Design Data 10

American Concrete Pipe Association

Manning's *n* Values History of Research

INTRODUCTION

Selection of the proper value for the coefficient of roughness of a pipe is essential in evaluating the flow through culverts and sewers. An excessive value is uneconomical and results in oversizing of pipe, while equally, a low value can result in hydraulically inadequate pipe. Proper values for the coefficient of roughness of commercially available pipe has been the objective of periodic investigations and, as a result, extensive knowledge and data are available on this often controversial subject. To the designer, the presently accepted values for the coefficient of roughness are of great importance. Of equal importance is an understanding of how these values were determined. Research often indicates new values for pipe materials significantly different from those previously used.

DESIGN VALUES

The difference between laboratory test values of Manning's *n* and accepted design values is significant. Numerous tests by public and other agencies have established Manning's *n* laboratory values. These laboratory results, however, were obtained utilizing clean water and straight pipe sections without bends, manholes, debris, or other obstructions. The laboratory results indicated the only differences were between smooth wall and rough wall pipes. Rough wall, such as unlined corrugated metal pipe have relatively high *n* values which are approximately 2.5 to 3 times those of smooth wall pipe.

Smooth wall pipes were found to have *n* values ranging between 0.009 and 0.010 but, historically, engineers familiar with sewers have used 0.012 or 0.013. This "design factor" of 20-30 percent takes into account the difference between laboratory testing and actual installed conditions. The use of such design factors is good engineering practice and, to be consistent for all pipe materials, the applicable Manning's *n* laboratory value should be increased a similar amount in order to arrive at comparative design values. Recommended design values are shown in Table 1.

Table 1 Recommended Values of Manning's *n*

Pipe Material	Values of Manning's *n*		
	Lab Values	Promoted Values	ACPA Recommended Values
Concrete	0.009-0.010[1]	0.010-0.012[1]	storm sewer - 0.011-0.012[1] sanitary sewer - 0.012-0.013[1]
HDPE lined	0.009-0.015[2]	0.009-0.013[3]	storm sewer - 0.012-0.020[2]
PVC solid wall	0.009-0.011[4]	0.009[4]	storm & sanitary sewer - 0.011-0.013[2]
Corrugated Pipe	0.012-0.030[5]	0.012-0.026[6]	0.021-0.029[7]

1 American Concrete Pipe Association's "Concrete Pipe Design Manual" - 2000
2 Tullis and Barfuss Study - 1989
3 CPPA Specifications
4 Uni-Bell's "Handbook of PVC Pipe" - 2001
5 University of Minnesota test on Culvert Pipes - 1950
6 NCSPA'S "Modern Sewer Design" - 1999
7 U.S. Department of Transportation Federal Highway Administration's "Hydraulic Design of Highway Culverts" - 2001

FLOW FORMULAS

The Kutter flow formula was developed about 1870 and extensively used for many years to calculate pipe flows. Roughness coefficient values for use in the Kutter formula were derived and are known as Kutter *n* values. The Kutter formula was mathematically cumbersome, even though charts and graphs were developed as design aids.

The simpler Manning formula, developed in 1890, has generally replaced the Kutter formula in use. Manning's formula, in terms of flow, is expressed as follows:

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

where: Q = flow in pipe, cubic feet per second
A = cross-sectional area of flow, square feet
R = hydraulic radius, equal to the cross-sectional area of flow divided by the wetted perimeter of pipe, feet
S = slope of pipe, feet per foot
n = coefficient of roughness appropriate to the type of pipe

The Manning formula factors are similar to those in Kutter formula and are expressed in the same units. Values for the coefficient of roughness, *n*, were at first thought to be the same as those used in the Kutter formula but this assumption has been proven to be wrong.

MANNING *n* VALUE RESEARCH

As the Manning formula came into more common use, the direct interchange of *n* values with Kutter's was questioned. A series of studies, prior to 1924, at the University of Iowa provided the first extensive data on this disputed point. These were cooperative studies sponsored by the Bureau of Public Roads, U.S. Department of Agriculture, and the University of Iowa. The test program consisted of 1,480 hydraulic experiments on 12, 18, 24 and 30-inch concrete pipe, corrugated metal pipe, and clay pipe. Results of these tests were published in 1926 by the University of Iowa in Bulletin No. 1, "The Flow of Water Through Culverts," by David L. Yarnell, Floyd A. Nagler and Sherman M. Woodward. Values obtained from the test results for Manning and Kutter roughness coefficients, are given in Table 2. After the Iowa test results were published, many designers re-evaluated the *n* values for Manning's formula and used 0.013 for smooth wall pipe and 0.024 for corrugated pipe. These values were not universally accepted, however, and other designers used *n* = 0.015 for concrete and clay pipe. Metal pipe manufacturers were advocating *n* = 0.021 for corrugated metal pipe, and some designers still erroneously use this comparatively low value for corrugated pipe today.

