UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS HYDRAULIC LABORATORY

LORENZ G. STRAUB, Director

Technical Paper No. 5, Series B

Hydraulic Tests on Corrugated Metal Culvert Pipes

by
LORENZ G. STRAUB
and
HENRY M. MORRIS

July, 1950
Minneapolis, Minnesota

1851 • UNIVERSITY OF MINNESOTA CENTENNIAL • 1951

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HYDRAULIC TESTS
ON CORRUGATED METAL CULVERT PIPES

I. INTRODUCTION

Experimental studies on culverts conducted at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, beginning in 1946, included several series of observations on commercial, corrugated metal culvert pipes. The primary purpose of these large-scale tests was to obtain pipe friction and entrance loss coefficients which would be more accurate and dependable than those currently recommended in culvert design literature. A previous paper in this series gives a discussion of the comparison with the results of parallel studies on concrete culverts. The present paper is confined to a discussion of the corrugated pipe culvert test program and an analysis of the results of the studies.

Two types of corrugated metal culverts were tested, namely, the circular and the pipe arch types. In each case, three different nominal diameter pipe sections were tested--18 in., 24 in., and 36 in., respectively--, making a total of six corrugated metal culverts in the test program. Each pipe was 193 ft long and laid on a slope of 0.20 per cent.

For the pipe arch culverts, the identifying dimensions refer to the diameters of circular pipes having the same length of periphery. For example, the 36-in. pipe arch and the 36-in. circular culvert have equal perimeters although their heights, widths, and areas are unequal. Cross sections of the various pipes, with controlling dimensions, appear in Fig. 1. (Note that the corrugation height in each case is 1/2 in. and that all computations have been based on the inside section, that is on the minimum cross-sectional area.)

Friction and entrance loss coefficients were established for the culverts under the usual conditions of field operation. With this objective in view, each pipe was tested for the following conditions:

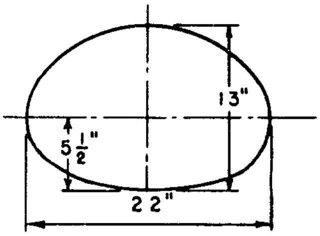
(a) Full flow with submerged inlet and outlet.

(b) Part-full flow at uniform depth.

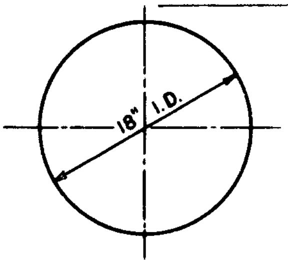
For each flow condition, several values of head and discharge were used. In addition, five of the culverts were tested with two different entrance conditions; namely,

(a) Pipe projecting 2 ft into the headwater pool.

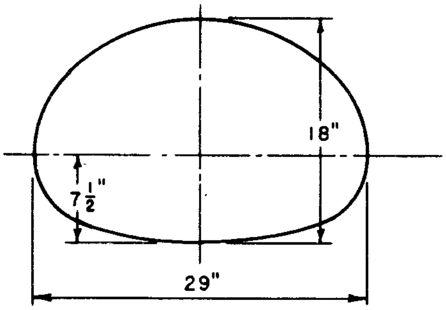
(b) Pipe entrance flush with headwall.



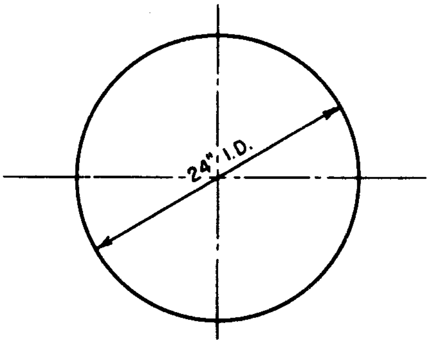
18 - in. Corrugated Metal Pipe Arch



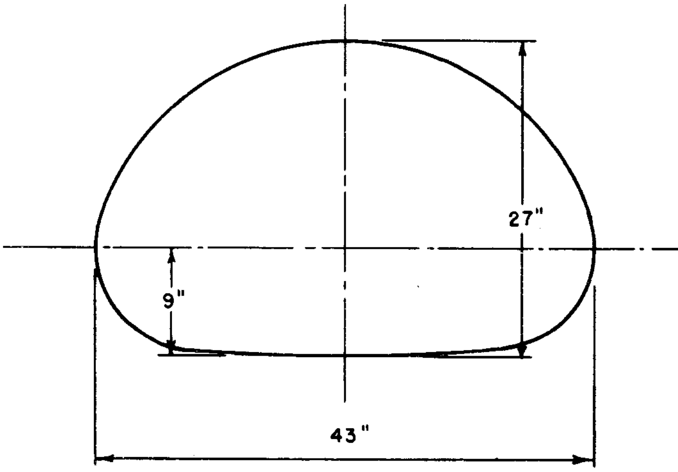
18 - in. Corrugated Metal Circular Pipe



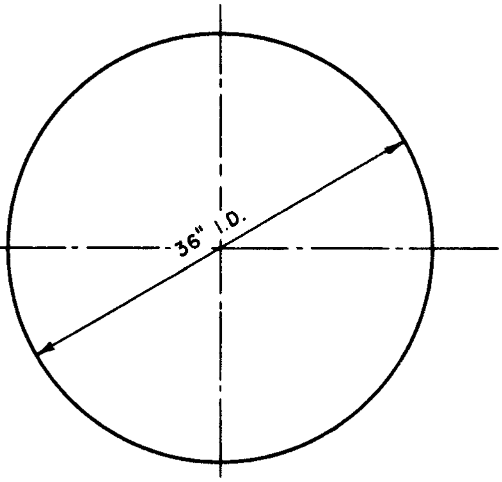
24 - in. Corrugated Metal Pipe Arch



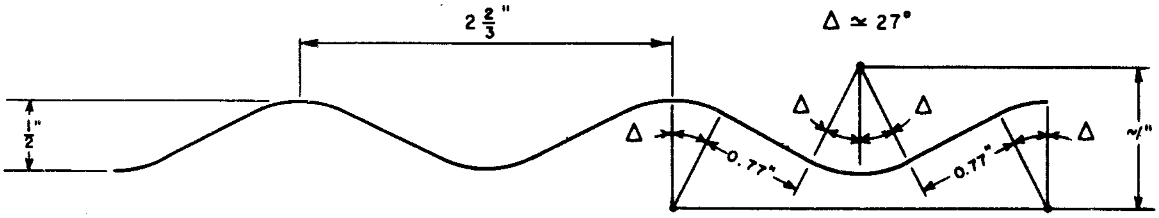
24 - in. Corrugated Metal Circular Pipe



36-in. Corrugated Metal Pipe Arch



36-in. Corrugated Metal Circular Pipe



Dimensions of Standard Corrugated Metal Sheets

Fig. 1 — Dimensions of Corrugated Metal Culverts

II. RESUME OF EXPERIMENTAL PROGRAM

A. Full-Flow Tests

The Manning roughness coefficient $\underline{n}^*$ in the Manning formula

$$Q = \frac{1.486}{n} A (R)^{2/3} S^{1/2} \tag{1}$$

was computed for each run and was found to increase systematically with increasing discharge and water temperature. This unanticipated result was indicated quite definitely and systematically by the experiments. The summarized results of these computations are given in Table I.

TABLE I

ROUGHNESS COEFFICIENTS FOR FULL FLOW

Pipe	No. of Tests	Manning Roughness Coefficient		
		From	To	Average
18-in. Circular	11	0.022	0.0251	0.0242
24-in. Circular	13	0.0228	0.0252	0.0242
36-in. Circular	12	0.0216	0.0247	0.0232
All Circular Pipes	36	0.0216	0.0252	0.0239
18-in. Arch	23	0.0210	0.0255	0.0239
24-in. Arch	7	0.0217	0.0245	0.0236
36-in. Arch	9	0.0216	0.0240	0.0231
All Arch Pipes	39	0.0210	0.0255	0.0237
All Pipes	75	0.0210	0.0255	0.0238

In the above table, the high values should be used in design, rather than the average, since the design would normally be based on a maximum discharge. A value of $\underline{n}$ of about 0.025 should be recommended for design of corrugated culverts flowing full.

Coefficients of entrance loss were also computed for each run, with the results indicated in Table II.

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[*] All symbols are defined in the Glossary on page 24.

TABLE II

ENTRANCE LOSS COEFFICIENTS FOR FULL FLOW

Pipe	K_e for Projecting Inlet				K_e for Flush Inlet			
	No. of Tests	Max	Min	Avg	No. of Tests	Max	Min	Avg
18 in. Circular	4	0.89	0.63	0.79	7	0.60	0.25	0.42
24 in. Circular	6	0.88	0.78	0.81	7	0.56	0.50	0.53
36 in. Circular	6	0.86	0.62	0.75	6	0.68	0.43	0.53
All Circular Pipes	16	0.89	0.62	0.78	20	0.68	0.25	0.49
18 in. Arch	12	1.08	0.72	0.90	9	0.59	0.42	0.51
24 in. Arch	6	0.96	0.66	0.89	0	-	-	-
36 in. Arch	7	1.03	0.76	0.88	2	0.45	0.33	0.39
All Arch Pipes	25	1.08	0.66	0.89	11	0.59	0.33	0.49
All Pipes	41	1.08	0.62	0.85	31	0.68	0.25	0.49

The entries in Table II are values of the entrance loss coefficient K_e in the entrance head loss equation

$$H_e = K_e \frac{V^2}{2g} \tag{2}$$

The indicated variations in K_e are random, as far as could be ascertained within experimental limitations, and therefore, the average quantities shown are suggested for use in design calculations. In general, a value of 0.9 is recommended for pipes with projecting inlets and a value of 0.5 for pipes with flush headwall inlets.

