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ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, *Director*

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Resistance to Flow in Two Types of Concrete Pipe

by
LORENZ G. STRAUB,
CHARLES E. BOWERS, *and* MEIR PILCH

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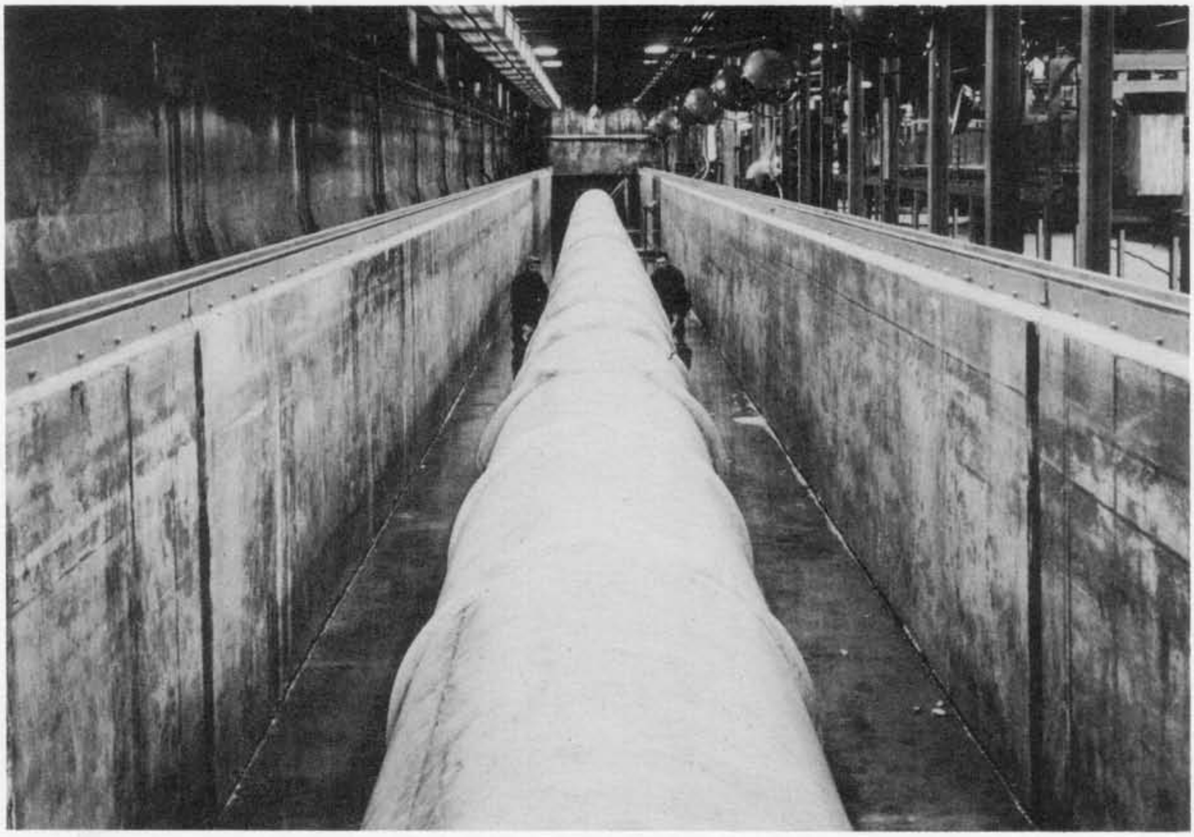

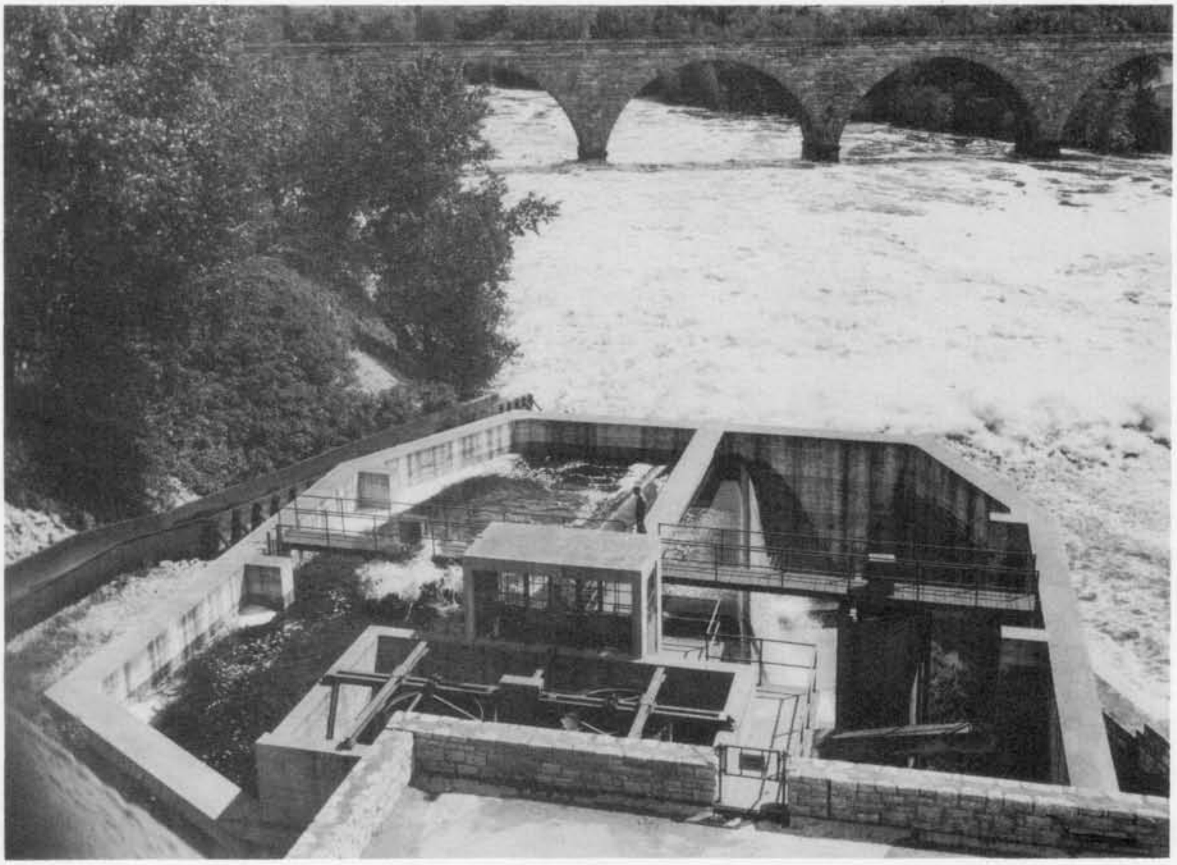

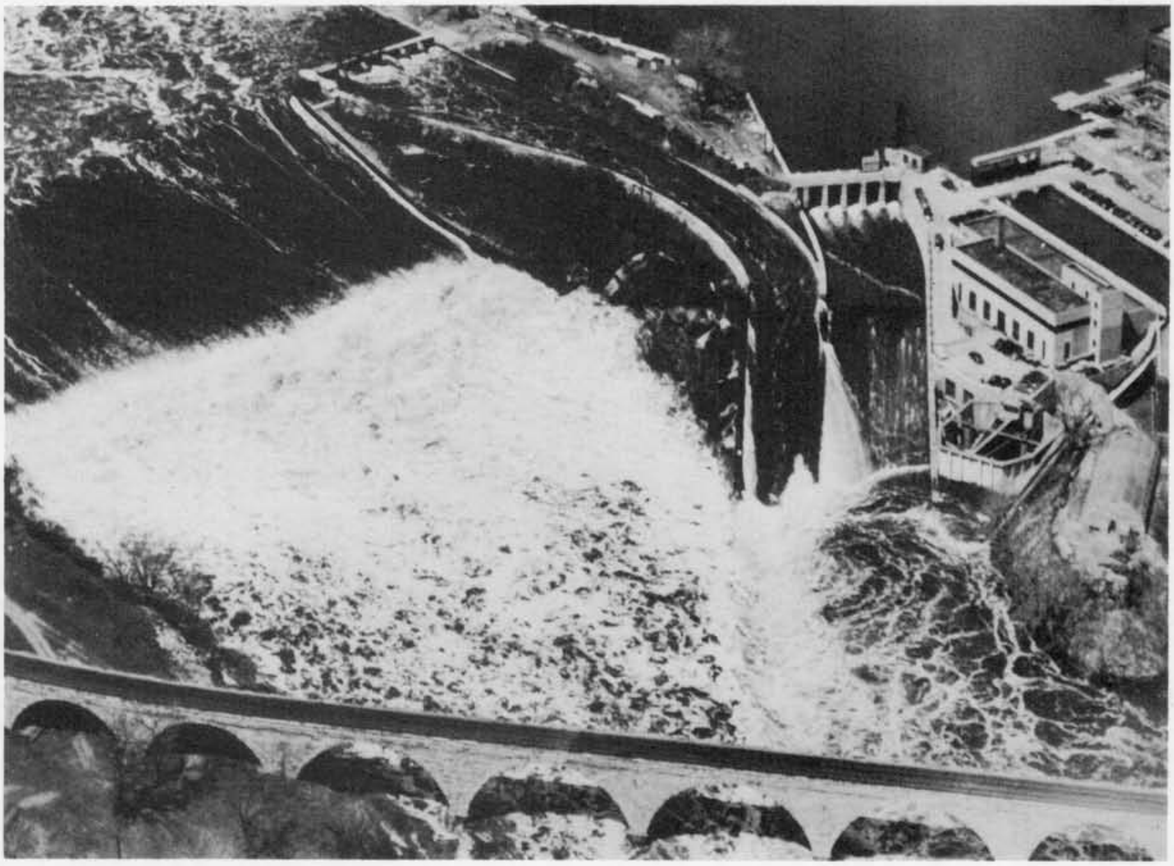

PREFACE

The experimental studies described in this report were initiated in June 1956 through the interest of the State Road Department of Florida. In May 1957 the program was expanded and placed under joint sponsorship of the State Road Department of Florida and the Bureau of Public Roads.

The studies were performed at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota.

The pipe used in the tests was supplied by the State Road Department of Florida and was received at the Laboratory during the period June-September 1956.

Arthur West, Assistant State Highway Engineer (Planning), and Thomas Bransford, Engineer of Research and In-Service Training, both of the State Road Department of Florida, collaborated with the Laboratory in establishing the scope and general features of the experimental program and contributed many helpful suggestions during the course of the studies. Carl F. Izzard and Herbert G. Bossy, Division of Hydraulic Research, Bureau of Public Roads, made further substantial contributions to the study program and assisted in the analysis of some of the data, particularly with suggestions concerning the analysis of losses at the pipe joints.

The assistance of many members of the St. Anthony Falls Hydraulic Laboratory staff in the procurement and analysis of the data and in preparation of the illustrations is acknowledged. Edward Silberman made many helpful comments and suggested the method for computation of local shear and friction factors on the basis of velocity measurements. The report was edited and reproduced under the supervision of Loyal A. Johnson and Mary Anne Peterson.

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FRONTISPIECES

The photographs illustrate the flow facilities used in the experimental studies. They include a view of the downstream end of the 36-in. pipe with a discharge of 150 cfs, a view of the 36-in. pipe installed for tests, an exterior view of the volumetric tanks which are used to measure large discharges, and an aerial view of the Laboratory site at St. Anthony Falls on the Mississippi River.

ABSTRACT

Experimental studies were performed on 24-in. and 36-in. concrete culvert pipe to determine the effect of interior surface finishes and joint irregularities on the frictional resistance of the pipe. Cast and vibrated pipe and machine-tamped pipe were used in the tests. The studies are grouped into several more or less related categories.

For the purpose of establishing the flow resistance of pipe joints, tests were made on pipes laid in two ways, namely: (1) with the pipe laid comparable to normal construction practice closely simulating field measurements of joint irregularities, and (2) with pipe laid extremely carefully to eliminate, as far as possible, all flow interference at the joints. The first condition is referred to as "average" joints and the second as "good" joints.

A comparison of the test data for pipe with good and average joints indicated that average field irregularities produced an increase in f and n on the order of 3.6 per cent and 1.9 per cent respectively. The coefficients for pipe with bad joints were estimated, based on an analysis of the data for pipes with good and average joints.

Experimental observations were also made to provide a comparison between flow resistance of pipes produced by two different fabrication processes, cast and vibrated pipe on the one hand and machine-tamped pipe on the other. It was found that the cast and vibrated pipe was notably smoother than the machine-tamped pipe. For flows in the Reynolds number range from 75,000 to 3,500,000 in the cast pipe, the Darcy friction factor f and also n in the Manning formula decreased with increasing Reynolds number approximately as in a hydraulically smooth pipe. In the case of the tamped pipe the coefficients were relatively constant for Reynolds numbers greater than 500,000. This constant value of the coefficients is characteristic of the rough-pipe flow regime. Numerical values for 36-in. tamped pipe with average joints were 0.01588 for the Darcy f and 0.0111 for the Manning n within the range of Reynolds numbers from 500,000 to 4,500,000. For the 24-in. tamped pipe with average joints and Reynolds numbers greater than 500,000, the numerical coefficients were 0.0177 for f and 0.0110 for n.

At low Reynolds numbers, particularly in the region up to about 100,000, the flow through tamped pipes follows a smooth-pipe flow regime. A

semi-empirical curve was developed for the transition from smooth-pipe flow to rough-pipe flow in the tamped pipe.

Limited experimental data in various other categories were obtained and analyzed. This included (1) the velocity distribution in the pipe, (2) kinetic energy correction factors, (3) elevation of the grade line at the outlet of the pipe, (4) losses produced by a small pipe passing transversely through the main pipe, and (5) local friction factors based on the velocity distribution near the wall of the pipe.

Some of the analytical phases of the study and tables of basic data have been placed in the Appendices. This arrangement was selected to assist those who are primarily interested in the general results; at the same time it provides more detailed data for those who may desire such information.

C O N T E N T S

LIST OF ILLUSTRATIONS

Figure | Page

LIST OF SYMBOLS

A - Area

D - Diameter of test pipe

D' - Diameter of transverse pipe through main pipe

d - Depth

$\bar{e}$ - Average height of joint irregularity

e_o - Offset height at joint

e_b - Bead height at joint

f - Darcy friction factor

f_ℓ - Limiting value of f in rough pipe regime

f_p - Friction coefficient for pipe barrel

H - Total head in feet

h - Head loss in feet

k - Roughness height

k' - Roughness height above or below mean line

k_s - Equivalent uniform sand grain diameter

L - Length of surface roughness sample, or length of pipe in friction computations

ΔL - Increment length for measurements of surface roughness

ℓ - Length of pipe section (joint spacing)

n - Manning roughness coefficient

Q - Discharge

r_o - Internal radius of pipe

r - Radius

Re - Reynolds number $= \frac{\bar{V}D}{\nu}$

V - Local velocity

V_e - Local velocity at distance $\bar{e}$ from wall

$\bar{V}$ - Average velocity = Q/A

V^* - Shear velocity

y - Distance from wall of pipe

Y - Intercept at outlet

Z - Distance from inlet end of pipe

α - Kinetic energy correction factor

ν - Kinematic viscosity

RESISTANCE TO FLOW IN TWO TYPES OF CONCRETE PIPE

I. INTRODUCTION

This report presents the results of experimental studies of the frictional resistance to flow in 24-in. and 36-in. concrete pipe. The studies were performed at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, under joint sponsorship of the State Road Department of Florida and the Bureau of Public Roads, and had as their primary objective an evaluation of the effect of interior surface finishes of the pipe and joint irregularities upon the frictional resistance. In addition, data were obtained on (1) the hydraulic grade line at the outlet of the pipe, (2) the velocity distribution in the pipe, and (3) pressure losses created by smaller transverse pipes through the main conduit.

Two types of 36-in. diameter pipe were used in the tests. One was of the cast and vibrated type, hereafter referred to as cast pipe; the other was a machine-tamped pipe, hereafter referred to as tamped pipe. The interior surfaces of the two types differ in smoothness, due to the method of manufacture. During manufacture of the cast pipe, the concrete is placed in the annular ring between two metal forms and vibrated by various means to insure proper filling of the forms and to reduce air pockets. The pipe is then allowed to cure for a specified period before the forms are removed. The tamped pipe is produced by a machine process in which a relatively dry concrete mix is inserted in the space between the forms and continuously tamped as the form is filled, while the outer form and bottom pallet are rotated about the stationary core or inner form. Soon after the form has been filled, the non-collapsible inner form is removed. Rotation of the outer form and withdrawal of the inner form produces a surface finish somewhat similar to a "wood-float" finish sometimes used on flat concrete slabs.

The frictional losses in the pipe consist of two parts: that due to boundary shear on the walls, and local losses due to irregularities at the joints. These irregularities consist of offsets, grooves, and mortar beads, all of which disturb the boundary layer and produce additional energy loss. The irregularities may be due to improper installation or to variations in pipe diameter and the shape of tongues and grooves at the ends of the pipe.

Prior to the Laboratory tests the State Road Department of Florida obtained measurements of joint irregularities in pipe installed in ten projects throughout the state. These data were analyzed and used as a guide to the Laboratory installations. Two types of joints were used in the Laboratory. One, referred to as average joints, involved simulation of the magnitude, circumferential length, and frequency of occurrence of the field joint irregularities. The second, referred to as good joints, involved the smoothest joints obtainable. A third possibility, not tested, is a pipe with a continuous series of bad joints.

The pipe used in the test was provided by the State Road Department of Florida and was selected, without advance notice, from the stock on hand in the yards of four manufacturers in the State of Florida. An effort was made to select pipe typical of that in use by the Road Department in 1955-56. The selection committee consisted of the following personnel from the State Road Department:

(a) Engineer of Research,
(b) Engineer of Drainage,
(c) Engineer of Materials and Tests, and
(d) Assistant State Highway Engineer for Construction.

At the invitation of the State Road Department a representative of the American Concrete Pipe Association observed the selection of the pipe.

In the Laboratory tests of 36-in. pipe, thirty 8-ft sections were used in each test, giving a total length of about 240 ft. The zone of flow establishment varied from 60 to 100 ft, dependent on pipe roughness, leaving an effective length of 140 to 180 ft for determination of the friction coefficients. In the tests of 24-in. pipe, 24 sections were used, with a total length of 192 ft. The zone of flow establishment was about 40 ft long, leaving an effective length of about 152 ft.

II. CHARACTERISTICS OF PIPE AND PIPE JOINTS

A. Surface Finish of the Pipe Used in Tests

The surface finish of the pipe used in the tests is shown in Figs. 1, 2, and 3. The photographs illustrate the range of surface textures encountered in these samples of pipe. Considerable variation was noted in the

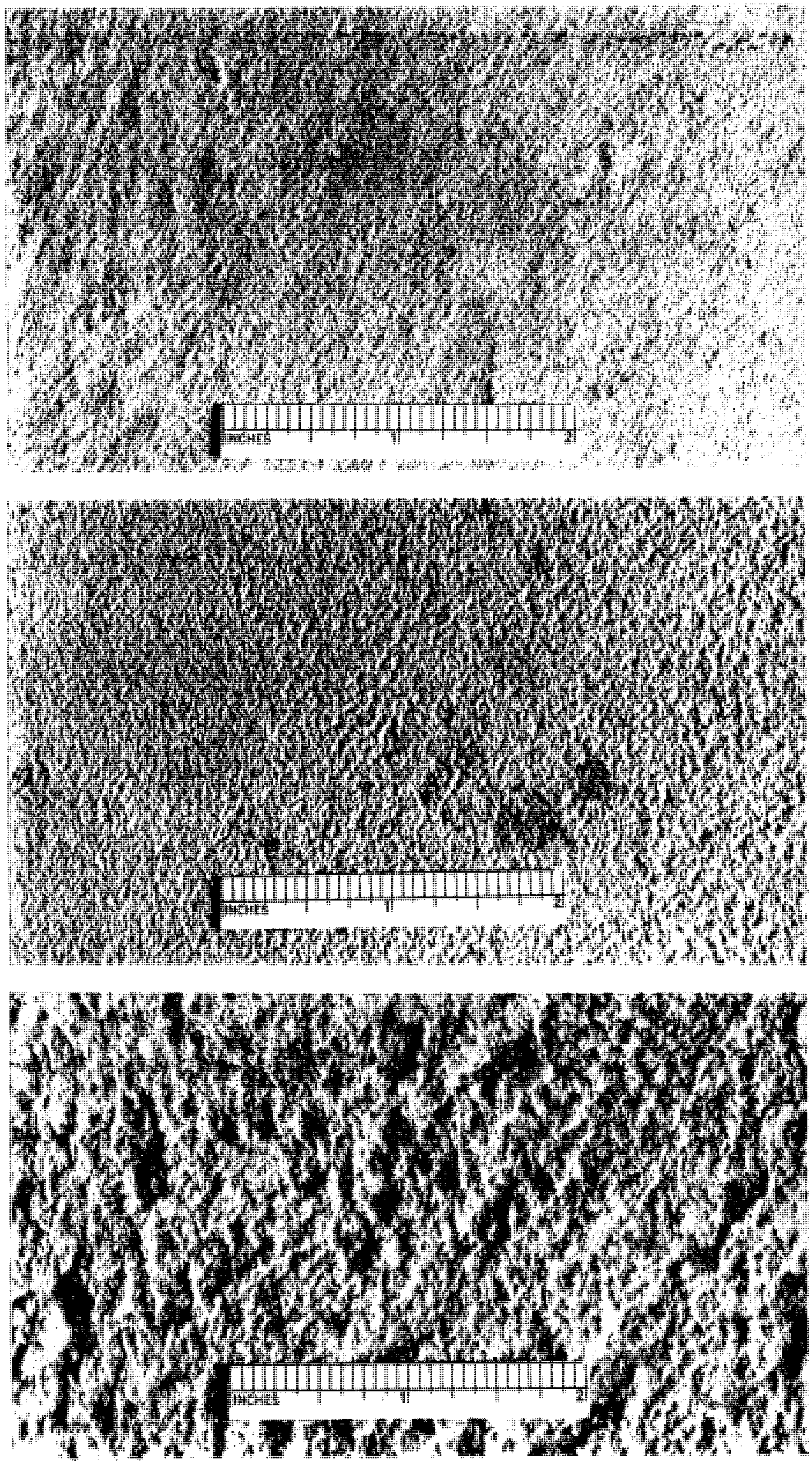


Fig. 1 – Interior Surface of 36-in. Tamped Pipe. Upper––good surface; middle––average surface; lower––rough surface. (Only one of 40 sections had a roughness similar to this sample.)

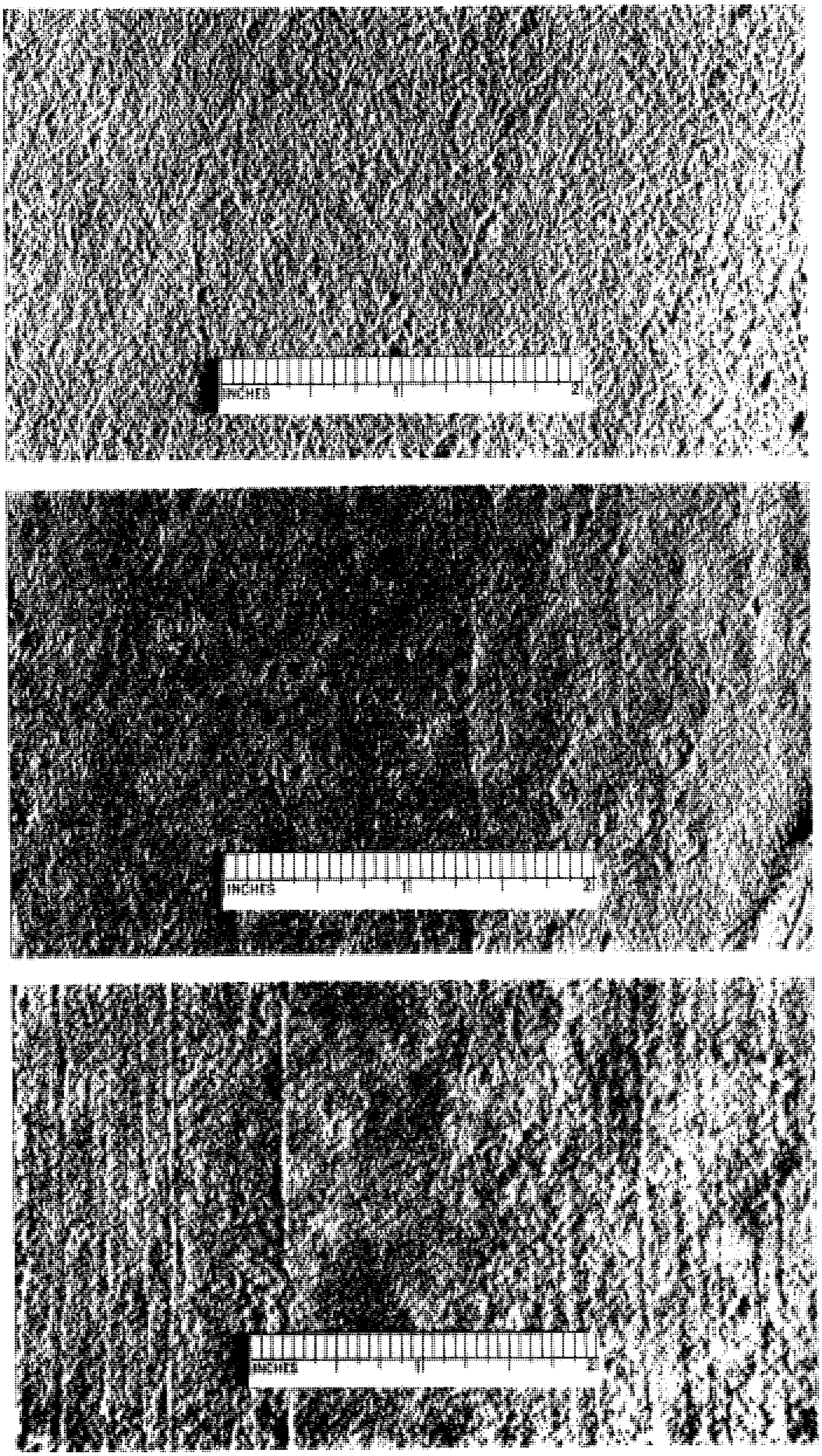


Fig. 2 - Interior Surface of 24-in. Tamped Pipe. Upper--good surface; middle--average surface; lower--rough surface. The effective roughness of middle sample is larger than that of upper sample because of waves and deformities such as shown at lower right corner of middle photograph.

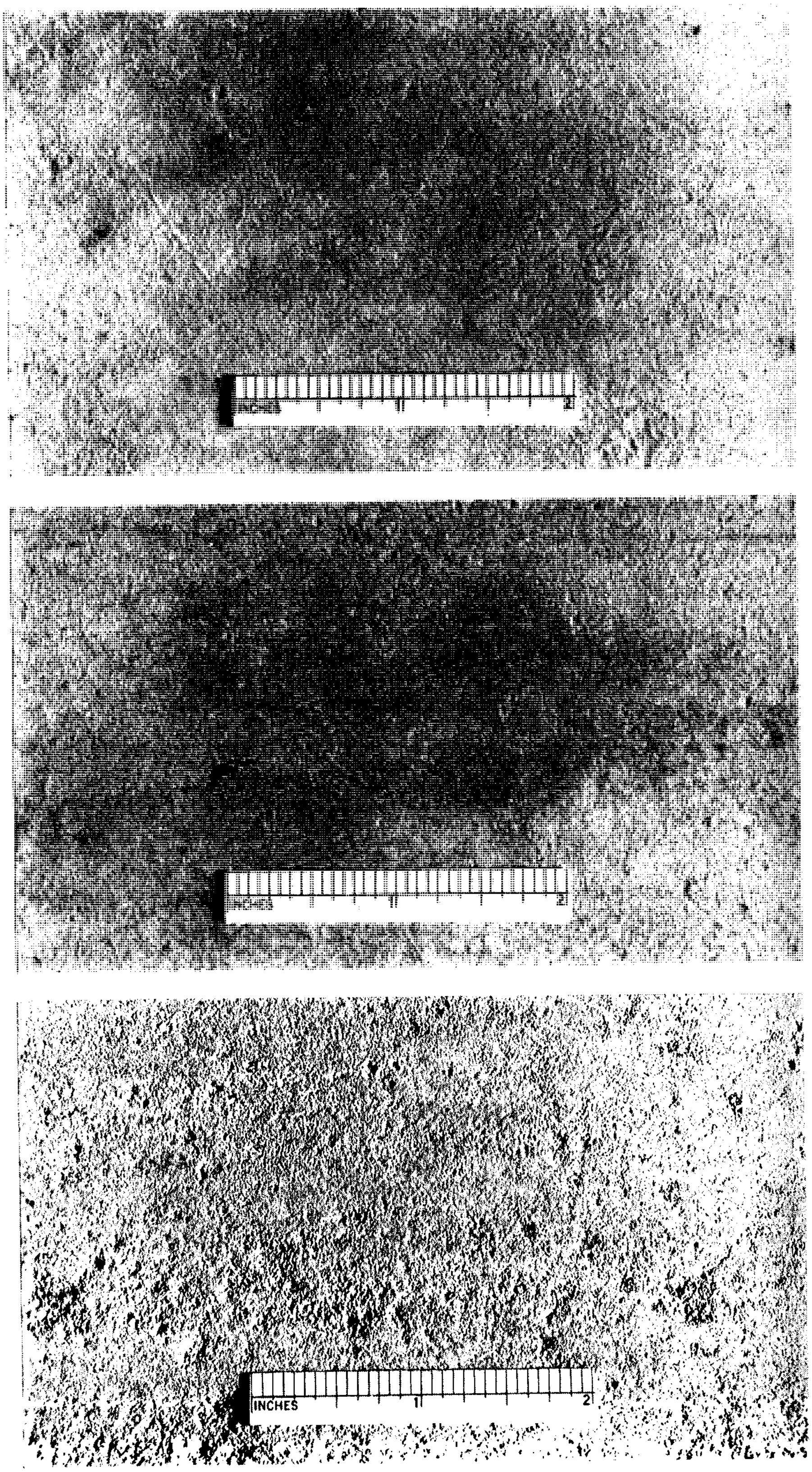


Fig. 3 – Interior Surface of 36-in. Cast Pipe. Upper--good surface; middle--average surface; lower--rough surface.

texture of the tamped pipe both over the area of an individual pipe section and between the various sections; as a result it was difficult to select a specific area with an average texture. In Fig. 1 selected areas are shown for the 36-in. tamped pipe, representing "smoother than average," "average," and "rougher than average" textures. Figure 1c shows the roughest section of 36-in. tamped pipe. Only one section out of 40 sections available had a surface of this type.

Figure 2 illustrates the texture of the 24-in. tamped pipe and Fig. 3 the texture of the 36-in. cast pipe. The surface of the cast pipe was very smooth except for small holes which apparently were caused by entrapped air. It is unlikely that these holes had an appreciable effect on the friction loss in the pipe because their area was quite small as compared to the total wetted surface of the pipe.

Sections 6 in. by 9 in. were sawed from the pipe and are preserved as a permanent record with the State Road Department of Florida in Gainesville and the Bureau of Public Roads in Washington, D. C.

As a supplement to the photographs and the pipe samples, measurements were obtained of the nominal roughness height of the interior surface of the pipe. The measurements were made with a dial gage which was traversed along an accurately machined base plate placed in the pipe. The gage could be read to the nearest 0.0001 in. and was fitted with a concave tip having a terminal diameter of 0.007 inch. The measuring procedure and detailed data are presented in Appendix C. Briefly, it involved gage readings at intervals of 0.02 ft over a length of 1.3 ft, in each of twelve or thirteen pipe samples selected at random from each type of pipe. This provided a total of about 858 readings for each type of pipe. Though dependent to a considerable extent on the method of analysis, the data generally indicated that the average roughness height of the tamped pipe was on the order of three times that of the cast pipe. The analysis also indicated that the surface of the pipe had waves of small amplitude in addition to a texture roughness. These were of minor importance in the tamped pipe as the texture roughness tended to mask the waves. The texture of the cast pipe, however, was sufficiently smooth so that waves on the order of 0.01 in. high by 4 to 12 in. long were recorded. These probably had some effect on the frictional resistance of the cast pipe. The method of analysis presented in Appendix C provides an indication of both texture and waves.

B. Field Investigation of Pipe Joints

Prior to the Laboratory tests, the State Road Department of Florida in cooperation with a representative of the St. Anthony Falls Hydraulic Laboratory obtained measurements of joint irregularities in 36-in. concrete pipe that had been installed on ten projects throughout the state. It was noted that these irregularities were of three basic types:

(a) offsets--due to misalignment or variation in diameter of the pipe,

(b) grooves--formed by annular opening between tongue and groove ends of pipe, and

(c) beads and fillets--formed by mortar smoothed over the interior surface of joint.

Figure 4 illustrates the irregularities noted in the field joints and a cross section of the pipe showing the average circumferential length of grooves and beads.

The maximum offset encountered in the field measurements was 1.37 inches. This occurred in pipe in which the inside diameter was about 0.75 in. larger at one end than at the other; thus, the taper was about 2 per cent of the pipe diameter. Most of the joints in the project where this joint was encountered had offsets ranging from 1 in. to 1.37 inches. Three of these are included in the field sample.

The offsets were divided into two types. If the downstream edge extended radially inward farther than the edge of the upstream pipe, the flow would be forced to contract; this is referred to as a positive offset. The opposite case, with an expansion at the joint, is referred to as a negative offset. If two circular pipes of the same diameter were displaced transversely at the joint, positive and negative offsets of the same magnitude would result.

The diaper seal was used at all joints. In some instances mortar ran through the joint into the interior of the pipe. This mortar was troweled over the joint, forming a bead or fillet. If mortar did not pass through the joint it was usually applied from the inside. The average joint had a bead or fillet over the lower two-thirds of the circumference, but one-third of the joint, at the crown, was usually not covered. This left a groove ranging up to 1.54 in. wide by about 1 in. deep. The bead height, with respect

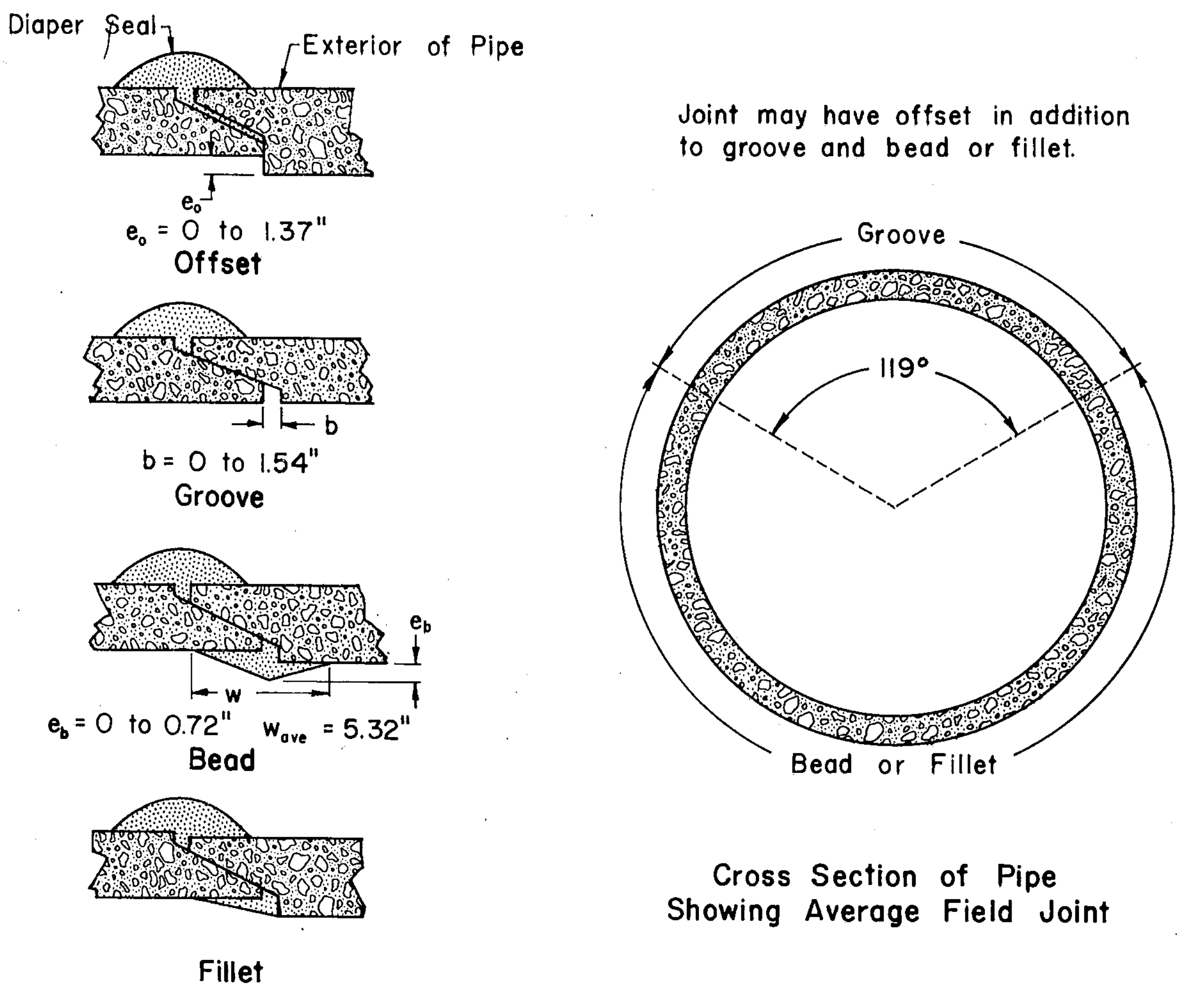


Fig. 4 – Pipe Joint Details

to the inner edge of the joint, ranged from zero (for a fillet) up to 0.72 inch.

The height of beads and offsets was measured by means of a dial gage mounted on a bar which was placed against the surface of the pipe. The bead height was measured with respect to the innermost pipe surface at the joint. Sufficient measurements were taken around the circumference to define the maximum height of beads and offsets and significant changes in height. The circumferential position of all measurements was recorded. From these data the area, length, and average height of offsets and beads were determined.

Figure 5 illustrates some of the field data on beads and offsets. The graph of maximum offset height per joint provides an indication of the maximum offsets encountered but is of limited value in an analysis of energy loss at the joints. Accordingly, the bead area and the positive offset area were added and the sum divided by the nominal cross-sectional area of the pipe. When multiplied by 100, this gave the reduction in area at the joint, in per cent. These data are shown in the fourth graph of Fig. 5. It may be noted that the median value is about 2 per cent.

Additional data on the field joints are summarized in Table I and Appendix B.

All of the data in Fig. 5 and the field data in Table I are for 36-in. machine-tamped pipe. An attempt was made to procure data on 24-in. pipe and 36-in. cast pipe but these efforts were unsuccessful except for two joints in 24-in. pipe.

C. Laboratory Data on Pipe Joints

The Laboratory tests conformed to two basic conditions:

(a) pipe installed with joint conditions similar to average field installations, hereafter referred to as "average" joints, and

(b) pipe installed with the best joints obtainable, hereafter referred to as "good" joints.

The 36-in. tamped pipe was installed in accordance with these criteria; the corresponding data are illustrated in Fig. 6.

TABLE I

SUMMARY DATA ON FIELD AND LABORATORY PIPE JOINT CHARACTERISTICS

(Each value is mean per joint, except those specified as average)

	Field		Laboratory						
			36-in. Cast		36-in. Tamped		24-in. Tamped		
	36-in. Pipe	Equiv. 24-in. Pipe	Average Joints	Good Joints	Average Joints	Good Joints	Average Joints (A)	Average Joints (B)	Good Joints
Maximum positive offset	0.213	0.142	0.172	0.172	0.373	0.192	0.161	0.161	0.111
Maximum negative offset	0.304	0.203	0.301	0.301	0.218	0.148	0.299	0.299	0.185
Mean offset height	0.187	0.125	0.130	0.130	0.182	0.098	0.149	0.149	0.118
Positive offset area	7.35	3.27	4.03	4.03	13.37	6.28	3.09	3.09	2.92
Negative offset area	13.80	6.13	10.64	10.64	7.23	4.77	8.17	8.17	6.04
Total offset area	21.15	9.50	14.67	14.67	20.60	11.05	11.25	11.25	8.96
Length of bead or fillet	79.57	53.05	79.57	113.1	79.57	113.1	57.40	57.40	75.4
Average width of bead or fillet	5.50	-	4.60	5.00	5.10	5.00	4.35	4.88	5.00
Maximum height of bead or fillet	0.265	0.177	0.296	0	0.273	0	0.132	0.063	0
Average height of bead or fillet	0.167	0.111	0.173	0	0.177	0	0.103	0.032	0
Average covered area of bead	541.4	-	366.4	0	405.9	0	318.2	358.3	0
Projected area of bead or fillet	13.26	5.90	13.76	0	14.11	0	5.93	1.83	0
Length of groove	33.53	22.35	33.53	0	33.53	0	18.00	18.00	0
Average width of groove	0.711	-	0.219	0	0.750	0	0.555	0.555	0
Area reduction	20.61	9.16	17.80	4.03	27.49	6.28	9.02	4.92	2.92
Area reduction (per cent)	2.03	2.03	1.75	1.40	2.70	0.62	1.99	1.09	0.65

Units are inches and square inches.

