Culverts for Flow Measurement in Irrigation Systems

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THERE are many types of both open channel and closed conduit water measuring devices available. Culverts can serve as a combination open channel and closed conduit flow measurement structure, depending upon the type of flow condition in the culvert.

Most of the research involving the hydraulics of culverts has been concerned with the use of such structures under highways. Most frequently, a highway culvert is designed to operate with full flow (closed conduit) at the design discharge. Much of this research has been concerned with inlet control and submerged outlet control.

For culverts placed in an irrigation conveyance channel usually free surface (open channel) flow occurs in the culvert. In addition, downstream conditions will likely control the depth of flow in the culvert. For this particular condition of free surface subcritical culvert flow, only an approximate solution is presently available for determining the discharge.

If accurate discharge ratings could be developed for free surface subcritical culvert flow, then the culverts found in irrigation systems could be used as a flow measurement structure. Also, small culverts could be used as a portable flow measuring device, which could be easily installed while water was flowing in the channel. If the ratings included the effect of barrel slope, then the culvert would not have to be perfectly horizontal, like most flow measuring flumes, in order to obtain accurate discharge measurements.

Culverts placed in irrigation conveyance channels are open channel constrictions. Since only an approximate solution is presently available for determining the discharge under free surface subcritical culvert flow, the possibility of utilizing the submerged flow analysis recently developed for flow measuring flumes (Skogerboe et al 1967) and weirs (Skogerboe et al 1967d) to provide an accurate discharge equation was investigated. If the submerged flow analysis can be applied to this special problem, the transition from inlet control to free surface subcritical culvert flow can be described. Then, a method for describing the transition from free surface subcritical culvert flow to submerged outlet control can be explored.

HYDRAULICS OF CULVERTS

The classification of the hydraulic performance of culverts can take several forms. Three primary groupings will be used to describe the hydraulics of culverts. The primary groups are based on the three parts of the culvert that exert primary control on the culvert performance and its capacity: the inlet, the barrel, and the outlet.

Usually, one of the primary controls determines the performance and capacity of the culvert. An example of this is a projecting, square-edged inlet with the barrel on a steep slope and flowing partly full. If the inlet is not submerged, the upstream water level (headwater) is determined by the inlet characteristics alone. At other times, two or even all three primary controls can simultaneously affect the performance and capacity. For example, if the inlet and outlet are submerged and the barrel is full, then the elevation of the headwater is determined by adding the outlet losses, the barrel friction losses, and the inlet losses to the tailwater elevation.

The classification is further subdivided under each main group, as shown in Table 1 (Blaisdell, 1966). The classification is presented to indicate the number of items the designer must consider when determining the performance of a culvert and computing its capacity.

Only those items that exert a control on the hydraulic performance of a culvert are listed in Table 1. Many alternatives are possible for each control. For example, each type of inlet will have a different effect on the culvert performance, and each effect must be evaluated.

Many of the items listed in Table 1 are interrelated, which further complicates an already difficult problem. For instance, the depth of flow just inside the culvert entrance depends on the inlet geometry. If this depth is less than the normal depth of flow, a water surface profile must be computed beginning with the contracted depth of flow to determine the flow depth at the culvert outlet. If the computed outlet depth exceeds the barrel height, the culvert is hydraulically long, the barrel will fill, and the control will be the inlet, the barrel, and the outlet. If the computed depth at the outlet is less than the barrel height, the barrel is only part full and the culvert is considered hydraulically short, will not fill, and the control will remain at the inlet. Whether a culvert is hydraulically long or hydraulically short depends on such items as the culvert slope and the culvert material. In fact, just changing from corrugated pipe to concrete pipe can change the hydraulic length of a culvert from long to [illegible] A similar effect could result from a [illegible]nge in the inlet geometry.

Flow in c[illegible]ts is also controlled by the hydraulic capacity of one section of the installation. The discharge is either controlled at the culvert entrance or at the outlet and is designated inlet control and outlet control, respectively. In general, inlet control will exist as long as the ability of the culvert pipe to carry the flow exceeds the ability of water to enter the culvert through the inlet. Outlet control will exist when the ability of the pipe barrel to carry water way from the entrance is less than the flow that can enter the inlet. The location of the control section will shift as the relative capacities of the entrance and barrel sections change with increasing or decreasing discharge.

