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Culvert-Flow Characteristics

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Bulletin 126

Culvert-Flow Characteristics

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Foreword

This bulletin presents two papers on flow characteristics of culverts. The first, by Carstens and Holt, was recommended for publication by the Committee on Surface Drainage of Highways, because it illustrates, by a series of photographs, most of the typical water-surface profiles which can occur in a culvert. This paper should be especially useful to university instructors and others who are endeavoring to get across to students in college or to engineers taking an in-service-training course in highway hydraulics just what happens as water flows into and through a culvert. However, attention is called to the fact that the model culvert used is the same width as the flume, so there is no contraction of the flow horizontally. At the committee's suggestion, the authors added Figure 6, which shows how the water surface is disturbed by standing waves initiated by a horizontal contraction. Except for the increased inlet pool elevation and this waviness, the profiles in Figures 1 to 5 are still good representations of the essential forms which are more clearly depicted in this manner.

The second paper by Schiller, reports on tests which he performed on model culverts with a number of standard inlet conditions and includes design charts. Subsequent to his work the Bureau of Public Roads began a comprehensive program of testing a wide variety of culvert entrances at the Hydraulic Laboratory of the National Bureau of Standards. Attention is invited to the discussion of Schiller's paper by French, who is in charge of the tests at the National Bureau of Standards.

Contents

Demonstration of Possible Flow Conditions in a Culvert

M. R. CARSTENS, Associate Professor, Georgia Institute of Technology and
A. R. HOLT, Lt. U. S. Army
Corps of Engineers, Fort Belvoir, Virginia

● THE majority of possible flow profiles within a highway culvert were produced in a two-dimensional laboratory channel. The flow profiles were photographed; classified by the position of the control section; and analyzed in detail. From this qualitative study, the effects of entrance streamlining, barrel length and roughness, and outlet submergence are readily visualized.

NOMENCLATURE

The following nomenclature is used:

y	-	depth of flow
y_o	-	uniform flow depth or normal depth,
y_c	-	critical depth
D	-	height of the rectangular culvert section,
A	-	adverse slope ($S_o < 0$) ,
H	-	horizontal slope ($S_o = 0$ with $y_o \rightarrow \infty$),
M	-	mild slope ($S_o > 0$ and $y_o > y_c$),
S	-	steep slope ($S_o > 0$ and $y_o < y_c$),
S_c	-	Critical slope ($S_o > 0$ and $y_o = y_c$), and
S_o	-	bottom slope

APPARATUS

In order to obtain a photographic record of many of the flow profiles in a highway culvert, a two-dimensional model was constructed with sidewalls of clear plastic. With rear lighting through the transparent culvert barrel, the water surface was readily photographed. The culvert barrel was rectangular in cross-section, 0.167 foot wide by 0.300 foot high by 3.00 feet long. The culvert slope and the discharge through the culvert were adjustable. Slide gates could be inserted either upstream downstream from the culvert barrel. A removable insert was used to alter the inlet from an unstreamlined inlet to a streamlined inlet. With this experimental arrangement, a large number of geometric and flow variations could be qualitatively observed.

SCOPE

The outlet conditions were varied from that of a free outlet to that of a completely submerged outlet. This control was by means of a downstream slide gate and a perpendicular drop in the channel bottom at the barrel outlet section.

The value of the critical depth y_c in relation to the culvert height D is a primary variable in the analysis of flow conditions through a highway culvert. The value of D was fixed but the value of y_c was varied by discharge adjustment. In Figures 1 through 5, the black line parallel to the culvert is placed on the value of y_c.

The length, roughness, and slope of the barrel are interdependent (except for short culverts in which the length-height ratio is less than about three) in the effect upon the form of the free surface profile. The validity of this statement is apparent by consider-ing the similarity of form of the standard backwater curves,[1] that is, of the A2, H2, and M2 and of the A3, H3, and M3. A major difference between these A, H, and M

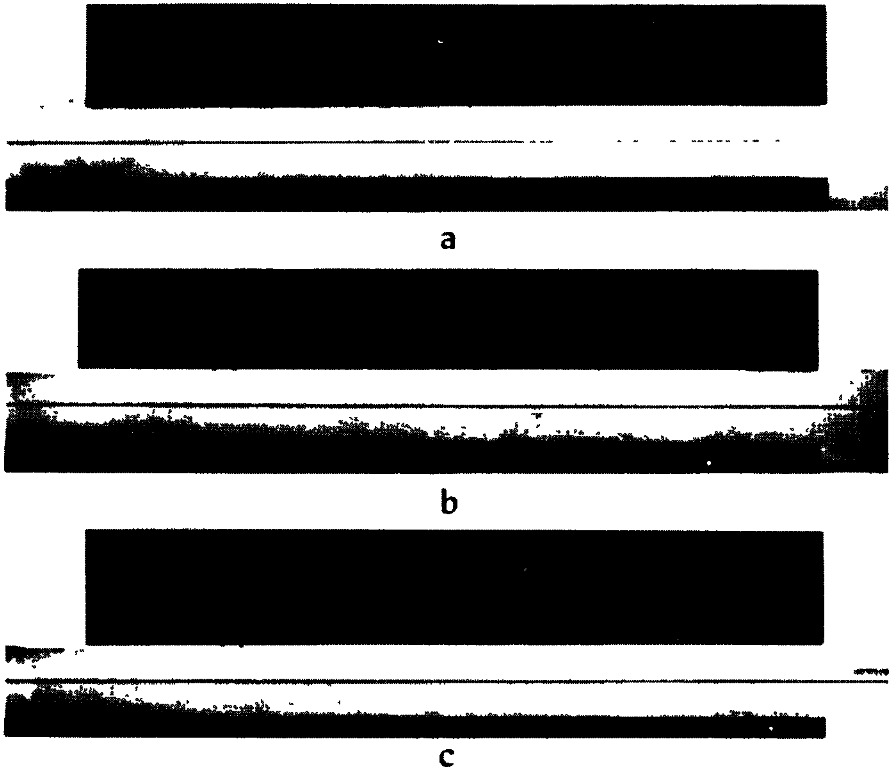


Figure 1. Downstream control.

TABLE 1

DOWN STREAM CONTROL

Item	Figure Number 1a	1b	1c
Inlet		Sharp or Rounded	
S_o	Immaterial	A, H or M	
y_c	No Meaning	$y_c < D$	
y_o	No Meaning		
Surface Profile Shown	Enclosed Flow	M1	A2, H2, or M2
Factors Determining Headwater Elevation	Calculated in the same manner as any enclosed-flow conduit between two reservoirs.	Downstream Depth, Outlet Energy Losses Slope, Relative Roughness, and Geometry of Barrel Entrance Energy Losses Entrance Geometry	
Remarks	The effect of inlet streamlining is limited to the entrance losses and does not influence the essential characteristics of the flow.		

[1] Posey, C. J., Engineering Hydraulics, edited by Hunter Rouse, John Wiley and Sons 1950 Chap. IX, p. 611.

profiles is in the length of channel required to obtain a given depth change. The profiles on the adverse slope are much shorter than on a mild slope. Hence, for purposes of illustration, the depth changes have been exaggerated with adverse slopes in Figures

TABLE 2

OUTLET CONTROL

Item	Figure Number	
	2a	2b and 2c
Inlet	Sharp or Rounded	
S_o	A, H, or M	
y_c	$y_c < D$	
y_o		
Surface Profile Shown	A2, H2, or M2	Upstream portion enclosed; downstream portion -A2, H2, or M2
Factors Determining Headwater Elevation	Elevation of Outlet Slope, Relative Roughness, and Geometry of the barrel Entrance Energy Losses Entrance Geometry	
Remarks		Figures 2b and 2c are identical except for the degree of inlet streamlining. The difference in the two flow conditions is restricted only to the energy losses at the inlet.

