UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, Director

Technical Paper No. 3, Series B

Hydraulic Data Comparison of Concrete and Corrugated Metal Culvert Pipes

by
LORENZ G. STRAUB
and
HENRY M. MORRIS

July, 1950
Minneapolis, Minnesota

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HYDRAULIC DATA COMPARISON OF CONCRETE AND CORRUGATED METAL CULVERT PIPES

I. INTRODUCTION

Full-scale tests were conducted at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota primarily for the purpose of obtaining pipe friction and entrance loss coefficients for concrete and corrugated metal culvert pipes, which would be more accurate and dependable than those currently recommended in culvert design literature. Comparison of these test data is presented in this paper and recommendations are given for design values of the coefficients under various flow conditions.

The experimental studies were made on new culverts, all of which were installed and maintained with excellent alignment. A high degree of accuracy was possible in these tests for all of the culverts. Sizes up to 3 ft in diameter were investigated.

Analytical studies were made of the data obtained from the experimental observations which are significant to basic pipe flow theory where systematic form roughness and large diameters come into consideration.

II. RESUME OF EXPERIMENTAL PROGRAM

A. Scope of Tests

A total of nine culverts were tested, ranging in size from 18 inches in diameter to 36 inches in diameter, each with an overall length of approximately 193 ft. The culverts fall into three groups as follows:

(a) Circular concrete pipes
(b) Circular corrugated metal pipes
(c) Corrugated metal pipe arches

In each group, tests were made with pipe diameters of 18 inches, 24 inches, and 36 inches. In the case of the pipe arch sections, the identifying dimension refers to a circular section of equal periphery.

Each pipe was tested when flowing full and also when flowing partly full, and a wide range of discharges was used for each of these two main flow conditions. Friction and entrance loss determinations were made for all runs. For the partly full flow condition, uniform subcritical flow was established as the basis for measurements.

Technical Papers No. 4 and No. 5, Series B, respectively, describe in detail the hydraulic tests on the concrete culvert pipes and the corrugated metal culvert pipes separately. However, the salient test results for both types of culverts are presented in this paper (Technical Paper No. 3).

Each pipe, with the exception of the 24-in. concrete pipe and the 24-in. corrugated pipe arch, was tested under two types of entrance conditions; namely, (1) inlet projecting 2 ft into the headwater pool, and (2) inlet flush with the headwall. The two pipes mentioned as exceptions were tested only with projecting inlets.

B. Summary of Results

The main quantities determined for use in culvert design were the Manning roughness coefficient $\underline{n}$* and the entrance loss coefficient, K_e, which are defined in terms of Eqs. (1) and (2) respectively:

$$Q = \frac{1.486}{n} AR^{2/3} S^{1/2} \tag{1}$$

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

For the pipe flowing full, the test results are summarized in Table I. This tabulation shows maximum, minimum, and average values of $\underline{n}$ and K_e for each pipe. The manner in which the coefficients varied is also indicated.

A similar summary tabulation for the partly full flow condition appears in Table II.

The significance to be attached to the indicated variations in the coefficients is discussed later in this report. For accurate analysis or design, these variations must be properly considered. However, for the usual culvert design this degree of accuracy would not be warranted. Recommended design values, assuming new, straight pipe, are given in Table III, based on the results of the studies described in this report.

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*All symbols are defined in the Glossary on page 23.

TABLE I
SUMMARY OF TEST RESULTS - PIPES FLOWING FULL

Pipe	No. of Tests	Maximum	Minimum	Average	Type of Variation
MANNING ROUGHNESS COEFFICIENT					
18" diam corrugated	11	0.0251	0.0222	0.0242	
24" diam corrugated	13	0.0252	0.0228	0.0242	Increases as Reynolds No. increases
36" diam corrugated	12	0.0247	0.0216	0.0232	Decreases as diameter increases
Group	36	0.0252	0.0216	0.0239	
18" corrugated pipe arch	23	0.0255	0.0210	0.0239	
24" corrugated pipe arch	7	0.0245	0.0217	0.0236	Increases as Reynolds No. increases
36" corrugated pipe arch	9	0.0240	0.0216	0.0232	Decreases as diameter increases
Group	39	0.0255	0.0210	0.0237	
18" diam concrete	12	0.0108	0.0091	0.0097	
24" diam concrete	9	0.0104	0.0093	0.0100	Decreases as Reynolds No. increases
36" diam concrete	11	0.0108	0.0103	0.0106	Increases as diameter increases
Group	32	0.0108	0.0091	0.0101	
ENTRANCE LOSS COEFFICIENT, PROJECTING INLET					
18" diam corrugated	4	0.89	0.63	0.79	
24" diam corrugated	6	0.88	0.78	0.81	Random
36" diam corrugated	6	0.86	0.62	0.75	
Group	16	0.89	0.62	0.78	
18" corrugated pipe arch	12	1.08	0.72	0.90	
24" corrugated pipe arch	6	0.96	0.66	0.89	Random
36" corrugated pipe arch	7	1.03	0.76	0.88	
Group	25	1.08	0.66	0.89	
18" diam concrete	4	0.12	0.09	0.10	
24" diam concrete	8	0.19	0.07	0.11	Increases as diameter increases
36" diam concrete	6	0.21	0.12	0.16	
Group	18	0.21	0.07	0.12	
ENTRANCE LOSS COEFFICIENT, FLUSH INLET					
18" diam corrugated	7	0.60	0.25	0.42	
24" diam corrugated	7	0.56	0.50	0.53	Random
36" diam corrugated	6	0.68	0.43	0.53	
Group	20	0.68	0.25	0.49	
18" corrugated pipe arch	9	0.59	0.42	0.51	
24" corrugated pipe arch	0	-	-	-	Random
36" corrugated pipe arch	2	0.45	0.33	0.39	
Group	11	0.59	0.33	0.49	
18" diam concrete	7	0.13	0.05	0.08	
24" diam concrete	-	-	-	-	Increases as diameter increases
36" diam concrete	5	0.12	0.05	0.10	
Group	12	0.13	0.05	0.09	

TABLE II

SUMMARY OF TEST RESULTS - PIPES FLOWING PARTLY FULL

Pipe	No. of Tests	Maximum	Minimum	Average	Type of Variation
		MANNING ROUGHNESS COEFFICIENT			
18" diam corrugated	8	0.0258	0.0248	0.0252	
24" diam corrugated	10	0.0244	0.0232	0.0240	Random
36" diam corrugated	14	0.0243	0.0228	0.0236	
Group	32	0.0258	0.0228	0.0242	
18" corrugated pipe arch	10	0.0233	0.0216	0.0223	
24" corrugated pipe arch	3	0.0228	0.0213	0.0220	Random
36" corrugated pipe arch	13	0.0230	0.0221	0.0226	
Group	26	0.0233	0.0213	0.0224	
18" diam concrete	10	0.0110	0.0102	0.0107	
24" diam concrete	6	0.0108	0.0102	0.0104	Random
36" diam concrete	-	-	-	-	
Group	16	0.0110	0.0102	0.0106	
		ENTRANCE LOSS COEFFICIENT, PROJECTING INLET			
18" diam corrugated	4	0.77	0.58	0.71	
24" diam corrugated	5	0.77	0.63	0.69	Random
36" diam corrugated	7	0.81	0.58	0.69	
Group	16	0.81	0.58	0.70	
18" corrugated pipe arch	5	0.82	0.43	0.65	
24" corrugated pipe arch	3	0.96	0.34	0.68	Random
36" corrugated pipe arch	7	0.54	0.41	0.46	
Group	15	0.96	0.34	0.57	
18" diam concrete	8	0.20	0.13	0.16	
24" diam concrete	6	0.23	0.02	0.08	Random
36" diam concrete	-	-	-	-	
Group	14	0.23	0.02	0.12	
		ENTRANCE LOSS COEFFICIENT, FLUSH INLET			
18" diam corrugated	4	0.56	0.28	0.41	
24" diam corrugated	5	0.54	0.42	0.48	Random
36" diam corrugated	6	0.53	0.37	0.42	
Group	15	0.56	0.28	0.44	
18" corrugated pipe arch	5	0.43	0.17	0.30	
24" corrugated pipe arch	0	-	-	-	Random
36" corrugated pipe arch	6	0.33	0.15	0.26	
Group	11	0.43	0.15	0.28	
18" diam concrete	2	0.15	0.06	0.10	Random
24" diam concrete	-	-	-	-	
36" diam concrete	-	-	-	-	
Group	2	0.15	0.06	0.10	