B. Part-Full Flow Tests

Roughness and entrance loss coefficients were also determined for each run when the culvert was flowing partly full. Various depths of uniform flow were established in order to make this determination. The culvert was then acting as an open channel. The slope of the pipe was 0.002, and the slope of the water surface was also as near to 0.002 as could be reasonably secured.

This slope was always less than the so-called "critical slope" for the particular culvert, and, therefore, the type of open-channel flow studied was subcritical, or tranquil, flow in every instance. The test results described below are thus strictly applicable only if the culvert is laid on a mild slope.

There was little indication of any systematic variation in Manning's n for part-full uniform flow, except a small effect due to shape of cross section, and average values are suggested for use in design calculations, as given in Table III.

TABLE III

ROUGHNESS COEFFICIENTS FOR UNIFORM TRANQUIL FLOW

Pipe	No. of Tests	Manning Roughness Coefficient		
		From	To	Average
18-in. Circular	8	0.0248	0.0258	0.0252
24-in. Circular	10	0.0232	0.0244	0.0240
36-in. Circular	14	0.0228	0.0243	0.0236
All Circular Pipes	32	0.0228	0.0258	0.0242
18-in. Arch	10	0.0216	0.0233	0.0223
24-in. Arch	3	0.0213	0.0228	0.0220
36-in. Arch	13	0.0221	0.0230	0.0226
All Arch Pipes	26	0.0213	0.0233	0.0224
All Pipes	58	0.0213	0.0258	0.0234

A design value of 0.0235 or 0.0240 is recommended for uniform tranquil flow in corrugated metal culverts. There does seem to be some effect of shape of section, however, and if greater precision is desired, a value of n of 0.0224 might be used for arch sections and 0.0242 for circular sections.

Entrance loss coefficients for the part-full flow condition are given in Table IV on the next page.

TABLE IV
ENTRANCE LOSS COEFFICIENTS FOR UNIFORM TRANQUIL FLOW

Pipe	K_e for Projecting Inlet				K_e for Flush Inlet			
	No. of Tests	Max	Min	Avg	No. of Tests	Max	Min	Avg
18-in. Circular	4	0.77	0.58	0.71	4	0.56	0.28	0.41
24-in. Circular	5	0.77	0.63	0.69	5	0.54	0.42	0.48
36-in. Circular	7	0.81	0.58	0.69	6	0.53	0.37	0.42
All Circular Pipes	16	0.81	0.58	0.70	15	0.56	0.28	0.44
18-in. Arch	5	0.82	0.43	0.65	5	0.43	0.17	0.30
24-in. Arch	3	0.96	0.34	0.68	0	-	-	-
36-in. Arch	7	0.54	0.41	0.46	6	0.33	0.15	0.26
All Arch Pipes	15	0.96	0.34	0.57	11	0.56	0.15	0.28
All Pipes	31	0.96	0.34	0.63	26	0.56	0.15	0.37

As the range of values in Tables II and IV would indicate, the physical nature of the entrance loss mechanism, no less than the difficulty of making a precise experimental determination of its magnitude, results in a fairly wide range of values of the coefficient. The indicated average values, however, should be fairly trustworthy. It is recommended, therefore, that coefficients of 0.7 and 0.4, for projecting and flush inlets respectively, be used in computing entrance losses for corrugated metal culverts flowing partly full on subcritical slopes.

III. EXPERIMENTAL METHODS

The experimental installation for one of the culverts is shown in Fig. 2. The culverts were tested in the main testing channel of the St. Anthony Falls Hydraulic Laboratory. This channel system has an overall length of about 300 ft and is 9 ft wide and 6 ft deep. At the upstream end of the channel is an electrically operated sluice gate, which controls the amount of water entering the channel. Above the sluice gate is a pressure tunnel leading to the headwater pool on the Mississippi River above St. Anthony Falls. The entrance to the tunnel is controlled by an electrically operated weir gate.

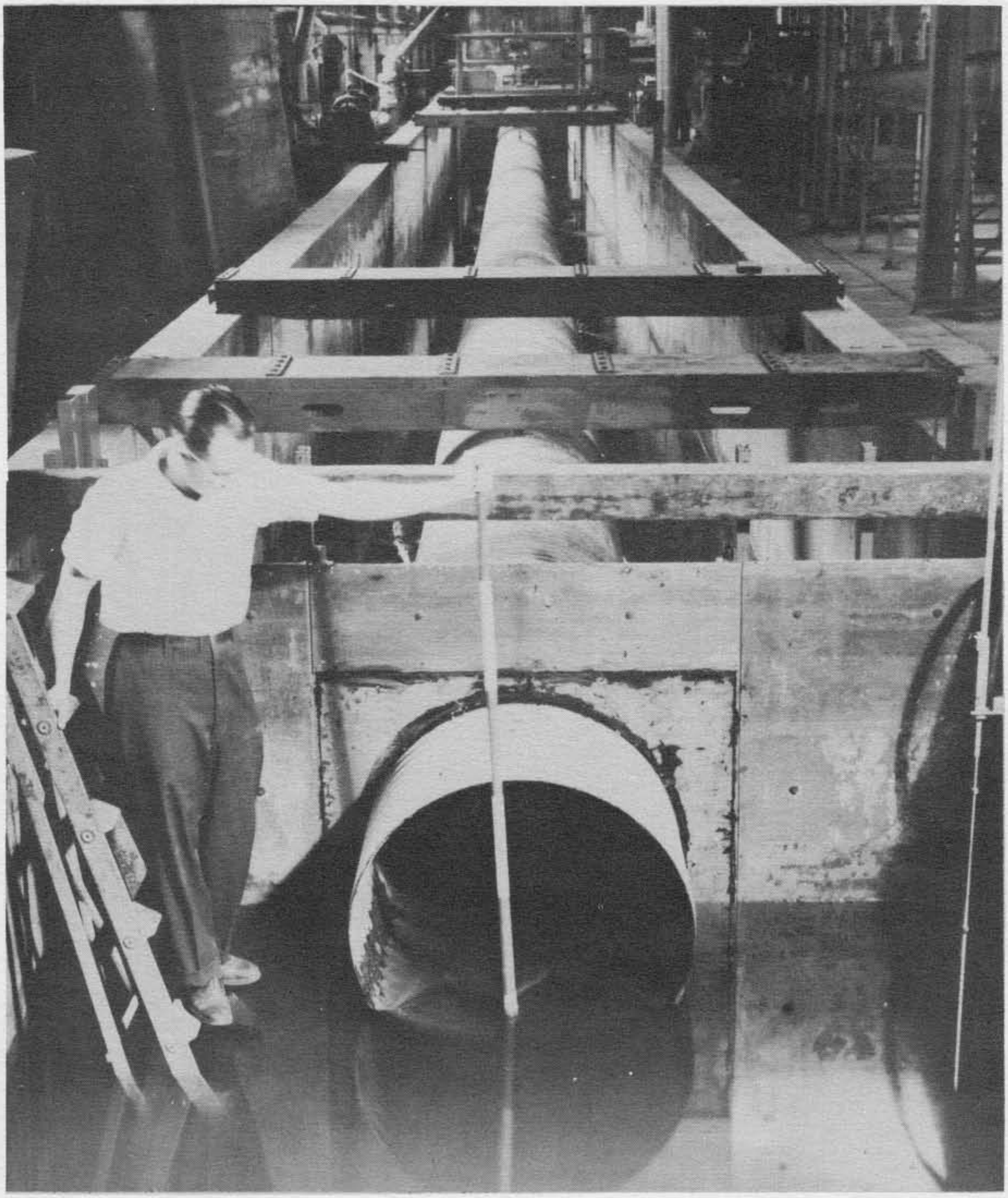

Fig. 2– Test Installation for 36-in. Circular Culvert

With the combined control of the weir gate and sluice gate, large discharges could be quite satisfactorily adjusted and maintained in the test channel. For small discharges, an auxiliary 8-in. pipe was installed, leading into the test channel, through which small rates of flow could be accurately maintained.

When the sluice gate was used to control discharge, there was considerable turbulence in the headwater pool. However, this fact was found to have no influence on pipe roughness coefficients, by means of several check runs made with the weir gate providing the only discharge control. This latter condition produced a quieter headwater pool but could not be used for the bulk of the experiments because of the fluctuating reservoir stage above the weir gate.

Each culvert pipe was laid on a slope of 0.002. It was cradled at frequent intervals on wooden support blocks, which were built up individually to give a slope of precisely 0.002.

