Tests on Circular-Pipe-Culvert Inlets

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● THE effect of various types of inlets on flow through short model circular pipe culverts has been investigated experimentally at the hydraulic laboratory, A & M College of Texas, for some time. Experiments were performed without sponsorship, under the engineering-experiment-station sponsorship and finally under the sponsorship of some 14 Texas concrete-pipe manufacturers.

Tests were carried out on the following inlets: (1) square edged flush inlets with flared wingwalls, with straight wingwalls and with parallel wingwalls; (2) thin walled projecting inlet; (3) mitered sharp-edged inlet ($1\frac{1}{2}$ to 1 slope); (4) mitered rounded inlet ($r/D=0.125$); (5) tongue and groove projecting inlet; and (6) rounded projecting inlet ($r/D=0.15$).

All transparent lucite pipes, which were 69 inches long, with the exception of the square edged pipe models 52 inches long, were installed in the bottom of a wooden flume 17 feet 10 inches long, 2 feet 8 inches wide and 1 foot 9 inches deep. The inverts of the square-edged pipes, the thin-wall projecting-inlet pipe, the mitered, sharp-edged-inlet pipe were at the same elevation as the bottom of the flume at both the inlet and exit ends. Due to the necessary pipe wall thickness increase, the other inlet inverts were a slight distance above the bottom of the flume.

Actually, the inlets, with the exception of the square-edged flush inlets with wingwalls, were attached to or formed on a section of pipe 17 inches long and were then attached by flange to a 52-inch length of pipe. The various wingwalls were attached to the 52-inch pipe. The same 52-inch pipe remained in place during all tests.

The model pipe diameter was 5 inches. Fill side slopes were simulated by plywood boards set on a slope of $1\frac{1}{2}$ horizontal to 1 vertical. The approach and exit channels were rectangular in shape. The culverts were tested under free or unsubmerged outfall conditions only. The pipe, being set in the bottom of the flume, had the same slope as the flume. This slope was varied by raising or lowering one end of the flume.

Details of the model and weir flume appear in Figure 1. Figures 2 through 6 show details of the various types of inlets.

TEST PROCEDURE

Generally, discharges were increased from a minimum up to the capacity of the flume during tests. A number of point gage readings were made and averaged for one setting of the supply valve. A sufficient time for the heads to become stabilized was allowed before readings were begun.

Tests were run to determine the influence of inlets alone on the discharge capacity of the pipe. The width of the flume was sufficient for the outlet condition of the pipe to be free or unsubmerged in all cases. No attempt was made to raise the tailwater during tests.

TEST RESULTS

If the relationship H/D versus $Q/(g^{1/2}D^{5/2})$ is plotted on arithmetic coordinate paper, the resulting curve will define the flow characteristics for a wide range of pipe sizes. However, the acceleration due to gravity, g, may be assumed to be a constant and the term $g^{1/2}$ omitted.

Figure 7 shows the curves as determined by test results. No attempt was made to determine a theoretical curve. Generally the curves agree reasonably well with those determined by Mavis and Straub in their experiments.

CONCLUSIONS FROM TEXAS A & M TESTS

The following conclusions are drawn from the results of tests on the various types of pipe inlets with the pipe under free outfall conditions:

1. In concrete pipe culverts, it reduces the efficiency of the culvert to miter the

upstream end as compared to the square-ended inlet placing the groove end of a tongue and groove pipe upstream.

2. Only two types of inlets tested, the groove-projecting inlet and the rounded-projecting inlet, showed that the culverts would flow full depending upon inlet control

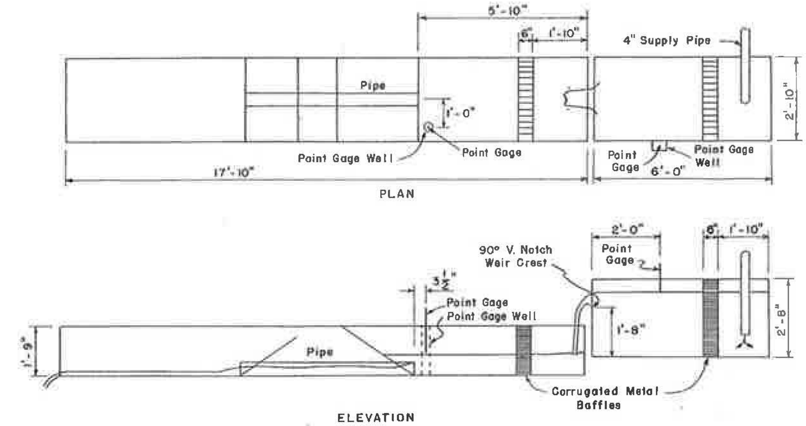

Figure 1. Details of Model and Weir Flumes.