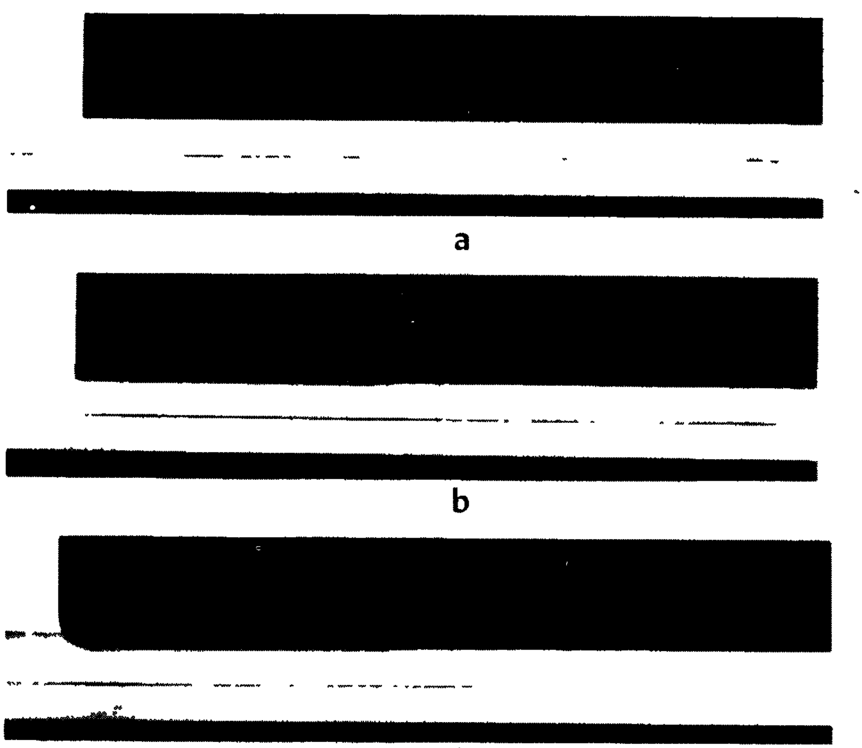


Figure 2. Outlet control.

1c 2a, 2b, 2c, 4c, 4e, 4f, 5c, and 5d. There are no similar profiles to the M1, S1, S2, and S3 profile which can be obtained by slope adjustment. However, the length of channel required to obtain a given depth change can be adjusted by roughness variation. As the channel roughness is increased, the length of the surface profile is decreased. In Figure 5d added roughness was used. Thus the geometric length of the culvert was fixed at a value of 10D but the effective length of the culvert was greater in the cases mentioned.

Only the extreme limits of the inlet geometry have been illustrated. The sides and bottom of the inlet were suppressed. One limit was obtained by the use of a sharp (right-angle) junction between the barrel roof and the headwall. With the sharp inlet, the contracted jet would be the same as the jet from under a sluice gate with a coefficient of contraction of approximately 0.6. Since this contraction occurs solely on the upper surface and since the surface waves are a minimum with supressed sides, this inlet condition represents an extreme limit of surface contraction. The limit of no jet contraction was obtained with a well-rounded junction between the barrel roof and the headwall. These two extremes of inlet geometry are shown in Figures 3 and 4.

The control would be upstream from the culvert only in case the flow were supercritical approaching the culvert. This condition was obtained by means of an adjustable sluice gate upstream from the inlet as shown in Figure 5.

TABLE 3

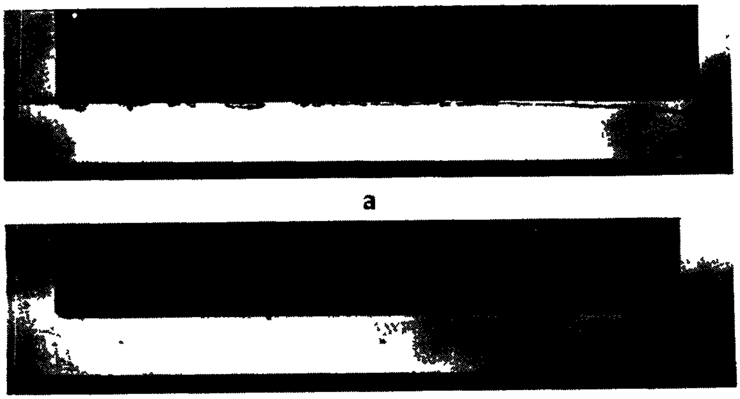
TUBE CONTROL

Item	Figure Number	
	3a	3b
Inlet	Rounded	Sharp or Rounded
S_o	S	Immaterial
y_c		$y_c \geq D$
y_o	$y_o \leq D$	No Meaning but limit is $y_o > D$
Surface Profile Shown	Uniform Flow in Barrel	Enclosed Flow
Factors Determining Headwater Elevation	Slope, Relative Roughness, and Geometry of the barrel. Entrance Energy Loss. Entrance Geometry	Calculated in the same manner as any enclosed-flow conduit discharging into the atmosphere
Remarks	On a steep slope with a rounded inlet, the profile sequence with increasing discharge is as follows: [a] (a) Figure 4g; (b) Figure 3a; (c) an unsteady flow pattern in which "slugs" of air are periodically transported; (d) Figure 3b (when the headwater elevation is in excess of 1.5D).	If the inlet is rounded and $y_o \geq D$, barrel will flow full. However, if the inlet is sharp, the control may shift to inlet control (Figure 4).

[a]Straub, Lorenz G., Anderson, Alvin G., and Bowers, Charles E., "Importance of Inlet Design on Culvert Capacity", St. Anthony Falls Hydraulic Laboratory Technic Paper, No. 13, Series B, 1953.

ANALYSIS

The analysis of the possible conditions within a culvert is presented on the following figures and the tables associated with each figure. The flow conditions are first classified as to control section. The control section is defined as the section from which calculations must be started in order to calculate headwater elevation if the discharge and the geometric characteristics are known. In each figure are shown the profiles for a



a

b

Figure 3. Tube control.

single control. Following each figure is a table in which the details of the various profiles are presented. The information in the tables is general. The entries pertaining to "y_c," "y_o," and "remarks" are qualifications to the other entries in a column. Thus the entry, $y_o < y_c$, would not appear in the column since this information is given by the slope designation. Thus, all entries in a column are complementary.

DISCUSSION

In each of the preceding tables the factors which must be considered in order to determine the headwater elevation were tabulated. These factors are identical to the factors which must be considered in any enclosed conduit or open channel flow problem. However, in the case of culverts, the length of the uniform flow zone (or the gradually varied flow zone) will generally be of the same order of magnitude as the length of the nonuniform flow zone (or rapidly varying flow zone). As a consequence, greater attention must be given to the nonuniform flow zones in a culvert. Some of the uncertainties associated with these nonuniform flow zones are now discussed.

Consider first the submerged inlet which is a control section (Figures 4a, 4b, and 4c). These photographs illustrate a two-dimensional sluice-gate type of inlet for which a satisfactory analysis is available. However, the usual culvert inlet would involve a side contraction of the jet as shown in Figure 6a. The readily visualized uncertainties of the pressure and velocity distribution in the contracted jet section preclude an elementary analysis. Experimental laboratory determination of the coefficient of discharge for a systematic range of inlet geometries is the most feasible method of determining the characteristics of inlet controls. On the other hand, if the problem is that of design then it is more logical to eliminate inlet control and to obtain full flow within the culvert barrel by proper inlet design.

