035	.011299	105.7	.0139	.0137
1494-1496	132.75	11.002	1.882	2.420	0.485	0.053	0.028	.013433	102.5	.0144	.0142
1497-1499	140.45	11.639	2.106	2.756	0.546	0.104	0.050	.015124	102.2	.0143	.0142
1500-1502	150.58	12.479	2.421	3.193	0.631	0.141	0.058	.017489	101.8	.0144	.0142

Table 104—4-ft. by 2¼-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 9.009 square feet; mean hydraulic radius, 0.7202 feet

1533-1535	19.44	2.158	0.072	0.096	0.024	–0.001	–0.019	0.000675	98.0	0.0143	0.0144
1536-1538	25.11	2.787	0.121	0.151	0.039	–0.008	–0.070	.001081	100.0	.0141	.0141
1539-1541	29.45	3.269	0.166	0.208	0.050	–0.008	–0.048	.001386	104.9	.0136	.0135
1542-1544	33.55	3.724	0.216	0.264	0.053	–0.005	–0.023	.001478	114.9	.0125	.0123
1545-1547	38.43	4.266	0.283	0.357	0.088	–0.014	–0.049	.002448	102.4	.0139	.0138
1548-1550	43.69	4.849	0.365	0.463	0.100	–0.002	–0.006	.002781	108.6	.0132	.0130
1551-1553	48.78	5.414	0.456	0.572	0.124	–0.007	–0.016	.003437	109.1	.0131	.0129
1554-1556	54.82	6.085	0.576	0.734	0.175	–0.017	–0.029	.004859	103.0	.0138	.0137
1515-1517	61.42	6.818	0.723	0.937	0.242	–0.028	–0.038	.006698	98.4	.0144	.0143
1518-1520	67.82	7.528	0.881	1.130	0.255	–0.007	–0.008	.007068	105.5	.0135	.0133
1521-1523	73.41	8.149	1.032	1.314	0.294	–0.012	–0.011	.008139	106.6	.0134	.0132
1524-1526	80.46	8.931	1.240	1.587	0.355	–0.008	–0.006	.009830	106.3	.0134	.0132
1527-1529	87.32	9.693	1.461	1.852	0.392	0.000	0.000	.010855	109.7	.0131	.0129
1530-1532	94.05	10.440	1.695	2.159	0.485	–0.021	–0.012	.013433	106.3	.0135	.0132
1504-1506	101.90	11.311	1.989	2.588	0.549	0.050	0.025	.015216	108.0	.0132	.0130
1507-1509	109.00	12.099	2.276	2.985	0.636	0.074	0.032	.017618	107.4	.0133	.0131
1510-1512	116.52	12.933	2.600	3.459	0.732	0.127	0.049	.020279	107.0	.0133	.0131
1513-1514, and 1503	125.37	13.917	3.014	3.990	0.813	0.163	0.054	.022533	109.5	.0131	.0128

GROUP XV—CONTINUED

Table 105—4-ft. by 2¼-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 9.009 square feet; mean hydraulic radius, 0.7202 feet

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1578-1580	23.98	2.662	0.110	0.165	0.032	0.023	0.207	0.000877	106.2	0.0133	0.0133
1581-1583	29.42	3.265	0.166	0.251	0.047	0.039	0.235	.001293	107.0	.0133	.0131
1584-1586	33.30	3.695	0.212	0.322	0.055	0.054	0.254	.001533	111.3	.0129	.0127
1587-1589	38.84	4.311	0.289	0.430	0.060	0.082	0.281	.001653	125.1	.0117	.0113
1590-1592	44.05	4.889	0.371	0.564	0.088	0.105	0.281	.002430	116.9	.0124	.0121
1593-1595	49.63	5.509	0.472	0.723	0.119	0.132	0.280	.003307	113.0	.0127	.0124
1596-1598	54.68	6.069	0.572	0.880	0.128	0.180	0.314	.003547	120.5	.0121	.0117
1599-1601	60.81	6.750	0.708	1.094	0.156	0.230	0.324	.004324	121.0	.0120	.0116
1602-1604	68.26	7.576	0.892	1.391	0.193	0.306	0.342	.005349	122.3	.0119	.0115
1605-1607	73.57	8.166	1.036	1.630	0.223	0.371	0.357	.006171	122.6	.0119	.0115
1608-1610	79.81	8.859	1.220	1.908	0.264	0.425	0.348	.007308	122.2	.0119	.0115
1611-1614	86.84	9.639	1.444	2.358	0.315	0.599	0.415	.008738	121.6	.0120	.0116
1615-1618	98.84	10.971	1.874	2.996	0.440	0.682	0.365	.012202	118.0	.0123	.0120
1619-1621	108.36	12.027	2.249	3.657	0.599	0.809	0.360	.016602	110.2	.0130	.0128
1622-1625	115.64	12.836	2.562	4.162	0.582	1.018	0.397	.016144	119.4	.0122	.0118

Table 106—4-ft. by 2-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 8.037 square feet; mean hydraulic radius, 0.668 feet

1657-1659	20.30	2.526	0.099	0.141	0.032	0.010	0.097	0.000896	103.8	0.0134	0.0134
1660-1662	24.70	3.073	0.147	0.221	0.053	0.021	0.141	.001469	98.3	.0142	.0142
1663-1665	28.76	3.579	0.199	0.302	0.072	0.031	0.153	.001986	98.3	.0141	.0142
1666-1668	33.84	4.211	0.276	0.426	0.093	0.057	0.206	.002587	101.6	.0138	.0137
1669-1671	38.95	4.847	0.365	0.566	0.111	0.090	0.246	.003086	106.8	.0132	.0130
1636-1638	44.24	5.505	0.471	0.754	0.147	0.136	0.289	.004084	105.7	.0133	.0132
1639-1641	50.33	6.263	0.610	0.977	0.198	0.169	0.276	.005497	103.3	.0136	.0134
1642-1644	55.19	6.867	0.733	1.166	0.193	0.239	0.326	.005358	115.4	.0124	.0121
1645-1647	60.63	7.544	0.885	1.413	0.245	0.283	0.320	.006800	112.3	.0127	.0124
1648-1650	67.21	8.363	1.087	1.771	0.308	0.376	0.346	.008536	111.5	.0128	.0125
1651-1653	73.26	9.116	1.292	2.106	0.348	0.466	0.361	.009645	114.3	.0125	.0122
1654-1656	79.94	9.947	1.538	2.503	0.446	0.519	0.338	.012352	109.7	.0129	.0127
1633-1635	86.05	10.707	1.782	2.904	0.573	0.549	0.308	.015873	104.1	.0135	.0134
1630-1632	93.87	11.680	2.122	3.492	0.634	0.736	0.347	.017582	108.1	.0131	.0129
1626-1629	102.06	12.699	2.508	4.126	0.736	0.881	0.351	.020406	108.8	.0130	.0128

Table 107—4-ft. by 2-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 8.037 square feet; mean hydraulic radius, 0.668 feet

1672-1674	20.01	2.490	0.096	0.122	0.033	−0.007	−0.077	0.000924	100.5	0.0138	0.0138
1675-1677	24.76	3.081	0.148	0.195	0.053	−0.005	−0.036	.001469	98.5	.0141	.0141
1678-1680	30.34	3.776	0.221	0.293	0.082	−0.010	−0.045	.002264	97.2	.0143	.0143
1681-1683	33.76	4.201	0.274	0.358	0.092	−0.008	−0.029	.002550	102.1	.0137	.0136
1684-1686	38.74	4.820	0.361	0.470	0.102	0.007	0.017	.002827	111.7	.0127	.0125
1687-1689	43.65	5.430	0.459	0.585	0.157	−0.031	−0.067	.004342	101.0	.0138	.0138
1690-1692	49.53	6.163	0.591	0.767	0.203	−0.026	−0.045	.005626	100.7	.0139	.0138
1693-1695	55.43	6.897	0.739	0.978	0.257	−0.018	−0.025	.007114	100.3	.0139	.0138
1696-1698	61.12	7.605	0.899	1.170	0.272	−0.002	−0.002	.007548	107.2	.0131	.0130
1699-1701	67.04	8.342	1.082	1.461	0.367	0.012	0.011	.010172	101.3	.0138	.0137
1702-1704	73.88	9.192	1.314	1.767	0.436	0.017	0.013	.012085	102.3	.0137	.0136
1705-1707	81.14	10.096	1.578	2.115	0.521	0.016	0.010	.014440	102.8	.0136	.0135
1708-1709	87.12	10.840	1.827	2.432	0.576	0.028	0.016	.015978	104.9	.0134	.0132
1710-1711	94.78	11.792	2.162	2.866	0.689	0.016	0.007	.019096	104.4	.0134	.0133
1712-1714	104.52	13.005	2.631	3.574	0.838	0.105	0.040	.023234	104.5	.0134	.0133

GROUP XV—CONTINUED

Table 108—4-ft. by 1-ft. box culvert with square cornered entrance. Length, 36.08 feet; area of cross-section, 4.000 square feet; mean hydraulic radius, 0.400 feet (See Plate XVI-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient
1725-1727	14.82	3.704	0.214	0.398	0.105	0.079	0.373	0.002910	108.8	0.0119	0.0117
1728-1730	19.87	4.968	0.384	0.703	0.203	0.116	0.303	.005636	104.8	.0123	.0122
1731-1733	24.94	6.236	0.605	1.101	0.319	0.177	0.292	.008851	104.9	.0123	.0122
1734-1736	29.23	7.308	0.833	1.482	0.418	0.231	0.276	.011576	107.8	.0120	.0118
1737-1739	35.13	8.782	1.199	2.113	0.576	0.338	0.282	.015964	109.9	.0118	.0116
1740-1742	39.47	9.867	1.514	2.657	0.736	0.407	0.269	.020390	109.2	.0119	.0117
1717-1719	44.57	11.142	1.930	3.468	0.966	0.572	0.296	.026765	107.7	.0120	.0118
1720-1722	49.31	12.326	2.363	4.218	1.113	0.743	0.315	.030840	111.0	.0117	.0115
1723-1724	54.14	13.536	2.848	5.062	1.328	0.886	0.311	.036809	111.6	.0117	.0114
1715-1716	56.68	14.169	3.122	5.482	1.448	0.912	0.292	.040135	111.9	.0116	.0114

Table 109—4-ft by 1-ft. box culvert with entrance end rounded on top side of culvert only. Length, 36.08 feet; area of cross-section, 4.000 square feet; mean hydraulic radius, 0.400 feet (See Plate XVI-B)

1743-1745	9.062	2.266	0.080	0.122	0.046	–0.004	–0.046	0.001266	101.6	0.0125	0.0126
1746-1748	13.30	3.326	0.172	0.260	0.086	0.002	0.008	.002393	107.5	.0120	.0119
1749-1751	15.78	3.944	0.242	0.361	0.121	–0.001	–0.006	.003344	108.0	.0120	.0118
1752-1754	20.03	5.007	0.390	0.591	0.200	0.002	0.003	.005543	106.5	.0121	.0120
1755-1757	24.85	6.213	0.600	0.931	0.317	0.013	0.022	.008786	104.8	.0123	.0122
1758-1760	28.53	7.132	0.791	1.229	0.431	0.008	0.010	.011936	103.3	.0124	.0123
1761-1763	33.49	8.373	1.090	1.715	0.599	0.025	0.023	.016602	102.7	.0125	.0124
1764-1766	38.93	9.731	1.473	2.328	0.808	0.047	0.033	.022394	102.8	.0125	.0124
1767-1769	44.08	11.042	1.895	2.970	0.986	0.089	0.047	.027318	105.7	.0122	.0121
1770-1771	48.41	12.102	2.277	3.558	1.228	0.052	0.023	.034035	103.8	.0124	.0123

Table 110—4-ft. by 1-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 4.000 square feet; mean hydraulic radius, 0.400 feet (See Plate XVI-C)

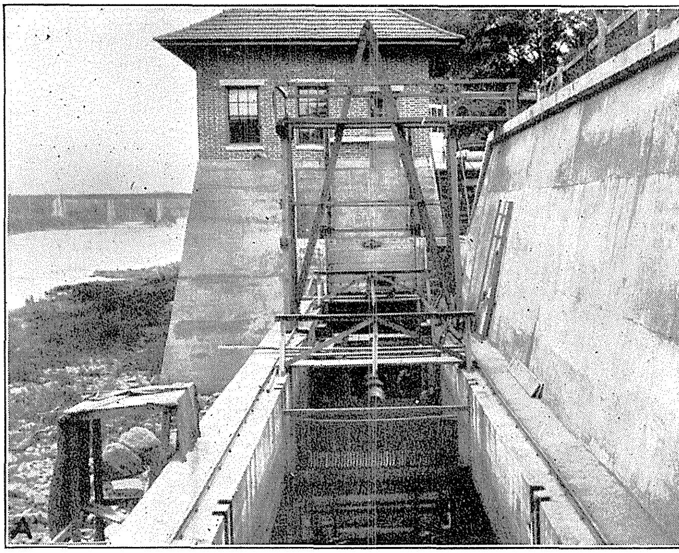
1772	8.470	2.118	0.070	0.108	0.045	–0.007	–0.100	0.001247	94.8	0.0132	0.0135
1773-1774	9.947	2.486	0.096	0.145	0.063	–0.014	–0.146	.001746	94.1	.0132	.0136
1775-1777	13.74	3.435	0.183	0.269	0.099	–0.014	–0.077	.002753	103.8	.0123	.0123
1778-1780	16.07	4.017	0.251	0.371	0.130	–0.010	–0.039	.003594	106.1	.0121	.0120
1781-1783	20.41	5.102	0.405	0.601	0.214	–0.017	–0.042	.005922	104.9	.0122	.0122
1784-1786	24.48	6.117	0.582	0.886	0.330	–0.026	–0.044	.009147	101.2	.0126	.0126
1787-1789	28.97	7.242	0.815	1.258	0.440	0.003	0.003	.012205	103.7	.0124	.0123
1790-1792	34.18	8.546	1.137	1.734	0.635	–0.037	–0.032	.017600	102.0	.0125	.0125
1793-1795	38.23	9.558	1.420	2.144	0.734	–0.010	–0.007	.020335	106.0	.0122	.0120
1796-1798	44.53	11.133	1.927	2.940	1.034	–0.021	–0.011	.028659	104.0	.0124	.0123
1799-1800	47.94	11.984	2.234	3.424	1.174	0.016	0.006	.032554	105.0	.0122	.0122
1801	50.99	12.748	2.527	3.807	1.210	0.070	0.028	.033537	110.1	.0118	.0116

Table 111—4-ft. by ½-ft. box culvert with rounded lip entrance. Length, 36.08 feet; area of cross-section, 2.000 square feet; mean hydraulic radius, 0.222 feet

