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HYDRAULIC RESISTANCE OF SMALL-DIAMETER HELICALLY CORRUGATED METAL PIPE

Bruce M. McEnroe, Ph.D., P.E.
Travis R. Malone
The University of Kansas
Lawrence, Kansas

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16 Abstract

The hydraulic resistance of helical CMP is strongly dependent on helix angle – the angle of the corrugations relative to the longitudinal axis of the pipe. Smaller-diameter pipes have smaller helix angles. Helical corrugations with a significant downstream orientation (small helix angle) offer less resistance to flow than annular corrugations.

This report documents an experimental investigation of Manning n values for small-diameter helical CMP with 2.67" x 0.50" corrugations. Sixty-foot lengths of 18-inch, 15-inch and 12-inch pipe were tested in the University of Kansas hydraulics laboratory. Each test pipe was assembled from three 20-foot pipe sections. The helical CMP sections were manufactured with 12 inches of annular corrugations at each end to accommodate the connector bands. The 18-inch pipe was tested on a 0.39% slope, the 15-inch pipe on a 0.85% slope, and the 12-inch pipe on a 0.68% slope. The pipes were tested flowing full and partly full at depths ranging from 30% to 90% percent of the pipe diameter.

The full-flow tests yielded Manning n values of 0.0178 for the 18-inch pipe, 0.0154 for the 15-inch pipe, and 0.0142 for the 12-inch pipe. These n values are considerably lower than the accepted values for annular CMP but higher than the values recommended by the American Iron and Steel Institute for helical CMP. The Manning n values obtained for partly full flow varied with the depth of flow. These tests yielded n values in the following ranges: 0.0184-0.0206 for the 18-inch pipe, 0.0170-0.0180 for the 15-inch pipe, and 0.0160-0.0194 for the 12-inch pipe. Manning n values for partly full flow tend to be higher for shallower flow. Manning n values for nearly fully flow (80-90% full) are about 10% higher, on average, than n values for full flow. The annular corrugations at the section joints cause significant local energy losses. The Manning n values computed from the experimental data account for these local losses across the joints as well as the losses through the helical sections.

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Prepared by

Bruce M. McEnroe, Ph.D., P.E.
Travis R. Malone

Department of Civil, Environmental and Architectural Engineering
The University of Kansas
1530 W. 15th Street, 2150 Learned Hall
Lawrence, KS 66045-7609

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

The hydraulic resistance of helical CMP is strongly dependent on helix angle – the angle of the corrugations relative to the longitudinal axis of the pipe. Smaller-diameter pipes have smaller helix angles. Helical corrugations with a significant downstream orientation (small helix angle) offer less resistance to flow than annular corrugations.

This report documents an experimental investigation of Manning n values for small-diameter helical CMP with 2.67" x 0.50" corrugations. Sixty-foot lengths of 18-inch, 15-inch and 12-inch pipe were tested in the University of Kansas hydraulics laboratory. Each test pipe was assembled from three 20-foot pipe sections. The helical CMP sections were manufactured with 12 inches of annular corrugations at each end to accommodate the connector bands. The 18-inch pipe was tested on a 0.39% slope, the 15-inch pipe on a 0.85% slope, and the 12-inch pipe on a 0.68% slope. The pipes were tested flowing full and partly full at depths ranging from 30% to 90% percent of the pipe diameter.

The full-flow tests yielded Manning n values of 0.0178 for the 18-inch pipe, 0.0154 for the 15-inch pipe, and 0.0142 for the 12-inch pipe. These n values are considerably lower than the accepted values for annular CMP but higher than the values recommended by the American Iron and Steel Institute for helical CMP. The Manning n values obtained for partly full flow varied with the depth of flow. These tests yielded n values in the following ranges: 0.0184-0.0206 for the 18-inch pipe, 0.0170-0.0180 for the 15-inch pipe, and 0.0160-0.0194 for the 12-inch pipe. Manning n values for partly full flow tend to be higher for shallower flow. Manning n values for nearly fully

flow (80-90% full) are about 10% higher, on average, than n values for full flow. The annular corrugations at the section joints cause significant local energy losses. The Manning n values computed from the experimental data account for these local losses across the joints as well as the losses through the helical sections.

ACKNOWLEDGMENTS

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CHAPTER 1 - INTRODUCTION

1.1 Overview

Friction losses in culverts and storm sewers are normally computed with the Manning equation. The Manning n value is a measure of hydraulic resistance to flow. The Manning n value depends on the characteristics of the pipe and, to a lesser extent, the characteristics of the flow. Appropriate Manning n values for design are generally established through laboratory testing of the pipe over a range of flow conditions.