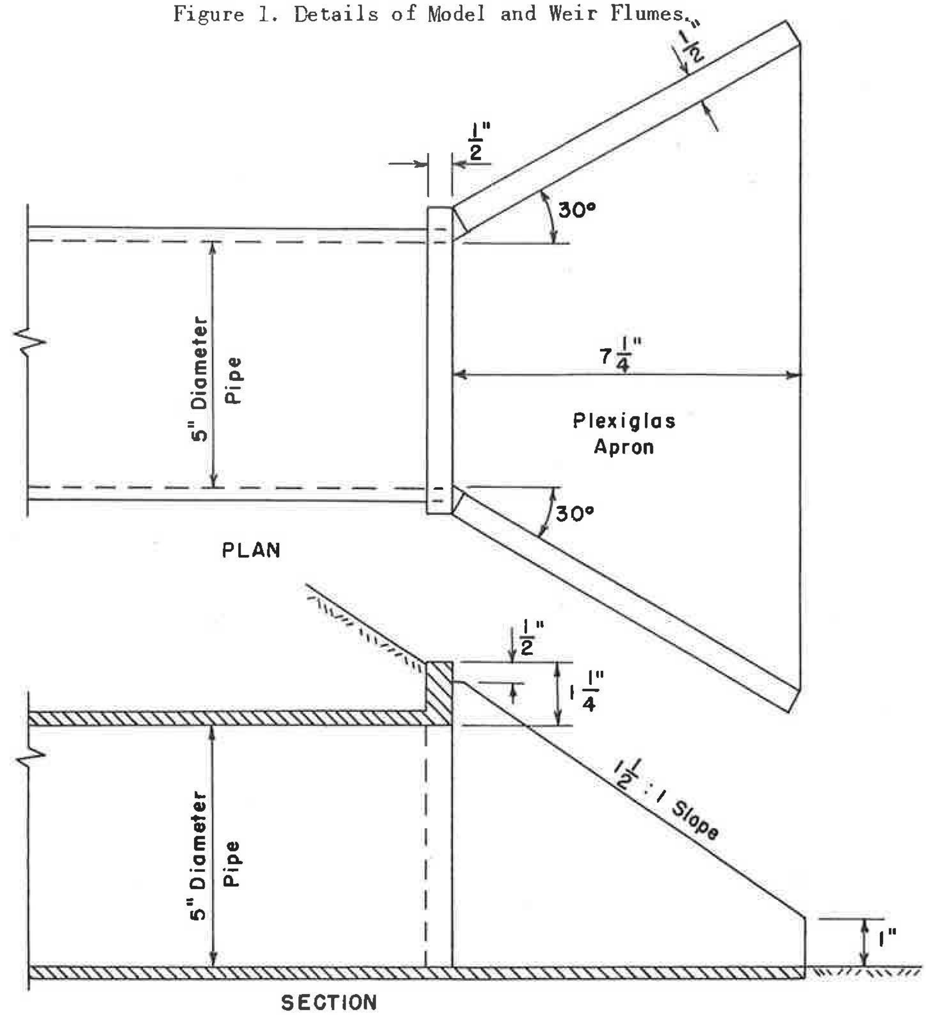

Figure 2. Details of Flared Wingwall Inlet to Square Edged Pipe.

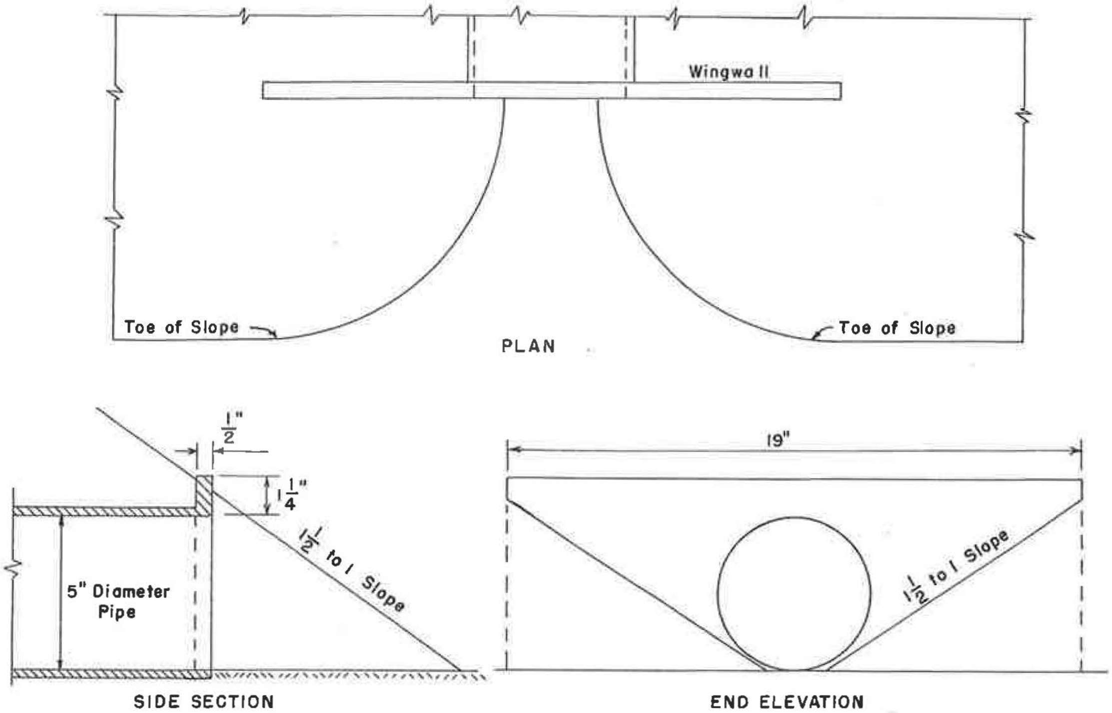

Figure 3. Details of Straight Wingwall Inlet to Square Edged Pipe.

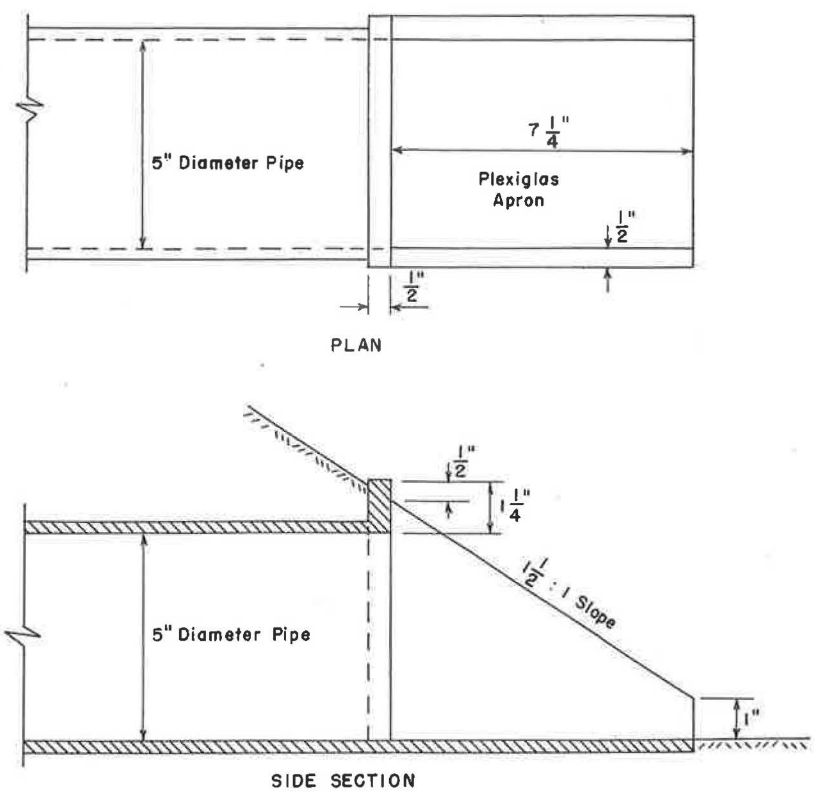

Figure 4. Details of Parallel Wingwall Inlet to Square Edged Pipe.