1810	7.323	3.662	0.208	0.405	0.198	–0.001	–0.005	0.005488	104.9	0.0110	0.01102
1811	9.606	4.803	0.359	0.695	0.326	0.010	0.028	.009036	107.2	.0108	.01079
1812	12.06	6.030	0.565	1.113	0.536	0.012	0.021	.01486	104.9	.0110	.01102
1813	13.47	6.735	0.705	1.386	0.653	0.028	0.040	.01810	106.2	.0109	.01089
1814	14.31	7.155	0.796	1.567	0.742	0.029	0.036	.02057	105.8	.0109	.01093
1815	16.12	8.060	1.010	1.980	0.909	0.061	0.060	.02519	107.7	.0108	.01074
1816	20.31	10.155	1.604	3.180	1.516	0.060	0.037	.04202	105.1	.0110	.01100
1817	22.22	11.110	1.919	3.716	1.750	0.047	0.024	.04850	107.0	.0108	.01081
1818	23.39	11.695	2.127	4.176	2.002	0.047	0.022	.05549	105.3	.0109	.01098
1819	24.53	12.265	2.339	4.705	2.272	0.094	0.040	.06297	103.7	.0111	.01115
1820	26.77	13.385	2.786	5.490	2.700	0.004	0.001	.07483	103.8	.0111	.01114
1821	27.14	13.570	2.863	5.670	2.776	0.031	0.011	.07694	103.8	.0111	.01114

PLATES

(Listed on pages 5, 6 and 7)



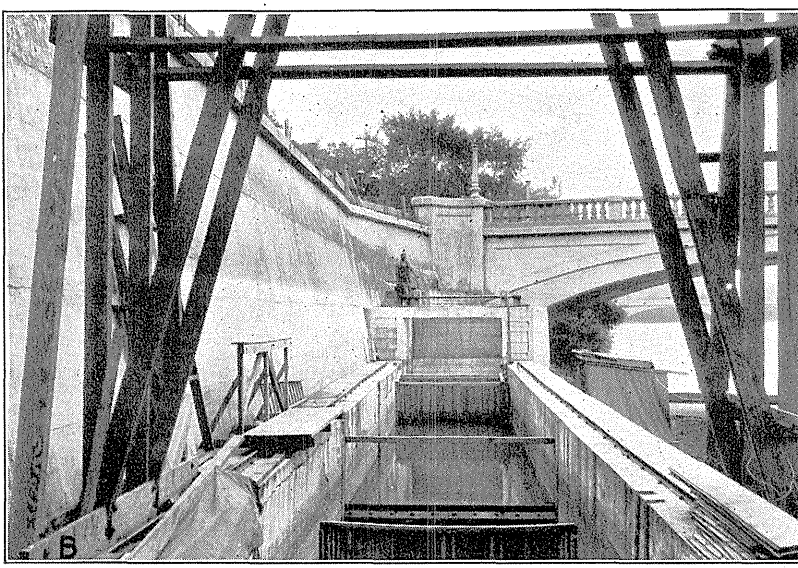
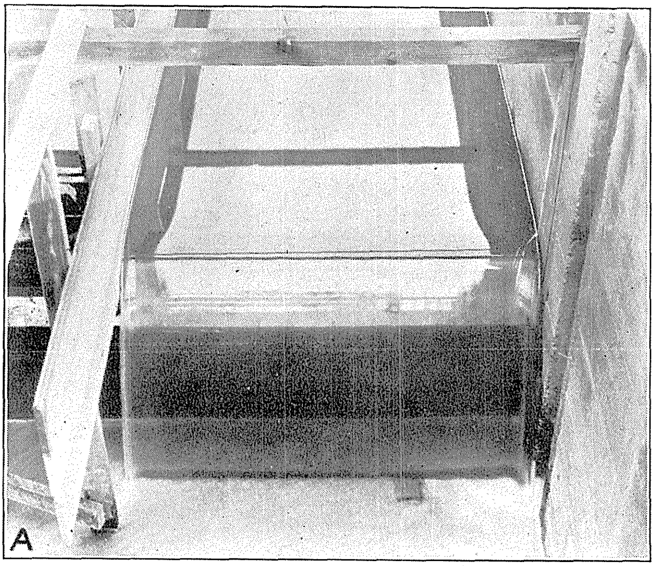


PLATE I. HYDRAULIC LABORATORY OF THE STATE UNIVERSITY OF IOWA

A. Testing canal with pipe culvert in place for experimental work, looking downstream towards laboratory building

B. Testing canal looking upstream towards headgate



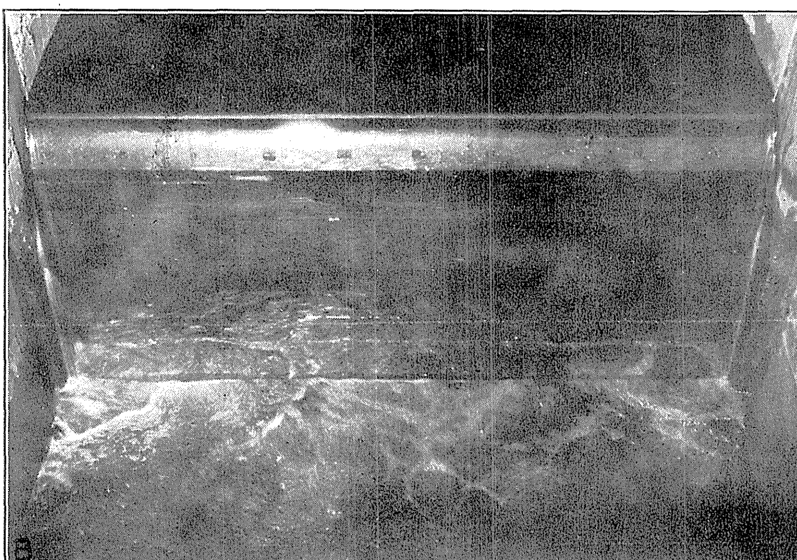


PLATE II. MEASURING WEIRS USED IN CULVERT TESTS

A. Weir with crest five feet long discharging 3.6 cubic feet per second.

B. Weir with crest ten feet long discharging 3.03 cubic feet per second

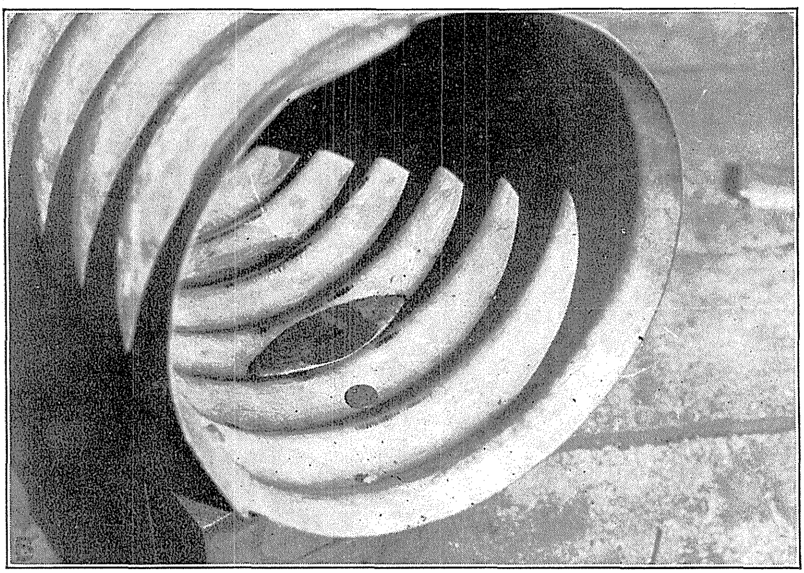
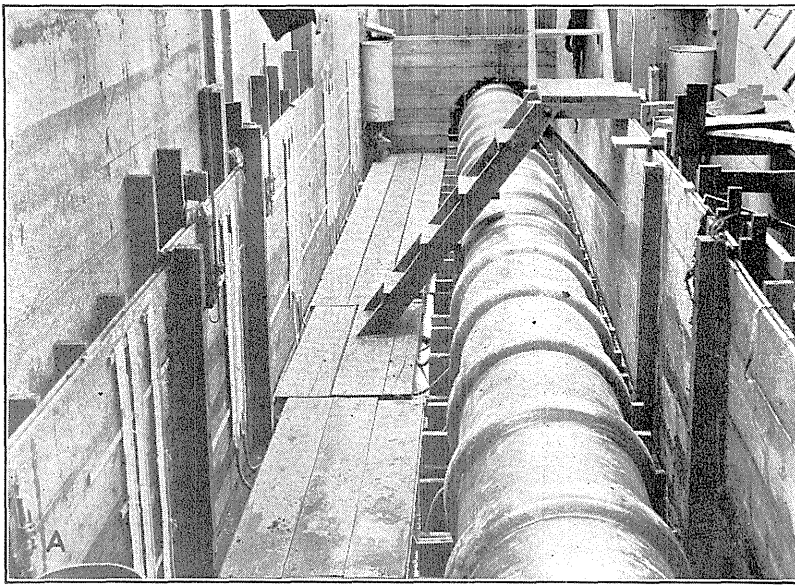


PLATE III. PIEZOMETER CONNECTIONS ON INSIDE OF CULVERT PIPE

A. Vitrified-clay pipe, 30 inches in diameter. See text, page 30.

B. Corrugated-metal pipe, 12 inches in diameter. See text, page 31.



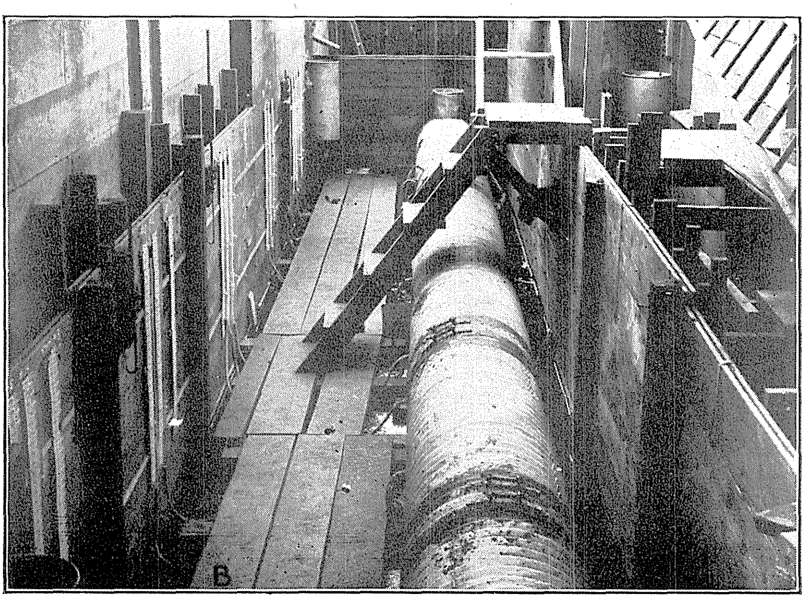
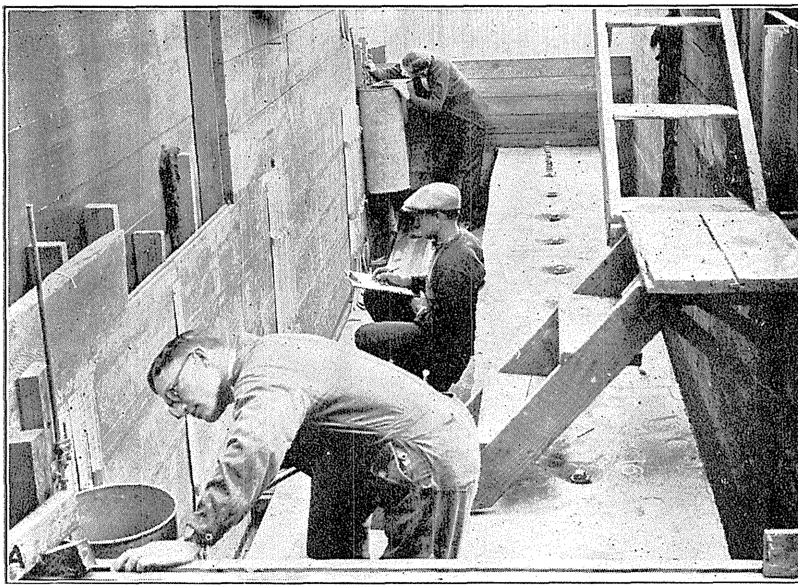


Plate IV. PIPE CULVERTS AS INSTALLED FOR TESTING

A. Vitrified-clay pipe, 24 inches in diameter

B. Corrugated-metal pipe, 24 inches in diameter



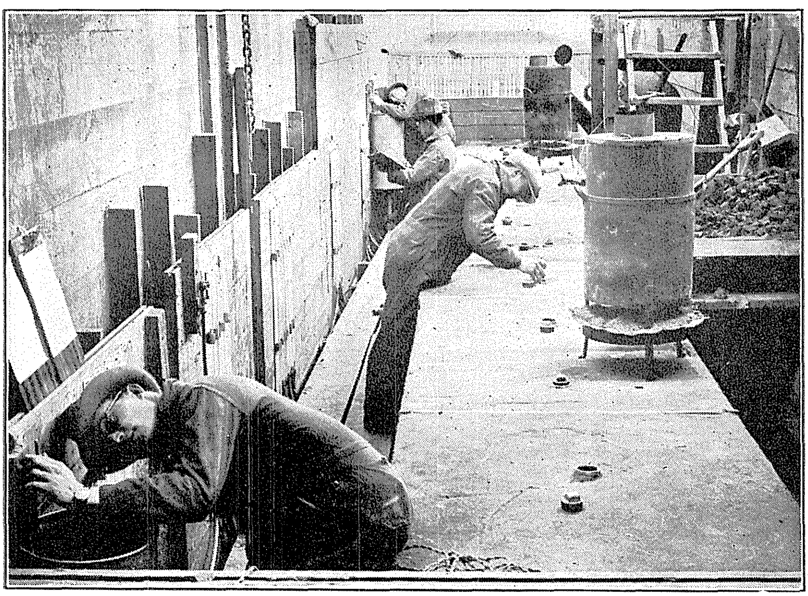


PLATE V. TESTING CONCRETE BOX CULVERTS

A. 2-ft. by 2-ft. by 24-ft. size flowing full

B. 3-ft. by 3-ft. by 36-ft. size flowing partly full

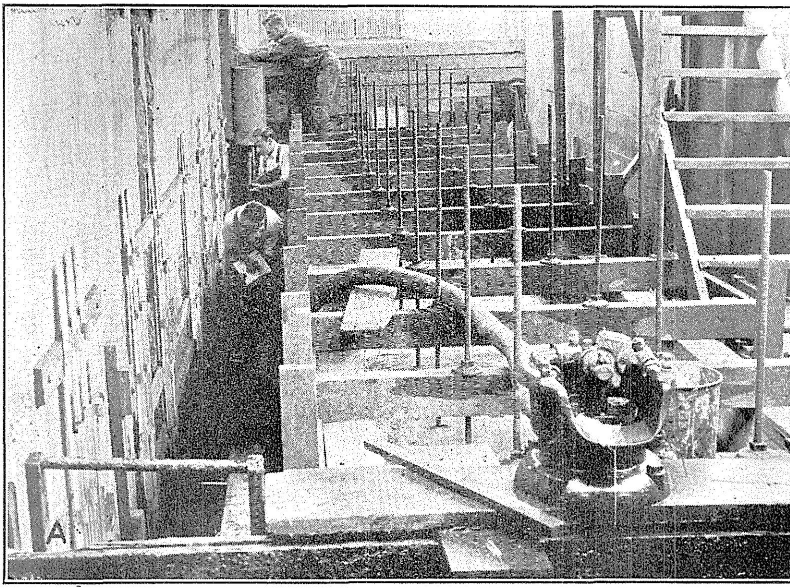


PLATE VI. CONCRETE BOX CULVERTS AS INSTALLED FOR TESTING

A. 4-ft. by 3-ft. by 36-ft. size

B. 3-ft. by 3-ft. by 36-ft. size with flared outlet. This culvert with outlet end submerged will discharge 59 per cent more water than a 3-ft. by 3-ft. by 36-ft. box culvert of uniform bore. See table 97 and text, page 33