Manning n relationships for corrugated metal pipe (CMP) with helical corrugations are complex and have not been investigated thoroughly in the laboratory. Consequently, appropriate Manning n values for design of helical CMP are uncertain. The design recommendations that appear in many technical references are not adequately supported by laboratory test results.

This report documents an experimental investigation of Manning n values for small-diameter corrugated metal pipe (CMP) with 2.67" x 0.50" helical corrugations. Pipes with diameters of 12, 15 and 18 inches were tested flowing full and partly full flow. These tests were performed in the hydraulics laboratory of the Department of Civil, Environmental and Architectural Engineering at the University of Kansas.

1.2 Hydraulic Resistance of Helical CMP

The major factors affecting the Manning n value for helical CMP are the corrugation dimensions, the pipe diameter and the helix angle. The helix angle is defined as the angle of the corrugations relative to the longitudinal axis of the pipe (90º for annular corrugations). The Manning n is affected to a lesser degree by the internal

surface roughness and the Reynolds numbers of the flow. If the pipe is flowing partly full, the Manning n may also vary with the depth of flow and the Froude number.

The helix angle of the corrugations depends on the pipe diameter and the width of the metal strip from which the pipe is fabricated, as follows:

$$\theta = \tan^{-1}\left(\frac{\pi D_{av}}{L_s}\right) \qquad \text{(Equation 1.1)}$$

θ = helix angle
D_{av} = average pipe diameter (average of inside and outside diameters)
L_s = finished strip width (width between seams)

The smaller the pipe diameter for a given strip width, the smaller the helix angle; i.e., the greater the downstream orientation of the corrugations.

Several previous laboratory studies have shown that a spiral flow pattern can develop for full flow in long straight sections of small-diameter helical CMP. The spiral flow pattern suppresses turbulence and reduces the resistance to flow, as measured by the Manning n. The smaller the helix angle, the lower the Manning n.

In culvert and storm drainage applications, fully developed spiral flow is unlikely for several reasons. First, the lengths of undisturbed flow through culverts and between storm-drainage drainage structures are generally too short. Second, the ends of helical CMP sections are normally re-rolled with annular corrugations so that the pipe sections can be connected with hugger bands. This practice results in a two-foot-long segment of annular corrugations across each section joint. These annular corrugations retard the development of spiral flow. Third, spiral flow does not occur in pipes flowing less than full. Culverts that operate under inlet control do not flow full, and most storm sewers are sized to flow slightly less than full at the design discharge.

1.3   Previous Research and Design Guidance

Most of the previous laboratory studies of the hydraulic resistance of helically corrugated pipe were performed prior to 1980. The Federal Highway Administration's Report TS-80-216, "Hydraulic Flow Resistance Factors for Corrugated Metal Conduits" (FHWA,1980), provides a comprehensive review of these early studies. Figure 1.1, reproduced from Report TS-80-216, summarizes the Manning n values reported in these studies. These Manning n values were obtained for full flow in pipes with continuous helical corrugations (no annular corrugations at section ends). These results indicate that the Manning n is determined mainly by the pipe diameter and plate width (which together determine the helix angle) and the corrugation type. The effect of discharge on the Manning n is minimal.

FHWA's Report TS-80-216 provides the following cautionary guidance for selection of Manning n values for helical CMP:

> While it is true that helical CMP may have much lower resistance values than annular C.M.P., care must be exercised in the use of the reduced resistance values.
>
> Since the low values depend on the development of spiral flow across the entire cross-section of the pipe, the designer must assure himself that fully developed spiral flow can occur in his design situation. It is recommended that care be taken when the following conditions exist:
>
> 1.   Partly full flow in the conduit.

2. When high sediment loads can cause sedimentation in the pipe invert during low flow periods. This sediment may hinder the development of spiral flow in the conduit until the sediment is washed out of the conduit.

If the following conditions exist, use the full flow resistance factor for the annular C.M.P. with the same corrugation shape, pipe size and flow rate. It is felt that it is better to introduce some conservatism and extra capacity into the pipe design rather than risk flooding by depending on a flow condition which will not develop.

3. Short culverts, less than about 20 diameters long, where the spiral flow cannot fully develop.

4. Non-circular conduits, such as pipe-arches.

5. When the helical CMP is partly lined.

For condition 5, use the resistance factor for a partly lined annular C.M.P. of the same size and corrugation type. (FHWA, 1980)

FHWA's Hydraulic Design Series No. 5, "Hydraulic Design of Highway Culverts" (Normann, et al., 2005) recommends Manning n values for helical CMP that are consistent with Figure 1-1. However, the cautions from Report TS-80-216, cited above, are omitted. HDS-5 states that the Manning n values for full flow should be increased by 11% for partly full flow. The basis for this recommendation is not stated.