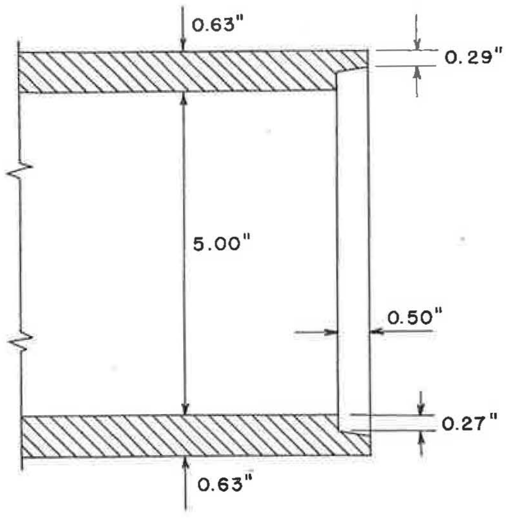

Figure 5. Details of Groove Inlet.

conditions when H/D was less than 3.7, and these flowed full only when H/D was greater than about 1.5. Between the val of H/D of 1.2 and 1.5, the flow conditior were variable for the groove and roundec inlets and the flow was not stabilized unt: a H/D of about 1.5 was reached.

3. The sharp-edged projecting inlet and the mitered sharp-edged inlet are no as efficient as the square-edged flush in- let.

DESIGN NOMOGRAPHS

Nomographs, which are the solutions the various head-discharge curves appea ing in Figure 7, have been prepared to e able the eingineer to design pipe culverts quickly. These nomographs, Figures 10 and 11 may be used to solve directly for

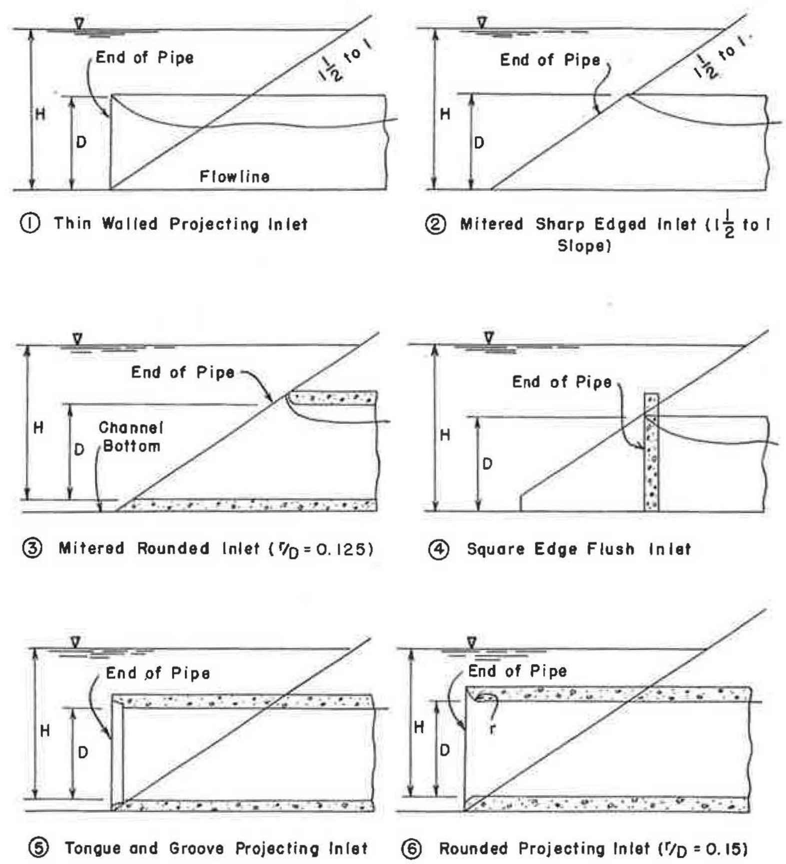

Figure 6. Inlet Details. Side Elevations.

pipe sizes, wherever the culvert discharges freely and flows partly full on a steep slope, if it is fairly long. Slope is not too important for short culverts, and the nomographs may be used to solve directly for pipe sizes when short pipes are set on flat or steep slopes.