Figure 6 has been included in order to provide a comparison between the two-dimensional flow patterns of Figures 1-5, inclusive, and the three-dimensional flow patterns. The three-dimensional pattern shown is a half-section of a square box culvert with a perpendicular square-edged headwall. The rectangular approach channel is two and one-half times the width of the culvert barrel. Since the bottom was horizontal, similar surface configurations would occur on mild, horizontal, or adverse slopes; providing, of course, that the tailwater was low enough to prevent downstream control

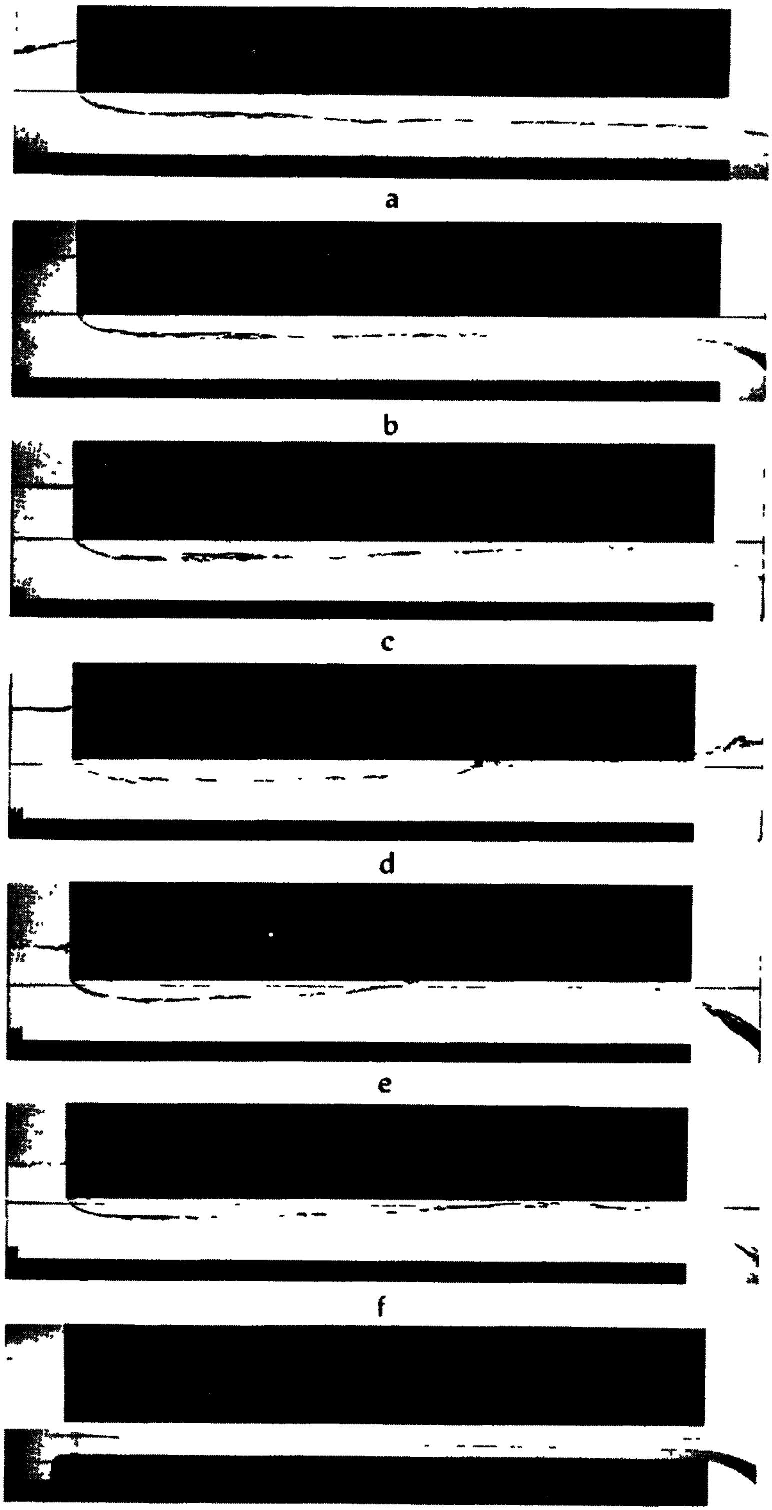


Figure 4. Inlet control.

TABLE 4

INLET CONTROL

Item	Figure Number						
	4a	4b	4c	4d	4e	4f	4g
Inlet	Sharp						Sharp or Rounded
S_o	S		A, H, or M				S
y_c	$y_c > 0.6D$				$D > y_c > 0.6D$		$y_c < D$
y_o	$y_o < 0.6D$	$y_o > 0.6D$					
Surface Profile	S2	S3	A3, H3 or M3	A3, H3, or M3; Hydraulic Jump	A3, H3, or M3; Surface Wave		S2
Factors Determining Headwater Elev.	Entrance Geometry						
Remarks			If the flow profiles shown are steady, there must be adequate admission of air. This air may be admitted over the free surface as in Figures 4c and 4f. Air may also be admitted through an opening between the headwall and culvert barrel as in Figures 4d and 4e. Air might also be admitted in sufficient quantity with conditions favorable to violent vortex formation. In addition, the pressure must be negative at the barrel roof following the inlet if the barrel flowed full.				This condition can arise either by side contraction, bottom contraction, or by change of slope at the inlet.

(Figure 1) and that the culvert was short enough (or smooth enough) to prevent outlet control (Figure 2). Figure 6a is directly comparable with Figure 4c. All of the entries in Table 4 pertaining to Figure 4c apply equally to Figure 6a. The outstanding difference in the two patterns is the pronounced wave action in the three-dimensional case. These waves originate at the junction of the headwall and culvert barrel. Perhaps the most-significant difference in the two patterns is absence of a two-dimensional counterpart to Figure 6b. From Figure 6b it is apparent that the culvert inlet is a control section even before the inlet is submerged; whereas in the two-dimensional case the control will remain at the outlet (Figure 2a) until the inlet is submerged. Consequently the flow pattern illustrated by Figure 6a is a natural consequence of a rising hydrograph in the three-dimensional flow. Conversely, the flow pattern illustrated by Figures 2a, 2b, or 3b is a natural consequence of a rising hydrograph in the two-dimensional flow and even though the pattern of Figure 4c is stable the barrel must initially be vented to obtain this pattern.