The most recent tests of the hydraulic resistance of a helical CMP were conducted by Tullis (1991) at Utah State University for the National Corrugated Steel Pipe Association. A 200-ft length of 24-inch helical CMP was assembled from ten 20-ft sections, installed on a 1% slope, and tested under conditions of full flow and partly full

flow. These tests yielded average Manning n values of 0.016 for full flow and 0.018 for partly full flow.

The American Iron and Steel Institute's *Handbook of Steel Drainage and Highway Construction Products* (1994) recommends the Manning n values in Table 1.1 for full flow and partly full flow in helical CMP with 2.67" x 0.50" corrugations.

Table 1.1: Manning n values recommended by AISI (1994) for helical CMP with 2.67" x 0.50" helical corrugations

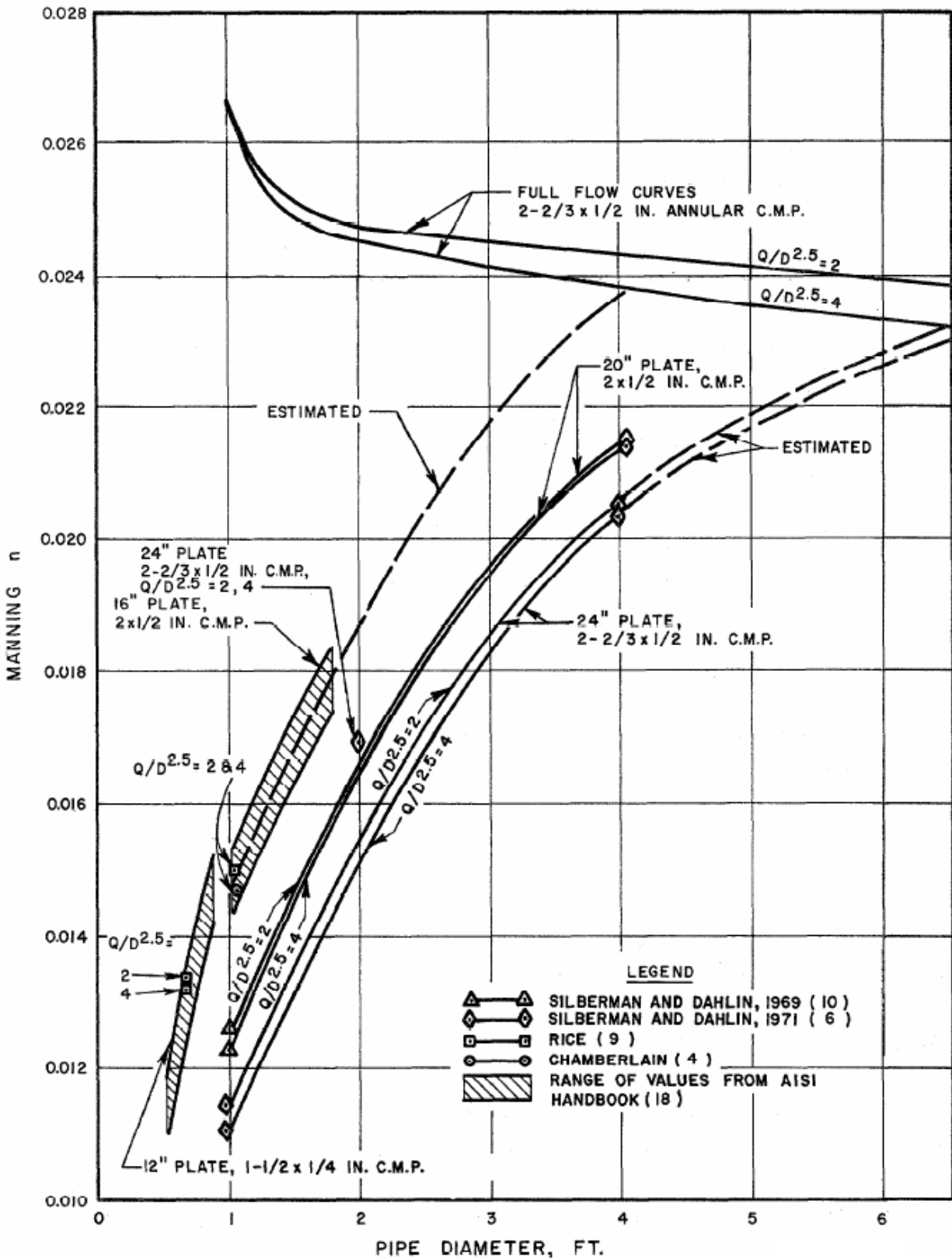| Diameter	Manning n	
(in.)	Full flow	Partly full
12	0.011	0.012
15	0.012	0.013
18	0.013	0.015
24	0.015	0.017
30	0.017	0.019
36	0.018	0.020
42	0.019	0.021
48	0.020	0.022
54 & larger	0.021	0.023