TABLE III

RECOMMENDED DESIGN COEFFICIENTS FOR CORRUGATED METAL AND CONCRETE CULVERTS

Item	Corrugated Metal*	Concrete*
Manning coefficient, full flow	0.0250	0.0100
Manning coefficient, partly full flow	0.0240	0.0110
Projecting inlet coefficient, full flow	0.90	0.15
Projecting inlet coefficient, partly full flow	0.70	0.15
Flush inlet coefficient, full flow	0.50	0.10
Flush inlet coefficient, partly full flow	0.40	0.10

*The above recommended values apply to new, straight pipe with no obstructions, side openings, or other flow-disturbing features. The Manning coefficients for corrugated metal apply to corrugations with 1/2-in. height and 2 2/3-in. spacing. The Manning coefficients for concrete apply to pipe manufactured by the cast-and-vibrated process in 6-ft lengths of pipe and with non-pressure rubber ring joints.

As a culvert material, corrugated metal is obviously much less efficient hydraulically than concrete; detailed comparisons appear later in the report. In general, it may be said that a culvert usually can, and should, be designed to flow full under the given conditions of discharge and available head. Such a design would usually be most economical, regardless of which material is used. However, a concrete culvert flowing full has a much higher hydraulic capacity than a corrugated culvert of the same diameter. Therefore, whenever hydraulic efficiency is the controlling design factor in a given culvert, concrete or other smooth-walled pipe is much superior to corrugated metal.

III. METHODS OF TESTING AND ANALYSIS

All of the pipes were tested in the main testing channel of the St. Anthony Falls Hydraulic Laboratory. Each pipe was approximately 193 ft long and on a slope of approximately 0.002. Bulkheads were installed near the two ends of the pipe in order to form headwater and tailwater pools. The general experimental installation is shown on Fig. 1.

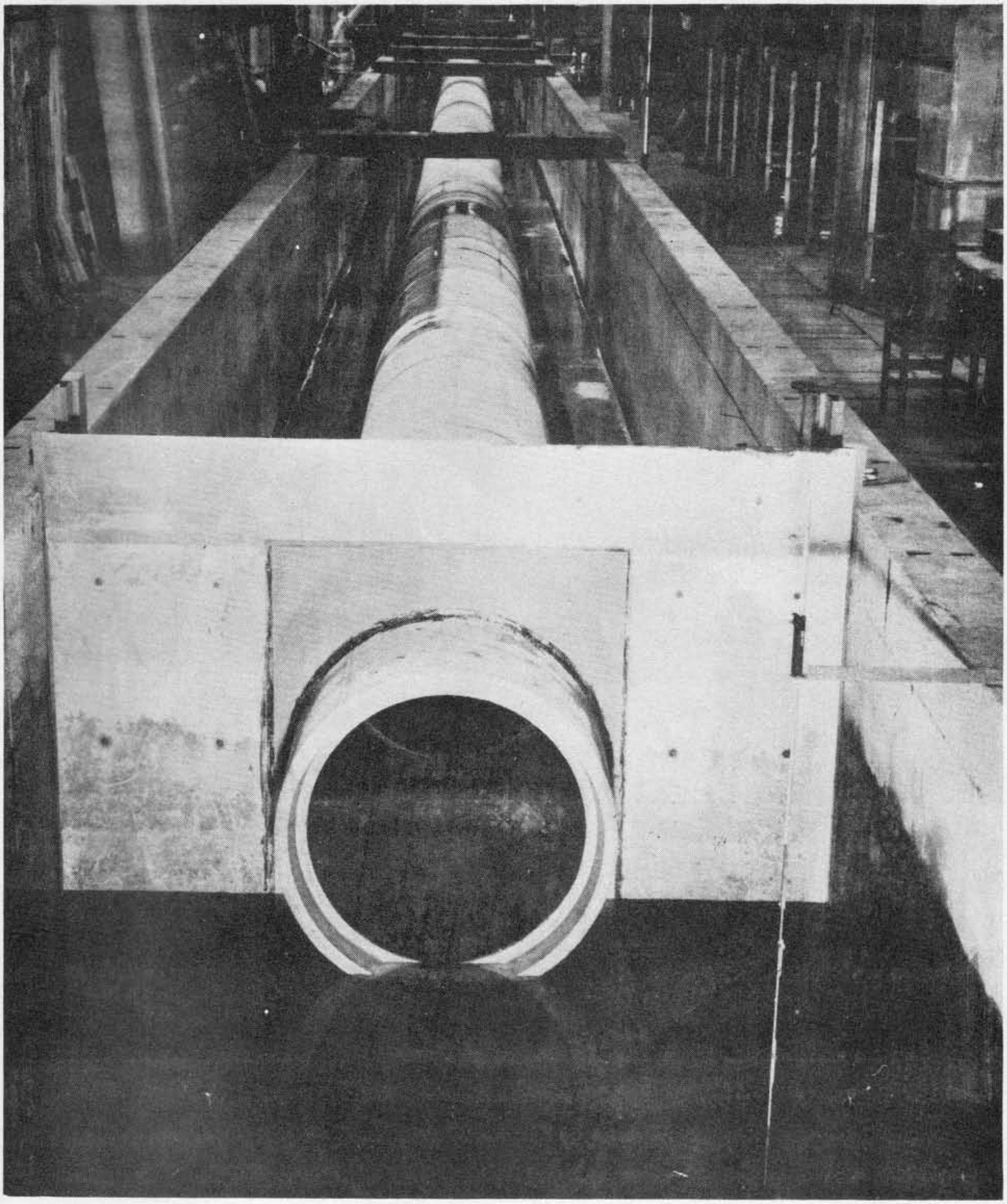

Fig. 1– 36-in. Concrete Culvert Test Installation

A large number of runs was made in each pipe for both full and part-full flow conditions and for both projecting and flush inlets in an attempt to study as wide a range of flow conditions as facilities would permit. The false bulkhead used to simulate a flush entrance is shown in Fig. 2.