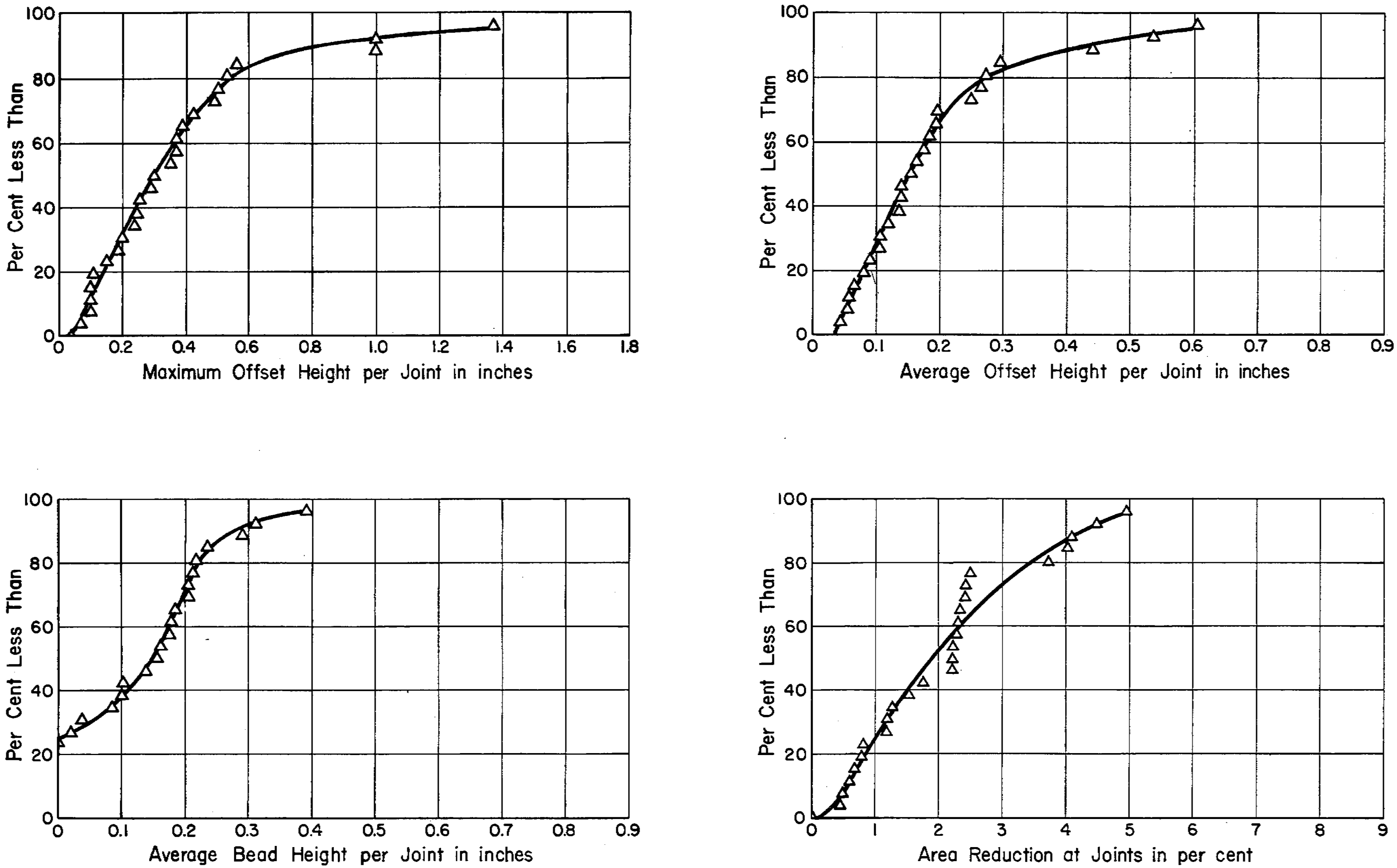


Fig. 5 – Field Data on Joint Irregularities

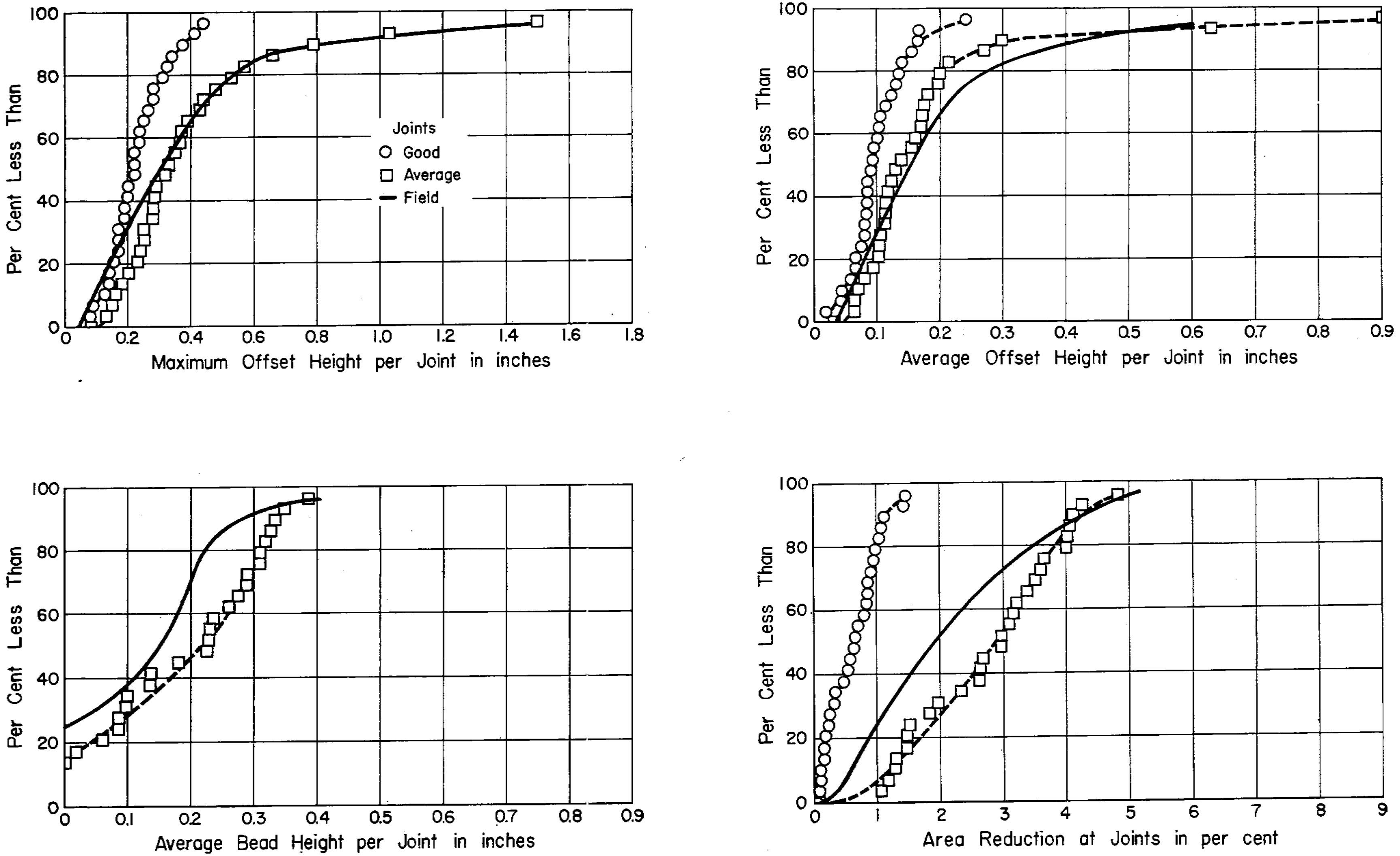


Fig. 6 – Laboratory Data on Joint Irregularities in the 36-In. Tamped Pipe

The installation representing average joints in 36-in. tamped pipe involved placement of the pipe sections so that the maximum offset at the various joints corresponded to the distribution of maximum offsets in the field. The offset was then measured at eight points around the circumference so that an average could be determined. Mortar was troweled around the lower 241 degrees of the circumference to form either a bead or fillet, in accordance with field data. After the mortar had set, the height and width were measured. These data are included in Appendix B.

At the conclusion of hydraulic tests of the 36-in. tamped pipe with average joints, the sections were taken apart, the joints cleaned, and the sections reassembled with minimum possible offsets. After the offsets were measured, mortar was troweled around the joint to fill the grooves and to form a fillet about 3 in. long where positive or negative offsets did exist.

As field data were not available on 36-in. cast pipe and as there was a possibility that fabrication methods might result in less variation in dimensions of the tongues and grooves, a different procedure was followed. For the average joint condition the cast pipe was assembled with procedures similar to those used in the field. For example, the pipe was supported from the midpoint and forced against the previously laid section by a crowbar. The downstream end of the section was then adjusted to grade and supported by wooden blocks. In effect the only support for each section was at the downstream or tongue end of each section. This tended to produce the maximum offset which would result from irregularities in the tongue and groove parts of the pipe. After the pipe was completely laid the offsets were measured. Beads and fillets were then added in accordance with field measurements of the tamped pipe, as it was reasoned that the workmanship in application of the mortar would be similar for the two types of pipe. As may be noted in Fig. 7, the range of offsets obtained with the cast pipe was much narrower than that of the field data for the tamped pipe. The bead height and the reduction in area for the average joints were fairly close to the field data. Initially it was intended to re-lay the cast pipe to obtain the smoothest possible good joints. However, weather conditions affecting exterior portions of the test facilities necessitated curtailment of the program; it was decided to remove the beads and otherwise smooth up the joints of the initial installation of cast pipe and obtain test data on this system. Since the offsets were the same as those for the average joints, a comparison of frictional resistance in tests of good and average joints for <u>cast</u> pipe indicates only the effect of the beads.

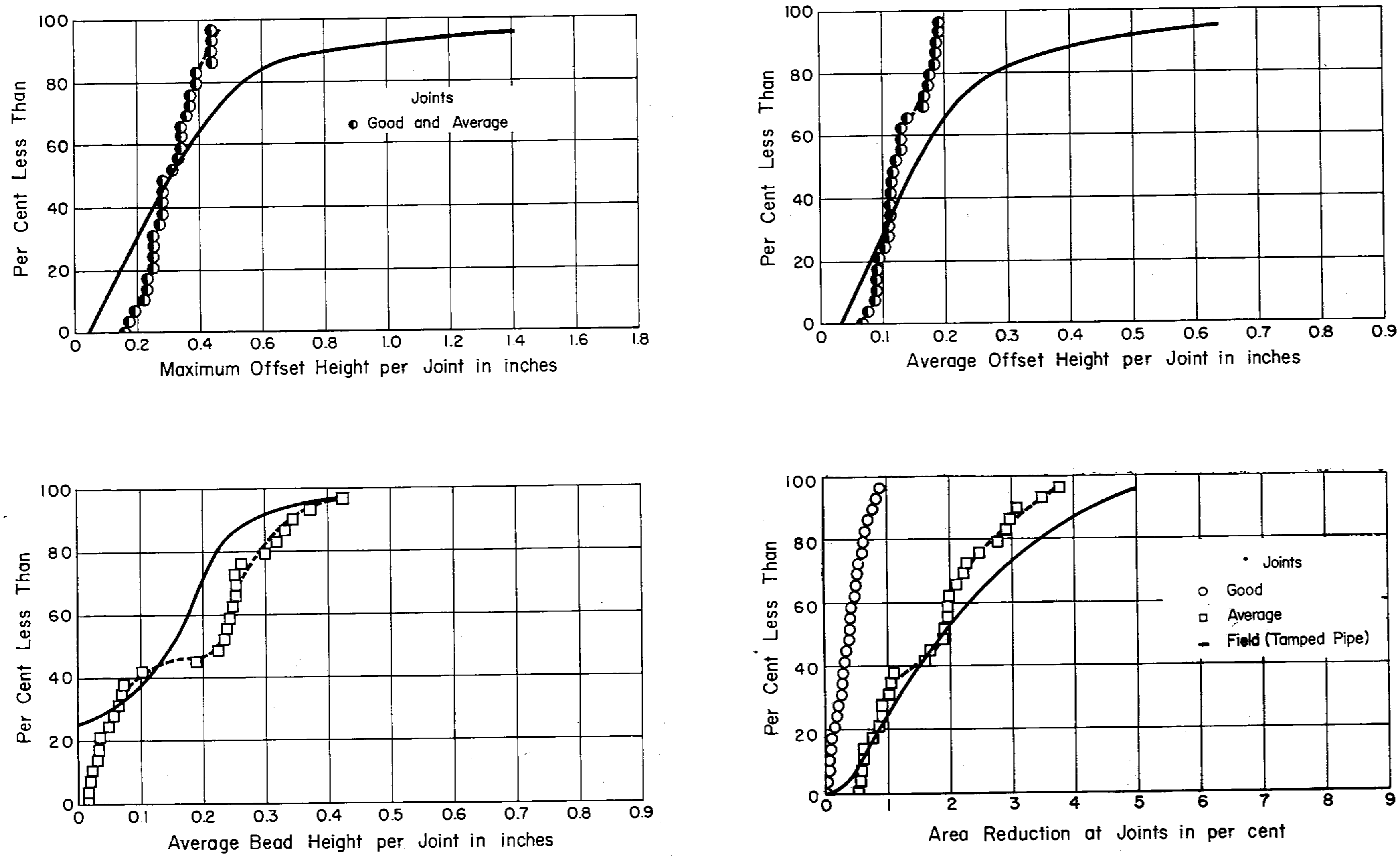


Fig. 7 – Laboratory Data on Joint Irregularities in the 36-In. Cast Pipe

The tests of 24-in. pipe were initiated before all field data were available. Moreover, except for two joints, the field data were obtained on joints in 36-in. pipe, necessitating some judgment in application of the results to 24-in. pipe. It was finally decided to scale down the field offsets in accordance with the diameter ratio and to use beads somewhat similar to the 36-in. pipe. The two 24-in. field joints for which data were available had untroweled mortar extrusions up to 3/4 in. high. These were reproduced in the 24-in. pipe although it was recognized that an untroweled joint was the exception rather than the rule. Tests were performed with and without the extrusions on two joints. For reference purposes the respective conditions were referred to as average-A and average-B joints. Subsequently the 24-in. pipe was relaid with the smoothest joints possible, referred to as good joints.

Figure 8 illustrates data on the Laboratory joint irregularities and equivalent field data for the 24-in. pipe. As noted above, the latter are based on offsets two-thirds as high as the 36-in. field data. The Laboratory offsets were initially in good agreement with the initial field curves. Subsequent additional field data were received, modifying the field curves; as a result the Laboratory offsets for average joints are rougher than they should be. However, the good joints, which represent minimum possible offsets, are very close to the equivalent field curve. This indicates that the equivalent field curve is probably incorrect and that the field offsets do not scale down from the 36-in. data in accordance with the diameter ratio. The data on bead height also do not agree with the final field curves, where the latter are based on a diameter ratio.

The primary value of Fig. 8 is to illustrate the conditions tested in the Laboratory, with the conclusion that they may or may not simulate field conditions for 24-in. pipe. In general, it appears that the average-A joints are probably representative of bad field joints in 24-in. pipe and the average-B joints are probably close to average field joints. In the analysis of energy loss due to joint irregularities the primary emphasis should be placed on the tests of 36-in. pipe where field data are available and where the Laboratory data closely approximate the field conditions.

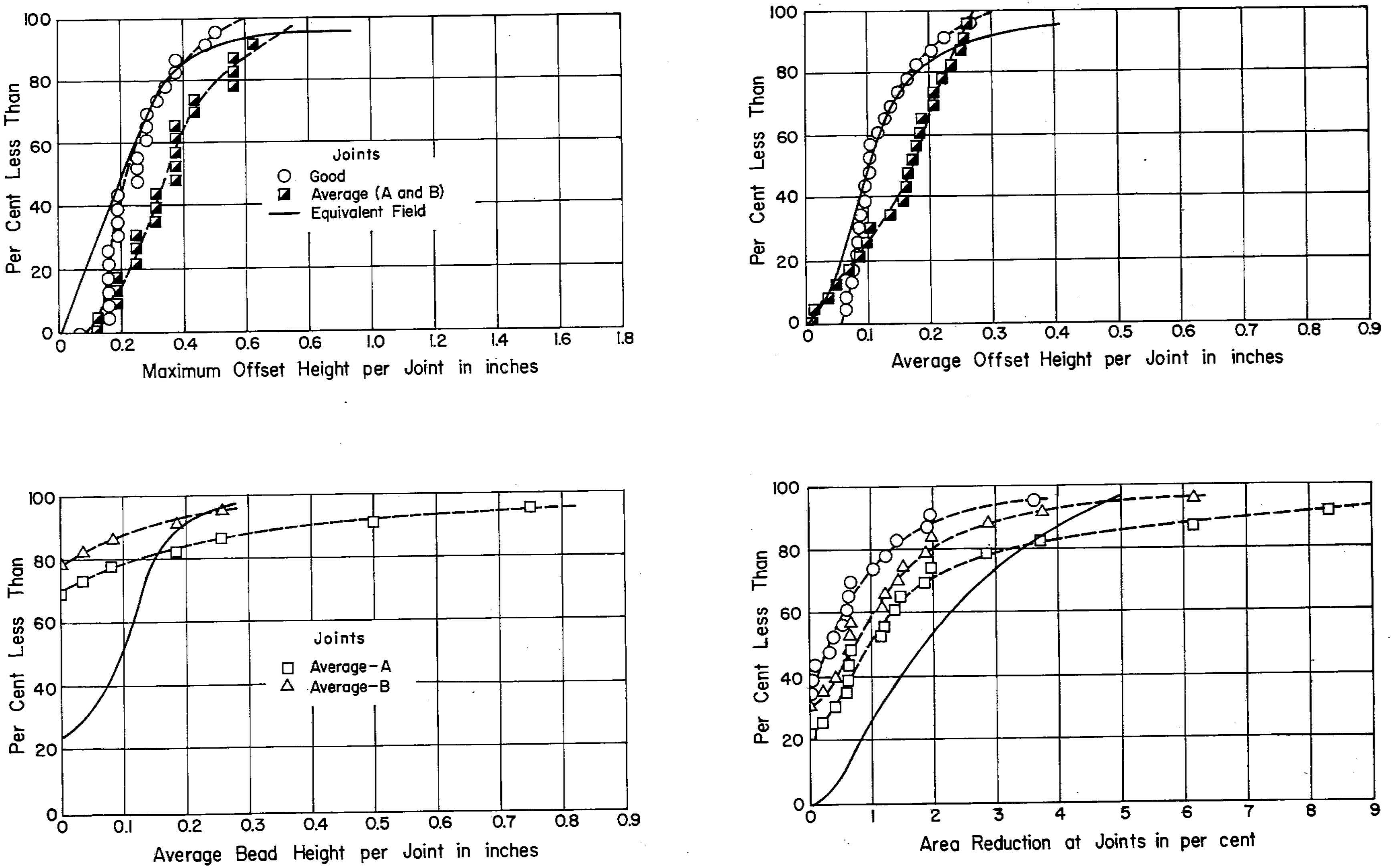


Fig. 8 – Laboratory Data on Joint Irregularities in the 24-In. Tamped Pipe

D. Pipe Diameter and Related Data

The 24- and 36-in. tamped pipes used in the tests were obtained from four different pipe companies. The 36-in. cast pipes were all obtained from the same company. As there was a possibility that the surface texture might vary in the tamped pipe, sections from the various companies were intermixed in the Laboratory installation. Tables 9-11 of Appendix B illustrate the sequence in which the pipe was laid for all tests. The average diameter at both ends of each section is indicated. In sections where piezometers were located, the diameter at the piezometer is also indicated. In tests of average joints in 24- and 36-in. tamped pipe, the pipes were selected at random, except for the effort to intermix pipe from the various companies.

The average diameter of the groove end of the 24-in. pipe was 0.10 in. larger than the tongue end, resulting in some offset regardless of the care in laying the pipe. No appreciable variation of this type was noted in the 36-in. pipe.

Twenty-four 8-ft sections of 24-in. pipe and thirty 8-ft sections of 36-in. pipe were used in the tests. The following table summarizes the length, slope, and average diameter of the test installations.

TABLE II

PIPE DATA

Pipe	Joints	Average Diameter	Total Length	Slope
36 in. Tamped	Average	36.07 in.	241.3 ft	0.00097
	Good			0.00100
36 in. Cast	Average	35.99	241.7	0.00100
	Good			
24 in. Tamped	Average (A and B)	24.14	193.0	0.00103
	Good	24.11	194.0	0.00112

As the determination of the hydraulic grade lines and resultant friction coefficient were based on the zone in which established flow occurred, the average pipe diameter was also computed for this zone. The zone of flow establishment varied from about 40 ft for the 24-in. pipe, to 60 ft for the 36-in.

tamped pipe and to 95 ft for the 36-in. cast pipe. As a somewhat arbitrary figure, the upstream six sections and eight sections of pipe were disregarded in computations of average diameter of the 24-in. and 36-in. pipe respectively. In the remaining sections, the data on end diameters as well as midpoints (in sections where data were available) were averaged, with equal weight for all measurements.

III. TEST FACILITIES AND PROCEDURES

The basic test facilities, manometers, static tubes, and the associated test procedures are described in Appendix D.

IV. EXPERIMENTAL RESULTS--FRICTIONAL RESISTANCE

A. Hydraulic Grade Line and Zone of Flow Establishment

The discharges used in this series of tests ranged from 2.8 to 153 cfs in the 36-in. pipe, and 2.7 to 29 cfs in the 24-in. pipe. These ranges are somewhat greater than the range of interest in normal installations using these pipe sizes. The data obtained with high discharges and corresponding high Reynolds numbers may assist in extrapolation of the results to larger pipe sizes. The data obtained at low discharges should contribute to an evaluation of the transition zone between the smooth-pipe curve and the relatively constant coefficients associated with rough-pipe flow.

Figures 9 and 10 illustrate typical hydraulic grade lines for the two types of pipe and two discharges. It may be noted that the apparent zone of flow establishment for the tamped pipe extends about 65 ft from the inlet. Beyond this zone the grade line has no noticeable curvature. The apparent zone of flow establishment for the cast pipe extends to a point about 100 ft from the inlet. Subsequent measurements of the velocity distribution in the pipe indicated that the velocity profile was not fully developed at the above locations, but the change in the downstream zone was apparently so small that it did not produce a measurable change in the hydraulic grade line.

The fact that the cast pipe yielded a longer zone of flow establishment than the tamped pipe is in agreement with available theory. As the cast pipe is smoother than the tamped pipe, the boundary shear is lower and the growth of the boundary layer proceeds at a slower rate. Computations based

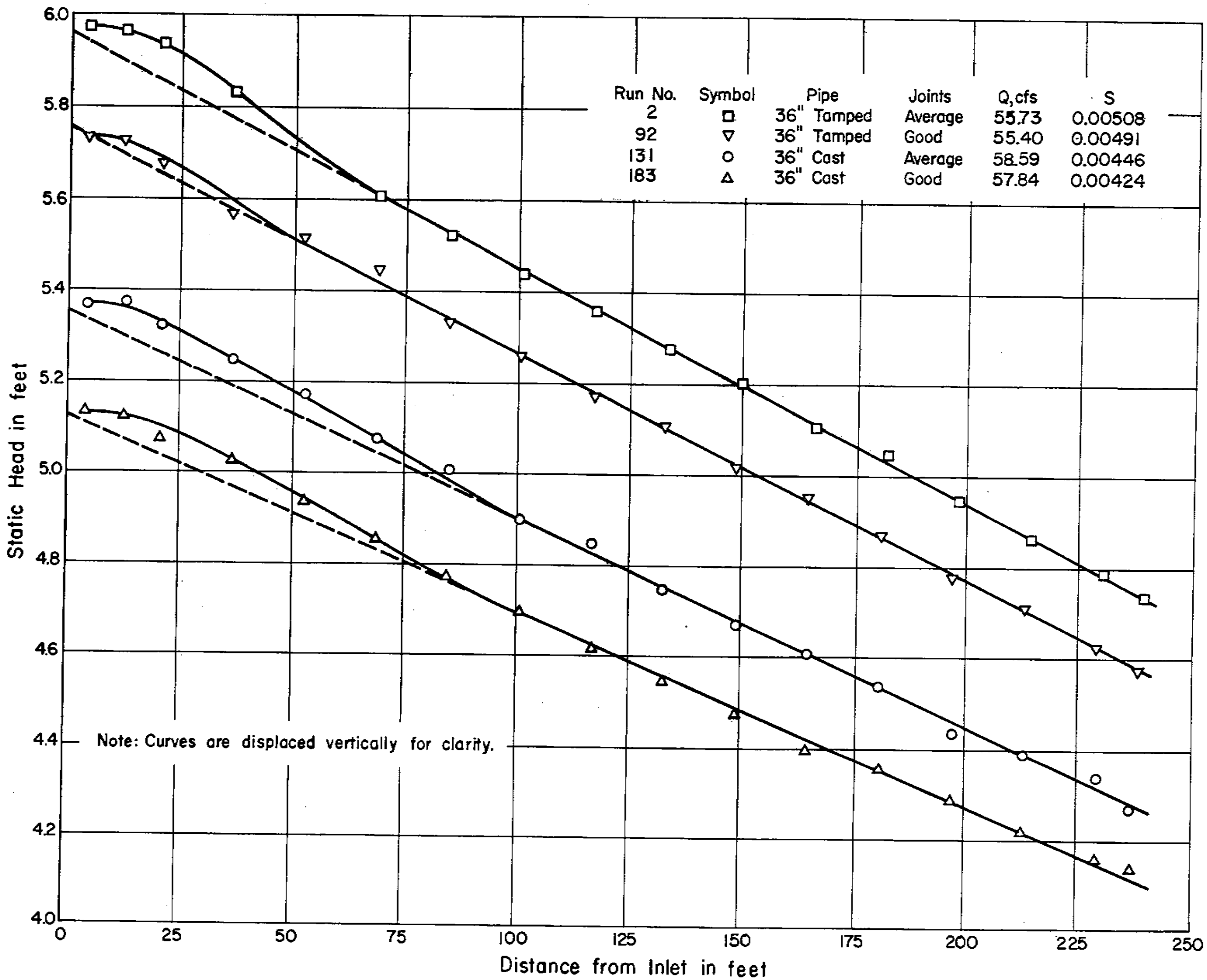


Fig. 9 – Typical Hydraulic Grade Lines for Average Test Discharges

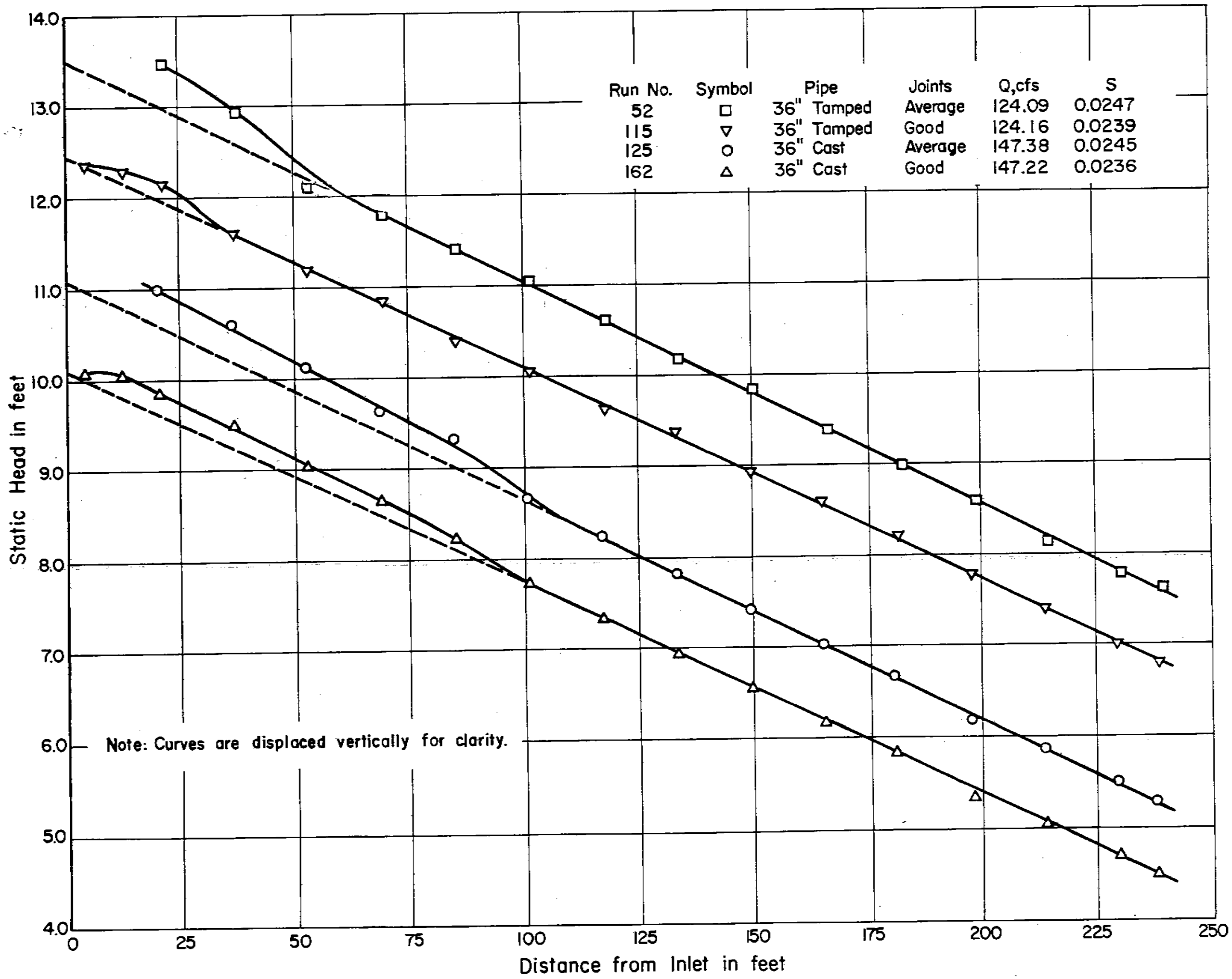


Fig. 10 – Typical Hydraulic Grade Lines for High Test Discharges

on a theory proposed by Keulegan [1]* indicated a length of about 60 ft for the 36-in. tamped pipe and 95 ft for the cast pipe. The computation is based on the boundary shear as indicated by Darcy's f. In these computations use was made of the experimental data on f, for the two types of pipe. In general, the experimental data on the zone of flow establishment were in good agreement with the theory.

In the zone of established flow a few static readings deviate or scatter slightly about a straight line. Some of the scatter can be attributed to variations in the boundary roughness, joint irregularities, and variations in pipe diameter. Where piezometers were located within 4 ft of a bad joint, the static readings were adversely affected by the joint, usually indicating a low pressure. Before computing the slope the velocity head, based on the average local velocity at each piezometer, was added to the static readings to correct for variations in the diameter of the pipe. This reduced the scatter shown in Figs. 9 and 10.

B. Basic Equations

Frictional resistance was evaluated in terms of both Darcy's friction factor f and n in Manning's formula. The Darcy equation is

$$h = f \frac{L}{D} \frac{\bar{V}^2}{2g} \tag{1}$$

where $\bar{V}$ = average velocity of flow,
h = head loss due to barrel friction and joint losses,
L = length of pipe, and
D = average pipe diameter.

The Manning equation is

$$\bar{V} = \frac{1.486\, R^{2/3}\, S^{1/2}}{n} \quad \text{or} \quad h = \frac{L\, n^2 \bar{V}^2}{2.21\, R^{4/3}} \tag{2}$$

where R = hydraulic radius, and
S = slope of energy grade-line.

---

*Numbers in brackets refer to List of References on p. 75.

The diameter used in both of the above equations was the average value for the downstream 22 sections of 36-in. pipe and the downstream 18 sections of 24-in. pipe. The actual values are listed in Table II. In most instances the nominal pipe diameter would be acceptable for design purposes. In an analysis of the experimental data, however, the average diameter of the test pipes was used to insure an accurate evaluation of the friction coefficients. It may be noted that in the Darcy equation

$$f = \frac{2g\ h}{L} \cdot \frac{D}{\overline{V}^2} = \frac{2g\ h}{LQ^2} \cdot \frac{\pi^2\ D^5}{16} = \frac{2g\ h\pi^2}{16\ LQ^2} \cdot D^5 \qquad (3)$$

As the equation involves D^5, a small variation in D can be significant in an evaluation of the friction coefficient.

The experimental data on discharge, energy grade-line slope, Reynolds number, friction coefficients, and computed values of various parameters are tabulated in Appendix A.

C. Data for the 36-in. Tamped Pipe

Figure 11 illustrates the experimental data on the 36-in. tamped pipe for average (simulated field) joints, with Darcy's f and Manning's n plotted as a function of Reynolds number. Data were obtained for Reynolds numbers ranging from 100 thousand to 4.4 million. The Karman-Prandtl smooth-pipe curve

$$1/\sqrt{f} = 2 \log Re\sqrt{f} - 0.8 \qquad (4)$$

is shown on the upper graph of Fig. 11 for reference purposes.

For Reynolds number below 2×10^5 the experimental data fall almost on the smooth-pipe curve. With increasing Reynolds numbers the data deviate from the smooth-pipe curve and f becomes relatively independent of Reynolds number for $Re > 5 \times 10^5$. The general trend of the curve is characteristic of the rough-pipe regime in turbulent flow.

There is a slight hump or crest in the curve at $Re \simeq 2 \times 10^6$. It is possible that this may be caused by separation of flow at the joints; if separation does occur, the length of the separated zone and the consequent energy loss would depend to some extent on the turbulence level in the flow

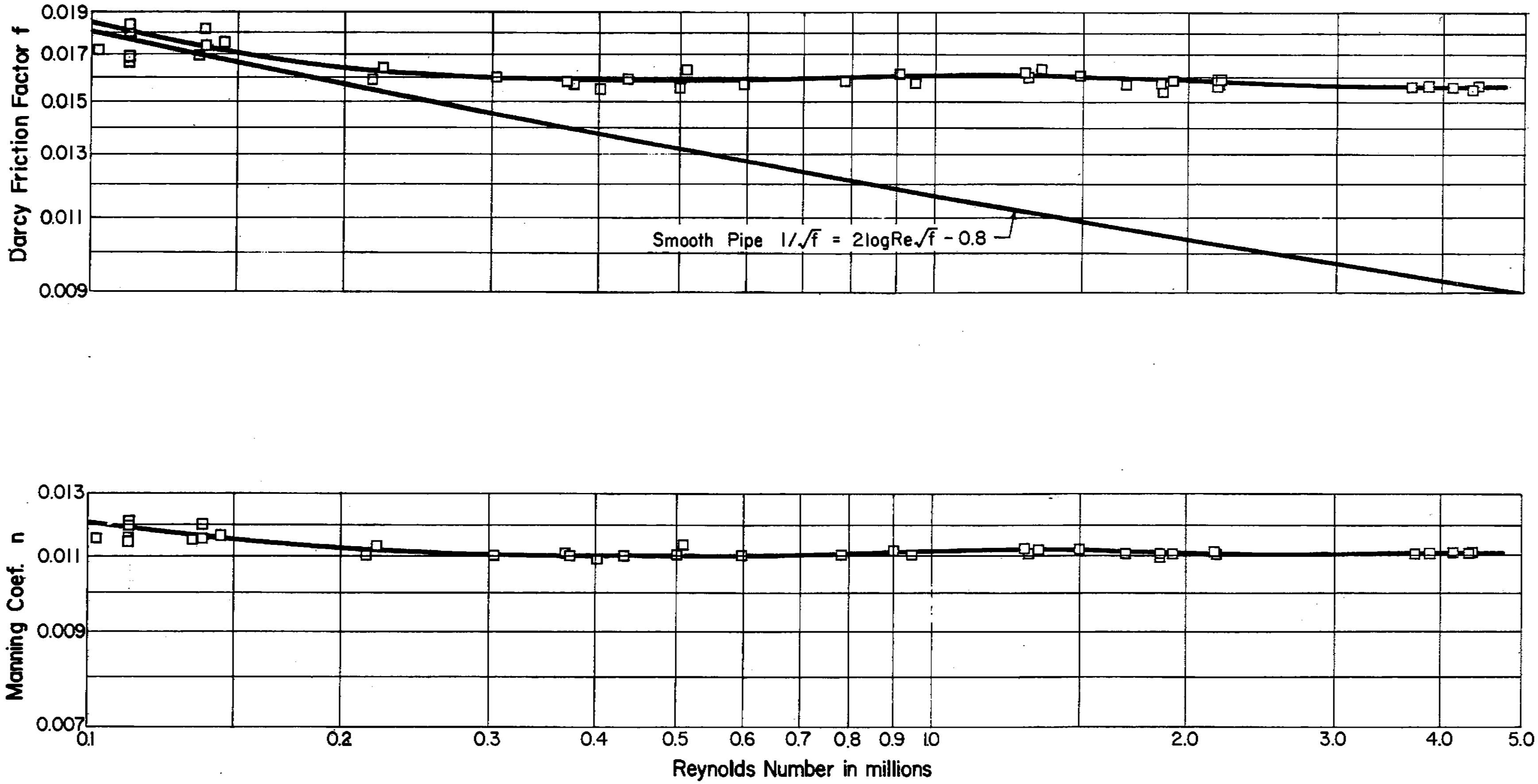


Fig. 11 - Friction Coefficients for the 36-In. Tamped Concrete Pipe with Average Joints

and as a result would depend on the Reynolds number. Although the total effect on the friction coefficient is quite small, it is of interest.

As noted above, the value of Darcy's f was essentially constant for Reynolds numbers in excess of 5×10^5; an average of all data with Reynolds numbers above this value could be used to determine the limiting or rough-pipe regime value of f for this pipe. However, due to the fact that some minor variations did exist, the limiting value was based on data with $Re > 3 \times 10^6$. The resultant average values were $f_\ell = 0.01570$ and $n_\ell = 0.01106$. The Nikuradse sand-grain roughness corresponding to this value of f is $k_s = 0.00114$ ft, and $r_o/k_s = 1321$. For design purposes there would be some merit in using all data with $Re > 5 \times 10^5$; the corresponding data for this condition are $f_\ell = 0.01588$, $n_\ell = 0.01113$, $k_s = 0.00120$ ft, and $r_o/k_s = 1253$.

The parameter $\frac{Re\sqrt{f}}{D/k}$ is sometimes used to define the upper limit of the transition zone between smooth-pipe and rough-pipe regimes. The above data for Reynolds numbers above 3×10^6 would correspond to $\frac{Re\sqrt{f}}{D/k} > 142$. The data for $Re > 5 \times 10^5$ would correspond to $\frac{Re\sqrt{f}}{D/k} > 25$.

Referring to Fig. 11, it may be noted that there is very little scatter of data except at very low Reynolds numbers. The scatter in this region is primarily due to errors in measurement of the pressure or head loss. For example, with a discharge of 2.93 cfs, the corresponding Reynolds number was 1.12×10^5 and the head loss between two piezometers 145.458 ft apart was only 0.00214 ft or 0.0257 inch. The micro-manometer used for low discharges could be read to 0.001 inch. Considering that two micrometers must be read to obtain the differential pressure, the nominal error could range up to 0.002 in. or ± 8 per cent of the above differential. The probable error was reduced by taking from 10 to 20 readings of each micrometer and averaging the results. While three of eight points in this region deviate from a mean line by 5 to 7 per cent, the remaining data have very little scatter. In view of the extremely small head differentials associated with the low Reynolds numbers, the data are considered quite good.

Figure 12 illustrates the experimental data for the 36-in. tamped pipe with good joints. As noted in a preceding section, this test arrangement resulted in the best possible joints obtainable with the 36-in. tamped pipe. At the conclusion of the tests with average (simulated field) joints the pipe

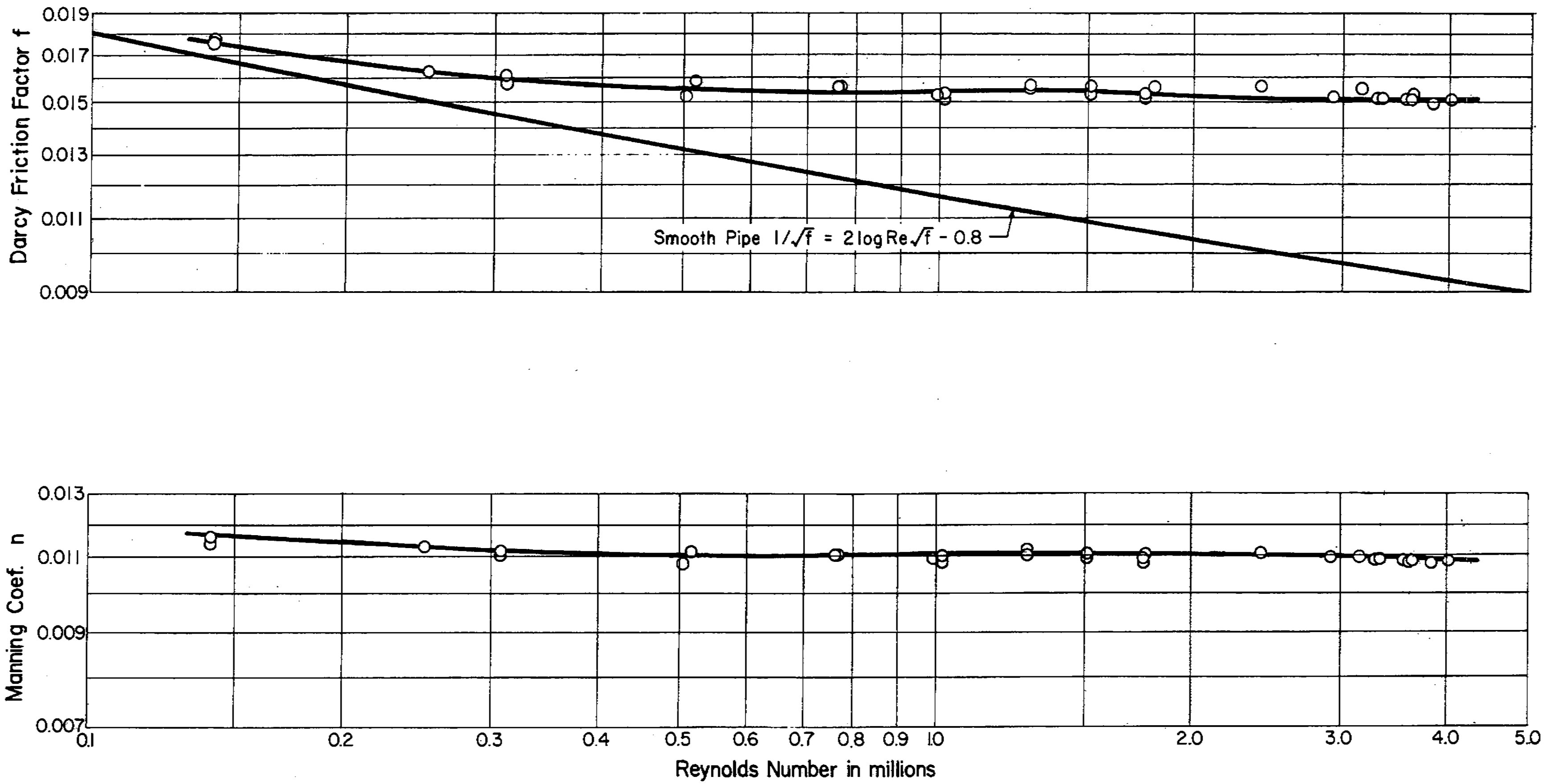


Fig. 12 – Friction Coefficients for the 36-In. Tamped Concrete Pipe with Good Joints

sections were taken apart, the ends cleaned, and the sections assembled with minimum offsets. If the groove end of the pipe had a different diameter than the tongue end of the adjacent section, the end of one section was moved vertically or laterally to distribute the difference, rather than having the total offset at one location. As some sections were slightly elliptical in shape, it was sometimes necessary to rotate the pipe about its axis to obtain the best joint alignment. After the pipe was aligned, diaper seals were installed on the exterior portion of the joint and fillets added on the interior to reduce the effect of offsets at the joints. The grooves were filled with mortar.

Referring to Table B-3 of Appendix B it will be noted that the average offset height for the good joints was reduced to 0.098 in. as compared to 0.182 in. for the preceding average joints. Figure 6 illustrates the range and distribution of offsets for both average and good joints; the maximum offset encountered in the good joints was 0.45 in. as compared to 1.5 inches in the average joints. The reduction in area at the joints was lowered from 2.70 per cent to 0.62 per cent. Elimination of the beads in the good joint tests had a significant effect on the reduction in area at the joints.

A graph of the Darcy friction factor f as a function of Reynolds number (Fig. 12) is quite similar to the data obtained for the average joints. The limiting values of f and n, for $Re \geq 3 \times 10^6$, are 0.01515 and 0.01087 respectively. While slight variations occur, the friction coefficients are relatively constant for Reynolds numbers above 5×10^5.

A comparison of Figs. 11 and 12 indicates that average field joints in tamped pipe result in an f value about 3.6 per cent higher and an n value about 1.7 per cent higher than comparable coefficients for tamped pipe with minimum-obtainable joint irregularities. While the difference is not large it is significant. Also, it should be noted that the above values indicate the difference between average field joints and good joints in tamped pipe. A continuous series of bad joints would result in higher coefficients, as shown in a subsequent section.

D. Data for the 36-in. Cast Pipe

Due to the fact that most of the 36-in. concrete pipe installed on highway projects in the State of Florida (at the time measurements were obtained) was of the tamped type, no field data on joint irregularities in cast pipe were obtained. As noted in a preceding section, an attempt was made to use field methods in the Laboratory installation on the premise that the resulting offsets would be typical of average field joints. Beads and fillets were then installed in accordance with field data for the tamped pipe. As shown in Table B-4 of Appendix B the average offset height for average joints in 36-in. cast pipe was 0.130 in. as compared to 0.182 in. for the tamped pipe. Also, the range in offset heights was much smaller, as shown in Fig. 7. The average bead height for the cast pipe was almost identical to that for the tamped pipe (0.173 in. as compared to 0.177 in.).

Figure 13 illustrates the Laboratory data on friction coefficients for average joints in the 36-in. cast pipe. The data fall on a line decreasing with increasing Reynolds number and diverging slightly from the smooth-pipe curve. A straight line **has** been drawn through the data although it is probable that a slight curvature may exist.

One of the most significant aspects of these data is that the coefficients decrease with increasing Reynolds number, characteristic of a relatively smooth pipe. Apparently, roughness elements in the pipe wall have a height less than the thickness of the laminar sublayer, and the joint irregularities do not seriously disrupt the boundary layer for the range of Reynolds numbers covered in the tests.

A similar curve, Fig. 14, was obtained in tests of the **cast** pipe with good joints. As noted above, time limitations did not permit re-laying the pipe, so the only difference between average and good joints was elimination of the mortar beads. This resulted in a decrease in the value of f of about 1.9 per cent at $Re = 3.4 \times 10^6$.