Figure 1.1: Manning n values from pre-1980 tests of helical CMP (FHWA, 1980)

CHAPTER 2 - EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Pipes Tested

The pipes tested were 16-gauge galvanized corrugated-steel pipes with 2.67" x 0.50" helical corrugations and nominal diameters (minimum inside diameters) of 12, 15 and 18 inches. These pipes were manufactured by Contech Construction Products, Inc., in conformance with the AASHTO M218 and ASTM A929 standards. The pipes were constructed from 27.25-inch-wide steel plate; the finished width between seams was 24.5 inches. The helix angles were 67º for the 18-inch pipe, 63º for the 15-inch pipe, and 58º for the 12-inch pipe. The ends of the 20-foot long pipe sections had been re-corrugated with annular corrugations at the factory to accommodate the connector bands. The annular corrugations extended 12 inches from the ends of the pipe sections.

2.2 Apparatus and Procedures

Sixty-foot lengths of pipe were tested in the University of Kansas hydraulics laboratory. Each test pipe was assembled from three 20-foot pipe sections. The test pipe was installed on a steel frame constructed alongside the 30-inch-wide water flume in the hydraulics laboratory (Figure 2.1). The frame consisted of a 60-foot-long W12x50 wide-flange steel beam with steel crossbars welded to the top. The frame was supported on jacks, which were used to adjust the longitudinal slope and minimize deflection. The laboratory's recirculating water-supply system provided the flow for the tests. The upstream end of the 30-inch flume was temporarily converted into a head tank with a rectangular weir, which diverted the flume's water supply to the pipe-testing apparatus as shown in Figure 2.2. The discharge was determined from the head on the

weir. The large wooden box upstream of the pipe served as a stilling basin. The test pipe discharged into a gated steel box as shown in Figure 2.3. The flow exited this box through a sluice gate at floor level. The outflow was channeled to the laboratory's sump tank. The tailwater level in the gated box was adjusted with the sluice gate to achieve nearly uniform flow in the pipe.

The rectangular weir for flow measurement was constructed in accordance with the recommendations in the U. S. Bureau of Reclamation's *Water Measurement Manual* (1997). The crest length was 30 inches and the height of the weir crest above the flume bottom was 40.5 inches. The length of the head tank (the dimension parallel to the weir crest) was 95 inches long. The head on the weir crest was measured in a stilling well constructed of Plexiglas tubing mounted outside the head tank on side opposite the weir. A short section of hose connected the stilling well to the head tank. The water level in the stilling well was measured using a point gage with a Vernier scale (Figure 2.4).