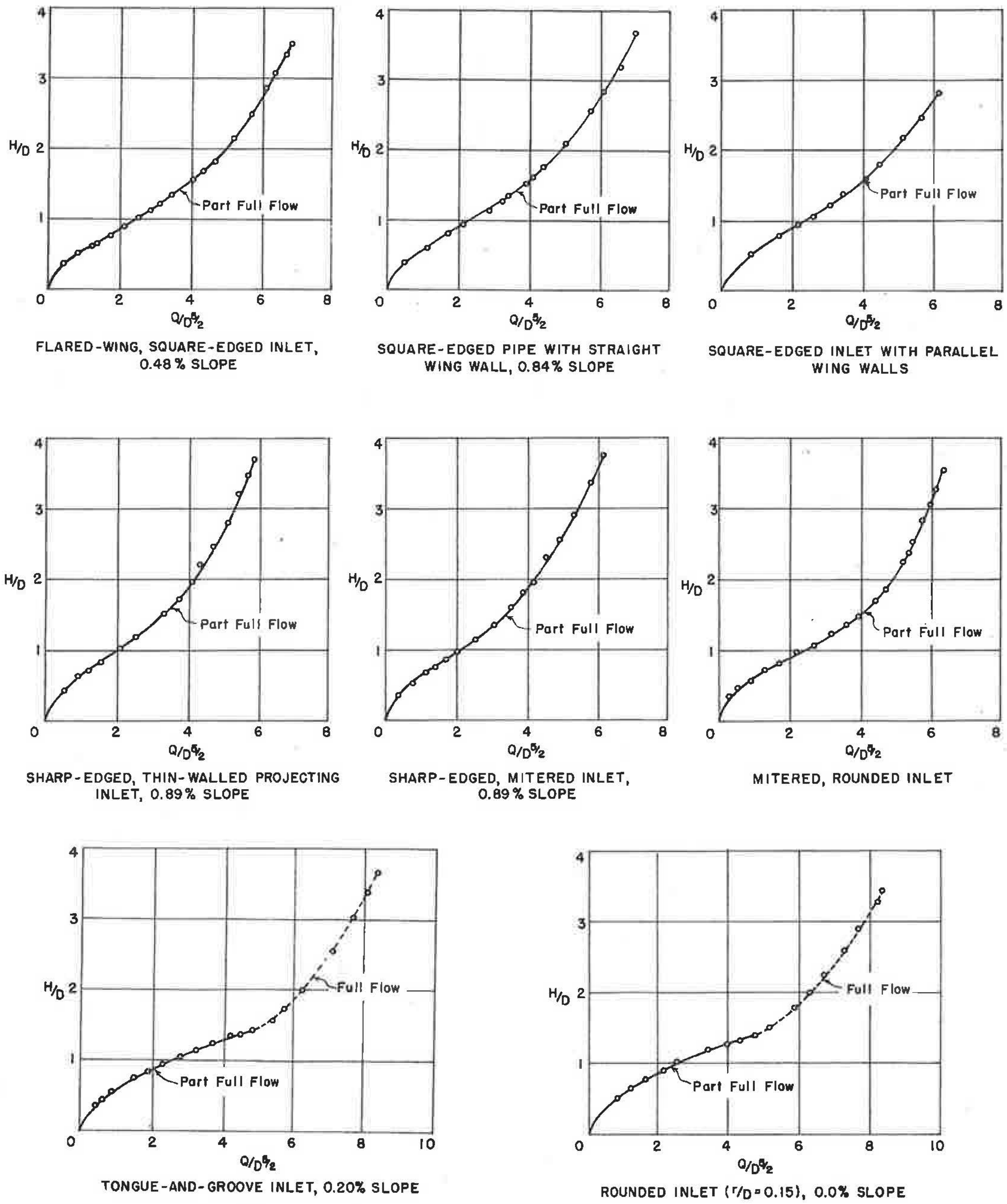

Figure 7. Comparison of Head Discharge Curves.

When long pipes are set on mild slopes, the nomographs will not give correct answers, due to the effect of backwater.

FULL FLOW WITH FREE OUTFALL

Whenever a pipe flows full with free outfall, the culvert control is the outlet and the nomograph H/D values (Figures 10 and 11) may be incorrect. H/D may be determined by an application of Bernoulli's theorem to the flow so that

$$H/D - \tfrac{1}{2} + \frac{L'S}{D} = 0.0252 \left(1 + K_i + \frac{185n^2L}{D^{4/3}}\right)\left(\frac{Q}{D^{5/2}}\right)^2$$

Figures 8 and 9 show typical flow conditions, to be expected, in pipes operating under various conditions. The probable type of flow, for most conditions, may be determined from these curves.

BERNOULLI'S THEOREM APPLICATION RULES

The following rules may be used to indicate which H/D value (Nomograph or Bernoulli) should be used when Bernoulli's theorem is applied.

For corrugated metal pipe with projecting or flush inlet: (1) the nomograph H/D value should be used if the Bernoulli H/D value is less than the nomograph H/D value and (2) the Bernoulli H/D value should be used if the Bernoulli H/D value is greater than the nomograph H/D value.

For concrete pipe with groove inlet; (1) the nomograph H/D value should be used if the Bernoulli H/D value is less than 1.5 and is less than the nomograph H/D value; (2) the Bernoulli H/D value should be used if the Bernoulli H/D value is from 1.2 to 1.5 and is larger than the nomograph H/D value; and (3) the Bernoulli H/D value should be used if the Bernoulli H/D value is $\geq$ 1.5

The above rules do not apply unless $H/D \geq 1.2$.

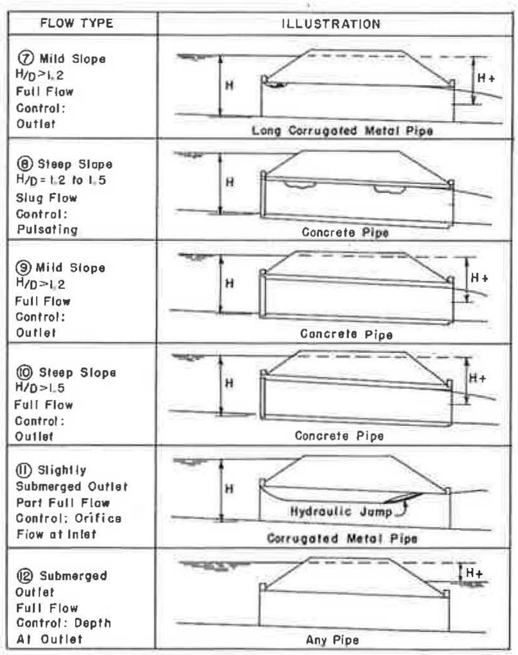

Figure 9. Typical Flow Conditions - Full Flow in Pipes.

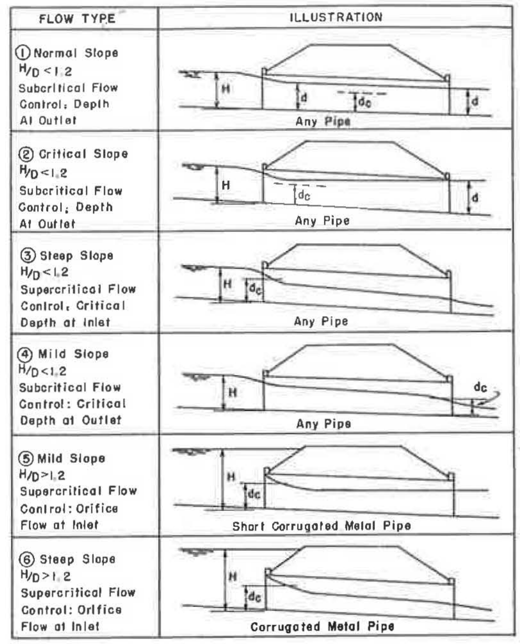

Figure 8. Typical Flow Conditions - Partly Full Flow in Pipes.