The bulkheads for the culvert were designed to accommodate any size culvert that would be tested and also to facilitate dismantlement and reassembly, since the test channel had to be used for other purposes between successive culvert tests. The bulkheads were aluminum plates on bolted steel frames, each with a center plywood panel designed to fit the particular culvert. Figure 3 shows the 24-in. pipe arch culvert installed in the testing channel.

The upstream bulkhead was located 56 ft from the sluice gate, with the pipe projecting back 2 ft into the headwater pool, forming a re-entrant inlet. Also, tests were made with a false bulkhead of wooden construction, fitted over the lip of the pipe to simulate a flush headwall entrance. This false bulkhead, with the 36-in. round culvert, is shown in Fig. 4. The downstream bulkhead was 25 ft from the tailgate at the downstream end of the test channel. The pipe projected about 17 ft beyond the downstream bulkhead into the tailwater pool.

Discharge measurements were made in different ways. Most of the discharges, including all above 10 cfs, were measured in the large, calibrated outside volumetric tanks of the Laboratory. Flows of less than 5 cfs were in some cases measured by means of a calibrated elbow meter in the auxiliary supply pipe mentioned previously. In both cases, the tailwater elevation was controlled by means of the electrically operated tailgate at the downstream end of the test channel.

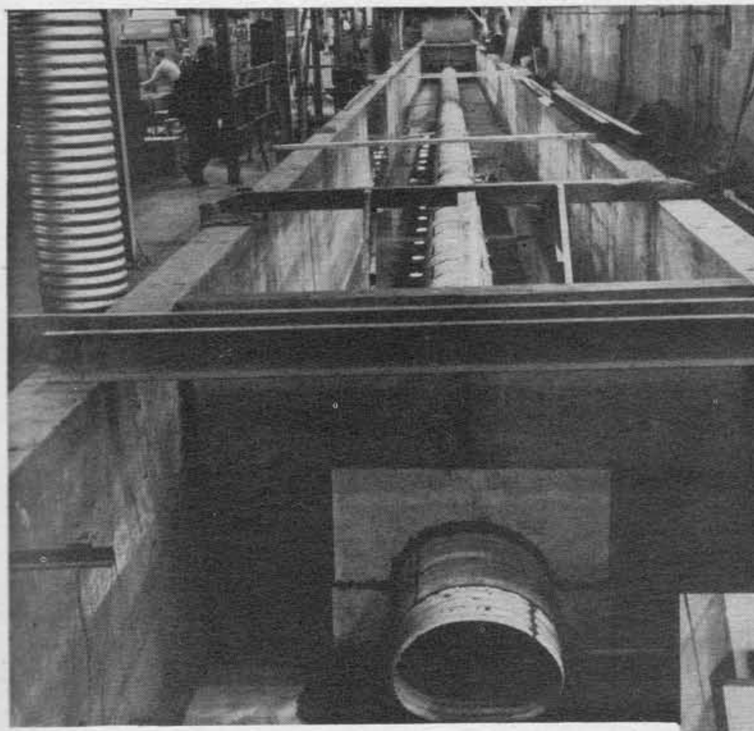

Fig. 3 – 24-in. Pipe Arch Installation

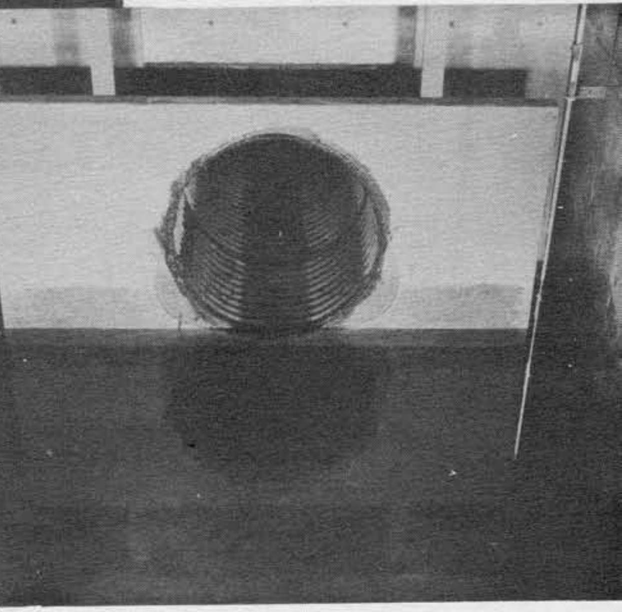

Fig. 4 – Flush Headwall Inlet

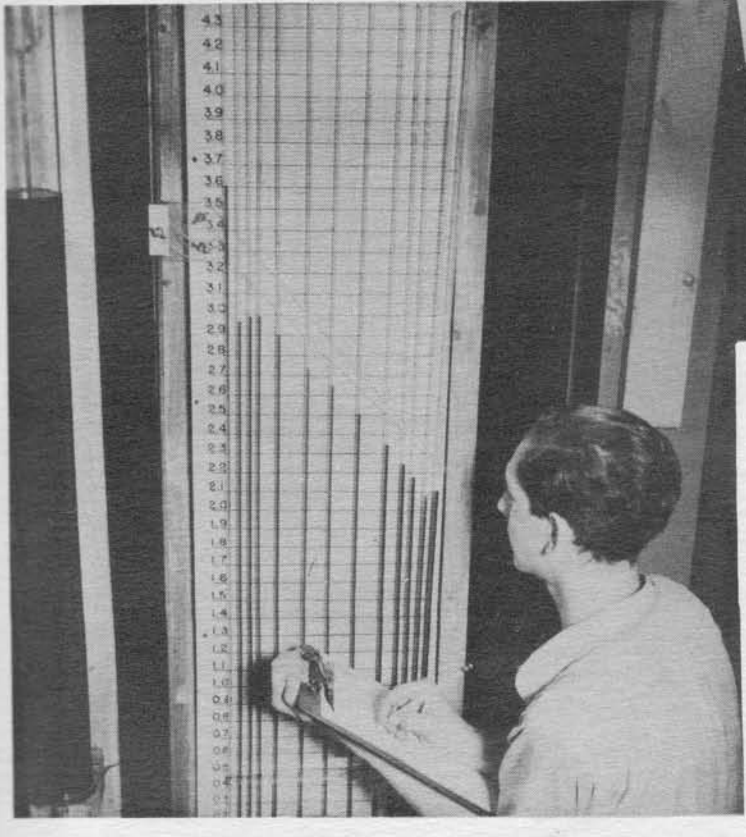

Fig. 5 – Manometry Apparatus

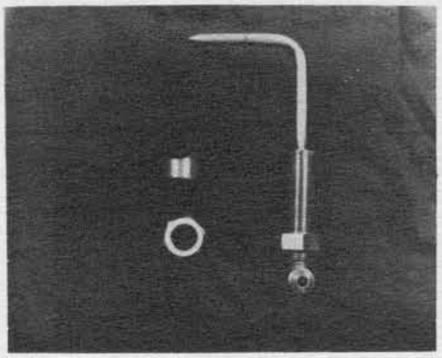

Fig. 6 – Static Pressure Tube

During freezing winter weather, discharges between 5 and 10 cfs in magnitude were measured in the Laboratory's pneumatically controlled weighing tanks. The downstream tailgate was completely raised and its pressure seal turned on. A diversion gate in one side of the test channel near its discharge end opened on a channel leading to the weighing tanks. Vertical stop logs in the diversion gate opening were used to control the tailwater elevation.

Pressure readings in the culvert were obtained by means of Pitot-type static tubes located at intervals along the bottom centerline of the pipe. Altogether, eleven such tubes were used, located 3, 9, 15, 27, 45, 75, 105, 136, 166, 184, and 190 ft from the pipe inlet.

Each of these tubes projected vertically into the pipe about 3 inches. Here it was bent through 90°; the horizontal leg was pointed upstream and tapered to end in a point. Four static-pressure holes on the periphery of this horizontal leg permitted the entrance of water under a pressure which, after the attainment of equilibrium, was equal to the static pressure of the flow in the pipe at that point.

The pressure was transmitted from the tube through a 1/2-in. copper pipe to a glass piezometer tube. All of these piezometer tubes, including one connected to the headwater pool and one to the tailwater pool, were attached to a common manometer board, which had a graduated scale for reading elevations. The horizontal placement of the tubes on the manometer board was geometrically similar to the positions of their respective pressure taps in the pipe, so that water surface or pressure slopes could be more easily adjusted.

For more accurate readings of the headwater pool elevation, a stilling well was mounted near the manometer board and surface readings therein taken with an electric point gage. The manometer board and stilling well were both mounted in the observation pit beside the glass-walled portion of the test channel. A point gage was also placed directly in the headwater pool for reading low surface elevations.

All air was expelled from the manometer lines prior to beginning each series of runs to avoid any significant errors in the data due to faulty manometer indications. The stilling well, which was 4 inches in diameter, served to provide a reference level to correct for minor capillary effects in the tubes on the manometer board. Manometer readings were read and recorded to hundredths of a foot. Pressure fluctuations of varying frequency and amplitude appeared in the manometers and may have been a source of some error, but careful observation techniques minimized this effect. The manometry apparatus is shown in Fig. 5, and one of the static pressure tubes is shown in Fig. 6. Leakage through the joints of the corrugated pipes was prevented by heavy applications of tar, supplemented in some instances by strips of asbestos paper and by cementing.