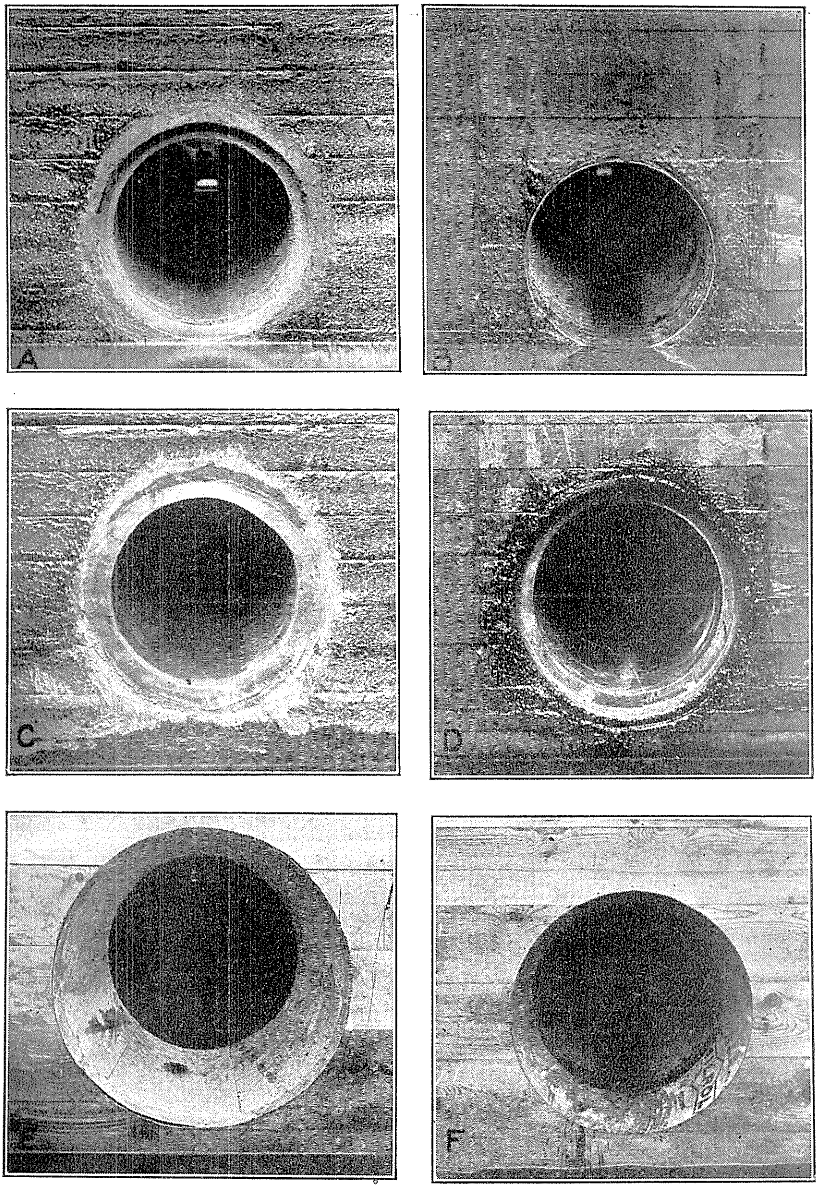


PLATE VII. STRAIGHT ENDWALL ENTRANCES TO 24-INCH PIPE

A. Concrete pipe, beveled-lip end upstream. See table 24 and page 52.
B. Corrugated-metal pipe, rodded end entrance. See table 36 and page 52.
C. Concrete pipe, square-cornered entrance. See table 28 and page 51.
D. Vitrified-clay pipe, bell end entrance. See table 32 and page 52.
E. Conical entrance, 20 inches long with 13-degree angle, attached to vitrified-clay pipe. See table 48 and text, page 52.
F. Conical entrance, 10 inches long with 13-degree angle, attached to corrugated-metal pipe. See table 50 and text, page 53.

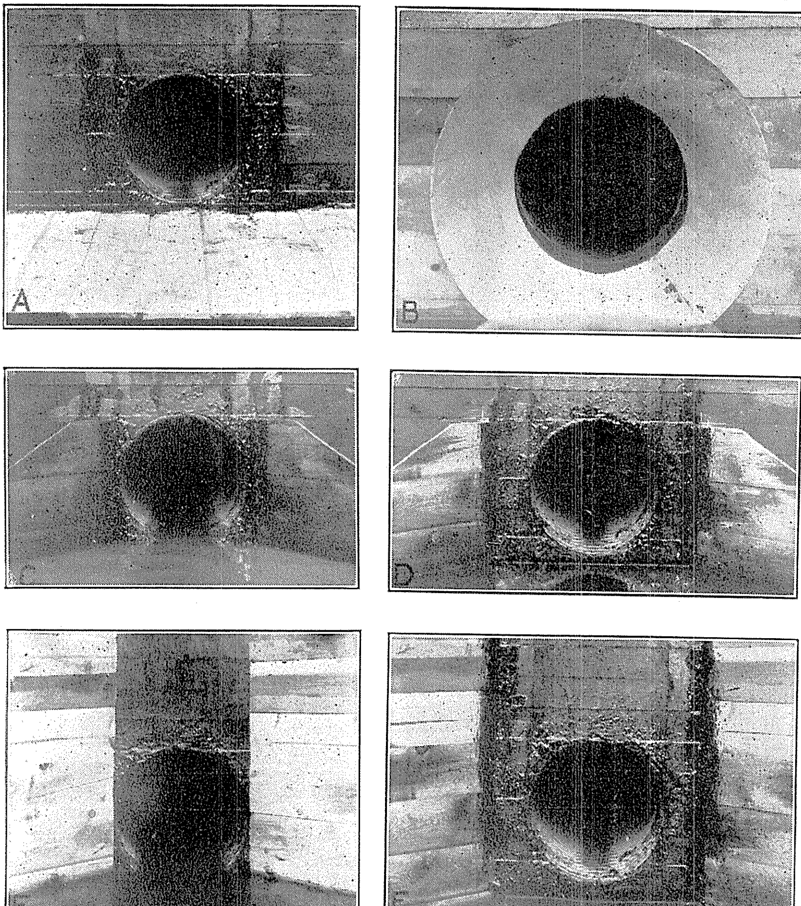


PLATE VIII. ENTRANCES TO 24-INCH PIPE CULVERTS

A. Straight endwall entrance to corrugated-metal pipe with floor in front of entrance built level with inside bottom of pipe. See table 46 and text, page 54.

B. Conical entrance, 10 inches long with 45-degree angle, attached to vitrified-clay pipe. See table 49 and text, page 53.

C. Wingwalls, standard height, at 45 degrees to corrugated-metal pipe, set flush with inside edge of pipe. No floor in front of entrance. See table 57 and text, page 53.

D. Wingwalls, standard height, at 45 degrees to corrugated-metal pipe, set 6 inches from inside edge of pipe. No floor in front of entrance See table 59 and text, page 53.

E. Wingwalls, full height, at 45 degrees to corrugated-metal pipe, set flush with inside edge of pipe. No floor in front of entrance. See table 56 and text, page 53.

F. Wingwalls, full height, at 45 degrees to corrugated metal pipe, set 6 inches from inside edge of pipe. No floor in front of entrance. See table 58 and text, page 53.

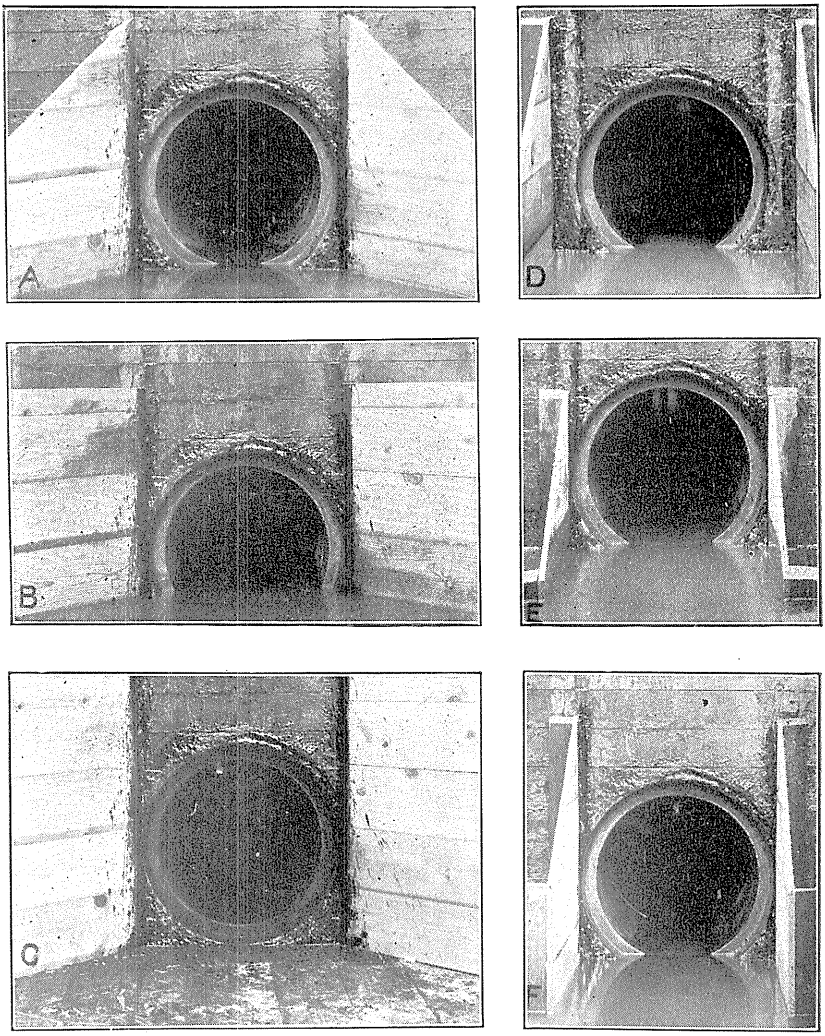


PLATE IX. ENTRANCES TO 24-INCH VITRIFIED-CLAY PIPE CULVERTS WITH FLOOR IN FRONT

A. Wingwalls at 45 degrees cut on bevel to top of standard endwall and set flush with inside edge of bell. See table 62 and text, page 53.

B. Wingwalls at 45 degrees cut level with top of standard endwall and set flush with inside edge of bell. See table 61 and text, page 53.

C. Wingwalls at 45 degrees, full height, set flush with inside edge of bell. See table 60 and text, page 53.

D. U-type wingwalls cut on bevel to top of standard endwall and set 6 inches from inside edge of bell. See table 66 and text, page 54.

E. U-type wingwalls, standard height, set flush with inside edge of bell. See table 67 and text, page 54.

F. U-type wingwalls, cut on bevel to top of standard endwall and set flush with inside edge of bell. See table 65 and text, page 54.

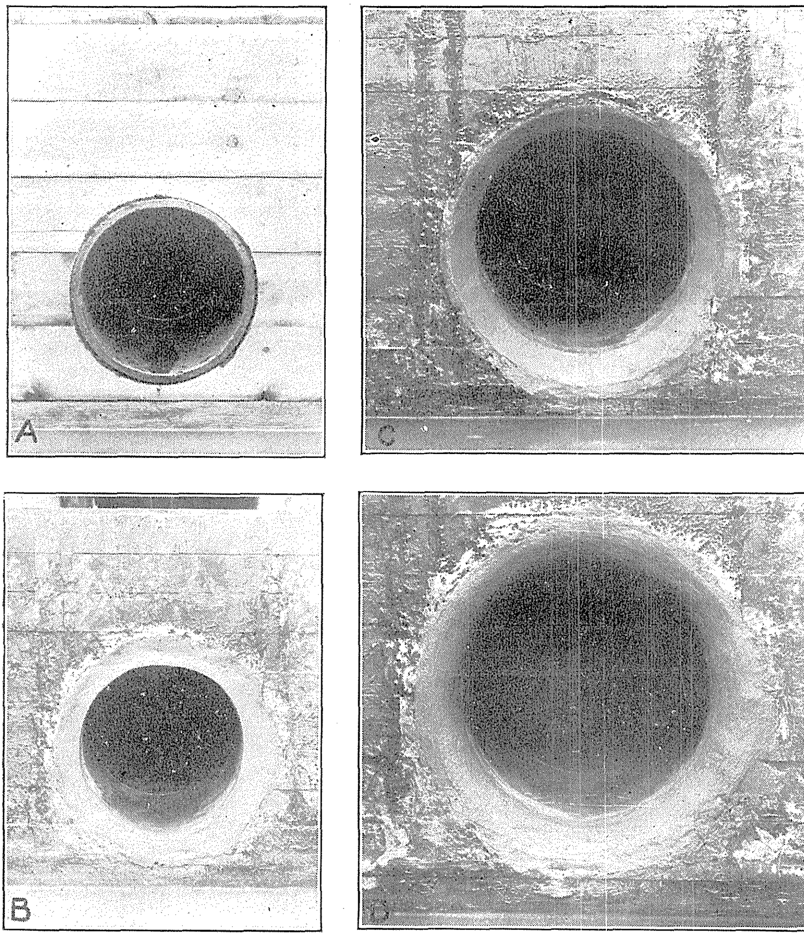


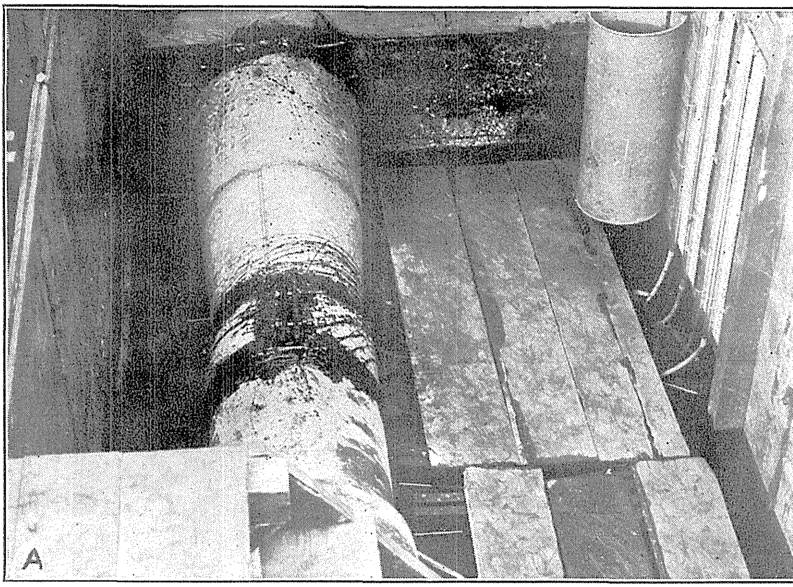
PLATE X. ENTRANCES TO VITRIFIED-CLAY PIPE CULVERTS

A. Standard commercial 18-inch to 20-inch increaser used as entrance to 18-inch pipe culvert. See table 55 and text, page 53.