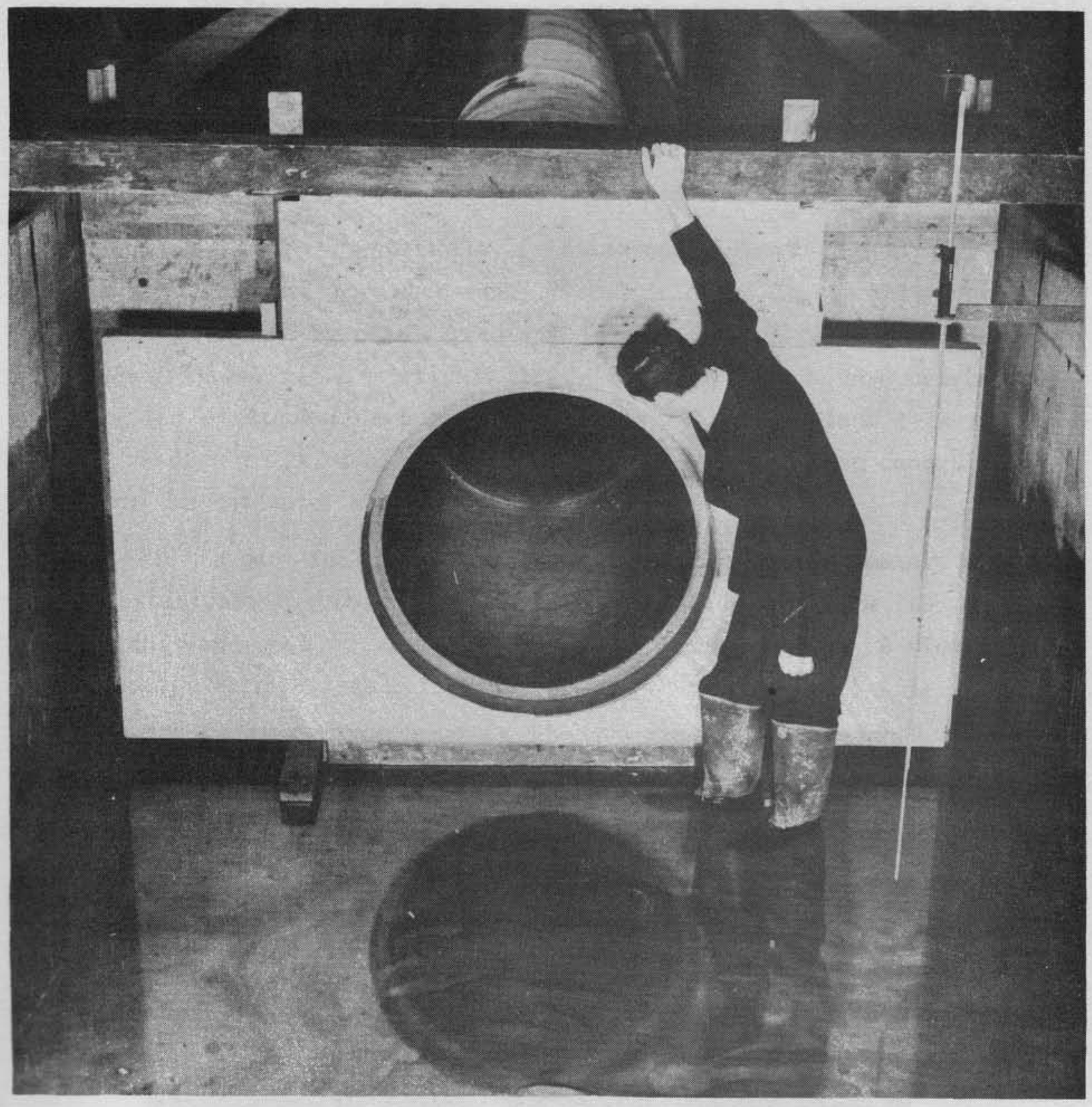

Fig. 2- Flush Headwall at Inlet to 36-in. Concrete Culvert

For each run, careful measurements were made of the discharge, the hydraulic grade line, and the water temperature. The discharge was controlled by gates at the entrance to the testing channel and was usually measured in large volumetric tanks, although weighing tanks or a calibrated supply-line meter were used for some runs. The tailwater level was controlled by a weir gate at the downstream end of the channel in order to adjust the hydraulic grade line. The latter was determined by piezometric measurements at intervals along the pipe, each piezometer tap being connected to a central manometer board, where simultaneous static pressure readings could be observed for all reaches of the pipe.

For details of the experimental apparatus and procedure, Technical Papers No. 4 and No. 5 of this series should be consulted. It is believed that accurate and reliable results have been obtained.

From the experimental data, friction coefficients and entrance coefficients were computed for each run. Barrel friction losses were obtained from the slope of the hydraulic gradient in the central reaches of the pipe where the gradient was a straight line. Entrance losses were obtained by extending the straight-line portion of the hydraulic gradient back to the plane of the pipe inlet, adding the pipe velocity head and then deducting the total from the headwater elevation.

In the part-full flow tests, a condition of approximately uniform flow was established for the particular depth and discharge. Thus, the hydraulic gradient was equal or nearly equal to the culvert slope. A view at the culvert outlet with part-full flow in the barrel appears in Fig. 3.

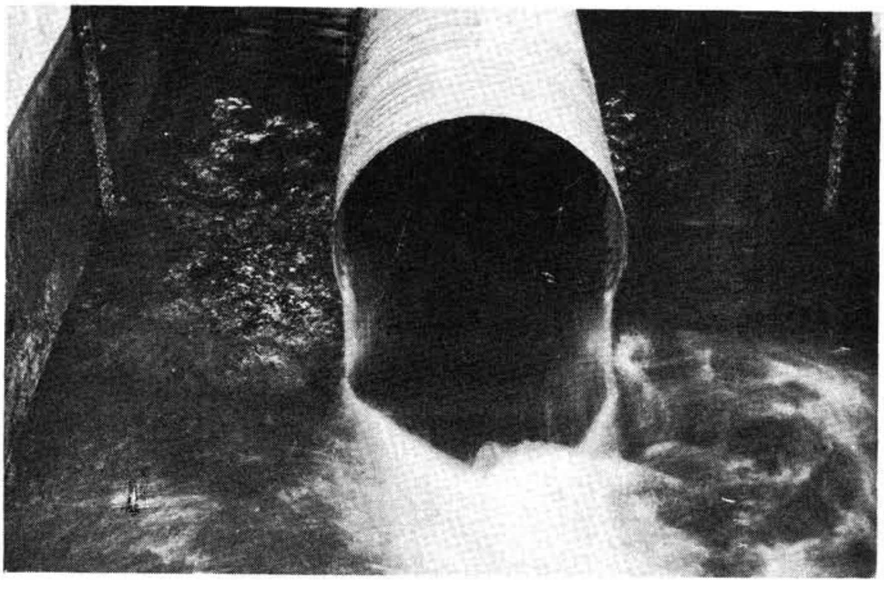

Fig. 3 — Outlet of 36-in. Diameter Corrugated Culvert
(Flowing Partly Full)

In most cases, this condition was also a tranquil flow condition. However, the critical slope for the 36-in. concrete pipe was so near the actual slope of the pipe that near-critical flow was obtained at nearly all depths in this pipe. The resultant excessive waviness and variability of the water surface made it impossible to determine coefficients for the uniform part-full flow condition in this pipe.

Reference may again be made to Technical Papers No. 4 and No. 5 for more detailed explanations of the computational procedures employed.

The experimental rating curves for all of the pipes are shown in Figs. 4, 5, 6, and 7.

IV. ANALYSIS AND DISCUSSION OF RESULTS

A. General Analytic Relations

The general equation defining flow through a culvert is

$$H = K_e \frac{V^2}{2g} + K_f \frac{V^2}{2g} + K_o \frac{V^2}{2g} \tag{3}$$

In this equation, $\underline{H}$ is the difference between total head in the headwater and tailwater pools. If the velocity heads in the pools are small or if they are nearly equal, then $\underline{H}$ may be taken as the difference in elevations between the headwater and tailwater pools. The average velocity of flow, $\underline{V}$, is measured in the central reaches of the pipe where the flow is uniform. The normal barrel friction loss, $K_f\ (V^2/2g)$, is the loss which would occur in an interior reach of a very long hypothetical pipe of the same cross section and material, the reach having a length equal to the length of the actual culvert.

The entrance loss, $K_e\ (V^2/2g)$, is the excess friction loss near the pipe inlet over the normal barrel friction loss in that region. In the experiments described in this paper, the entrance loss was obtained by extending the straight-line portion of the hydraulic grade line to the plane of the entrance, adding the uniform velocity head, and deducting the total from the headwater elevation. Similarly, the outlet loss, $K_o\ (V^2/2g)$, was obtained by extending the hydraulic gradient linearly to the plane of the outlet, adding the velocity head, and subtracting the tailwater elevation from the sum.