The 24-in. pipe arch had been tested a year previously under slightly different conditions. The slope of the pipe was 0.0024. Measuring stations were at 3, 33, 63, 93, 123, 153, and 183 ft downstream from the inlet. Discharges were all measured in the volumetric tanks. Wooden bulkheads were used and all tests were made with a re-entrant inlet. Otherwise, the general testing procedure was the same.

IV. COMPUTATICNAL METHODS

A. General

The experimental data consisted of a series of measured discharges and their corresponding hydraulic gradients and water temperatures. As mentioned previously, the discharges were determined by direct measurement in volumetric tanks, in weighing tanks, or by calibrated elbow meter, depending upon circumstances. Hydraulic gradients were obtained by simultaneous piezometric pressure measurements at various points along the pipe.

In every case equilibrium or steady state conditions were established both of discharge and pressure gradient, before taking readings. The hydraulic grade line was determined then by the manometer readings.

B. Full Flow

When a culvert is flowing full, the total head producing flow through the culvert is defined by

$$H = \text{Headwater Elevation} - \text{Tailwater Elevation} \qquad (3)$$

By a simple application of the Bernoulli equation, disregarding the negligible velocity heads in the headwater and tailwater channels, this total head can be equated to the sum of the various energy losses in the culvert as follows:

$$H = K_e \frac{V^2}{2g} + K_f \frac{V^2}{2g} + K_o \frac{V^2}{2g} \qquad (4)$$

The three terms on the right represent head losses resulting from the entrance, barrel friction, and outlet, respectively.

In the tests at full flow, the velocity head $V^2/2g$ was computed from the measured discharge and the known cross-sectional area of the pipe. The three coefficients then were determined by a study of the hydraulic gradient.

The relative importance of K_e, K_f, and K_o depends primarily on the pipe length. For relatively short or smooth culverts, K_e and K_o are most important, but for long, rough culverts such as the ones tested, K_f is predominant. In order to evaluate K_f, the slope $\underline{S}$ of the straight-line portion of the hydraulic gradient was computed statistically from the piezometer readings. Because of influence from the entrance and exit conditions, the gradient was linear over only a central region of the pipe, usually between the measuring stations located 15 ft from the inlet and 9 ft from the outlet. This computation was sensitive to slight differences in piezometer readings and thus the computed slope may be regarded as subject to a possible error of ± 0.005 per cent (of slope). For example, a hydraulic gradient recorded as 0.900 per cent would be within the slope range from 0.895 per cent to 0.905 per cent.

Several typical hydraulic grade lines obtained on the 36-in. diam pipe are shown in Fig. 7. These lines illustrate the fact that, despite effects due to the entrance and the developing turbulent boundary layer, the gradient was linear within experimental accuracy throughout the larger part of the pipe length. The linear portion of the gradient would be still longer for the smaller pipes. Thus, an accurate determination of friction slope was possible in every case.

The slope thus determined could be multiplied by the total length of the pipe to get the total equivalent barrel friction loss. Actually, however, it was merely inserted in the Manning formula, Eq. (1), which then was solved for the roughness coefficient $\underline{n}$.

Also, the friction factor $\underline{f}$ in the Darcy equation, commonly used in pipe line problems, was computed. The Darcy equation is

$$H_f = f \frac{L}{4R} \frac{V^2}{2g} \tag{5}$$

Since H_f/L is equal to $\underline{S}$, this can be written

$$f = \frac{8gRS}{V^2} \tag{6}$$

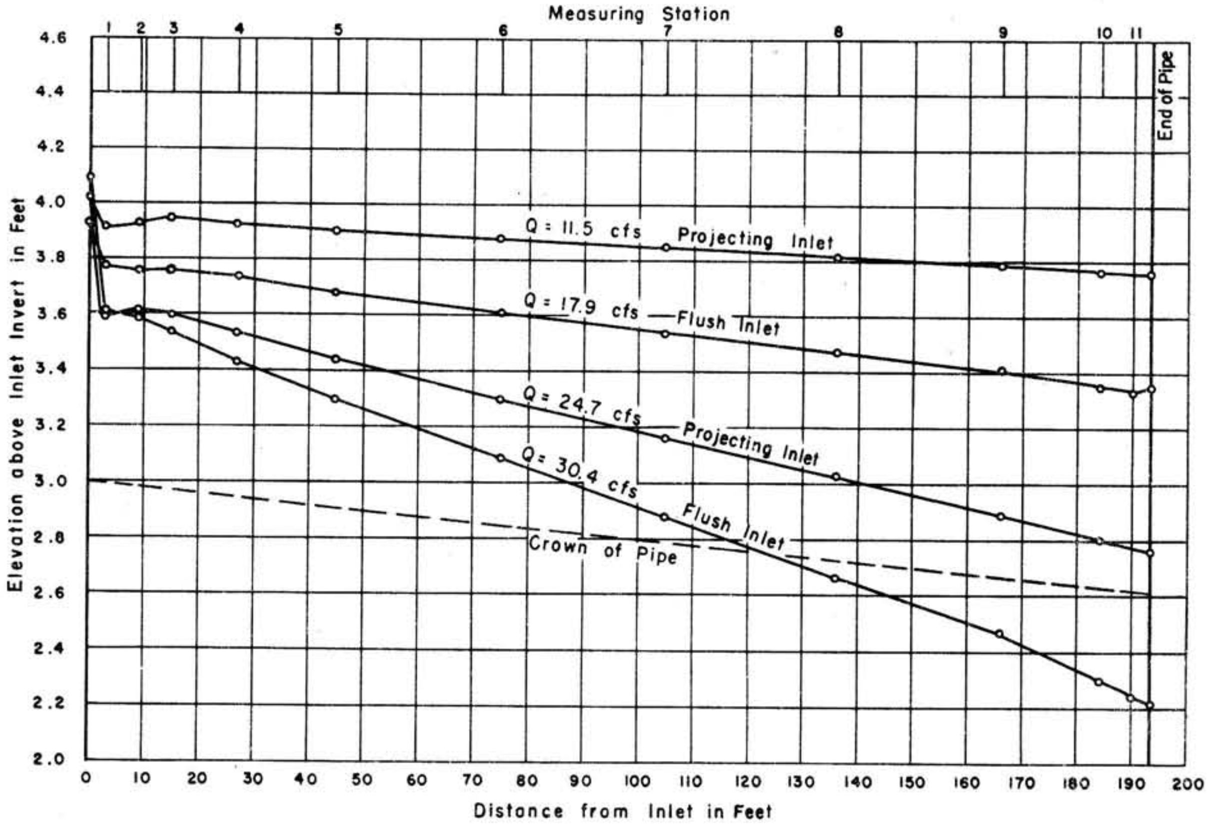

Fig. 7 – Typical Hydraulic Grade Lines
(36-in. Circular Corrugated Pipe Flowing Full)

Another quantity of importance that was computed for each run was the Reynolds number,

$$\mathrm{Re} = \frac{4RV}{\nu} \tag{7}$$

The kinematic viscosity of the water ν varies with water temperature, and, therefore, the water temperature was recorded for the various runs.

The outlet loss for a jet discharging into a large reservoir is theoretically equal to the velocity head of flow in the pipe. When the pipe discharges into a relatively narrow channel, some of this energy is conserved, a fact indicated chiefly by the experimental observation of a slight rise in the hydraulic gradient when the pipe flow enters the tailwater pool. However, this rise is small (and would be smaller in the typical field installation, unless a flared outlet section is used) and difficult to measure with precision. Study of the actual hydraulic gradients indicated that K_o was approximately 0.9 for velocities high enough so that the jet itself reached the tailgate before its energy was dissipated, but experimental difficulties make this value uncertain, and it is believed sufficiently accurate to take it equal to unity.

The entrance loss then was computed by extending the linear portion of the hydraulic gradient to the plane of the entrance, adding $V^2/2g$ to the elevation thus obtained, and then subtracting this total from the headwater elevation. This procedure, which is the best available, has the disadvantage of throwing errors in determination of head and friction loss, and in neglect of nonuniform velocity distribution into the computed entrance loss, which partly accounts for the dispersion of entrance coefficients.

C. Part-Full Flow

In the part-full flow tests, the tailwater was adjusted for each discharge to the proper elevation to give flow at uniform depth and velocity in the culvert. In other words, the slope of the water surface (which is the hydraulic gradient in open channel flow) was made equal to 0.002, the culvert slope, or as nearly so as possible.

Often the slope could not be stabilized at this value within a reasonable length of time, though no measurements were accepted which indicated slopes outside of the range from 0.00175 to 0.00225.

In computing $\underline{n}$ and $\underline{f}$, the actual measured slopes and discharges were used. For part-full flow, of course, the hydraulic radius $\underline{R}$ was not constant but varied with flow depth. To facilitate computation, curves were prepared for the various culvert sections showing the variation of flow area and hydraulic radius with depth. When the slope had some value other than 0.002, the computations were based on the average depth of flow. The Manning and Darcy equations technically apply only to uniform flow, but the flow was so nearly uniform in every case that the errors involved in thus computing $\underline{n}$ and $\underline{f}$ are not important.