During the good-joint tests measurements were obtained with rather low discharges. While the accuracy of the measurements decreases with discharge, the data do provide an indication of the relationship between the experimental data and the smooth-pipe curve at low Reynolds numbers. For practical purposes the two are tangent at Reynolds numbers on the order of 130,000

A comparison of Figs. 11 and 12 or 13 and 14 indicates that the resistance of the cast pipe is less than that of the tamped pipe for Reynolds numbers in excess of 500,000 and that the difference in resistance increases with Reynolds number. At a Reynolds number of 3.4 million the value of f

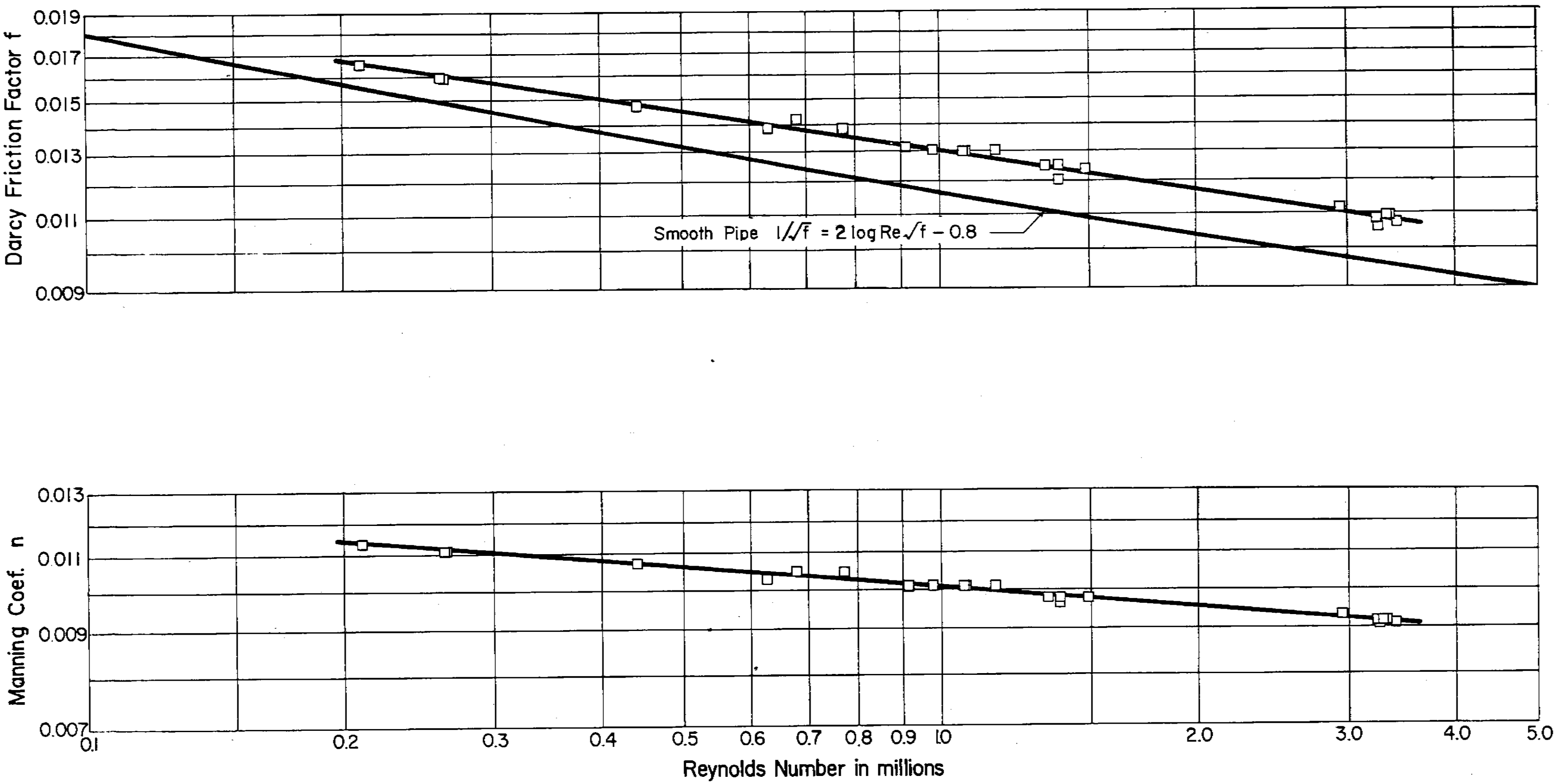


Fig. 13 - Friction Coefficients for the 36-In. Cast Concrete Pipe with Average Joints

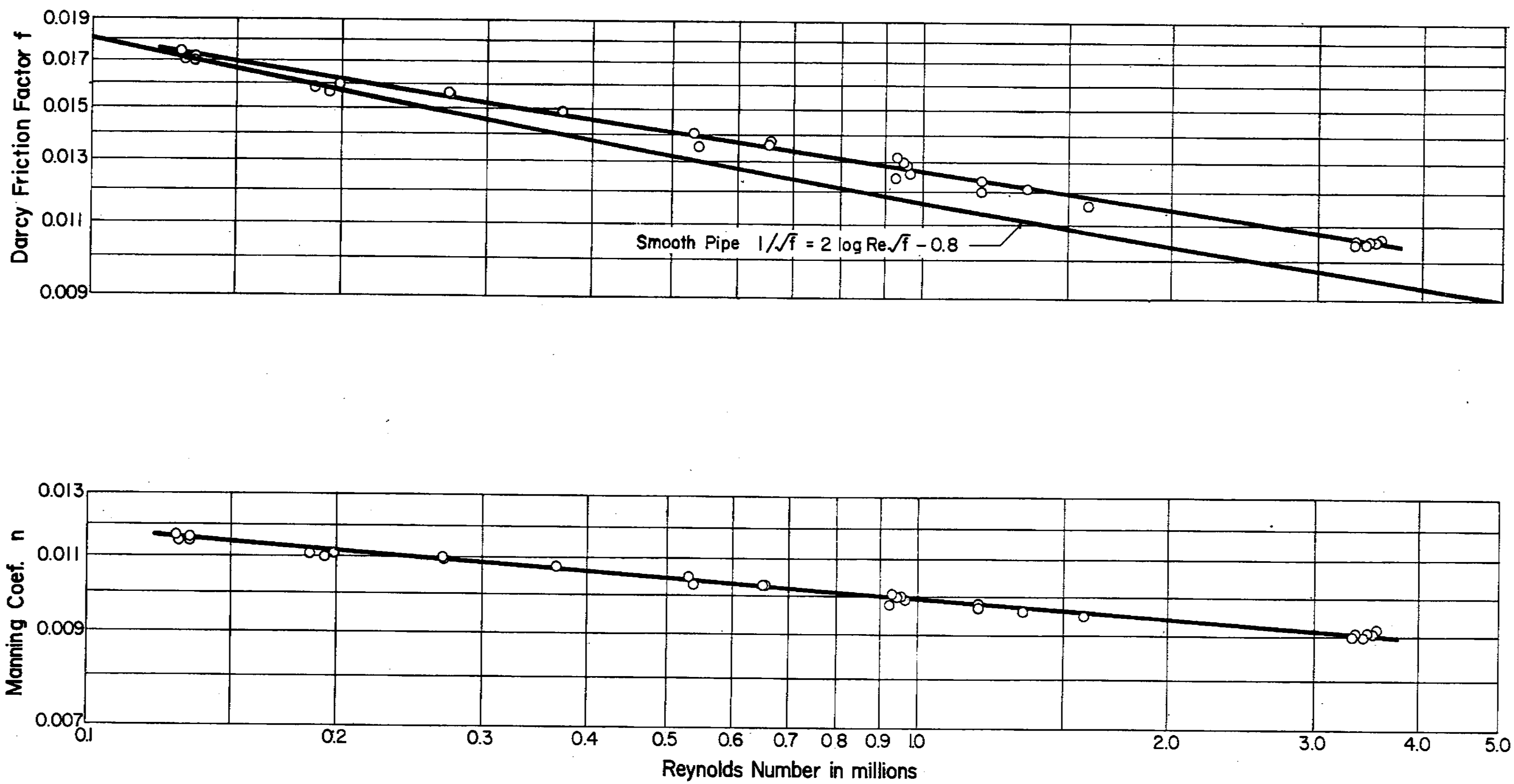


Fig. 14 - Friction Coefficients for the 36-In. Cast Concrete Pipe with Good Joints

for the cast pipe (average joints) is 68 per cent of that for the tamped pipe. The corresponding figure for Manning's n is 83 per cent. Thus, in installations where frictional resistance is an important factor and the Reynolds number is sufficiently large, the use of cast pipe would result in a significant increase in discharge capacity or a decrease in head loss as compared to a similar installation involving tamped pipe.

E. Data for the 24-in. Tamped Pipe

The tests of the 24-in. tamped pipe were performed prior to the tests of the 36-in. pipe, but due to a lack of information on field installations of this size of pipe and several other associated conditions, the results are not considered as useful as those for the 36-in. pipe.

Two sets of tests were performed, simulating average field joints and referred to as average-A and average-B joints. The two conditions were identical except for two joints out of a total of 23 joints. In the average-A tests these two joints had extruded mortar fins up to 3/4 in. high, similar to two untroweled field joints. Apparently, the extrusions were formed by mortar running through the joint when the diaper seal was poured. While the condition is probably quite unusual, it was considered desirable to obtain some test data with two joints of this type interspersed with normal field joints and then to obtain comparative data with the fins removed (average-B joints). Following the tests the pipe was relaid to obtain good joints.

Figure 15 illustrates the experimental data for average-A joints in the 24-in. tamped pipe. The range of Reynolds numbers covered in these tests is not so large as in the preceding tests of the 36-in. pipe because of the experimental setup used with the 24-in. pipe. Over the Reynolds number range of 200,000 to 1,500,000 covered in the tests, the coefficients f and n appear to be constant, with average values of 0.01809 and 0.01111 respectively. Removal of the fins on the two joints referred to above decreased the values of f and n to 0.01757 and 0.01094 respectively, as shown in Fig. 16. The two joints with fins were numbers 13 and 19 and were located 104 ft and 152 ft respectively from the inlet; both were in the zone of established flow. Removal of the fins resulted in a reduction of 2.9 per cent in f and 1.5 per cent in n. Obviously, a series of joints with mortar extrusions would substantially increase the frictional resistance.

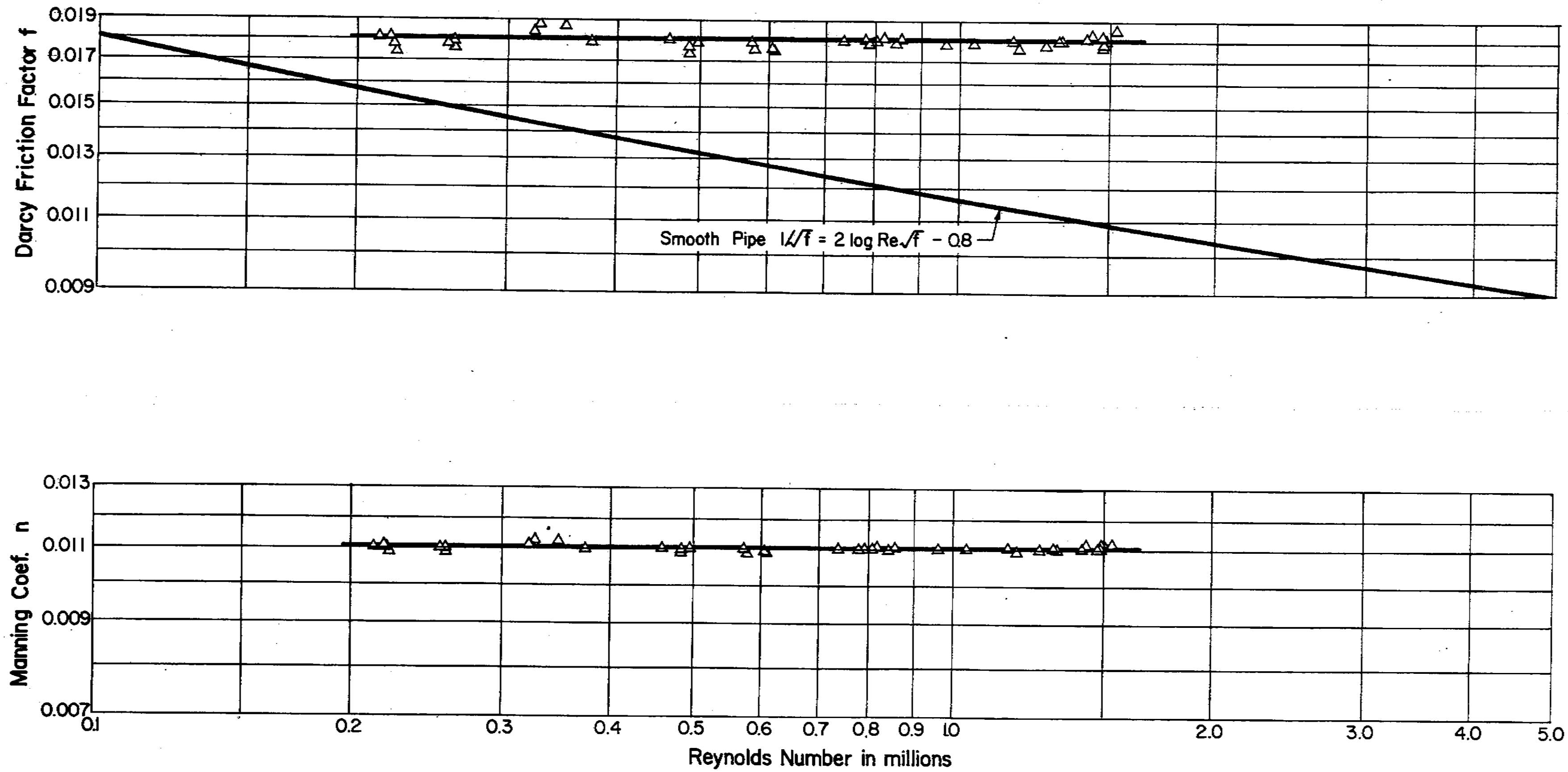


Fig. 15 – Friction Coefficients for the 24-In. Tamped Concrete Pipe with Average-A Joints

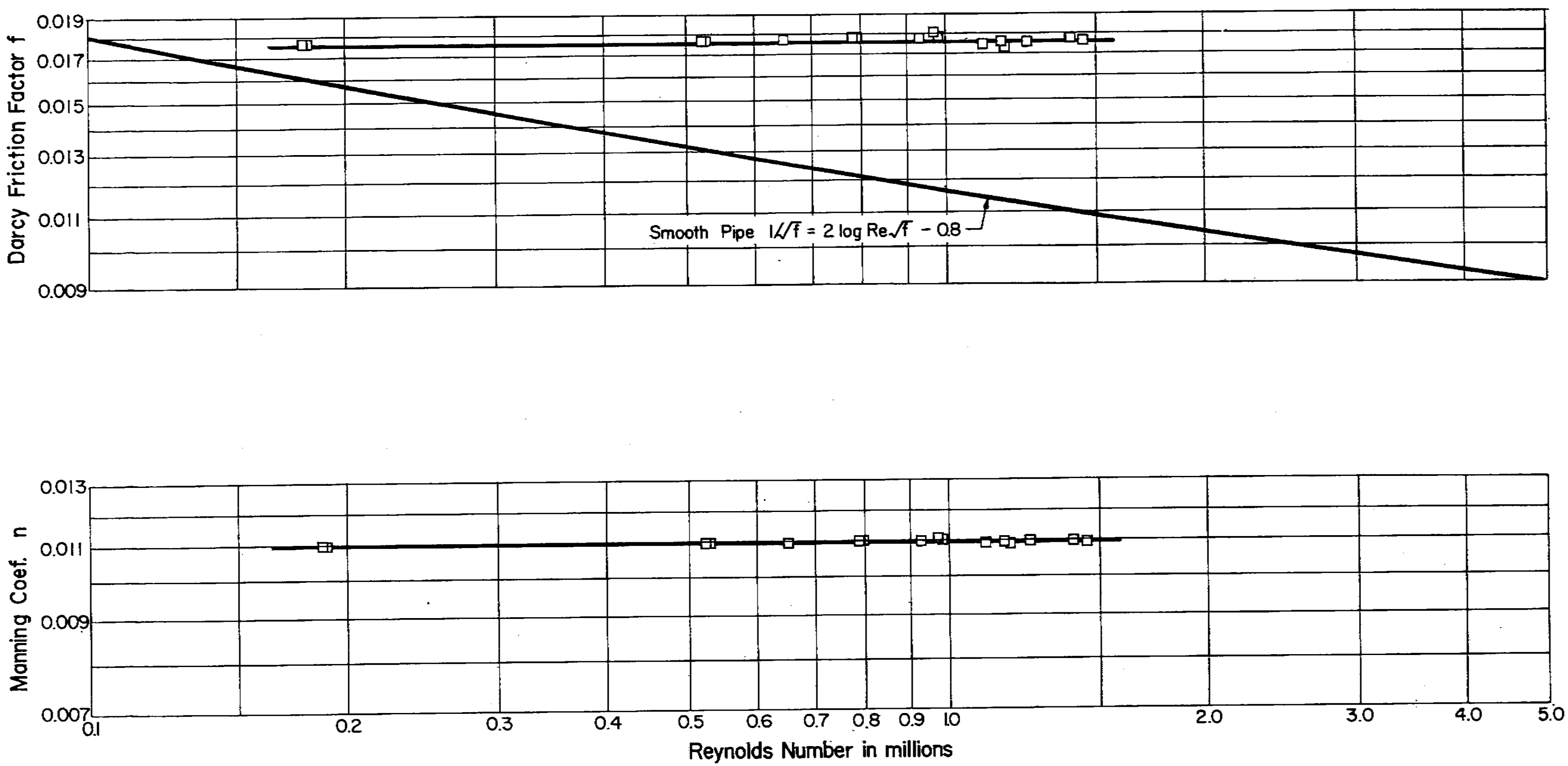


Fig. 16 – Friction Coefficients for the 24-In. Tamped Concrete Pipe with Average-B Joints

Following the above tests, the 24-in. tamped pipe was taken apart, cleaned, and reassembled with the best joint alignment. Fillets were used to decrease the effect of offsets. The average offset height was reduced from 0.149 in. to 0.118 in., the average bead height was reduced from 0.032 in. to zero, and the per cent reduction in area was reduced from 1.09 per cent to 0.65 per cent. It should be noted here that the groove end of the 24-in. tamped pipe was about 0.10 in. larger than the tongue end; as a result, it was not possible to eliminate all offsets at the joints.

Figure 17 illustrates the test data obtained with the good-joint test condition. The friction coefficients f and n are essentially constant for Reynolds numbers in excess of 400,000 and have average values of 0.01638 and 0.01057 respectively for Reynolds numbers in excess of one million. This represents a decrease in f of 9.5 per cent (4.9 per cent for n) as compared to the average-A joints, and of 6.8 per cent (3.5 per cent for n) as compared to the average-B joints. As noted earlier, these differences are not as significant as comparable data for the 36-in. pipe because the irregularities for average joints may not represent field conditions for 24-in. pipe, whereas the average joints in the 36-in. pipe were very close to average field installations.

A comparison of the Darcy f for 24-in. and 36-in. tamped pipe with good joints ($f = 0.01638$ and $f = 0.01515$ respectively) indicates a higher friction coefficient for the 24-in. pipe. Assuming that the actual height of the roughness elements is the same in both pipes, the f value would be expected to increase with a decrease in diameter. Actual measurements of the roughness height indicated that the average height was very nearly the same in both sizes of pipes (Figs. 3 and 4 of Appendix C). Since both behaved as rough pipes, the Karman-Prandtl equation for rough pipes provides an indication of the relationship of the f values for the two pipes:

$$\frac{1}{\sqrt{f}} = 2 \log \frac{r_o}{k_s} + 1.74 \tag{5}$$

where r_o = pipe radius, and

k_s = equivalent Nikuradse sand-grain roughness height.

Substituting $f = 0.01515$ and $r_o = 18.035$ in this equation and solving for k_s for the 36-in. tamped pipe with good joints, we obtain

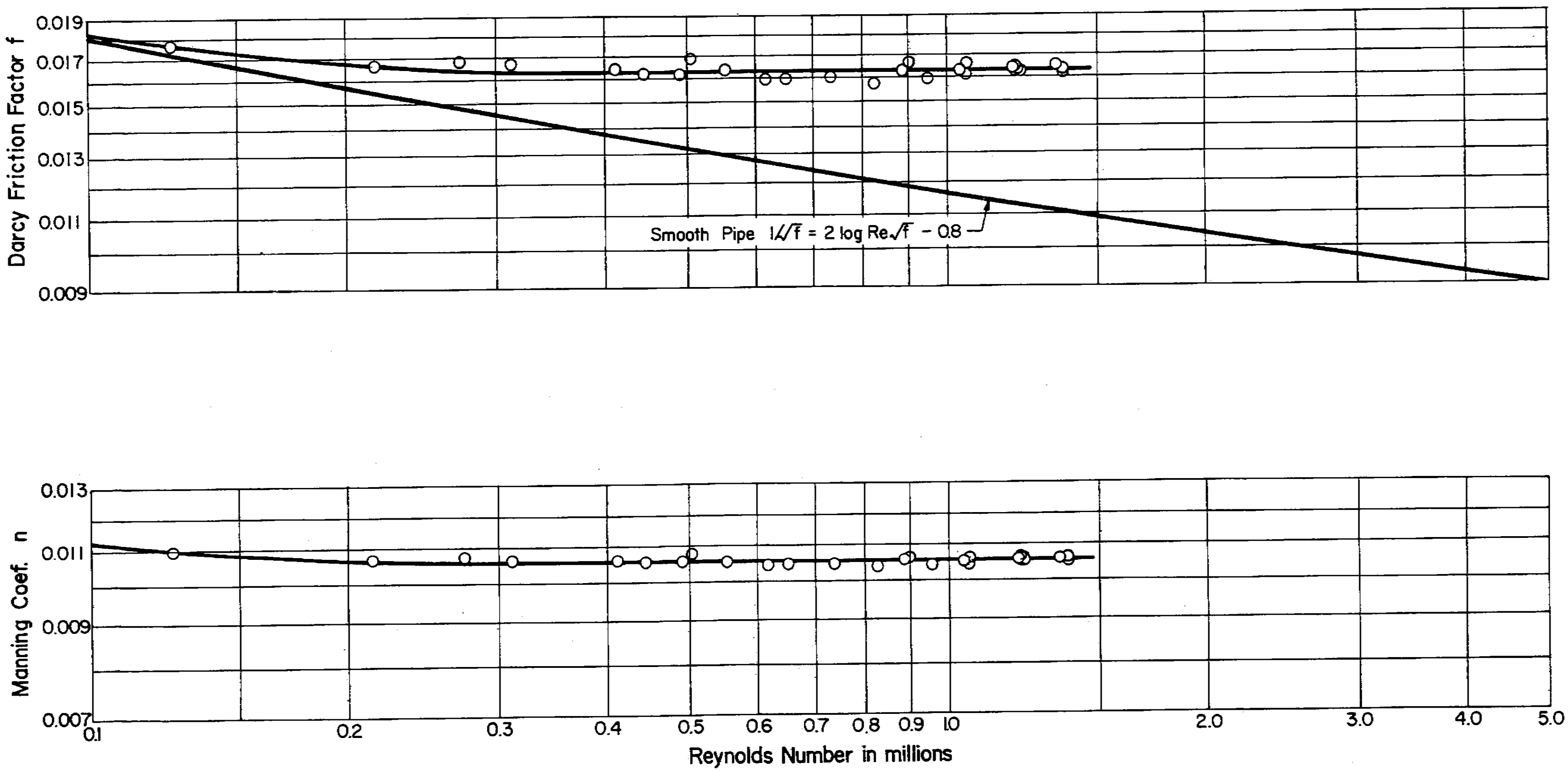


Fig. 17 - Friction Coefficients for the 24-In. Tamped Concrete Pipe with Good Joints

$$k_s = 0.01158 \text{ in.}$$

Substituting this value and $r_o = 12.055$ inches in the same equation, we obtain

$$f = 0.01654$$

for the 24-in. pipe as compared to an actual measured value of $f = 0.01638$ for the 24-in. pipe with good joints. Thus, by assuming the same absolute roughness in both 24-in. and 36-in. tamped pipe, the Karman-Prandtl equation indicates a higher f value for the 24-in. pipe and the computed value agrees with the measured value within one per cent.

F. Analysis of Joint Losses

A comparison of the friction coefficients for good and average joints in concrete pipes indicates that joint irregularities comparable to field conditions produced an increase in Darcy's f of about 3.6 per cent and an increase in Manning's n of about 1.7 per cent. While these values are not large, they are of interest. These values are not indicative of the increased losses which can result from a series of bad joints. Also, it should be noted that the ratio of joint spacing to pipe diameter will affect the results.

To assist in an evaluation of some of these variables, the losses attributed to the joints can be related to the physical measurements of the joint irregularities. However, it should be noted that any relationship of this type is based on relatively small differences in test data for good and average joints and the resultant analysis indicates only the order of magnitude of the joint losses.

Two basic approaches can be considered in an analysis of joint losses:

(a) The loss at a joint can be expressed as a function of the change in pipe area at the joint and the resultant change in average velocity of flow.

(b) The loss can be expressed in terms of a drag force produced by the joint irregularity.

The first of these two approaches does not appear to be practical because the change in area and resultant change in velocity are quite small, on the order of one per cent. Available data on expansion and contraction coefficients are based on much larger changes in area.

The second method is somewhat more complex than the first but should permit better correlation of joint losses with the area of joint irregularities. This method is discussed in some detail in Appendix E. A brief description is included here.

Referring to Fig. 18, it is necessary first to determine the average height of positive and negative offset and the average height of beads at each joint. In a typical joint the mortar bead covered only 241 degrees of the circumference, leaving 119 degrees at the crown exposed as a groove. Also, the lower half of the joint usually had a negative offset and the upper half a positive offset. Several methods could be used to summarize the heights and areas of beads and offsets to arrive at effective heights and areas for the computation of drag. The method used herein involved a direct addition of the bead area, positive offset area, and negative offset area at each joint; the resultant total projected area A_j was then divided by the circumferential length of the joint to give an average height of joint irregularity $\bar{e}$ for each joint. It was reasoned that the average height $\bar{e}$ and total area A_j would provide the best indices of the joint irregularities even though the mechanism of energy loss at positive offsets may differ somewhat from that at negative offsets.

The drag or resistance produced by the joint can be expressed by

$$F_D = C_D A_j \rho \frac{V_e^2}{2} \tag{6}$$

where F_D = drag in pounds,
C_D = empirical drag coefficient,
A_j = projected area of joint,
ρ = density of the fluid,
V_e = velocity of flow at a distance $\bar{e}$ from the wall, and
$\bar{e}$ = average height of beads and offsets.

As the height of joint irregularities is small compared to the pipe diameter, the velocity used in the computations was the computed velocity at a distance $\bar{e}$ from the wall rather than the mean velocity $\bar{V}$ (Fig. 19).

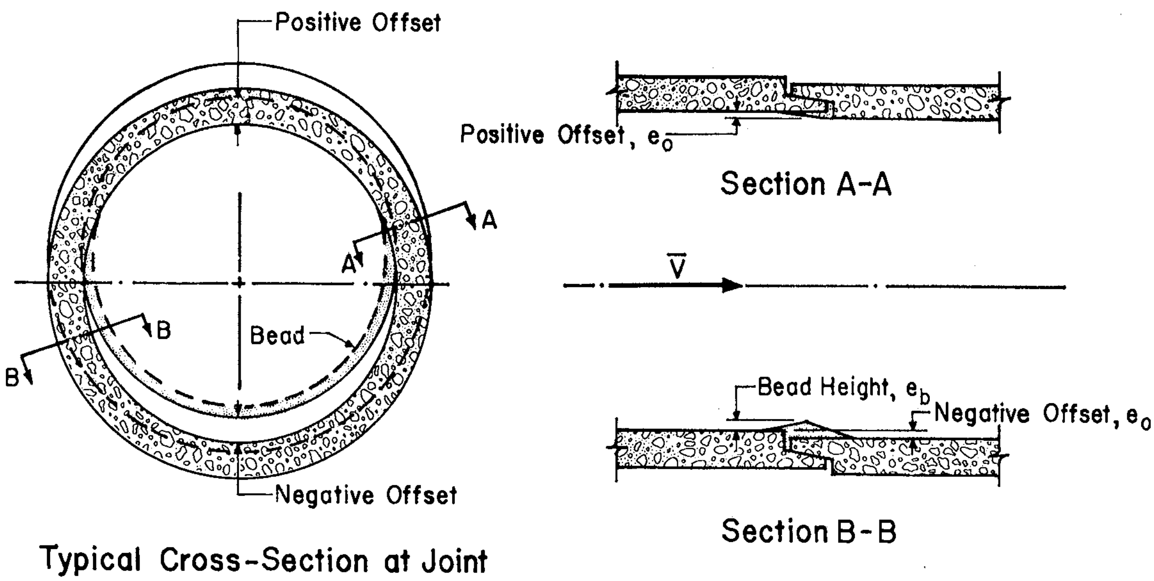
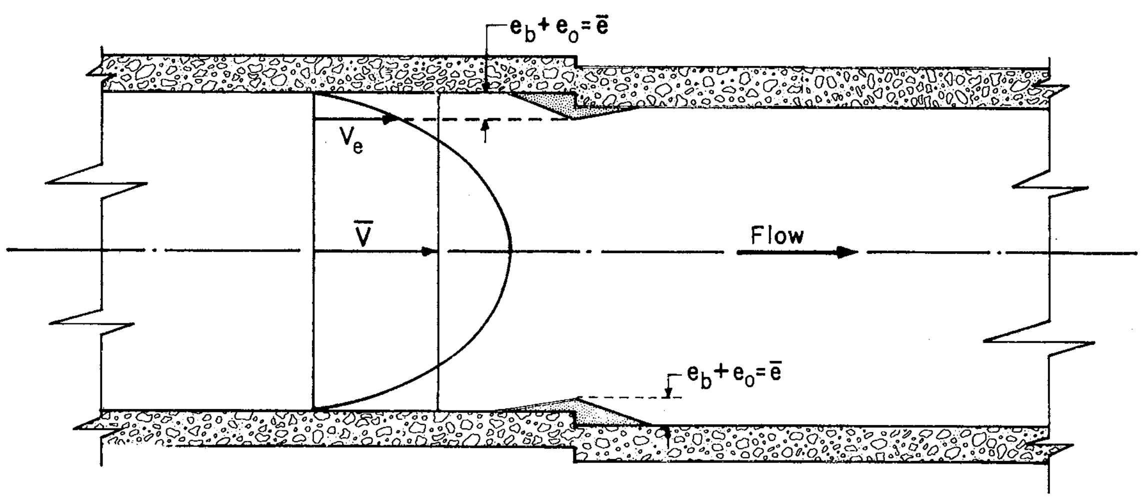


Fig. 18 - Sketch Illustrating Positive and Negative Offsets



Note: Bead and offsets exaggerated for clarity in sketches

Fig. 19 - Sketch Illustrating Velocity Used in Analysis of Drag Force at Joints

This was usually on the order of 60 per cent of the mean velocity of flow in the pipe.

The above drag force can be converted to a pressure drop in the pipe by use of pressure-momentum principles. Considering two sections immediately upstream and downstream of the joint,

$$p_1 A_1 + Q\rho \bar{V}_1 = p_2 A_2 + Q\rho \bar{V}_2 + F_D$$

Assuming the average area and velocity upstream and downstream are the same, $A_1 = A_2$ and $\bar{V}_1 = \bar{V}_2$, and the pressure head change caused by the joint is

$$h_j = \frac{p_1 - p_2}{w} = \frac{F_D}{wA} \tag{7}$$

where A = area of pipe, and
w = specific weight of water.

As the joints are spaced a distance ℓ apart (in this case 8 ft), the head loss can be expressed as an equivalent friction factor by

$$h_j = f_j \frac{\ell}{D} \frac{\bar{V}^2}{2g} \quad \text{or} \tag{8}$$

$$f_j = h_j \frac{D}{\ell \bar{V}^2/2g} \tag{9}$$

The total loss, including friction on the walls, is

$$h = h_p + h_j, \quad \text{and}$$

$$f = f_p + f_j$$

where f = total friction coefficient measured in the experimental tests, and
f_p = friction coefficient which would exist if there were no joints in the pipe.

A combination of the preceding formulas gives:

$$C_D = (f - f_p) \frac{\ell A}{D} \Big/ \left(\frac{V_\theta}{\bar{V}}\right)^2 A_j \tag{10}$$

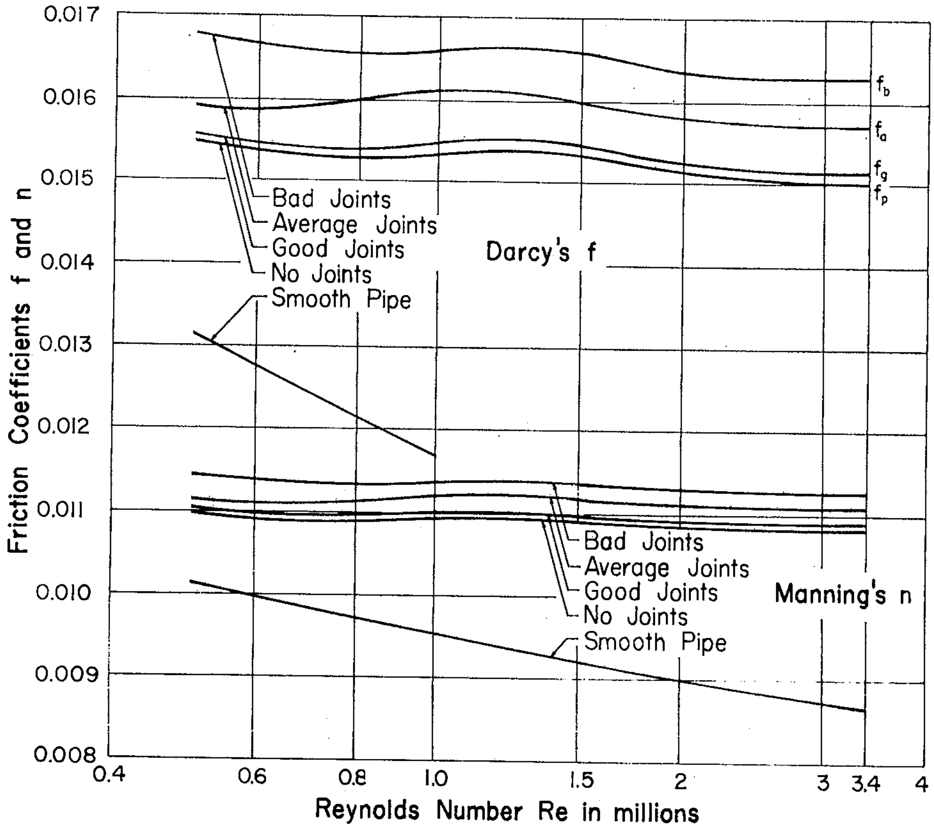


Fig. 20 - Friction Coefficients for the 36-In. Tamped Pipe with Various Joint Conditions

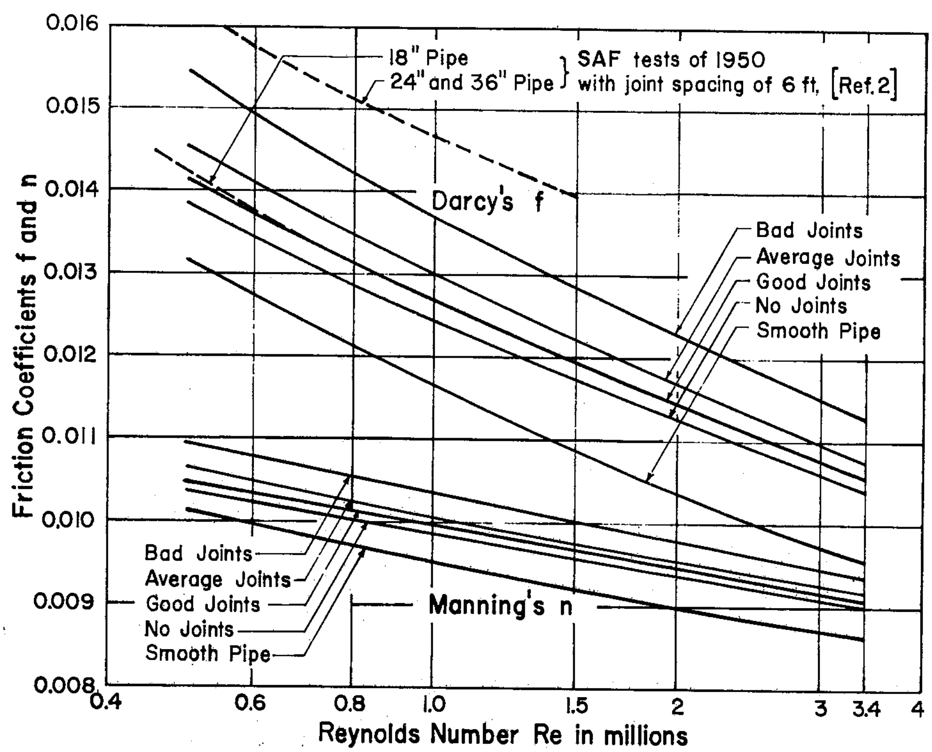


Fig. 21 - Friction Coefficients for the 36-In. Cast Pipe with Various Joint Conditions

The term $(f - f_p)$ in Eq. (10) is the difference between the friction factor actually measured in the tests and the friction factor f_p for a pipe with no joints. This is illustrated in Fig. 20, with $f = f_g$ for good joints or $f = f_a$ for average joints. The value of f_p is unknown although it is probably quite close to f_g for good joints. A solution of Eq. (10) is possible if it is assumed that the drag coefficient is the same for both good and average joints, permitting the simultaneous solution of two equations. Since this appeared reasonable, as opposed to a direct assumption of C_D, this procedure was followed. Equation (10) is for a single pipe section or use of average values of A_j and $\bar{e}$ for the complete set of joints in a pipe; it was modified to provide a summation of the effects of the complete series of joints. (See Eq. (E-9) of Appendix E.)

Solution of this equation for the 36-in. tamped pipe gave $C_D = 0.10$ and $f_p = 0.01499$. The friction coefficients for the cast pipe vary with Reynolds number, therefore a solution was obtained at each of four Reynolds numbers. The results are as follows:

$Re \times 10^{-6}$	f_a	f_g	f_p	C_D
0.5	0.01454	0.01414	0.01384	0.120
1.0	0.01300	0.01270	0.01248	0.090
2.0	0.01169	0.01144	0.01125	0.075
3.4	0.01076	0.01056	0.01041	0.060

Variations in the value of C_D are caused by convergence of the curves of f for good and average joints with increasing Reynolds numbers.

The preceding analysis is based on a relatively small difference between the experimental data for good and average joints. A one per cent error in the value of f_a or f_g would produce a variation of 30 to 50 per cent in C_D. As a result the agreement between values of C_D for the tamped and cast pipe is considered quite good.

While C_D probably varies to some extent with the size and shape of beads and offsets, the method does provide an indication of the magnitude of the coefficient and a rough indication of the friction factor for a pipe with no joints. The method can also provide a guide as to the effect of a continuous series of bad joints or the effect of variations in joint spacing.

Using the above coefficients, a curve for bad joints has been computed. The area and height of the joints were based on three field joints with maximum offsets ranging from 1.0 to 1.4 inches. The data for these joints were obtained from a single project in which most of the joints were of the same character. The offsets are admittedly much larger than normal and were caused primarily by poor quality pipe in which the taper or variation in diameter in a single section was about twice the normal acceptable value. The average values of A_j and $\bar{e}$ for the three joints were 69.8 sq in. and 0.54 in. respectively. In computing curves for bad joints it was assumed that all joints in the 36-in. pipe had projected areas and heights equal to these values. On the basis of this analysis the following data were computed for bad joints in the 36-in. tamped pipe (experimental data for good and average joints and for no joints are included for comparison purposes):

Limiting Roughness Data for the 36-in. Tamped Pipe
($Re > 3 \times 10^6$)

Joint Condition	Darcy f	k_s inches	r_o/k_s	Manning's n
none	0.01499	0.01100	1683	0.01081
good	0.01515	0.01158	1556	0.01087
average	0.01570	0.01365	1321	0.01106
bad	0.01629	0.01617	1115	0.01127

With cast pipe there is no equivalent sand-grain roughness k_s, and the values of f vary with Reynolds number (Fig. 21). The following data are for a Reynolds number of 2 million; additional data are given in Table E-5 of Appendix E.

Joint Condition	Darcy f
none	0.01125
good	0.01138
average	0.01156
bad	0.01205

The computed values of f for bad joints were based on $C_D = 0.10$ for the tamped pipe and $C_D = 0.06$ to 0.12 for the cast pipe.

G. Extrapolation to Other Diameters--Tamped Pipe

The experimental data in this report were obtained on 24-in. and 36-in. pipe. It is desirable to obtain experimental data on larger sizes of pipe. In the absence of such data for larger pipe the available data on 24-in. and 36-in. pipe can be extrapolated although some assumptions are necessary. If these extrapolations are used, the designer should be cognizant of these assumptions. It should also be noted that the extrapolation procedure for cast pipe is different from that for tamped pipe because the latter is characteristic of a rough pipe whereas the former is close to a smooth pipe. Furthermore, the extrapolation for tamped pipe has been extended to 8-ft diameters although it is not usually available in diameters larger than 5 or 6 ft.

The basic assumptions for extrapolation of the data for tamped pipe are:

1. The absolute roughness k_s based on f_ℓ is assumed constant regardless of diameter.
2. The average height of joint irregularities $\bar{e}$ is assumed constant regardless of diameter; as a result the projected area of the joint (A_j) varies as the pipe diameter.

With a joint spacing of 8 ft, two methods of extrapolation can be used for the tamped pipe:

1. The computed values of k_s for each of the joint conditions in the 36-in. pipe can be assumed constant and the respective values substituted in the Karman-Prandtl rough-pipe equation, using various values of r_o, and the equation solved for f.
2. The value of k_s for the 36-in. pipe with no joints can be substituted in the Karman-Prandtl equation and an extrapolation obtained for a pipe with no joints. Average values of A_j and $\bar{e}$ for good, average, and bad joints can be substituted in Eq. (10), with $C_D = 0.10$, and the

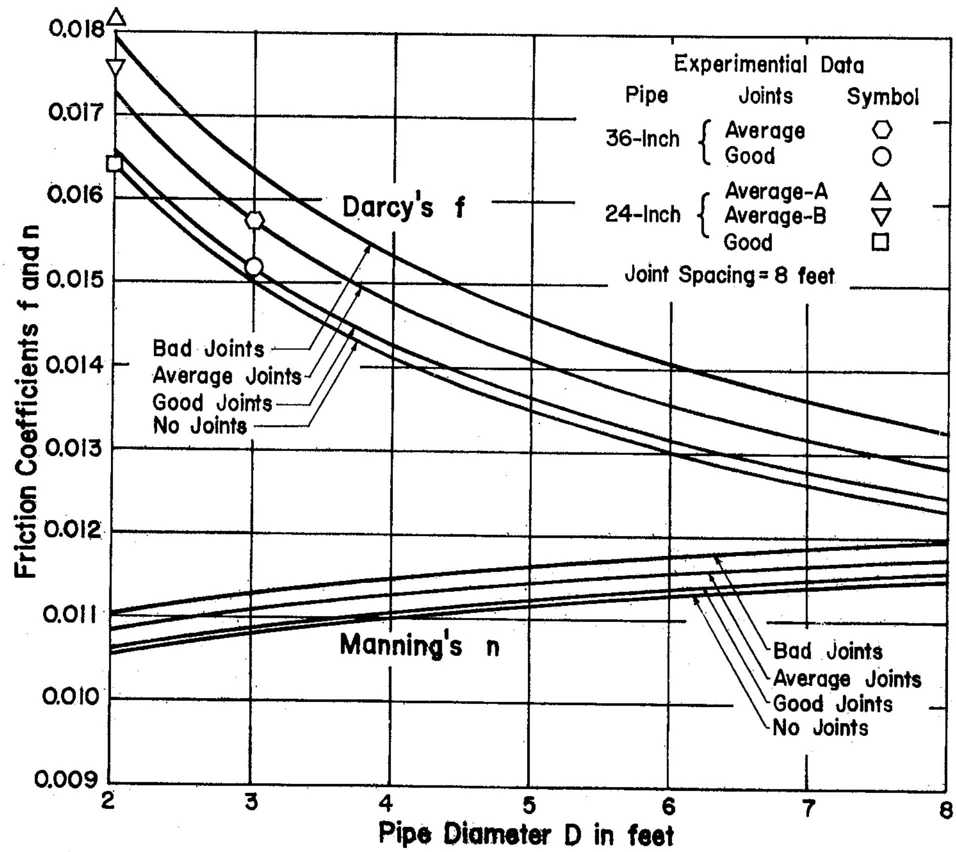


Fig. 22 – Friction Coefficients for Tamped Concrete Pipe as a Function of Pipe Diameter

equation solved for the increment $(f - f_p)$. This increment can then be added to the extrapolated value of f_p to obtain the curves for good, average, and bad joints. This method has an advantage if the joint spacing (ℓ) is something other than 8 ft.