The entrance and outlet loss coefficients, K_e and K_o, are usually obtained experimentally for different types of entrances and outlets, although

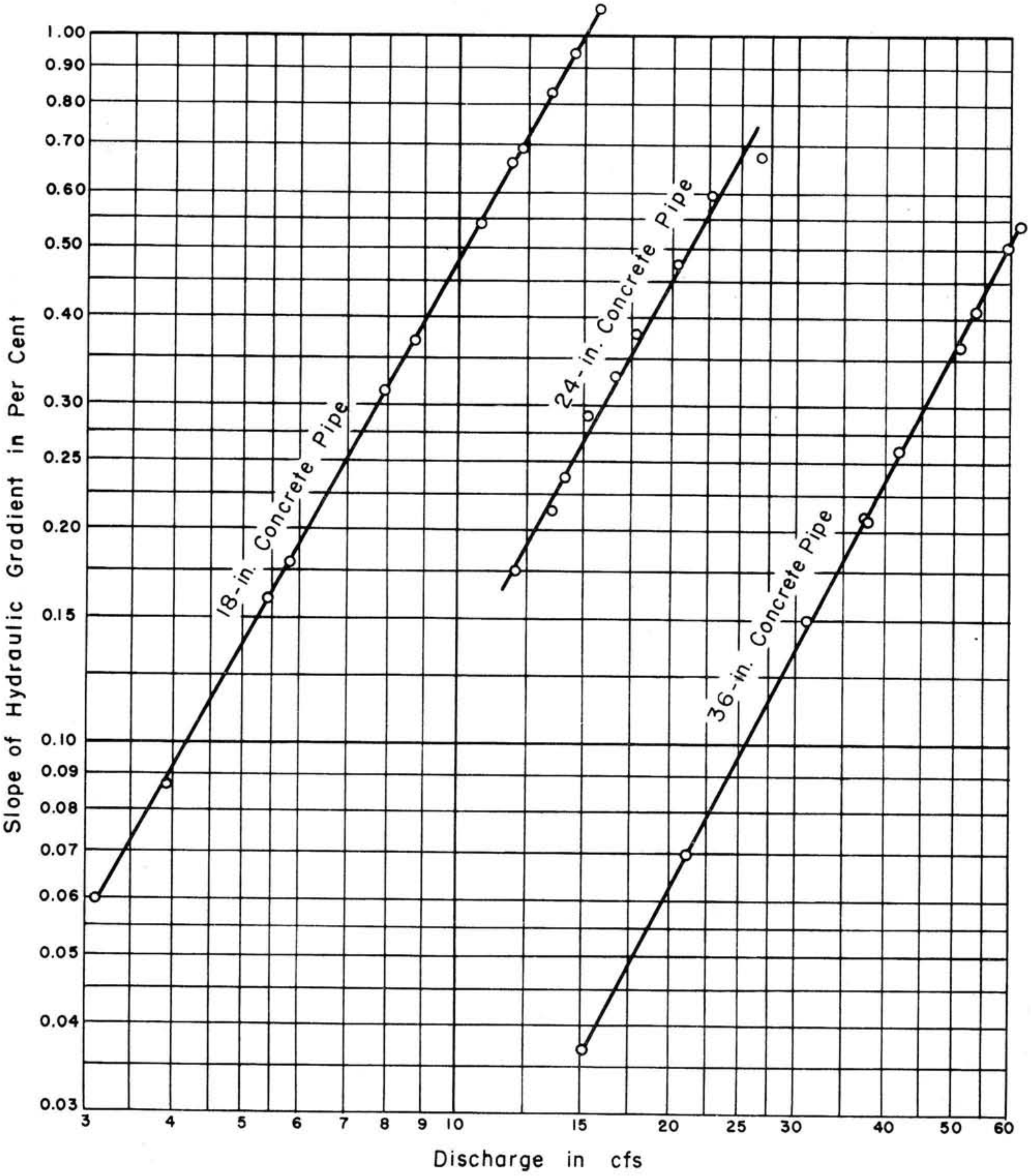

Fig. 4– Experimental Rating Curves
(Concrete Culverts Flowing Full)

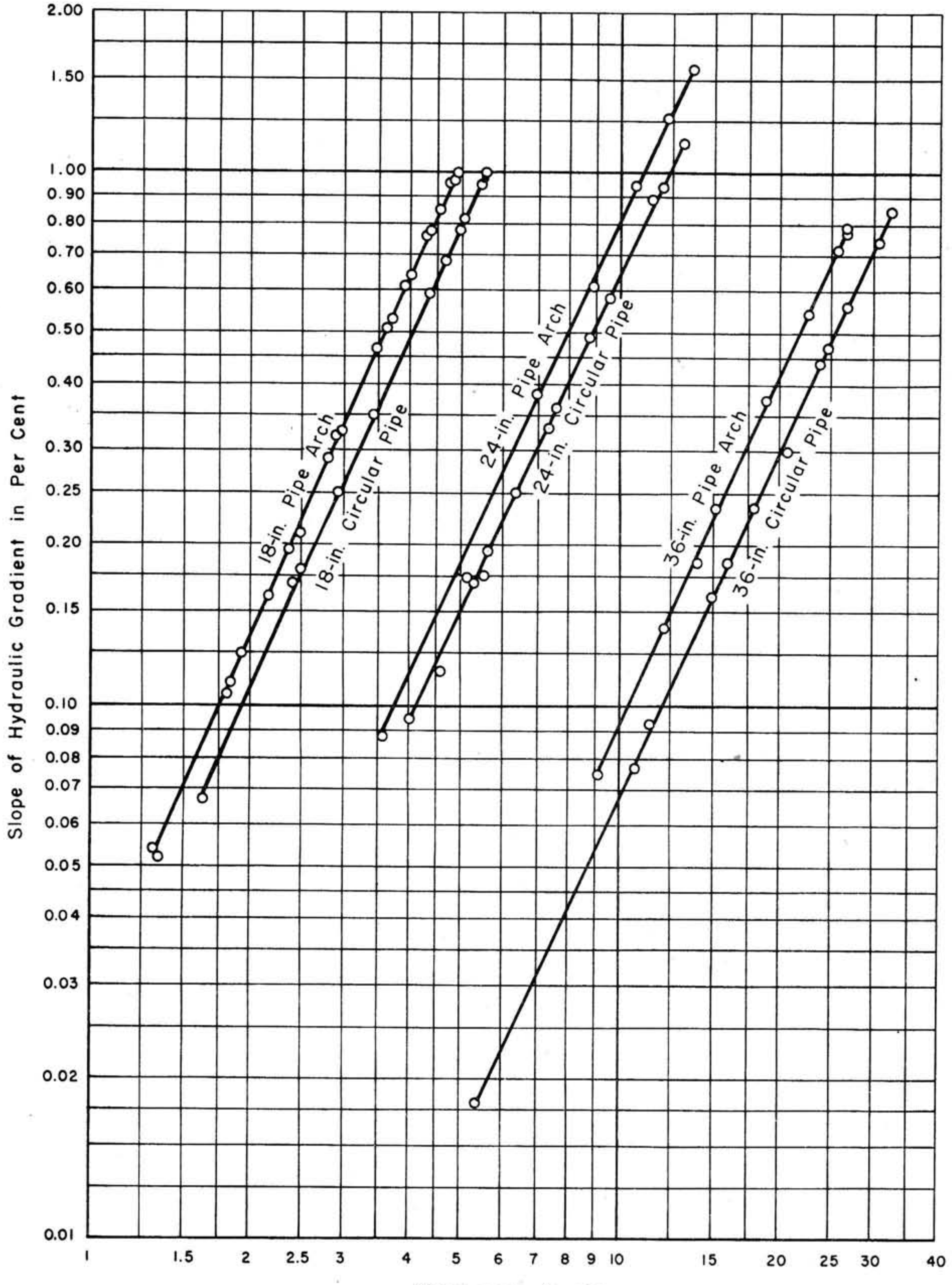

Fig. 5– Experimental Rating Curves
(Corrugated Metal Culverts Flowing Full)