Inlet Control

Inlet control means that the discharge capacity of a culvert is controlled at the culvert entrance by the depth of headwater, HW, and the entrance geometry, including the barrel shape and

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TABLE 1. CLASSIFICATION OF CULVERT HYDRAULIC CONTROLS (1)

- I. Inlet
  - A. Unsubmerged
    - 1. Weir
    - 2. Surface profile
  - B. Submerged
    - 1. Orifice
    - 2. Vortex
    - 3. Full
- II. Barrel
  - A. Length
    - 1. Short
    - 2. Long
  - B. Slope
    - 1. Mild
      - i. Barrel slope less than critical slope
        - a. Part full, normal depth greater than critical depth
        - b. Full, not applicable
      - ii. Barrel slope less than friction slope
        - a. Part full, depth increases along barrel
        - b. Full, barrel under pressure
    - 2. Steep
      - i. Barrel slope steeper than critical slope
        - a. Part full, normal depth less than critical depth
        - b. Full, not applicable
      - ii. Barrel slope steeper than friction slope
        - a. Part full, depth decreases along barrel (increases if the inlet causes the depth inside the inlet to be less than the normal depth)
        - b. Full, barrel under suction
  - C. Flow
    - 1. Part full
    - 2. Slug and mixture
    - 3. Full
- III. Outlet
  - A. Part full
    - 1. Critical depth
    - 2. Tailwater
  - B. Full
    - 1. Free
    - 2. Submerged

cross-sectional area and the type of inlet edge. Inlet control flow for both unsubmerged and submerged projecting entrances are shown in Figs. 1(a) and 1(b). A submerged mitered entrance with inlet control is shown in Fig. 1(c). With inlet control, the roughness and length of the culvert barrel, as well as outlet conditions (including depth of tailwater), are not factors in determining culvert capacity. An increase in barrel slope reduces headwater to a small degree and any correction for slope can be neglected for conventional or commonly used culverts flowing with inlet control (Utah State Department of Highways 1965).

Barrel Control

Under barrel control, the discharge in the culvert is controlled by the combined effect of entrance, length, slope, and roughness of the pipe barrel. The characteristics of the flow do not always identify the type of flow. It is possible, particularly at low flows, for length, slope, and roughness to control the discharge, without causing the pipe to flow full. This is, however, not a common occurrence at design discharges. The usual condition for this type of flow at design discharges is one in which the pipe cross section flows full for a major portion of the length of the culvert. The discharge in this case is controlled by the combined effect of all hydraulic factors.

Outlet Control

Culverts flowing with outlet control can flow with the culvert barrel full or part full for part of the barrel length, or for all of it (Fig. 2). If the entire cross section of the barrel is filled with water for the total length of the barrel, the culvert is said to be in full flow or flowing full, as shown in Figs. 2(a) and 2(b). The flow condition in Fig. 2(a) is called submerged outlet control flow, while the flow in Fig. 2(b) represents a unique condition in which the discharge due to inlet or barrel controls are in balance. Two other common types of outlet control flow are shown in Figs. 2(c) and 2(d). Procedures are available for determining the headwater depth for the flow conditions shown in Figs. 2(a), 2(b), and 2(c). The method given for part full flow condition, Fig. 2(d), gives an approximate solution for headwater depth that decreases in accuracy as the headwater decreases.

METHOD OF FLOW ANALYSIS

In irrigation systems, free surface

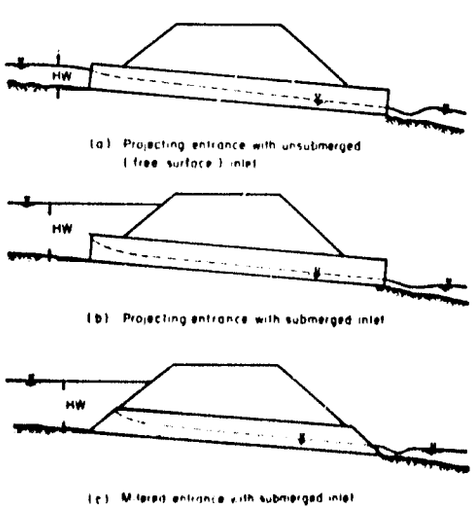

FIG. 1 Inlet control flow conditions.