The significance of the geometry of the inlet can be illustrated by comparing unstreamlined and streamlined inlets. First by proper streamlining, the energy inlet loss is reduced. Since the inlet energy loss is generally a small portion of the total energy loss, the advantage of entrance streamlining for this purpose alone is likely to be insignificant. The only difference between Figure 2b and Figure 2c is that of inlet streamlining. The difference in headwater elevation is not discernable from the photographs, indicating that the inlet streamlining was of dubious value in this case. The second effect of inlet streamlining is that of eliminating the contracted jet downstream from the inlet. The only difference between Figure 3a and Figure 4b is that of inlet streamlining. The greatly reduced headwater elevation of Figure 3a in contrast to that of Figure 4b indicates a decided superiority of the streamlined inlet in this case. The energy inlet losses are negligible and the streamlined inlet advantage

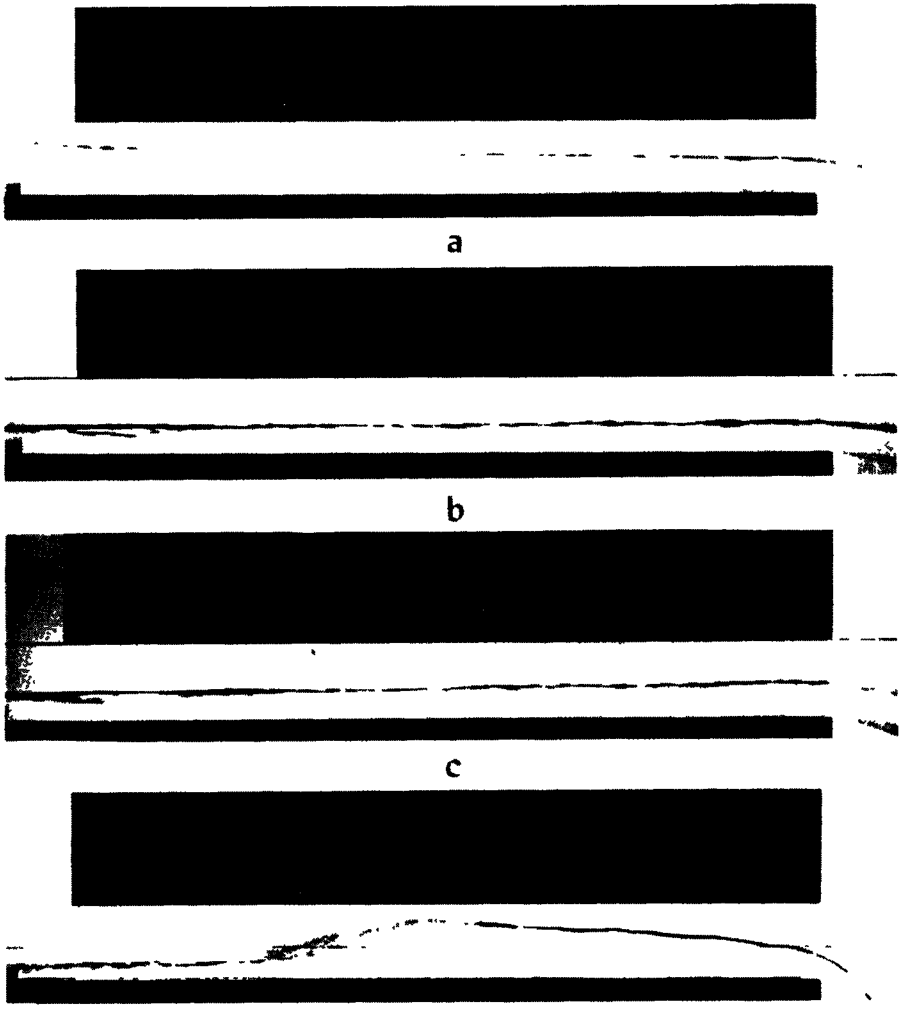


Figure 5. Upstream control.

is attributable solely to the elimination of the jet contraction. Shoemaker and Clayton have experimented with inlets composed of geometrically plane surfaces which also eliminate the jet contraction.

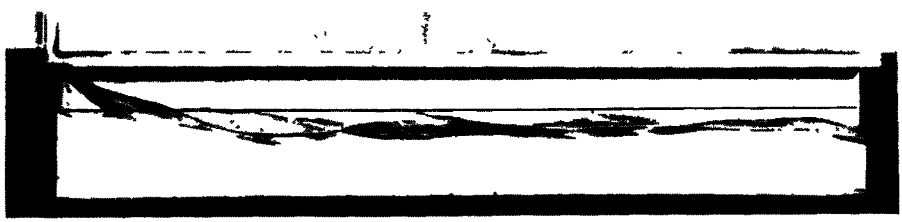
Even in the case of full flow within the culvert barrel uncertainties exist as to the average energy content of the water at the unsubmerged outlet (Figure 3b). The outlet section is definitely a nonuniform flow zone with nonhydrostatic pressure distribution and nonuniform velocity distribution. The computations for headwater elevation are based upon an energy analysis. Consequently, the error in estimating the average energy content at the outlet will result in the same error in the computed headwater elevation. The usual assumption, that the piezometric headline intersects the mid-

[2] Shoemaker, Roy H., and Clayton, Leslie A., "Model Studies of Tapered Inlets for Box Culverts," Culvert Hydraulics, Highway Research Board, Research Report 15-B 1953.

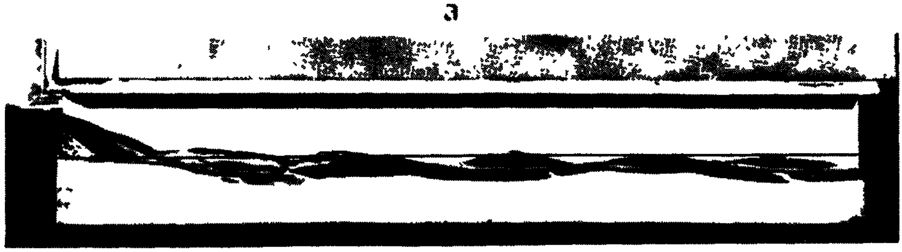
TABLE 5

UPSTREAM CONTROL

Item	Figure Number			
	5a	5b	5c	5d
Inlet		Sharp or Rounded		
S_o	S		A, H, or M	
y_c		$y_c > y$		$y_c < 0.7D$
y_o	$y_o < y$ at inlet	$y_o > y$ at inlet		
Surface Profile Shown	S2	S3	A3, H3 or M3	A3, H3, or M3; Hydraulic Jump; A2, H2, or M2.
Factors Determining Headwater Elevation	Relative Roughness, Slope, Distance from the Upstream Control, and Upstream Channel Geometry.			
Remarks	None of these profiles is likely to occur in a highway culvert at design discharges. The side contraction at the culvert inlet would likely cause the culvert to be a control section. In this event the profile would be one of those shown on Figures 1, 2, 3, or 4.			



a



b

Figure 6

height of the culvert outlet may lead to an appreciable error in headwater computations for a short culvert of considerable height. A series of unpublished masters degree theses of the State University of Iowa (Waldo E. Smith, 1924; H. D. Brockman, 1926, Fred B. Smith, 1927; J.C. Ducommun, 1928; Raymond N. Weldy, 1929; Nolan Page, 1931 and Rueda-Briceno, 1954) indicated that the average energy content at the outlet is essentially a function of the Froude number. These results indicate that the average energy content is greater than that determined from the midheight rule for values of the Froude number less than 3.4 and conversely the average energy content is less for values of the Froude number greater than 3.4.

Another zone of nonuniform flow to which special attention must be given in the analysis of flow through culverts is the unsubmerged outlet control section (Figure 2). Two depth characteristics are apparent from the photographs. First, the outlet depth is less than the computed critical depth y_c which is shown by the black line on the photographs. Second, the position at which the depth of flow y is equal to the computed critical depth y_c is an appreciable distance upstream from the outlet. Again the pressure and velocity distributions are unknown at the outlet with the result that the average energy content is uncertain. However, the pressure distribution will be nearly hydrostatic a short distance upstream from the outlet. Thus the average energy content of the water could be closely approximated for the point at which the depth is equal to the critical depth. Hence this point is a logical starting point for the headwater computations in a culvert with outlet control.

SUMMARY

The majority of possible flow profiles within a highway culvert have been presented by photographs. Tabular information was presented delineating the conditions for which a given profile could exist. Finally, some of the uncertainties pertaining to the nonuniform flow zones within a culvert were discussed.