HDPE PIPE

Research by Tullis and Barfuss in 1989, presented to the American Society of Civil Engineers showed that tests on corrugated HDPE pipe with a liner has a laboratory Manning's *n* value in the range of 0.009 to 0.015, depending on the condition of the liners. The bonding of the liner to the corrugations, in many cases, made the pipe interior wavy, explaining the broad range in *n* values. This waviness causes the HDPE pipe to have hydraulic values similar to CMP. Manning's *n* concerns regarding HDPE pipe, however, are not widely understood because the pipe has never been tested under an external load, and further research is required. Because of the broad range of *n* values, an *n* value of 0.012 for HDPE pipe will not provide a 20 to 30 % factor of safety and is not recognized by the FHWA and the Army Corps of Engineers.

Frequently the inner liner of a double wall (profile) wall HDPE pipe undergoes a phenomenon called corrugation growth. After a short period of time, sometimes prior to installation, plastic deformation occurs in the liner creating waviness that makes the interior of HDPE pipe appear similar to corrugated metal pipe. The inner lining is intended to produce a smooth-walled pipe, however, a corrugated pattern results when stresses are transferred from the outer corrugated wall to the inner liner. The smooth liner is unable to resist stresses from the outer wall and corrugation growth appears. Designers of piping systems utilizing lined HDPE pipe should size the pipe using a Manning's *n* value similar to that of corrugated metal pipe.

COMPARATIVE TESTS FOR CONCRETE AND CORRUGATED METAL PIPE

The next significant investigation of Manning *n* values for pipe began in 1946 and continued over a four-year period at St. Anthony Falls Hydraulic Laboratory, University of Minnesota. A primary purpose of these large-scale tests was to obtain pipe friction coefficients which would be more accurate and dependable. A total of 181 hydraulic tests were run on 18, 24, and 36-inch circular concrete pipe and corrugated metal pipe, and corrugated metal pipe

Table 2 University of Iowa Tests on Culvert Pipe - 1926. Average Values for the Coefficient of Roughness in Concrete, Vitrified-clay, and Corrugated Metal, Culvert Pipe

Diameter of Pipe Inches	Kutter Coefficient			Manning Coefficient		
	Concrete	Clay	Metal	Concrete	Clay	Metal
12	0.0117	0.0101	0.0194	0.0119	0.00998	0.0228
18	.0121	.0119	.0217	.0121	.0118	.0248
24	.0130	.0127	.0216	.0130	.0125	.0239
30	.0127	.0131	.0232	.0125	.0131	.0254

Notes on pipe used in the Iowa tests: The 12" and 18" concrete pipe were in 2-foot lengths. The 24" and 30" concrete pipes were in 3-foot lengths. The vitrified-clay pipes were all in 30-inch lengths. Corrugated metal pipes were supplied in 6 and 8-foot lengths. Corrugated metal pipe had a 1/2 x 2-3/4 inch corrugation pattern. Joints in the concrete pipe where made with cement mortar. Joints in the vitrified-clay pipe amde with oakum and cement mortar.

Table 3 University of Minnesota Test on Culvert Pipes - 1950. Summary of Test Results								
Type and Size of Pipe	Pipes Flowing Full				Pipes Flowing Partly Full			
	No. of Tests	Manning Roughness Coefficient			No. of Tests	Manning Roughness Coefficient		
		Maximum	Minimum	Average		Maximum	Minimum	Average
18-inch corrugated	11	0.0251	0.0222	0.0242	8	0.0258	0.0248	0.0252
24-inch corrugated	13	0.0252	0.0228	0.0242	10	0.0244	0.0232	0.0240
36-inch corrugated	12	0.0247	0.0216	0.0232	14	0.0243	0.0228	0.0236
Group	36	0.0252	0.0216	0.0239	32	0.0258	0.0228	0.0242
18-inch corrugated arch	23	0.0255	0.0210	0.0239	10	0.0233	0.0216	0.0223
24-inch corrugated arch	7	0.0245	0.0217	0.0236	3	0.0228	0.0213	0.0220
36-inch corrugated arch	9	0.0240	0.0216	0.0232	13	0.0230	0.0221	0.0226
Group	39	0.0255	0.0210	0.0237	26	0.0233	0.0213	0.0224
18-inch concrete	12	0.0108	0.0091	0.0097	10	0.0110	0.0102	0.0107
24-inch concrete	9	0.0104	0.0093	0.0100	6	0.0108	0.0102	0.0104
36-inch concrete	11	0.0108	0.0103	0.0106				
Group	32	0.0108	0.0019	0.0101	16	0.0110	0.0102	0.0106