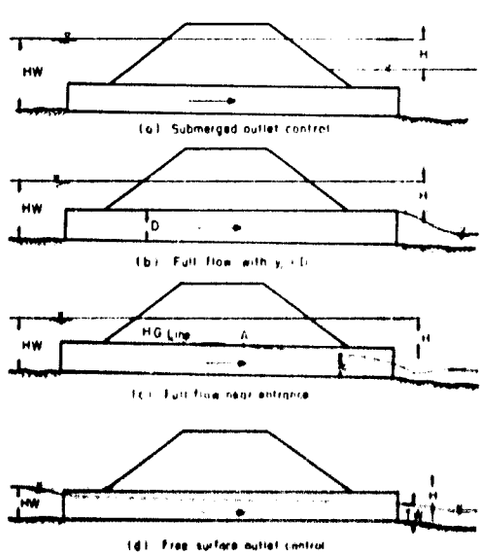

FIG. 2 Outlet control flow conditions.

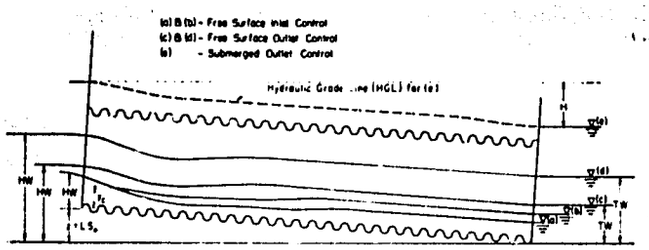

FIG. 3 Illustration of flow conditions for culverts in irrigation systems placed on a mild slope and having a short length.

flow with outlet control is commonly encountered, which is the type of flow condition illustrated in Fig. 2(d). This same flow condition is listed in Table 1 under outlet control with part full flow determined by the depth of tailwater. Also, culverts in irrigation systems are usually short, while being installed on a mild slope. As stated previously, a technique is not presently available for analytically describing free surface subcritical flow in culverts.

In recent years, an analytical technique for subcritical flow at open channel constrictions has been developed (Skogerboe et al 1967a). This technique has been shown to apply to flow measuring flumes (Skogerboe 1967b,c), weirs (Skogerboe 1967d), and bridge constrictions (Skogerboe et al 1970). Since a culvert is a flow constriction, this method of subcritical flow analysis should be applicable to describing free surface subcritical outlet control flow in culverts.

For culverts in irrigation systems placed on a mild slope and having a short length, three flow conditions should describe the types of flow to be encountered. Beginning with free surface inlet control, the downstream flow depth can be increased until the headwater is increased just slightly. Free surface flow will still exist, but flow conditions are now affected by changes in tailwater. This flow condition can be described as free surface outlet control. Finally, the tailwater can be raised sufficiently to submerge the outlet. For a short culvert installed on a mild slope, a submerged outlet should result in a submerged inlet, with the flow condition being submerged outlet control.

The method of flow analysis is different for each of the three flow conditions mentioned above. The technique for developing the discharge equation describing each of the flow conditions will be presented below.

Inlet Control

Under free surface inlet control conditions, critical depth occurs in the vicinity of the culvert entrance. This critical depth makes it possible to determine the flow rate knowing only the upstream depth, HW. This is possible because whenever critical depth occurs in the culvert, the upstream depth, HW, is not affected by changes in the downstream depth, TW, as shown by water surface profiles (a) and (b) in Fig. 3, thereby resulting in a unique relationship between discharge, Q, and headwater, HW.

For culvert operation with inlet control, a plot is made of flow rate, Q, in cfs, against headwater depth, HW, with Q as the ordinate and HW as the abscissa. When these two variables are plotted on logarithmic paper, all of the points can be represented by a straight line over the narrow range of $0<HW<D$ (this will be discussed further under "Results"). The equation for this inlet control flow rating can be written as

$$Q = C\,(HW)^{n_1} \quad \ldots\ldots\ldots\ldots [1]$$

where

- Q = flow rate, in cfs;
- C = inlet control flow coefficient;
- HW = headwater depth, the vertical distance from the culvert invert at the entrance to the elevation of the upstream pool water surface, in feet; and
- n_1 = inlet control flow exponent.

The coefficient C contains the effects of inlet geometry.