Table E-4 of Appendix E summarizes the computations for an extrapolation based on the first method. Figure 22 illustrates the computed values of Darcy's f and Manning's n for pipe diameters ranging from 2 ft to 8 ft. The experimental points are also shown. It is of interest to note that with a constant roughness height the value of f decreases with increasing diameter whereas the value of n increases with increasing diameter. The curves of Fig. 22 are valid only for Reynolds numbers large enough to insure rough-pipe flow, or for the zone in which f is independent of Reynolds number. For practical purposes this range can be assumed as $Re > 5 \times 10^5$.

The curves for Manning's n were computed from corresponding curves for Darcy's f, using the relationship

$$n = \frac{D^{1/6} f^{1/2}}{13.6} \quad \text{or} \quad n = \frac{R^{1/6} f^{1/2}}{10.8} \tag{11}$$

H. Extrapolation to Other Diameters--Cast Pipe

The friction factors for cast pipe decrease with increasing Reynolds number over the complete range covered in the tests, similar to the smooth-pipe friction factors. While test data for larger pipe diameters are desirable also for the cast pipe, it is possible to make several assumptions which may be acceptable in an extrapolation of the available data. One method involves the assumption that the friction factor is a constant for any given Reynolds number, regardless of pipe diameter. If the concrete mix is the same and the forms used in casting the pipe are all of the same texture and accuracy of shape, this assumption is probably on the conservative side.

This assumption can be made for all joint conditions, provided the joint spacing is 8 ft. If the joint spacing is something other than 8 ft, the procedure would be more complex; one method would be to compute the incremental joint friction factor $(f - f_p)$ for various values of joint spacing (ℓ/D) and add the values to the base curve of f_p shown in Fig. 21. This would result in several figures similar to Fig. 21, each for a different value of (ℓ/D).

Auxiliary graphs for selected temperatures and pipe diameters could be computed to assist in the selection of f and n if a wide range in Reynolds number is anticipated.

Experimental curves from an earlier SAFHL study of cast concrete culvert pipe [2] are also shown in Fig. 21. These tests were made some 10 years ago to determine the flow resistance of 18-in., 24-in., and 36-in. pipe. The pipe sections were all 6 ft long; they were connected for the test setup with non-pressure rubber ring joints. The joints of the 24-in. and 36-in. pipe were filled with cement mortar applied to the inside of the joint in the customary manner; this was not done on the 18-in. pipe because of its small size. No measurements were made of either wall roughness or joint irregularities for any of these test pipes. It will be noted that the friction coefficients for the 18-in. pipe, as plotted in Fig. 21, are between the curves for 36-in. cast pipe with good and average joints. The coefficients for the 24-in. and 36-in. pipe are about 11 per cent higher than the current data for 36-in. pipe with average joints, and about 6 per cent higher than for the 36-in. pipe with bad joints. Inasmuch as the earlier tests were conducted on 24-in. and 36-in. pipe taken from stock fabricated some 12 years ago and no special attention was paid to the joints, it is quite possible that somewhat rougher pipe was obtained than that used in the more recent tests, although the earlier 18-in. pipe appears to have been smoother than the larger pipes, both with reference to pipe surface and joints. In any case, such variations in roughness probably depend on the shape and cleanliness of the interior forms used in casting the pipe; unless proper attention is given to cleaning of the forms and control of the concrete mix so as to avoid a course internal wall texture, the higher hydraulic roughness values might result.

V. TRANSITION FROM SMOOTH-PIPE TO ROUGH-PIPE FLOW

A. Transition Data for Tamped Pipe

Examination of the test data for tamped pipe (Figs. 11, 12, 15, 16, and 17) indicates that the transition from smooth-pipe to rough-pipe flow does not follow the Colebrook transition equation and the corresponding resistance diagram for uniform flow in commercial pipe. The experimental data fall on a fairly well defined transition curve located between the Colebrook curve and the Nikuradse curve for uniform sand-grain roughness.

The transition is usually considered to be dependent on the shape and size of wall roughness elements. Experimental data for various types of pipe indicate that considerable variation exists in the transition zone. The curve proposed by Colebrook is an average of experimental curves for various sizes and types of pipes; it appears to be most representative of commercial metal pipe with diameters in the smaller size range.

The tamped concrete pipe used in the current SAFHL tests had roughness elements ranging in size from fine sand and cement grains up to 0.06-in. striations created in part by removal of the inner core before the concrete had set. Thus, it is not surprising that its transition differs from both the Colebrook and Nikuradse transitions.

Figure 23 illustrates the SAFHL data as well as the Colebrook and Nikuradse curves; the data plotted are on a graph with ordinates of

$$\frac{1}{\sqrt{f}} - 2 \log \frac{r_o}{k_s}$$

and abscissas of $\frac{Re\sqrt{f}}{r_o/k_s}$.

The Colebrook equation is

$$\frac{1}{\sqrt{f}} - 2 \log \frac{r_o}{k_s} = 1.74 - 2 \log \left(1 + 18.7 \frac{r_o/k_s}{Re\sqrt{f}} \right) \tag{12}$$

The Nikuradse curve consists of three segments, each defined by a separate equation.

The objective of all of the curves is to define a transition from the smooth-pipe curve

$$\frac{1}{\sqrt{f}} = 2 \log Re\sqrt{f} - 0.8 \tag{4}$$

to the Karman-Prandtl rough-pipe curve

$$\frac{1}{\sqrt{f}} = 2 \log \frac{r_o}{k_s} + 1.74 \tag{5}$$

In the analysis of the SAFHL data, a curve was initially fitted to the data visually. This was apparently tangent to the smooth-pipe curve at

$$\frac{Re\sqrt{f}}{r_o/k_s} = 8$$

and to the rough-pipe curve at

$$\frac{Re\sqrt{f}}{r_o/k_s} = 200, \quad \text{or} \quad \frac{Re\sqrt{f}}{D/k_s} = 100$$

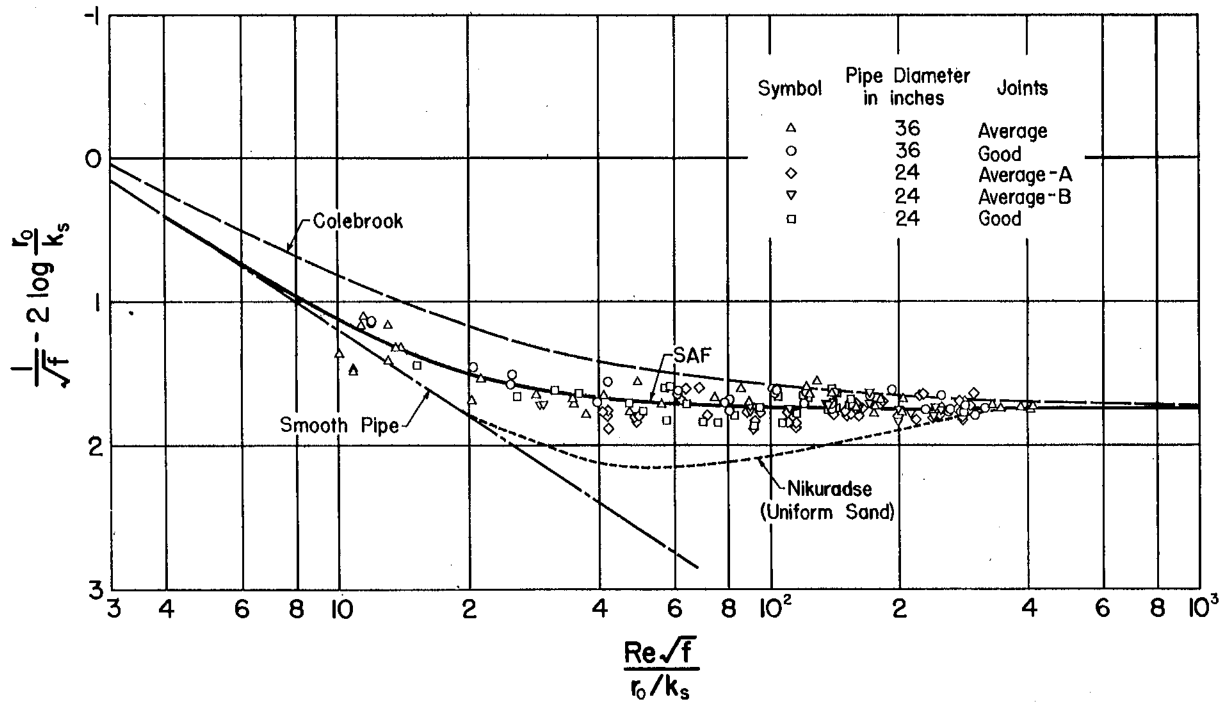


Fig. 23 – Transition Function for Tamped Concrete Pipe

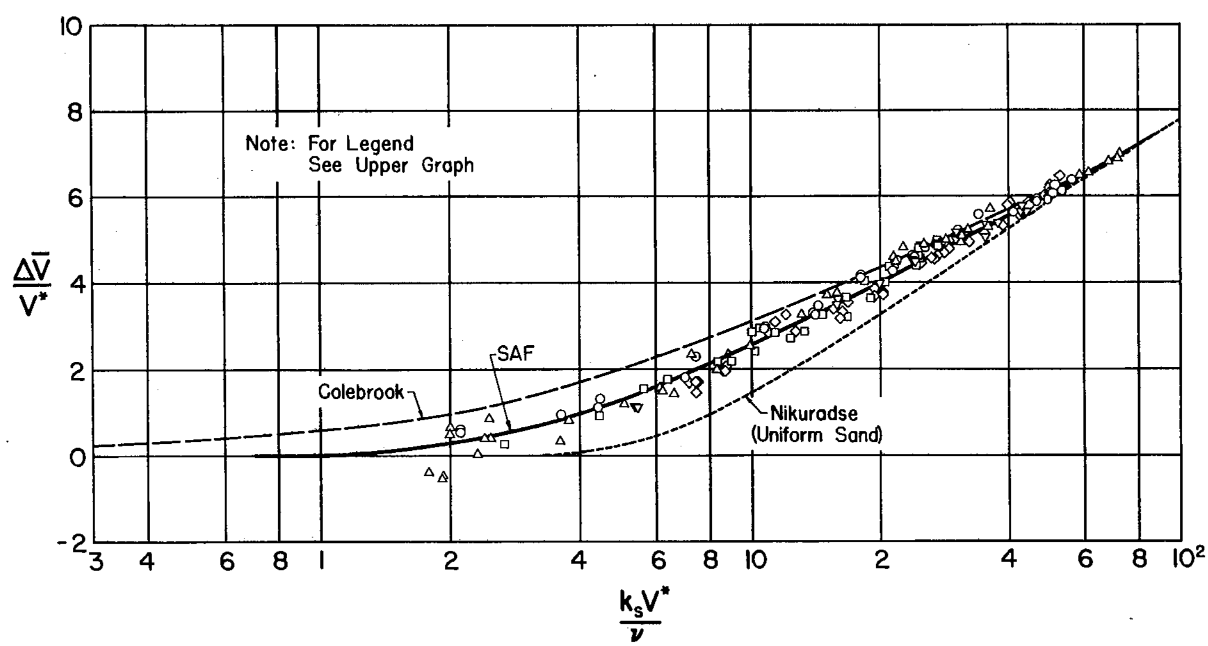


Fig. 24 – Transition Function for Tamped Concrete Pipe in Terms of Reynolds Number Based on Shear Velocity

A semi-empirical logarithmic curve was then developed which approximated the initial curve. The development of the SAFHL equation is described in detail in Appendix E. The equation is:

$$\frac{1}{\sqrt{f}} - 2 \log \frac{r_o}{k_s} = 1.74 - \log \left[1.002 - \frac{1.56}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)} + \frac{311}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)^2} + \frac{104}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)^3} \right] \qquad (13)$$

for

$$4 \leq \frac{Re\sqrt{f}}{r_o/k_s} \leq 400$$

This equation is tangent to the smooth-pipe curve at $\frac{Re\sqrt{f}}{r_o/k_s} = 4$ and to the Karman-Prandtl rough-pipe curve at $\frac{Re\sqrt{f}}{r_o/k_s} = 400$. For comparison purposes, the Colebrook equation is tangent to the smooth- and rough-pipe equations at $\frac{Re\sqrt{f}}{r_o/k_s}$ equal to zero and infinity respectively.

The logarithmic term on the right side of the SAFHL equation is quite complex, involving the first four terms of a series. Some other type of equation can be developed to describe the transition, or several equations might be used, following the example of Nikuradse. However, since the SAFHL equation does provide a satisfactory fit, the complex form is not of interest to the user because the necessary coordinates have already been computed (Appendix F) for use in the form of the conventional resistance diagram. The latter is shown in Fig. 25 with f as a function of Reynolds number for various values of r_o/k_s.

As noted above, the SAFHL curve is tangent to the Karman-Prandtl rough-pipe curve at

$$\frac{Re\sqrt{f}}{r_o/k_s} = 400.$$

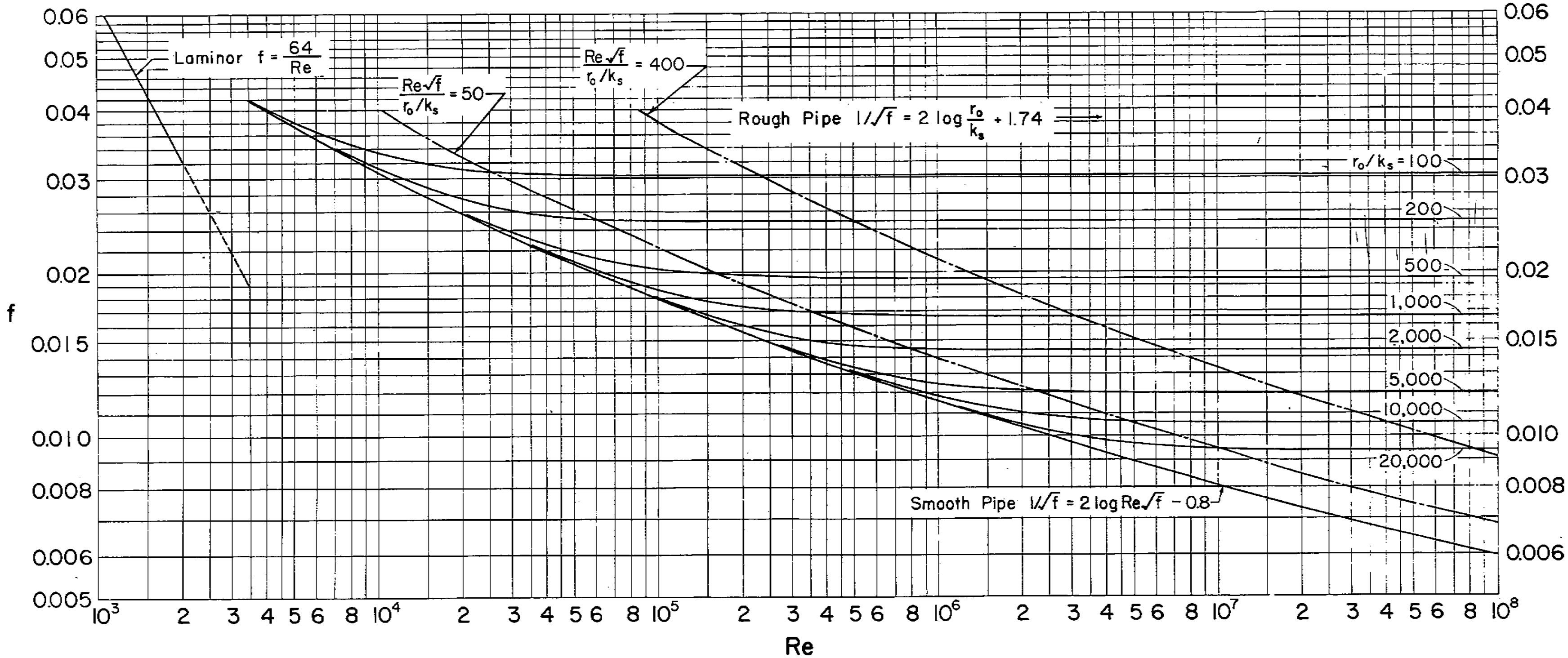


Fig. 25 - General Resistance Diagram for Uniform Flow in Tamped Concrete Pipe

However, the transition is so gradual that there are very small differences for values of this parameter much less than 400. The following table illustrates the difference:

(1)	(2)	(3)	(4)
$\frac{Re\sqrt{f}}{r_o/k_s}$	$\frac{1}{\sqrt{f}} - 2 \log \frac{r_o}{k_s}$	1.74 - Col. (2)	Per Cent Difference
400	1.74	0.000	0
200	1.739	0.001	0.05
100	1.732	0.008	0.5
60	1.714	0.026	1.5

As noted in a preceding section, the experimental data indicated very little variation in the value of f for Reynolds numbers in excess of 5×10^5. For the 36-in. tamped pipe with average joints the corresponding value of

$$\frac{Re\sqrt{f}}{r_o/k_s} \quad \text{is } 50$$

For the 36-in. tamped pipe with good joints the corresponding value is 42.

The line between the transition zone and the rough-pipe regime is usually indicated at a value of the above parameter of 400; as the effective limit of the rough pipe regime appeared to occur at about 50 in tests of the tamped pipe, a second line has been shown on Fig. 25 for reference purposes. This is of interest only for tamped concrete pipe as other types of concrete or metal pipe may have a different transition curve.

Figure 24 is a second type of plot for the transition zone, following a method proposed by Hama [3]. The ordinate is $\Delta\overline{V}/V$ and the abscissa is $k_s V^*/\alpha$. The term $\Delta\overline{V}/V^*$ represents a shift in the velocity profile (as compared to smooth-pipe flow) and V^* is the shear velocity.

$$V^* = \sqrt{\tau_o/\rho} = \sqrt{gRS} = \overline{V}\sqrt{f/8} \tag{14}$$

Here R is the hydraulic radius, S is the slope of energy gradient, and ν is the kinematic viscosity. The term $\Delta\overline{V}/V^*$ can be determined from the equation

$$\frac{\Delta\overline{V}}{V^*} = \left(\sqrt{\frac{8}{f}}\right)_{\substack{\text{smooth}\\\text{pipe}}} - \left(\sqrt{\frac{8}{f}}\right)_{\substack{\text{rough}\\\text{pipe}}} \tag{15}$$

In this graph the smooth-pipe equation is represented by the horizontal line $\Delta\overline{V}/V^* = 0$, and the Karman-Prandtl rough-pipe equation by the sloping line at the right side of the graph.

B. Transition Curves for Cast Pipe

It is not possible to plot the frictional data for the cast pipe with the same parameters used for the tamped pipe in Figs. 23 and 24 because the rough-flow regime did not occur with the cast pipe; therefore, it is not possible to determine the equivalent sand-grain roughness k_s for the cast pipe.

The maximum Reynolds number achieved in tests of the cast pipe was about 3.6 million; at this Reynolds number the data showed no deviation from a basic line approximately parallel to the smooth-pipe curve. As the laminar sub-layer decreases in thickness with increasing Reynolds number, it appears that at sufficiently high Reynolds numbers the roughness elements of the cast pipe will disrupt the laminar sub-layer and the rough-pipe regime will develop.

VI. VELOCITY DISTRIBUTION

A. Experimental Data

Under the basic test program it was requested that data on velocity distributions in the pipe be obtained if time and funds permitted. Accordingly, velocity traverses were made in the 36-in. pipe at two to four stations along the pipe, usually for one discharge around 40 to 45 cfs and a second in excess of 110 cfs.

The velocity distributions were measured with a Prandtl-type Pitot tube having a nose section 3/8 inch in diameter and supported by a 3/4-in.

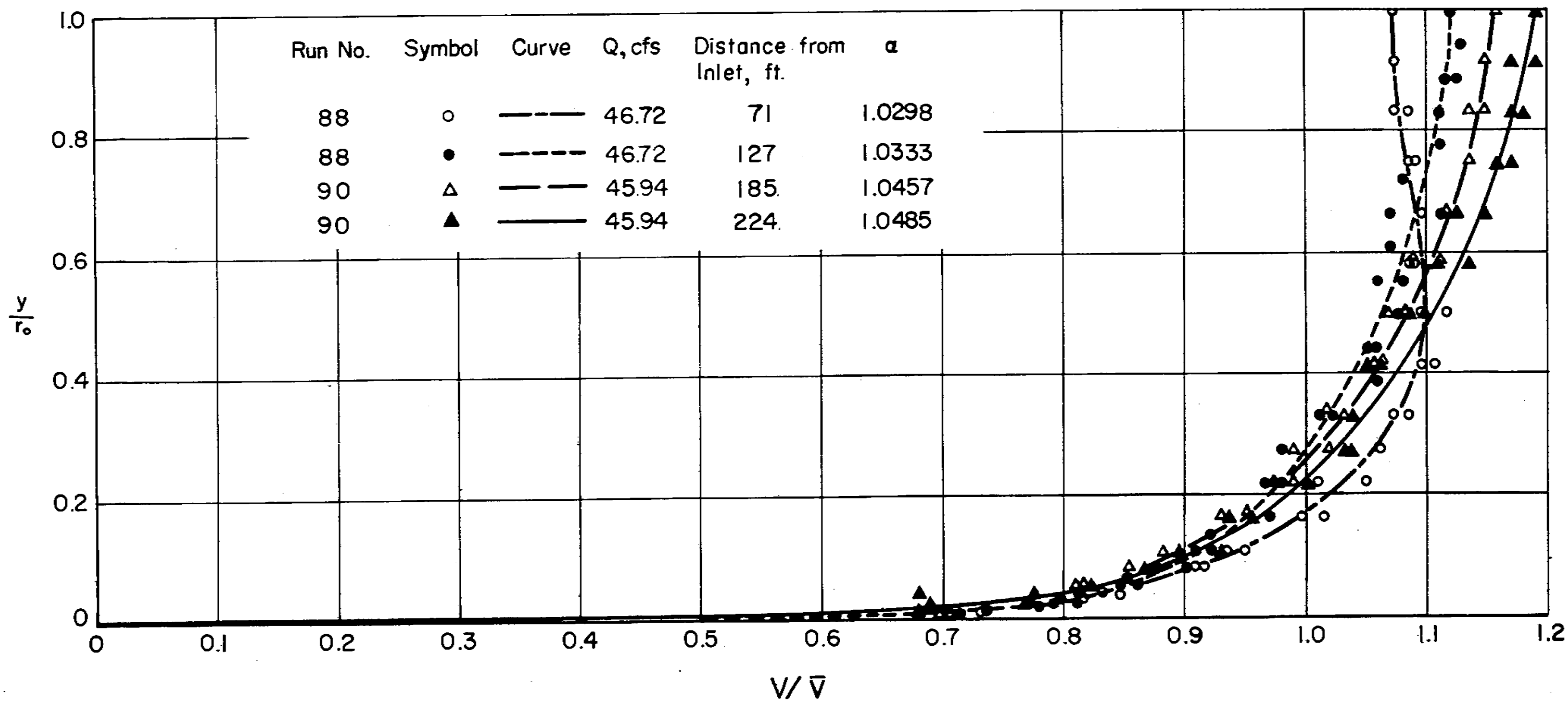


Fig. 26 - Velocity Distribution in the 36-In. Tamped Pipe with Good Joints

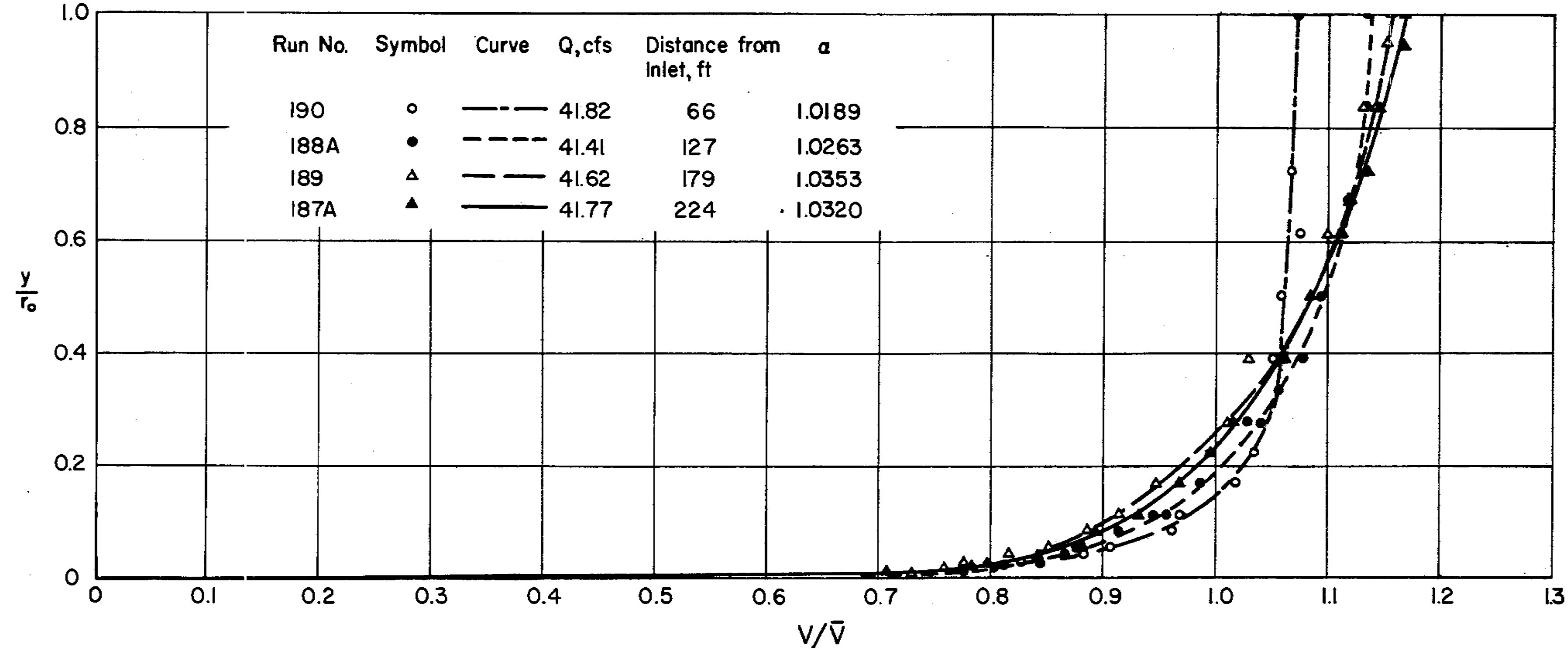


Fig. 27 - Velocity Distribution in the 36-In. Cast Pipe with Good Joints

diameter tube. It would have been desirable to utilize a second tube of much smaller diameter for measurements near the wall, but time limitations did not permit this refinement.

Figures 26 and 27 illustrate the velocity distributions at four stations in the tamped and cast pipe respectively, both with good joints. Referring to Fig. 26 for the tamped pipe, it may be noted that the velocity distribution changes gradually throughout the pipe length. However, except for the change between the first and second stations the variation is very small. Actually, the effect on the kinetic-energy correction factor α is quite small even when the first station is included. As noted in Fig. 26 the change in α is only 1.8 per cent from a point 71 ft from the inlet to a point 224 ft from the inlet.

Referring to Fig. 27, it may be noted that the boundary layer in the cast pipe is not as well developed at the upstream station as in the tamped pipe. This is due to the lower boundary shear in the cast pipe. The three downstream stations in the cast pipe show less variation in α than is the case in the tamped pipe, or 0.9 per cent.

Computations of α were based on the following equation:

$$\alpha = \frac{n^2 \sum V^3}{(\sum V)^3} \tag{16}$$

where $n = 18$, the number of equal annular areas into which the pipe cross section was divided, and V is the velocity at the centroid of each annular area.

In visual inspections of graphs of the type shown in Figs. 26 and 27, it should be noted that velocity variations in the region approaching the pipe centerline are sometimes given more weight than they deserve; for example, the central area or core (of 18 annular areas) comprises only 1/18 of the pipe area but extends over about 1/4 the area of the graph (from $y/r_o = 0.76$ to 1.0).

For comparison purposes, the value of α for fully established turbulent flow in rough pipes can be computed by the following formula:

$$\alpha = 1 + 2.93f - 1.55f^{3/2} \tag{17}$$

This formula was developed by Streeter [4] from an analysis based on the Karman-Prandtl universal logarithmic velocity distribution law. The computed value of α for the tamped pipe test shown in Fig. 26 is 1.0425, which compares very well with the measured values.

Table III summarizes the test data on velocity distributions in terms of the kinetic-energy correction factor α; in addition, the ratio of the computed to measured discharge Q_V/Q is also shown. The computed discharge was obtained by integrating the velocity distribution. The ratio Q_V/Q is of interest because it provides an indication of the accuracy of the velocity measurements. An examination of these data indicates that the velocity measurements have an average error on the order of one per cent. Normally this accuracy would be considered quite good. It is difficult to evaluate the order of accuracy of computed values of α, but examination of the data and comparison with Streeter's formula indicate a precision on the order of one per cent.

The friction coefficients discussed in a preceding section were based on the measured hydraulic grade line with velocity-head corrections for changes in area of the pipe at the piezometers. There was no measurable curvature of the grade line in the downstream 180 ft of the 36-in. tamped pipe or the 140 ft of 36-in. cast pipe. The values of α determined in these tests tend to substantiate the observations based on the hydraulic grade line in that kinetic-energy changes were very minor. While the measured values of α could have been incorporated in the computations of f (for runs where they were available), they would have produced (in most instances) an insignificant change in the f value; furthermore, since the use of α in the friction computations would reduce the f value and a complete set of α values was not available, the most conservative approach was to disregard α.

Figures 28 and 29 illustrate logarithmic plots of $V/\overline{V}$ as a function of relative distance from the wall (y/r_o). Although these plots are on a small scale, they do indicate that a power law distribution of velocity for the overall cross section, with various powers depending on the roughness and Reynolds number, is applicable to these data.

B. Local Friction Factors

Following a suggestion by Silberman [5], based in part on work by Hama [3] and Clauser [6], the local friction factor has been computed from

TABLE III

SUMMARY OF DATA ON KINETIC ENERGY FACTOR α

Pipe	Joints	Run	Station	Distance from Inlet (ft)	Q (cfs)	Q_V/Q	α	Re x 10^{-6}
36-Inch Tamped	Good	88	1	71	46.72	1.0169	1.0298	1.320
		88	2	127	46.72	0.9825	1.0333	1.320
		90	3	185	45.94	0.9846	1.0457	1.277
		90	4	224	45.94	0.9994	1.0485	1.277
		111	2	127	109.40	0.9754	1.0385	2.896
		110	3	185	110.60	1.0013	1.0319	2.928
		109	4	224	109.30	1.0026	1.0420	2.894
36-Inch Cast	Average	158	1	66	39.34	0.9934	1.0248	0.917
		157	2	127	39.41	1.0178	1.0286	0.919
		156	3	179	41.18	0.9913	1.0302	0.960
		155	4	224	40.91	1.0034	1.0287	0.954
	Good	190	1	66	41.87	1.0089	1.0189	0.958
		188A	2	127	41.41	1.0167	1.0263	0.948
		189	3	179	41.62	0.9954	1.0351	0.953
		187A	4	224	41.77	1.0027	1.0319	0.956
		197	1	66	151.21	0.9794	1.0237	3.525
		196	2	127	152.10	1.0001	1.0259	3.546
		197	3	179	151.87	1.0086	1.0259	3.540
		196	4	224	151.89	1.0244	1.0257	3.541

NOTE: Q = measured discharge in cfs, and Q_V = discharge integrated from the velocity distribution.

Run No.	Joints	Q, cfs	Distance from Inlet, ft
67	Rough	38.90	185
68	Rough	120.08	185
90	Smooth	45.94	224
109	Smooth	109.30	224

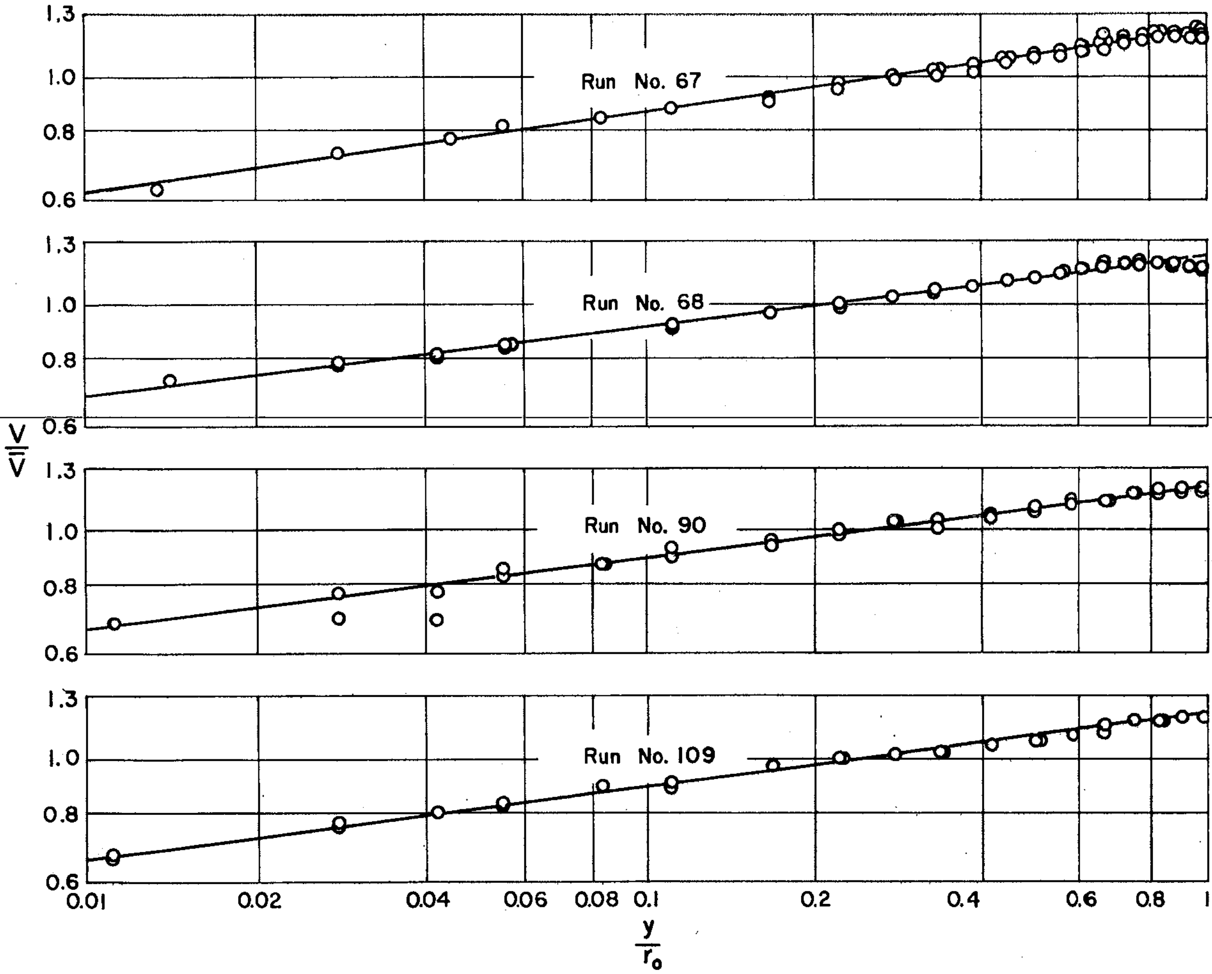


Fig. 28 - Logarithmic Plot of Typical Velocity Distribution in the 36-In. Tamped Pipe

Run No.	Joints	Q, cfs	Distance from Inlet, ft.
155	Average	40.91	224
187A	Good	41.77	224
196	Good	151.89	224

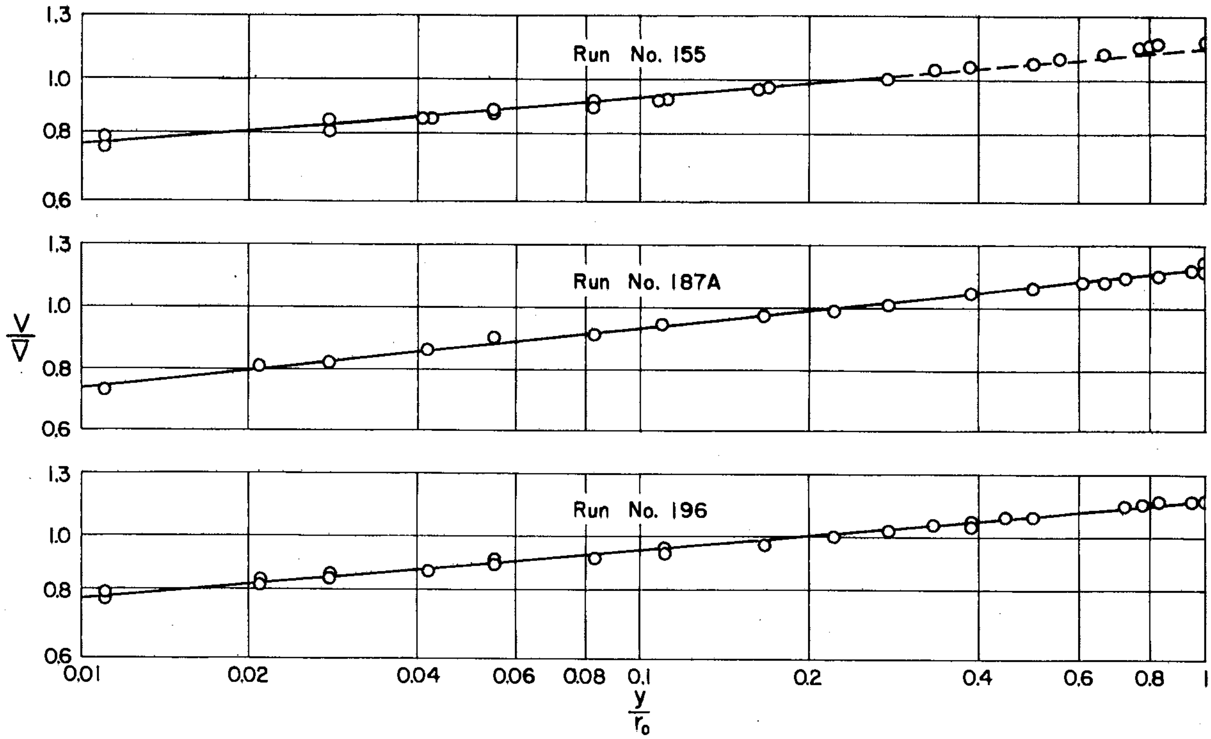


Fig. 29 - Logarithmic Plot of Typical Velocity Distribution in the 36-In. Cast Pipe

velocity measurements near the wall of the pipe. These measurements are not sufficiently accurate near the wall for a proper application of this technique, but the method may still be of interest.

Figure 30 illustrates the basic principles involved. Essentially, the method is based on the fact that the velocity distribution near the wall of the test pipe ($y/r_o < 0.15$), as compared to the distribution for a smooth pipe, is an index of the local shear and friction factor.

The velocity distribution near a smooth boundary can be described by

$$\frac{V}{V^*} = 5.6 \log \frac{yV^*}{\nu} + 4.9 \qquad (18)$$

using the constant 5.6 proposed by Clauser, where

$$V^* = \text{shear velocity} = \sqrt{\tau_o/\rho} = \overline{V}\sqrt{f/8}$$

Near a rough boundary,

$$\frac{V}{V^*} = 5.6 \log \frac{yV^*}{\nu} + 4.9 - \frac{\Delta V}{V^*} \qquad (19)$$

where the term $\frac{\Delta V}{V^*}$ is a downward shift of the velocity curve due to the wall roughness (see lower graph of Fig. 30). ($\frac{\Delta V}{V^*}$ depends on $\frac{k_s V^*}{\nu}$ as shown in Fig. 24.)

For a pipe the distribution can be expressed also in the form

$$\frac{V}{\overline{V}} = \frac{5.6\ V^*}{\overline{V}} \log \frac{y}{r_o} + \text{constant.} \qquad (20)$$

This can be developed from the preceding equation by noting that at a given station or location V^* and r_o are constants and can be removed from and inserted into the log term by modifying the constant in the equation.