Tests on Circular-Pipe-Culvert Inlets

R. E. SCHILLER, Jr., Assistant Professor
Texas A & M College

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 (1½ 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 1½ 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

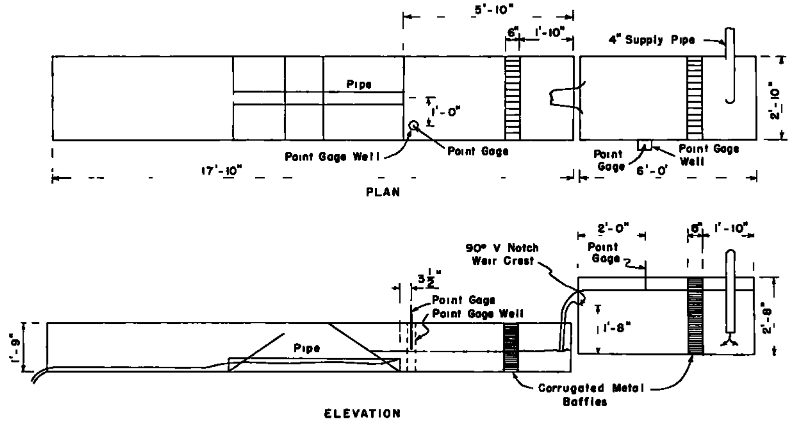


Figure 1. Details of Model and Weir Flumes.

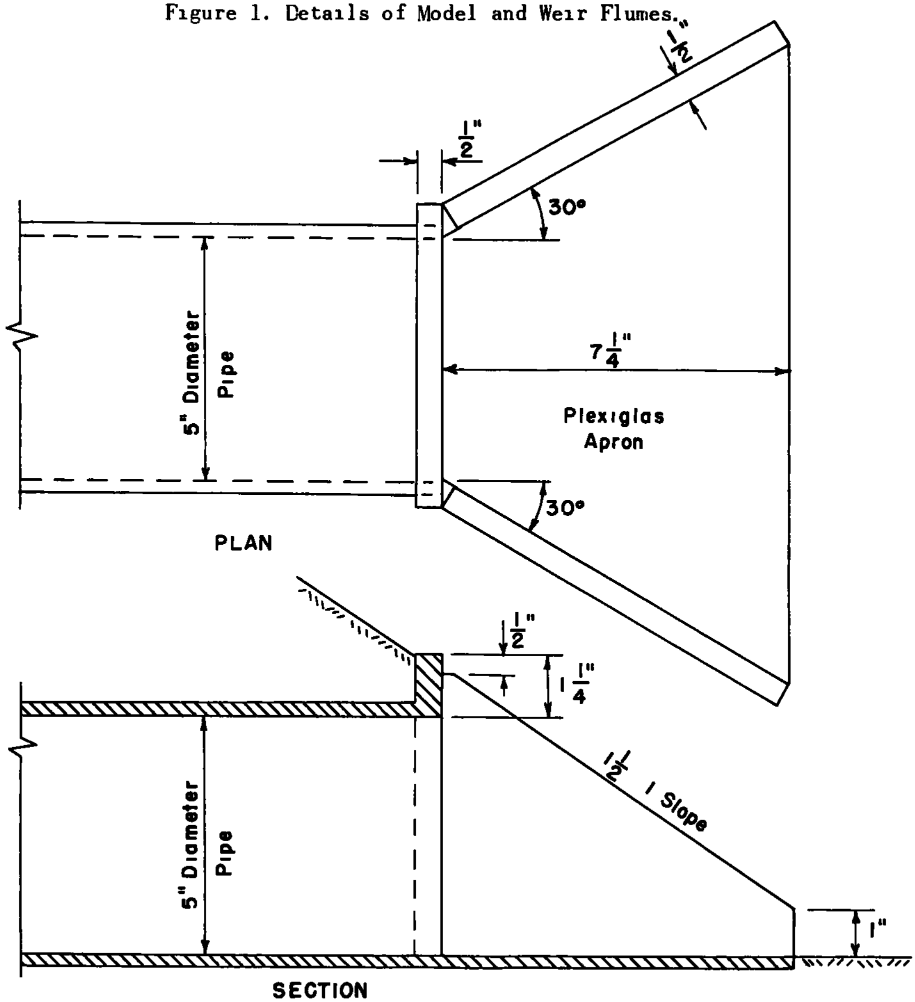


Figure 2. Details of Flared Wingwall Inlet to Square Edged Pipe.

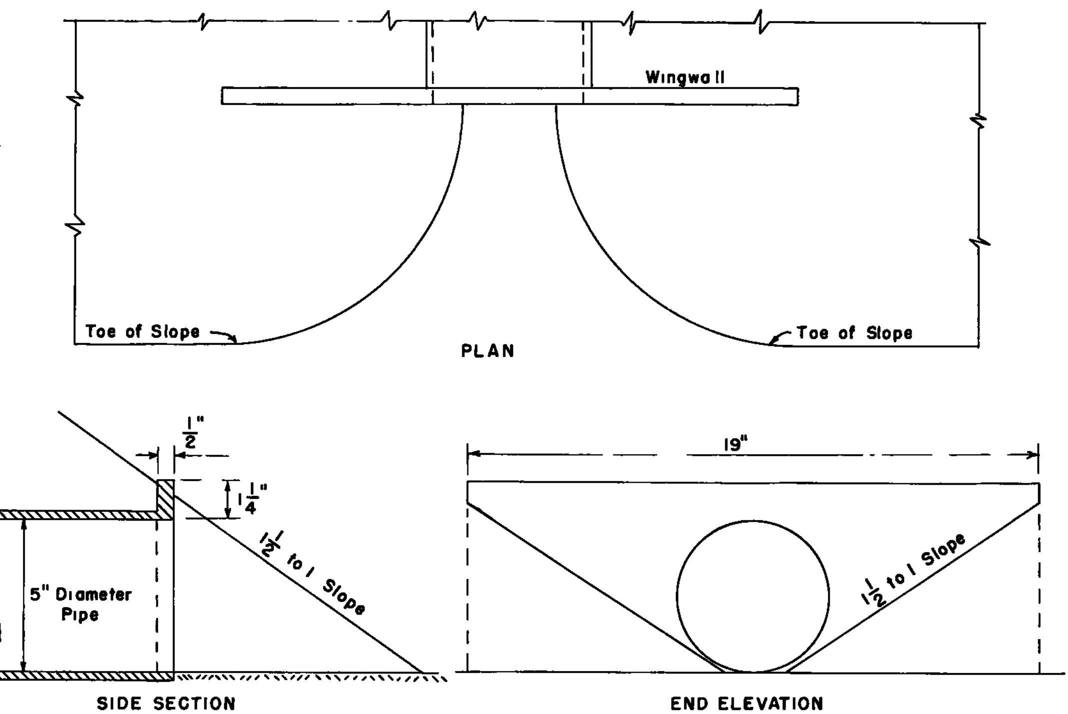


Figure 3. Details of Straight Wingwall Inlet to Square Edged Pipe.