Free Surface Outlet Control

When the flow conditions are such that the downstream flow depth, TW, is raised to the extent that the flow depths at any point through the structure become greater than critical depth, resulting in a change in the upstream depth, HW, then the culvert is operating under free surface subcritical flow, as shown in Figs. 3(c) and 3(d). The term which will be used to describe this particular flow condition will be "free surface outlet control." A culvert operating under free surface outlet control flow conditions requires that two flow depths be measured, one upstream (HW) at the culvert invert, and one near the downstream end of the culvert, such as TW.

The definition given to submergence, shown as S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth. For the more general case shown in Fig. 3, where the culvert is placed with a positive slope (sloping downward in the direction of flow), the submergence, S, is defined by the following expression:

$$S = TW/(HW + z) \quad \ldots\ldots\ldots\ldots [2]$$

where z is the drop in elevation of the culvert invert between inlet and outlet. For the special case of a horizontal culvert, z = 0. The drop of the culvert, which is z, can also be expressed as the culvert length, L, multiplied by the slope of the culvert barrel, S_o. Thus,

$$z = LS_o \quad \ldots\ldots\ldots\ldots [3]$$

and

$$S = TW/(HW + LS_o) \quad \ldots\ldots\ldots [4]$$

Free surface outlet control flow calibration curves are determined for the culvert by preparing three dimensional plots of the parameters describing free surface subcritical flow. The data are plotted on logarithmic paper with the discharge, Q, as the ordinate; difference in upstream and downstream depths of flow, (HW + z) − TW or H, as the abscissa; and the submergence, TW/HW + z), as the varying parameter. Lines are then drawn connecting points of equal submergence. These are straight lines having a slope identical to the slope of the inlet control rating curve (which is n_1) for the same geometry.

From the submerged flow plots, an equation has been developed (Skogerboe et al, 1967a) which can be used to describe the flow rate through the culvert. The equation is:

$$Q = \frac{C_1\,(H)^{n_1}}{(-\log S)^{n_2}} \quad \ldots\ldots\ldots [5]$$

where

- Q = flow rate in cfs;
- H = difference between upstream and downstream depths, HW + z − TW, in ft;

C_1 = free surface outlet control coefficient;
n_1 = inlet control flow exponent;
n_2 = free surface outlet control exponent; and
S = surbmergence, TW/(HW + z).

The coefficient C_1 contains the effects of inlet and barrel geometry.

Having determined the values of the constants in the free surface outlet control equation, it is now possible to evaluate the flow rate for any combination of upstream and downstream flow depths that might be encountered (Skogerboe et al 1967a).

The transition submergence, S_t, is the value of submergence at which the discharge passes from inlet control flow condition to free surface outlet control flow condition or vice versa (Fig. 3b). Under this unique condition, both the inlet control flow equation and the free surface outlet control equation will predict the same value of discharge.

To determine the transition submergence, S_t, the inlet control flow equation and the free surface outlet control equation are set equal to one another (equations [1] and [5]).

$$C(HW)^{n_1} = \frac{C_1 (HW + z - TW)^{n_1}}{[-\log[TW/(HW + z)]]^{n_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [6]$$

The value of submergence, S, that makes equation [6] valid is the transition submergence, S_t. This equation can be solved by trial and error to obtain a value of the transition submergence for the special case where z = 0. For sloping open channel constrictions, a transition submergence can be obtained if energy is used, rather than flow depths (Skagerboe et al 1970).

In order to determine whether inlet control or free surface outlet control flow conditions exist in a culvert, it is necessary to calculate the submergence, which is then compared with the transition submergence to determine which flow equation should be used. If the submergence is less than the transition submergence, then inlet control conditions exist; but the culvert is operating under free surface outlet control flow conditions if the submergence is greater than the transition submergence, S_t.

Submerged Outlet Control

When the flow conditions are such that the downstream flow depth, TW, is raised to the extent that the culvert is completely full throughout the culvert length, resulting in a change in the upstream depth, HW, then the culvert is operating under submerged outlet control, as shown in Fig. 3 (water surface profile e). The culvert operating under submerged outlet control flow conditions also requires that two flow depths be measured, one upstream (HW) at the culvert invert, and one downstream near the end of the culvert (TW).