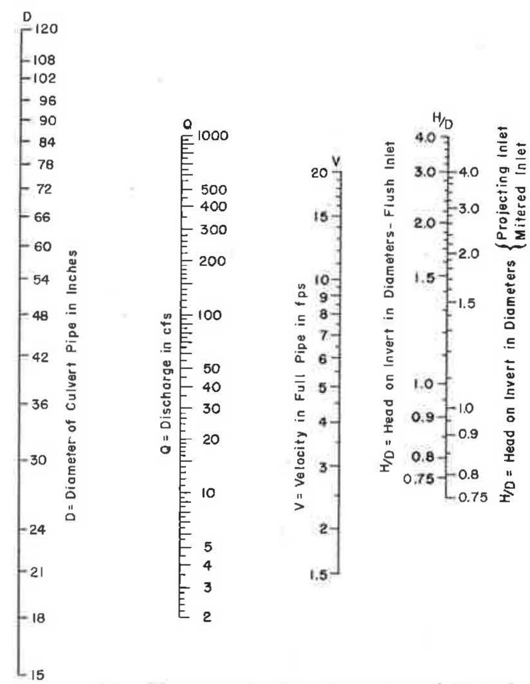

Figure 10. Nomograph for Corrugated Metal Pipe Culverts with Free Outfall.

SUBMERGED FLOW

Whenever the outlet of a culvert is completely submerged, the culvert will flow full and the discharge will be a function of the difference in elevation between the upstream and downstream pools. The nomograph in Figure 12 may be used to solve design problems directly.

In some instances, with high discharges, the outlet may be barely submerged and a culvert with a sharp edged inlet may still flow part full. The discharge will then be a function of the head on the inlet. For outlets just submerged, determine the head for free outfall and the head for a submerged outlet for corrugated metal only. Use the highest value determined.

DESIGN EXAMPLE FREE OUTFALL

Design a projecting inlet corrugated metal pipe 100 feet long to discharge 85 cfs. with a depth upstream equal to or less than the pipe diameter. Determine the depth

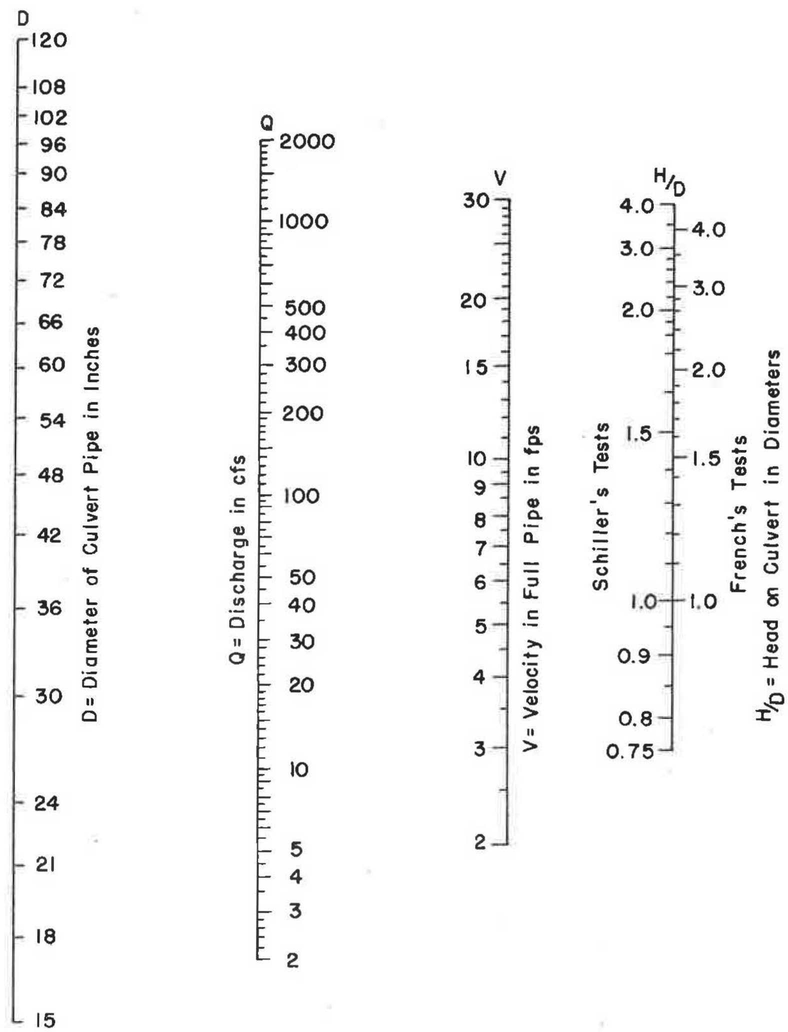

Figure 11. Nomograph for Concrete Pipe Culverts with Free Outlet.

of flow upstream for the pipe selected when the discharge is 195 cfs. An examination of the downstream channel indicates depths of flow of 1.9 feet when Q = 85 cfs. and 2.9 feet when Q = 195 cfs. The average channel slope at the culvert site is 0.7 percent.

Solution: Assume free outfall and place a straight edge so that it intersects Q = 85 cfs. and H/D = 1.0 for projecting inlet in Figure 10; 54-inch pipe is indicated. The outfall is free, since the depth downstream is 1.9 feet when Q = 85 cfs. When Q = 85 cfs. H/D = 1.00 and when Q = 195 cfs. H/D = 2.35. If the pipe is set on a slope of 0.7

percent it is possible it will flow full when discharging the 100-year flood. Applying Bernoulli's theorem when Q = 195 cfs.

$$H/D - \tfrac{1}{2} + \frac{100 \times 0.007}{4.5} = 0.0252\ (1 + 0.9 + \frac{(185)\ (0.025)^2(100)}{4.5^{4/3}})\ (\frac{195}{4.5^{2.5}})^2$$

$$H/D = 2.13$$

Therefore, the pipe is not long enough to flow full with free outfall and the nomograph H/D value of 2.35 should be used. The depth upstream will be 1.00 x 4.5 + 100 x 0.007 = 4.5 + 0.7 = 5.2 + feet approximately above the downstream datum when Q = 85 cfs.