NOTE: From Technical Paper No. 3, Series B

arches for the full flow and partly full flow conditions. Many of the shortcomings of previous hydraulic tests were eliminated in the Minnesota tests. Culvert test lengths were 193 feet, which were longer and more representative of actual installation conditions. Pipe section lengths were closer to actual commercial lengths, particularly for concrete pipe, with six-foot sections being used instead of the two-foot and three-foot lengths used in the 1926 Iowa test. The test results were published in 1950 by the University of Minnesota in *Technical Paper No. 3, Series B*, "Hydraulic Data Comparison of Concrete and Corrugated Metal Pipes" by Lorenz G. Straub and Henry M. Morris and are as shown in Table 3. These results indicate a significantly lower value of Manning's *n* for concrete pipe than the 1926 Iowa tests. *Technical Paper No. 3* also included recommended design values for *n* for both corrugated metal and concrete pipe as reproduced in Table 4. Comparing the values from Tables 2, 3 and 4, it is readily apparent that no safety factors were applied to the laboratory values when converting them to design values. The footnote beneath Table 4, however, qualifies the application of the recommended values to such an extent that they could not be used for realistic pipe installation. As previously discussed, laboratory values should not be used for design purposes without appropriate safety factors.

During the period 1960-1962, research was conducted in Canada to determine design values of *n* for pipe used in culvert construction. The research was under the auspices of the Cooperative Highway Research Program in Alberta, which included the provincial Department of Highways, the Research Council of Alberta, and the Faculty of Engineering of the University of Alberta as participating bodies. Tests were made on field installations of 60-inch structural plate corrugated metal pipe culverts 70 and 150-feet long

Table 4 University of Minnesota Tests on Culvert Pipe - 1950. Recommended Design Coefficients of Corrugated Metal and Concrete Culverts

Items	Corrugated Metal*	Concrete*
Manning coefficient of roughness, n, full flow	0.0250	0.0100
Manning coefficient of roughness, n, partly full flow	0.0240	0.0110

NOTE: From Technical Paper No. 3, Series B - Table III, Page 5

*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-inch height and 2-2/3 inch spacing. The Manning coefficients for concrete apply to pipe manufactured by the cast-and-vibrated process in 6-foot lengths of pipe and with non-pressure rubber ring joint.

with various inlet shapes and slopes from 1 to 3 percent, and on a 48-inch concrete pipe culvert 78-feet long on a slope of 0.5 percent. Laboratory tests were conducted on 15-inch diameter standard corrugated metal pipe 36 and 724-feet long with slopes from 0 to 8 percent. Test results were published by the Research Council of Alberta in the 1962 Alberta Highway Research Report 62-1 titled "Hydraulic Tests on Pipe Culverts" by C. R. Neill. Summaries of the Manning n values computed for the 60-inch structural plate pipe are quoted as follows:

"The *n* values computed from 33 tests showed a normal type of statistical scatter, with a mean of 0.0357 and a standard deviation of 0.0025. Pending further tests, the value of 0.035 was adopted for structural plate corrugated metal pipe."

Manning *n* values determined for the 15-inch standard corrugated metal pipe, are quoted as follows:

"Values ranged from 0.021 at very low velocities to 0.025 at high velocities. It appeared that 0.026 was probably a peak value and that 0.025 was reasonable for design purposes."

Additional quotes as to values of Manning's *n* for concrete pipe are as follows:

"No determination was made of roughness coefficients, since the pipe was too short and smooth to show appreciable friction losses."