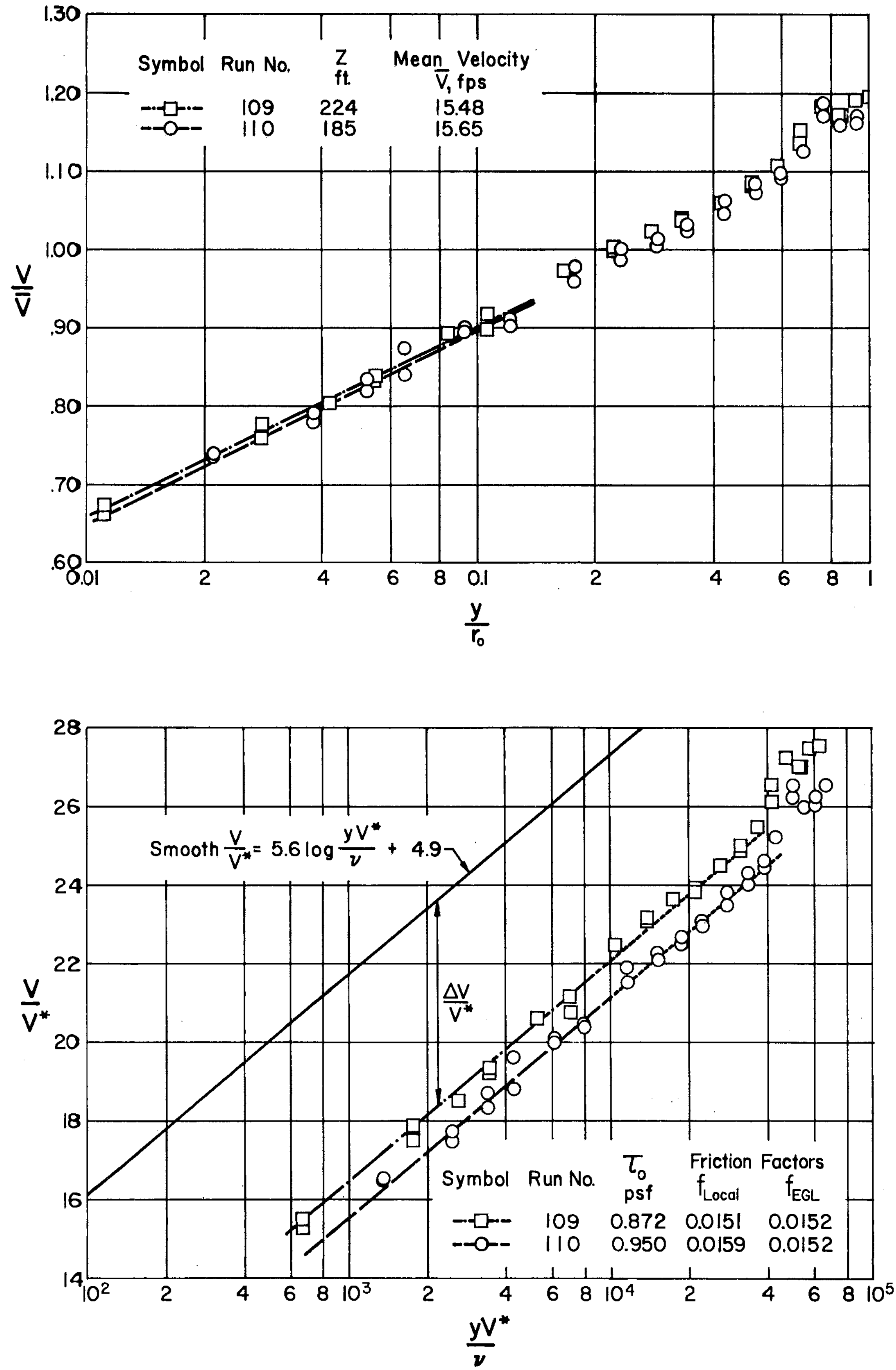


Fig. 30 – Velocity Distribution near the Boundary in the 36-In. Tamped Pipe with Good Joints

Referring to the upper graph of Fig. 30, ($V/\overline{V}$ vs y/r_o), Eq. (20) can be evaluated at the two points $y/r_o = 0.01$ and 0.1. Letting $a = V/\overline{V}$ at $y/r_o = 0.01$ and $b = V/\overline{V}$ at $y/r_o = 0.1$, and noting that $\log 0.01 = -2$ and $\log 0.1 = -1$, two equations are obtained:

$$a - \text{constant} = -2\,\frac{5.6\,V^*}{\overline{V}} \qquad (21)$$

$$b - \text{constant} = -1\,\frac{5.6\,V^*}{\overline{V}} \qquad (22)$$

Subtracting one from the other,

$$\frac{V^*}{\overline{V}} = \frac{b-a}{5.6}, \quad \text{and}$$

$$f = 8\left(\frac{V^*}{\overline{V}}\right)^2 = 8\left(\frac{b-a}{5.6}\right)^2 \qquad (23)$$

As $\overline{V}$, b, and a are known, the values of f and V^* can be computed. If desired, a graph similar to the lower graph of Fig. 30 can then be prepared. The difference between the smooth-surface curve and the experimental curve of V/V^* vs yV^*/ν is the downward shift caused by the wall roughness, or $(\Delta V/V^*)$. The meaning of this term is illustrated by the following computation:

$$\frac{\Delta V}{V^*} = \left.\frac{V}{V^*}\right|_{\text{smooth}} - \left.\frac{V}{V^*}\right|_{\text{rough}} = \left.\frac{\overline{V}}{V^*}\right|_{\text{smooth}} - \left.\frac{\overline{V}}{V^*}\right|_{\text{rough}}$$

$$= \left(\sqrt{\frac{8}{f}}\right)_{\substack{\text{smooth}\\ \text{wall}}} - \left(\sqrt{\frac{8}{f}}\right)_{\substack{\text{rough}\\ \text{wall}}} \qquad (24)$$

The local friction factors for two runs are shown in the lower graph of Fig. 30, together with the values of f computed from the hydraulic grade line. In this example the agreement is very good. Computations for other runs indicate some variation in the local value of f; these variations, ranging up to ±5 per cent of the grade-line friction factor, may be caused by (1) variations in wall roughness, (2) boundary-layer disturbances caused by the joints, and (3) inaccurate measurements near the wall, due to the large Pitot tube.

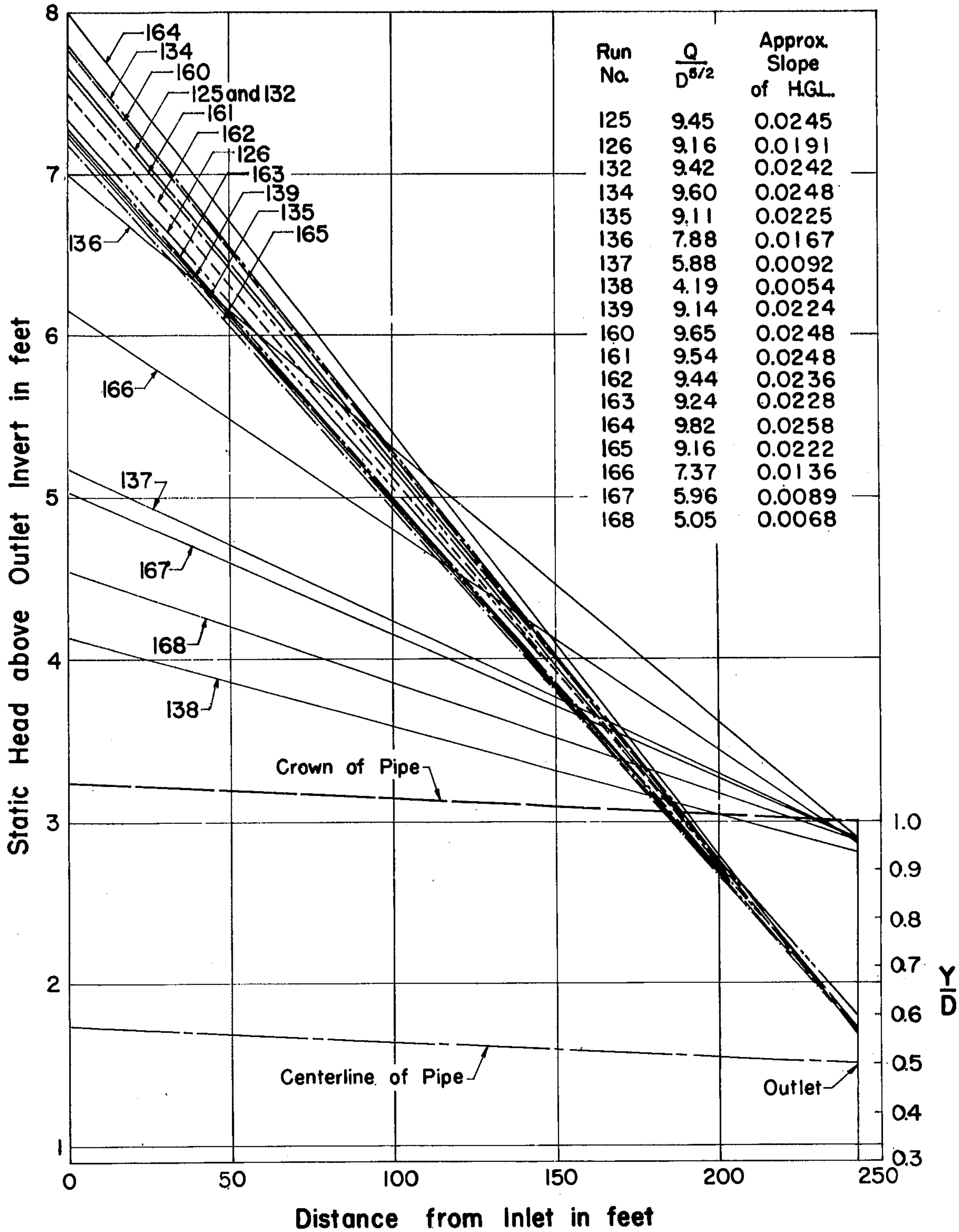
VII. ELEVATION OF HYDRAULIC GRADE LINE AT OUTLET OF PIPE

As a secondary part of the experimental studies, some data were obtained on the elevation of the hydraulic grade line at the outlet of the pipe with a free outfall. For the purpose of this discussion, this elevation is the intercept at the outlet of a straight-line extension of the grade line. With high discharges the grade line is straight to within a few diameters of the outlet, whereas for low discharges the grade line curves for a considerable distance upstream; in the latter case a straight-line extension is somewhat arbitrary.

The elevation of the intercept above the pipe invert is defined as Y; division of this quantity by the diameter D provides a dimensionless ratio. The grade-line elevation varies as a function of discharge and most investigators use the term $Q/D^{5/2}$ as a discharge ratio. This is not a dimensionless term (to be dimensionless it should be divided by $g^{1/2}$ but since g is a constant it is acceptable in place of a dimensionless quantity).

Figure 31 illustrates some of the test data, with grade-line elevation plotted as a function of distance from the inlet. The lines shown are actually straight-line extensions at both ends of the pipe in that curvature in the zone of flow establishment and at the outlet has been disregarded. Grade lines are shown for $Q/D^{5/2}$ ranging from 4.19 to 9.82. With discharge ratios between 9 and 10 the grade lines intercept the outlet at $Y/D \approx 0.57$. For these discharge ratios, the grade line passes through the crown of the pipe about 60 ft upstream of the outlet; thus, the flow near the crown is under negative pressure for the downstream 60 ft of pipe. With discharge ratios less than nine, the value of Y/D may range from 0.54 to 0.97. Figure 32 illustrates data on Y/D as a function of $Q/D^{5/2}$ for $0.4 < Q/D^{5/2} < 9.7$. A curve showing critical depth for free-surface flow in circular conduits is shown for reference purpose. Curves for Y/D obtained by Blaisdell [7], French [8], and Li and Patterson [9] are also shown.

In the current tests it was noted that part-full flow always occurred for discharge ratios less than 3.5. For discharges less than this value, the straight-line extension of the grade line intercepts the outlet at values of Y/D somewhat larger than critical depth. The divergence from critical depth is due to curvature of the water surface near the outlet.



Run No.	$\frac{Q}{D^{5/2}}$	Approx. Slope of H.G.L.
125	9.45	0.0245
126	9.16	0.0191
132	9.42	0.0242
134	9.60	0.0248
135	9.11	0.0225
136	7.88	0.0167
137	5.88	0.0092
138	4.19	0.0054
139	9.14	0.0224
160	9.65	0.0248
161	9.54	0.0248
162	9.44	0.0236
163	9.24	0.0228
164	9.82	0.0258
165	9.16	0.0222
166	7.37	0.0136
167	5.96	0.0089
168	5.05	0.0068

Fig. 31 - Variation in Hydraulic Grade-line Profile at Various Discharges

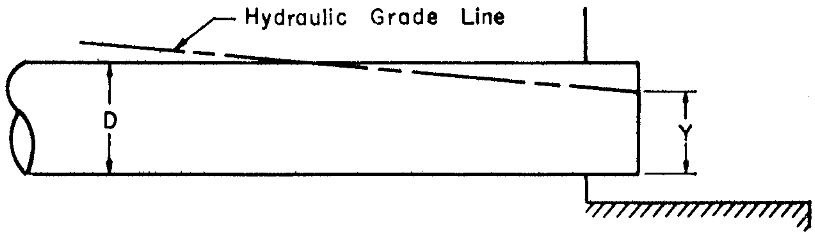
With discharge ratios between 3.5 and 9, the intercept Y/D may occur at two different values, dependent on whether entrained air is present in the conduit. For example, with a discharge ratio of 7 the intercept may occur at $Y/D \approx 0.64$ if no air is present. However, if a small amount of air is added, it apparently breaks the suction downstream of the point where the grade line passes through the crown of the pipe. A free-surface is then established with critical depth near the outlet. For the discharge ratio of 7, this causes the value of Y/D to increase from 0.64 to about 0.95.

The amount of air required to break the suction at the outlet was measured for a discharge ratio of about 8. The addition of a quantity of air equal to about one-tenth of one per cent (by volume) of the water discharge caused the pipe to flow part-full and the value of Y/D to increase from 0.57 to 0.92. The air was added about 180 ft upstream of the outlet by forcing it through a Pitot-tube gland near the top of the pipe.

When full flow was again established, air was admitted through a gland 16 ft from the outlet, that is, in the region of negative pressure at the crown. This did not affect the flow. A pressure line was then attached to the gland and air forced into the pipe at a discharge rate of about one-tenth of one per cent of the main flow. This also did not affect the flow. It was concluded that the air must be admitted far enough upstream to permit the air to collect in pockets at the crown of the pipe.

In Fig. 32 several curves are shown in the region of $3.5 < Q/D^{5/2} < 9$. The three upper curves (shown by open symbols) resulted from tests of the 36-in. pipe in which air was sometimes entrained in the drop shaft of the intake system. The upper limit of discharges for which air was entrained depended on the resistance offered by the test pipe and by a flow-control baffle in the system. By partially closing the flow-control baffle, air entrainment in the shaft could be eliminated, resulting in the lower curve defined by solid symbols.

It should be noted that data for runs in which air was present in the conduit were not used to compute friction coefficients. In the tests of the 24-in. pipe the inlet end of the pipe extended through a bulkhead into a free-surface pool 56 ft long by 9 ft wide. During the initial tests it was noted that a vortex frequently formed at the inlet, producing fluctuations in the downstream piezometers. A large piece of plywood was anchored over the



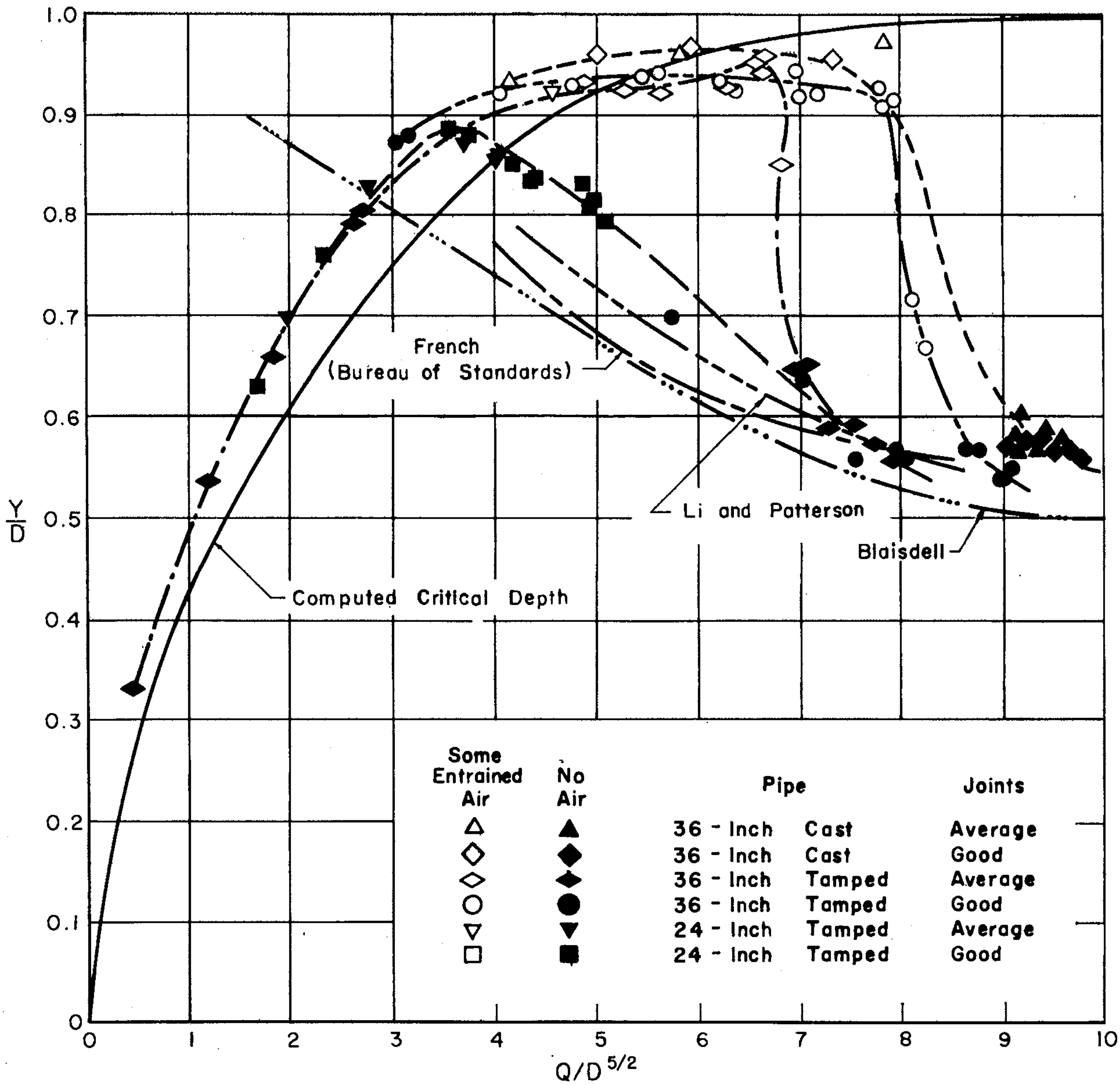


Fig. 32 - Hydraulic Grade-line Intercepts at Pipe Outlet

inlet end of the pipe to eliminate the vortex. This stabilized the manometers and also prevented air from being drawn into the pipe. Some of the data for the 24-in. pipe tests are shown in Fig. 32. One test point was considerably higher than the others at $Q/D^{5/2} = 4.6$. Initially it was thought that this was in error, but later after tests of the 36-in. pipe it was concluded that a vortex must have formed, resulting in entrainment of air in the flow and creation of part-full flow at the outlet.

The primary conclusion to be drawn from these tests is that, for some flows, the elevation of the grade line at the outlet is dependent on the presence or absence of entrained air in the flow. If air is present, due to a vortex or other mechanism, the upper curves of Fig. 32 roughly define the value of Y/D. If air is not present, the value of Y/D should decrease from 0.9 at $Q/D^{5/2} = 3.5$ to $Y/D = 0.57$ in the region of $Q/D^{5/2} = 8.0$.

It is possible that the grade line at the outlet is affected differently, to some extent, by an increasing flow than by a decreasing flow; the test data are not adequate to support any definite conclusions regarding this effect.

VIII. HEAD LOSS CAUSED BY TRANSVERSE PIPES

Occasionally it is necessary to pass water mains or other conduits transversely through storm sewers. It was requested that data be obtained on the head loss caused by such installations. At the conclusion of tests on the 36-in. tamped pipe, standard steel pipes with outside diameters of 8.62, 6.62, and 3.50 in. were inserted individually in the main pipe at a point 160 ft from the inlet. The smaller pipes extended transversely from wall to wall at the centerline of the main pipe. Data were obtained on the hydraulic grade line upstream and downstream of the transverse pipe for flow velocities up to about 16 fps. The two grade lines were extended to the transverse pipe; the difference in elevation of the grade lines at the transverse pipe was determined and plotted in the upper graph of Fig. 33 as the head loss caused by the transverse pipe. The abscissa of the graph is the average velocity of flow Q/A upstream and downstream of the pipe.

With a flow velocity of 10 fps, the 8.62-, 6.62-, and 3.50-in. transverse pipes produced head losses of about 0.6, 0.35, and 0.15 ft respectively.

A computed curve is shown also on the upper graph of Fig. 33, based on a drag coefficient of 1.2. For the purposes of this computation, it was assumed that the drag was the same as that of a 36-in. length of transverse pipe in two-dimensional unconfined flow. This assumption is not valid, especially near the walls of the main pipe, but the results are of interest for comparison purposes. The computed drag was converted to a head loss in the main conduit by pressure-momentum relationships on the basis of the following formula:

$$h_p = C_D \frac{4}{\pi} \frac{D'}{D} \frac{\overline{V}^2}{2g} \qquad (25)$$

where h_p = head loss in feet,
C_D = empirical drag coefficient,
D' = diameter of transverse pipe,
D = diameter of main pipe, and
$\overline{V}$ = average velocity in main pipe.

In the lower graph of Fig. 33 the drag coefficient, computed from the measured head loss, is plotted as a function of a Reynolds number based on the diameter of the transverse pipes. This coefficient varies due to boundary layer separation on the transverse pipe and to a minor extent with the diameter ratio (D'/D).

IX. SUMMARY

A. General

The present report is a natural sequel to hydraulic tests conducted on concrete culvert pipes at the St. Anthony Falls Hydraulic Laboratory ten years earlier. The tests reported in 1950 were less comprehensive and the instrumentation less elaborate, but the results presented showed considerably lower resistance to flow in concrete pipe than had been customarily accepted. The experiments were on 18-in., 24-in., and 36-in. pipe manufactured by the cast and vibrated process, all carefully laid with non-pressure rubber ring joints. There was, naturally, the question as to the limitations of these tests as compared to concrete pipe laid under normal field conditions. There was also the question of the hydraulic resistance of this cast and vibrated

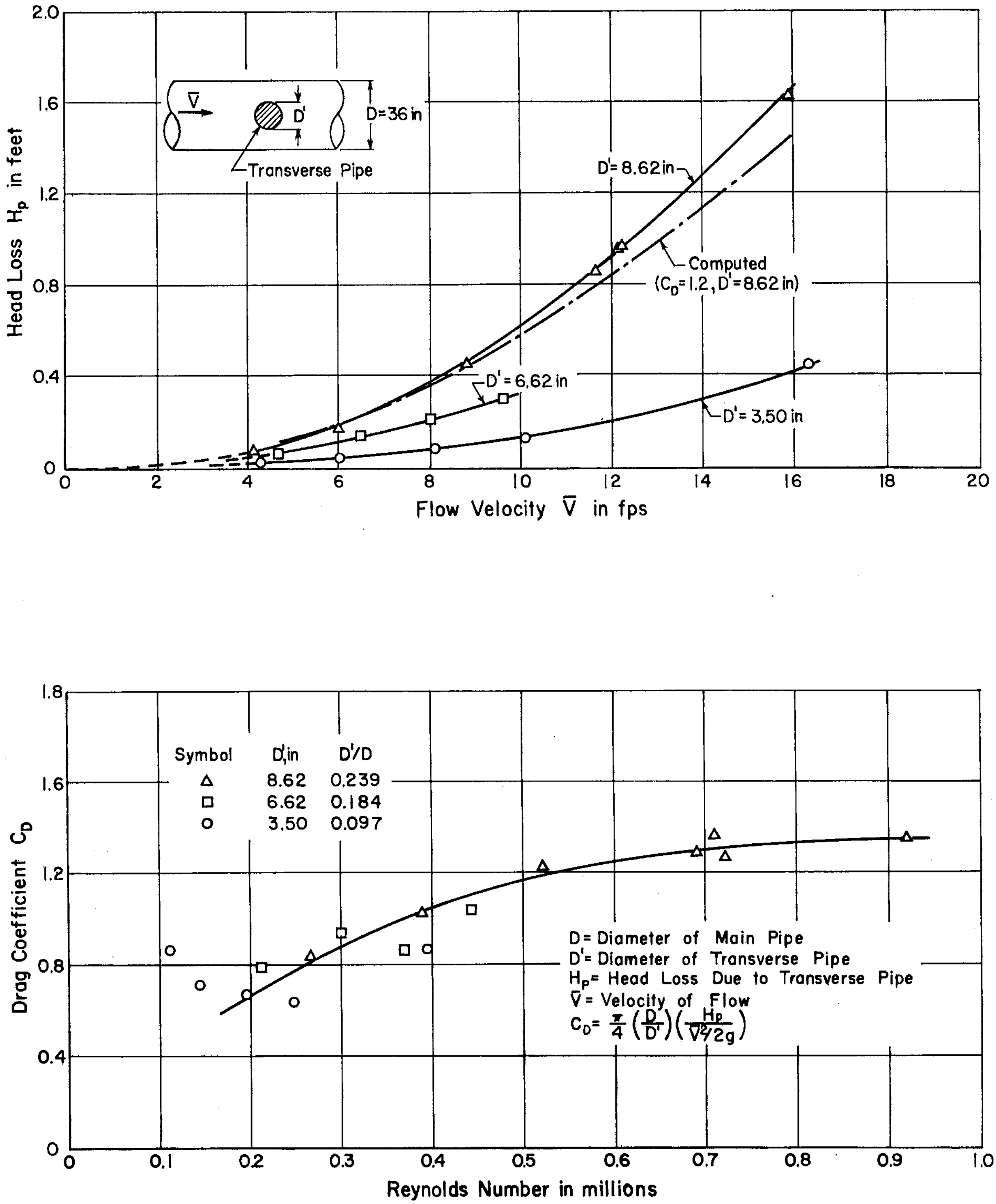


Fig. 33 - Head Loss Due to Smaller Pipes Passing Transversely through the Main Conduit

pipe as compared to the hydraulic resistance of pipe fabricated by the machine-tamped process.

The tests here reported have been directed toward answering these questions. In particular, the studies were planned to simulate normal field constructed concrete pipe installations and pipes generally available in the normal process of fabrication respectively by the cast and the tamped process. For the purpose of summarizing the results of the studies, the following discussion is presented under several headings as follows: (a) frictional resistance in the pipes; (b) observed velocity distribution in the pipe cross section; (c) hydraulic grade-line at outlet of pipe; (d) part-full flow observations; (e) head loss caused by transverse pipe obstructions; and (f) entrance loss coefficients.

B. Frictional Resistance in the Pipes

1. Experimental tests of 24-in. and 36-in. tamped pipe indicated very little variation in Darcy's f or the n value in the Manning formula for Reynolds numbers greater than 500,000. A slight hump in the curves occurred in the region of Reynolds number of about 1,500,000. For practical purposes the characteristic value of f or n could be obtained by an average of all data for Reynolds numbers greater than 500,000. However, for analytical purposes the limiting values of the coefficient were based on all data for Reynolds numbers greater than 3,000,000 for 36-in. tamped pipe and greater than 1,000,000 for 24-in. tamped. These data are summarized as follows:

Pipe Diameter	Joints	f	n	k_s
36-in.	Average	0.01570	0.01106	0.01365 in.
36-in.	Good	0.01515	0.01087	0.01158 in.
24-in.	Average-B	0.01757	0.01094	0.01512 in.
24-in.	Good	0.01638	0.01057	0.01108 in.

2. The tests of 36-in. cast pipe indicated that Darcy's f and Manning's n decreased with increasing Reynolds number over the complete test range of Reynolds number from 75,000 to 3,500,000. The experimental data are plotted in Figs. 13 and 14. Minimum values of the coefficients for cast pipe with average joints were on the order of f = 0.0107 and n = 0.0091 for Re = 3,425,000. Minimum values for cast pipe with good joints were f = 0.0105

and n = 0.0090. The data indicate that the cast pipe would produce substantially less head loss than tamped pipe at high Reynolds numbers.

3. A comparison of data for 36-in. tamped pipe with (1) joints similar to average field joints, and (2) the smoothest joints obtainable indicated a difference in f of 3.6 per cent and a difference in n of 1.7 per cent. Extrapolation of the data to an arbitrary condition of a pipe with bad joints resulted in f values 7.5 per cent higher than those for the pipe with good joints. Since the definition of a bad joint is somewhat arbitrary, it is possible that joint irregularities in some installations may cause larger losses than the above values would indicate.

4. In the transition zone of Reynolds number between the smooth-pipe and rough-pipe regimes, the data for tamped pipe were between the Colebrook curve and the Nikuradse curve for uniform sand-grain roughness. A semi-empirical curve was fitted to the data; a family of curves was then plotted in the form of a resistance diagram.

C. Velocity Distribution in the Pipe Cross Section

1. A limited number of velocity traverses were obtained in the 36-in. pipe at medium and high discharges, at four stations along the pipe. Analysis of the data indicated kinetic-energy correction factors (α) on the order of 1.046 for the tamped pipe and 1.034 for the cast pipe. Variations in α in the downstream 116 ft of pipe were quite small, on the order of 1 per cent.

2. A method for computing local friction factors, on the basis of velocity distribution near the pipe wall, is illustrated in a form applicable to the flow in pipes. While some variation can be expected in the local f values due to variations in the wall roughness and joint irregularities, the agreement with average values based on the hydraulic grade line was considered good.

D. Hydraulic Grade Line at Outlet of Pipe

1. Data were obtained on the elevation of the hydraulic grade line at the outlet of the pipe, with the tailwater lowered to provide a free outfall. The test data are illustrated in Fig. 32.

2. Addition of a small amount of air, which at times may be supplied by vortices at the inlet, produced a significant change in the grade line.

E. Part-Full Flow Observations

1. A limited number of tests were performed with part-full flow. The data have not been included in the report as further study and analysis are considered desirable.

2. On the basis of a preliminary review, the following observations were made: (a) the accuracy of measurements for part-full flow is not as good as corresponding measurements for full flow due to standing waves created by joint irregularities; and (b) for nominal water depths greater than half the pipe diameter, a reasonably good profile can be computed using the values of Manning's n obtained in the full flow tests.

F. Head Loss Caused by Transverse Pipe Obstructions

1. Measurements were made of the head loss caused by small pipes passing transversely through the main conduit. The losses can be computed approximately by a form of the drag equation, using a drag coefficient of about 1.2.

2. The head loss caused by an 8.62-in. diameter pipe passing transversely through a 3-ft diameter pipe was on the order of 0.6 ft for a flow velocity of 10 ft per second.

G. Entrance-Loss Coefficients

The test arrangement for the 24-in. tamped pipe involved an upstream bulkhead through which the pipe projected a distance of about 3 ft. The groove end of the pipe was upstream. An analysis of the data for full flow in the pipe indicated an entrance loss coefficient on the order of 0.07.

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INDEX TO APPENDICES AND RELATED ILLUSTRATIONS AND TABLES

APPENDIX A

EXPERIMENTAL DATA ON FRICTION LOSSES

TABLE A-1

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 36-INCH TAMPED CONCRETE PIPE WITH AVERAGE JOINTS

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Run No.	Q cfs	$S \times 10^2$	$\bar{V}$ fps	$Re \times 10^{-6}$	f	n	f_{sp}	$\frac{Re\sqrt{f}}{r_o/k_s}$	$1/\sqrt{f} - 2\log\frac{r_o}{k_s}$	$\frac{k_s V^*}{\nu}$	$\frac{\Delta\bar{V}}{V^*}$
1	55.81	0.49800	7.865	2.177	0.01558	0.01113	0.01023	205.5	1.770	36.34	5.305
2	55.73	0.50800	7.854	2.173	0.01594	0.01115	0.01023	207.6	1.679	36.70	5.728
3	43.60	0.30600	6.144	1.701	0.01569	0.01106	0.01064	161.1	1.741	28.48	4.841
4	38.67	0.24700	5.449	1.493	0.01610	0.01120	0.01086	143.3	1.639	25.33	4.839
6	24.44	0.09700	3.444	0.950	0.01583	0.01111	0.01175	90.4	1.706	15.97	3.774
7	13.35	0.03000	1.881	0.515	0.01641	0.01131	0.01310	50.0	1.564	8.83	2.633
9*	5.54	0.00500	0.781	0.216	0.01588	0.01112	0.01540	20.6	1.693	3.64	0.348
10*	12.41	0.02460	1.749	0.505	0.01557	0.01102	0.01315	47.7	1.772	8.41	1.999
11*	9.90	0.01560	1.395	0.402	0.01551	0.01099	0.01370	37.9	1.788	6.70	1.453
13*	9.48	0.01470	1.336	0.370	0.01594	0.01115	0.01390	35.3	1.679	6.23	1.587
14	23.13	0.08900	3.260	0.902	0.01622	0.01124	0.01188	86.8	1.609	15.34	3.741
15	19.85	0.06450	2.797	0.787	0.01596	0.01115	0.01215	75.2	1.674	13.29	3.270
16	32.13	0.17200	4.528	1.281	0.01624	0.01125	0.01114	123.4	1.605	21.81	4.603
17	48.57	0.38500	6.845	1.938	0.01591	0.01113	0.01042	184.9	1.778	32.67	5.245
18*	15.32	0.03800	2.159	0.597	0.01578	0.01109	0.01275	56.8	1.718	10.03	2.532
19*	11.17	0.02050	1.574	0.435	0.01602	0.01117	0.01310	41.6	1.658	7.36	2.365
20*	7.78	0.09960	1.096	0.304	0.01604	0.01117	0.01443	29.1	1.654	5.13	1.214
21*	5.68	0.00546	0.800	0.222	0.01650	0.01134	0.01532	21.6	1.543	3.81	0.832
22*	9.71	0.01530	1.368	0.375	0.01582	0.01110	0.01387	35.6	1.708	6.29	1.529
23*	3.44	0.00207	0.485	0.134	0.01705	0.01153	0.01697	13.3	1.417	2.34	0.050
33	34.36	0.19900	4.842	1.340	0.01643	0.01132	0.01106	129.8	1.560	22.94	4.832
35A	49.35	0.38800	6.955	1.880	0.01553	0.01100	0.01046	177.2	1.782	31.31	4.958
35B	49.35	0.39300	6.955	1.880	0.01573	0.01107	0.01046	178.3	1.731	31.51	5.102
36	34.14	0.19200	4.811	1.300	0.01606	0.01119	0.01112	124.7	1.649	22.02	4.503
37*	2.75	0.00134	0.388	0.103	0.01727	0.01160	0.01788	10.2	1.367	1.81	-0.370
38*	3.62	0.00247	0.510	0.138	0.01837	0.01209	0.01685	13.1	1.158	2.48	0.920
39*	3.63	0.00236	0.512	0.138	0.01746	0.01166	0.01685	13.7	1.326	2.43	0.413
40*	2.93	0.00147	0.413	0.112	0.01669	0.01141	0.01760	11.0	1.498	1.93	-0.573

TABLE A-1 (continued)

Run No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
41*	2.93	0.00148	0.413	0.112	0.01680	0.01144	0.01760	11.0	1.472	1.94	-0.498
49*	3.20	0.00190	0.451	0.112	0.01809	0.01191	0.01760	11.5	1.173	2.01	0.349
50*	3.19	0.00193	0.450	0.113	0.01849	0.01200	0.01754	11.6	1.112	2.03	0.556
51*	4.07	0.00296	0.574	0.144	0.01742	0.01166	0.01672	14.2	1.330	2.52	0.444
52	124.09	2.47000	17.487	4.345	0.01564	0.01104	0.00918	411.2	1.754	72.66	6.904
53	117.84	2.23500	16.606	4.125	0.01569	0.01106	0.00925	391.0	1.741	69.09	6.828
61	120.70	2.35000	17.009	4.377	0.01572	0.01107	0.00917	415.3	1.734	73.42	6.993
64	113.73	2.08000	16.027	3.917	0.01567	0.01108	0.00933	276.4	1.746	65.62	6.629
65	108.41	1.90000	15.277	3.733	0.01576	0.01108	0.00941	354.7	1.724	62.70	6.506

*Measurements made with micromanometer.
Average diameter D = 36.07 inches.
Limiting friction factors $f_\ell = 0.01570$ and $n_\ell = 0.01106$ for Reynolds number $Re > 3 \times 10^6$.
Equivalent sand roughness $k_s = 0.01365$ inch.
f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-2

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 36-INCH TAMPED CONCRETE PIPE WITH GOOD JOINTS

Run No.	Q cfs	$S \times 10^2$	$\bar{V}$ fps	$Re \times 10^{-6}$	f	n	f_{sp}	$\frac{Re\sqrt{f}}{r_o/k_s}$	$1/\sqrt{f} - 2\log\frac{r_o}{k_s}$	$\frac{k_s V^*}{\nu}$	$\frac{\Delta\bar{V}}{V^*}$
69	140.46	3.07000	19.794	4.034	0.01517	0.01087	0.00929	318.9	1.734	56.34	6.383
70	140.67	3.04000	19.824	3.844	0.01497	0.01080	0.00936	301.9	1.786	53.37	6.116
78	63.08	0.63600	8.889	1.780	0.01558	0.01100	0.01055	142.7	1.627	25.22	4.878
86*	18.29	0.05450	2.577	0.516	0.01588	0.01112	0.01307	41.8	1.550	7.37	2.297
90A	45.94	0.33700	6.474	1.276	0.01556	0.01101	0.01114	102.1	1.632	18.06	4.105
90B*	45.94	0.33920	6.474	1.276	0.01566	0.01105	0.01114	102.6	1.606	18.12	4.178
91	63.14	0.62500	8.898	1.754	0.01528	0.01091	0.01058	139.2	1.704	24.60	4.620
91A*	63.14	0.61905	8.898	1.754	0.01514	0.01086	0.01058	138.7	1.724	24.54	4.512
92	55.40	0.49100	7.807	1.514	0.01559	0.01102	0.01084	121.4	1.642	21.44	4.517
92A*	55.40	0.48070	7.807	1.514	0.01527	0.01091	0.01084	120.0	1.704	21.22	4.281
93	27.72	0.12300	3.906	0.758	0.01560	0.01103	0.01223	60.7	1.621	10.73	2.930
93A*	27.72	0.12290	3.906	0.758	0.01560	0.01103	0.01223	60.7	1.621	10.73	2.930
94	37.15	0.21750	5.235	1.015	0.01536	0.01094	0.01160	80.7	1.683	14.28	3.441
94A*	37.15	0.21420	5.235	1.015	0.01513	0.01085	0.01160	80.1	1.750	14.17	3.267
99	136.80	2.89000	19.278	3.622	0.01505	0.01083	0.00943	285.3	1.766	50.42	6.071
100	134.91	2.81000	19.012	3.572	0.01505	0.01083	0.00947	281.3	1.766	49.73	6.011
103	142.17	3.16000	20.035	3.628	0.01524	0.01088	0.00945	287.5	1.714	50.84	6.188
114	124.58	2.41000	17.556	3.340	0.01514	0.01086	0.00957	263.6	1.742	46.64	5.926
115	124.16	2.38500	17.497	3.329	0.01509	0.01084	0.00957	262.5	1.758	46.40	5.887
116	109.77	1.87000	15.469	2.943	0.01513	0.01086	0.00976	232.4	1.744	41.08	5.638
117	89.77	1.29500	12.651	2.407	0.01566	0.01105	0.01007	193.3	1.606	34.18	5.584
118	117.94	2.21000	16.620	3.162	0.01549	0.01099	0.00965	252.6	1.650	44.66	6.071
119*	5.18	0.00487	0.730	0.137	0.01769	0.01173	0.01682	11.7	1.134	2.06	0.540
119A*	5.18	0.00488	0.730	0.137	0.01773	0.01176	0.01682	11.7	1.125	2.06	0.565
120*	9.34	0.01459	1.316	0.247	0.01630	0.01127	0.01496	20.2	1.445	3.57	0.971
121*	19.05	0.05710	2.685	0.504	0.01534	0.01093	0.01316	40.1	1.689	7.07	1.819
123*	37.62	0.22150	5.301	0.996	0.01526	0.01091	0.01165	78.9	1.710	13.96	3.307
124*	11.83	0.02305	1.667	0.313	0.01605	0.01118	0.01435	25.4	1.508	4.49	1.284
124A*	11.83	0.02270	1.667	0.313	0.01581	0.01110	0.01435	25.3	1.568	4.47	1.116

TABLE A-2 (continued)

*Measurements made with micromanometer.
Average diameter $D = 36.07$ inches.
Limiting friction factors $f_\ell = 0.01515$ and $n_\ell = 0.01087$ for Reynolds number $Re > 3 \times 10^6$.
Equivalent sand roughness $k_s = 0.01158$ inch.
f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-3

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 36-INCH CAST CONCRETE PIPE WITH AVERAGE JOINTS

Run No.	Q cfs	S x 10^2	$\overline{V}$ fps	Re x 10^{-6}	f	n	f_{sp}
125	147.38	2.4500	20.862	3.373	0.01087	0.00920	0.00956
127	50.92	0.3500	7.208	1.165	0.01301	0.01007	0.01134
128	43.01	0.2505	6.088	0.984	0.01305	0.01008	0.01168
129	29.69	0.1300	4.203	0.679	0.01422	0.01052	0.01246
130	33.66	0.1625	4.765	0.770	0.01383	0.01038	0.01220
131	58.59	0.4460	8.293	1.341	0.01252	0.00987	0.01106
132	146.77	2.4200	20.775	3.359	0.01083	0.00919	0.00948
133	129.00	1.9300	18.260	2.952	0.01118	0.00933	0.00976
134	149.64	2.4850	21.181	3.425	0.01070	0.00913	0.00954
135	142.06	2.2550	20.109	3.251	0.01077	0.00916	0.00961
138	65.27	0.5450	9.239	1.494	0.01233	0.00980	0.01086
139	142.47	2.2350	20.167	3.261	0.01061	0.00909	0.00961
145	46.10	0.2840	6.525	1.075	0.01288	0.01002	0.01150
145A*	46.10	0.2850	6.525	1.075	0.01293	0.01003	0.01150
146	59.51	0.4400	8.424	1.387	0.01198	0.00966	0.01100
146A*	59.51	0.4570	8.424	1.387	0.01244	0.00984	0.01100
149*	11.26	0.0208	1.594	0.263	0.01581	0.01110	0.01473
150*	11.21	0.0208	1.587	0.261	0.01596	0.01115	0.01473
151*	3.20	0.0020	0.453	0.075	0.01883	0.01195	0.01910
152*	9.02	0.0139	1.277	0.210	0.01647	0.01133	0.01544
153*	18.91	0.0543	2.677	0.441	0.01464	0.01068	0.01347
154*	27.03	0.1041	3.826	0.630	0.01373	0.01034	0.01264
159	39.34	0.2125	5.569	0.917	0.01324	0.01015	0.01183

*Measurements made with micromanometer.
Average diameter D = 35.99 inches.
f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-4

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 36-INCH CAST CONCRETE PIPE WITH GOOD JOINTS

Run No.	Q cfs	S x 10^2	$\overline{V}$ fps	Re x 10^{-6}	f	n	f_{sp}
160	150.40	2.4800	21.289	3.506	0.01057	0.00907	0.00950
161	148.70	2.4300	21.048	3.467	0.01059	0.00908	0.00952
162	147.22	2.3600	20.839	3.432	0.01050	0.00904	0.00953
163	144.04	2.2800	20.389	3.358	0.01059	0.00908	0.00956
164	153.05	2.5800	21.664	3.568	0.01062	0.00909	0.00948
165	142.75	2.2200	20.206	3.328	0.01050	0.00904	0.00957
169	68.39	0.5600	9.681	1.594	0.01154	0.00948	0.01074
170*	50.94	0.3320	7.211	1.188	0.01233	0.00980	0.01129
170A	50.94	0.3235	7.211	1.188	0.01204	0.00968	0.01129
171*	28.01	0.1110	3.965	0.653	0.01364	0.01031	0.01254
172*	28.03	0.1121	3.968	0.653	0.01375	0.01035	0.01254
173*	11.55	0.0217	1.635	0.269	0.01568	0.01105	0.01475
174*	11.57	0.0217	1.638	0.270	0.01563	0.01103	0.01475
175*	5.74	0.0059	0.812	0.134	0.01726	0.01159	0.01697
176*	5.76	0.0058	0.815	0.134	0.01685	0.01146	0.01697
177*	8.49	0.0117	1.202	0.194	0.01565	0.01104	0.01574
178*	8.16	0.0110	1.155	0.187	0.01592	0.01113	0.01583
179*	23.50	0.0779	3.326	0.538	0.01360	0.01029	0.01299
180*	23.00	0.0773	3.256	0.526	0.01409	0.01048	0.01305
181*	15.81	0.0385	2.238	0.369	0.01485	0.01075	0.01391
182	39.68	0.2175	5.617	0.925	0.01332	0.01018	0.01181
182A*	39.85	0.2060	5.641	0.929	0.01250	0.00987	0.01180
183	57.84	0.4240	8.187	1.348	0.01222	0.00976	0.01072
184*	5.64	0.0058	0.798	0.129	0.01758	0.01170	0.01710
185*	5.70	0.0058	0.807	0.130	0.01721	0.01158	0.01708
186*	8.69	0.0125	1.230	0.199	0.01596	0.01115	0.01564
187	41.69	0.2320	5.901	0.954	0.01287	0.01001	0.01175
188	41.35	0.2295	5.853	0.946	0.01294	0.01004	0.01177
191	42.25	0.2335	5.980	0.967	0.01261	0.00991	0.01172

*Measurements made with micromanometer.
Average diameter D = 35.99 inches.
f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-5

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-A JOINTS

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Run No.	Q cfs	$S \times 10^2$	$\overline{V}$ fps	$Re \times 10^{-6}$	f	n	f_{sp}	$\frac{Re\sqrt{f}}{r_o/k_s}$	$1/\sqrt{f} - 2\log\frac{r_o}{k_s}$	$\frac{k_s V^*}{\nu}$	$\frac{\Delta\overline{V}}{V^*}$
17	4.30	0.025	1.353	0.259	0.01770	0.01098	0.01485	48.9	1.824	8.65	1.944
18	9.50	0.124	2.989	0.573	0.01798	0.01107	0.01284	109.2	1.763	19.31	3.869
19	13.40	0.247	4.216	0.807	0.01800	0.01108	0.01210	153.9	1.759	27.21	4.630
20	21.20	0.612	6.670	1.260	0.01782	0.01102	0.01118	239.0	1.796	42.26	5.561
21	25.80	0.948	8.117	1.533	0.01864	0.01127	0.01082	297.4	1.629	52.59	6.474
24	4.02	0.022	1.265	0.255	0.01782	0.01102	0.01490	48.3	1.796	8.55	1.984
25	12.75	0.227	4.012	0.817	0.01827	0.01116	0.01207	156.9	1.703	27.75	4.821
26	9.03	0.110	2.841	0.579	0.01765	0.01097	0.01282	109.3	1.832	19.33	3.689
27	4.01	0.022	1.262	0.259	0.01791	0.01105	0.01485	49.2	1.779	8.70	2.069
40*	4.20	0.241	1.321	0.220	0.01788	0.01104	0.01534	41.8	1.783	7.38	1.684
41*	4.25	0.241	1.337	0.222	0.01746	0.01091	0.01530	41.7	1.872	7.37	1.462
42*	4.17	0.240	1.312	0.218	0.01806	0.01110	0.01536	41.6	1.746	7.35	1.777
43	9.00	0.108	2.832	0.485	0.01745	0.01091	0.01324	91.0	1.875	16.10	3.171
44	9.15	0.115	2.879	0.496	0.01798	0.01107	0.01318	94.5	1.762	16.71	3.545
45	8.48	0.099	2.668	0.460	0.01802	0.01108	0.01336	87.7	1.754	15.51	3.399
46	6.07	0.053	1.910	0.326	0.01883	0.01133	0.01423	63.6	1.594	11.24	3.094
47	5.95	0.050	1.872	0.321	0.01848	0.01122	0.01427	62.0	1.661	10.95	2.869
48	8.89	0.107	2.797	0.485	0.01772	0.01099	0.01324	91.7	1.817	16.22	3.335
49	6.73	0.062	2.117	0.374	0.01791	0.01105	0.01388	71.1	1.777	12.57	2.874
50	6.29	0.057	1.979	0.349	0.01885	0.01134	0.01404	68.0	1.548	12.02	3.267
51	3.81	0.020	1.199	0.212	0.01803	0.01109	0.01545	40.5	1.752	7.15	1.690
56	13.47	0.250	4.238	0.780	0.01803	0.01109	0.01217	148.8	1.752	26.31	4.573
57	13.62	0.255	4.285	0.789	0.01799	0.01107	0.01214	150.3	1.760	26.57	4.584
58	22.64	0.707	7.123	1.311	0.01805	0.01109	0.01111	250.3	1.748	44.25	5.782
59	10.52	0.149	3.310	0.605	0.01762	0.01096	0.01272	114.1	1.838	20.17	3.771
60	10.54	0.149	3.316	0.606	0.01755	0.01094	0.01272	114.1	1.853	20.17	3.729
61	14.55	0.290	4.578	0.843	0.01793	0.01105	0.01200	160.4	1.773	28.36	4.689

TABLE A-5 (continued)

Run No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
62	14.76	0.302	4.644	0.855	0.01814	0.01112	0.01198	163.6	1.730	28.93	4.839
66	26.38	0.975	8.300	1.478	0.01834	0.01118	0.01088	284.3	1.691	50.28	6.225
67	26.43	0.970	8.316	1.480	0.01817	0.01113	0.01087	283.4	1.723	50.12	6.147
68	25.55	0.917	8.039	1.431	0.01838	0.01119	0.01094	275.6	1.681	48.73	6.180
69	25.40	0.894	7.992	1.423	0.01814	0.01112	0.01096	272.2	1.731	48.13	6.011
70	20.70	0.580	6.513	1.170	0.01771	0.01099	0.01133	221.2	1.819	39.10	5.320
71	20.45	0.578	6.434	1.156	0.01809	0.01111	0.01135	220.9	1.740	39.05	5.518
72	28.33	1.100	8.913	1.476	0.01794	0.01106	0.01088	280.9	1.771	49.66	5.999
73	28.40	1.105	8.935	1.479	0.01793	0.01106	0.01087	281.4	1.773	49.75	6.006
74	25.15	0.875	7.913	1.310	0.01810	0.01111	0.01111	250.4	1.737	44.29	5.812
75	19.93	0.543	6.271	1.038	0.01789	0.01104	0.01156	197.2	1.781	34.87	5.159
76	17.23	0.405	5.421	0.961	0.01785	0.01103	0.01173	182.4	1.789	32.25	4.941
77	13.20	0.240	4.153	0.736	0.01803	0.01109	0.01229	140.4	1.752	24.83	4.449

*Measurements made with micromanometer.