For the submerged outlet control flow condition, a plot is made of flow rate, Q, against the difference between upstream and downstream flow depths, H, with Q as the ordinate and H as the abscissa (e.g., Fig. 8). When these two variables are plotted on logarithmic paper, all of the points will fall on a straight line. The equation for this submerged outlet control flow rating can be written as:

$$Q = C_3 (H)^{n_3} \quad \ldots\ldots\ldots\ldots [7]$$

where
Q = flow rate, in cfs;
H = difference between upstream and downstream flow depths, HW + z - TW:
C_3 = submerged outlet control flow coefficient, which is the value of Q when H = 1 ft; and
n_3 = submerged outlet control flow exponent, which is the slope of the submerged outlet control flow rating when plotted on logarithmic paper.

The coefficient C_3 contains the effects of inlet, barrel, and outlet geometry.

In order to determine whether free surface outlet control flow or submerged outlet control flow conditions exist in a culvert, it is at least required that the culvert outlet be just submerged, while the culvert inlet is also submerged. Thus, the downstream flow depth, TW, must exceed the diameter or height of the culvert, D.

EXPERIMENTAL DESIGN

To test the validity of the subcritical flow technique (Skogerboe et al 1967a) to analytically describe free surface outlet control, a 12-in. diameter corrugated metal culvert was selected. A square-edged flush headwall was attached to the culvert. Thus, only one inlet condition was used in the experimental design. Three culvert lengths, along with four barrel slopes for each length, were incorporated in the experimental program. For a culvert length of 5 ft, barrel slopes of 0.0000 (horizontal), 0.0333, 0.0667, and 0.1167 were used. In addition to the horizontal case, slopes of 0.0167, 0.0333, and 0.0583 were used with the 10-ft culvert length. The 20-ft culvert length utilized slopes of 0.0000, 0.0083, 0.0167 and 0.0292.

Using four slopes for each of three culvert lengths provided 12 cases to be investigated in the laboratory. For each case, sufficient hydraulic data had to be collected in order that discharge ratings could be developed for the three flow conditions of free surface inlet control, free surface outlet control, and submerged outlet control.

EXPERIMENTAL FACILITY

This hydraulic experimental study utilized the 4-ft wide by 60-ft long recirculating flume located in the Engineering Research Center at Colorado State University. The 12-in. diameter corrugated metal pipe (CMP) culvert was placed inside the 4-ft flume with the bottom of the culvert placed 7 in. above the laboratory flume floor. The upstream end of the culvert was welded to the steel headwall, which had a rubber seal around the periphery for leakage protection. The headwall served as the hinge for tilting the culvert. A flexible rubber sheet was used between the headwall of the culvert and the channel iron cutoff attached to the walls and the floor of the laboratory flume, thereby allowing the culvert to be tilted without any leakage occurring. Wood blocks were placed at various points underneath the culvert to support the pipe in order to maintain the required slopes. The maximum drop of the culvert exit was approximately 7 in.

In running the hydraulic tests, the culvert was set horizontally and eight different discharges were run with the tailwater gate being fully open, thereby resulting in inlet control flow conditions. Next, a constant discharge was set with the tailgate fully open. Then, the tailgate was lowered into the flow, which resulted in an increased tailwater depth. After recording the piezometer readings, the tailgate was again lowered and the piezometers read again. This procedure was continued until sufficient data had been collected to describe free surface outlet control and submerged outlet control. Then, a new constant discharge was set and another series of hydraulic data collected. Four discharges were run for each slope and each pipe length.