As one purpose of the experiments was to determine the possible hydraulic advantages of using concrete pipe instead of corrugated metal pipe, the following statements from the test report are significant:

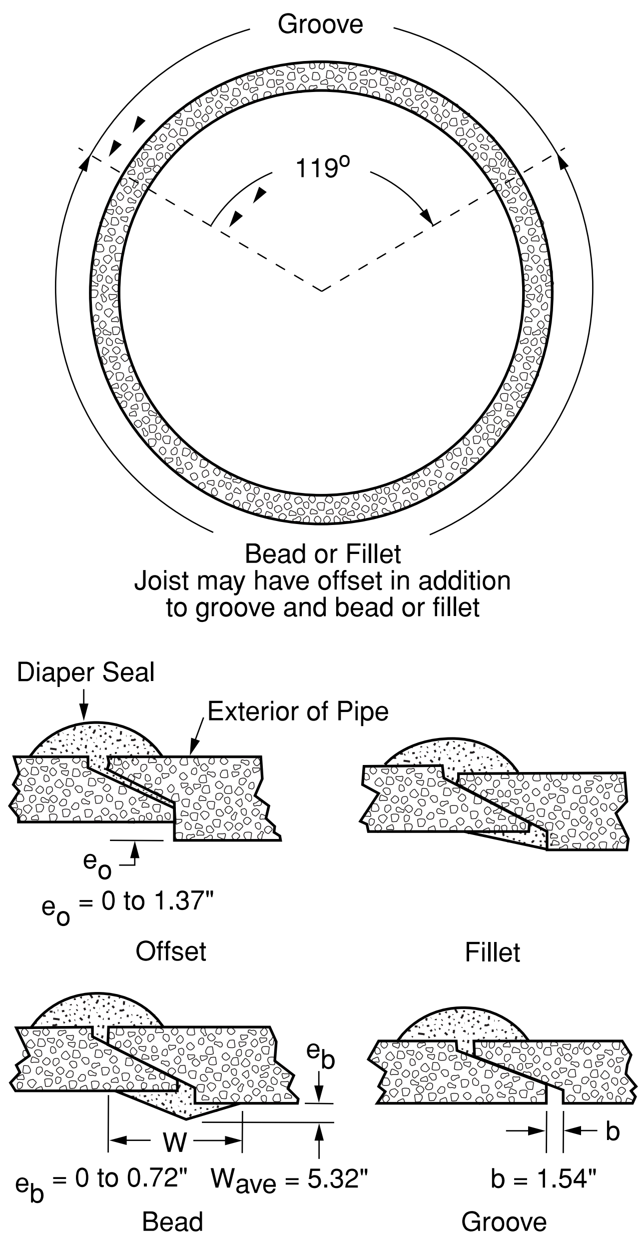
"By comparison, it can be seen that the capacity of the 48-inch concrete culvert was approximately the same as that of the 60-inch structural plate corrugated metal one, of approximately the same length. At the upper end of the test range, the concrete culvert showed rather better performance."

"The tests on concrete pipe culvert showed that a concrete culvert of given diameter was considerably more efficient than a corrugated metal one in most design situations especially when subjected to high headwater depths, the main reason being the much smaller friction losses in the concrete pipe. It appeared that concrete culverts prime readily when their inlets are slightly submerged, and may then be assumed to flow full throughout, and also that the standard type of grooved inlet is quite efficient."

CONCRETE PIPE TESTS

In addition to those previously discussed, other tests have been performed on concrete pipe. In June 1956, experimental studies on 24 and 36-inch concrete pipe were initiated by the State Road Department of Florida to determine the effect of interior surface finishes and joint irregularities on the pipe coefficient of friction. The test program was expanded in May 1957, placed under joint sponsorship of the State Road Department of Florida and the Bureau of Public Roads, and studies were performed at St. Anthony Falls Hydraulic Laboratory, University of Minnesota. This series of tests is significant in that field laying conditions were simulated, a condition designers found lacking in other hydraulic studies. Laboratory test installations were 240-feet long for the 36-inch pipe and 192-feet for the 24-inch pipe. Tests were made on pipe installed in two ways: (1) pipe laid with normal construction practices and closely simulating field measurements of joint irregularities, and (2) pipe laid with extreme care to eliminate, as far as possible, all flow interference at

Figure 1 Cross-Section of Concrete Pipe Test Joints



the joints. The first condition was referred to as "average" joints and the second as "good" joints. Figure 1 illustrates the irregularities noted in field joints and a cross section of the pipe showing the average circumferential length of grooves and beads. Joint irregularities were of three basic types:

- offsets-due to misalignment or variation in diameter of pipe.
- grooves-formed by annular openings between tongue and groove ends of pipe.
- beads and fillets-formed by mortar smoothed over the interior surface of the joint.