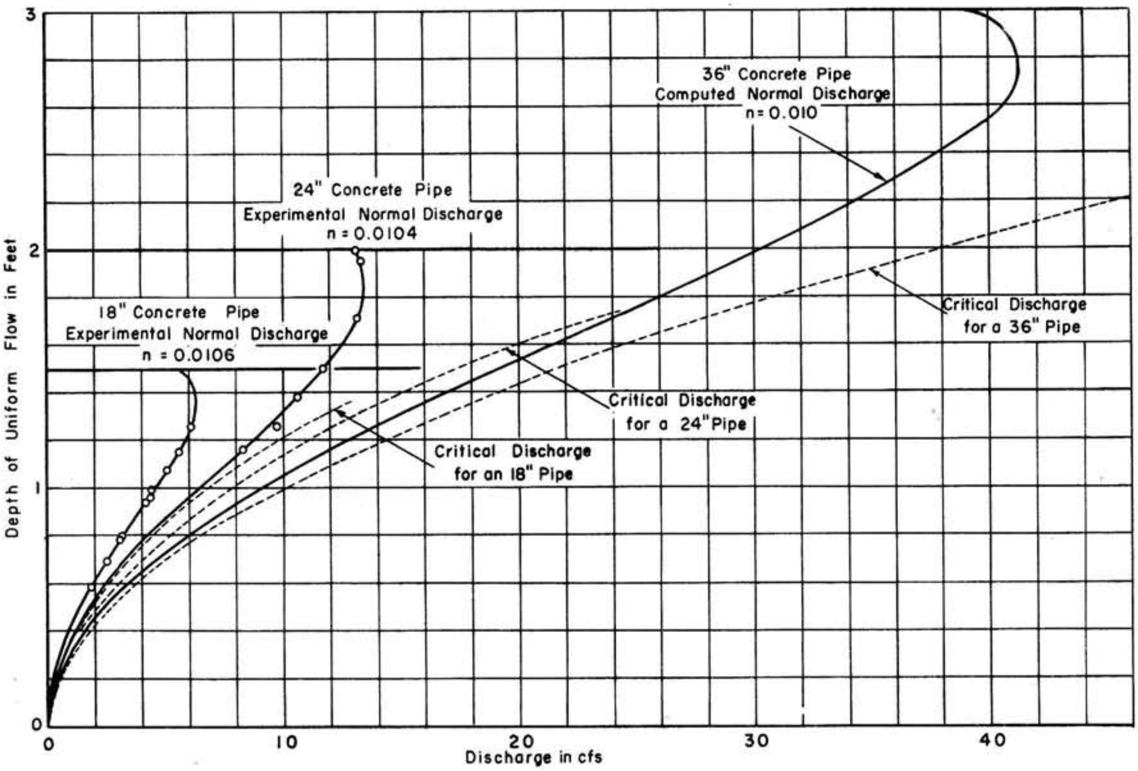

Fig. 6– Experimental Rating Curves
(Concrete Culverts Flowing Partly Full)

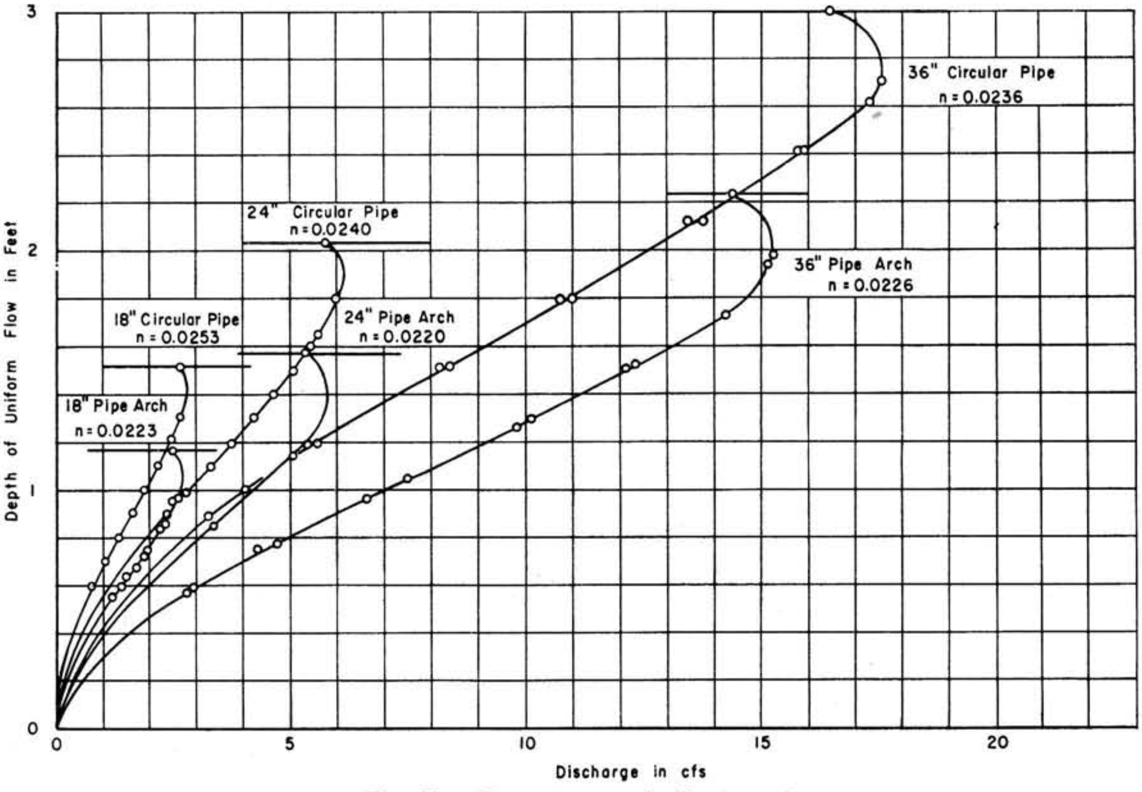

Fig. 7– Experimental Rating Curves
(Corrugated Metal Culverts Flowing Partly Full)

they may be closely computed analytically in many cases from principles of hydrodynamics.

The barrel friction loss coefficient, K_f, is usually expressed in terms of one or more of the various pipe-flow formulas. The most commonly used formulas of this type are the Darcy formula and the Manning formula. The latter formula has already been given as Eq. (1). The Darcy formula is

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

The Darcy friction factor, f, is related to the Manning roughness coefficient, n, by the following:

$$f = 117 \frac{n^2}{R^{1/3}} \tag{5}$$

Both the Manning coefficient and Darcy friction factor can be computed from the measured discharge, cross-sectional dimensions, and hydraulic gradient.

The friction factor is known to be a function of the Reynolds number and the pipe material. The Reynolds number, Re, is defined by the expression

$$Re = \frac{4RV}{\nu} \tag{6}$$

In this expression, the kinematic viscosity, ν, is a fluid property which, for a given fluid, varies with temperature.

The Manning coefficient has commonly been supposed to be dependent only on the pipe material for the usual design flows in engineering conduits. However, the present studies have demonstrated that it is also dependent on the Reynolds number, at least within the usual range of flows in concrete and corrugated metal conduits. This would also be found true with the coefficients of the Scobey, Hazen-Williams, and other empirical pipe-flow formulas.

B. Friction Losses for Full Flow

The Darcy friction factor, f, is known to depend upon the Reynolds number, Re, and the pipe roughness. For pipes of a given material, the absolute roughness is presumed to be the same, regardless of the pipe size. However, the relative effect of a given type of wall roughness on the flow should decrease as the pipe size increases.