RESULTS

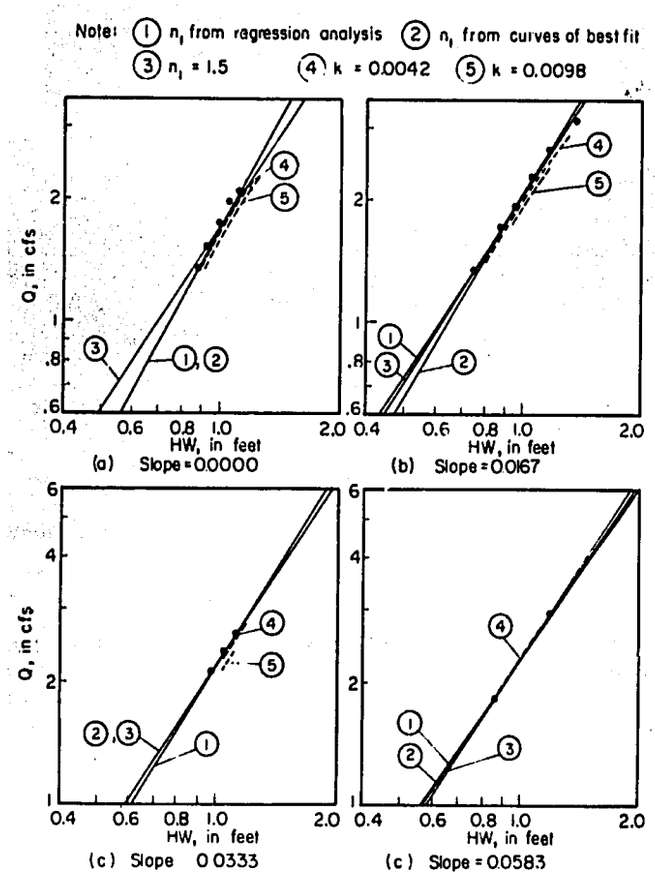

FIG. 4 Inlet control ratings for experimental culvert length of 10 ft using various criteria.

Inlet Control Ratings

The inlet control data were first analyzed using a computer program involving a regression analysis in order to arrive at estimates of the inlet control coefficient, C, and inlet control exponent, n_1. The results of using different techniques for arriving at an inlet control rating are represented in Fig. 4 for a culvert length of 10 ft. Five different techniques were employed. First of all, the n_1 developed from the line of best fit for the experimental data using regression analysis was tested. Secondly, a value of n_1 developed from smooth curve relationships involving the barrel slope was tested against the data. Next, the line of best fit through the data using a value of the inlet control exponent equal to 1.5 was used. Finally, two different values of k (coefficient used in flow equation commonly used by Highway Engineers) were used for comparison with the actual experimental data.

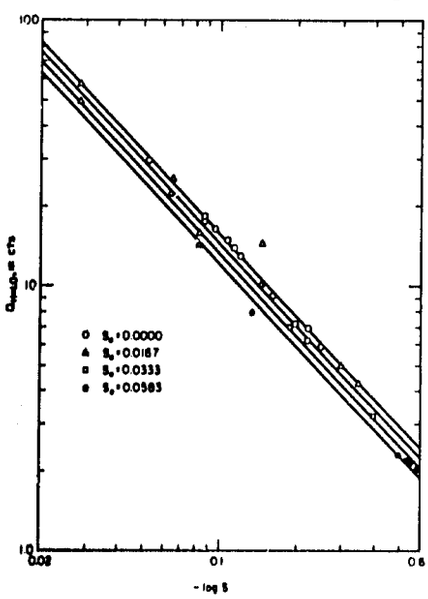

FIG. 5 Effect of barrel slope upon free surface outlet control ratings for experimental culvert 10 ft long.

Because the experimental data covers a narrow range of inlet flow depths, it can be seen from Fig. 4 that a considerable degree of latitude exists as to the format of the inlet control ratings. For purposes of simplicity in the ratings to follow regarding the free surface outlet control and submerged outlet control flow conditions, criterion 3 employing n_1 = 1.5 has been selected as representing the inlet control ratings. From a theoretical standpoint, criterion 3 is only valid for rectangular cross-sections. Actually, criterion 4, which is slightly curvilinear, is more valid. However, for the narrow range of HW used in these experiments, criterion 3 introduces very little error to the analysis and has the advantage of simplifying the analysis.

Free Surface Outlet Control Ratings

In order to determine the free surface outlet control ratings, the coefficient, C_1, and exponent, n_2, in equation [5] must be evaluated. This is accomplished using plots similar to Fig. 5, which has been prepared for the experimental culvert length of 10 ft. The slope of these ratings, which is the free surface outlet control exponent, n_2, has a constant value of 1.04. Thus, the variation in the free surface outlet control ratings due to barrel slope, S_o, and culvert length, L, can be expressed in terms of the free surface outlet control coefficient, C_1.

Because of the difficulties in collecting accurate discharge data, there is considerable scatter in the data points shown in Fig. 5, which results in inaccuracies in arriving at the value of the coefficient, C_1. To partially overcome this problem, the first estimates of the free surface outlet control coefficient, C_1, were plotted against the barrel slope, S_o, to test for consistency in the relationships. By plotting the relationship for each culvert length, L, on the same graph, definite trends in the relationships could be seen. Finally, the curves relating C_1 and S_o were established by eye, which required that three data points be adjusted, with one data point being adjusted for each culvert length. In each case, the original estimate of C_1 was reduced. The degree of adjusteimnt amounted to 8 percent for the one data point on the curve in Fig. 6 for a culvert length of 5 ft, 12 percent for one of the data points for the culvert length of 10 ft, while the adjustment required for the curve in Fig. 6 for a culvert length of 20 ft was 4 percent. After developing the relationships shown in Fig. 6, the final rating curves, as represented by Fig. 5, were developed.