Results of this series of tests were published in December 1960, by St. Anthony Falls Hydraulic Laboratory, University of Minnesota, *Technical Paper No. 22, Series B*, titled "Resistance to Flow in Two Types of Concrete Pipe" by Lorenz G. Straub, Charles E. Bowers and Meir Pilch. A comparison of the test data for pipe with "good" and "average" field irregularities indicates a difference in Manning's *n* on the order of 1.9 percent. Numerical values of n for 36-inch and 24-inch pipe with "average" joints were 0.0111 and 0.0110, respectively and, as a result, ASTM Specification C76 was written to require, "the joints shall be of such design and the ends of the concrete pipe sections so formed that when the sections are laid together they will make a continuous line of pipe with a smooth interior free from appreciable irregularities in the flow line."

In the mid-1980's, laboratory tests of concrete and plastic pipe were conducted at the T. Blench Hydraulics Laboratory, Department of Civil Engineering, The University of Alberta. A report by D.K. May, A.W. Peterson and N. Rajaratnam, "A Study of Manning's Roughness Coefficient for Commercial Concrete and Plastic Pipe", was published in January, 1986. Commercially available concrete pipe in 8, 10 and 15-inch diameters and PVC plastic pipe in 8, 10 and 18-inch diameters were tested with clean water and straight alignment. The average Manning's n values were found to be 0.010 for concrete pipe and 0.009 for PVC pipe as presented in Table 5.

To reconfirm the results of the Alberta and previous studies, the American Concrete Pipe Association commissioned additional tests on 8, 12 and 18-inch diameter precast concrete pipe at the Utah Water Research Laboratory, Utah State University, Logan, Utah. Results were published in Hydraulics Report Number 157, J. Paul Tullis, October, 1986. Laboratory values of Manning's *n* for precast concrete pipe were reconfirmed as 0.010. Results are shown in Table 6.

Table 5 University of Alberta - 1986. Summary of Test Results

Type and Size of Pipe	No. of Tests	Manning's n Values		
		Maximum	Minimum	Average
8-inch PVC	63	0.0115	0.0080	0.0088
10-inch PVC	60	0.0104	0.0077	0.0089
18-inch PVC	62	0.0096	0.0073	0.0091
Group	185	0.0115	0.0073	0.0089
8-inch concrete	58	0.0138	0.0092	0.0101
10-inch concrete	61	0.0136	0.0087	0.0098
15-inch concrete	60	0.0116	0.0076	0.0097
Group	179	0.0138	0.0076	0.0099

Table 6 Utah State University - 1986. Summary of Test Results

Type and Size of Pipe	No. of Tests	Manning's n Values		
		Maximum	Minimum	Average
8-inch PVC	21	0.0100	0.0097	0.0098
10-inch PVC	20	0.0102	0.0098	0.0100
18-inch PVC	23	0.0103	0.0097	0.0100
Group	64	0.0103	0.0097	0.0099

CORRUGATED METAL PIPE TESTS

Prior to 1950, comparatively few tests had been made on large size corrugated metal pipe. For this reason, U.S. Army Chief of Engineers Office, in 1951, authorized tests on 3, 5, and 7-foot diameter corrugated metal pipe at the Bonneville Hydraulic Laboratory, Bonneville, Oregon. Length of the test installations was 350 feet for all diameters. All pipe had a corrugation pattern of $^1/_2$-inch x $2^2/_3$-inch. The experimental conditions, as far as size and length of pipe tested, exceeded any previously used. Results of these tests were published in 1959, in the Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, "Friction Factors in Corrugated Metal Pipe" by Marvin J. Webster and Laurence R. Metcalf. Recommended Manning *n* values are presented graphically in the report. As a conclusion, the report states that for 3, 5 and 7-foot nominal diameter corrugated pipe with a $^1/_2$-inch x $2^2/_3$-inch corrugations and flowing full, a Manning's $n = 0.024$ was obtained.

In 1958, a program of hydraulic tests was initiated by the U. S. Army Corps of Engineers, and the Bureau of Public Roads at the U. S. Army Waterways Experiment Station, for the purpose of determining roughness factors for structural plate corrugated metal pipe. The results were presented in a paper at the 44th Annual Meeting of the Highway Research Board, January 1965, and published in Highway Record No. 116. The paper is titled "Friction Factors for Hydraulic Design of Corrugated Metal Pipe," by John L. Grace, Jr. A major highlight of this research report was the preparation of graphs showing the relationship of Manning's *n* with pipe size for three commercially available corrugation patterns. These graphs are reproduced in Design Data 2 (Friction Factors for Corrugated Metal Pipe). A summary of the range of *n* values and the applicable equations relating Manning's *n* to pipe diameters are presented in Table 7.