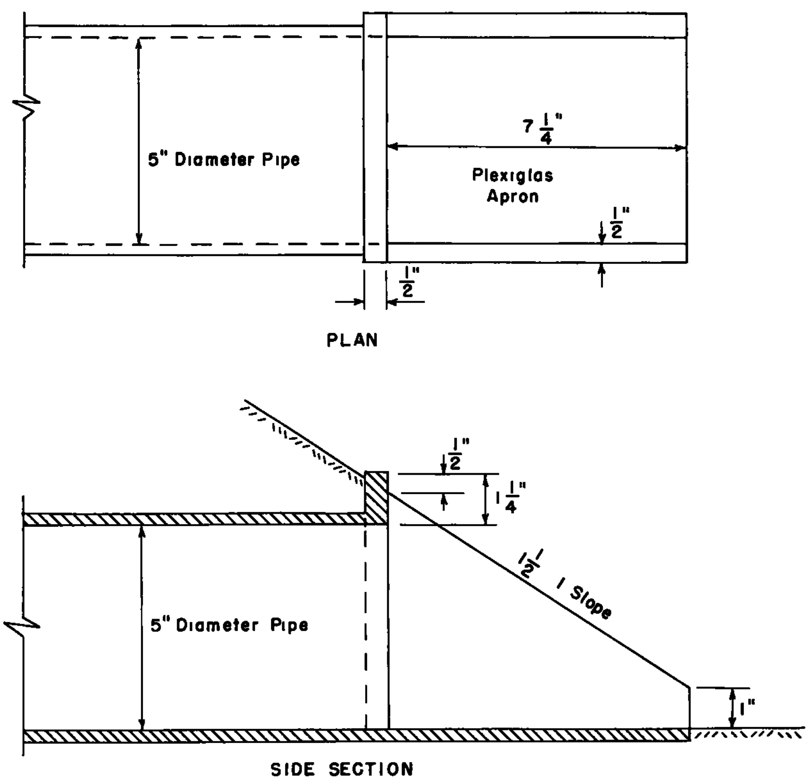


Figure 4. Details of Parallel Wingwall Inlet to Square Edged Pipe.

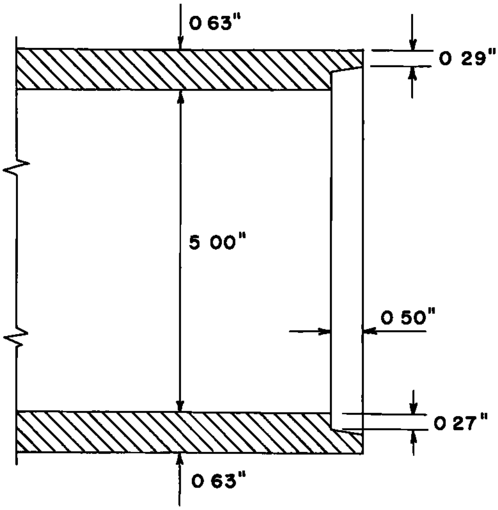


Figure 5. Details of Groove Inlet.

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 valu of H/D of 1.2 and 1.5, the flow conditions were variable for the groove and rounded inlets and the flow was not stabilized until a H/D of about 1.5 was reached.

3. The sharp-edged projecting inlet and the mitered sharp-edged inlet are not as efficient as the square-edged flush inlet.

DESIGN NOMOGRAPHS

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

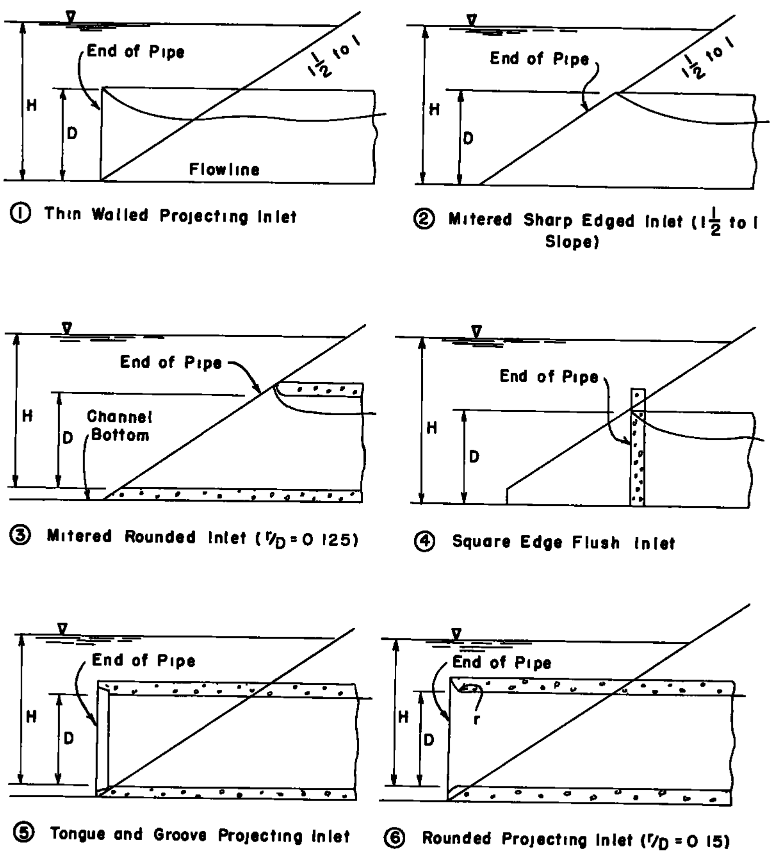


Figure 6. Inlet Details. Side Elevations.

pipe sizes, wherlever 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.