It has become common in recent years to use the ratio of equivalent sand diameter to pipe diameter as a measure of the relative roughness of a pipe. The equivalent sand diameter, K_s, is understood to be the diameter of uniform sand grains which could be coated on a smooth pipe of the same diameter as the pipe under consideration and would cause the same friction loss as obtained in the actual pipe. The friction factor can then be written as a function of the Reynolds number and relative roughness, thus:

$$f = \text{fn}\,(\text{Re}, \frac{K_s}{D}) \tag{7}$$

In the laminar and partly turbulent regimes of flow, the wall roughness has no persistent influence upon the flow structure, and thus the friction factor is a function of the Reynolds number only. The functional relation of Eq. (7) is then expressible by the following equations for laminar and partly turbulent (smooth-pipe) flow, respectively:

$$f = \frac{64}{\text{Re}} \tag{8}$$

and

$$f = \frac{1}{(2 \log \text{Re} \sqrt{f} - 0.8)^2} \tag{9}$$

Equation (8) is the Poiseuille equation for viscous flow. Equation (9) is due to Nikuradse and is only one of several semi-empirical equations which have been suggested by various authors to describe the partly turbulent regime, though probably the most generally accepted of such equations.

In the regime of full turbulence, the wall roughness predominates and the friction factor does not vary with increasing Reynolds number. The Nikuradse equation for this regime is:

$$f = \frac{1}{(1.14 - 2 \log \frac{K_s}{D})^2} \tag{10}$$

The transition between the regimes of partial and full turbulence has been largely ignored in most hydraulic design practice heretofore. The traditional empirical pipe design formulas have neglected the effect of viscosity, which implicitly assumes fully turbulent conditions. An equation which has been fairly extensively used for this transitional realm is that of Colebrook and White:

$$f = \frac{1}{\left[1.14 - 2 \log \left(\frac{K_s}{D} + \frac{9.35}{Re \sqrt{f}}\right)\right]^2} \qquad (11)$$

The Colebrook-White curve is asymptotic to the Nikuradse smooth-pipe and rough-pipe curves, as defined by Eqs. (9) and (10), and purports to represent the transitional region of pipe flow as obtained on actual commercial pipes.

The friction factor - Reynolds number curves for the corrugated metal and concrete pipes included in the experiments reported herein are shown in Fig. 8, along with the smooth-pipe curve. Both sets of experimental curves indicate a functional dependence of the friction factor upon both the Reynolds number and the relative roughness, implying that the flow regime is transitional between partial and full turbulence.

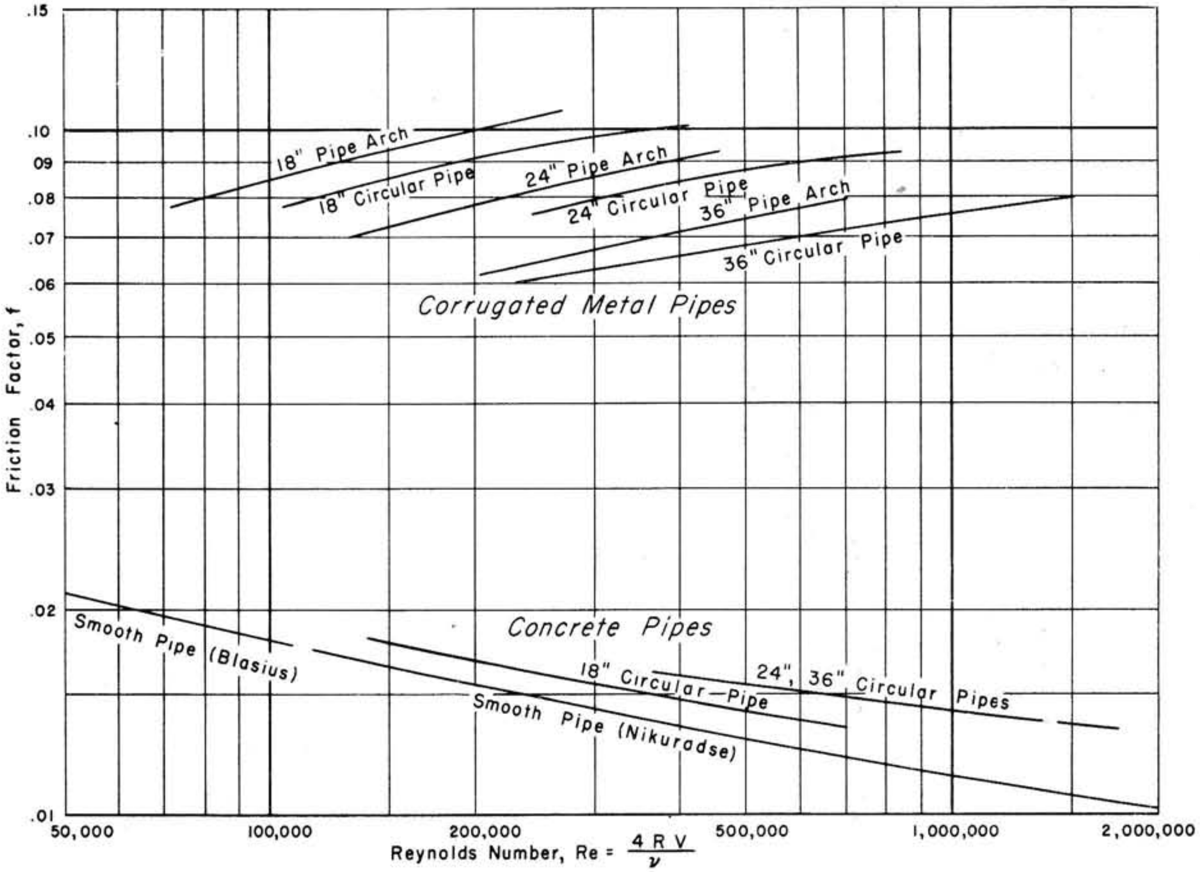

Fig. 8 – Comparison of Friction Factors
(Concrete and Corrugated Metal Culverts)

However, neither the curves for the corrugated pipes nor those for the concrete pipes can be satisfactorily expressed in terms of the Colebrook equation. The corrugated pipes especially gave results contradictory to those that would be expected from the Colebrook equation, since a definite increase in friction factor with increasing Reynolds number was noted for each of them, whereas the equation postulates a decreasing friction factor.

These curves seem to approach the horizontal at high Reynolds numbers, but they all show a rising characteristic throughout the experimental range. Such a rising characteristic was unexpected and is unique among commercial pipes. These results serve to emphasize the fact that pipes with "regular" patterns of roughness may behave quite differently hydraulically from pipes of "random" roughness patterns, for which the Colebrook equation was derived. The detailed hydrodynamics of friction losses in corrugated pipe is still obscure and undoubtedly quite complex, but the essential fact of the rising friction factor - Reynolds number curve for this material is a significant finding of these experiments.