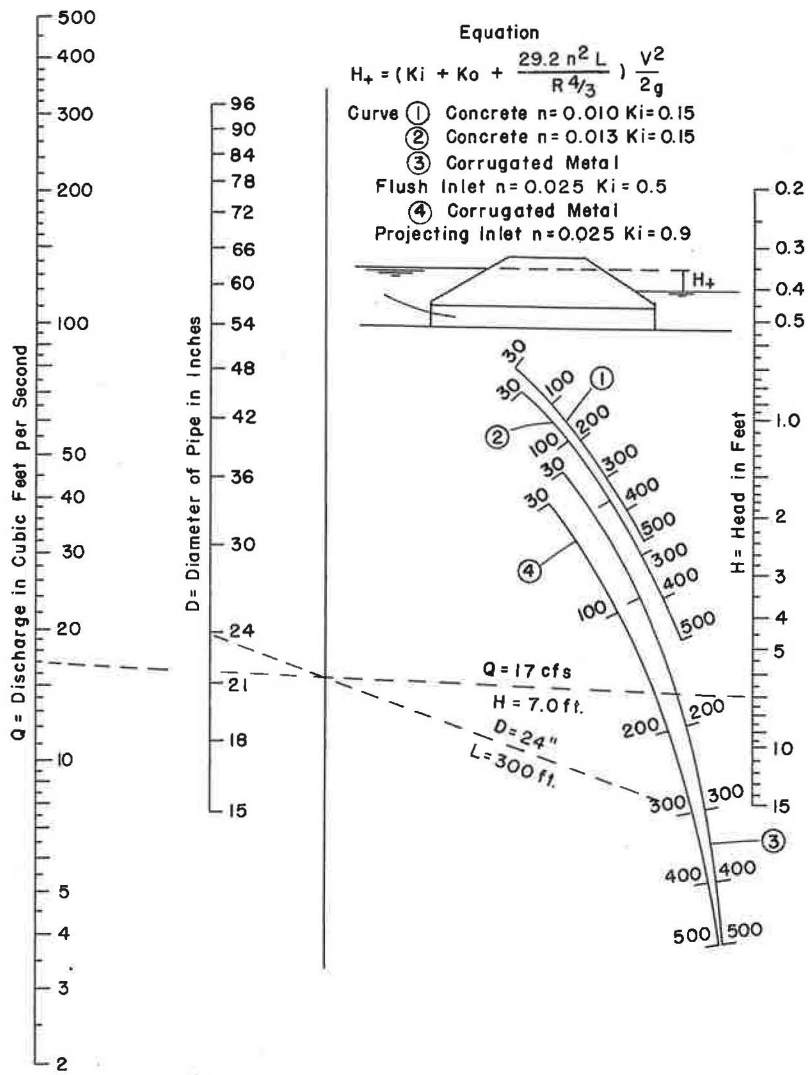

Figure 12. Nomograph for Round Pipe Culverts with Submerged Outlet.

and 2.35 x 4.5 + 100 + 0.007 = 10.6 + 0.7 = 11.3 feet above the downstream datum when Q = 195 cfs. If the depth upstream is excessive, a larger pipe or a multiple installation may be used. When the discharge is 85 cfs., the depth will be somewhat in excess of 5.2 feet above the downstream datum, due to the effect of backwater.

The part full flow factors for critical flow may be determined from Figure 13. When Q = 85 cfs, $Q/D^{5/2} = 85/4.5^{5/2} = 1.99$ and $V_c/V_f = 1.57$, $d_c/D = 0.61$ and $R_c/D = 0.278$. The full velocity from Figure 10 is 5.4 fps. when Q = 85 cfs. The critical depth of flow is 0.61 x 4.5 = 2.7 feet, the critical velocity of flow is 5.4 x 1.57 = 8.47 fps. and the hydraulic radius is 0.278 x 4.5 = 1.25 feet.

The critical slope may be determined by

$$S_c = \frac{n^2 V_c^3}{2.21 R_c^{4/3}}$$

$$S_c = \frac{(0.024)^2 (8.5)^2}{(2.21)(1.25)^{1.33}}$$

$$S_c = \frac{(0.000576)(72.2)}{(2.21)\ (1.346)}$$

$$S_c = 0.014 = 1.4\ \%$$

If the pipe is set on the critical slope the depth upstream will be 1.00 x 4.5 + 100 x 0.014 = 4.5 + 1.4 $\pm$ 5.9 feet above the downstream datum when Q = 85 cfs. and 2.35

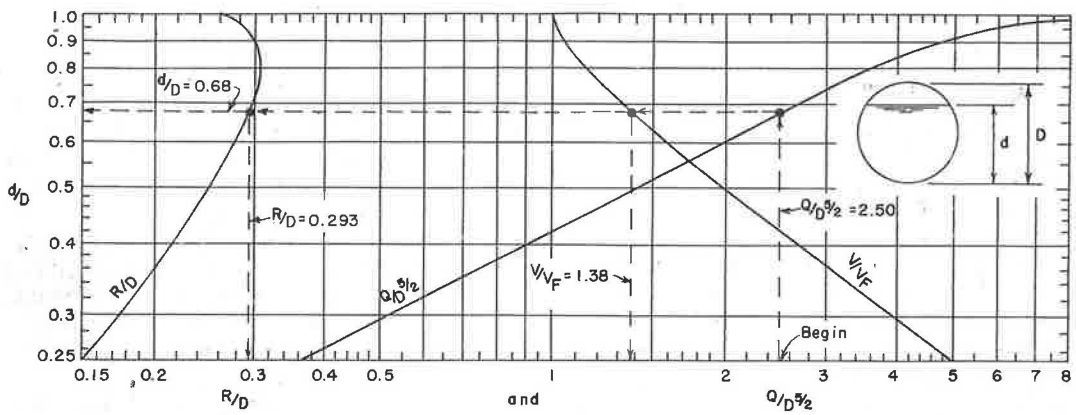

Figure 13. Partly Full Flow Factors for Circular Pipes.

x 4.5 + 100 x 0.014 = 10.6 + 1.4 = 12.0 feet above the downstream datum when Q = 195 cfs.