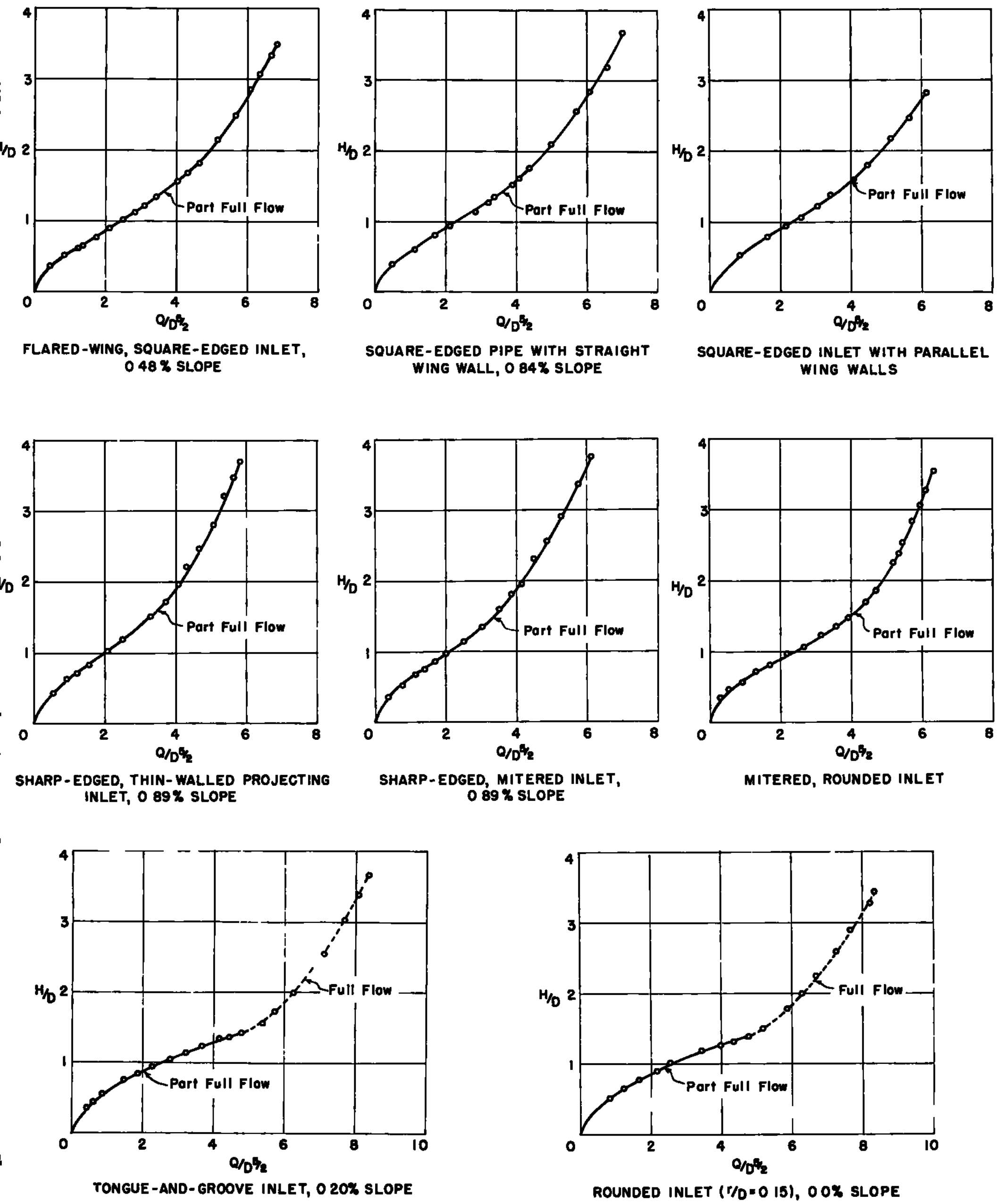


Figure 7. Comparison of Head Discharge Curves.

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

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

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 ≥ 1.5

The above rules do not apply unless H/D ≥ 1.2.

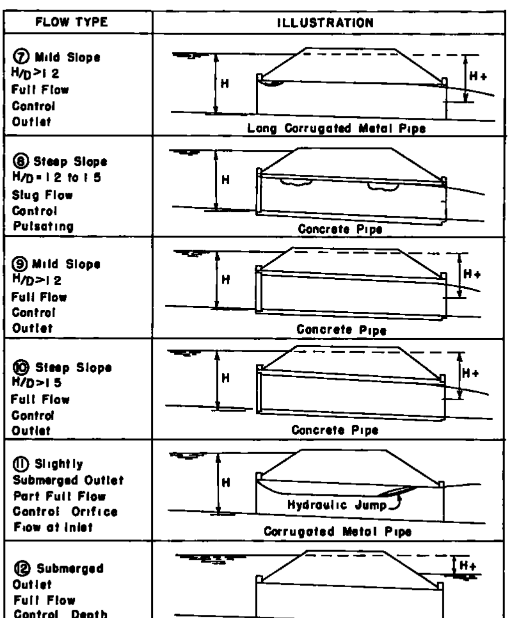


Figure 9. Typical Flow Conditions - Full Flow in Pipes.

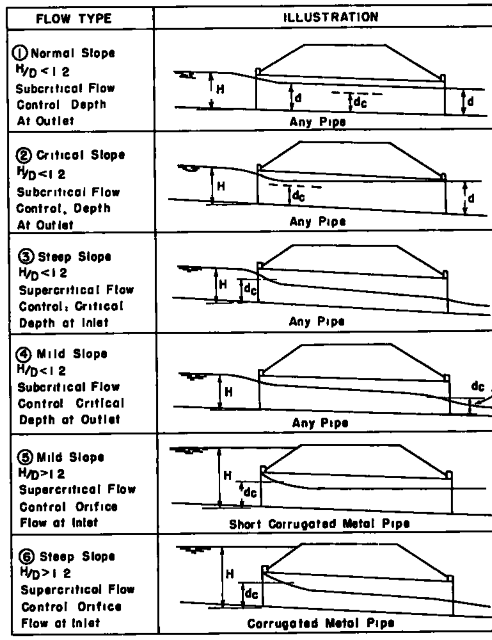


Figure 8. Typical Flow Conditions - Part Full Flow in Pipes.

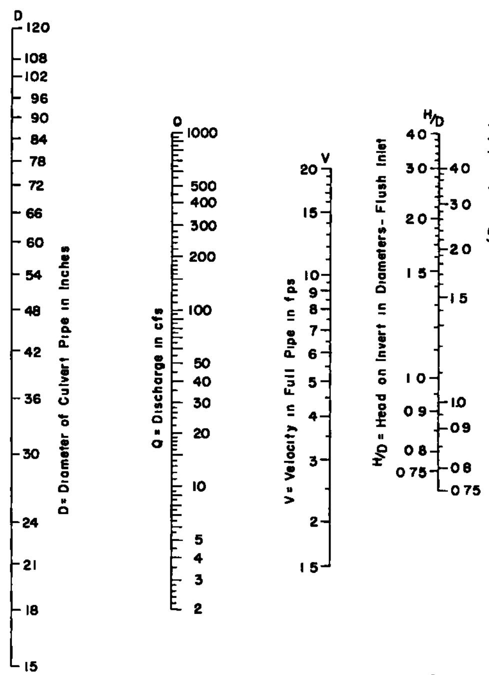


Figure 10. Nomograph for Corrugated Metal Pipe Culverts with Free Outfall.

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

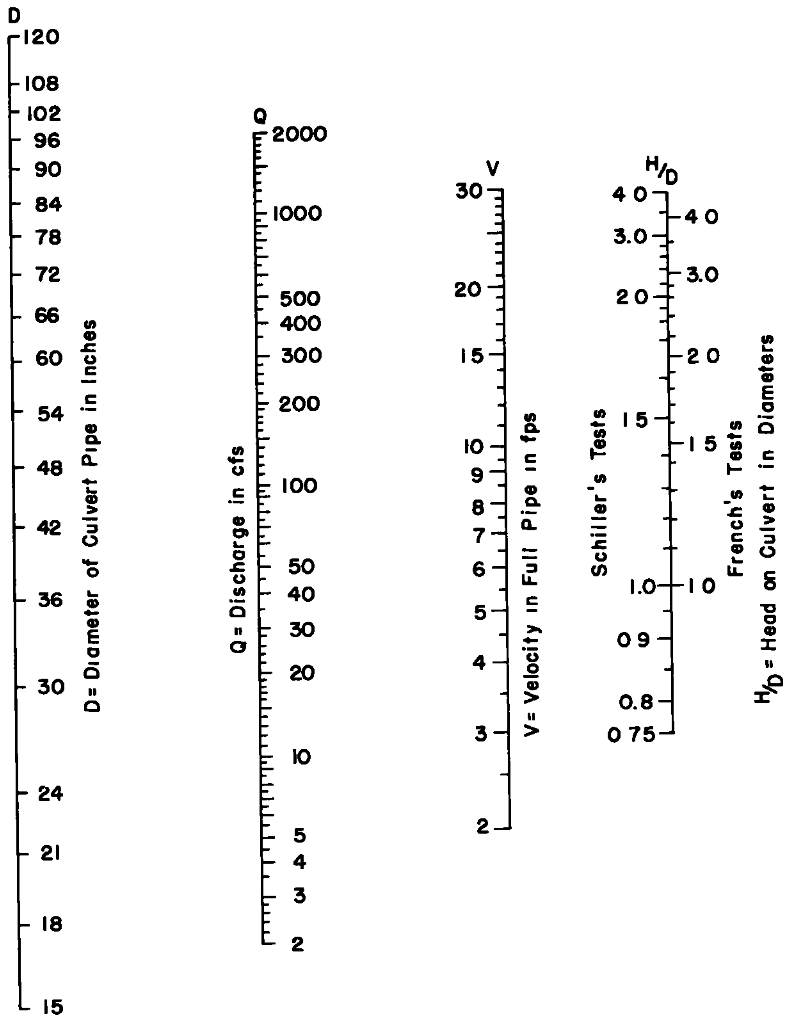


Figure 11. Nomograph for Concrete Pipe Culverts with Free Outlet.