If greater accuracy were desired, $\underline{S}$ could be taken as the slope of the energy gradient rather than the hydraulic gradient. This was done in a few instances, but very little effect was produced on the roughness coefficients as computed from the hydraulic gradient, and it was not judged worth while to make such refinements in the bulk of the computations.

The elevation of the headwater pool depends on the entrance loss, and therefore, entrance losses also were computed for the part-full condition. This was done in the same manner as for full flow.

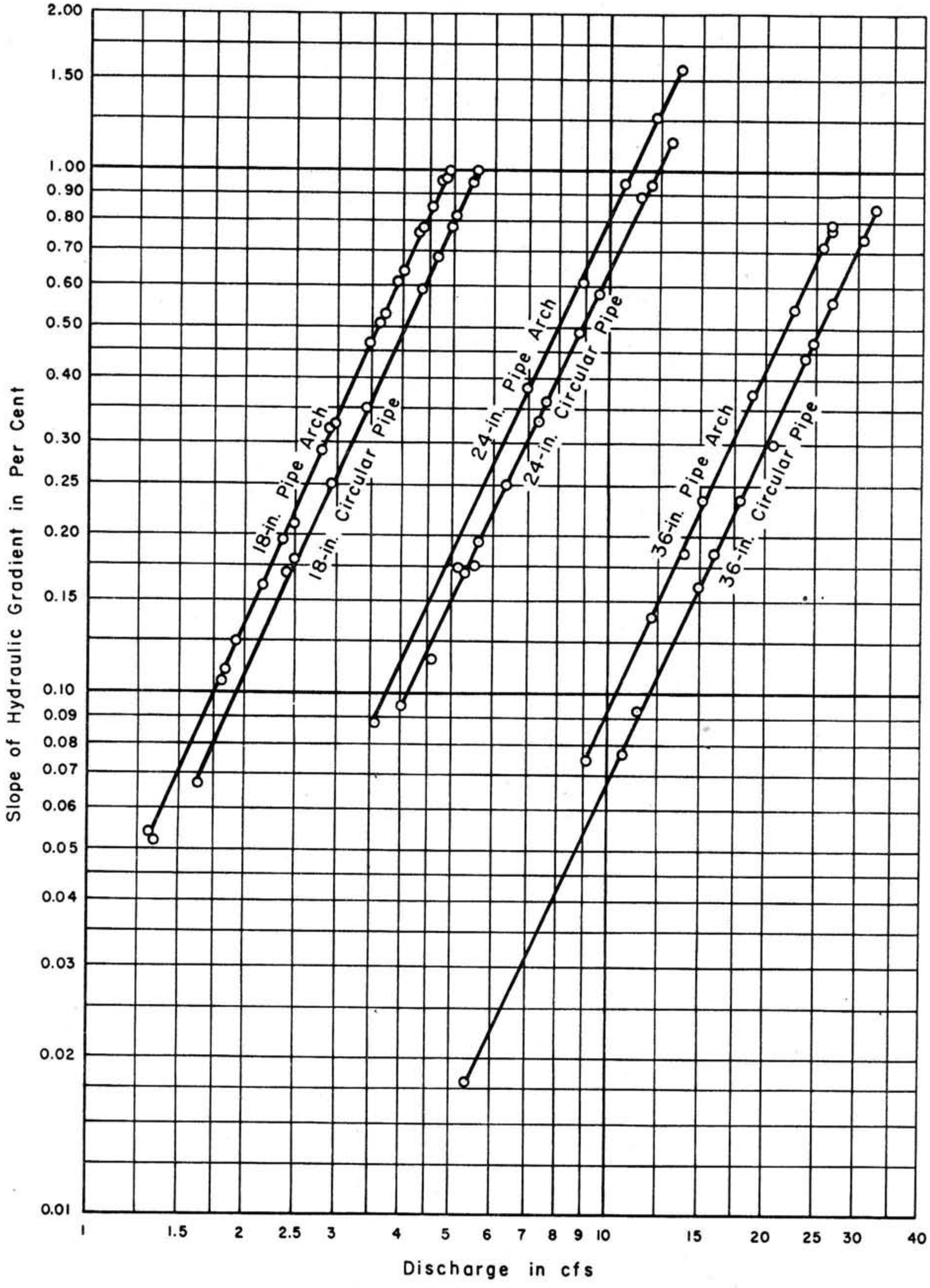

Fig. 8 – Experimental Rating Curves
(Corrugated Metal Pipes Flowing Full)

D. Accuracy of Experimental Data

Rating curves were computed and plotted for each culvert and each flow condition tested in order to judge the general accuracy and dependability of the experimental data. The complete set of rating curves for the full and part-full condition is shown in Figs. 8 and 9.

The full-flow rating curve in Fig. 8 shows the hydraulic gradient plotted against the measured discharge. This relation is exponential in form and, therefore, should appear on logarithmic paper as a straight line. The strong conformity of the experimental data to this requirement is evident.

In order to plot rating curves for the open channel condition, it was necessary to reduce the measurements to equivalent values for a slope of 0.002. Since discharge, as given by the Manning formula, is proportional to the square root of the slope, measured discharges were multiplied by the factor $(\frac{0.00200}{\text{Measured Slope}})^{1/2}$, to obtain discharge quantities for the rating curves.

Average flow depths were plotted against these discharges, giving the rating curves of Fig. 9. Again, the consistency of the data is evident.

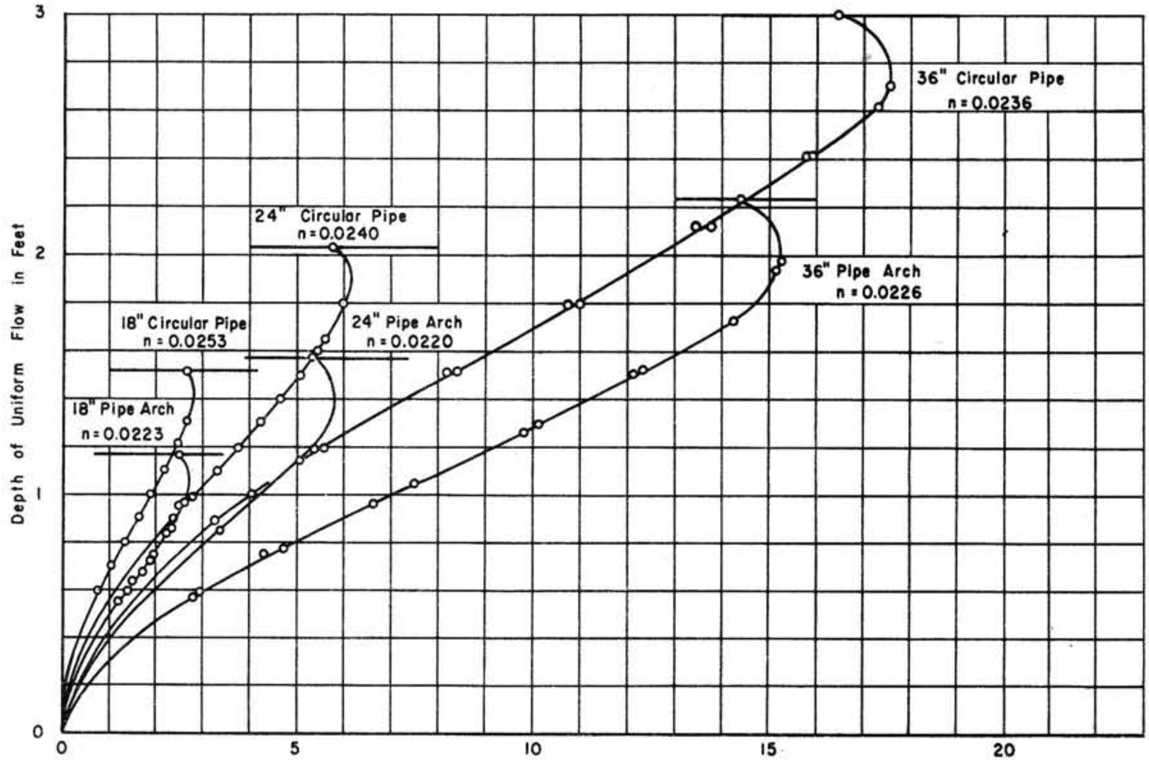

Fig. 9 - Experimental Rating Curves
(Corrugated Metal Pipes Flowing Partly Full)

V. ANALYSIS OF TEST RESULTS

A. Friction Losses for Full Flow

Long culverts flowing full behave hydraulically as pipes, and it is of interest to compare the data obtained for the corrugated culverts with equations and methods commonly in use in pipe problems. Hydraulic data on corrugated metal as a pipe material are very scarce, and previous opinions on this subject have been, to a considerable extent, modified by the results of the present studies.

The flow of water in commercial pipe is usually assumed to be fully turbulent and most of the traditional empirical pipe-flow formulas implicitly assume such flow.