B. Straight endwall entrance to 24-inch pipe culvert with bell filled with concrete shaped to give a square-cornered entrance. See table 71.

C. Straight endwall entrance to 24-inch pipe culvert with bell filled with concrete and surfaced off straight from inside edge of pipe to inside edge of bell. See table 69 and text, page 52.

D. Straight endwall entrance to 24-inch pipe culvert with bell filled with concrete shaped to the form of an ellipse from the inside edge of pipe to inside edge of bell. See table 70 and text, page 52.



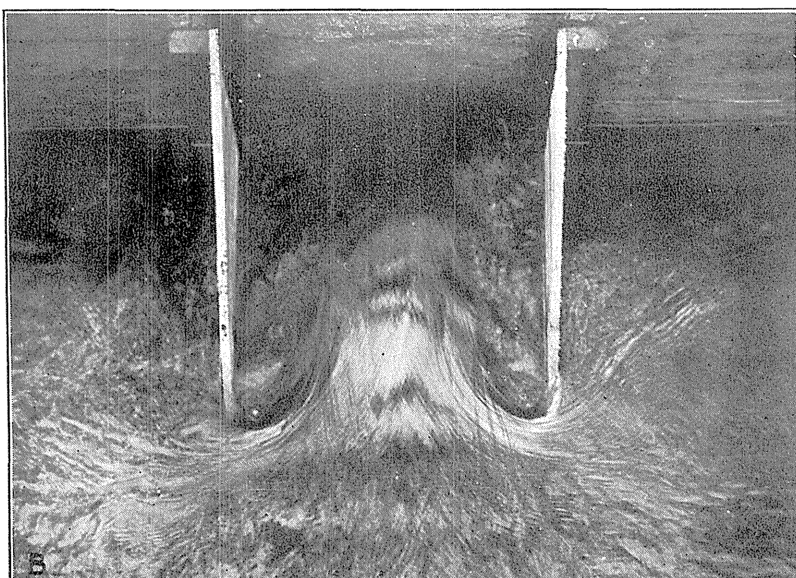


PLATE XI. A. CONICAL OUTLET ATTACHED TO 18-INCH VITRIFIED-CLAY PIPE CULVERT

This culvert with the outlet end submerged will discharge about 40 per cent more water than the 18-inch vitrified-clay pipe of uniform bore. See table 79.

B. WATER ENTERING A 24-INCH VITRIFIED-CLAY PIPE CULVERT WITH U-TYPE WINGWALLS, 10.5 SECOND FEET

Note drop in water surface at entrance. See text, Page 54.

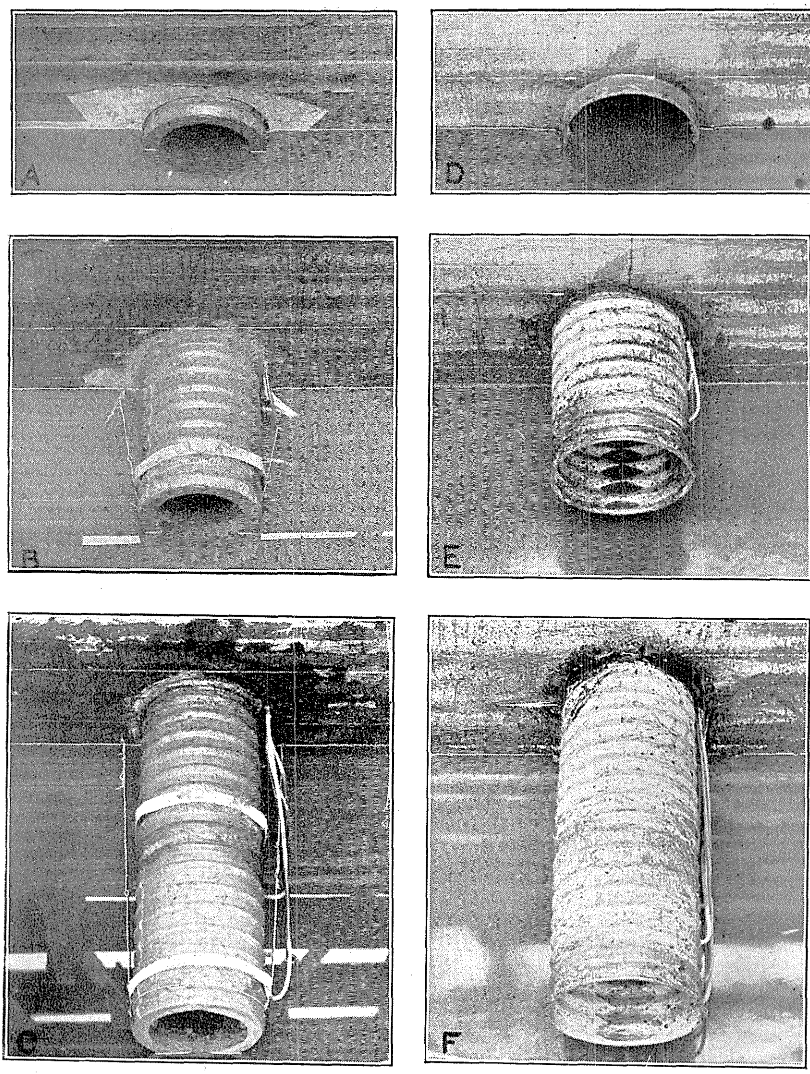


PLATE XII. PIPE CULVERTS WITH END OF CULVERT PROJECTING THROUGH ENTRANCE HEADWALL

A. Concrete pipe, 12-inch size, 3-inch projection. See table 72.

B. Concrete pipe, 12-inch size, 24-inch projection. See table 73.

C. Concrete pipe, 12-inch size, 47-inch projection. See table 74.

D. Corrugated-metal pipe, 18-inch size, 3-inch projection. See table 76.

E. Corrugated-metal pipe, 18-inch size, 24-inch projection. See table 77.

F. Corrugated-metal pipe, 18-inch size, 48-inch projection. See table 78.

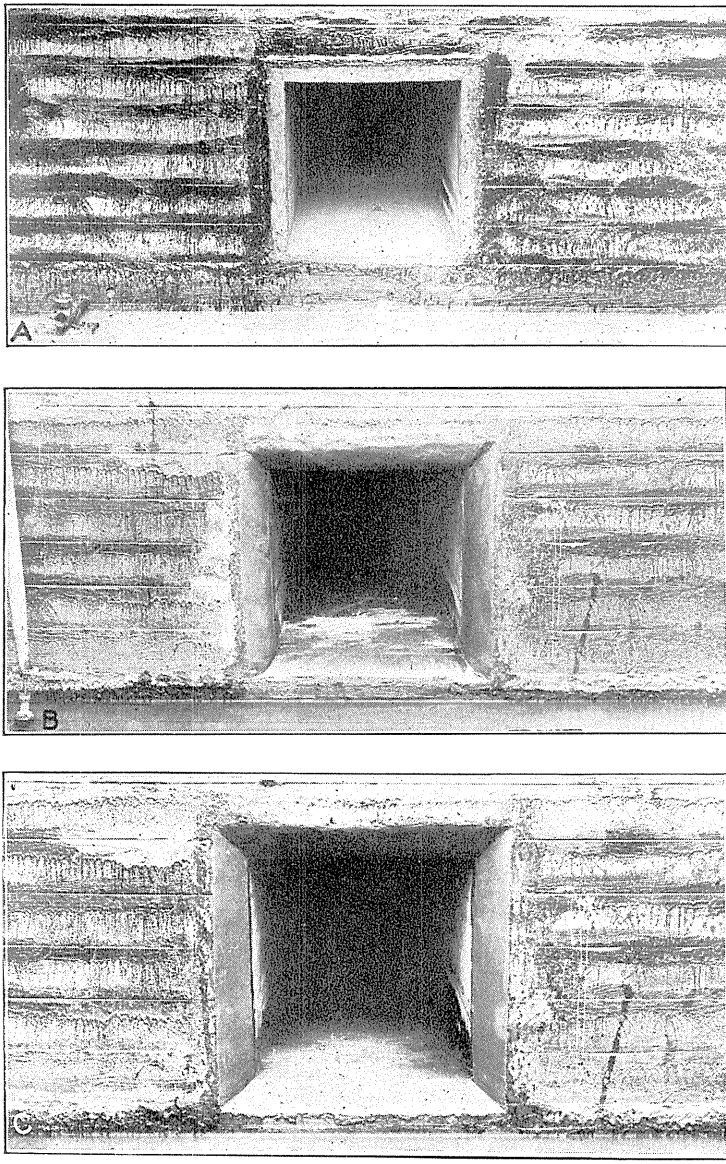


PLATE XIII. TYPES OF ENTRANCES TO 2-FT. BY 2-FT. BOX CULVERT

A. Square-cornered entrance. See tables 80, 81, and 82

B. Rounded-lip entrance. See table 84

C. Beveled-lip entrance. See table 83

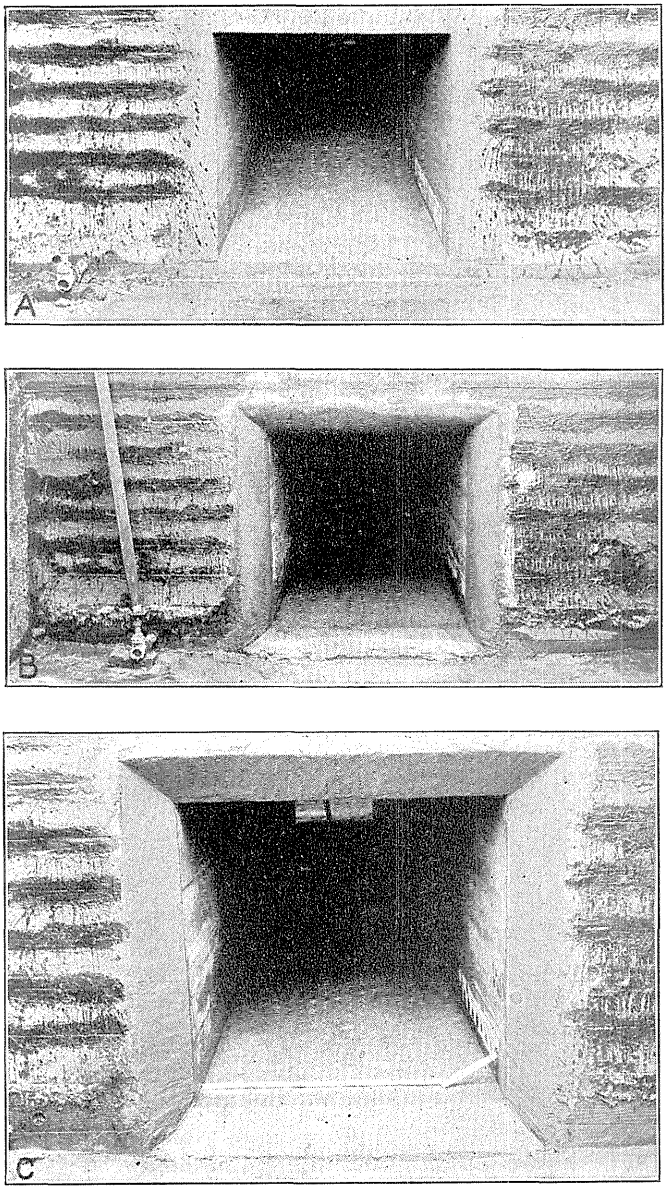
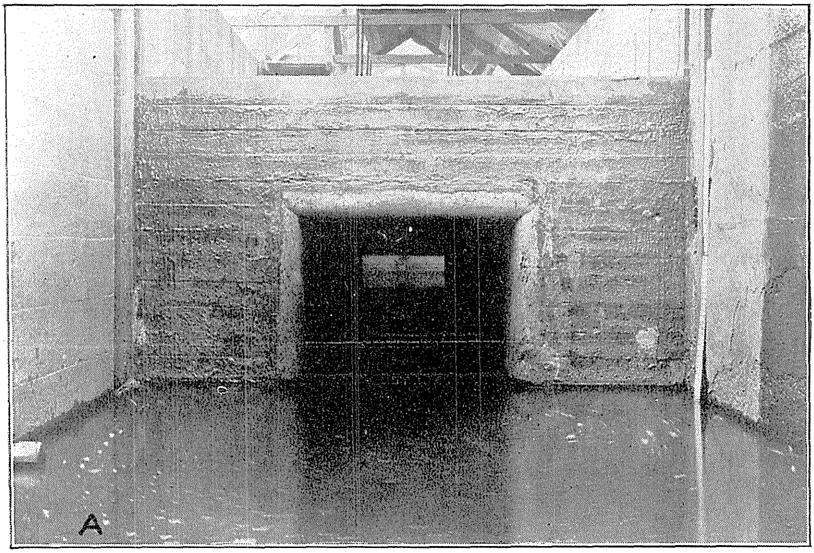