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 nomogra H/D value of 2.35 should be used. The depth upstream will be 1.00 x 4.5 + 100 x 0.0 4.5 + 0.7 = 5.2 + feet approximately above the downstream datum when Q = 85 cfs.

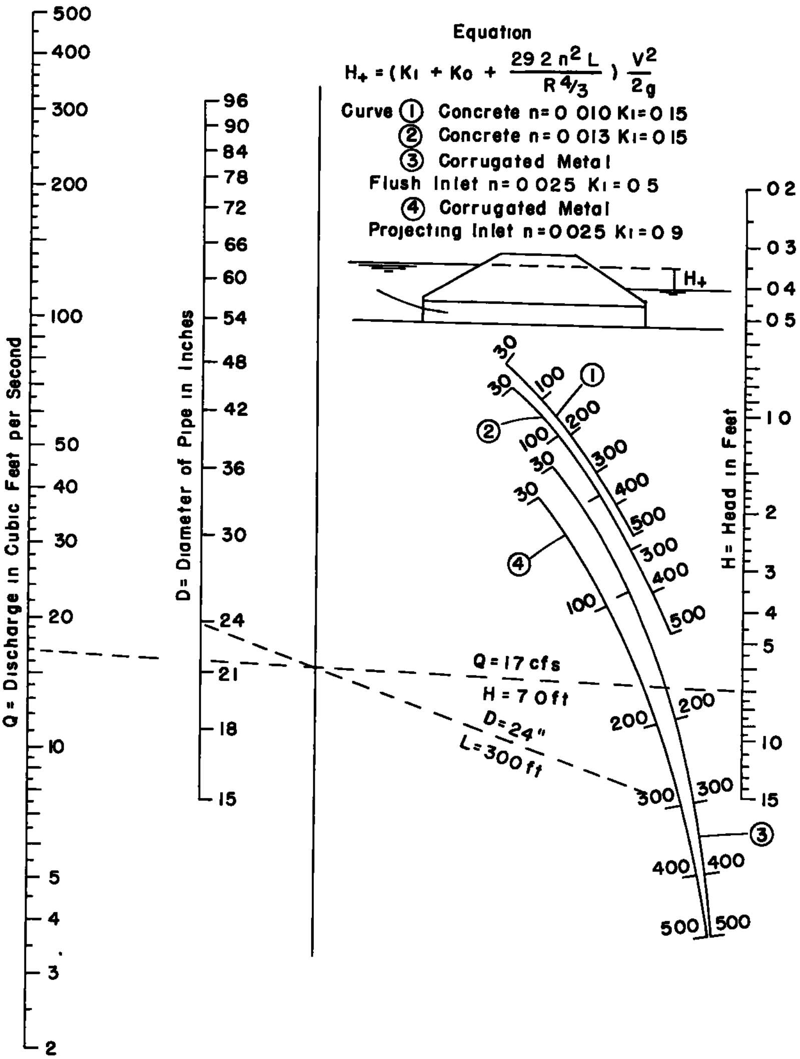


Figure 12. Nomograph for Round Pipe Culverts with Submerged Outlet.

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 $R_c/D = 0.2$ 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 ± 5.9 feet above the downstream datum when Q = 85 cfs. and 2.35

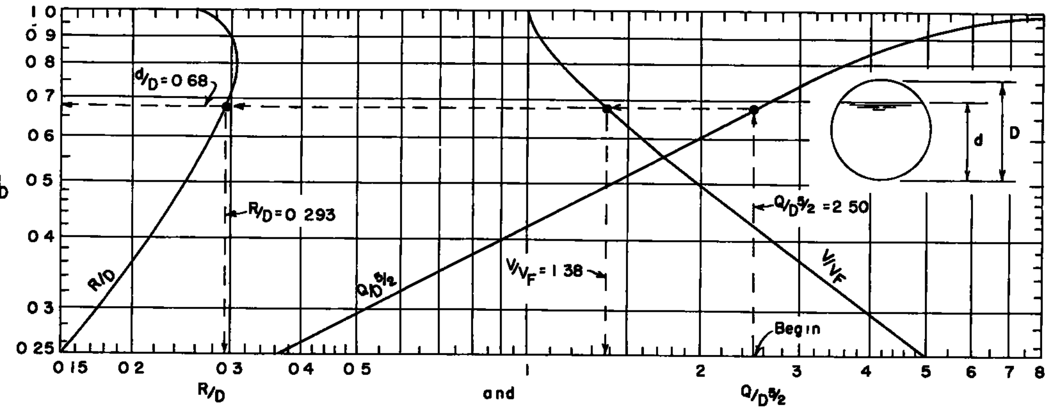


Figure 13. Partly Full Flow Factors for Circular Pipes.

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_1 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 Fall 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 suppli 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 obtain 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 tw 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 wil flow full when submerged is based upon data obtained with barrel slopes of respective 0.2 percent and zero. In this connection, current and uncompleted experimental worl 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 owin 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. A 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 obtaine 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 wer 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 attentic 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 coefficien 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 initiatec 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 chann upon the ability of rounded inlets to produce full flow, it is not obvious that the use of 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 fo 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 model 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 hydraulic 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 channel 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 (1½ 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.

Some Highway Research Board Publications Relating to Culverts and Drainage

RESEARCH REPORT 6-B: SURFACE DRAINAGE OF HIGHWAYS (1948) 29 pp. $.4
Progress Report of Committee on Surface Drainage of Highways; Description of Apparatus and Procedure for Testing Flow in Gutters and Storm Drain Inlets; Theory of Flow through Short Tubes with Smooth and Corrugated Surfaces and with Square-Edged Entrances; Experiments on Flow through Inlet Gratings for Street Gutters.

RESEARCH REPORT 11-B: SURFACE DRAINAGE (1950) 54 pp. $.90
Progress Report of Committee on Surface Drainage; Regional Flood Frequency; Surface Runoff from Agricultural Watersheds; Tentative Results on Capacity of Curb Opening Inlets.

RESEARCH REPORT 15-B: CULVERT HYDRAULICS (1953) 71 pp. $1.05
Model Studies of Tapered Inlets for Box Culverts; Importance of Inlet Design on Culvert Capacity.

BULLETIN 45: SUBSURFACE DRAINAGE (1951) 20 pp. $.45
This is a tabulation of replies to a questionaire prepared by the Committee on Subsurface Drainage.

BULLETIN 90: VERTICAL SAND DRAINS (1954) 37 pp. $.60
Checking up on Vertical Sand Drains; Hawaii's Experience with Vertical Sand Drains.

BULLETIN 102: TESTS ON LARGE CULVERT PIPE (1955) 18 pp. $.45
Tests on Large-Diameter Reinforced-Concrete Pipe; Deflections of Timber-Strutted Corrugated-Metal-Pipe Culverts Under Earth Fills.

BULLETIN 115: VERTICAL SAND DRAINS FOR STABILIZATION OF EMBANKMENTS (1955) 52 pp. $.90
Modification of Sand-Drain Principle for Pressure Relief in Stabilizing Embankment Foundation; Sand Drains for Embankment on Marl Foundation: Stabilizatio of Marsh Deposit; Economic Aspects of Vertical Sand Drains; Control of Slide by Vertical Sand Drains.

BULLETIN 126: CULVERT-FLOW CHARACTERISTICS (1956) 23 pp. $.60

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