Average diameter $D = 24.14$ inches.

Limiting friction factors $f_\ell = 0.01809$ and $n_\ell = 0.01111$ for Reynolds number $Re > 1 \times 10^6$.

Equivalent sand roughness $k_s = 0.01715$ inch.

f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-6

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-B JOINTS

Run No.	Q cfs	$S \times 10^2$	$\overline{V}$ fps	$Re \times 10^{-6}$	f	n	f_{sp}	$\frac{Re\sqrt{f}}{r_o/k_s}$	$1/\sqrt{f} - 2 \log \frac{r_o}{k_s}$	$\frac{k_s V^*}{\nu}$	$\frac{\Delta \overline{V}}{V^*}$
78	27.90	1.049	8.778	1.459	0.01764	0.01097	0.01091	242.7	1.724	42.91	5.784
79	23.85	0.763	7.504	1.248	0.01755	0.01094	0.01120	207.1	1.743	36.60	5.376
80	17.77	0.427	5.591	0.932	0.01770	0.01098	0.01179	155.4	1.712	27.46	4.796
81	12.34	0.206	3.883	0.650	0.01770	0.01098	0.01256	108.3	1.712	19.14	3.978
82	23.11	0.706	7.271	1.175	0.01730	0.01086	0.01131	193.1	1.798	34.14	5.091
83	22.86	0.706	7.192	1.162	0.01768	0.01098	0.01134	193.0	1.715	34.12	5.289
84	19.42	0.515	6.110	0.987	0.01787	0.01104	0.01168	165.0	1.676	29.16	5.002
85	19.25	0.515	6.057	0.979	0.01819	0.01114	0.01170	165.0	1.610	29.16	5.177
86	14.90	0.302	4.688	0.792	0.01780	0.01102	0.01214	132.4	1.690	23.41	4.472
87	14.90	0.302	4.688	0.792	0.01780	0.01102	0.01214	132.4	1.690	23.41	4.472
88	9.80	0.130	3.083	0.521	0.01772	0.01099	0.01305	86.9	1.709	15.36	3.505
89	9.82	0.130	3.090	0.522	0.01764	0.01097	0.01305	86.9	1.725	15.36	3.462
90*	3.33	0.015	1.048	0.179	0.01770	0.01098	0.01599	29.8	1.712	5.27	1.108
91*	3.33	0.015	1.048	0.179	0.01770	0.01098	0.01599	29.8	1.712	5.27	1.108
92	26.11	0.925	8.215	1.403	0.01776	0.01100	0.01098	234.2	1.699	41.40	5.768
93	21.11	0.595	6.642	1.119	0.01747	0.01091	0.01141	185.3	1.761	32.76	5.078

*Measurements made with micromanometer.
Average diameter D = 24.14 inches.
Limiting friction factors f_ℓ = 0.01757 and n_ℓ = 0.01094 for Reynolds number $Re > 1 \times 10^6$.
Equivalent sand roughness k_s = 0.01512 inch.
f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

TABLE A-7

EXPERIMENTAL DATA ON FRICTIONAL LOSSES FOR FULL FLOW IN 24-INCH TAMPED CONCRETE PIPE WITH GOOD JOINTS

Run No.	Q cfs	$S \times 10^2$	$\overline{V}$ fps	$Re \times 10^{-6}$	f	n	f_{sp}	$\frac{Re\sqrt{f}}{r_o/k_s}$	$1/\sqrt{f} - 2\log\frac{r_o}{k_s}$	$\frac{k_s V^*}{\nu}$	$\frac{\Delta\overline{V}}{V^*}$
99	28.31	1.009	8.929	1.374	0.01639	0.01057	0.01101	161.6	1.738	28.56	4.838
100	28.32	1.009	8.932	1.374	0.01636	0.01056	0.01101	161.4	1.745	28.53	4.843
101	25.02	0.792	7.892	1.214	0.01645	0.01059	0.01125	143.0	1.723	25.28	4.613
102	25.10	0.792	7.917	1.218	0.01635	0.01056	0.01124	143.0	1.747	25.28	4.559
103	21.44	0.577	6.762	1.040	0.01633	0.01055	0.01156	122.1	1.752	21.58	4.173
104	20.28	0.503	6.397	0.959	0.01591	0.01041	0.01174	111.1	1.855	19.63	3.680
105	17.57	0.373	5.542	0.828	0.01571	0.01035	0.01204	95.3	1.905	16.84	3.213
106	13.92	0.238	4.390	0.652	0.01597	0.01044	0.01255	75.7	1.842	13.38	2.858
107	10.79	0.152	3.403	0.505	0.01698	0.01076	0.01313	60.4	1.601	10.68	2.978
111	8.80	0.098	2.776	0.412	0.01646	0.01059	0.01363	48.6	1.721	8.59	2.179
112	12.01	0.182	3.788	0.557	0.01641	0.01057	0.01292	65.6	1.733	11.59	2.818
113	15.79	0.308	4.980	0.737	0.01607	0.01046	0.01218	85.8	1.815	15.17	3.213
114	19.16	0.460	6.043	0.889	0.01630	0.01054	0.01188	104.2	1.759	18.43	3.795
115	22.15	0.609	6.986	1.051	0.01614	0.01049	0.01154	122.6	1.798	21.67	4.064
116	26.05	0.847	8.216	1.209	0.01623	0.01052	0.01126	141.5	1.776	25.00	4.453
117	29.05	1.074	9.163	1.348	0.01655	0.01062	0.01105	159.3	1.700	28.16	4.915
118	10.75	0.144	3.391	0.491	0.01620	0.01051	0.01320	57.4	1.783	10.15	2.396
119*	9.72	0.115	3.066	0.444	0.01621	0.01051	0.01345	52.0	1.782	9.19	2.172
120*	6.83	0.060	2.154	0.312	0.01673	0.01068	0.01432	37.0	1.659	6.55	1.767
121*	2.71	0.010	0.855	0.124	0.01771	0.01099	0.01725	15.2	1.441	2.68	0.281
122*	4.75	0.029	1.498	0.217	0.01672	0.01067	0.01540	25.8	1.661	4.56	0.917
123*	6.15	0.049	1.940	0.273	0.01685	0.01072	0.01470	32.6	1.631	5.76	1.540
124	13.95	0.238	4.400	0.618	0.01591	0.01041	0.01268	71.6	1.855	12.65	2.694
125	27.49	0.954	8.671	1.218	0.01642	0.01058	0.01123	143.3	1.730	25.33	4.606
126	27.73	0.962	8.746	1.229	0.01627	0.01053	0.01122	144.0	1.767	25.45	4.521
127	23.83	0.728	7.516	1.056	0.01667	0.01066	0.01152	125.2	1.672	22.13	4.438
128	20.32	0.528	6.409	0.900	0.01663	0.01065	0.01188	106.6	1.681	18.85	4.017

*Measurements made with micromanometer.

Average diameter D = 24.11 inches.

Limiting friction factors f_ℓ = 0.01638 and n_ℓ = 0.01057 for Reynolds number $Re > 1 \times 10^6$.

Equivalent sand roughness k_s = 0.01108 inch.

f_{sp} is the friction factor for smooth pipe at the given Reynolds number.

APPENDIX B

DATA ON PIPE DIAMETERS, PIPE JOINTS, AND PIEZOMETER LOCATIONS

TABLE B-1

FIELD DATA ON JOINT CHARACTERISTICS OF 36-INCH TAMPED CONCRETE PIPE

Joint No.	Maximum Offset			Offset Area			Ave. Offset
	Pos.	Neg.	Over-all	Pos.	Neg.	Total	
1	0.350	0	0.350	15.60	0	15.60	0.138
2	0.137	0.254	0.254	3.56	9.80	13.36	0.118
3	0.530	1.000	1.000	17.80	42.72	60.52	0.535
4	0.243	1.000	1.000	5.04	44.72	49.76	0.440
5	0.390	1.370	1.370	11.56	56.88	68.44	0.605
11	0.250	0.492	0.492	6.84	21.20	28.04	0.248
13	0.500	0.220	0.500	8.00	25.56	33.56	0.296
16	0.100	0.100	0.100	4.88	4.20	9.08	0.080
17	0.040	0	0.040	0.50	0	0.50	0.004
18	0	0.560	0.560	0	15.72	15.72	0.139
19	0.089	0.100	0.100	3.24	3.16	6.40	0.057
20	0.070	0.020	0.070	5.96	0.20	6.16	0.054
21	0.246	0	0.246	12.00	0	12.00	0.106
22	0.190	0.110	0.190	16.80	3.92	20.72	0.183
23	0.390	0.190	0.390	14.76	7.12	21.88	0.194
24	0.100	0	0.100	4.88	0	4.88	0.043
25	0.090	0.300	0.300	3.40	14.08	17.48	0.154
26	0.240	0.180	0.240	7.08	11.32	18.40	0.163
27	0.230	0.290	0.290	5.68	13.96	19.64	0.174
28	0.010	0.200	0.200	0.96	9.28	10.24	0.091
32	0	0.150	0.150	0	15.30	15.30	0.135
36	0	0.370	0.370	0	22.10	22.10	0.196
39	0.030	0.110	0.110	0.24	7.20	7.44	0.066
40	0.530	0.340	0.530	14.92	15.88	30.80	0.272
41	0.420	0.400	0.420	17.04	12.84	29.88	0.264
43	0.370	0.060	0.370	10.48	1.52	12.00	0.106
Total	5.545	7.906	9.742	191.22	358.68	549.90	4.861
Mean per joint	0.213	0.304	0.375	7.35	13.80	21.15	0.187
Average	-	-	-	-	-	-	0.187

Units are inches and square inches.
Area reduction = positive offset area plus projected area of bead.
Estimated fillet width = 5 inches.
Average bead (or fillet) width = covered area/length.
Average covered area = total area/number of beaded joints.
Average bead height = projected area/length.
Average groove width = total width/number of grooves.

TABLE B-1 (continued)

FIELD DATA ON JOINT CHARACTERISTICS OF 36-INCH TAMPED CONCRETE PIPE

Beads and Fillets						Grooves		Area Reduction	
Length	Width	Covered Area	Max. Height	Proj. Area	Ave. Height	Length	Width	sq in.	per cent
113.1	4.90	554.0	0.440	35.13	0.311	0	0	50.73	4.98
113.1	5.54	627.0	0.275	20.18	0.178	0	0	23.74	2.33
73.1	5.00	365.5	0	0	0	40.0	0.19	17.80	1.75
31.6	2.00	63.2	0.200	3.16	0.100	81.5	0.16	8.20	0.81
18.1	2.00	36.2	0.040	0.36	0.020	95.0	0.40	11.92	1.17
0	0	0	0	0	0	113.1	1.54	6.84	0.67
0	0	0	0	0	0	113.1	0.84	8.00	0.79
0	0	0	0	0	0	113.1	0.87	4.88	0.48
113.1	2.74	309.8	0.150	4.24	0.037	0	0	4.74	0.46
113.1	5.00	565.5	0	0	0	0	0	0	0
63.4	1.26	79.9	0.720	18.50	0.292	49.7	1.26	21.74	2.14
0	0	0	0	0	0	113.1	0.78	5.96	0.59
0	0	0	0	0	0	113.1	0.95	12.00	1.18
113.1	4.47	505.8	0.340	24.03	0.212	0	0	40.83	4.01
113.1	7.20	814.5	0.280	23.21	0.205	0	0	37.97	3.73
113.1	5.58	631.1	0.180	18.23	0.161	0	0	23.11	2.27
113.1	6.34	716.8	0.140	9.48	0.084	0	0	12.88	1.27
113.1	6.67	754.7	0.190	17.54	0.155	0	0	24.62	2.42
113.1	6.27	709.0	0.220	19.80	0.175	0	0	25.48	2.50
113.1	5.62	635.5	0.220	20.89	0.185	0	0	21.85	2.15
113.1	4.28	483.7	0.200	15.55	0.138	0	0	15.55	1.53
113.1	6.83	772.2	0.300	24.52	0.217	0	0	24.52	2.41
113.1	6.43	727.0	0.370	23.13	0.205	0	0	23.37	2.30
113.1	8.30	936.4	0.330	26.56	0.235	0	0	41.48	4.08
73.1	4.96	362.4	0.720	28.69	0.392	40.0	0.12	45.73	4.49
113.1	7.24	818.8	0.250	11.50	0.102	0	0	21.98	2.16
2068.9	108.63	11369.0	5.565	344.70	3.404	871.7	7.11	535.92	52.67
79.57	-	-	0.265	13.26	-	33.53	-	20.61	2.03
-	5.50	541.4	-	-	0.167	-	0.711	-	-

TABLE B-2

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 36-INCH TAMPED CONCRETE PIPE WITH AVERAGE JOINTS

Joint No.	Maximum Offset			Offset Area			Ave. Offset
	Pos.	Neg.	Over-all	Pos.	Neg.	Total	
1	0.250	0.200	0.250	7.94	5.31	13.25	0.117
2	0.660	0.330	0.660	23.53	10.28	33.81	0.299
3	0.480	0.225	0.480	17.24	2.10	19.34	0.171
4	0.790	0.520	0.790	13.22	17.30	30.52	0.270
5	0.365	0.085	0.365	15.64	3.78	19.42	0.172
6	0.280	0.120	0.280	5.84	2.17	8.01	0.071
7	0.300	0.440	0.440	7.60	16.50	24.10	0.213
8	0.060	0.085	0.085	0.85	2.60	3.45	0.031
9	0.120	0.150	0.150	1.71	8.35	10.06	0.094
10	0.240	0.050	0.240	11.92	0.78	12.70	0.112
11	0.250	0.050	0.250	10.66	1.07	11.73	0.104
12	0.130	0.430	0.430	3.39	10.49	13.88	0.123
13	0.390	0.270	0.390	13.99	8.65	22.64	0.200
14	0.160	0	0.160	12.84	0	12.84	0.114
15	0.370	0.080	0.370	10.97	0.59	11.56	0.102
16	1.030	0.970	1.030	30.37	40.89	71.26	0.630
17	0.200	0.080	0.200	5.51	1.70	7.21	0.064
18	0.090	0.350	0.350	1.65	9.96	11.61	0.103
19	0.285	0.020	0.285	17.39	0.09	17.48	0.155
20	1.500	1.260	1.500	49.11	52.75	101.86	0.902
21	0.130	0.100	0.130	3.07	4.22	7.29	0.064
22	0.330	0.250	0.330	15.16	5.37	20.53	0.181
23	0.180	0	0.180	8.88	0	8.88	0.079
24	0.320	0.070	0.320	17.79	0.46	18.25	0.161
25	0.230	0	0.230	14.52	0	14.52	0.128
26	0.570	0.070	0.570	21.53	1.77	23.30	0.197
27	0.280	0	0.280	15.62	0	15.62	0.138
28	0.290	0	0.290	12.80	0	12.80	0.113
29	0.530	0.110	0.530	17.08	2.56	19.64	0.174
Total	10.810	6.315	11.565	387.82	209.74	597.56	5.282
Mean per joint	0.373	0.218	0.399	13.37	7.23	20.60	0.182
Average	-	-	-	-	-	-	0.182

Units are inches and square inches.
Area reduction = positive offset area plus projected area of bead.
Estimated fillet width = 5 inches.
Average bead (or fillet) width = covered area/length.
Average covered area = total area/number of beaded joints.
Average bead height = projected area/length.
Average groove width = total width/number of grooves.

TABLE B-2 (continued)

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE
36-INCH TAMPED CONCRETE PIPE WITH AVERAGE JOINTS

Beads and Fillets						Grooves		Area Reduction	
Length	Width	Covered Area	Max. Height	Proj. Area	Ave. Height	Length	Width	sq in.	per cent
74.2	6.33	469.6	0.219	7.20	0.097	38.9	0.59	15.14	1.49
74.2	5.45	404.0	0.281	17.47	0.235	38.9	1.69	41.00	4.03
74.2	6.00	444.8	0.218	10.09	0.136	38.9	1.28	27.33	2.68
113.1	5.00	565.5	0	0	0	0	0	13.22	1.30
74.2	5.60	415.2	0.281	16.94	0.228	38.9	1.00	32.58	3.20
113.1	1.50	169.6	0.812	35.00	0.309	0	0	40.84	4.01
74.2	5.27	391.3	0.125	4.37	0.059	38.9	0.34	11.97	1.17
74.2	5.00	371.0	0	0	0	38.9	1.03	0.85	0.08
74.2	5.88	436.1	0.313	16.98	0.229	38.9	0.19	18.69	1.84
74.2	6.32	468.8	0.406	24.73	0.333	38.9	0.44	36.65	3.66
74.2	5.00	371.0	0	0	0	38.9	1.47	10.66	1.05
74.2	5.69	422.4	0.438	23.62	0.318	38.9	0.53	27.01	2.65
74.2	4.96	367.7	0.062	1.37	0.018	38.9	1.59	15.36	1.51
74.2	6.24	463.0	0.344	22.86	0.308	38.9	0.63	35.70	3.51
74.2	5.69	422.5	0.500	25.82	0.348	38.9	0.63	36.79	3.61
113.1	5.00	565.5	0	0	0	0	0	30.37	2.98
74.2	5.43	402.5	0.375	21.35	0.288	38.9	0.28	26.86	2.64
74.2	4.96	367.7	0.249	13.33	0.180	38.9	0.87	14.98	1.47
74.2	3.53	261.7	0.125	6.32	0.085	38.9	1.69	23.71	2.33
113.1	5.00	565.5	0	0	0	0	0	49.11	4.82
74.2	5.07	376.0	0.203	10.08	0.136	38.9	0.37	13.15	1.29
74.2	5.82	432.0	0.469	19.24	0.259	38.9	0.62	34.40	3.38
74.2	5.13	380.8	0.344	21.45	0.289	38.9	0.25	30.33	2.98
74.2	5.55	411.8	0.312	13.82	0.186	38.9	0.03	31.61	3.10
74.2	6.31	467.8	0.484	28.72	0.387	38.9	0.75	43.24	4.25
74.2	5.70	423.1	0.454	20.39	0.275	38.9	0.87	41.92	4.12
74.2	2.90	215.5	0.219	16.63	0.224	38.9	0.44	32.25	3.17
74.2	4.32	320.5	0.156	7.31	0.099	38.9	0.02	20.11	1.98
74.2	5.35	397.2	0.516	24.20	0.326	38.9	1.12	41.28	4.06
2307.4	150.00	11770.1	7.905	409.29	5.352	972.5	18.72	797.11	78.36
79.57	-	-	0.273	14.11	-	33.53	-	27.49	2.70
-	5.10	405.9	-	-	0.177	-	0.750	-	-

TABLE B-3

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 36-INCH TAMPED CONCRETE PIPE WITH GOOD JOINTS

Joint No.	Maximum Offset Pos.	Maximum Offset Neg.	Maximum Offset Over-all	Offset Area Pos.	Offset Area Neg.	Offset Area Total	Ave. Offset	Area Reduction (per cent)
1	0.090	0.075	0.090	1.03	0.69	1.72	0.015	0.10
2	0.080	0.060	0.080	3.43	1.51	4.94	0.044	0.34
3	0.050	0.030	0.050	1.87	0.23	2.10	0.019	0.18
4	0.235	0.030	0.235	9.23	0.42	9.65	0.085	0.91
5	0.200	0	0.200	8.60	0	8.60	0.076	0.84
6	0.310	0.250	0.310	8.81	6.98	15.79	0.140	0.87
7	0.090	0.200	0.200	1.72	11.02	12.74	0.113	0.17
8	0.060	0.140	0.140	1.06	3.81	4.87	0.043	0.10
9	0.060	0.140	0.140	0.56	7.88	8.44	0.075	0.05
10	0.125	0.090	0.125	1.61	4.90	6.51	0.058	0.16
11	0.220	0.060	0.220	6.53	1.10	7.63	0.067	0.64
12	0.265	0.130	0.265	8.79	2.79	11.58	0.102	0.86
13	0.440	0.310	0.440	14.83	12.49	27.32	0.242	1.46
14	0.170	0.130	0.170	6.59	2.84	9.43	0.083	0.65
15	0.170	0.170	0.170	3.36	6.13	9.49	0.084	0.33
16	0.190	0.340	0.340	2.22	13.01	15.23	0.135	0.22
17	0.235	0.190	0.235	4.87	6.96	11.83	0.105	0.48
18	0.060	0.250	0.250	0.86	9.34	10.20	0.090	0.08
19	0.220	0	0.220	10.77	0	10.77	0.095	1.06
20	0.280	0.375	0.375	5.85	12.84	18.69	0.165	0.57
21	0.080	0.280	0.280	2.51	8.03	10.54	0.093	0.25
22	0.325	0.250	0.325	10.46	8.48	18.94	0.167	1.03
23	0.190	0	0.190	11.42	0	11.42	0.101	1.12
24	0.280	0.220	0.280	9.67	4.89	14.56	0.129	0.95
25	0.155	0.080	0.155	8.18	0.97	9.15	0.081	0.80
26	0.410	0.130	0.410	14.54	2.83	17.37	0.154	1.43
27	0.170	0.090	0.170	5.60	1.81	7.41	0.066	0.55
28	0.190	0.190	0.190	10.11	3.78	13.89	0.123	0.99
29	0.220	0.080	0.220	7.17	2.49	9.66	0.085	0.70
Total	5.570	4.290	6.475	182.25	138.22	320.47	2.835	17.89
Mean per joint	0.192	0.148	0.223	6.28	4.77	11.05	0.098	0.62

Units are inches and square inches.
Area reduction = positive offset area.

TABLE B-4

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 36-INCH CAST CONCRETE PIPE WITH AVERAGE JOINTS

Joint No.	Maximum Offset			Offset Area			Ave. Offset
	Pos.	Neg.	Over-all	Pos.	Neg.	Total	
1	0.13	0.28	0.28	2.82	9.47	12.29	0.109
2	0.13	0.39	0.39	3.38	9.88	13.26	0.117
3	0.25	0.33	0.33	6.16	15.60	21.76	0.192
4	0.05	0.23	0.23	0.62	7.81	8.43	0.075
5	0.17	0.34	0.34	2.24	10.28	12.52	0.111
6	0.16	0.37	0.37	6.46	7.30	13.76	0.122
7	0.09	0.22	0.22	0.64	12.06	12.70	0.112
8	0.19	0.28	0.28	5.11	7.93	13.04	0.115
9	0.09	0.28	0.28	2.79	9.99	12.78	0.113
10	0.16	0.17	0.17	2.08	8.00	10.08	0.089
11	0.19	0.44	0.44	4.35	16.47	20.82	0.184
12	0.25	0.34	0.34	5.30	9.52	14.82	0.131
13	0.13	0.34	0.34	3.03	16.56	19.59	0.173
14	0.28	0.44	0.44	9.12	12.09	21.21	0.188
15	0.31	0.44	0.44	8.56	13.21	21.77	0.192
16	0.28	0.28	0.28	7.20	13.84	21.04	0.186
17	0.03	0.23	0.23	0.28	9.87	10.15	0.090
18	0.25	0.22	0.25	5.80	6.90	12.70	0.112
19	0.20	0.25	0.25	4.47	5.60	10.07	0.089
20	0.39	0.31	0.39	8.02	10.70	18.72	0.166
21	0.13	0.19	0.19	3.60	7.05	10.65	0.094
22	0.11	0.36	0.36	1.69	13.10	14.79	0.131
23	0.19	0.44	0.44	5.49	13.53	19.02	0.168
24	0.06	0.16	0.16	1.03	6.45	7.48	0.066
25	0.03	0.27	0.27	0.31	11.32	11.63	0.103
26	0.09	0.25	0.25	1.27	13.54	14.81	0.131
27	0.13	0.25	0.25	4.27	5.54	9.81	0.087
28	0.31	0.27	0.31	6.73	13.21	19.94	0.176
29	0.20	0.37	0.37	4.14	11.75	15.89	0.140
Total	4.98	8.74	8.89	116.96	308.57	425.53	3.762
Mean per joint	0.172	0.301	0.307	4.03	10.64	14.67	0.130
Average	-	-	-	-	-	-	0.130

Units are inches and square inches.
Area reduction = positive offset area plus projected area of bead.
Estimated fillet width = 5 inches.
Average bead (or fillet) width = covered area/length.
Average covered area = total area/number of beaded joints.
Average bead height = projected area/length.
Average groove width = total width/number of grooves.

TABLE B-4 (continued)

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 36-INCH CAST CONCRETE PIPE WITH AVERAGE JOINTS

Beads and Fillets						Grooves		Area Reduction	
Length	Width	Covered Area	Max. Height	Proj. Area	Ave. Height	Length	Width	sq in.	per cent
75.7	5.31	402.0	0.312	14.31	0.189	37.4	0.030	17.13	1.68
75.7	4.53	342.9	0.619	32.10	0.425	37.4	0.015	35.48	3.49
75.7	4.81	364.1	0.125	5.00	0.066	37.4	0.250	11.16	1.10
113.1	4.37	494.2	0.188	8.25	0.073	0	0	8.87	0.87
75.7	5.56	420.9	0.544	28.07	0.544	37.4	0.340	30.31	2.98
75.7	3.69	279.3	0.094	4.31	0.057	37.4	0.125	10.77	1.06
75.7	5.25	397.4	0.156	5.37	0.071	37.4	0.030	6.01	0.59
75.7	4.63	350.5	0.063	2.50	0.033	37.4	0.280	7.61	0.75
75.7	6.47	489.8	0.344	18.77	0.248	37.4	0.630	21.56	2.12
75.7	5.84	442.1	0.312	18.02	0.238	37.4	0.190	20.10	1.97
113.1	0.75	84.8	0.812	34.00	0.301	0	0	38.35	3.77
75.7	5.50	416.4	0.558	26.07	0.345	37.4	0.250	31.37	3.08
75.7	4.31	326.3	0.094	2.42	0.032	37.4	0.015	5.45	0.54
75.7	6.00	454.2	0.500	19.08	0.252	37.4	0.190	28.20	2.77
75.7	5.37	406.5	0.250	7.80	0.103	37.4	0.060	16.36	1.61
113.1	4.00	452.4	0.063	1.92	0.017	0	0	9.12	0.90
75.7	5.47	414.1	0.385	25.08	0.332	37.4	0.500	25.36	2.49
75.7	5.44	411.8	0.391	17.03	0.225	37.4	0.220	22.83	2.24
75.7	3.66	277.1	0.047	1.74	0.023	37.4	0.250	6.21	0.61
75.7	3.53	267.2	0.031	1.21	0.016	37.4	0.030	9.23	0.91
75.7	2.62	198.3	0.125	2.65	0.035	37.4	0.015	6.25	0.61
75.7	5.31	402.0	0.375	17.71	0.234	37.4	0.220	19.40	1.91
75.7	4.78	361.8	0.530	24.11	0.318	37.4	0.125	29.60	2.91
75.7	5.44	411.8	0.281	18.32	0.242	37.4	0.440	19.35	1.90
75.7	5.44	411.8	0.406	19.83	0.262	37.4	0.030	20.14	1.98
75.7	6.00	454.2	0.406	19.08	0.252	37.4	0.160	20.35	2.00
75.7	2.59	196.1	0.063	1.51	0.020	37.4	0.380	5.78	0.57
75.7	3.97	300.5	0.109	3.79	0.050	37.4	0.530	10.52	1.03
75.7	5.22	395.2	0.391	19.08	0.252	37.4	0.380	23.22	2.28
2307.5	135.86	10625.7	8.574	399.13	5.259	972.4	5.685	516.09	50.72
79.57	-	-	0.296	13.76	-	33.53	-	17.80	1.75
-	4.60	366.4	-	-	0.173	-	0.219	-	-

TABLE B-5

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 36-INCH CAST CONCRETE PIPE WITH GOOD JOINTS

Joint No.	Maximum Offset Pos.	Maximum Offset Neg.	Maximum Offset Over-all	Offset Area Pos.	Offset Area Neg.	Offset Area Total	Ave. Offset	Area Reduction (per cent)
1	0.13	0.28	0.28	2.82	9.47	12.29	0.109	0.28
2	0.13	0.39	0.39	3.38	9.88	13.26	0.117	0.33
3	0.25	0.33	0.33	6.16	15.60	21.76	0.192	0.61
4	0.05	0.23	0.23	0.62	7.81	8.43	0.075	0.06
5	0.17	0.34	0.34	2.24	10.28	12.52	0.111	0.22
6	0.16	0.37	0.37	6.46	7.30	13.76	0.122	0.63
7	0.09	0.22	0.22	0.64	12.06	12.70	0.112	0.06
8	0.19	0.28	0.28	5.11	7.93	13.04	0.115	0.50
9	0.09	0.28	0.28	2.79	9.99	12.78	0.113	0.27
10	0.16	0.17	0.17	2.08	8.00	10.08	0.089	0.20
11	0.19	0.44	0.44	4.35	16.47	20.82	0.184	0.43
12	0.25	0.34	0.34	5.30	9.52	14.82	0.131	0.52
13	0.13	0.34	0.34	3.03	16.56	19.59	0.173	0.30
14	0.28	0.44	0.44	9.12	12.09	21.21	0.188	0.90
15	0.31	0.44	0.44	8.56	13.21	21.77	0.192	0.84
16	0.28	0.28	0.28	7.20	13.84	21.04	0.186	0.71
17	0.03	0.23	0.23	0.28	9.87	10.15	0.090	0.03
18	0.25	0.22	0.25	5.80	6.90	12.70	0.112	0.57
19	0.20	0.25	0.25	4.47	5.60	10.07	0.089	0.44
20	0.39	0.31	0.39	8.02	10.70	18.72	0.166	0.79
21	0.13	0.19	0.19	3.60	7.05	10.65	0.094	0.35
22	0.11	0.36	0.36	1.69	13.10	14.79	0.131	0.17
23	0.19	0.44	0.44	5.49	13.53	19.02	0.168	0.54
24	0.06	0.16	0.16	1.03	6.45	7.48	0.066	0.10
25	0.03	0.27	0.27	0.31	11.32	11.63	0.103	0.03
26	0.09	0.25	0.25	1.27	13.54	14.81	0.131	0.12
27	0.13	0.25	0.25	4.27	5.54	9.81	0.087	0.42
28	0.31	0.27	0.31	6.73	13.21	19.94	0.176	0.66
29	0.20	0.37	0.37	4.14	11.75	15.89	0.140	0.41
Total	4.93	8.74	8.89	116.96	308.57	425.53	3.762	11.49
Mean per joint	0.172	0.301	0.307	4.03	10.64	14.67	0.130	0.40

Units are inches and square inches.
Area reduction = positive offset area.

TABLE B-6

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-A JOINTS

Joint No.	Maximum Offset			Offset Area			Ave. Offset
	Pos.	Neg.	Over-all	Pos.	Neg.	Total	
1	0	0.438	0.438	0	16.51	16.51	0.219
2	0.313	0.188	0.313	2.97	3.52	6.49	0.086
3	0	0.375	0.375	0	13.36	13.36	0.177
4	0.188	0	0.188	2.73	0	2.73	0.036
5	0.125	0.313	0.313	2.94	4.44	7.38	0.098
6	0	0.375	0.375	0	10.20	10.20	0.135
7	0	0.188	0.188	0	3.61	3.61	0.048
8	0.375	0.250	0.375	8.44	3.80	12.24	0.162
9	0	0.250	0.250	0	14.10	14.10	0.187
10	0.125	0	0.125	1.00	0	1.00	0.013
11	0.188	0.563	0.563	2.86	12.67	15.53	0.206
12	0.313	0	0.313	5.23	0	5.23	0.069
13	0	0.250	0.250	0	18.85	18.85	0.250
14	0.563	0.313	0.563	8.45	7.11	15.56	0.206
15	0.188	0.750	0.750	2.91	16.65	19.56	0.259
16	0.188	0	0.188	13.00	0	13.00	0.172
17	0	0.563	0.563	0	11.82	11.82	0.157
18	0.313	0.438	0.438	6.73	7.10	13.83	0.183
19	0	0.375	0.375	0	17.62	17.62	0.234
20	0.250	0.250	0.250	2.93	4.75	7.68	0.102
21	0.188	0.625	0.625	1.92	17.19	19.11	0.253
22	0.375	0.250	0.375	8.89	3.50	12.39	0.164
23	0	0.125	0.125	0	1.00	1.00	0.013
Total	3.692	6.879	8.318	71.00	187.80	258.80	3.429
Mean per joint	0.161	0.299	0.362	3.09	8.17	11.25	0.149
Average	-	-	-	-	-	-	0.149

Units are inches and square inches.
Area reduction = positive offset area plus projected area of bead.
Estimated fillet width = 5 inches.
Average bead (or fillet) width = covered area/length.
Average covered area = total area/number of beaded joints.
Average bead height = projected area/length.
Average groove width = total width/number of grooves.

TABLE B-6 (continued)

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-A JOINTS

Beads and Fillets						Grooves		Area Reduction	
Length	Width	Covered Area	Max. Height	Proj. Area	Ave. Height	Length	Width	sq in.	per cent
75.4	5.00	377.0	0	0	0	0	0	0	0
75.4	5.00	377.0	0	0	0	0	0	2.97	0.66
75.4	5.00	377.0	0	0	0	0	0	0	0
75.4	5.00	377.0	0	0	0	0	0	2.73	0.60
75.4	5.41	408.2	0.375	13.87	0.184	0	0	16.81	3.72
65.4	5.00	327.0	0	0	0	10.0	0.219	0	0
75.4	3.07	231.5	0.156	6.18	0.082	0	0	6.18	1.37
75.4	4.59	346.4	0.375	19.37	0.257	0	0	27.81	6.15
56.4	5.00	282.0	0	0	0	19.0	0.125	0	0
0	0	0	0	0	0	75.4	0.813	1.00	0.22
67.4	4.89	329.5	0.219	2.66	0.035	8.0	1.000	5.52	1.22
75.4	5.00	377.0	0	0	0	0	0	5.23	1.16
75.4	0.19	14.2	0.500	37.70	0.500	0	0	37.70	8.33
0	0	0	0	0	0	75.4	0.813	8.45	1.87
0	0	0	0	0	0	75.4	0.469	2.91	0.64
0	0	0	0	0	0	75.4	0.313	13.00	2.87
75.4	5.00	377.0	0	0	0	0	0	0	0
0	0	0	0	0	0	75.4	0.688	6.73	1.49
75.4	0.25	18.8	0.750	56.55	0.750	0	0	56.55	12.50
75.4	5.00	377.0	0	0	0	0	0	2.93	0.65
75.4	5.00	377.0	0	0	0	0	0	1.92	0.42
75.4	5.00	377.0	0	0	0	0	0	8.89	1.97
75.4	5.00	377.0	0	0	0	0	0	0	0
1320.2	78.40	5727.6	2.375	136.33	1.808	414.0	4.440	207.33	45.84
57.40	-	-	0.132	5.93	-	18.00	-	9.02	1.99
-	4.35	318.2	-	-	0.103	-	0.555	-	-

TABLE B-7

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-B JOINTS

Joint No.	Maximum Offset			Offset Area			Ave. Offset
	Pos.	Neg.	Over-all	Pos.	Neg.	Total	
1	0	0.438	0.438	0	16.51	16.51	0.219
2	0.313	0.188	0.313	2.97	3.52	6.49	0.086
3	0	0.375	0.375	0	13.36	13.36	0.177
4	0.188	0	0.188	2.73	0	2.73	0.036
5	0.125	0.313	0.313	2.94	4.44	7.38	0.098
6	0	0.375	0.375	0	10.20	10.20	0.135
7	0	0.188	0.188	0	3.61	3.61	0.048
8	0.375	0.250	0.375	8.44	3.80	12.24	0.162
9	0	0.250	0.250	0	14.10	14.10	0.187
10	0.125	0	0.125	1.00	0	1.00	0.013
11	0.188	0.563	0.563	2.86	12.67	15.53	0.206
12	0.313	0	0.313	5.23	0	5.23	0.069
13	0	0.250	0.250	0	18.85	18.85	0.250
14	0.563	0.313	0.563	8.45	7.11	15.56	0.206
15	0.188	0.750	0.750	2.91	16.65	19.56	0.259
16	0.188	0	0.188	13.00	0	13.00	0.172
17	0	0.563	0.563	0	11.82	11.82	0.157
18	0.313	0.438	0.438	6.73	7.10	13.83	0.183
19	0	0.375	0.375	0	17.62	17.62	0.234
20	0.250	0.250	0.250	2.93	4.75	7.68	0.102
21	0.188	0.625	0.625	1.92	17.19	19.11	0.253
22	0.375	0.250	0.375	8.89	3.50	12.39	0.164
23	0	0.125	0.125	0	1.00	1.00	0.013
Total	3.692	6.879	8.318	71.00	187.80	258.80	3.429
Mean per joint	0.161	0.299	0.362	3.09	8.17	11.25	0.149
Average	-	-	-	-	-	-	0.149

Units are inches and square inches.
Area reduction = positive offset area plus projected area of bead.
Estimated fillet width = 5 inches.
Average bead (or fillet) width = covered area/length.
Average covered area = total area/number of beaded joints.
Average bead height = projected area/length.
Average groove width = total width/number of grooves.

TABLE B-7 (continued)

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 24-INCH TAMPED CONCRETE PIPE WITH AVERAGE-B JOINTS

Beads and Fillets						Grooves		Area Reduction	
Length	Width	Covered Area	Max. Height	Proj. Area	Ave. Height	Length	Width	sq in.	per cent
75.4	5.00	377.0	0	0	0	0	0	0	0
75.4	5.00	377.0	0	0	0	0	0	2.97	0.66
75.4	5.00	377.0	0	0	0	0	0	0	0
75.4	5.00	377.0	0	0	0	0	0	2.73	0.60
75.4	5.41	408.2	0.375	13.87	0.184	0	0	16.81	3.72
65.4	5.00	327.0	0	0	0	10.0	0.219	0	0
75.4	3.07	231.5	0.156	6.18	0.082	0	0	6.18	1.37
75.4	4.59	346.4	0.375	19.37	0.257	0	0	27.81	6.15
56.4	5.00	282.0	0	0	0	19.0	0.125	0	0
0	0	0	0	0	0	75.4	0.813	1.00	0.22
67.4	4.89	329.5	0.219	2.66	0.035	8.0	1.000	5.52	1.22
75.4	5.00	377.0	0	0	0	0	0	5.23	1.16
75.4	5.00	377.0	0	0	0	0	0	0	0
0	0	0	0	0	0	75.4	0.813	8.45	1.87
0	0	0	0	0	0	75.4	0.469	2.91	0.64
0	0	0	0	0	0	75.4	0.313	13.00	2.87
75.4	5.00	377.0	0	0	0	0	0	0	0
0	0	0	0	0	0	75.4	0.688	6.73	1.49
75.4	5.00	377.0	0	0	0	0	0	0	0
75.4	5.00	377.0	0	0	0	0	0	2.93	0.65
75.4	5.00	377.0	0	0	0	0	0	1.92	0.42
75.4	5.00	377.0	0	0	0	0	0	8.89	1.97
75.4	5.00	377.0	0	0	0	0	0	0	0
1320.2	87.96	6448.6	1.125	42.08	0.558	414.0	4.440	113.08	25.01
57.40	-	-	0.063	1.83	-	18.00	-	4.92	1.09
-	4.88	358.3	-	-	0.032	-	0.555	-	-

TABLE B-8

LABORATORY DATA ON JOINT CHARACTERISTICS OF THE 24-INCH TAMPED CONCRETE PIPE WITH GOOD JOINTS

Joint No.	Maximum Offset Pos.	Maximum Offset Neg.	Maximum Offset Over-all	Offset Area Pos.	Offset Area Neg.	Offset Area Total	Ave. Offset	Area Reduction (per cent)
1	0	0.500	0.500	0	20.03	20.03	0.266	0
2	0.031	0.313	0.313	0.47	7.25	7.72	0.102	0.10
3	0.141	0.156	0.156	2.93	3.66	6.59	0.087	0.65
4	0.125	0.281	0.281	1.79	9.44	11.23	0.149	0.40
5	0	0.250	0.250	0	12.37	12.37	0.164	0
6	0.250	0.125	0.250	4.76	2.70	7.46	0.072	1.05
7	0	0.344	0.344	0	13.54	13.54	0.180	0
8	0.031	0.281	0.281	0.36	7.42	7.78	0.103	0.08
9	0.031	0.188	0.188	0.34	5.93	6.27	0.083	0.07
10	0.156	0.156	0.156	2.47	2.18	4.65	0.062	0.55
11	0.031	0.188	0.188	0.18	6.96	7.14	0.095	0.04
12	0.063	0.063	0.063	1.67	1.08	2.75	0.036	0.37
13	0.188	0	0.188	8.84	0	8.84	0.117	1.95
14	0.188	0	0.188	6.48	0	6.48	0.086	1.43
15	0	0.156	0.156	0	7.07	7.07	0.094	0
16	0.375	0.094	0.375	8.63	0.98	9.61	0.127	1.91
17	0	0.281	0.281	0	10.31	10.31	0.137	0
18	0	0.250	0.250	0	7.66	7.66	0.102	0
19	0	0.375	0.375	0	15.32	15.32	0.203	0
20	0.469	0	0.469	16.79	0	16.79	0.223	3.71
21	0.156	0	0.156	5.60	0	5.60	0.074	1.24
22	0.156	0.156	0.156	2.79	3.38	6.17	0.082	0.61
23	0.156	0.094	0.156	3.06	1.59	4.65	0.062	0.68
Total	2.547	4.251	5.720	67.16	138.87	206.03	2.706	14.84
Mean per joint	0.111	0.185	0.249	2.92	6.04	8.96	0.118	0.65

Units are inches and square inches.
Area reduction = positive offset area.