PLATE XIV. TYPES OF ENTRANCES TO 3-FT. BY 3-FT. BOX CULVERT

A. Square-cornered entrance. See tables 91, 92, and 96

B. Rounded-lip entrance. See tables 94 and 98

C. Beveled-lip entrance. See table 93



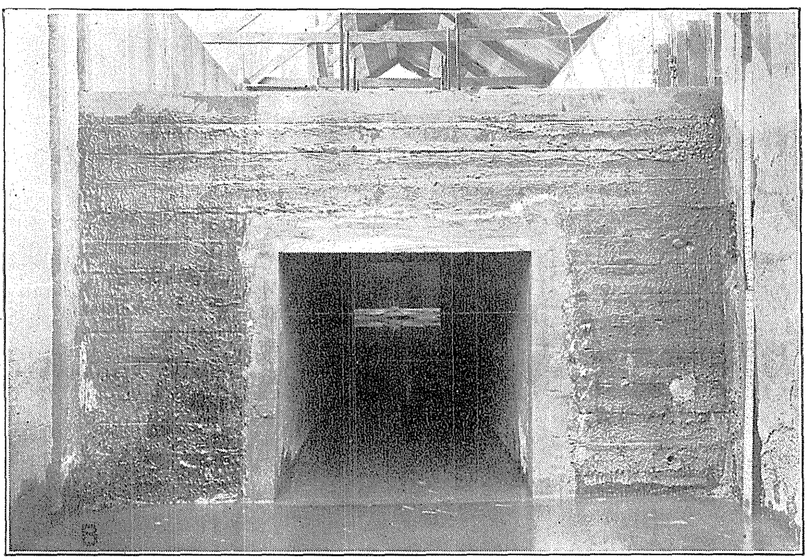
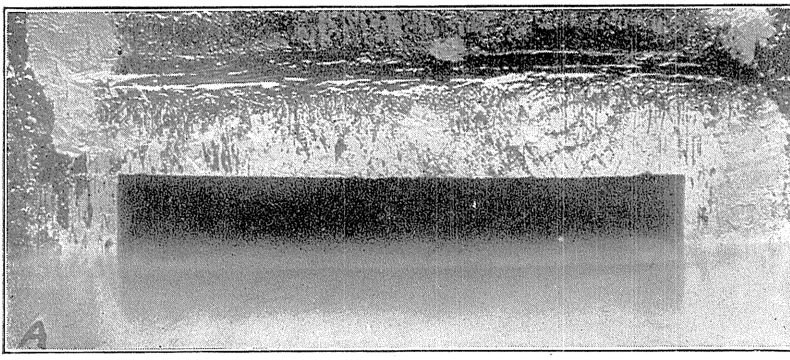
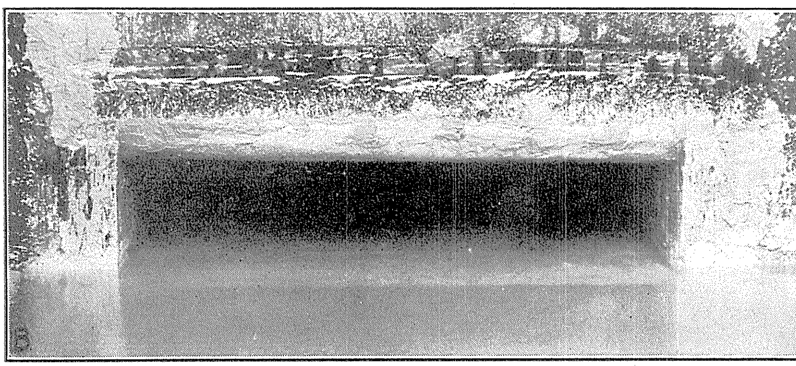


PLATE XV. STRAIGHT ENDWALL ENTRANCE TO 4-FT. BY 4-FT. BOX CULVERT

A. Rounded-lip entrance. See table 100

B. Square-cornered entrance. See table 101





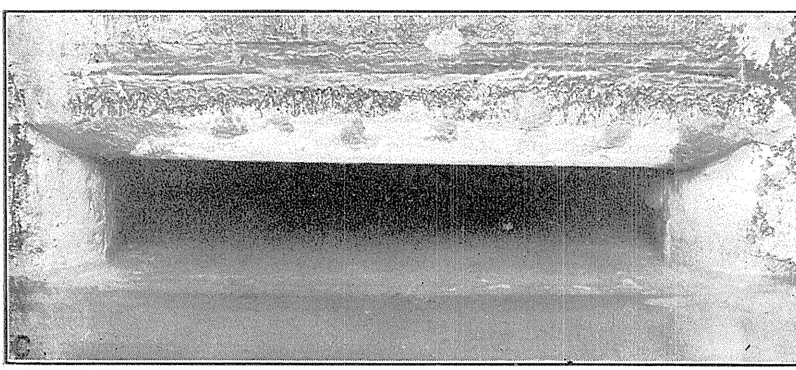
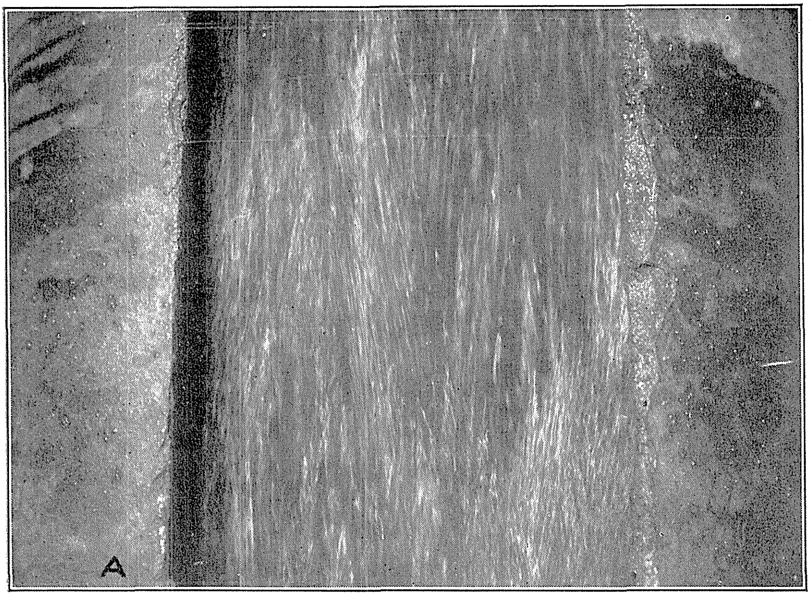


PLATE XVI. TYPES OF ENTRANCES TO 4-FT. BY 1-FT. BOX CULVERT

A. Square-cornered entrance. See table 108

B. Rounded on top edge only. See table 109

C. Rounded on top and both sides. See table 110



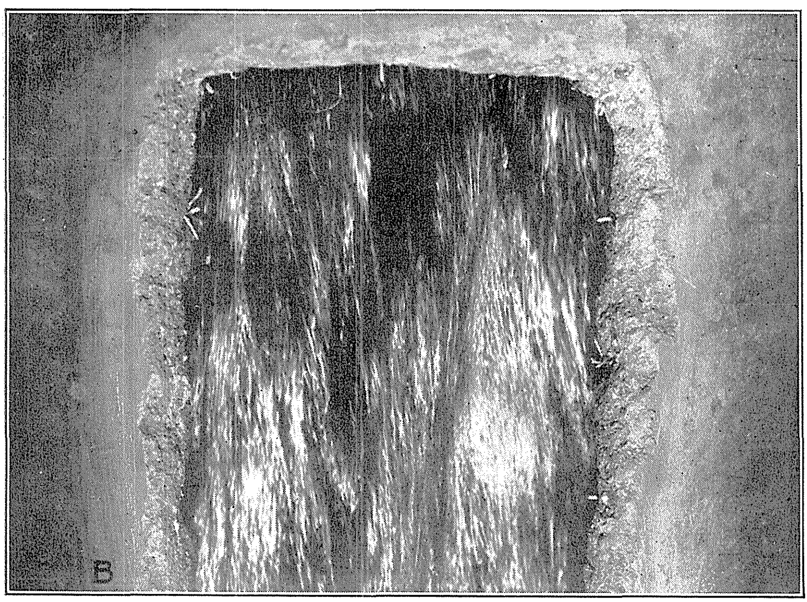


PLATE XVII. WATER FLOWING IN 24-INCH PIPE CULVERTS

A. Vitrified-clay pipe. View taken through opening cut in top of pipe. Velocity 6.98 feet per second. Pipe not quite full. Note smooth lines of flow

B. Concrete pipe. View taken through opening cut in top of pipe. Velocity 7.00 feet per second. Pipe not quite full. Note smooth lines of flow

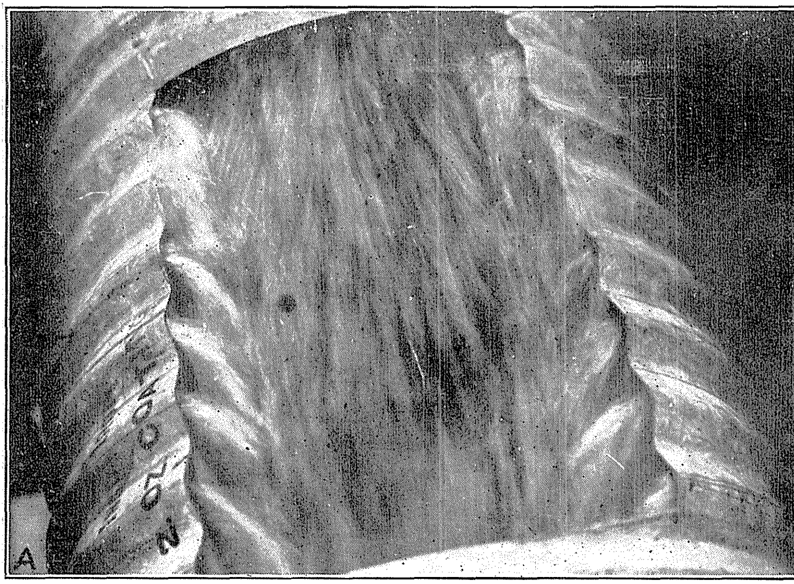


PLATE XVIII. A. WATER FLOWING IN 24-INCH CORRUGATED-METAL PIPE

View taken through opening in top of pipe. Velocity 5.96 feet per second. Pipe not quite full. Note disturbance of flow due to corrugations

B. DISCHARGE OF 18.56 CUBIC FEET PER SECOND FROM 24-INCH VITRIFIED-CLAY PIPE CULVERT

Note drop in water surface at end of pipe.

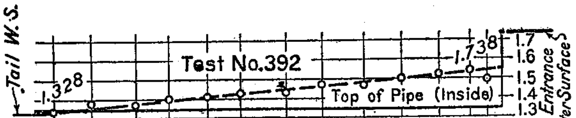


Fig.1. 24-inch Corrugated Metal Pipe; Length 30.6 Feet
Straight Endwall Entrance

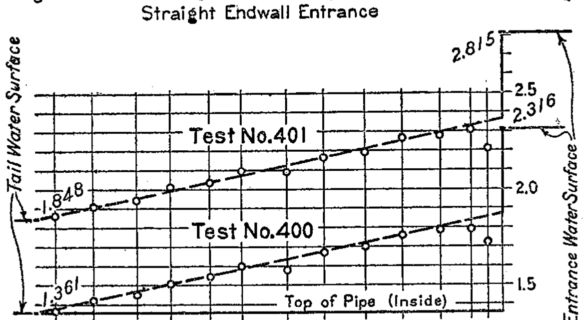


Fig.2. 24-inch Corrugated Metal Pipe; Length 30.6 Feet
Straight Endwall Entrance

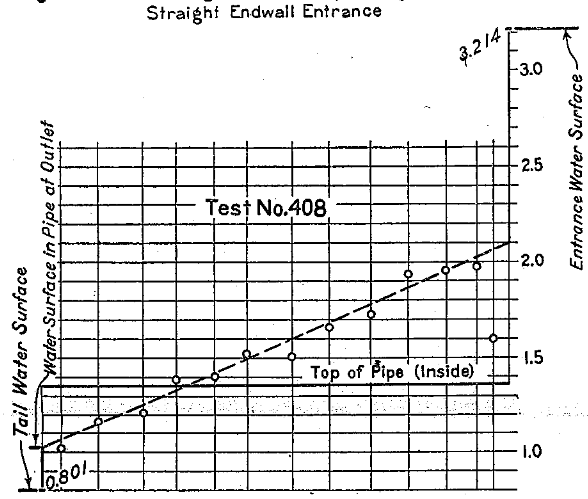


Fig.3. 24-inch Corrugated Metal Pipe; Length 30.6 Feet
Straight Endwall Entrance

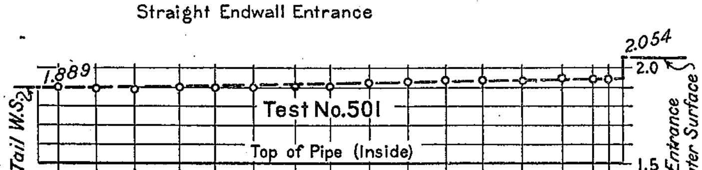


Fig.4. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance

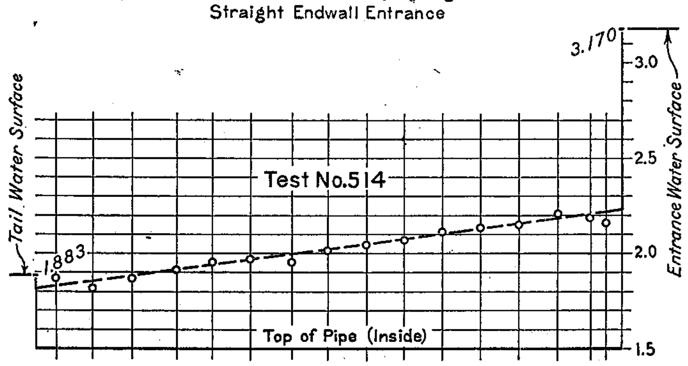


Fig.5. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance

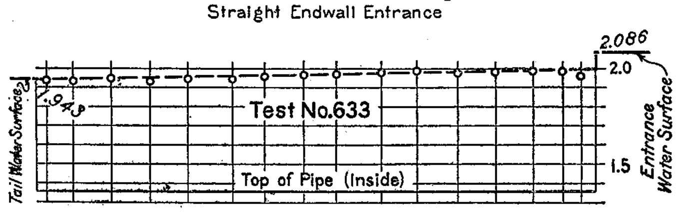
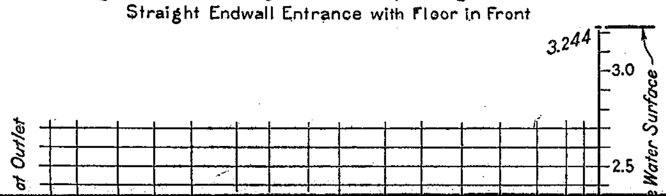


Fig.6. 24-inch Corrugated Metal Pipe; Length 36.7 Feet
Straight Endwall Entrance with Floor in Front