Figure 2.1: Testing the 12-inch pipe
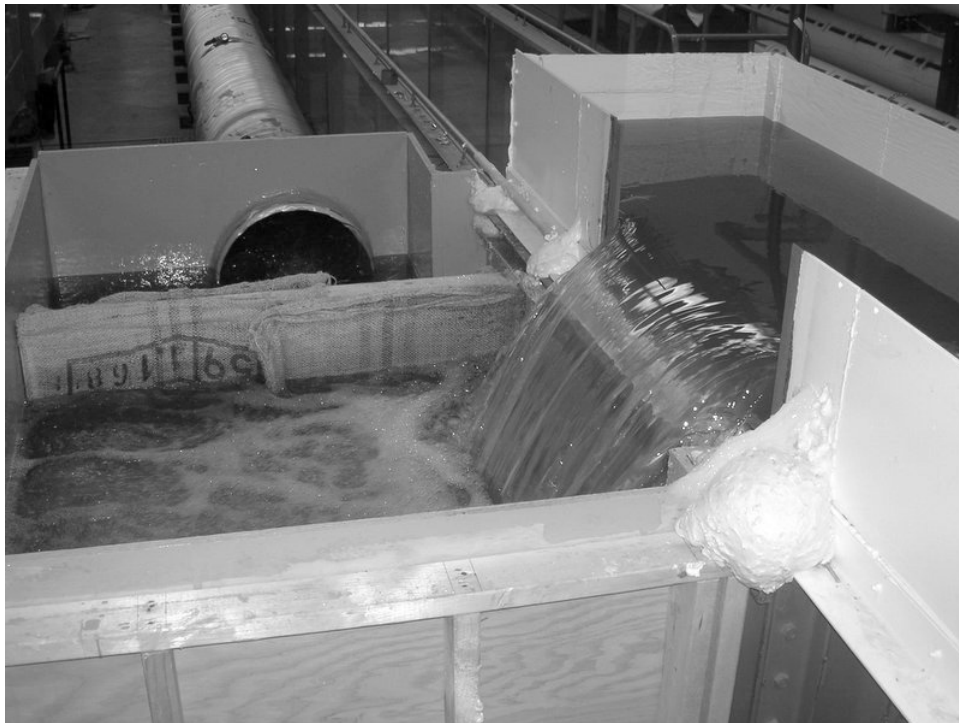
Figure 2.2: Water-supply and flow measurement system at pipe entrance
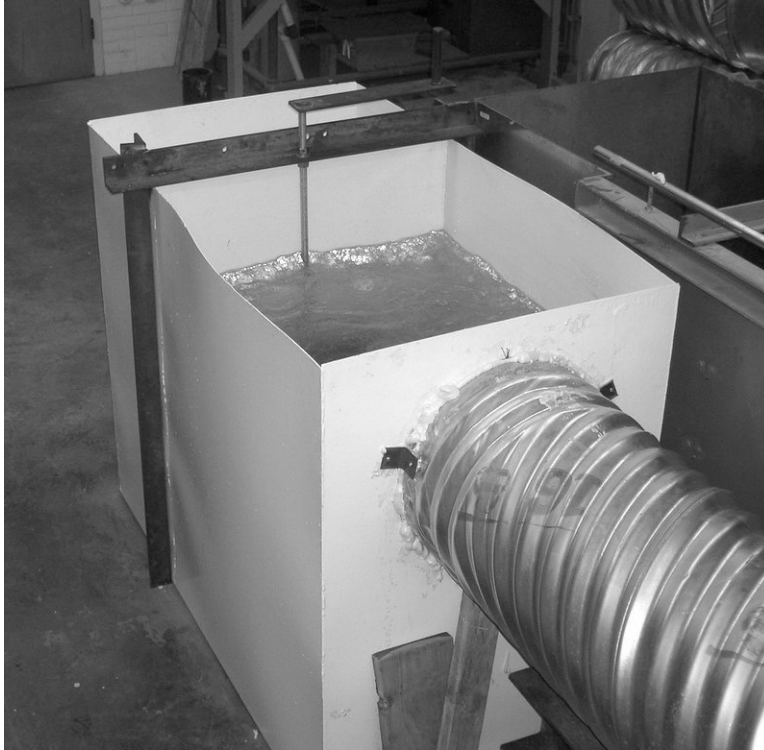
Figure 2.3: Gated box at pipe outlet for water-level control

Figure 2.4: Reading the weir head

The pipes were tested on mild slopes to avoid the standing waves associated with supercritical, critical and near-critical flow. The 18-inch pipe was tested on a 0.39% slope, the 15-inch pipe on a 0.85% slope, and the 12-inch pipe on a 0.68% slope.

Piezometric heads were measured at eight locations along the pipe. The eight piezometers were installed along the flowline of the pipe approximately 80 inches apart, starting 10 feet downstream of the pipe entrance. The piezometer holes were drilled with a #10 bit (0.194-inch diameter) at the points on the corrugations where the inside diameter of the pipe is a minimum. A short connector tube was soldered to the outside of each hole. The inside edges of each hole was carefully de-burred with a special tool before and after the connector tubes were attached. The eight piezometer taps were connected to an eight-tube manometer board (Figure 2.5) with equal lengths of Tygon tubing. The manometers were read to the nearest 0.005 ft. Flowline levels at the eight piezometers were established by reading the manometers after shutting off the inflow, dropping the tailwater below the flowline, and allowing the outflow to cease.

Figure 2.5: Reading the manometers

The pipes were tested flowing completely full and partly full. In the partly-full tests, the tailwater level was adjusted to maintain nearly uniform (constant-depth) flow throughout the pipe. These tests were run at multiple discharges with depths of uniform flow that ranged from 30% to over 80% of the diameter. The pipes were tested at full flow by raising the tailwater level to submerge the pipe outlet at a discharge sufficiently high that the pipe flowed full over its entire length. The data from a single test consisted of the point-gage reading of the weir headwater level and the manometer readings for the eight piezometers.

2.3   Data Analysis

The Manning equation for friction loss can be written in terms of discharge as

$$Q = \frac{1.49}{n} \frac{A^{5/3}}{P^{2/3}} S_f^{1/2}$$
(Equation 2.1)

in which

Q = discharge (cfs)
A = cross-sectional area of flow (ft2)
P = wetted perimeter (ft)
S_f = friction slope, or slope of energy grade line (ft/ft)
n = Manning resistance coefficient

This equation can be solved for the Manning n as follows

$$n = \frac{1.49}{Q} \frac{A^{5/3}}{P^{2/3}} S_f^{1/2}$$
(Equation 2.2)

The Manning n value for each test run was computed with Eq. 2.2 using values of A, P and S_f averaged over the central 40 ft of the 60-ft pipe, between piezometers #1 and #7. The data from each test run were analyzed as follows:

1. The discharge was computed from the measured head by the method of Kindsvater and Carter (1959) as presented in the *Water Measurement Manual* (USBR, 1997).
2. The depth of flow at each piezometer location was computed by subtracting the flowline (zero-flow) level from the manometer reading.
3. The piezometer readings were plotted versus distance from the pipe entrance, and this water-surface profile was examined for reasonableness.
4. The cross-sectional area and wetted perimeter at each piezometer location was computed from the depth of flow.
5. The velocity, V, at each piezometer location was computed from the relationship $V = Q / A$.
6. The total head, H, at each piezometer location was computed by adding the velocity head to the piezometric head.
7. The average values of A and P between piezometers #1 and #7 were computed, with the values at piezometers #1 and the #7 weighted one-half as much as the values at piezometers #2 through #5.
8. The average friction slope was determined from a linear regression analysis of total head versus distance from the pipe entrance for piezometers #1 through #7. The slope of the regression line was considered the average friction slope.
9. The Manning n value was computed with Eq. 2-2 using the average values of A, P and S_f.

CHAPTER 3 - TEST RESULTS

3.1 Summary of Results

Tables 3.1 through 3.3 summarize the test results for the three pipes. The ratio y/D is the ratio of the average depth of flow (y) to the pipe diameter (D). Figures 3.1 through 3.3 show how the Manning n varies with the ratio y/D for the three pipes.

Table 3.1: Test results for 18-inch pipe

Run number	Average depth (ft)	y/D	Discharge (cfs)	Average Velocity (ft/s)	Froude number	Friction Slope (ft/ft)	Manning n
18-1	1.127	0.751	4.311	3.03	0.51	0.00435	0.0191
18-2	1.087	0.724	4.034	2.94	0.51	0.00386	0.0184
18-3	0.965	0.644	3.224	2.68	0.52	0.00390	0.0198
18-4	0.868	0.579	2.839	2.68	0.56	0.00436	0.0202
18-5	0.686	0.457	1.788	2.27	0.55	0.00396	0.0207
18-6	0.575	0.384	1.327	2.13	0.57	0.00405	0.0205
18-7	0.458	0.305	0.869	1.90	0.58	0.00417	0.0206
18-8	0.781	0.521	2.340	2.52	0.56	0.00426	0.0204
18-9	1.075	0.717	3.757	2.77	0.49	0.00394	0.0197
18-10	1.359	0.906	4.857	2.89	0.37	0.00385	0.0187
18-11	1.155	0.770	4.248	2.91	0.48	0.00382	0.0187
18-12	1.264	0.843	4.581	2.88	0.42	0.00388	0.0190
18-13	0.780	0.520	2.340	2.52	0.56	0.00436	0.0206
18-14	0.940	0.627	3.183	2.73	0.54	0.00421	0.0200
18-15	1.191	0.794	4.394	2.92	0.46	0.00391	0.0189
18-16	1.159	0.773	4.298	2.93	0.48	0.00402	0.0191
18-17*	1.500	1.000	3.757	2.13	------	0.00239	0.0178