Table 7 Friction Factors for Hydraulic Design of Corrugated Metal Pipe

Equation	Corrugated Pattern	Pipe Size Range	n Value Range
$n = \frac{0.0259}{D^{0.044}}$	$2\,{}^{2}/_{3}" \times {}^{1}/_{2}"$	12" - 96"	0.0259 to 0.0237
$n = \frac{0.0360}{D^{0.075}}$	3" x 1"	36" - 96"	0.0282 to 0.0262
$n = \frac{0.0377}{D^{0.0775}}$	6" x 2"	36" - 96"	0.0333 to 0.0298

The corrugated metal pipe industry has formally recognized the higher laboratory values of Manning's *n,* which research has proven for available corrugation patterns. The values of *n* recommended for unpaved corrugated metal pipe in the May 1999 "Modern Sewer Design," published by the National Corrugated Steel Pipe Association and the American Iron and Steel Institute, are presented in Table 8.

Table 8 Values of Coefficient of Roughness n for Corrugated Steel Pipe (Mannings Formula)

Corrugations (Annular)	$2\,{}^{2}/_{3} \times {}^{1}/_{2}$ in.	3 x 1 in.	Structural Plate 6 x 2 in.
Diameter	1 to 8 ft.	3 to 8 ft.	5 to 20 ft.
Unpaved	0.024	0.027	0.031*

*BPR Circ. 10, Mar. 1965, p. 78. Based on 108-in. diam.

To date, limited testing has been conducted on helically corrugated metal pipe. Tests were conducted on helically corrugated metal pipe by A. R. Chamberlain and the results were published in 1955 at Colorado State University in a report titled "Effect of Boundary on Fine Sand Transport in Twelve Inch Pipes." Charles E. Rice conducted flow tests at the Stillwater Outdoor Hydraulic Laboratory, Stillwater, Oklahoma, on 8-inch and 12-inch pipe. His report titled "Friction Factors for Helical Corrugated Pipe," was published by the U. S. Department of Agricultural Research Service in 1966.

In 1970, the Federal Highway Administration, Offices of Research and Development published a report "Hydraulic Flow Resistance Factors for Corrugated Metal Conduits" by J. M. Norman and H. G. Bossy. The observations by the authors were that, "as the pipe diameters increases, the helix angle also increases, and as the helix angle approaches 90 degrees the pipe must behave as a corrugated pipe with annular corrugations. For a partly full flow condition in a helically corrugated metal pipe in which the spiral flow cannot be maintained, it is presumed that even a small helix angle would cause little reduction in resistance and that the same resistance coefficient as that for standard corrugated metal pipe should be used. There is a need to further test helically corrugated metal pipe, especially the larger sizes. At present, the use of a reduced resistance coefficient is indicated only for small diameters, 2 feet or less, and then only under full flow conditions.... The best course for conservative design, pending further test results, is to use annular corrugated metal pipe resistance coefficients for helically corrugated pipe."

An updated "Hydraulic Flow Resistance Factors for Corrugated Metal Conduits" was published by the Federal Highway Administration in January, 1980. In 2001, the Federal Highway Administration published "Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5" by J.M. Norman, R.J. Houghtalen and W.J. Johnston. Both publications recommend annular flow resistance factors be used for helically corrugated metal pipe installations unless all the following conditions are met:

- The conduit flows full.
- The conduit is circular in shape.
- There is no erosion resistant sediment build-up in the conduit.
- The conduit is greater than 20 diameters long.
- The conduit is unpaved.
- There are no manholes, wyes and tees.
- There are no changes in grade and alignment.

CORRUGATED ALUMINUM PIPE TESTS

In April 1971, a report was published titled "Further Studies of Friction Factors for Corrugated Aluminum Pipe Flowing Full" by Edward Silberman and Warren 0. Dahlin, St. Anthony Falls Hydraulic Laboratory, University of Minnesota. Laboratory tests were conducted on pipe which ranged in diameter from 12 inches to 66 inches and lengths from 100 feet to 220 feet using both annular and helical corrugated aluminum pipe. The tests were conducted with a head of 20 feet so that the pipe would flow full.