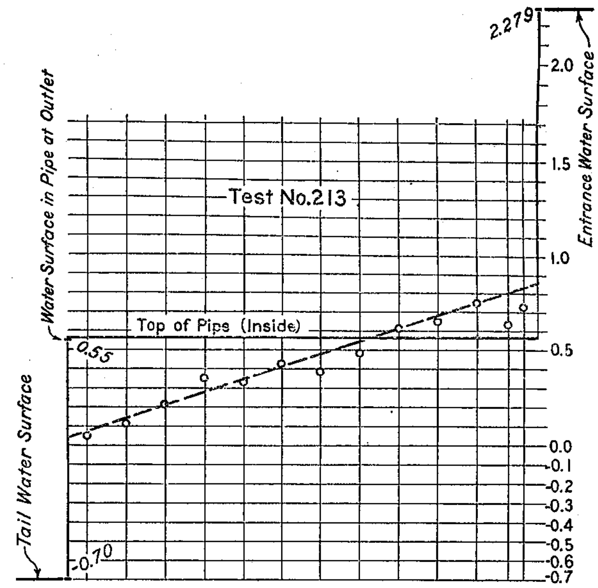


Fig.11. 12-inch Vitrified Clay Pipe; Length 30.6 Feet
Straight Endwall Entrance

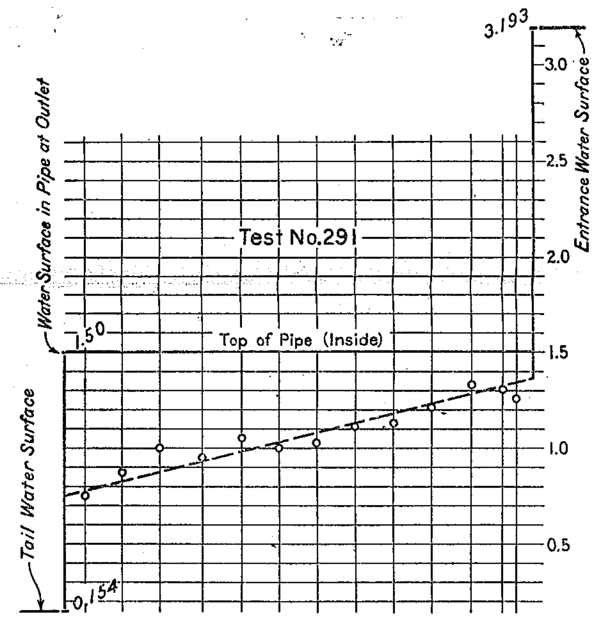


Fig.12. 24-inch Vitrified Clay Pipe; Length 30.7 Feet
Straight Endwall Entrance

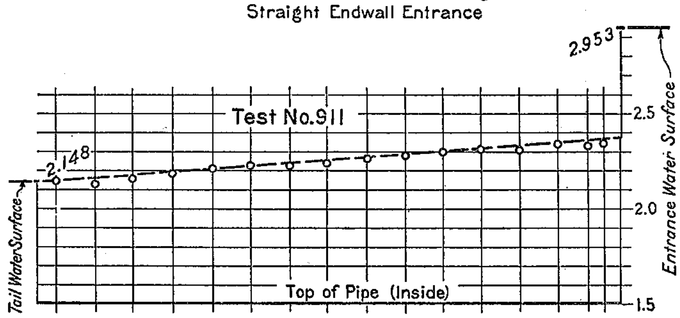


Fig.13. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
45-degree Wings, Standard Height, Set Flush with Inside Edge of Pipe
Floor in Front of Entrance

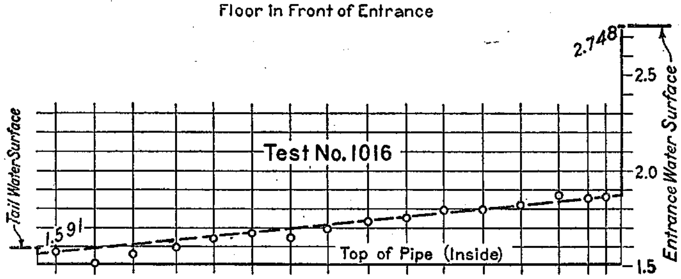
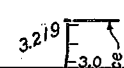


Fig.14. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance with Bell Filled with Concrete
Straight from Inside Edge of Bell to Inside Edge of Pipe



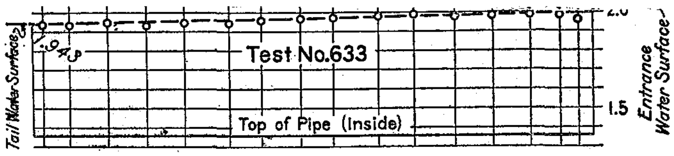


Fig.6. 24-inch Corrugated Metal Pipe; Length 36.7 Feet
Straight Endwall Entrance with Floor in Front

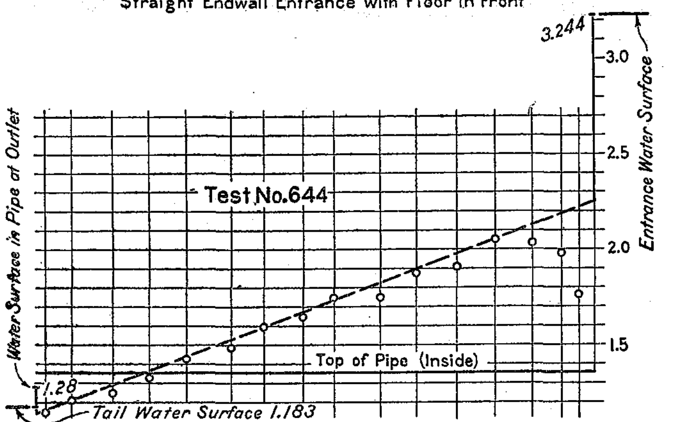


Fig.7. 24-inch Corrugated Metal Pipe; Length 36.7 Feet
Straight Endwall Entrance with Floor in Front

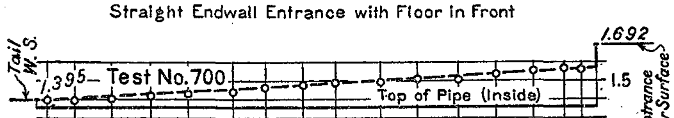


Fig.8. 24-inch Corrugated Metal Pipe; Length 36.7 Feet
Conical Entrance, 13-degree Angle, 10 Inches Long

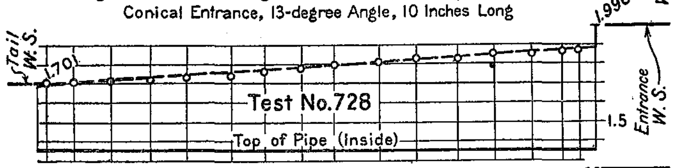


Fig.9. 24-inch Corrugated Metal Pipe; Length 36.7 Ft.
Conical Entrance, 24° 47′ Angle, 10 Inches Long

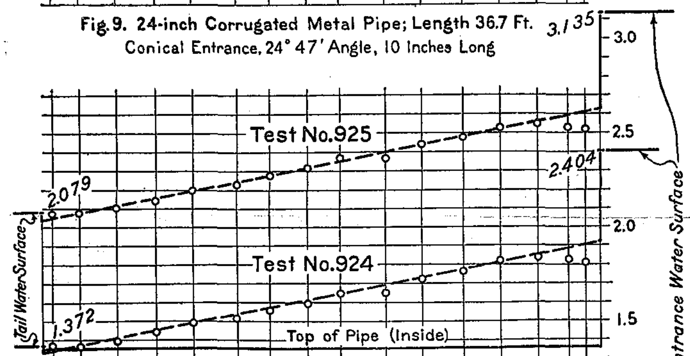


Fig.10 24-inch Corrugated Metal Pipe; Length 36.7 Feet
45-degree Wings, Standard Height, Set Flush with Inside Edge of Pipe
• Floor in Front of Entrance

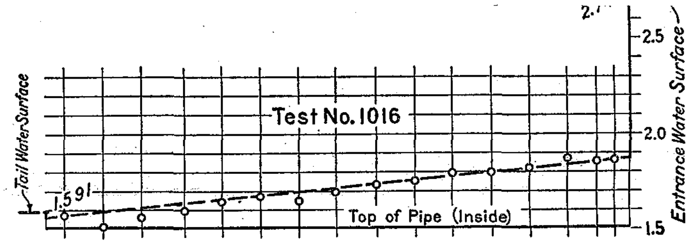


Fig.14. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance with Bell Filled with Concrete
Straight from Inside Edge of Bell to Inside Edge of Pipe

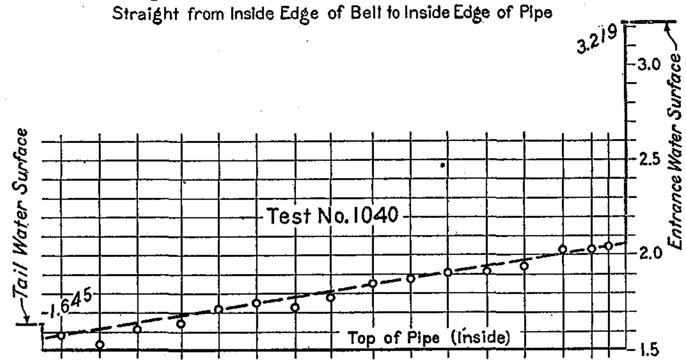


Fig.15. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance with Bell Filled with Concrete
to Form an Elliptical Shaped Entrance

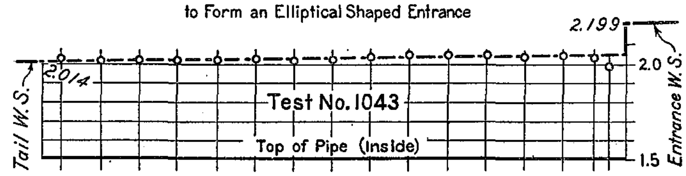


Fig.16. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance with Bell Filled with Concrete
to Form a Sharp Cornered Entrance

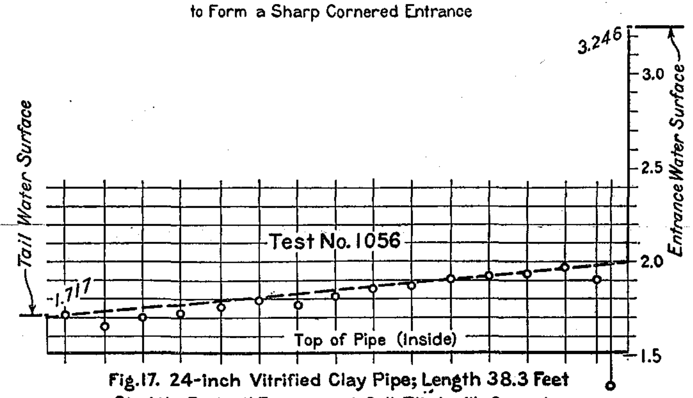


Fig.17. 24-inch Vitrified Clay Pipe; Length 38.3 Feet
Straight Endwall Entrance with Bell Filled with Concrete
to Form a Sharp Cornered Entrance

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	H	Q	A	V	$\frac{V^2}{2g}$									R	s	C	n	n′				
Test number	Head on weir. Feet	Discharge Cu. ft. per sec.	Area of flow. Sq. ft.	Velocity Feet per sec.	Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Friction loss coefficient	Entrance drop Feet	Entrance loss Feet	Entrance loss coefficient	Total head divided by velocity head	Column 9 plus column 12	Hydraulic radius Feet	Slope	Chezy coefficient	Kutter coefficient	Manning coefficient	Height of water surface at entrance above top of pipe at outlet Feet	Elevation of tail water referred to top of pipe at outlet Feet	Height of hydraulic gradient above top of pipe at outlet Feet	Elevation top of jet at outlet referred to top of pipe Feet
392	0.436	9.90	3.147	3.146	0.154	0.410	0.227	1.474	0.183	0.029	0.188	2.662	1.662	0.5004	0.00743	51.6	0.0228	0.0256	0.39	−0.02	−0.02	
400	0.596	15.63	3.147	4.966	0.383	0.955	0.509	1.329	0.446	0.063	0.164	2.493	1.493	0.5004	.01670	54.3	.0219	.0244	0.97	+0.01	0.01	
401	0.595	15.59	3.147	4.954	0.382	0.965	0.512	1.340	0.453	0.071	0.186	2.526	1.526	0.5004	.01680	54.0	.0220	.0245	1.47	+0.50	0.50	
408	0.792	23.79	3.147	7.560	0.889	2.192	1.078	1.213	1.114	0.225	0.253	2.466	1.466	0.5004	.0353	56.9	.0210	.0233	1.86	−0.55	−0.33	
501	0.413	9.15	3.336	2.743	0.117	0.159	0.049	0.419	0.110	−0.007	−0.060	1.359	0.359	0.5152	.00128	106.8	.0125	.0125	0.54	+0.38	0.39	
514	0.823	25.19	3.336	7.551	0.886	1.352	0.414	0.467	0.938	0.052	0.059	1.526	0.526	0.5152	.01082	101.1	.0132	.0132	1.66	+0.37	0.31	
633	0.303	5.86	3.142	1.865	0.054	0.140	0.054	1.000	0.086	0.032	0.593	2.593	1.593	0.5000	.00147	68.8	.0178	.0192	0.73	+0.58	0.59	
644	0.739	21.47	3.142	6.834	0.726	2.104	1.115	1.536	0.989	0.263	0.362	2.898	1.898	0.5000	.03040	55.4	.0217	.0239	1.88	−0.18	−0.22	−0.08
700	0.399	8.71	3.142	2.771	0.119	0.298	0.176	1.479	0.122	0.003	0.025	2.504	1.504	0.5000	.00479	56.6	.0212	.0234	0.33	+0.04	0.03	
728	0.402	8.80	3.142	2.801	0.122	0.306	0.182	1.492	0.124	0.002	0.016	2.508	1.508	0.5000	.0050	56.0	.0214	.0236	0.64	+0.34	0.33	
924	0.592	15.48	3.142	4.927	0.377	1.077	0.591	1.568	0.486	0.109	0.289	2.857	1.857	0.5000	.0161	54.9	.0218	.0241	1.04	+0.01	−0.03	
925	0.592	15.48	3.142	4.927	0.377	1.101	0.593	1.573	0.508	0.131	0.347	2.920	1.920	0.5000	.0161	54.9	.0218	.0241	1.78	+0.72	0.67	
213	0.592	7.74	0.8091	9.566	1.423	2.239	0.813	0.571	1.426	0.003	0.002	1.573	0.573	0.2538	.02654	116.6	.0104	.0101	1.73	−1.26	−0.52	−0.01
291	1.011	34.24	3.343	10.242	1.631	2.443	0.615	0.377	1.828	0.197	0.121	1.498	0.498	0.5158	.02003	100.8	.0133	.0132	1.69	−1.35	−0.75	−0.00
911	0.693	19.51	3.336	5.848	0.532	0.811	0.220	0.414	0.591	0.059	0.111	1.524	0.525	0.5152	.00575	107.4	.0126	.0124	1.44	+0.64	0.63	
1016	0.798	24.06	3.336	7.212	0.809	1.183	0.310	0.383	0.873	0.064	0.079	1.462	0.462	0.5152	.00810	111.6	.0122	.0119	1.24	+0.08	0.06	
1040	0.893	28.44	3.336	8.525	1.130	1.656	0.497	0.440	1.159	0.029	0.026	1.466	0.466	0.5152	.01299	104.2	.0129	.0128	1.71	+0.14	0.05	
1043	0.398	8.67	3.336	2.600	0.105	0.184	0.037	0.352	0.147	0.042	0.400	1.752	0.752	0.5152	.00097	116.3	.0116	.0114	0.69	+0.50	0.51	
1056	0.807	24.46	3.336	7.332	0.836	1.541	0.295	0.353	1.246	0.410	0.490	1.843	0.843	0.5152	.00771	116.3	.0118	.0114	1.74	+0.21	0.20	