The Reynolds number Re is an important pipe flow parameter, and its magnitude gives an index of the importance of viscosity in the flow pattern, with viscous effects becoming less important as the Reynolds number is increased.

The relative roughness K_s/D (or $K_s/4R$) is usually assumed to be an index of the importance of the pipe material as it affects the pattern and intensity of turbulence (and, therefore, energy loss). In this term, K_s, the equivalent sand grain diameter, denotes the sand grain size which, if uniformly coated on a smooth pipe, would result in the same friction loss as the pipe under consideration.

The value of the friction factor $\underline{f}$ in the Darcy equation is believed to depend only on the Reynolds number and the relative roughness. In laminar and partly turbulent ("smooth pipe") flow, the relative roughness has no influence on $\underline{f}$, which thus varies only with Re. In fully turbulent flow, no change in $\underline{f}$ occurs with increased values of the Reynolds number. It is only in the transitional realm between partly turbulent and fully turbulent flow that $\underline{f}$ varies both with Reynolds number and relative roughness.

Unanticipated, the flow in the corrugated culverts is found to lie in this latter range. Thus it is not possible to assign a definite Manning or Darcy coefficient for corrugated metal, since the friction loss coefficient will vary with the Reynolds number as well as with the relative roughness.

Most commercial pipes have been found experimentally to give a friction factor which gradually decreases as the Reynolds number is increased, finally becoming constant when the flow is fully turbulent. The value of the constant friction factor obtained at high Reynolds numbers depends only on the relative roughness of the pipe. For Reynolds numbers of the order of magnitude obtained in the present studies, such curves nearly always exhibit a decreasing or constant friction factor as Reynolds number increases.

However, for corrugated metal, the friction factor shows a marked increasing tendency as the Reynolds number increases, and this proclivity persists over the entire range of Reynolds numbers investigated from 76,000 to 1,263,000. The relative roughness also has a strong influence on the friction factor, as indicated by the different curves of f versus Re obtained for the different pipes. These curves are shown in Fig. 10.

The Manning coefficient has also been plotted against the Reynolds number in Fig. 11, and also shows n to increase over the Reynolds number range investigated. Thus, if the Manning coefficient is to be used in corrugated pipe design, its variation with the Reynolds number should be properly consisered.

B. Friction Losses for Part-Full Flow

For uniform subcritical flow, the Manning coefficient did not indicate a systematic variation with Reynolds number or pipe size within the accuracy of the experimental data.

A possibly significant difference was obtained, however, between the n-value for part-full flow in the circular and pipe arch sections. The average value of n for the circular pipes was 0.0242 and for the pipe arches was 0.0224.

For average conditions of subcritical flow in corrugated culverts, a Manning coefficient of 0.0235 or 0.0240 should be used.

C. Entrance Loss

The entrance loss coefficient in a culvert may depend upon many variables, but by far the most important factor is the geometry of the entrance itself. In these tests, entrance losses were determined for a re-entrant inlet and for a flush headwall inlet.

An average value of 0.85 was obtained for K_e for the re-entrant inlet and 0.49 for the flush inlet. Values of 0.90 and 0.50, respectively, are recommended for general design use.

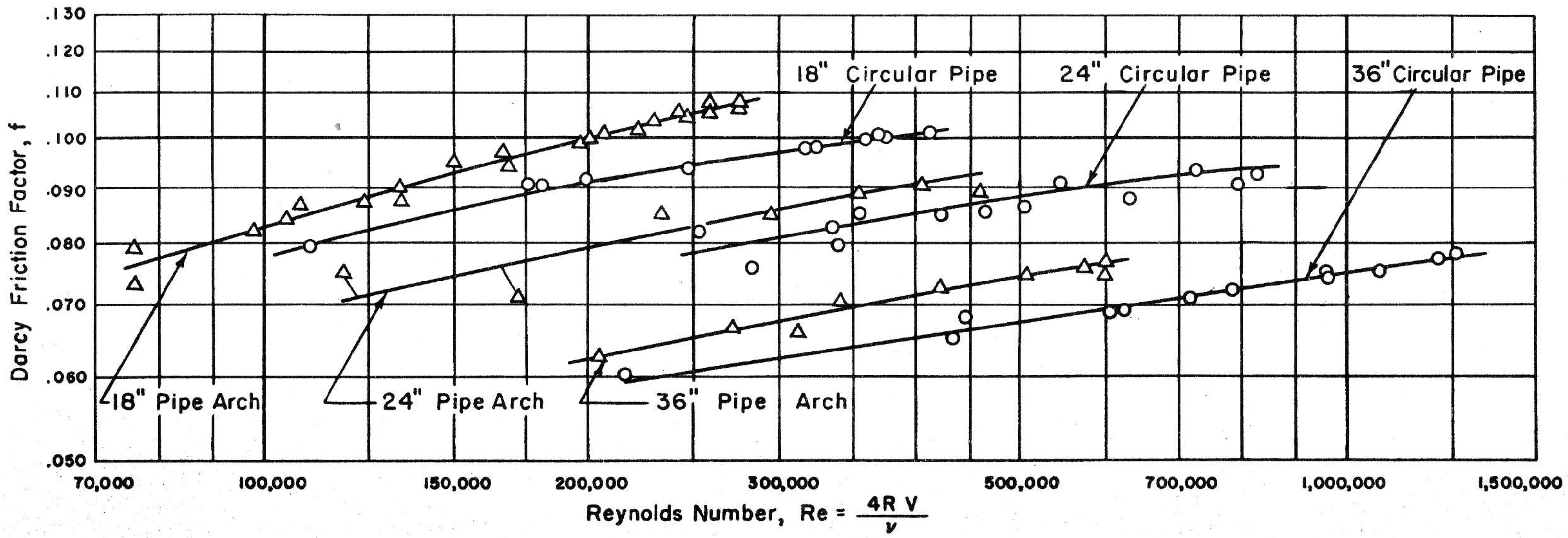

Fig. 10 – Variation of Friction Factor with Reynolds Number (Corrugated Metal Pipes Flowing Full)

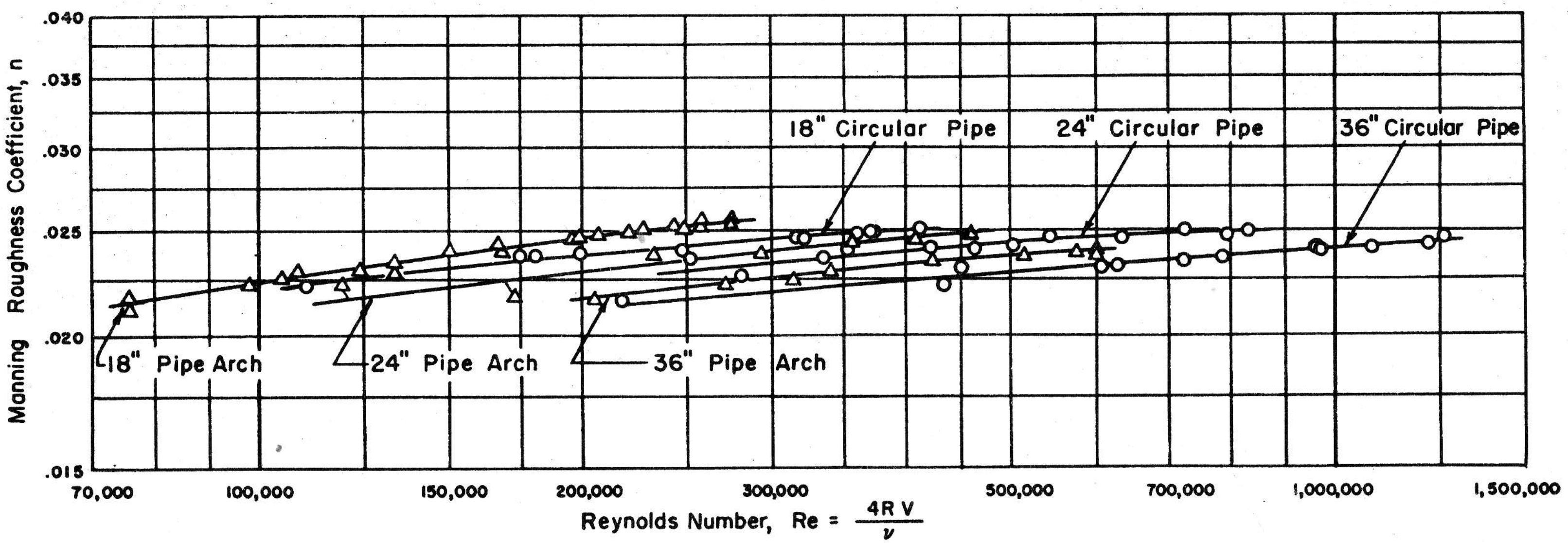

Fig. 11 – Variation of Manning Coefficient with Reynolds Number (Corrugated Metal Pipes Flowing Full)

It was not possible to evaluate quantitatively the respective influence of other variables on entrance loss, because of the overshadowing effect of experimental dispersion of data. However, the advantage of the flush inlet over the re-entrant inlet is evident. Photographs of flow conditions at each of the two types of inlets are shown in Figs. 12 and 13.