The conclusions reached by the authors are "The experiments described in this report have been conducted using corrugated aluminum pipes flowing full. The measurements were made following an entry region of 20 or more pipe diameters, and although this distance appears to be sufficient, it is not known whether this is a minimum distance for fully developed flow. Measurements were made under laboratory conditions with pipe carefully aligned and joints carefully made so as to avoid introducing additional roughness. The water used in the tests carried a light load of sand, mostly as suspended load, from the Mississippi River. No significant amount of sand was found in the pipes after the flow was shut down; it is not believed that the sand affected the results."

Values of Manning's *n* ranged from 0.0107 for 12-inch helical pipe to 0.0222 for 48-inch helical pipe. Use by designers of such low *n* values is not recommended as these are based on laboratory tests for full flow conditions, a 20-foot head, no appreciable bed loads, carefully aligned joints, and a 20 diameter length of flow development region. Therefore, the conclusions and recommendations of the Federal Highway Administration in the 2001 updated report *Hydraulic Design Series No. 5* regarding flow resistance factors for helical corrugations are applicable whether the pipe is made of aluminum or steel.

PVC PIPE TESTS

Tests were conducted by Lawrence C. Neale and Robert E. Price in 1962 at Alden Laboratory, Worcester Polytechnic Institute, Worcester, Massachusetts, on 8-inch and 12-inch PVC plastic pipe flowing both full and partially full, using clean water and straight sections. The only other published reports on laboratory tests of PVC pipe roughness coefficients are a 1985 Utah State University report on "Fluid Frictional Headloss Coefficient Determination for Spirally Wound Ribbed PVC Sewer Pipe" by Professor R.W. Jeppson and the 1986 University of Alberta Study previously cited. Test results indicated a laboratory *n* value of 0.009 which the plastic pipe industry recommends as a design value. For proper design, plastic pipe should be classed as any other smooth wall pipe with a design value for Manning's *n* as shown in Table 1.

Slime and grease adhere to all commonly used sewer pipe materials. Plastics, which although presenting a smooth surface, have become accepted for use as a biological filter media for which purpose slime adherence is a prime requisite. In January, 1978, the Journal of the Water Pollution Control Federation published a study, "Accumulation of Slime in Drainage Pipes and Their Effect on Flow Resistance," which was conducted at the Water Research Center, England by C.E.G. Bland, R.W. Bayley and E.V. Thomas. After passing raw domestic sewage through a pipeline consisting of equal pipe sizes and lengths of polyvinyl chloride, asbestos cement, bituminized fiber, unglazed clay, ceramic glazed clay and salt glazed clay, the study concluded the amount of accumulated slime was independent of pipe materials and surface finish. Slimes and grease are not the only factors to consider when selecting an *n* value for plastic pipe. Other factors such as debris, bends, manholes, connections, grit, warpage due to sunlight or storage, and scouring of walls due to cleaning, must be taken into account.

The joint *ASCE Manual Number 60 and Water Environment Federation Manual Number FD-5*, "Gravity Sanitary Sewer Design and Construction", makes the following statement about pipe materials and Manning's *n*:

"Generally, Manning's n for a given sewer, after some time in service, will approach a constant which is not a function of the pipe material but represents the grit accumulation and slime build -up on the pipe walls. This n will be on the order of 0.013. A coefficient which will yield higher friction losses should be selected for sewers where disturbing influences are known or anticipated. Because of the empirical nature of each formula, conservative design is prudent."

CLAY PIPE

From the Clay Pipe Engineering Manual published by the National Clay Pipe Institute, the following discussion of *n* values is quoted:

" *n* is an empirically derived coefficient which is used as a measure of the interior surface characteristics of a pipe designed for the transmission of liquids. This coefficient comes into use in determining the frictional losses in the conduit when transporting a liquid flow.

The value of *n* is affected by size, depth of flow, velocity or slope and quality of construction. The actual value of *n* in an installed line may be increased appreciably by debris, grit deposits and branch connections into the pipe. In controlled experiments, using clean water, values of *n* under 0.009 have consistently been obtained for vitrified clay pipe. However, because of the variations in *n* due to variable flow conditions, it is recommended that a conservative value of *n* be selected. A value of 0.013 is commonly used by experienced sanitary engineers. Recognized authorities point out that numerous tests have definitely established an *n* factor as the same for all materials commonly used in gravity flow sanitary sewer lines."