PLATE XIX. REPRESENTATIVE COMPUTATION DIAGRAMS FOR CULVERT PIPE

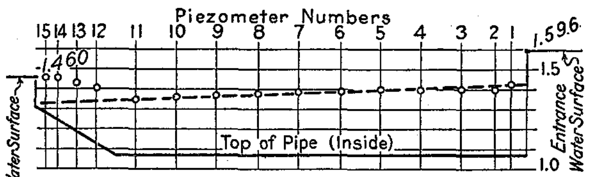


Fig. 1 *Test No. 1170*

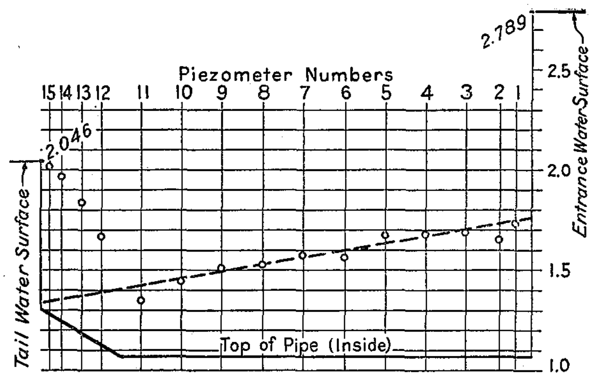


Fig. 2. *Test No. 1184*

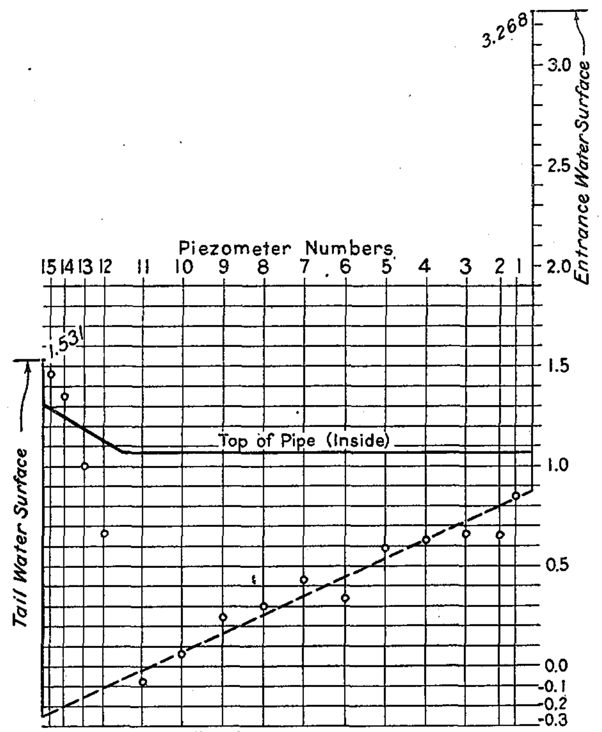


Fig. 4. *Test No. 1192*

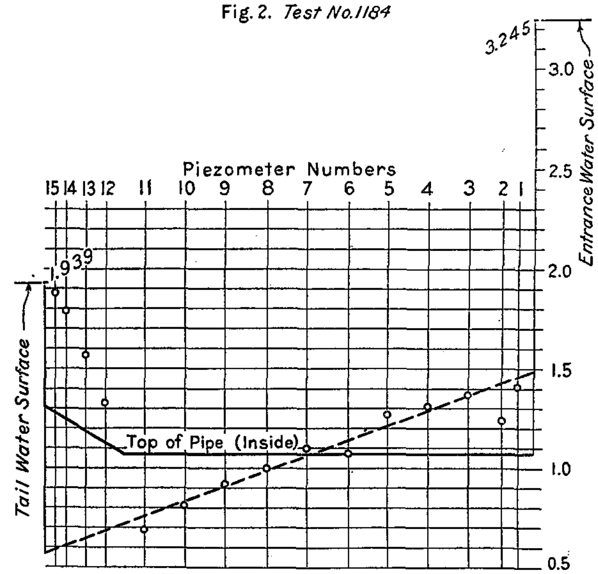
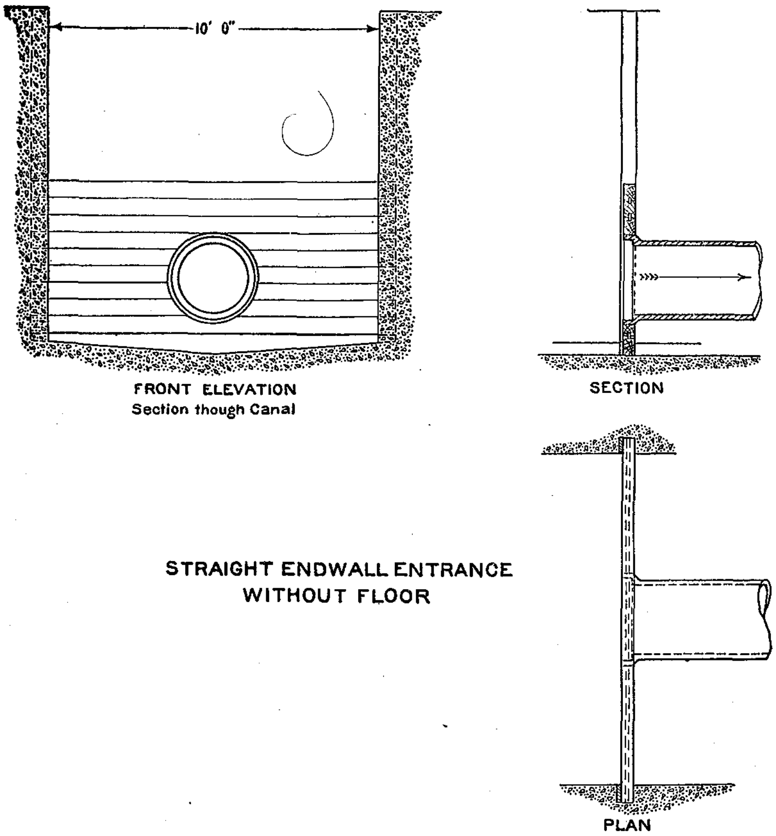


Fig. 3. *Test No. 1190*

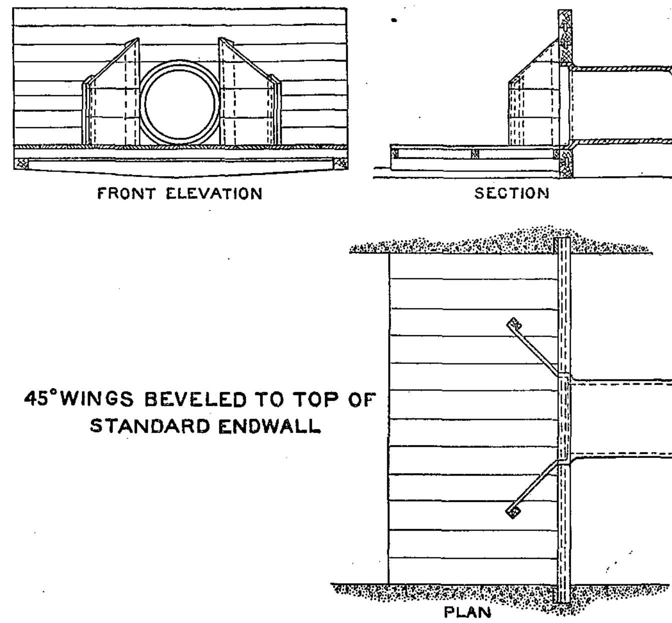
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Test number	H Head on weir. Feet	Q Discharge Cu. ft. per sec.	A Area of flow. Sq. ft.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head Feet	Total head on pipe Feet	Friction loss Feet	Friction loss coefficient	Entrance drop Feet	Entrance loss Feet	Entrance loss coefficient	Total head divided by velocity head	Column 9 plus column 12	R Hydraulic radius Feet	s Slope	C Chezy coefficient	n Kutter coefficient	n′ Manning coefficient	Height of water surface at entrance above top of increaser at outlet Feet	Elevation of tail water referred to top of increaser at outlet Feet	Height of hydraulic gradient above top of increaser at outlet Feet	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
1170	0.499	6.02	1.791	3.36	0.176	0.271	0.097	0.551	0.174	−0.002	−0.011	1.540	0.540	0.3775	0.00316	97.2	0.0128	0.0130	0.28	+0.14	0.01	0.14	0.135	0.767
1184	0.889	14.12	1.791	7.88	0.966	1.451	0.422	0.437	1.029	0.063	0.065	1.502	0.502	0.3775	.01380	109.3	.0117	.0116	1.47	+0.73	0.02	0.74	0.708	0.733
1190	1.081	18.92	1.791	10.56	1.734	2.675	0.912	0.526	1.763	0.029	0.017	1.542	0.543	0.3775	.02975	99.6	.0127	.0127	1.93	+0.62	−0.75	1.31	1.369	0.790
1192	1.186	21.76	1.791	12.15	2.295	3.518	1.125	0.490	2.393	0.098	0.043	1.533	0.533	0.3775	.03670	103.3	.0123	.0122	1.95	+0.21	−1.57	1.77	1.781	0.776

PLATE XX. REPRESENTATIVE COMPUTATION DIAGRAMS FOR 18-INCH VITRIFIED-CLAY PIPE

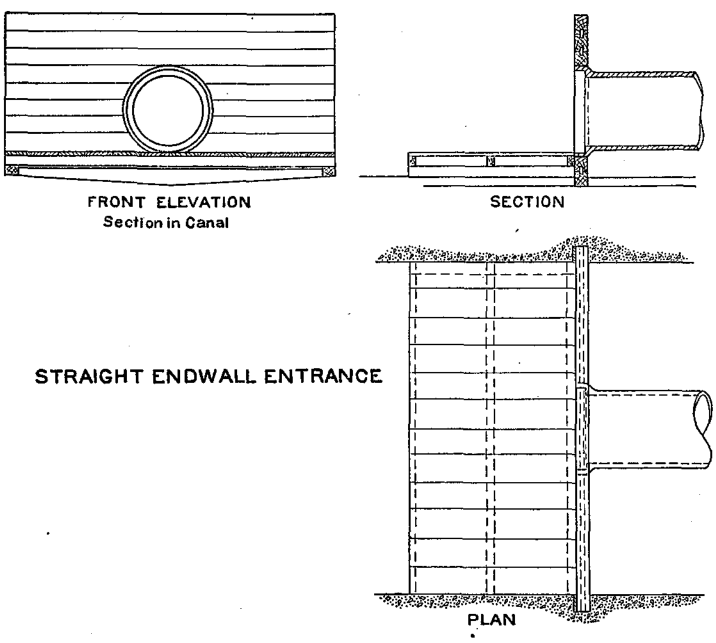
Length, 30.7 feet, with straight endwall entrance and 18-inch to 26-inch conical increaser, 60 inches long, at outlet end of culvert. No floor in front of entrance.



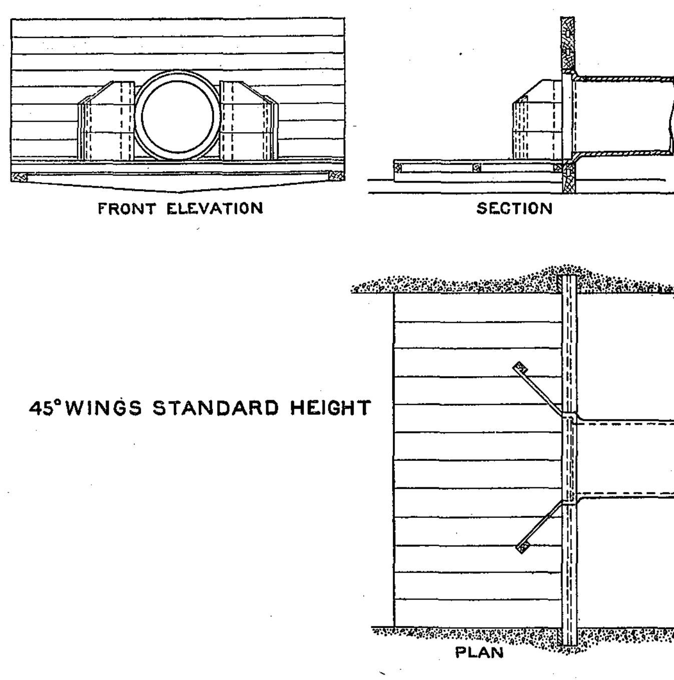
STRAIGHT ENDWALL ENTRANCE WITHOUT FLOOR



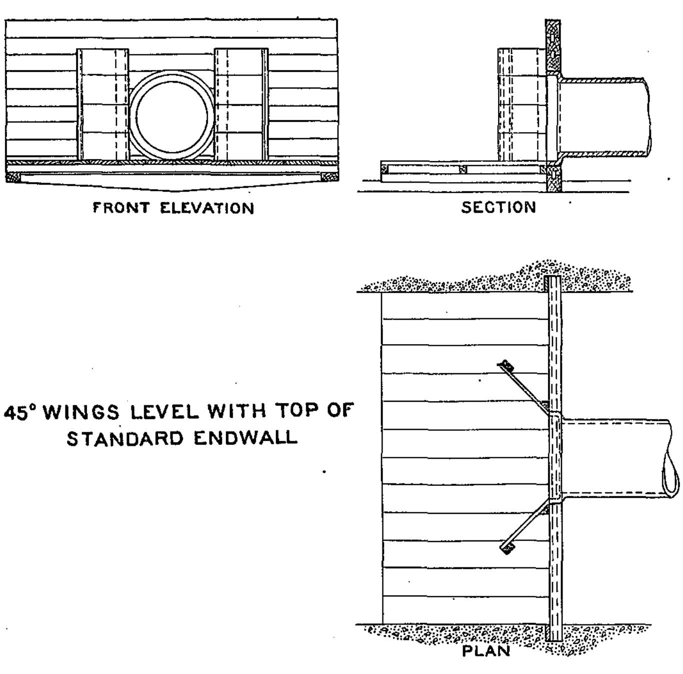
45° WINGS BEVELED TO TOP OF STANDARD ENDWALL



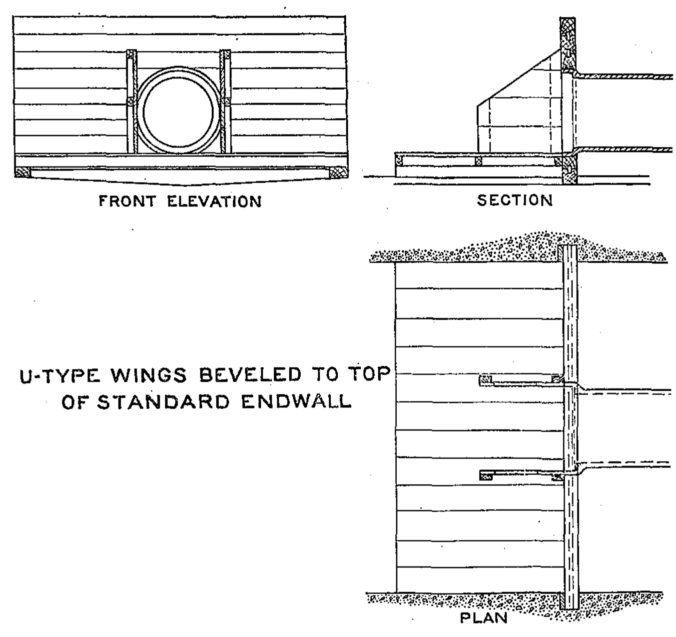
STRAIGHT ENDWALL ENTRANCE



45° WINGS STANDARD HEIGHT

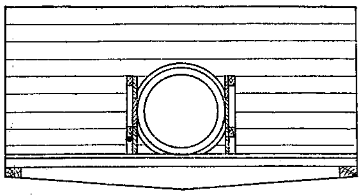


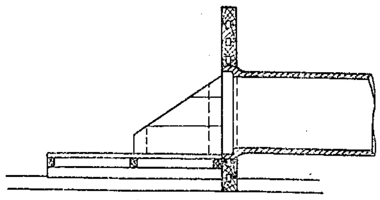
45° WINGS LEVEL WITH TOP OF STANDARD ENDWALL