For the part-full flow condition, some of the contraction of the entering streamlines is inhibited by the lowered headwater and the reduced peripheral contact at entrance. Since entrance loss is caused mostly by the excess turbulence generated when the contracted jet re-expands, any reduction in jet contraction and jet constraint will be followed by a reduction in entrance loss. Consequently, the loss coefficients for part-full flow are less than those for full flow.

For the projecting inlet, the average entrance loss coefficient was 0.63 and for the flush inlet it was 0.37, compared to 0.85 and 0.49, respectively, for the full-flow condition. For design use, values of 0.70 for the projecting inlet and 0.40 for the flush inlet are recommended as entrance loss coefficients for part-full subcritical flow.

Acknowledgment

The experimental program described in this report was sponsored by the American Concrete Pipe Association and the Portland Cement Association. All experiments were conducted at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, under the supervision of Dr. Lorenz G. Straub, Director. Most of the experimental observations and computations on five of the culverts tested were done by Thomas Timar, during the period January to September 1949. Earlier test runs involving the sixth culvert of the group, a 24-in. arch type, were made by Owen Lamb and William Dingman in December 1947 and January 1948. Leona Schultz and Lois Fosburgh edited and prepared the manuscript; illustrative material was arranged by Loyal A. Johnson.

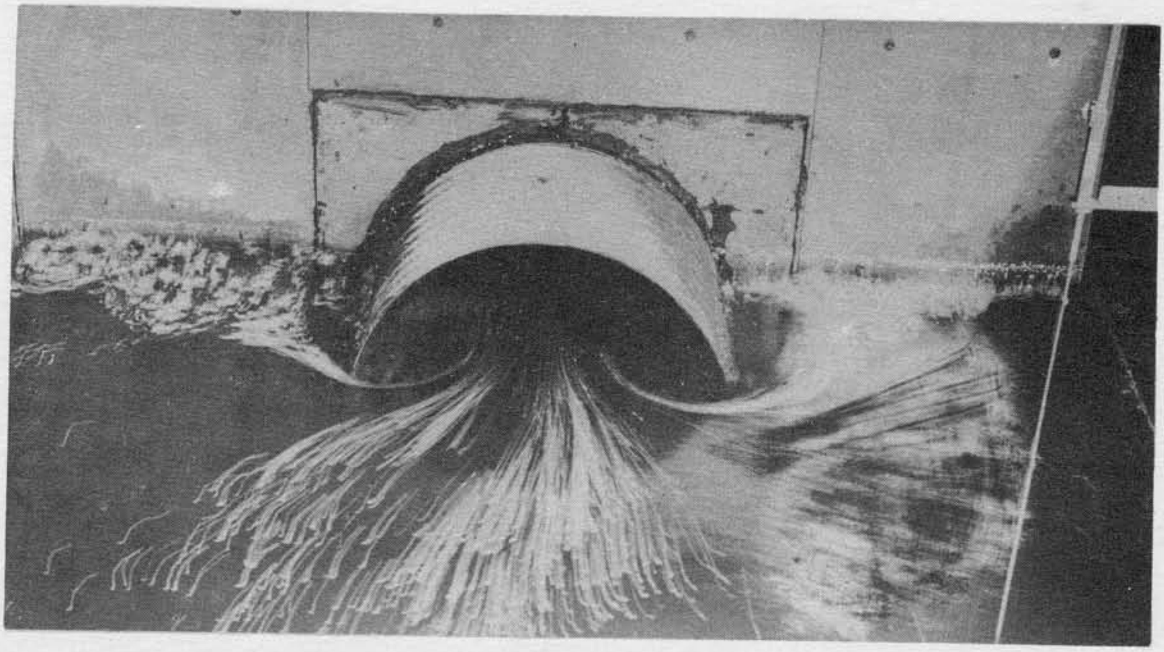

Fig. 12 – Open Flow into Projecting Inlet
(36-in. Circular Pipe)

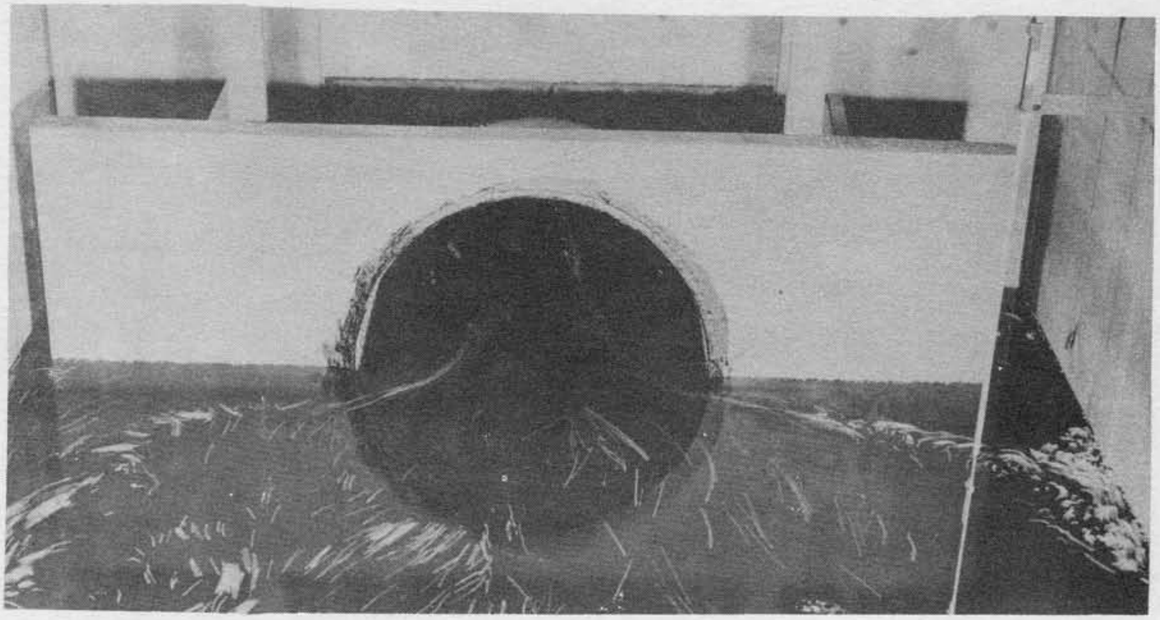

Fig. 13 – Open Flow into Flush Headwall Inlet
(36-in. Circular Pipe)