CAST IRON/DUCTILE IRON PIPE TESTS

Tests were conducted by Don E. Bloodgood and John M. Bell, Purdue University on 4-inch cast iron pipe and vitrified clay pipe. The tests used new pipe and clean water and the *n* value for cast iron was found to be .00835 compared to 0.00865 for clay.

The Ductile Iron Pipe Research Association, in its Handbook, uses the Hazen-Williams equation rather than the Manning's equation to calculate the flow. In the HazenWilliams formula, a C value is used as the coefficient of roughness for the pipe walls. The Hazen-Williams formula generally is used for pressure pipe calculations rather for gravity systems. The Ductile Iron Research Association recommended Hazen-Williams C values converted to Manning's *n* values results in *n* values of 0.010 to 0.013.

In the corrosion process (tuberculation), growths or mounds form on the walls of the iron pipe. These growths are often so large and numerous that the frictional resistance is greatly increased and, in addition, a serious reduction in the effective cross sectional area of the pipe is produced. The result is a tremendous reduction in hydraulic capacity. In order to offset the destructive effects of tuberculation, the cast iron and ductile iron pipe manufacturers generally supply pipe with either cement mortar linings or polyethylene linings. These are relatively thin linings, and it is quite probable that the linings will lose their protective capabilities within a few years, due to leaching and scrubbing action, and permit the start of tuberculation. For cast iron or ductile iron sewers an *n* value of 0.013 should be used regardless of the type of lining.

AGENCY POLICIES ON *n*

Beginning in 1953, many governmental agencies made policy statements relating to the Manning *n* values for use on work under their jurisdictions. Policy statements are listed in Table 9. Since these policy statements were so similar, the selection of the proper *n* value for different pipe types appeared to be settled. In the FHWA's *Hydraulic Design Series Number 5*, all *n* values are lab values. In all other policy statements, the fact that the *n* values for concrete pipe have a built in safety factor, however, was not considered and a corresponding safety factor is not applied to the laboratory values for some other smooth wall pipe nor for corrugated metal pipe.

Table 9 Policy Statements

Agency	Year	Publication	Values of Manning's Roughness Cofficients
Headquarters Department of the Army Office of Chief of Engineers	1978	Technical Manual – TM 5-820-3 Drainage and Erosion-Control Structures for Airfields and Heliports	Type of Pipe — n All smooth wall — 0.012 Corrugated metal pipe 2 2/3 by 1/2 inch — 0.024 3 by 1 inch — 0.027 6 by 2 inch — 0.028-0.033 9 by 2 1/2 inch — 0.033
Headquarters Department of the Army Office of Chief of Engineers	1983	Technical Manual – TM 5-820-4 Drainage for Areas Other Than Airfields	Type of Pipe — n All smooth wall — 0.012 Corrugated metal pipe 2 2/3 by 1/2 inch — 0.024 3 by 1 inch — 0.027 6 by 2 inch — 0.028-0.033 9 by 2 1/2 inch — 0.033
US Department of Transportation Federal Highway Administration	1980	Hydraulic Flow Resistance Factors for Corrugated Metal Conduits	Corrugation — Diameter Range (ft.) — n 2 2/3" x 1/2" — 1 - 8 — .0263 to .0235 3" x 1" — 3 - 8 — .0281 to .0260 6" x 1" — 3 - 8 — .0260 to .0270 6" x 2" struct. plate — 3 - 21 — .0330 to .0300 9" x 2 1/2 struct. plate — 7 - 15 — .0338 to .0318 For helically corrugated pipe - use the same values as an annular corrugated pipe
US Department of Transportation Federal Highway Administration	2001	Hydraulic Design Series Number 5, Hydraulic Design of Highway Culverts	Type of Pipe — n Concrete Pipe — 0.010 - 0.011 Concrete Box Culverts — 0.012 - 0.015 Spiral Rib Metal Pipe — 0.012 - 0.013 Corrugated Metal Pipe 2 2/3" x 1/2" — 0.022 - 0.027 6" x 1" — 0.022 - 0.025 5" x 1" — 0.025 - 0.026 3" x 1" — 0.027 - 0.028 6" x 2" — 0.033 - 0.035 9" x 2 1/2" — 0.033 - 0.037 Corrugated Metal Pipes, Helical Corrugations, Full Circular Flow 2 2/3" x 1/2 — 0.012 - 0.024 The Manning's *n* value ranges indicated in this table are laboratory values. In general, it is recommended that the annular resistance factors be used for corrugated metal pipes with helical corrugations.