GLOSSARY

d	Depth of flow in the culvert or channel
d_c	Critical depth of flow
D	Diameter of culvert pipe
g	Acceleration due to gravity
H	Depth above culvert invert of headwater
H+	Effective head for full flow
K_i	Inlet loss coefficient
K_o	Outlet loss coefficient for full flow
L	Length of culvert
n	The Manning roughness coefficient
Q	Discharge
R	Hydraulic radius
R_c	Critical hydraulic radius
S	Slope of culvert
S_c	Critical slope
S_n	Normal Slope
V	Mean velocity of flow
V_c	Critical velocity

References

1. F.T. Mavis "The Hydraulics of Culverts" Bulletin 56, Engineering Experiment

Station, The Pennsylvania State College (1942).

2. Lorenz G. Straub, and Henry M. Morris, Hydraulic Data Comparison of Concrete and Corrugated Metal Culvert Pipes, University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper 3, Series B, July, 1950

3. Lorenz G. Straub, A. G. Anderson, and C. E. Bowers, Importance of Inlet Design on Culvert Capacity, Highway Research Board Research Report 15-B, January, 1953. Tests performed at the St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

Discussion

JOHN L. FRENCH, National Bureau of Standards— Schiller's excellent paper supplies design data on certain types of culvert inlets for which little or no experimental information has heretofore been available.

The author has shown, for his experimental conditions, that the projecting-pipe groove and rounded inlet (radius = 0.15D) would flow full for a relative submergence of $\frac{H}{D} > 1.5$.

However, lest the generality of these conclusions be misleading to the design engineer, certain limitations of the data on which these conclusions are based should be emphasized. In this connection, reservations regarding the ability of the data obtained to adequately support a general conclusion that projecting-groove and rounded inlets will, under all field conditions cause full conduit flow, arise from consideration of two aspects of the experimental set-up. These are (1) the length and slope of the culvert barrels used and (2) the width and other characteristics of the approach channel.

With regard to Item 1, the conclusion that projecting socket and rounded inlets will flow full when submerged is based upon data obtained with barrel slopes of respectively 0.2 percent and zero. In this connection, current and uncompleted experimental work sponsored by the Bureau of Public Roads at the Hydraulic laboratory of the National Bureau of Standards has repeatedly shown that culvert-inlet designs which may permit full conduit flow on flat or mild slopes do not necessarily prevent reversion to part-full or sluice-type flow at slopes near or greater than critical slope. This phenomenon appears to be closely related to the stronger vortex action observed at the higher culvert slopes. The lowering of the pressure line at the culvert entrance owing to increased barrel slope appears to increase the flow of air to the culvert through vortex action, with increased tendency for separation to occur with consequent reversion to part-full or sluice-type flow.

Illustrative of the sometimes substantial effect of barrel slope on the type of flow prevailing in a culvert are the results of recent preliminary tests made by the writer on a square-edge culvert-pipe entrance in a head wall with 45-deg. wing walls. At zero slope full conduit flow occurred for values of H/D above approximately 1.3. At a slope of 0.5 percent sluice-type flow occurred, as might have been expected from the author's results with 30-deg. wing walls with a short culvert on a 0.48 percent slope. The length of culvert used by the writer was 12 diameters.

The strong implication of the above experimental observations is that data obtained with barrel slopes of 0.2 percent and zero should be used with great caution in predicting the type of flow and therefore, the head-discharge relationship for projecting socket and rounded inlets on culverts of higher slopes.

In regard to the question of projecting-grove inlets flowing full when submerged, recent unpublished tests made by the writer with socket grooves of slightly different dimensions than the one used by the author indicated part full or sluice type flow at zero slope for relative submergences in the range $1.5 < \frac{H}{D} < 4.7$. These results were obtained with an approach channel 6 feet wide with a lucite culvert model of barrel diameter 5.5 inches. Substantially the same results were obtained in a relatively narrow approach channel of trapezoidal cross-section with a wide flood plain.

The conflict of these experimental results with those of the author directs attention to the differences in the experimental set-ups. First, the two socket inlets used by the writer had the dimensions 0.050 D (radial) by 0.07 D and 0.083 D by 0.083 D with wall thicknesses of 0.090D and 0.120D, respectively, for the pipe. The differences between these dimensions and the dimensions of the socket used by the author as given in Figure 5 may or may not be sufficiently significant to account for the conflict in experimental results. However this may be, it is to be noted that the channel used in the author's investigation was 34 inches wide and that a stilling baffle was located 3 feet 6 inches upstream from the culvert inlet. Under these circumstances it would be expected that the approach velocity would be relatively high and, owing to the corrugated metal baffle and its nearness to the culvert inlet, that the turbulence level in the approach stream to the inlet would also be relatively high.

In this connection, the current tests at NBS have shown that the regime of flow in a rounded inlet (radius = 0.15D) to a culvert of length 12D on a 4 percent slope is strongly influenced by turbulence in the approach stream. For example, with a submerged entrance ($H/D < 3.8$) and with the inlet and culvert slope referred to, part-full or sluice-type flow occurred in the culvert for an approach channel width of 6 feet (13.1 pipe diameters). The culvert inlet ended flush with a head wall and a crushed stone stilling baffle was located 6.88 feet (15D) upstream of the inlet, and flow conditions in the approach channel above the inlet were relatively smooth and nondisturbed.

The width of the approach channel for a distance 8.5 diameters upstream was then reduced to four diameters, care being taken to reduce flow disturbance at the entrance to the narrow channel by gently rounding the entrance from the wider channel to the constricted channel. A wood slat stilling grid was placed in the channel 3.5 feet upstream from the culvert inlet. Under these conditions the culvert on a 4-percent slope with the rounded inlet in a headwall flowed full when the entrance was appreciably submerged. Significantly, the inlet did not produce full conduit flow when the grid was removed.