*full flow

Table 3.2: Test results for 15-inch pipe

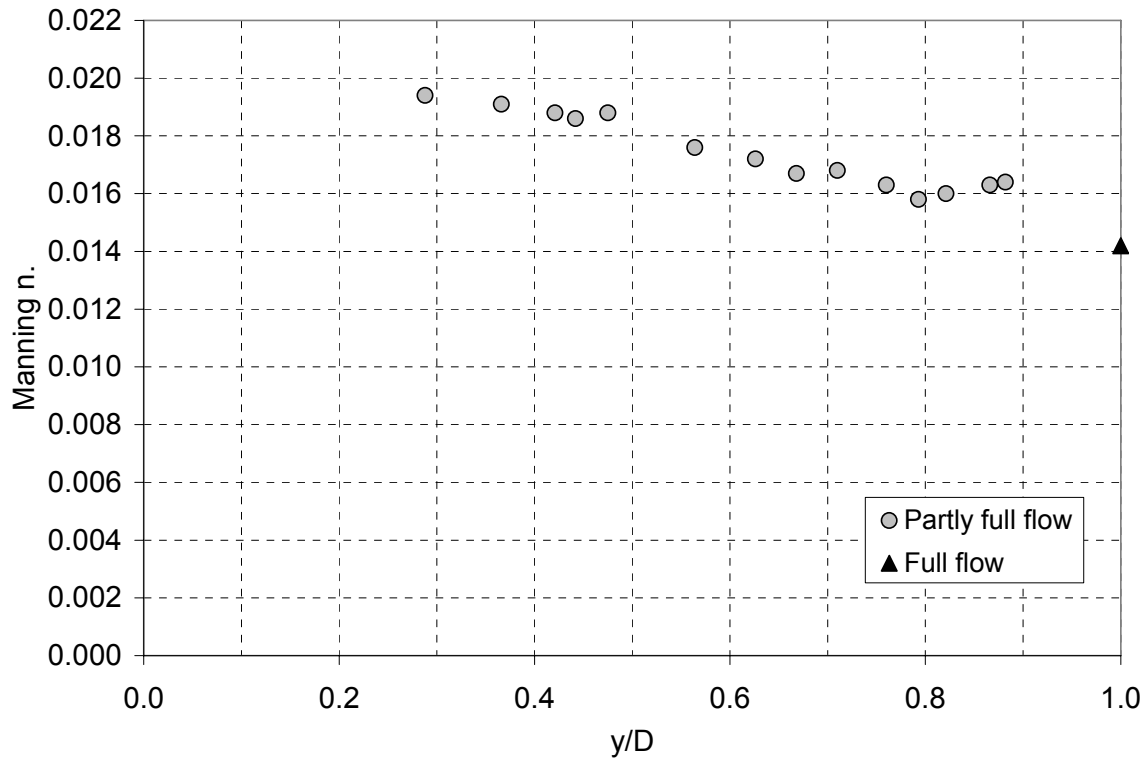| Run number	Average depth (ft)	y/D	Discharge (cfs)	Average Velocity (ft/s)	Froude number	Friction Slope (ft/ft)	Manning n
15-1	0.552	0.442	1.788	3.43	0.93	0.00845	0.0174
15-2	0.670	0.536	2.551	3.81	0.92	0.00845	0.0170
15-3	0.769	0.615	3.183	4.02	0.88	0.00854	0.0171
15-4	0.885	0.708	3.800	4.10	0.80	0.00860	0.0174
15-5	0.955	0.764	4.178	4.16	0.75	0.08880	0.0177
15-6	1.014	0.811	4.497	4.22	0.71	0.08810	0.0174
15-7	0.461	0.369	1.259	3.07	0.93	0.00841	0.0178
15-8	0.366	0.293	0.803	2.69	0.93	0.00843	0.0180
15-9*	1.500	1.000	2.428	2.79	------	0.00394	0.0154

*full flow

Table 3.3: Test results for 12-inch pipe

Run number	Average depth (ft)	y/D	Discharge (cfs)	Average Velocity (ft/s)	Froude number	Friction Slope (ft/ft)	Manning n
12-1	0.475	0.475	0.937	2.55	0.74	0.00683	0.0188
12-2	0.626	0.626	1.602	3.10	0.75	0.00684	0.0172
12-3	0.710	0.710	1.962	3.29	0.72	0.00691	0.0168
12-4	0.882	0.882	2.497	3.41	0.56	0.00698	0.0164
12-5	0.668	0.668	1.793	3.22	0.74	0.00673	0.0167
12-6	0.564	0.564	1.297	2.85	0.74	0.00654	0.0176
12-7	0.760	0.760	2.166	3.38	0.69	0.00672	0.0163
12-8	0.793	0.793	2.335	3.50	0.68	0.00675	0.0158
12-9	0.442	0.442	0.828	2.48	0.75	0.00679	0.0186
12-10	0.421	0.421	0.749	2.39	0.75	0.00671	0.0188
12-11	0.366	0.366	0.572	2.20	0.74	0.00677	0.0191
12-12	0.866	0.866	2.445	3.38	0.58	0.00680	0.0163
12-13	0.288	0.288	0.358	1.91	0.74	0.00678	0.0194
12-14	0.821	0.821	2.403	3.48	0.65	0.00687	0.0160
12-15*	1.000	1.000	3.511	4.47	------	0.01159	0.0142

*full flow

Figure 3.1: Manning n values for 18-inch pipe

Figure 3.2: Manning n values for 15-inch pipe

Figure 3.3: Manning n values for 12-inch pipe

3.2   Discussion of Results

Examination of the experimental results leads to the following observations, several of which confirm findings from other experimental studies. These observations apply to 12-inch, 15-inch and 18-inch helical CMP with 2.67" x 0.50" corrugations.

1.   Manning n values for small-diameter helical CMP are considerably lower than those for annular CMP.

2.   The Manning n values obtained from these tests are higher than those recommended by AISI (1994), shown in Table 1-1. Our n values for the 18-inch pipe are also slightly higher than the n values reported by Tullis (1992) for a 24-inch pipe.

3.   Manning n values for helical CMP vary with pipe diameter; the smaller the pipe, the lower the n value.

4.   Manning n values for partly full flow vary with the depth of flow. The n values tend to be higher for shallower flow.