TABLE V
SUMMARY OF TEST RESULTS
CORRUGATED METAL PIPES FLOWING FULL

Pipe Size	Shape	Inlet	A ft^2	R ft	Q cfs	H ft	S %	Re $\times 10^{-3}$	f	n	K_e
18"	Circular	Flush	1.51	0.378	2.40	0.36	0.170	175	0.0905	0.0237	0.25
					2.49	0.39	0.180	181	0.0905	0.0237	0.60
					3.41	0.76	0.350	248	0.0935	0.0240	0.39
					4.34	1.25	0.590	322	0.0980	0.0246	0.47
					4.94	1.66	0.780	360	0.0995	0.0248	0.44
					5.05	1.74	0.820	375	0.1002	0.0249	0.41
					5.53	2.10	1.000	411	0.1018	0.0251	0.38
18"	Circular	Proj.	1.51	0.378	1.63	0.153	0.067	111	0.0795	0.0222	0.79
					2.92	0.55	0.250	199	0.0912	0.0238	0.63
					4.65	1.51	0.680	318	0.0976	0.0246	0.89
					5.43	2.07	0.950	372	0.1003	0.0248	0.78
24"	Circular	Flush	3.24	0.508	3.99	0.22	0.095	252	0.0818	0.0237	0.54
					5.32	0.38	0.170	336	0.0824	0.0237	0.52
					5.61	0.45	0.195	354	0.0850	0.0241	0.55
					7.30	0.73	0.330	461	0.0851	0.0241	0.56
					8.70	1.10	0.490	543	0.0909	0.0249	0.54
					11.49	1.98	0.890	724	0.0932	0.0252	0.50
					13.15	2.14*	1.140	826	0.0923	0.0251	0.53
24"	Circular	Proj.	3.24	0.508	4.58	0.29	0.115	281	0.0754	0.0228	0.80
					5.53	0.42	0.175	340	0.0792	0.0232	0.78
					6.35	0.58	0.250	421	0.0846	0.0242	0.83
					7.59	0.85	0.360	502	0.0860	0.0243	0.88
					9.52	1.34	0.580	631	0.0880	0.0246	0.78
					12.00	2.18	0.940	795	0.0900	0.0248	0.82
36"	Circular	Flush	7.07	0.750	10.74	0.20	0.077	434	0.0650	0.0224	0.53
					14.98	0.42	0.160	605	0.0690	0.0231	0.68
					17.90	0.59	0.235	720	0.0710	0.0234	0.43
					23.80	1.09	0.440	960	0.0750	0.0241	0.46
					26.88	1.63	0.560	1078	0.0750	0.0241	0.56
					30.44	1.87*	0.740	1220	0.0770	0.0244	0.52
36"	Circular	Proj.	7.07	0.750	5.39	0.047	0.018	216	0.0600	0.0216	0.78
					11.48	0.26	0.093	449	0.0680	0.0230	0.73
					16.00	0.51	0.185	624	0.0690	0.0232	0.86
					20.07	0.81	0.300	785	0.0720	0.0236	0.75
					24.71	1.25	0.470	964	0.0740	0.0240	0.79
					32.36	2.57*	0.850	1263	0.0780	0.0247	0.62
18"	Arch	Flush	1.67	0.355	1.35	0.12	0.052	76	0.0730	0.0210	0.58
					1.92	0.27	0.125	108	0.0870	0.0230	0.42
					1.92	0.28	0.125	108	0.0870	0.0230	0.27
					2.36	0.43	0.195	133	0.0900	0.0233	0.56
					2.97	0.71	0.325	168	0.0940	0.0239	0.55
					3.46	1.00	0.465	196	0.0990	0.0245	0.52
					3.90	1.32	0.610	221	0.1020	0.0248	0.59
					4.30	1.65	0.760	243	0.1050	0.0252	0.57
					4.35	1.64	0.770	246	0.1040	0.0251	0.42
					4.88	2.10	0.990	275	0.1060	0.0253	0.42
18"	Arch	Proj.	1.67	0.355	1.32	0.12	0.054	76	0.0790	0.0218	0.56
					1.81	0.25	0.105	98	0.0820	0.0223	0.94
					1.83	0.24	0.110	105	0.0840	0.0226	0.72
					2.17	0.35	0.160	124	0.0870	0.0230	0.76
					2.49	0.46	0.210	134	0.0870	0.0229	0.88
					2.80	0.64	0.290	150	0.0950	0.0240	0.82
					2.90	0.69	0.320	166	0.0970	0.0242	0.91
					3.60	1.12	0.510	206	0.1010	0.0248	0.90
					3.70	1.17	0.530	199	0.0990	0.0246	0.91
					4.00	1.42	0.640	229	0.1030	0.0250	0.96
					4.55	1.88	0.850	258	0.1050	0.0252	1.00
					4.80	2.11	0.960	275	0.1070	0.0254	1.08
					4.82	2.12	0.970	258	0.1075	0.0255	0.95
24"	Arch	Proj.	2.98	0.471	3.56	0.28	0.088	119	0.0750	0.0223	0.95
					5.16	0.49	0.173	172	0.0710	0.0217	0.96
					6.98	0.95	0.383	233	0.0850	0.0238	0.66
					8.82	1.58	0.613	294	0.0850	0.0238	0.91
					10.69	2.33	0.942	357	0.0890	0.0244	0.88
					12.25	2.90	1.257	409	0.0900	0.0245	0.88
					13.77	3.77*	1.559	459	0.0890	0.0244	-
36"	Arch	Flush	6.32	0.673	15.20	0.56	0.235	342	0.0705	0.0230	0.33
					26.74	1.86	0.770	600	0.0749	0.0237	0.45
36"	Arch	Proj.	6.32	0.673	9.14	0.21	0.075	205	0.0622	0.0216	1.03
					12.10	0.37	0.140	272	0.0663	0.0223	0.95
					13.96	0.49	0.185	314	0.0658	0.0225	0.76
					18.89	0.95	0.375	424	0.0728	0.0235	0.84
					22.57	1.40	0.545	507	0.0743	0.0236	0.91
					25.67	1.85	0.715	577	0.0752	0.0238	0.86
					26.74	2.02	0.790	600	0.0766	0.0240	0.84

*Tailwater below outlet crown.

TABLE VI
SUMMARY OF TEST RESULTS
CORRUGATED METAL PIPES FLOWING PARTLY FULL

Pipe Size	Shape	Inlet	Q cfs	y ft	R ft	A ft^2	S %	n	K_e
18"	Circular	Flush	0.76	0.59	0.317	0.65	0.195	0.0258	0.28
			1.35	0.80	0.391	0.96	0.200	0.0254	0.33
			1.87	1.00	0.438	1.25	0.200	0.0255	0.46
			2.43	1.20	0.459	1.53	0.200	0.0249	0.56
18"	Circular	Proj.	1.05	0.70	0.344	0.81	0.200	0.0252	0.58
			1.63	0.90	0.416	1.11	0.200	0.0252	0.69
			2.17	1.10	0.451	1.40	0.200	0.0252	0.77
			2.61	1.30	0.456	1.64	0.200	0.0248	0.69
24"	Circular	Flush	2.80	1.00	0.502	1.62	0.195	0.0244	0.53
			3.74	1.20	0.559	1.99	0.200	0.0240	0.42
			4.62	1.40	0.600	2.38	0.200	0.0242	0.44
			5.43	1.60	0.618	2.74	0.200	0.0243	0.54
			5.99	1.80	0.609	3.04	0.200	0.0242	0.48
24"	Circular	Proj.	2.38	0.90	0.468	1.38	0.200	0.0232	0.63
			3.32	1.10	0.533	1.79	0.200	0.0234	0.77
			4.23	1.30	0.580	2.19	0.200	0.0239	0.69
			5.09	1.50	0.609	2.55	0.200	0.0238	0.65
			5.57	1.66	0.618	2.83	0.195	0.0241	0.72
36"	Circular	Flush	3.05	0.90	0.510	1.77	0.175	0.0230	-
			5.31	1.19	0.639	2.61	0.195	0.0238	0.41
			8.45	1.52	0.754	3.59	0.200	0.0234	0.37
			10.74	1.80	0.832	4.42	0.190	0.0236	0.39
			14.43	2.11	0.890	5.32	0.220	0.0238	0.44
			15.51	2.40	0.913	6.07	0.190	0.0238	0.41
			17.11	2.62	0.906	6.54	0.195	0.0234	0.53
36"	Circular	Proj.	3.16	0.90	0.510	1.77	0.185	0.0228	0.70
			5.41	1.20	0.643	2.64	0.185	0.0232	0.68
			7.91	1.51	0.753	3.56	0.185	0.0238	0.67
			10.36	1.80	0.833	4.43	0.185	0.0242	0.58
			12.78	2.12	0.890	5.33	0.180	0.0243	0.81
			15.38	2.41	0.913	6.09	0.190	0.0241	0.67
			17.32	2.71	0.893	6.71	0.195	0.0235	0.74
18"	Arch	Flush	1.14	0.56	0.348	0.85	0.180	0.0233	0.17
			1.50	0.64	0.380	0.99	0.190	0.0224	0.19
			1.92	0.75	0.412	1.18	0.195	0.0223	0.43
			2.25	0.84	0.427	1.30	0.205	0.0219	0.33
			2.61	0.97	0.431	1.48	0.220	0.0224	0.37
18"	Arch	Proj.	1.40	0.59	0.357	0.90	0.190	0.0219	0.45
			1.68	0.67	0.390	0.04	0.190	0.0227	0.43
			1.92	0.73	0.410	1.15	0.200	0.0216	0.74
			2.33	0.86	0.429	1.33	0.200	0.0226	0.82
			2.69	0.97	0.430	1.49	0.215	0.0221	0.82
24"	Arch	Proj.	3.67	0.85	0.505	1.72	0.233	0.0213	0.34
			4.37	1.01	0.552	2.08	0.232	0.0228	0.74
			5.32	1.17	0.579	2.41	0.221	0.0220	0.96
36"	Arch	Flush	2.91	0.59	0.424	1.71	0.200	0.0225	0.24
			4.67	0.78	0.539	2.37	0.195	0.0221	0.27
			7.42	1.05	0.671	3.31	0.195	0.0225	0.33
			9.87	1.30	0.760	4.16	0.190	0.0227	0.31
			12.65	1.52	0.815	4.86	0.210	0.0228	0.26
			14.78	1.94	0.803	5.92	0.190	0.0227	0.15
36"	Arch	Proj.	2.64	0.57	0.408	1.63	0.190	0.0224	0.41
			4.29	0.75	0.524	2.27	0.195	0.0224	0.43
			6.65	0.97	0.635	3.03	0.200	0.0225	0.49
			9.97	1.26	0.750	4.03	0.205	0.0225	0.47
			12.29	1.52	0.808	4.84	0.205	0.0230	0.41
			14.45	1.73	0.818	5.42	0.205	0.0230	0.54
			15.45	1.98	0.807	6.00	0.205	0.0227	0.49

GLOSSARY

A = Cross-sectional area of flow, sq ft

D = Equivalent pipe diameter = $4R$

f = Darcy friction factor

g = Acceleration of gravity = 32.16 ft/sec/sec

H = Total head on culvert, ft

H_e = Entrance loss, ft

H_f = Head loss due to pipe friction, ft

K_e = Entrance loss coefficient

K_f = Barrel friction loss coefficient

K_o = Outlet loss coefficient

K_s = Diameter of sand grain of equivalent roughness, ft

L = Length of culvert, ft

n = Manning roughness coefficient

Q = Rate of flow, cfs

R = Hydraulic radius, ft

Re = Reynolds number = $4R\,V/\nu$

S = Slope of hydraulic gradient

V = Average velocity of flow, fps

ν = Kinematic viscosity, sq ft/sec