These observations strongly imply that the ability of the rounded inlet to produce full conduit flow is substantially influenced by the turbulence level in the approach stream. That this is actually the case was demonstrated by using two other types of turbulence stimulators. The first consisted of simply placing vertically, a 1½-inch-thick wooden slat against each of the vertical side walls of the narrow approach channel, seven culvert diameters upstream from the inlet. With the two wooden slats in place full conduit flow occurred. With the slats removed strong separation at the inlet occurred with consequent part-full or sluice-type flow.

The second type of turbulence stimulator used with the r = 0.15D rounded inlet consisted of cementing a 1.5-mm.-diameter wire around the circumference of the rounded inlet a short distance downstream from the face of the head wall. Although the type of flow in the culvert is extremely sensitive to the location of the wires, careful adjustment of their location caused the 0.15D rounded inlet to flow full on a 6 percent slope with the 13.1D-wide approach channel. With the wires removed part-full flow was again obtained. Further experimental work of this nature has indicated, as would be expected from the above results, that roughening the surface of rounded inlets by cementing sand grains to the surface has a decided effect upon the ability of the inlet (specifically an inlet with radius of rounding of 0.25D) to produce full conduit flow.

The physical phenomena involved here is, of course, separation of the main flow from the inlet boundary surface. The effect of turbulence, both in the upstream approach stream and that generated in the throat of the inlet by such stimulators as trip wires and boundary roughness, suggests similarity to the separation effects found on spheres and cylinders. For such bodies, the location of the point of separation and, consequently, the magnitude of its effect, depends upon the shape and roughness of the boundary, the Reynolds number, and the intensity and scale of upstream turbulence. It is known, in the case of such curved spherical and cylindrical boundaries, that the onset of turbulence in the boundary layer will permit the boundary layer to advance farther against an adverse pressure gradient before separation occurs and, hence, enable the separation point to be located farther downstream with consequent decrease in separation effects.

It has been repeatedly shown that such apparently unimportant circumstances as a slight surface roughness or turbulence in the approach stream have a marked effect upon the onset of turbulence in the boundary layers of such bodies and, hence, upon the location of the separation point, the size of the wake, and upon the drag coefficient. For these reasons, roughening the boundary by means of cemented sand grains, trip wires, or pins has become a common means of decreasing separation effects. That such means would also be effective in decreasing to some degree the effects of separation in culvert inlets of curved boundaries was to be expected.

Lest the analogy between separation effects in curved culvert inlets and those encountered with spheres and cylinders be presumed too close, it may be noted that vortex action appears to play an important role in the culvert inlet phenomenon. In the NBS tests referred to previously, it was observed that gross separation with consequent reversion from full conduit flow to sluice-type flow appears to be initiated in some inlets by the increased air flow to the inlet accompanying stronger vortex action. This phenomena is analogous to the effect of aerating the nappe of a weir; with nonaeration of nappe, the flow remains in contact with the boundary surface; with aeration, the flow springs clear of the surface.

In view of the apparently significant effect of vortex action in wide-approach channe upon the ability of rounded inlets to produce full flow, it is not obvious that the use of a relatively narrow approach channel is justified in modeling such pehnomena.

From the foregoing experimental observations it appears evident that upstream-approach conditions exert a substantial effect upon the ability of certain of the small-scale inlets to cause a short, smooth culvert on a supercritical slope to flow full. Under these conditions, it appears questionable if the data presented by the author for small-scale models at flat or mild slopes with a comparatively narrow approach channel of possibly high turbulence level is adequate to support general conclusions that a projecting socket or rounded inlet will flow full under all field conditions. At full scale with a relatively deep, narrow, approach channel of natural roughness, it would be expected that the author's conclusions would be verified for culverts on flat or mild slopes. With the wider approach channels characteristic of a comparatively shallow stream with a flood plain, it is by no means equally evident from the data presently available that such would be the case for short culverts on either mild or steep slopes or for long culverts on steep slopes.

In this regard, the demonstrated sensitivity of the rounded culvert inlet models to upstream turbulence implies that scale effects will exist between small and large sizes of models. Further, since transition to turbulent flow in the boundary layer of the curved inlet shapes will occur with natural roughness as the Reynolds number increases with increased model size, it would be expected that the larger-scale models would not be as sensitive to separation effects and to the effect of approach stream turbulence on separation in the culvert model as the smaller models tested. Under these circumstances it is possible that an inlet which flows part full at the smaller size will, for the same relative depth of submergence flow full in the larger sizes. However, the relative magnitude of these possible effects of increased model size is a matter for experimental verification and is now indeterminate.

The author has followed the example of previous investigators of culvert hydraulics in that he has used a comparatively narrow approach channel. The writer's experimental work has indicated considerable more difficulty in obtaining full conduit flow with small models in a relatively wide approach channel than that experienced by the author, as well as by previous investigators with relatively narrow approach channels The purpose of the writer's comments has been to encourage a cautious approach to these problems by the design engineer until the problems involved can be throughly explored.

R. E. SCHILLER, JR., Closure--The author appreciates the interest shown by French. At the same time the author would like to point out that French discussed only the inlet tests which were at variance with his tests. French did not point out that his test results were practically the same as the author's for: (1) square edge flush inlets with flared wingwalls, with straight wingwalls, and with parallel wingwalls;(2) thin walled projecting inlet; (3) mitered sharp-edged inlet ($1\frac{1}{2}$ to 1 slope).

Subsequent tests have been carried out by the author with the groove inlet culvert slopes set at 1.5 percent and 3 percent. In these tests the culvert model flowed full when an H/D of about 1.5 was attained and continued to flow full up to an H/D of 3.7. Therefore, for the width of channel tested, the conclusion that the groove inlet will flow full when H/D >1.5 appears to be valid, at least up to slopes of 3.0 percent for the length of model tested.

Since French's tests do bring out the importance of width of channel on possible full flow, his test results for a socket or groove inlet have been added to Figure 11. Until full scale tests have been run, it is suggested that the designer use French's side of the H/D line if the culvert is situated in a wide flood plain. It is also suggested that the rules for application of Bernoullis theorem to flow through corrugated metal pipe be used for concrete pipe whenever French's side of the H/D line in Figure 11 is used.

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