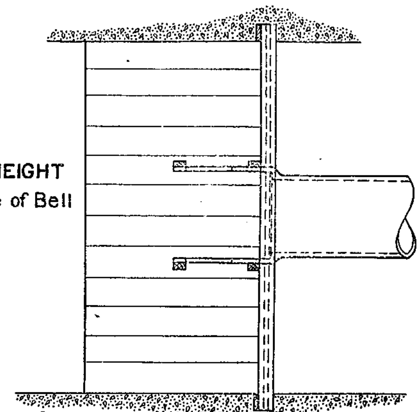
U-TYPE WINGS BEVELED TO TOP OF STANDARD ENDWALL

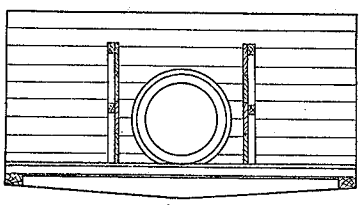
PLATE XXI. DETAILS OF ENTRANCES TO PIPE CULVERTS TE

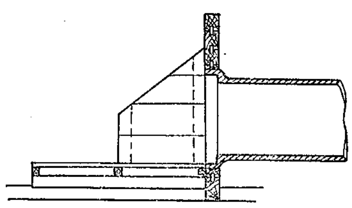

FRONT ELEVATION


SECTION

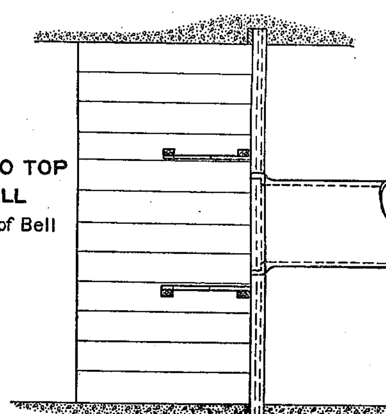
U-TYPE WINGS STANDARD HEIGHT
Wings set flush with inside edge of Bell

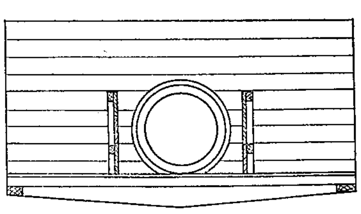

PLAN

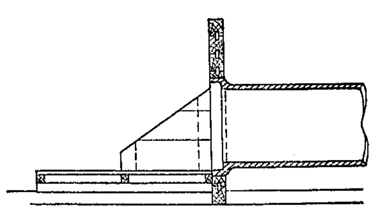

FRONT ELEVATION


SECTION

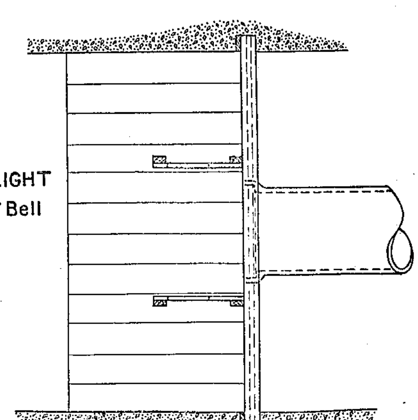
U-TYPE WINGS BEVELED TO TOP OF STANDARD ENDWALL
Wings 6 inches from inside edge of Bell


PLAN


FRONT ELEVATION


SECTION

U-TYPE WINGS STANDARD HEIGHT
Wings 6 inches from inside edge of Bell


PLAN

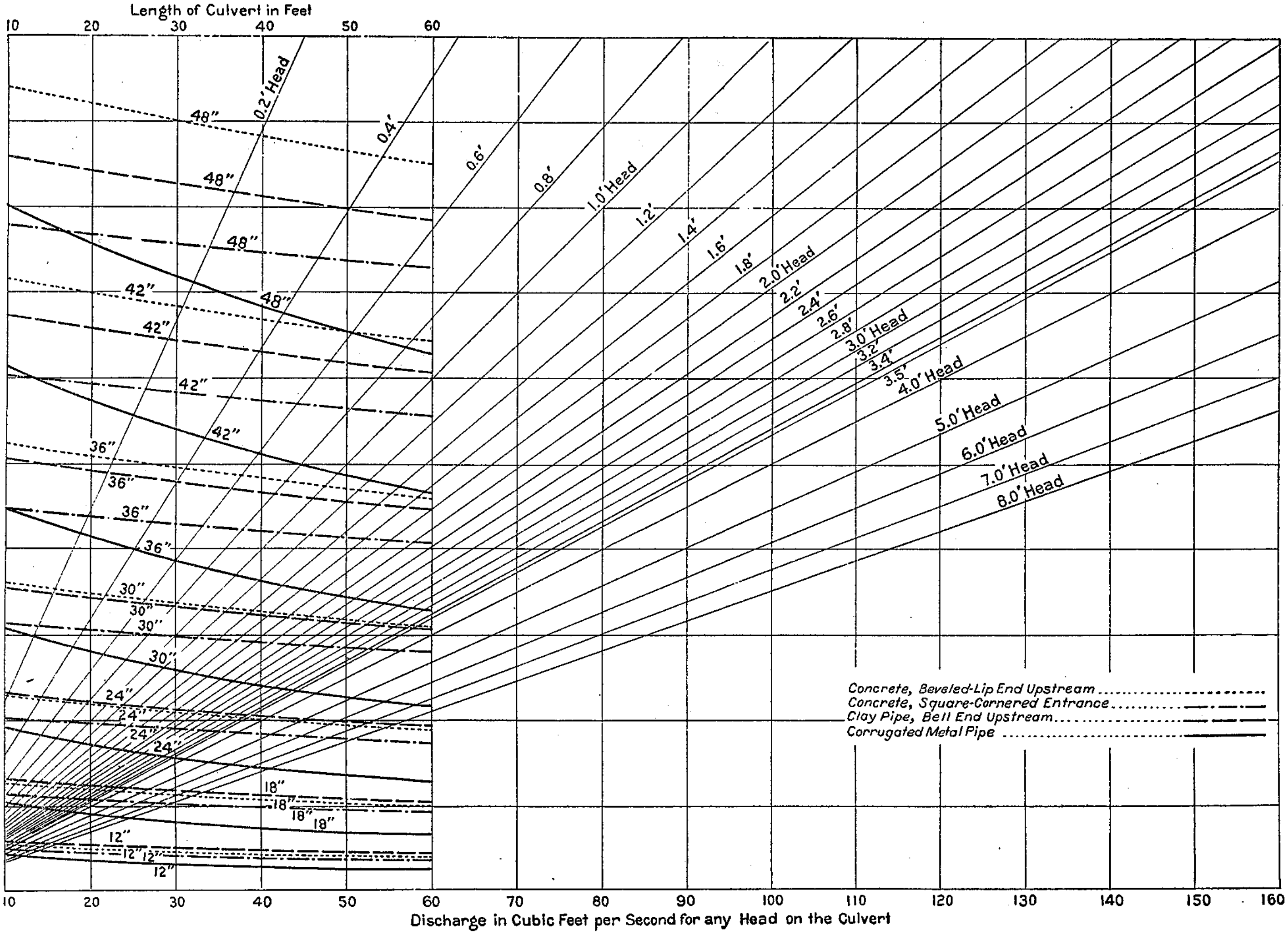


PLATE XXII. DIAGRAM FOR DETERMINING THE SIZE OF A PIPE CULVERT REQUIRED TO CARRY A KNOWN QUANTITY OF WATER UNDER A GIVEN HEAD FOR LENGTHS 10 TO 60 FEET. CULVERTS WITH STRAIGHT ENDWALL ENTRANCES

This diagram is based on the formula $Q = A\sqrt{\frac{2g\,H}{M}}$ in which M has different values for different kinds of pipe, as follows:

Concrete pipe with beveled lip end upstream $M = 1.1 + \frac{0.026L}{D^{1.2}}$; Concrete pipe with square cornered entrance $M = 1 + 0.31\,D^{0.5} + \frac{0.026L}{D^{1.2}}$

Vitrified-clay pipe with bell end upstream $M = 1 + 0.023\,D^{1.9} + \frac{0.022L}{D^{1.0}}$; Corrugated metal pipe $M = 1 + 0.16\,D^{0.6} + \frac{0.106L}{D^{1.2}}$

In these formulas: Q = discharge in cubic feet per second; D = diameter of pipe in feet; H = head on pipe in feet; L = length of pipe in feet; A = cross-sectional area of pipe in square feet; g = acceleration of gravity.

Directions for using this diagram. Given: Q, the quantity of water the culvert must carry; H, the safe head the culvert can operate under; and L, the length of the culvert. Find Q on the scale at the bottom of the diagram. From this point run vertically up the diagram to the diagonal line representing H, the safe head to use. From this intersection move horizontally to a point under L, the length of the culvert as given by the scale at the top of the chart. The curved line representing a size of culvert nearest to this point gives the required size of culvert.

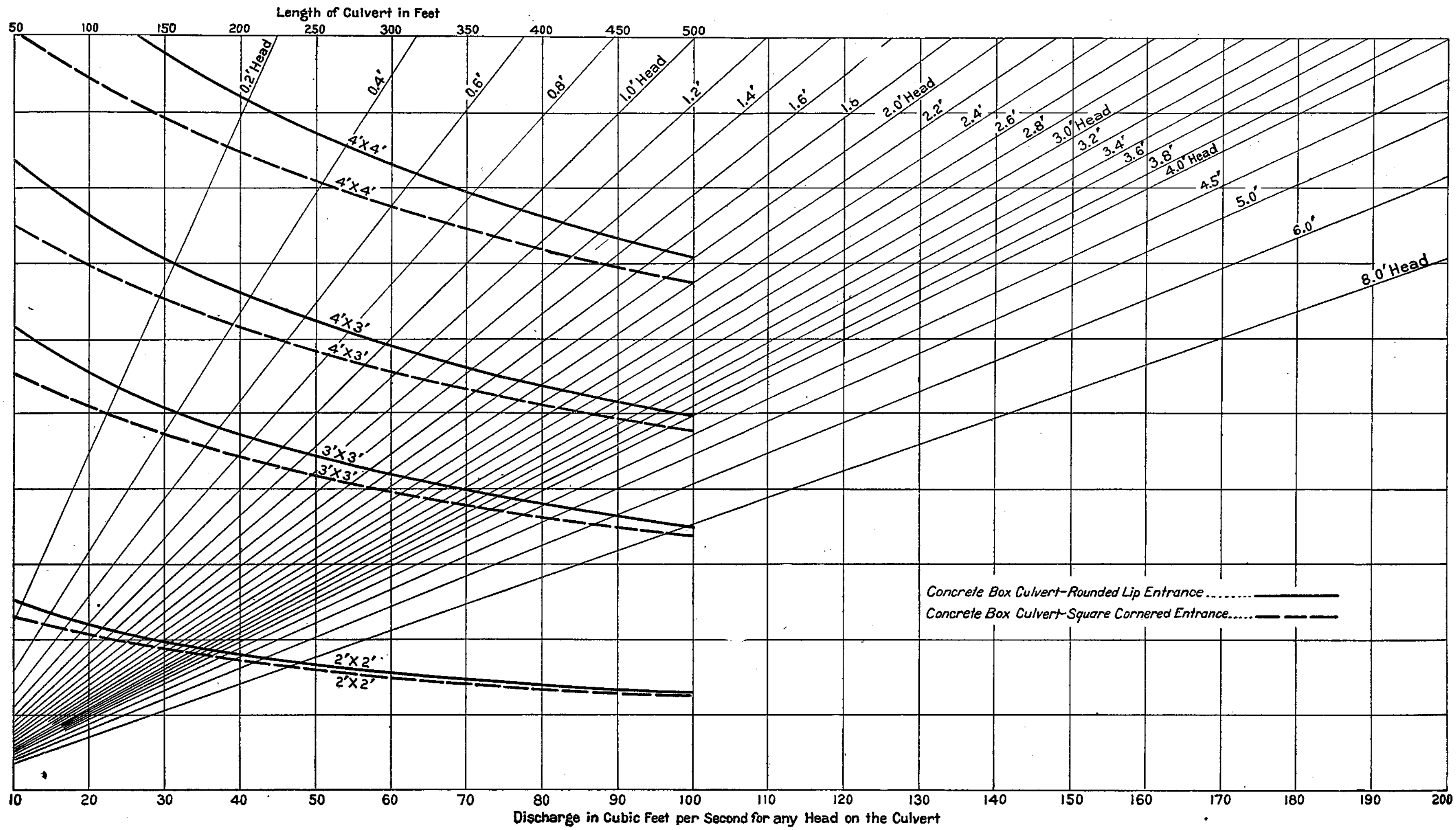


PLATE XXIII. DIAGRAM FOR DETERMINING THE SIZE OF A BOX CULVERT REQUIRED TO CARRY A KNOWN QUANTITY OF WATER UNDER A GIVEN HEAD FOR LENGTHS 50 TO 500 FEET. CULVERTS WITH STRAIGHT ENDWALL ENTRANCES.

This diagram is based on the formula $Q = A\sqrt{\frac{2gH}{M}}$

in which M has different values for different types of entrances, as follows:

Concrete box culverts with rounded lip entrances: $M = 1.05 + \frac{0.0045L}{R^{1.25}}$

Concrete box culverts with square cornered entrances: $M = 1 + 0.4\,R^{0.3} + \frac{0.0045L}{R^{1.25}}$

In these formulas: Q = discharge in cubic feet per second, R = mean hydraulic radius in feet, H = head on culvert in feet, L = length of culvert in feet, A = cross-sectional area of culvert in square feet, g = acceleration of gravity.

Directions for using this diagram. Given: Q, the quantity of water the culvert must carry; H, the safe head the culvert can operate under; and L, the length of the culvert. Find Q on the scale at the bottom of the diagram. From this point run vertically up the diagram to the diagonal line representing H, the safe head to use. From this intersection move horizontally to a point under L, the length of the culvert as given by the scale at the top of the chart. The curved line representing a size of culvert nearest to this point gives the required size of culvert.