TABLE B-9

DIMENSIONS AND LAYOUT OF THE 36-INCH TAMPED PIPE
WITH AVERAGE AND GOOD JOINTS

Pipe					Piezometer		
	Diameter (in.)					Distance from Inlet (ft)	
No.	Groove End	At Piez.	Tongue End	Ave.	No.	Ave. Joints	Good Joints
56	35.97	35.93	35.92		1	3.84	3.84
10	35.88	36.20	36.09		2	11.94	11.94
1	35.90	36.05	36.13		3	20.05	20.05
21	35.95	-	36.09		-	-	-
12	35.98	36.17	36.10		4	36.33	36.12
24	35.97	-	36.05		-	-	-
18	36.03	36.05	36.02		5	52.44	52.19
37	36.22	-	36.16		-	-	-
14	36.21	36.20	36.09	———	6	68.60	68.67
28	36.22	-	36.16	22 downstream sections D = 36.07	-	-	-
15	36.03	36.22	36.14		7	84.75	84.46
25	36.01	-	36.02		-	-	-
9	35.87	36.20	36.09		8	100.85	100.54
16	36.02	-	36.06		-	-	-
20	35.92	36.20	36.10		9	117.06	116.58
22	35.99	-	36.10		-	-	-
35	36.24	36.20	36.10		10	133.41	132.71
11	36.13	-	36.08		-	-	-
36	36.27	36.20	36.14		11	149.56	148.80
31	35.95	-	36.09		-	-	-
19	36.19	36.22	36.14		12	166.00	164.92
13	36.13	-	36.06		-	-	-
7	36.05	36.05	36.06		13	182.12	181.04
4	35.92	-	36.08		-	-	-
6	35.91	36.03	36.01		14	198.09	196.96
32	35.91	-	36.05		-	-	-
27	35.87	36.01	36.02		15	214.20	213.00
8	35.89	-	36.05		-	-	-
23	35.90	36.03	36.00		16	230.21	229.00
34	35.90	36.17	36.09		17	239.57	238.29
					Outlet	242.57	241.29

Slope = 0.000967 for average joints and 0.0010 for good joints.

TABLE B-10

DIMENSIONS AND LAYOUT OF THE 36-INCH CAST PIPE
WITH AVERAGE AND GOOD JOINTS

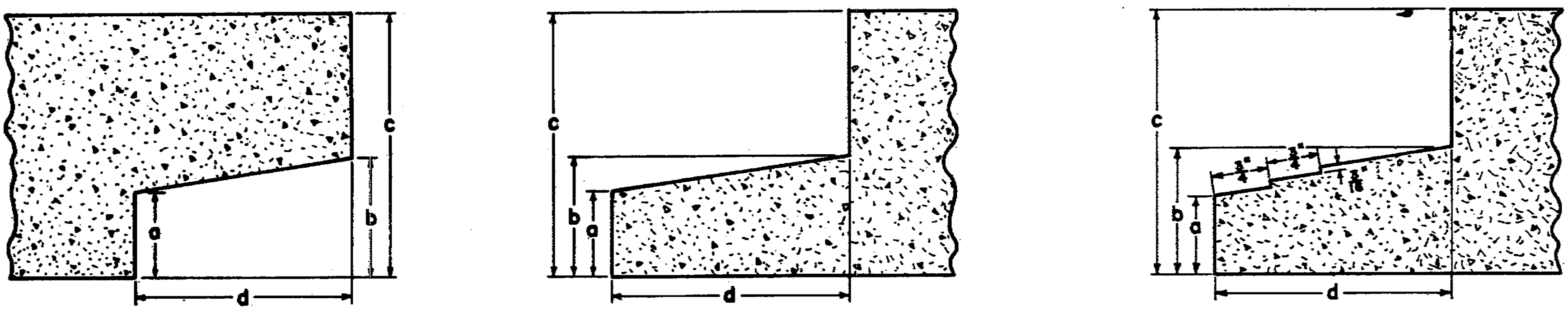
Pipe					Piezometer	
	Diameter (in.)					
No.	Groove End	At Piez.	Tongue End	Ave.	No.	Distance from Inlet (ft)
56	35.97	35.93	35.92		1	3.84
38	35.98	35.95	35.97		2	12.15
39	36.02	36.05	35.96		3	20.20
40	36.06	-	36.02		-	-
42	36.04	35.89	35.95		4	36.30
41	36.01	-	35.91		-	-
43	35.95	36.04	35.99		5	52.43
45	36.10	-	36.02		-	-
46	36.03	35.94	35.98	22 downstream sections D = 35.99	6	68.57
44	36.03	-	35.96		-	-
48	36.00	35.90	35.95		7	84.52
47	36.04	-	36.02		-	-
49	36.02	36.03	35.91		8	100.73
51	36.10	-	36.02		-	-
50	36.02	35.93	35.91		9	116.86
52	35.98	-	35.94		-	-
64	36.06	35.96	35.95		10	132.94
65	36.02	-	36.02		-	-
63	35.99	35.95	36.00		11	149.05
54	36.02	-	35.92		-	-
55	35.98	36.03	36.00		12	165.07
53	35.96	-	35.92		-	-
67	36.05	36.06	35.95		13	181.22
60	36.02	-	35.96		-	-
66	36.01	35.95	35.89		14	197.29
61	36.05	-	35.95		-	-
62	36.11	36.08	36.02		15	213.17
57	35.99	-	35.92		-	-
58	36.00	35.95	35.95		16	229.53
59	35.95	35.91	35.91		17	237.56
					Outlet	241.71

Slope = 0.0010.

TABLE B-11

DIMENSIONS AND LAYOUT OF THE 24-INCH TAMPED PIPE

Average Joints. Slope = 0.001035						Good Joints. Slope = 0.00112					
Pipe				Piezometer		Pipe				Piezometer	
	Diameter (in.)						Diameter (in.)				
No.	Groove End	Tongue End	Ave.	No.	Distance from Inlet (ft)	No.	Groove End	Tongue End	Ave.	No.	Distance from Inlet (ft)
				1	0					1	0
1	24.02	23.95		2	3.88	1	24.02	23.95		2	3.88
8	24.33	24.20		3	11.92	8	24.33	24.20		3	11.98
16	24.20	24.05		4	20.04	12	24.26	24.25		4	20.09
22	24.38	24.05		-	-	22	24.38	24.05		-	-
2	24.02	23.92		5	36.04	23	24.14	24.08		5	36.36
9	23.97	23.94	——	-	-	14	24.30	24.25	——	-	-
17	24.25	24.02		6	52.14	16	24.20	24.05		6	52.54
23	24.14	24.08		-	-	26	24.28	24.11		-	-
3	23.98	23.01		7	68.21	10	24.34	24.22		7	68.79
10	24.34	24.22		-	-	13	24.37	24.23		-	-
18	24.19	24.03		8	84.35	18	24.19	24.03		8	84.83
24	24.31	24.08		-	-	15	24.26	24.25		-	-
4	23.92	23.92	18 downstream sections D = 24.14	9	100.35	21	24.23	24.05	18 downstream sections D = 24.11	9	101.13
11	24.38	24.25		-	-	24	24.31	24.08		-	-
19	24.20	24.03		10	116.52	29	23.97	23.97		10	117.23
26	24.28	24.11		-	-	6	23.98	23.94		-	-
5	24.00	23.95		11	132.58	19	24.20	24.03		11	133.47
13	24.37	24.23		-	-	34	24.23	24.06		-	-
20	24.23	24.03		12	148.67	20	24.23	24.03		12	149.58
27	24.34	24.06		-	-	33	24.23	24.20		-	-
7	23.97	23.95		13	164.73	7	23.97	23.95		13	165.63
14	24.30	24.25		-	-	2	24.02	23.92		-	-
21	24.23	24.05		14	180.86	5	24.00	23.95		14	181.90
28	24.31	24.05		-	-	9	23.97	23.94		-	-
				Outlet	193.00					Outlet	194.00



Pipe	Mfg.	Groove End				Tongue End				Remarks
		a	b	c	d	a	b	c	d	
24" Tamped	A	1 1/8	1 3/4	3 1/2	2 3/4	1	1 1/2	3	2 7/8	
	B	1	1 3/8	3	2 1/2	1	1 3/8	3 1/8	2 3/4	
	C	1 1/4	2 1/8	3 5/8	2 5/8	1 1/8	1 1/2	3 1/8	2 3/8	
	D	7/8	1 5/8	2 7/8	2 5/8	3/4	1 1/4	2 7/8	2	
36" Tamped	A	1 1/2	2 1/8	4 1/8	3 3/4	1 3/8	2	4	3 3/4	Eight pipes have stepped tongues
	B	1 1/2	2 1/8	4	3 3/4	1 1/8	2	4	3 3/4	
	C	1 5/8	2 3/8	4 1/8	3 1/4	1 1/2	2	4 1/8	3 3/8	
36" Cast	C	1 3/4	2 1/4	4	3 1/2	1 1/4	2 1/8	4 1/8	3 1/2	All pipes but two have stepped tongues

Fig. B-1 - Pipe End Geometry and Dimensions

APPENDIX C

MEASUREMENTS OF PIPE WALL ROUGHNESS

A P P E N D I X   C

MEASUREMENTS OF PIPE WALL ROUGHNESS

In addition to photographs and the sample specimens cut from some of the test pipe, measurements were obtained of the wall roughness in twelve or thirteen pipe sections selected at random from each of the diameters and types tested. The scope of this part of the study is considered to be somewhat limited both with regard to the measurements and to their analysis.

The equipment used to measure wall roughness consisted of a dial gage reading to 0.0001 in. mounted on a slotted steel bar which was placed on the invert surface of the pipe section being measured. The bar was 2 ft long, 3 in. wide, and 3/4 in. thick, and had a slot 1.5 ft long through which the dial gage stem was inserted. After slotting and machining of the bar, it was placed on a surface grinder and ground to a flat surface of uniform thickness. The dial gage was mounted on a metal block which could be moved along the slot in the main bar.

The stem of the dial gage was fitted with a hardened concave point having a terminal diameter of 0.007 inch. (Initially, a terminal diameter of 0.004 in. was used, but preliminary checks on a precision ground metal table indicated that this diameter was so small that it was easily damaged.) With this assembly the gage had an effective travel of 1.3 ft and its longitudinal position could be measured by a scale attached to the main bar.

When using this equipment the main bar was placed on the invert of the pipe and aligned parallel to the pipe axis. A 15-lb weight was placed on each end of the bar to prevent movement. The dial gage and traveling block were then placed on the main bar with the gage point adjusted so that it could travel at least 0.2 in. above or below the bottom of the main bar. The gage was then moved to the longitudinal zero position of the bar and the point lowered to the concrete surface yielding a reading. Then the point was lifted and the gage moved 0.02 ft along the bar to the second position. This procedure was repeated, providing readings at spacings of 0.02 ft over a length of 1.3 ft. The main bar was transferred to a new section of pipe and the process repeated. Sixty-six readings were obtained for each section of pipe. Since twelve or thirteen sections were measured for each diameter or size of pipe, this provided a total of either 792 or 858 readings for each size or type.

The spacing of 0.02 ft between surface readings is too large for proper measurement of an accurate profile. However, it was considered desirable to use a fairly large spacing, as this would permit the checking of a larger number of pipe sections within the available funds. As noted in a preceding section, the surface roughness of the tamped pipe varied over a wide range both in a single section of pipe and from one section to another. Thus, a large number of measurements in a few sections of pipe was considered less representative of the total pipe surface than the same number of measurements distributed over a larger number of pipe sections.

The dial gage readings represented the distance between an arbitrary line and the surface of the concrete at the measured point; the arbitrary line was parallel to the surface of the main bar, and its elevation depended on the adjustment of the gage zero.

As a first step in the analysis of the data (for one pipe section), an average gage reading was computed for the 66 readings in one pipe section. This value was then subtracted from each gage reading giving individual values (plus or minus) of distance k' between the concrete surface and the mean line. The average of the absolute values was then determined and multiplied by two to give an indication of the nominal distance k from low points to high points of each sample. The standard deviation of k' was also determined. The above procedure was repeated for each of twelve or thirteen sections of pipe, and an average value of k determined for that type of pipe.

The above procedure is based on an average straight line (parallel to the base plate) over a length of 1.3 ft. If the surface of the concrete is characterized by fairly long waves, in addition to a texture roughness, the mean line may be continuously above (or below) the concrete surface over long segments of the sample. To avoid this, a smooth curve could be drawn through the plotted profile and values of k' determined with reference to this fitted curve. This procedure is objectionable because the end result depends on (1) the individual drawing the curve, and (2) it eliminates long undulations but does include the effects of shortwaves; this results in an arbitrary and variable analysis of wave and texture effects.

To assist in an analysis of these problems a process was developed in which mean lines of four different lengths were used. Considering one 1.3-ft sample length the data were first analyzed as described above, with a mean line over the 1.3-ft length (ΔL = 1.3 ft), and a value of k was determined. The sample was then split into two sections (or increment lengths) each 0.65 ft long (ΔL = 0.65 ft) and a mean line computed <u>for each section</u> from the initial dial gage readings. New values of k' were then determined for each section, averaged, and multiplied by two to give k for each of the two segments. The two values of k were then averaged to give a value of k for the complete sample. The sample length was then split into six samples (ΔL = 0.22 ft) and subsequently into thirteen sections (ΔL = 0.10 ft). For example, with ΔL = 0.1 ft, a mean line was determined for each of the thirteen segments into which the sample length was divided and the mean value subtracted from each gage reading in that segment yielding values of k'. An average of the sixty-six values of k' for the 1.3-ft sample constitutes the height k/2.

Figure C-4 illustrates the computed values of roughness height k as a function of increment length ΔL, for 24-in. and 36-in. tamped pipe and for 36-in. cast pipe. It may be noted that the lines for tamped pipe are considerably higher and have less slope than the line for cast pipe. This could be interpreted as indicating that the cast pipe has a surface texture only about one-fourth as rough as the tamped pipe (in the region of ΔL = 0.1 ft), but surface waves are present which give an apparent roughness about one-half that of the tamped pipe for ΔL = 1.3 ft. While the tamped pipe also includes waves in the roughness measurements, they are masked to some extent by the high texture roughness.

An examination of the graphs of surface measurements, similar to those of Fig. C-1, indicates the presence of waves of varying length in the pipe surface.

Figure C-2 illustrates the summary histograms of k' for the test pipes. A high narrow histogram indicates a relatively smooth surface.

Figure C-3 illustrates the variation in k between the twelve or thirteen sections of each type of pipe. Two graphs are presented, one for ΔL = 0.1 ft and the other for ΔL = 1.3 ft.

Since long waves of low height probably have a relatively minor effect on the friction loss, it is suggested that the data for ΔL on the order of 0.1 ft are the most significant. On this basis it appears that the tamped pipe is three to four times as rough as the cast pipe. However, the data on frictional resistance, as determined by the hydraulic tests, constitute a better evaluation of the roughness.

TABLE C-1

SUMMARY DATA ON PIPE-WALL ROUGHNESS MEASUREMENTS

Type of Pipe	Roughness Height k x 10^4 (in.) Increment Length ΔL (ft)				Standard Deviation σ x 10^4 (in.) Increment Length ΔL (ft)			
	0.10	0.22	0.66	1.32	0.10	0.22	0.66	1.32
36-in. Cast	7.0	13.6	17.8	25.2	4.5	8.3	10.8	15.8
	11.2	15.2	23.8	27.0	7.2	9.3	15.0	17.2
	11.6	17.4	25.2	33.8	7.6	11.5	16.8	22.2
	13.4	21.3	36.5	41.2	9.5	13.7	22.3	24.1
	16.1	22.1	54.4	59.9	10.7	14.2	31.6	37.3
	17.2	28.3	54.5	73.8	12.4	18.0	36.8	45.3
	20.4	33.0	64.5	87.4	14.1	23.0	43.6	53.5
	24.0	40.8	64.8	89.6	16.6	29.4	44.7	55.1
	27.0	42.6	73.3	103.2	18.6	29.9	45.1	64.5
	29.9	44.5	76.2	145.8	21.9	31.0	46.5	86.0
	31.9	57.7	90.4	163.8	22.5	35.4	55.1	99.2
	39.9	63.6	121.5	206.6	24.6	42.7	71.5	116.0
	80.2	105.8	203.5	211.2	54.1	70.8	122.0	128.6
Total	329.8	505.9	906.4	1268.5	224.3	337.2	561.8	764.8
Average	25.4	38.9	69.7	97.6	17.3	25.9	43.2	58.8
36-in. Tamped	42.1	53.3		94.6	30.7	36.3		57.1
	47.0	66.7		111.2	31.8	42.3		68.2
	62.2	69.9		130.0	40.6	47.0		71.9
	63.1	77.9		142.8	42.0	52.8		74.8
	77.2	103.4		157.4	47.9	61.8		95.5
	82.8	105.8		165.9	58.9	67.9		103.0
	92.2	112.5		166.0	62.4	73.5		107.2
	96.8	118.6		191.4	67.3	74.0		112.4
	116.6	138.5		193.0	72.1	84.9		127.1
	124.4	144.2		208.0	81.1	93.7		128.9
	137.3	166.6		208.0	88.3	110.0		142.9
	192.4	192.7		247.0	124.3	132.1		152.4
Total	1134.1	1350.1		2015.3	746.7	876.3		1241.3
Average	94.5	112.5		167.9	62.2	73.0		103.4
24-in. Tamped	63.1	82.6		101.5	40.1	52.8		67.0
	68.0	92.4		111.4	42.1	58.9		73.6
	69.4	94.8		111.8	46.7	59.3		74.3
	74.5	98.6		149.0	51.4	64.3		87.9
	75.6	100.5		163.0	52.5	67.9		111.7
	79.7	110.6		168.6	58.1	75.4		120.1
	90.0	110.8		175.8	58.8	87.2		132.2
	91.2	129.4		204.8	64.0	90.8		132.7
	92.8	138.7		209.2	75.7	92.4		133.3
	107.6	139.3		242.2	85.4	97.3		136.5
	138.6	156.6		287.0	93.5	103.7		181.5
	141.0	161.2		304.0	94.6	104.2		185.7
	218.8	271.0		365.8	144.1	167.9		224.6
Total	1310.3	1686.5		2594.1	907.0	1122.1		1661.1
Average	100.8	129.7		199.5	69.8	86.3		127.8

Spacing of measurements = 0.02 ft.

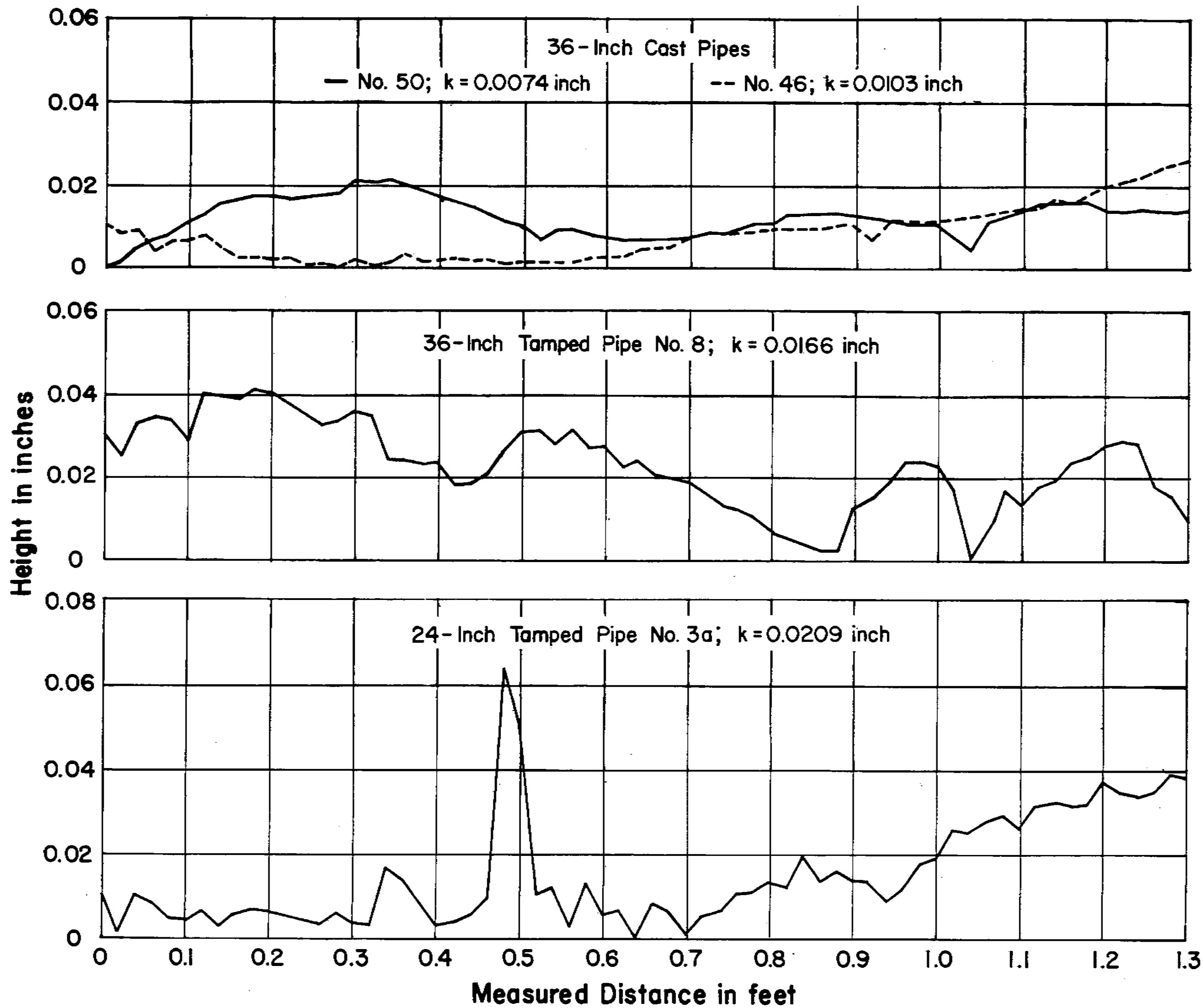


Fig. C-1 – Typical Measurements of Surface Roughness in the Test Pipe

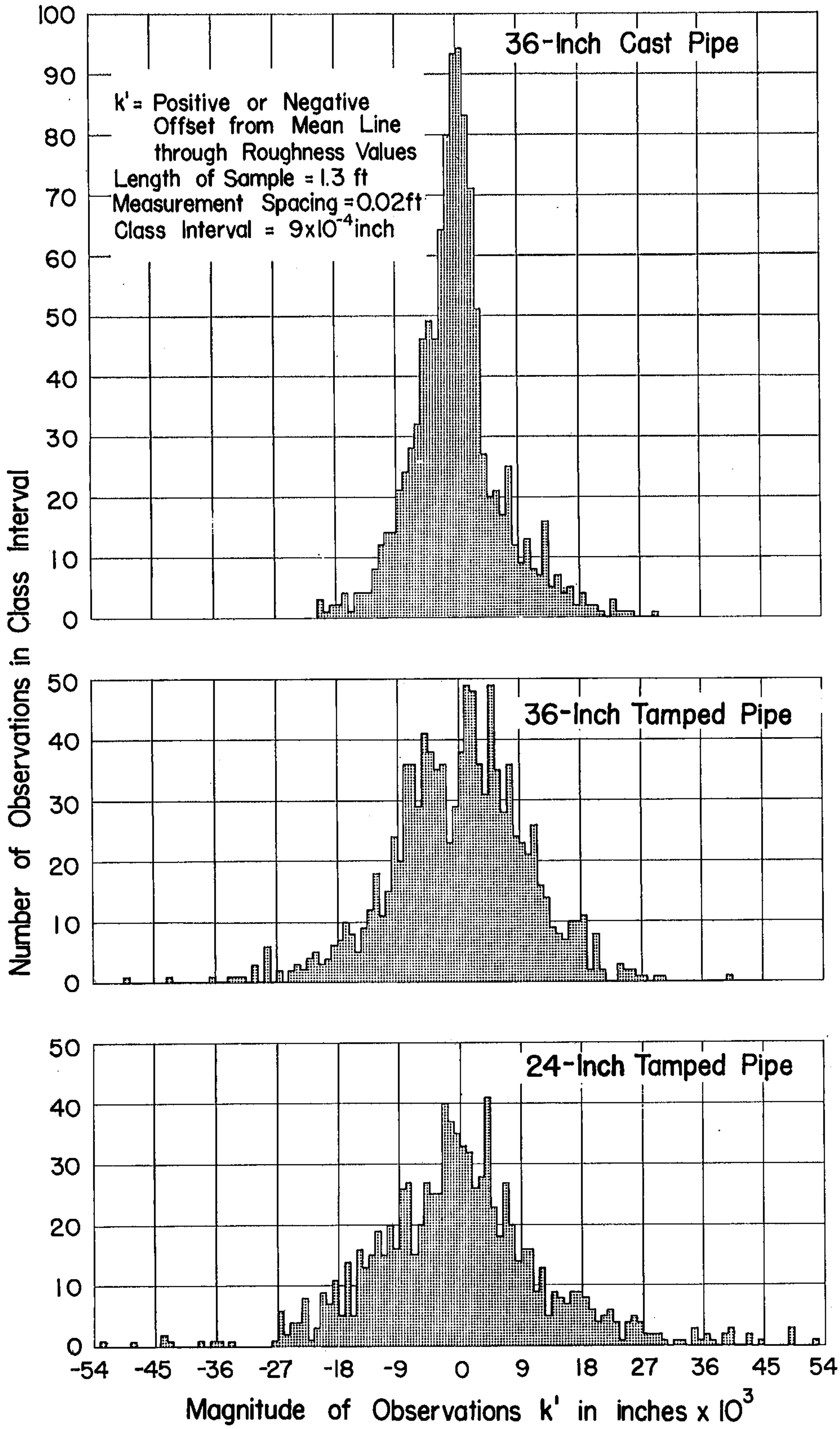


Fig. C-2 – Histograms of the Pipe Surface Roughness

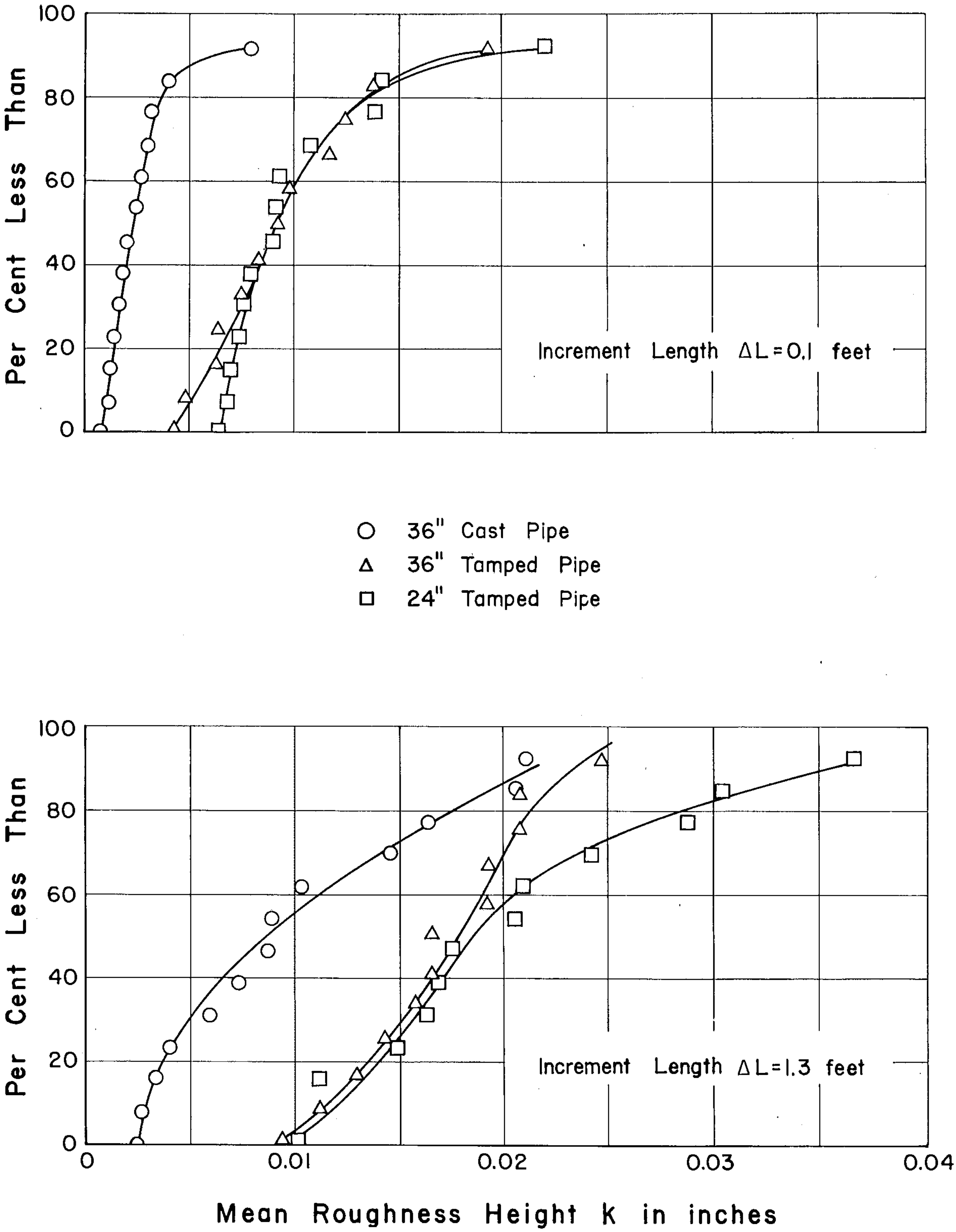


Fig. C-3 – Distribution Curves of Mean Roughness Height for Twelve or Thirteen Pipe Sections (Each symbol or data point represents the average roughness height for one section of pipe)

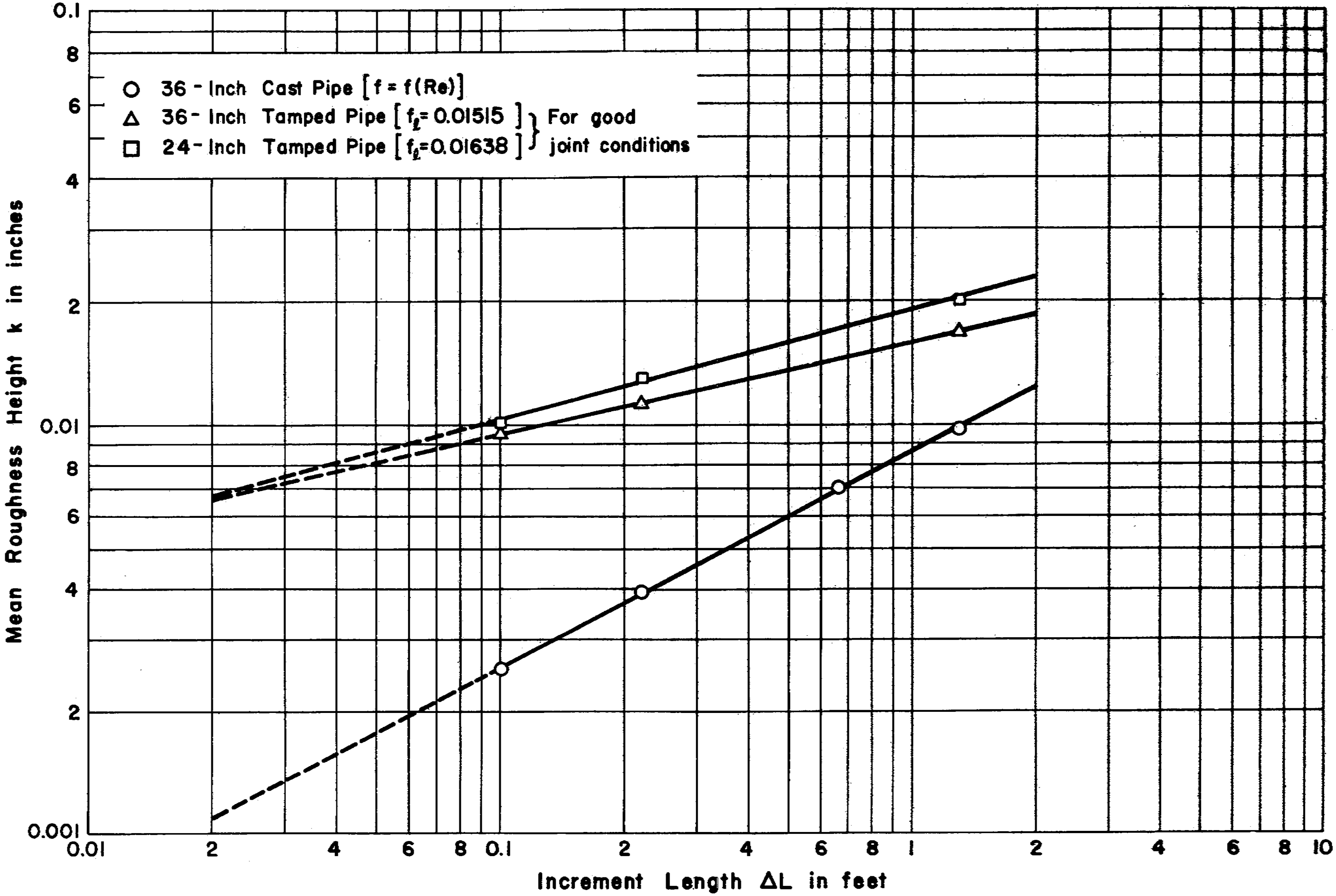


Fig. C-4 – Mean Roughness Height as a Function of Increment Length of Roughness Sample

APPENDIX D

TEST FACILITIES AND PROCEDURES

A P P E N D I X D

TEST FACILITIES AND PROCEDURES

Figures D-1, D-2, and D-3 illustrate the basic test facilities used in these studies. Water from the Mississippi River enters the system through a self-cleaning mechanical screen, then passes downward through a drop shaft, horizontally through a flow control baffle, and under a sluice gate into a channel 9 ft wide, 6 ft deep, and 253 ft long. It then passes over a tailgate and out to twin volumetric tanks. In tests of the 36-in. pipe, a bulkhead was placed under the sluice gate and the pipe attached to the bulkhead. A second bulkhead was placed near the downstream end of the pipe. This permitted the use of the full 20-ft head available in this facility.

The tests of the 24-in. pipe were performed prior to construction of the sluice-gate bulkhead. For these tests a wooden bulkhead was located about 50 ft downstream of the sluice gate. The downstream bulkhead was in the same location as for the 36-in. pipe tests. The pipe extended through both bulkheads, resulting in a reentrant bell-mouth inlet. The maximum head available was 6 ft and the pipe length was restricted to about 193 ft, as compared to 241 ft for the 36-in. pipe tests.

Discharges up to 30 cfs could be obtained with the 24-in. pipe arrangement and up to 150 cfs with the 36-in. pipe.

The twin volumetric tanks used to measure the discharge have a capacity of 35,000 cu ft each. They have been calibrated by both weight and volume methods with a precision of about one-fourth of 1 per cent.

Hydraulic grade lines were determined by a system of 17 Pitot static tubes connected to three types of manometers. The Pitot static tubes, shown in Fig. D-2, were used in place of piezometers to avoid some of the problems encountered in the installation of piezometers in concrete surfaces.

For high discharges a 20-tube differential manometer filled with Merriam No. 3 gage fluid was used. The specific gravity of the gage fluid was checked regularly to insure correct results. It was noted that the specific gravity of this fluid changes gradually from 2.97 when first installed to about 2.93 after several months use.

A differential micro-manometer was used for small discharges in the 36-in. pipe. This utilized two individual wells about 2 inches in diameter. Barrel-type micrometers with 0.001-in. divisions were used to measure the relative elevation of points which were placed in contact with the water surface. Two units of this type were used, one with maximum differential of 2 in. and a second with maximum differential of 8 inches. As this system could measure the differential only between two points, it was necessary to use special precautions to insure accurate results. Usually, the high discharges were measured first; this provided an indication of the zone of flow establishment and the reliability of individual static tubes which might be used with the micro-manometer. Two static tubes, in the zone of established flow and about 145 ft apart, were then selected for low discharge tests. An additional static tube was installed at each of these locations and connected in parallel to the existing tubes. The micro-manometer was then connected to the system. The differential obtained from the system was the drop in the hydraulic grade line over a distance of 145 ft. As a check on these data, the manometer was sometimes connected to another set of static tubes.

From 10 to 20 readings of the differential were taken and averaged for each discharge in which the micro-manometers were used in order to reduce human errors. The other manometers were usually read twice as a check on the person reading the manometer.

Immediately prior to all manometer readings, the connecting lines were flushed with the fresh-water supply system. This eliminated any air bubbles which might be present and assured a uniform temperature in the manometer lines.

Measurements involving friction coefficients for pipes flowing full were performed with the outlet submerged, unless the pipe would flow full with a free outlet. These tests were performed first and then followed by measurements of the grade line elevation with a free outlet. The latter were performed specifically to obtain data on conditions near the outlet and were not used for the determination of friction coefficients.

The discharge control was usually the head gate; the flow control baffle was sometimes used to insure full flow in the drop shaft and prevent air entrainment.

The discharge was measured at least twice and sometimes three times during each run, to eliminate computational errors and to check on any possible change in discharge.