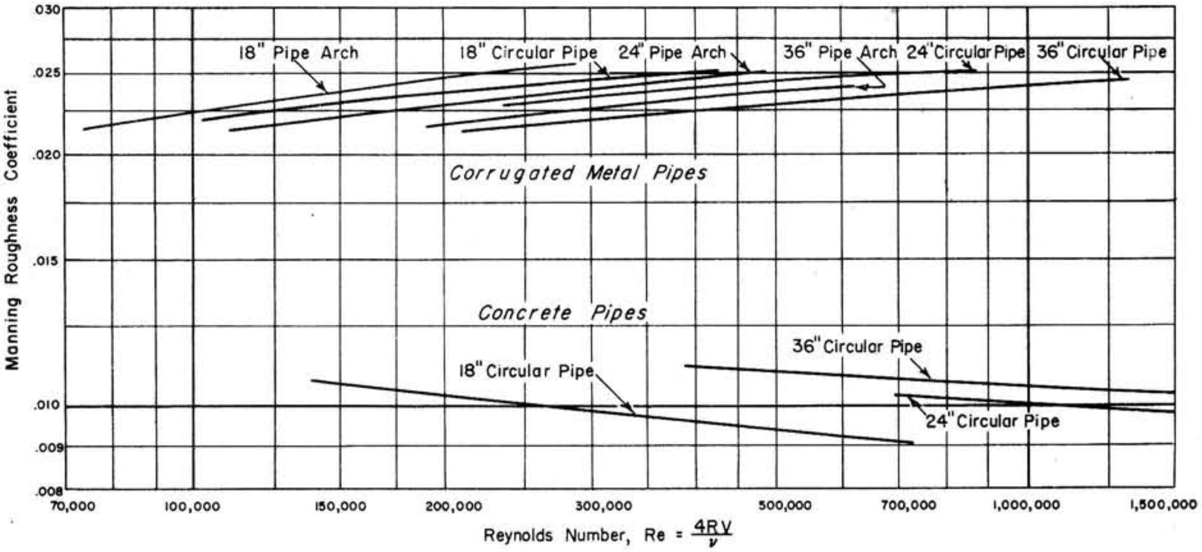

Fig. 9- Comparison of Roughness Coefficients
(Concrete and Corrugated Metal Culverts)

The same type of variation, though not so pronounced, is evident in the curve of experimental values of the Manning coefficient versus Reynolds number for the corrugated pipes, as shown on Fig. 9. Thus, the value of n to be used in the design of a corrugated pipe depends upon both the pipe size and the Reynolds number, and it is not a constant as has been customarily assumed.

The friction factor - Reynolds number curves for the concrete pipes show a falling characteristic, as would be implied from the Colebrook equation. However, they will not yield a constant value of the equivalent sand diameter, K_s, for concrete pipe. Rather, K_s was found to increase with Reynolds number for a given pipe and to increase with the size of pipe.

Thus the Nikuradse and Colebrook equations are inadequate to describe the flow in the pipes studied in these tests, both concrete and corrugated metal. The equivalent sand diameter, K_s, does not appear to serve satisfactorily as a representative length parameter for flow in such pipes.

The Manning coefficient, which has already been noted as varying with Reynolds number and with pipe size for the corrugated pipes, was nevertheless more nearly constant than the Darcy friction factor or than K_s as computed from the Nikuradse or Colebrook equations. Similarly, the Manning coefficient showed some variation with Reynolds number and pipe size for the concrete pipes, but the variation was much less than the variation in f or in K_s. For practical design use, the Manning coefficient still seems to be the most nearly constant measure of surface roughness. Figure 9 shows the Manning coefficient as a function of Reynolds number, giving experimental curves for all the pipes tested.

The values of n for corrugated pipes obtained in the present tests are considerably higher than the value of 0.021 which is commonly used at present. Further, it is important to recognize that, if the experimental facilities had permitted the establishment of flows of still higher Reynolds number in the pipes, still higher values of n would probably have been obtained for such pipes. Consequently, it is strongly urged that n-values used in corrugated pipe design should be selected from the curves of Fig. 9, and that if the design situation lies beyond the present experimental range, an n-value of at least 0.025 be used.

The values of n obtained for the concrete pipes, on the other hand, were lower than previously recommended values. Also, a tendency for n to decrease was noted for increasing Reynolds numbers. Consequently, a recommended value of 0.0110, and possibly as low as 0.0100, for n for new cast-and-vibrated concrete pipe seems warranted by the present experimental results.

The question as to how much, if any, these recommended n-values for both concrete and corrugated metal should be increased to allow for deterioration with age, for leakage, and other factors can be settled only on the basis of the individual conditions under which a particular pipe will be serving and will depend largely on the judgment of the designer.

C. Friction Losses for Part-Full Flow

The Manning coefficient was found to be very nearly constant for the condition of part-full, uniform, tranquil flow in a given type of pipe. The small variations that were noted were of an order of magnitude corresponding to possible random experimental variations.

For the corrugated pipes, the average n for part-full flow was 0.0234. No systematic variation with Reynolds number or with depth of flow was apparent, although it is possible that such variations may have existed but tended to offset each other. A small effect due to shape of section was noted. The average n for the pipe arch sections was 0.0224 and for the circular sections was 0.0242. For the circular sections, the Manning coefficient evidenced a slight decrease as the pipe diameter increased.

For the concrete pipes, the average n for part-full flow was 0.0106 and there was a very small range of variation from this average. For the 18-in. pipe, there seemed to be a slight systematic decrease in n as the depth of flow (and consequently the Reynolds number) increased, but this tendency was not observed on the 24-in. pipe, perhaps because of the greater magnitudes of experimental variations on this pipe. It was not possible to obtain part-full flow data on the 36-in. pipe because of the proximity of the pipe slope to the critical slope for most discharges in the pipe, a fact which resulted in troublesome waviness and instability on the water surface in the pipe and precluded dependable measurements.

For practical design purposes these small variations may be considered negligible. Reasonable recommended values of n for uniform tranquil flow appear to be 0.0240 for corrugated pipes and 0.0110 for concrete pipes of the type tested, assuming new, well-laid pipe without projecting elements.

D. Entrance Losses

The entrance loss is understood to be the excess of actual energy loss in the entrance region of a pipe over that which would be caused by normal pipe friction over the same length of pipe. The entrance loss is not confined to a small region right at the entrance, but it is spread over a length of pipe of at least several diameters. It is caused largely by re-expansion of the contracted jet of entering water. Much of the kinetic energy of the high-velocity entering jet forms excessive rotational turbulence in the flow when it approaches an adverse pressure gradient in expanding to fill the pipe. This excess turbulence is gradually damped out as the flow moves downstream. Simultaneously, development of the normal turbulent boundary layer is taking place from the pipe wall outward to its center.

If the entrance loss is written as an entrance coefficient multiplied by the velocity head of flow in the pipe, the most important factor governing the magnitude of the coefficient is the geometry of the entrance lip. The form of entrance controls the amount of contraction and therefore the amount of re-expansion and excess turbulence.

The chief item in the reduction of entrance loss is therefore the design of the entrance to reduce the entrance contraction. This can be done by rounding or beveling the entrance, or by providing some other approach transition.

The contraction will be greatest when the pipe entrance projects into the headwater pool and when the pipe thickness is small, that is, with a sharp-edged entrance. This condition is approached at the entrance to a corrugated pipe with a re-entrant inlet. The St. Anthony Falls Laboratory experimental values for the entrance coefficient for projecting corrugated pipe inlets were close to the theoretical value of 1.00 for re-expansion loss in such a situation. The average value obtained was 0.85. The slight rounding of the entrance due to the initial corrugation sufficed to cause the reduction from the theoretical value.

When a flush headwall inlet is used, the contraction is reduced. The theoretical re-expansion loss for a sharp-edged inlet is approximately

$0.41\ (V^2/2g)$, and this could be expected to decrease due to the rounding at the first corrugation, the amount depending somewhat on the pipe diameter. The St. Anthony Falls Laboratory tests for this condition indicated an average coefficient of 0.49, which was higher than expected. However, the data are dependable, without excessive scatter, and it appears necessary to recommend about 0.50 for K_e for corrugated pipes with flush inlets. A value of K_e of about 0.90 should be used for corrugated pipes with projecting inlets.

Entrance loss coefficients for concrete pipes are considerably lower than those for corrugated pipes. Concrete pipes are commonly made with either bell-and-spigot or tongue-and-groove type joints, laid with the bell or groove end upstream. This has the effect of an increased diameter at the culvert entrance from which the contraction is initiated, and therefore, less re-expansion is required from jet diameter to normal pipe diameter. The entrance loss coefficient depends somewhat on pipe diameter and the amount of widening at the joint, but average values can be used with sufficient accuracy.