5.   Manning n values for nearly fully flow (80-90% full) are about 10% higher, on average, than n values for full flow.

6.   The annular corrugations at the pipe joints cause significant local energy losses. Figure 3.4 shows the effects of these local losses on the water-surface profile for run #12-14. The water-surface slopes across the joints are steeper than the pipe slope due to the higher losses from the annular corrugations. The water-surface slopes upstream of the joints are milder than the pipe slope due to backwater effects from these local losses. (Effects from local features propagate upstream in subcritical flow.) The Manning n values computed from the experimental data account for these local losses across the joints as well as the losses through the helical sections.
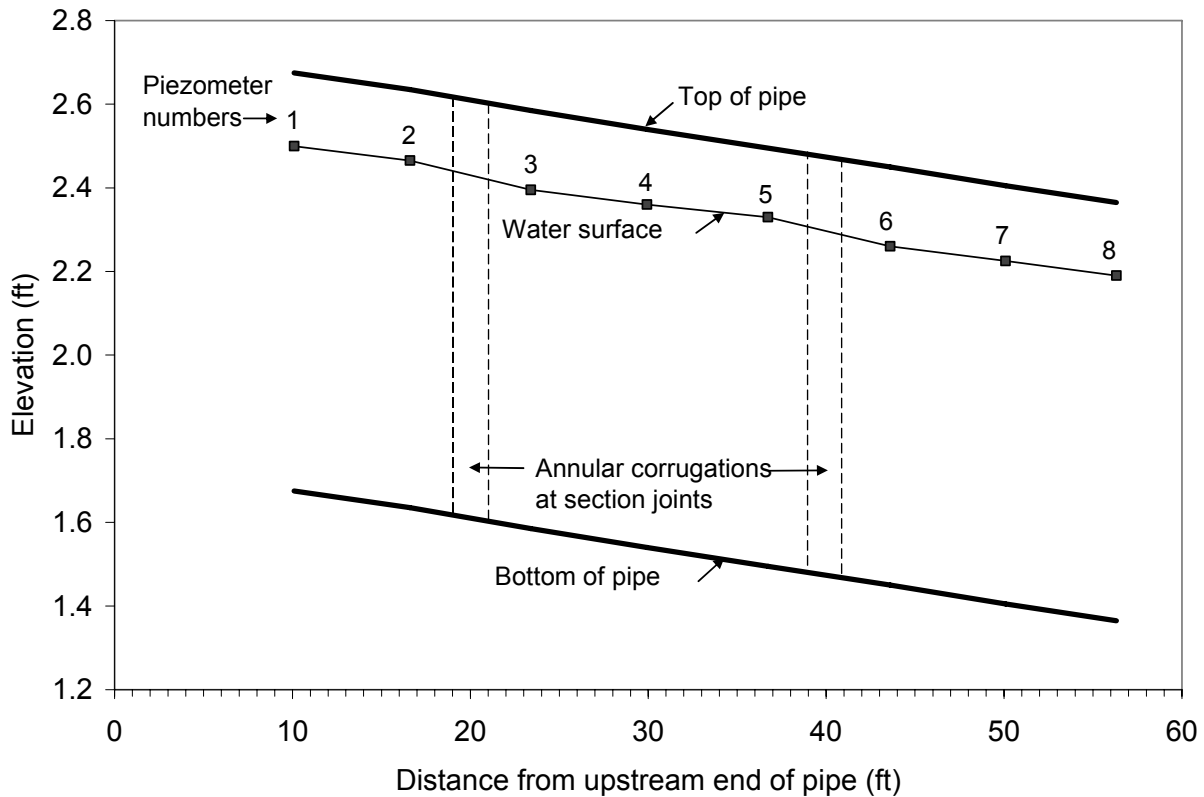
Figure 3.4: Water-surface profile for 12-inch pipe, test run #12-14, showing effect of section joints

3.3 Recommendations for Design

Manning n values for full flow are appropriate for design of culverts and storm sewers. In culvert design, the Manning n is used to analyze the outlet-control case. At the design discharge, a culvert operating under outlet control would flow full over all or most of its length. In storm sewer design, the Manning n is used to calculate the pipe size needed for barely-full uniform flow, and then the calculated pipe diameter is rounded up to a standard, commercially available size. Table 3-4 show our recommended minimum values of the Manning n for small-diameter helical CMP with 2.67" x 0.5" corrugations. These minimum values account for local losses across the section joints. Higher values might be appropriate for design to allow for increased hydraulic resistance due to factors not present in the laboratory tests.

Table 3.4: Recommended minimum values of Manning n for small-diameter helical CMP with 2.67" x 0.5" corrugations

Diameter (in.)	Manning n
12	0.014
15	0.016
18	0.018

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