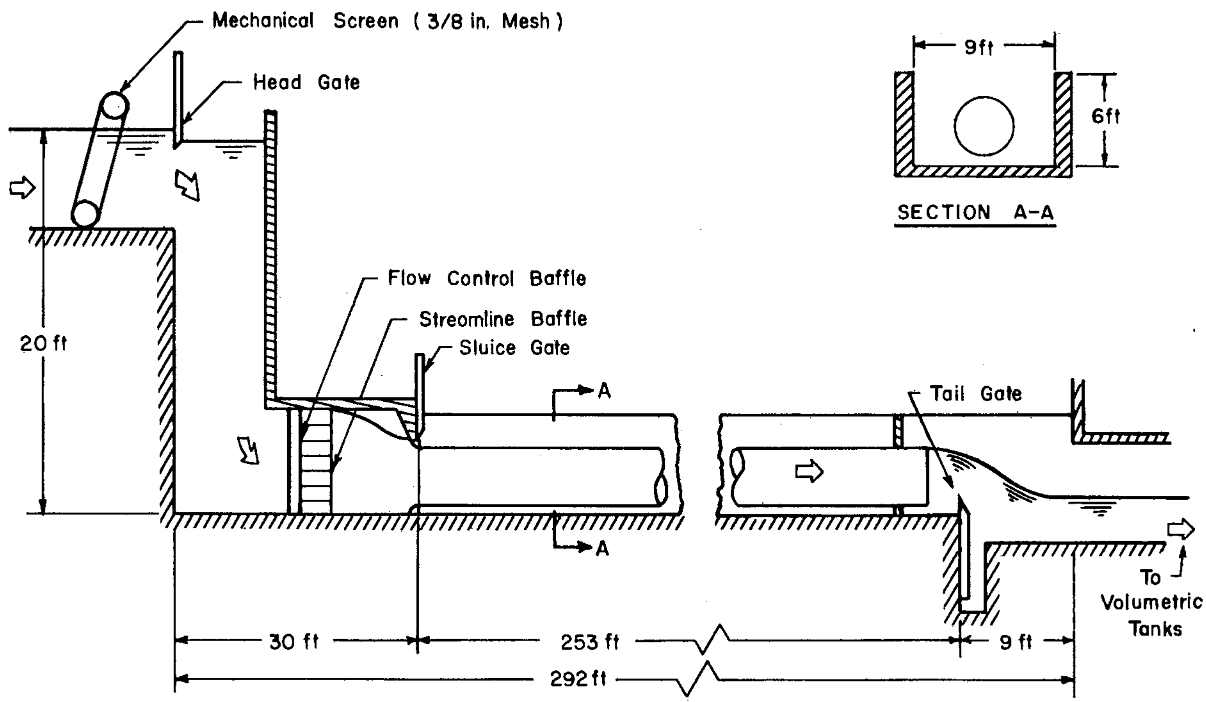


Fig. D-1 - Diagrammatic Sketch of Experimental Setup

Fig. D-2 - View of Static Tubes Installed in the 36-in. Cast Pipe

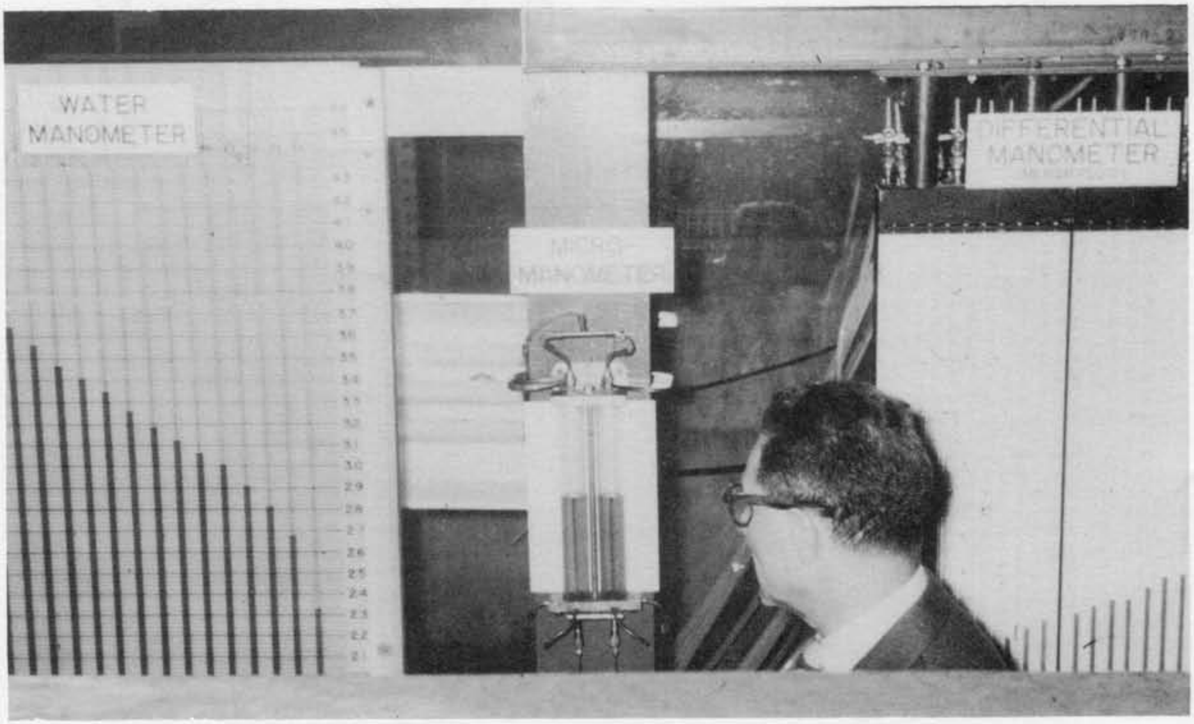
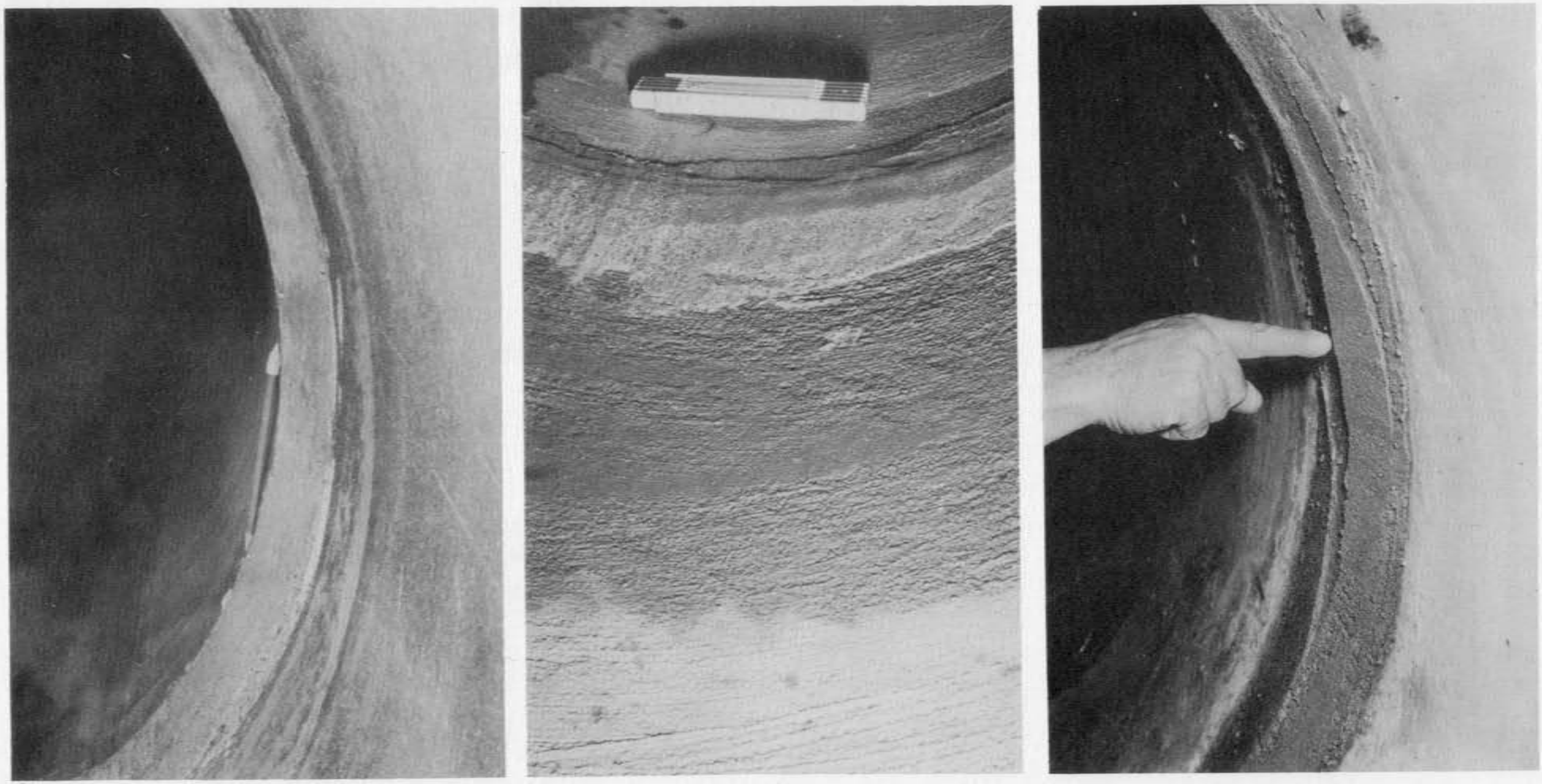


Fig. D-3 - Photograph of Upper Portion of Manometer System



(a) Joint No. 20 in 36-in. tamped pipe: 1.5-in. maximum offset with fillet

(b) Joint No. 14 in 36-in. tamped pipe: 0.16-in. maximum offset plus 0.344-in. maximum bead height

(c) Joint No. 23 in 36-in. cast pipe: 0.44-in. maximum offset plus 0.53-in. maximum bead height

Fig. D-4 - Views of Pipe Joints in Laboratory Installations

A P P E N D I X E

ANALYSIS OF HEAD LOSS DUE TO JOINTS

APPENDIX E

ANALYSIS OF HEAD LOSS DUE TO JOINTS

The experimental tests described in this report were restricted to 24- and 36-in. pipes with average and good joints and with a joint spacing of 8 ft. Additional data are desirable on pipes with bad joints and on pipes of other diameters and various joint spacings. As the latter data are currently not available, it was considered desirable to analyze the test data with the objective of evaluating the joint losses to assist in predicting friction coefficients for various conditions.

The method used in these studies involved the determination of an average drag coefficient C_D for the joints, based on the projected area of the joint irregularities. Actually, the drag coefficient probably varies for each joint in a pipe system, but preliminary efforts to compute the losses produced by some of the individual joints were not successful, necessitating the use of an average coefficient.

Referring to Figs. 18 and 19, the drag produced by a joint can be expressed as

$$F_D = C_D \, A_j \, \rho \, \frac{V_e^{\,2}}{2} \qquad \text{(E-1)}$$

where C_D = drag coefficient,
A_j = projected area of the joint irregularity, and
V_e = velocity of flow adjacent to the joint.

Several different assumptions can be used with regard to A_j; in the analysis it is defined as the area of beads plus both positive and negative offsets. Actually, the losses produced by positive and negative offsets probably differ, but as they could not be separated in the present study they have been considered as having the same effect. Division of the area A_j by the circumference of the pipe gives an average height of irregularity $\bar{e}$.

The effective velocity V_e is the local velocity at the height $\bar{e}$ away from the wall. This is on the order of 60 per cent of the average velocity of flow for the data associated with this study.

The drag force can be converted to a pressure loss in the pipe by pressure-momentum relationships. Considering stations 1 and 2 immediately upstream and downstream of the joint,

$$p_1 A_1 + Q\rho \overline{V}_1 = p_2 A_2 + Q\rho \overline{V}_2 + F_D \tag{E-2}$$

Assuming the average area and velocity upstream and downstream are the same (this is correct within about 2 per cent), $A_1 = A_2$ and $\overline{V}_1 = \overline{V}_2$, so that the preceding equation can be expressed as,

$$\frac{P_1 - P_2}{w} = \frac{F_D}{wA} = h_j \tag{E-3}$$

where h_j is the head loss, in feet, produced by the joint. Combining Eqs. (E-1) and (E-3),

$$h_j = \frac{C_D A_j}{wA} \rho \frac{V_e^2}{2} \tag{E-4}$$

The head loss produced by the joint can also be expressed in terms of an equivalent friction factor,

$$h_j = f_j \frac{\ell}{D} \frac{\overline{V}^2}{2g} \tag{E-5}$$

where ℓ is the spacing between joints. The head loss, as shown, would be in addition to the barrel friction, or

$$h = h_p + h_j \quad \text{and} \quad f = f_p + f_j \tag{E-6}$$

where f is the total or measured friction coefficient for a pipe with both barrel friction and joint losses, and f_p is the friction coefficient for a pipe with no joints. Then

$$h_j = (f - f_p) \frac{\ell}{D} \frac{\overline{V}^2}{2g} = \frac{C_D A_j \rho V_e^2}{2wA} \tag{E-7}$$

Solving for the drag coefficient,

$$C_D = (f - f_p) \frac{\ell A}{D} \Big/ \left(\frac{V_e}{\bar{V}}\right)^2 A_j \qquad \text{(E-8)}$$

In the above expression A is the cross-sectional area of the pipe and A_j is the projected area of the pipe joints. $\bar{V}$ is the average velocity of flow (Q/A) and V_e is the local velocity at a distance $\bar{e}$ from the wall.

Assuming that experimental data are available on the total friction coefficient f and that A_j, D, and $\bar{e}$ have been measured, Eq. (E-8) contains two unknowns C_D and f_p. For a pipe with n' dissimilar joints with a spacing ℓ sufficiently large so that the wake of one joint does not influence succeeding joints, we can write

$$C_D = \frac{(f - f_p) \frac{\ell n' A}{D}}{\sum_1^{n'} \left(\frac{V_e}{\bar{V}}\right)^2 A_j} \qquad \text{(E-9)}$$

A solution of Eq. (E-9) is possible if it is further assumed that C_D is a constant for two different pipe tests, one with good joints and the other with average joints, by solving two equations simultaneously. Using subscripts a and g for average and good joints respectively,

$$\frac{f_a - f_p}{f_g - f_p} = \frac{\sum_1^{n'} \left[\left(\frac{V_e}{\bar{V}}\right)^2 A_j\right]_a}{\sum_1^{n'} \left[\left(\frac{V_e}{\bar{V}}\right)^2 A_j\right]_g} \qquad \text{(E-10)}$$

The numerator and denominator on the right side of Eq. (E-10) can be evaluated using the measured values of A_j and $\bar{e}$ and the following equation[1] [10] for the velocity distribution in smooth and rough pipes:

---

[1]The above equation differs in form and in the choice of constants from that used in the body of the report for the computation of local friction factor. This expression was adopted because it is convenient to use, and is applicable to both smooth and rough pipes. The difference is very small, in any event.

$$\frac{V_e}{\overline{V}} = \sqrt{f}\ (2.15 \log y/r_o + 1.43) + 1 \tag{E-11}$$

with $y = \overline{e}$, and

f = measured friction coefficient f_a or f_g.

Assigning the abbreviated notation B_j to the right side of Eq. (E-10) and assuming that it has been evaluated

$$\frac{f_a - f_p}{f_g - f_p} = B_j \qquad \text{and} \tag{E-12}$$

$$f_p = \frac{f_a - B_j f_g}{1 - B_j}$$

Thus a hypothetical friction coefficient can be determined for a pipe with no joints. However, it should be noted that this is no more than an estimate of f_p. The solution is based on some assumptions and is further restricted by the fact that boundary layer disturbances caused by the joint irregularities in a pipe with joints cannot be properly isolated.

The determination of the total resistance of a pipe with a continuous series of bad joints may be of more interest than the case of a pipe with no joints. The choice of $\overline{e}$ and A_j is somewhat arbitrary and depends to some extent on the definition of a bad joint. Assuming that these values have been selected and that all joints in the pipe are the same, $\overline{e}/r_o$ and $V_e/\overline{V}$ are fixed (for given pipe and Re), although the latter term is unknown. Referring to Eq. (E-8) instead of (E-9), because all joints are the same,

$$f_b - f_p = \frac{C_D\ (V_e/\overline{V})^2\ A_j}{\ell\ A/D} \tag{E-13}$$

where f_b is the total friction factor for a pipe with bad joints. Since $A_j = \pi D\overline{e}$ and $A = \pi D^2/4$, this expression simplifies to

$$f_b - f_p = 4\ C_D \frac{\overline{e}}{\ell} \left(\frac{V_e}{\overline{V}}\right)^2 \tag{E-14}$$

Combining this with Eq. (E-11)

$$f_b - f_p = 4\ C_D \frac{\bar{e}}{\ell} [\sqrt{f_b}\ (2.15 \log \bar{e}/r_o + 1.43) + 1] \qquad \text{(E-15)}$$

With f_p determined from preceding computations and $\bar{e}$ selected for a series of bad joints, the only unknown is f_b.

Application of the preceding developments to the experimental data for 36-in. tamped pipe would utilize the following data from Tables A-1, A-2, and E-1:

$$\left.\begin{aligned} f_a &= 0.01570 \\ f_g &= 0.01515 \end{aligned}\right\} \text{ for } Re > 3 \times 10^6$$

$$\sum_1^{n'} \left[(V_e/\bar{V})^2\ A_j\right]_g = 93.21 \text{ and } \sum_1^{n'} \left[(V_e/\bar{V})^2\ A_j\right]_a = 400.87$$

$$B_j = 400.87/93.21 = 4.307$$

Referring to Eq. (E-12),

$$f_p = \frac{0.01570 - 0.01515\ (4.307)}{1 - 4.307} = 0.01499$$

and from Eq. (E-9)

$$C_D = \frac{(0.01570 - 0.01499)}{400.87} \cdot \frac{8 \times 21 \times 1022}{3} = 0.10$$

In this study the definition of a bad joint was arbitrarily based on an average of the three worst joints encountered in the field measurements of joint irregularities in 36-in. pipe. Referring to Table B-1, these were:

Joint No.	A_j sq in.	$\bar{e}$ in.	$\frac{\bar{e}}{r_o}$
3	60.52	0.535	0.0287
4	52.92	0.468	0.0260
5	68.80	0.608	0.0338
Average	69.75	0.537	0.0298

Solution of Eq. (E-15) with ℓ = 8 ft, f_p = 0.01499, C_D = 0.10, and $\bar{e}$ = 0.0447 ft resulted in a value of f_b = 0.01629 for 36-in. tamped concrete pipe with bad joints.

The experimental data for cast pipe indicated that f varied with Reynolds number over the complete test range; thus no limiting value of f_ℓ was obtained. The data were analyzed for four selected values of Reynolds number, using the same procedures as were used for the tamped pipe, with the following results:

Re x 10^{-6}	f_a	f_g	f_p	C_D	f_b
0.5	0.01454	0.01414	0.01384	0.12	0.01543
1.0	0.01300	0.01270	0.01248	0.09	0.01371
2.0	0.01169	0.0144	0.01125	0.07	0.01230
3.4	0.01076	0.01056	0.01041	0.06	0.01127

Friction Coefficients for Pipes with Various Diameters

Experimental data for cast and tamped concrete pipe with various diameters and joint conditions would be desirable. In the absence of such data, the results of the present study have been used to compute coefficients for tamped pipe with diameters ranging from 2 to 8 ft. The following equation for turbulent flow in rough pipes was used as a basis for this extrapolation:

$$\frac{1}{\sqrt{f}} = 2 \log \frac{r_o}{k_s} + 1.74 \qquad \text{(E-16)}$$

Values of k_s were computed for the 36-in. tamped pipe for various joint conditions (Table E-4). These were assumed to be constant regardless of pipe diameter; the value of f was then determined from Eq. (E-16). This procedure automatically assumes that $\bar{e}$ is a constant and that A_j is proportional to pipe diameter. The computed data are included in Table E-4. A trial computation was also made by assuming that k_s for a pipe with no joints is constant for all diameters; the value of f_p was determined and added to the computed value of $\Delta f = f - f_p$ for the respective diameters. With $\bar{e}$ a constant for all diameters, this results in approximately the same values of

f_a, f_b, and f_g, but the method would permit the use of some variation of $\bar{e}$ as a function of diameter if this were considered desirable.

Extrapolation of the experimental data for cast pipe by the same methods used for tamped pipe is not feasible because values of f_ℓ and k_s cannot be determined. However, it appears reasonable to assume that for a selected Reynolds number the value of f will be relatively independent of diameter if the surface roughness of the pipe is the same as the 3-ft pipe used in the tests. Thus, if the pipe diameter and Reynolds number have been determined, a reasonable approximation of f can be obtained from Fig. 21 and Table E-5 if the cast pipe has a good surface finish.

The preceding computations and the analysis of joint losses have been based on the assumption that C_D is a constant for the rough pipe regime in tamped pipe and that it is a constant for selected value of Reynolds number in the cast pipe. Actually, the value of C_D probably varies with each joint, but in the absence of quantitative data on the values of C_D it was necessary to make these assumptions and then solve for C_D. In view of the complex nature of this problem, the correlation between data for the 36-in. cast and 36-in. tamped pipe is considered reasonably good. As noted in a preceding section, the data for 24-in. tamped pipe do not agree with the 36-in. pipe data and have been excluded. It is believed that inaccurate measurements of the joint characteristics in the 24-in. pipe are in part responsible. Due to the smaller pipe size, measurements were much more difficult in the 24-in. than in the 36-in. pipe.

TABLE E-1

JOINT ANALYSIS DATA FOR THE 36-INCH TAMPED PIPE

Joint No.	Good Joints A_j	$\bar{e}$	$\frac{\bar{e}}{r_o}$	$\frac{V_e}{\bar{V}}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$	Average Joints A_j	$\bar{e}$	$\frac{\bar{e}}{r_o}$	$\frac{V_e}{\bar{V}}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$
1	1.72	0.015	0.0008	0.355	0.22	20.45	0.182	0.0101	0.640	8.38
2	4.94	0.044	0.0024	0.482	1.15	51.28	0.456	0.0253	0.750	28.84
3	2.10	0.019	0.0011	0.393	0.32	29.43	0.262	0.0145	0.685	13.81
4	9.65	0.085	0.0047	0.557	2.99	30.52	0.270	0.0150	0.688	14.44
5	8.60	0.076	0.0042	0.547	2.57	36.36	0.324	0.0180	0.710	18.33
6	15.79	0.140	0.0078	0.620	6.07	43.01	0.380	0.0211	0.728	22.80
7	12.74	0.113	0.0063	0.595	4.51	28.47	0.252	0.0140	0.680	13.16
8	4.87	0.043	0.0024	0.482	1.31	3.45	0.031	0.0017	0.432	0.64
9	8.44	0.075	0.0042	0.547	2.53	27.04	0.247	0.0137	0.678	12.43
10	6.51	0.058	0.0032	0.517	1.74	37.43	0.334	0.0185	0.712	18.97
11	7.63	0.067	0.0037	0.532	2.16	11.73	0.104	0.0058	0.578	3.92
12	11.58	0.102	0.0057	0.582	3.92	37.50	0.335	0.0186	0.712	19.01
13	27.32	0.242	0.0134	0.680	12.63	24.01	0.212	0.0117	0.660	10.46
14	9.43	0.083	0.0046	0.555	2.90	35.70	0.319	0.0177	0.706	17.79
15	9.49	0.084	0.0047	0.557	2.94	37.38	0.334	0.0185	0.712	18.95
16	15.23	0.135	0.0075	0.615	5.76	71.26	0.630	0.0349	0.785	43.91
17	11.83	0.105	0.0058	0.584	4.03	28.56	0.256	0.0142	0.682	13.28
18	10.20	0.090	0.0050	0.567	3.30	24.94	0.223	0.0124	0.665	11.03
19	10.77	0.095	0.0053	0.574	3.55	23.80	0.212	0.0117	0.660	10.37
20	18.69	0.165	0.0091	0.635	7.54	101.86	0.902	0.0500	0.830	70.17
21	10.54	0.093	0.0052	0.572	3.45	17.37	0.155	0.0086	0.622	6.72
22	18.94	0.167	0.0093	0.638	7.71	39.77	0.354	0.0196	0.720	20.62
23	11.42	0.101	0.0056	0.580	3.84	30.33	0.272	0.0151	0.688	14.36
24	14.56	0.129	0.0071	0.608	5.38	32.07	0.285	0.0158	0.694	15.44
25	9.15	0.081	0.0045	0.556	2.83	43.24	0.386	0.0214	0.730	23.04
26	17.37	0.154	0.0085	0.628	6.85	43.69	0.380	0.0211	0.728	23.16
27	7.41	0.066	0.0036	0.530	2.08	32.25	0.287	0.0159	0.695	15.58
28	13.89	0.123	0.0068	0.604	5.07	20.11	0.179	0.0099	0.640	8.24
29	9.66	0.085	0.0047	0.557	3.00	43.84	0.391	0.0217	0.731	23.42
Total for joints 9-29					93.21					400.87

Units in table are inches and square inches.
Number of joints used in analysis = 21 (joints 9-29).
Joint spacing = 8 ft.
Average diameter D = 36.07 inches.
Cross section of pipe = 1022 sq inches.

TABLE E-2

JOINT ANALYSIS DATA FOR THE 36-INCH CAST PIPE AT $Re = 3.4 \times 10^6$

Joint No.	Good Joints A_j	$\bar{e}$	$\bar{e}/r_o$	$V_e/\bar{V}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$	Average Joints A_j	$\bar{e}$	$\bar{e}/r_o$	$V_e/\bar{V}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$
1	12.29	0.109	0.0060	0.655	5.27	26.60	0.235	0.0131	0.728	14.10
2	13.26	0.117	0.0065	0.665	5.86	45.36	0.400	0.0222	0.780	27.60
3	21.76	0.192	0.0107	0.713	11.06	26.76	0.236	0.0131	0.728	14.18
4	8.43	0.075	0.0042	0.623	3.27	16.68	0.148	0.0082	0.684	7.80
5	12.52	0.111	0.0062	0.660	5.45	40.59	0.472	0.0262	0.795	25.65
6	13.76	0.122	0.0068	0.667	6.12	18.07	0.160	0.0089	0.691	8.63
7	12.70	0.112	0.0062	0.660	5.53	18.07	0.203	0.0113	0.714	9.21
8	13.04	0.115	0.0064	0.663	5.73	15.54	0.137	0.0076	0.676	7.10
9	12.78	0.113	0.0063	0.661	5.58	31.55	0.278	0.0154	0.745	17.51
10	10.08	0.089	0.0049	0.638	4.10	28.10	0.248	0.0138	0.738	15.30
11	20.82	0.184	0.0102	0.707	10.41	54.82	0.485	0.0269	0.800	35.08
12	14.82	0.131	0.0073	0.675	6.75	40.89	0.361	0.0200	0.770	24.24
13	19.59	0.173	0.0096	0.702	9.65	22.01	0.195	0.0108	0.710	11.10
14	21.21	0.188	0.0104	0.709	10.66	40.29	0.356	0.0198	0.768	23.76
15	21.77	0.192	0.0107	0.712	11.03	29.55	0.261	0.0145	0.739	16.14
16	21.04	0.186	0.0103	0.708	10.55	22.96	0.203	0.0113	0.715	11.74
17	10.15	0.090	0.0050	0.640	4.16	35.23	0.311	0.0173	0.756	20.13
18	12.70	0.112	0.0062	0.660	5.53	29.73	0.262	0.0146	0.740	16.28
19	10.07	0.089	0.0049	0.638	4.10	11.81	0.105	0.0058	0.650	4.99
20	18.72	0.166	0.0092	0.697	9.09	19.93	0.176	0.0098	0.700	9.77
21	10.65	0.094	0.0052	0.643	4.40	13.30	0.118	0.0066	0.663	5.85
22	14.79	0.131	0.0073	0.675	6.74	32.50	0.287	0.0159	0.751	18.33
23	19.02	0.168	0.0093	0.698	9.27	43.13	0.380	0.0211	0.775	25.90
24	7.48	0.066	0.0037	0.610	2.78	25.80	0.227	0.0126	0.725	13.56
25	11.63	0.103	0.0057	0.652	4.94	31.46	0.278	0.0154	0.744	17.41
26	14.81	0.131	0.0073	0.675	6.75	33.89	0.299	0.0166	0.752	19.16
27	9.81	0.087	0.0048	0.635	3.95	11.32	0.100	0.0056	0.646	4.72
28	19.94	0.176	0.0098	0.703	9.85	23.73	0.209	0.0116	0.717	12.20
29	15.89	0.140	0.0078	0.682	7.39	34.97	0.308	0.0171	0.754	19.88
Total for joints 9-29					147.68					343.05

Units in table are inches and square inches.
Number of joints used in analysis = 21 (joints 9-29).
Joint spacing = 8 ft.
Average diameter D = 35.99 inches.
Cross section of pipe = 1017 sq inches.

TABLE E-3

JOINT ANALYSIS DATA FOR THE 24-INCH TAMPED PIPE

Joint No.	Good Joints					Average-A Joints					Average-B Joints				
	A_j	$\bar{e}$	$\frac{\bar{e}}{r_o}$	$\frac{V_e}{\bar{V}}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$	A_j	$\bar{e}$	$\frac{\bar{e}}{r_o}$	$\frac{V_e}{\bar{V}}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$	A_j	$\bar{e}$	$\frac{\bar{e}}{r_o}$	$\frac{V_e}{\bar{V}}$	$\left(\frac{V_e}{\bar{V}}\right)^2 A_j$
1	20.03	0.260	0.0220	0.725	10.53	16.51	0.219	0.0182	0.690	7.86	16.51	0.219	0.0182	0.695	7.97
2	7.72	0.102	0.0085	0.615	2.92	6.49	0.086	0.0072	0.570	2.11	6.49	0.086	0.0072	0.580	2.18
3	6.59	0.087	0.0072	0.595	2.33	13.36	0.177	0.0146	0.662	5.85	13.36	0.177	0.0146	0.668	5.96
4	11.23	0.149	0.0120	0.655	4.82	2.73	0.036	0.0030	0.462	0.58	2.73	0.036	0.0030	0.472	0.61
5	12.37	0.164	0.0140	0.670	5.55	21.25	0.282	0.0233	0.724	11.02	21.25	0.282	0.0233	0.724	11.14
6	7.46	0.072	0.0060	0.575	2.47	10.20	0.135	0.0102	0.617	3.88	10.20	0.135	0.0102	0.623	3.96
7	13.54	0.180	0.0150	0.682	6.30	9.79	0.130	0.0108	0.622	3.79	9.79	0.130	0.0108	0.630	3.88
8	7.78	0.103	0.0085	0.615	2.94	31.61	0.419	0.0347	0.770	18.74	31.61	0.419	0.0347	0.774	18.94
9	6.27	0.083	0.0069	0.590	2.18	14.10	0.187	0.0155	0.670	6.33	14.10	0.187	0.0155	0.675	6.40
10	4.65	0.062	0.0051	0.552	1.42	1.00	0.013	0.0010	0.325	0.10	1.00	0.013	0.0010	0.335	0.11
11	7.14	0.095	0.0079	0.605	2.61	18.19	0.241	0.0200	0.700	8.91	18.19	0.241	0.0200	0.703	8.99
12	2.75	0.036	0.0030	0.490	0.66	5.23	0.007	0.0006	0.250	0.33	5.23	0.007	0.0006	0.270	0.38
13	8.84	0.117	0.0097	0.630	3.51	56.55	0.750	0.0622	0.845	40.38	18.85	0.250	0.0207	0.710	9.50
14	6.48	0.086	0.0070	0.590	2.26	15.56	0.206	0.0170	0.680	7.19	15.56	0.206	0.0170	0.685	7.30
15	7.07	0.094	0.0078	0.603	2.57	19.56	0.259	0.0214	0.710	9.86	19.56	0.259	0.0214	0.714	9.97
16	9.61	0.127	0.0105	0.640	3.94	13.00	0.172	0.0140	0.655	5.58	13.00	0.172	0.0140	0.662	5.70
17	10.31	0.137	0.0114	0.650	4.35	11.82	0.157	0.0130	0.645	4.92	11.82	0.157	0.0130	0.652	5.02
18	7.66	0.102	0.0085	0.615	2.90	13.83	0.183	0.0152	0.665	6.12	13.83	0.183	0.0152	0.672	6.24
19	15.32	0.203	0.0168	0.695	7.40	74.17	0.984	0.0814	0.878	57.18	17.62	0.234	0.0194	0.702	8.68
20	16.79	0.223	0.0185	0.705	8.34	7.68	0.102	0.0092	0.603	2.79	7.68	0.102	0.0092	0.611	2.87
21	5.60	0.074	0.0161	0.575	1.85	19.11	0.253	0.0210	0.705	9.50	19.11	0.253	0.0210	0.712	9.69
22	6.17	0.082	0.0068	0.587	2.13	12.39	0.164	0.0136	0.615	5.31	12.39	0.164	0.0136	0.660	5.40
23	4.65	0.062	0.0051	0.552	1.42	1.00	0.013	0.0010	0.325	0.10	1.00	0.013	0.0010	0.335	0.11
Total for joints 7-23					56.78					187.13					109.18

Average diameter D = 24.11 inches.
Cross section of pipe = 457 sq inches.

Average diameter = 24.14 inches.
Cross section of pipe = 458 sq inches.

Units in table are inches and square inches.
Number of joints used in analysis = 17 (joints 7-23).
Joint spacing = 8 ft.

TABLE E-4

FRICTION COEFFICIENTS FOR TAMPED CONCRETE PIPE WITH VARIOUS DIAMETERS AND JOINT CONDITIONS

(Joint Spacing = 8 ft; Re > 3 x 10^6)

Joint Conditions	D ft	r_o in.	$\frac{r_o}{k_s}$	$\log \frac{r_o}{k_s}$	$2 \log \frac{r_o}{k_s}$	$\frac{1}{\sqrt{f_\ell}}$	$\sqrt{f_\ell}$	f_ℓ	n_ℓ	Test Pipe D = 36.07 inches C_D = 0.10
No Joints	2	12	1089.32	3.03716	6.07432	7.81832	0.12797	0.01638	0.01056	f_p = 0.01499
	3	18	1633.98	3.21325	6.42650	8.16650	0.12245	0.01499	0.01081	n_p = 0.01081
	4	24	2178.64	3.33819	6.67638	8.41638	0.11882	0.01412	0.01100	$1/\sqrt{f_p}$ = 8.16907
	5	30	2723.30	3.43510	6.87020	8.61020	0.11614	0.01349	0.01116	$2 \log r_o/k_s$ = 6.42907
	6	36	3267.96	3.51428	7.02856	8.76856	0.11404	0.01301	0.01130	r_o/k_s = 1638.83
	7	42	3812.62	3.58123	7.16246	8.90246	0.11233	0.01262	0.01142	k_s = 0.01100 in.
	8	48	4357.28	3.63922	7.27844	9.01844	0.11088	0.01229	0.01152	
Good	2	12	1035.84	3.01530	6.03060	7.77060	0.12869	0.01656	0.01061	f_g = 0.01515
	3	18	1553.76	3.19139	6.38278	8.12278	0.12311	0.01515	0.01087	n_g = 0.01087
	4	24	2071.68	3.31633	6.63266	8.37266	0.11944	0.01426	0.01106	$1/\sqrt{f_g}$ = 8.12447
	5	30	2589.60	3.41324	6.82648	8.56648	0.11673	0.01363	0.01122	$2 \log r_o/k_s$ = 6.38447
	6	36	3107.52	3.49242	6.98484	8.72484	0.11461	0.01314	0.01135	r_o/k_s = 1556.78
	7	42	3625.44	3.55937	7.11874	8.85874	0.11288	0.01274	0.01147	k_s = 0.01158 in.
	8	48	4143.36	3.61556	7.23112	8.97112	0.11147	0.01243	0.01159	
Average	2	12	879.02	2.94400	5.88800	7.62800	0.13110	0.01719	0.01081	f_a = 0.01570
	3	18	1318.53	3.12009	6.24018	7.98018	0.12531	0.01570	0.01106	n_a = 0.01106
	4	24	1758.04	3.24503	6.49006	8.23006	0.12151	0.01476	0.01125	$1/\sqrt{f_a}$ = 7.98186
	5	30	2197.55	3.34194	6.68388	8.42388	0.11871	0.01409	0.01141	$2 \log r_o/k_s$ = 6.24186
	6	36	2637.06	3.42112	6.84224	8.58224	0.11652	0.01358	0.01154	r_o/k_s = 1321.09
	7	42	3076.57	3.48807	6.97614	8.71614	0.11473	0.01316	0.01166	k_s = 0.01365 in.
	8	48	3516.08	3.54606	7.09212	8.83212	0.11322	0.01282	0.01177	
Bad	2	12	742.24	2.87055	5.74110	7.48110	0.13367	0.01787	0.01103	f_b = 0.01629
	3	18	1113.36	3.04664	6.09328	7.83328	0.12766	0.01630	0.01127	n_b = 0.01127
	4	24	1484.48	3.17158	6.34316	8.08316	0.12371	0.01531	0.01145	$1/\sqrt{f_b}$ = 7.83496
	5	30	1855.60	3.26849	6.53798	8.27793	0.12080	0.01459	0.01161	$2 \log r_o/k_s$ = 6.09496
	6	36	2226.72	3.34767	6.69534	8.43534	0.11855	0.01405	0.01174	r_o/k_s = 1115.54
	7	42	2597.84	3.41462	6.82934	8.56934	0.11669	0.01362	0.01186	k_s = 0.01617 in.
	8	48	2968.96	3.47261	6.94532	8.68532	0.11514	0.01326	0.01197	

Coefficients are based on tests of 36-in. tamped concrete pipe.

TABLE E-5

FRICTION AND DRAG COEFFICIENTS FOR CAST CONCRETE PIPE WITH VARIOUS DIAMETERS AND JOINT CONDITIONS

$\overline{V}$ fps	Re x 10^{-6}	D ft	No Joints f_p	n_p	Good Joints f_g	n_g	Average Joints f_a	n_a	Bad Joints f_b	n_b	C_D
3	0.5	2.175	0.01384	0.00984	0.01413	0.00994	0.01453	0.01008	0.01574	0.01049	0.120
3	1.0	4.350	0.01248	0.01049	0.01266	0.01056	0.01291	0.01067	0.01359	0.01095	0.090
3	2.0	8.700	0.01125	0.01118	0.01138	0.01124	0.01156	0.01133	0.01205	0.01157	0.075
3	3.4	14.790	0.01041	0.01175	0.01050	0.01180	0.01063	0.01187	0.01098	0.01206	0.060
5	0.5	1.305	0.01384	0.00984	0.01418	0.00915	0.01464	0.00929	0.01585	0.00967	0.120
5	1.0	2.610	0.01248	0.01049	0.01268	0.00971	0.01298	0.00983	0.01376	0.01011	0.090
5	2.0	5.220	0.01125	0.01118	0.01140	0.01034	0.01161	0.01043	0.01217	0.01068	0.075
5	3.4	8.874	0.01041	0.01175	0.01052	0.01084	0.01067	0.01092	0.01107	0.01112	0.060
8	0.5	0.816	0.01384	0.00984	0.01423	0.0848	0.01475	0.00863	0.01611	0.00902	0.120
8	1.0	1.631	0.01248	0.01049	0.01273	0.0900	0.01305	0.00911	0.01393	0.00941	0.090
8	2.0	3.262	0.01125	0.01118	0.01143	0.0957	0.01167	0.00967	0.01229	0.00992	0.075
8	3.4	5.546	0.01041	0.01175	0.01053	0.01004	0.01071	0.01012	0.01115	0.01033	0.060
2.175	0.5	3	0.01384	0.01038	0.01414	0.01049	0.01454	0.01064	0.01543	0.01096	0.120
4.350	1.0	3	0.01248	0.00986	0.01270	0.00995	0.01300	0.01006	0.01371	0.01033	0.090
8.700	2.0	3	0.01125	0.00936	0.01144	0.00944	0.01169	0.00954	0.01224	0.00976	0.075
14.790	3.4	3	0.01041	0.00901	0.01056	0.00907	0.01076	0.00916	0.01127	0.00937	0.060

$T = 55^{o}$ F; $\nu = 1.305 \times 10^{-5}$ ft^2/sec; $D = Re\ \nu/\overline{V}$; $\overline{e}_g = 0.01095$ ft; $\overline{e}_a = 0.02145$ ft; $\overline{e}_b = 0.04475$ ft

A P P E N D I X F

TRANSITION FROM SMOOTH-PIPE TO ROUGH-PIPE FLOW IN TAMPED CONCRETE PIPE

APPENDIX F

TRANSITION FROM SMOOTH-PIPE TO ROUGH-PIPE FLOW IN TAMPED CONCRETE PIPE

The experimental data on the Darcy friction factor for 24- and 36-in. machine tamped pipe indicated that the transition from the smooth-pipe to the rough-pipe regime did not agree with the Colebrook equation. When the data are plotted in the form shown in Fig. 23 the transition for the tamped pipe is between the Colebrook curve and the Nikuradse curve for pipe with uniform sand grain roughness. As the transition is dependent on the type of roughness elements forming the pipe boundary, it is not surprising that this difference exists.

The semi-empirical curve which provides a reasonably good fit for the SAF experimental data is as follows:

$$\frac{1}{\sqrt{f}} - 2 \log \frac{r_o}{k_s} = 1.74 - \log\left[1.002 - \frac{1.56}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)} + \frac{311}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)^2} + \frac{104}{\left(\frac{Re\sqrt{f}}{r_o/k_s}\right)^3}\right] \qquad \text{(F-1)}$$

for $4 \leq \frac{Re\sqrt{f}}{r_o/k_s} \leq 400.$

This expression is tangent to the smooth-pipe curve $(1/\sqrt{f} = 2 \log Re \sqrt{f} - 0.8)$ at

$$\frac{Re\sqrt{f}}{r_o/k_s} = 4$$

and to the rough pipe equation

$$(1/\sqrt{f} = 2 \log r_o/k_s + 1.74) \quad \text{at} \quad \frac{Re\sqrt{f}}{r_o/k_s} = 400$$

As noted in a preceding section the Darcy friction factor for 36-in. tamped pipe is relatively constant for Reynolds numbers above 500,000. The corresponding value of the parameter

$$\frac{Re\sqrt{f}}{r_o/k_s}$$

is about 47. Considering the data for both 24- and 36-in. tamped pipe, with both good and average joints, a transition equation could be written tangent to the rough pipe equation at about

$$\frac{Re\sqrt{f}}{r_o/k_s} = 50$$

rather than the value of 400 actually used. However, the latter value is customarily defined as the demarcation between the rough-pipe regime and the transition zone and was used in the present analysis. The suggested equation shows little variation (about 1.6 per cent) in the value of $1/\sqrt{f} - 2 \log r_o/k_s$ for

$$50 \leq \frac{Re\sqrt{f}}{r_o/k_s} \leq 400.$$

Equation (F-1) is somewhat complex but this need not be of concern because a tabulated solution of the equation is included in Table F-1.

TABLE F-1

TABULATED DATA FOR THE SAF GENERAL RESISTANCE DIAGRAM
(For Uniform Flow in Tamped Concrete Pipes)

$\frac{r_o}{k_s}$	$\frac{Re\sqrt{f}}{r_o/k_s}$	4	6	10	20	40	60	100	200	400
	$1/\sqrt{f} - 2\log\frac{r_o}{k_s}$	0.40405	0.74602	1.13147	1.50587	1.67592	1.71352	1.73242	1.73913	1.73998
100	Re	1.76×10^3	2.85×10^3	5.13×10^3	1.10×10^4	2.27×10^4	3.43×10^4	5.73×10^4	1.15×10^5	2.30×10^5
	f	0.05156	0.04440	0.03798	0.03300	0.03104	0.03063	0.03043	0.03036	0.03035
200	Re	4.00×10^3	6.42×10^3	1.15×10^4	2.44×10^4	5.02×10^4	7.58×10^4	1.27×10^5	2.54×10^5	5.07×10^5
	f	0.03990	0.03496	0.03042	0.02680	0.02537	0.02507	0.02492	0.02487	0.02486
500	Re	1.16×10^4	1.84×10^4	3.26×10^4	6.90×10^4	1.41×10^5	2.13×10^5	3.56×10^5	7.14×10^5	1.43×10^6
	f	0.02971	0.02649	0.02346	0.02098	0.01998	0.01977	0.01967	0.01963	0.01963
1000	Re	2.56×10^4	4.05×10^4	7.13×10^4	1.50×10^5	3.07×10^5	4.63×10^5	7.73×10^5	1.55×10^6	3.10×10^6
	f	0.02438	0.02197	0.01967	0.01775	0.01697	0.01680	0.01672	0.01670	0.01669
2000	Re	5.60×10^4	8.82×10^4	1.55×10^5	3.24×10^5	6.62×10^5	9.98×10^5	1.67×10^6	3.34×10^6	6.67×10^6
	f	0.02037	0.01852	0.01672	0.01521	0.01459	0.01446	0.01440	0.01437	0.01437
5000	Re	1.56×10^5	2.44×10^5	4.26×10^5	8.93×10^5	1.81×10^6	2.73×10^6	4.56×10^6	9.14×10^6	1.83×10^7
	f	0.01643	0.01508	0.01375	0.01261	0.01215	0.01205	0.01200	0.01198	0.01198
10,000	Re	3.36×10^5	5.25×10^5	9.13×10^5	1.90×10^6	3.87×10^6	5.83×10^6	9.73×10^6	1.95×10^7	3.90×10^7
	f	0.01416	0.01307	0.01199	0.01107	0.01068	0.01060	0.01056	0.01054	0.01054
20,000	Re	7.20×10^5	1.12×10^6	1.95×10^6	4.04×10^6	8.22×10^6	1.24×10^7	2.07×10^7	4.14×10^7	8.27×10^7
	f	0.01233	0.01144	0.01056	0.00979	0.00947	0.00940	0.00936	0.00935	0.00935

This table gives the magnitudes of Reynolds number Re and corresponding friction coefficient f for various values of r_o/k_s, calculated from the parameters indicated in the upper two rows.

APPENDIX G

ELEVATION OF HYDRAULIC GRADE LINE AT OUTLET OF PIPE

TABLE G-1

SUMMARY DATA ON HYDRAULIC GRADE LINE AT PIPE OUTLET

36-Inch Cast Pipe

	Average Joints			Good Joints		
	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$
No Entrained Air	125	9.45	0.583	160	9.65	0.567
	126	9.16	0.600	161	9.54	0.567
	132	9.42	0.573	162	9.44	0.577
	134	9.60	0.573	163	9.24	0.573
	135	9.11	0.567	164	9.82	0.557
	139	9.14	0.577	165	9.16	0.573
Some Entrained Air	136	7.88	0.970	166	7137	0.953
	137	5.88	0.960	167	5.96	0.967
	138	4.19	0.933	168	5.05	0.960

36-Inch Tamped Pipe

	Average Joints			Good Joints		
	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$
No Entrained Air	42	2.73	0.806	69	9.01	0.540
	43	1.86	0.661	70	9.02	0.540
	44	1.20	0.538	79	3.18	0.880
	45	0.46	0.332	80	3.06	0.873
	52	7.96	0.560	99	8.78	0.567
	53	7.55	0.593	100	8.65	0.567
	54	7.08	0.650	103	9.12	0.550
	61	7.75	0.573	114	8.00	0.560
	63	2.64	0.793	115	7.96	0.563
	64	7.30	0.590	116	7.04	0.640
	65	6.95	0.647	117	5.76	0.700
				118	7.57	0.560
Some Entrained Air	55	6.61	0.950	71	7.85	0.907
	56	6.68	0.940	72	8.26	0.667
	57	6.30	0.927	73	7.97	0.913
	58	5.66	0.920	74	7.22	0.920
	59	5.31	0.923	75	6.39	0.923
	60	4.87	0.933	76	5.64	0.940
	62	6.85	0.850	77	4.81	0.930
	66	6.68	0.957	78	4.09	0.920
				101	8.13	0.717
				102	7.00	0.943
				104	7.80	0.927
				105	6.23	0.933
				106	5.48	0.937
				111	7.02	0.917

24-Inch Tamped Pipe

	Average-B Joints			Good Joints		
	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$	Run No.	$\frac{Q}{D^{5/2}}$	$\frac{Y}{D}$
No Entrained Air	82	4.08	0.853	99	5.01	0.811
	83	4.08	0.853	100	5.01	0.811
	93	3.73	0.873	101	4.43	0.834
	94	2.79	0.828	102	4.43	0.834
	95	2.00	0.698	103	3.79	0.880
				117	5.13	0.791
				126	4.90	0.831
				127	4.22	0.851
				128	3.58	0.886
				129	2.36	0.761
				130	1.71	0.631
Some Entrained Air	92	4.61	0.920			