Furthermore, the pipe wall thickness is almost sufficient to serve as a flush headwall when the pipe projects into the headwater. Consequently, the entrance loss coefficient for concrete pipe culverts is affected very little by whether the pipe has a projecting or flush inlet. On the basis of the experimental results, a value of 0.15 has been recommended for projecting concrete pipe inlets and 0.10 for flush inlets.

When the headwater elevation drops below the inlet crown, a part of the entering jet contraction is removed, constraint at the water surface is removed, and therefore the entrance loss coefficient becomes smaller. However, the entrance coefficients for concrete pipe are so small as to be subject to large relative inaccuracies. The present experimental data do not appear to warrant design values of K_e less than 0.15 and 0.10 for projecting and flush concrete pipe inlets, respectively, for part-full flow conditions, even though these are the same values recommended for full flow.

For corrugated pipes, however, a material reduction of the entrance coefficients was obtained when the culvert flowed only partly full. Recommended design values for this condition are 0.70 and 0.40 for projecting and flush inlets, respectively.

The above entrance coefficients apply only if the flow in the pipe is subcritical. Supercritical slopes and velocities are accompanied by much higher entrance coefficients when applied to the normal part-full flow condition.

E. Outlet Losses

Theoretically, the outlet loss for a pipe discharging into a relatively quiescent tailwater pool is equal to the velocity head of the flow in the pipe at its exit, for both full and part-full flow.

Under certain conditions, part of this exit velocity head may be conserved and converted into useful head in the outlet channel flow. This will be true especially when the outlet channel is relatively narrow, as was the case in the experimental installation.

The outlet loss coefficient was found to average about 0.90 for full flow in both concrete and corrugated pipes. Determinations of outlet loss were not made for the part-full condition, but they would undoubtedly be about the same, provided the coefficient was determined with reference to the actual exit velocity head.

For design purposes the outlet coefficient normally should be taken equal to unity, unless a specially designed, flared-outlet section is used.

F. Comparison of St. Anthony Falls Laboratory Results with Other Data

The test results reported in this paper have considerably extended previous knowledge on the hydraulics of concrete and corrugated metal pipes. The most dependable data on this subject prior to the new results were obtained in a series of studies conducted at the University of Iowa over a period of several years ending in 1924[*]. The Iowa tests were made on concrete and corrugated pipes 12, 18, 24, and 30 inches in diameter, with lengths varying from 24 to 36 ft.

Values of the Manning and Kutter roughness coefficients, as obtained in these tests[**] are given in Table IV.

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[*] D. L. Yarnell, F. A. Nagler, and S. M. Woodward, The Flow of Water Through Culverts, (University of Iowa Studies in Engineering, Bulletin 1, June, 1926).

[**] Ibid, p. 55.

TABLE IV

AVERAGE ROUGHNESS COEFFICIENTS, IOWA TESTS ON CULVERT PIPES

Pipe Diam (in.)	Concrete Pipe		Corrugated Metal Pipe	
	Kutter n	Manning n	Kutter n	Manning n
12	0.0117	0.0119	0.0194	0.0228
18	0.0121	0.0121	0.0217	0.0248
24	0.0130	0.0130	0.0216	0.0239
30	0.0127	0.0125	0.0232	0.0254

The Kutter coefficient was computed from the Kutter formula

$$Q = A\sqrt{RS}\,\frac{41.65 + \frac{0.00281}{S} + \frac{1.811}{n}}{1 + \left(41.65 + \frac{0.00281}{S}\right)\frac{n}{\sqrt{R}}} \tag{12}$$

The Manning formula, which has largely superseded the Kutter formula, was originally designed with the intent that its roughness coefficient would be the same as the Kutter roughness coefficient for a given pipe or open-channel material. As is evident from Table IV, this interchangeability of coefficients is satisfactory for the low values of n associated with concrete pipe.

For corrugated pipe, the Manning n is considerably higher than the Kutter n, so that they cannot be used interchangeably. However, it appears that they were used interchangeably in subsequent design literature for corrugated pipe. The average Kutter n for corrugated pipe is about 0.021 as indicated by the Iowa tests and also by other studies, whereas the average Manning n was about 0.024. Most corrugated culvert manufacturers recommend a Manning coefficient of not more than 0.021 for use in design of corrugated pipe culverts and sewers*.

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*For example, Handbook of Culvert and Drainage Practice, by Armco Drainage and Metal Products, Inc. (Indiana: R. R. Donnelley & Sons Company, 1947) pp. 209-13.

The St. Anthony Falls Laboratory tests confirm the fact that an n of 0.021 for corrugated pipe is much too low. A value of n of at least 0.025 is recommended on the basis of present knowledge.

Previously recommended values of n for concrete pipe have, however, been higher than the values obtained in the St. Anthony Falls Laboratory tests. The Iowa tests indicated that n averaged about 0.0125 for concrete culverts flowing full, whereas the St. Anthony Falls Laboratory tests justify a value as low as 0.0100 for new concrete pipe of the type tested. It is probable that methods of manufacture of precast concrete pipe have sufficiently improved in the two decades that have elapsed since the Iowa tests and other significant tests on concrete culvert pipe to produce surfaces of a higher degree of smoothness and better joints than were then obtainable.

The American Concrete Pipe Association, on the basis of previous tests and recommendations by various authors, has until now recommended an n of 0.013 for use in the Kutter or Manning formulas. In view of the new results, it appears that this value is quite conservative, unless a considerable increase in roughness with age of the culvert is to be anticipated, or unless the pipe manufacturing process employed is such as to produce a materially rougher surface than in the experimental pipes.

The Iowa tests, which were the most extensive and significant tests available prior to the St. Anthony Falls Laboratory tests, did not reveal the very significant trends in friction factor and roughness coefficient with Reynolds number that the present tests have brought to light. No measurements of water temperature were reported for the Iowa tests, so that it is not possible to compute accurate values of the Reynolds number for those tests. In view of this fact, certain trends that might have been inferred from the Iowa tests, such as variation of n with discharge or pipe diameter, cannot be substantiated.

Furthermore, the Iowa investigations did not include a study of part-full flow conditions in culverts. There have been a few tests reported, however, on concrete pipes flowing partly full*. These have sometimes indicated that the friction factor or roughness coefficient is slightly greater for part-full flow than for full flow, and that it usually exhibits a slight

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*C. F. Johnson, "Determination of Kutter's n for Sewers Partly Filled," Transactions, American Society of Civil Engineers, Vol. 109, (1944), pp. 223-47. Especially see discussion by T. R. Camp, R. G. Coulter, and C. E. Ramser.

increase as the depth of uniform flow decreases. A slight tendency of this kind was also noted on the 18-in. pipe in the present tests.

In considering this phenomenon one must recognize that actually one is comparing flow conditions which are geometrically dissimilar and that the arbitrary use of the hydraulic radius as the linear dimension of comparison is only an approximation which has been found to give acceptable results.

No part-full flow tests in corrugated pipes of the nature discussed in this report, seem to have been published previously. A few tests have been reported on corrugated metal flumes. R. E. Horton has given n-values for such flumes ranging from 0.0225 to 0.0300.

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GLOSSARY

A = Cross-sectional area of flow, sq ft

D = Pipe diameter, ft

f = Darcy friction factor

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

H = Total head on culvert, ft

H_e = Entrance head loss, ft

H_f = Friction head loss, 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

Re = Reynolds number = $\frac{4RV}{\nu}$

n = Manning roughness coefficient

Q = Rate of flow, cfs

R = Hydraulic radius, ft

S = Slope of hydraulic gradient

V = Average velocity of flow, fps

ν = Kinematic viscosity, sq ft/sec