The transition submergence, S_t, between inlet control and free surface

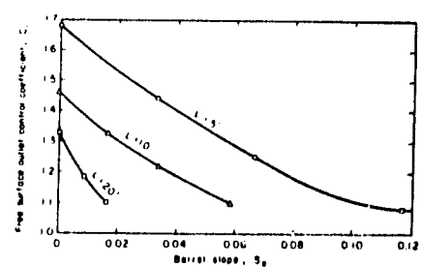

FIG. 6 Relationships between barrel slope and free surface outlet control coefficient for experimental culverts.

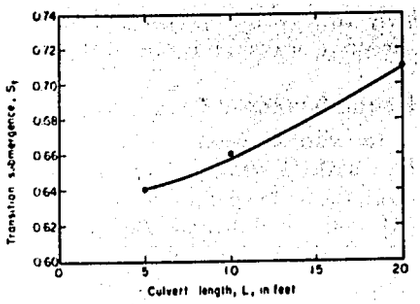

FIG. 7 Effect of culvert length upon transition submergence.

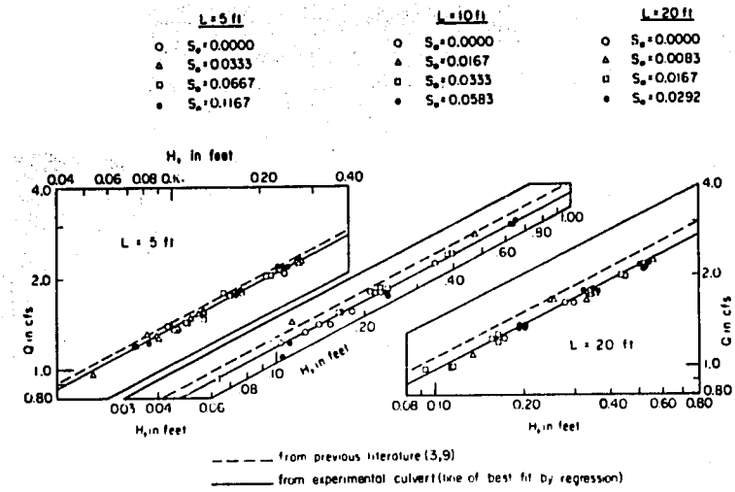

FIG. 8 Submerged outlet control flow ratings for experimental culverts.

outlet control was evaluated using equation [6] for the special case where z = 0(horizontal culvert). A solution of equation [6] for sloping culverts is complex because the culvert fall, z, does not allow a simple unique solution for S_t. The relationship between culvert length, L, and the transition submergence, S_t, is shown in Fig. 7. For culvert lengths of 5 ft, 10 ft, and 20 ft, the transition submergence was 0.64, 0.66, and 0.71, respectively.

Submerged Outlet Control Ratings

Since submerged outlet control ratings are given in the literature (Portland Cement Assoc. 1964, Utah State Dept. of Hwys. 1965), a comparison of reported ratings with the data collected for the experimental culverts was undertaken. For the experimental culvert under study, wherein a constant diameter corrugated metal pipe has a square-edged flush headwall, the rating equation is a function of culvert length.

The laboratory data for submerged outlet control flow conditions has been plotted in Fig. 8. For purposes of comparison, the predicted discharge ratings from the literature have been shown in Fig. 8. In each case, the laboratory discharge rating predicts lower discharges than the ratings reported in the literature. Using equation [9] to describe the submerged outlet control rating, the exponent, n_3, has a constant value of 1/2 in all cases. The effect of culvert length on the discharge rating is reflected in the coefficient, C_3, with culvert length, L, for the laboratory ratings is less (about 5 percent) than the ratings reported in the literature.

Composite Ratings

A summary of the exponents and coefficients in the discharge rating equations for inlet control, free surface outlet control, and submerged outlet control are listed in Table 2. For the special case of horizontal culverts (S_o =0), the ratings for all three flow conditions can be presented on a single graph. The composite ratings for the experimental culvert are shown in Fig. 9 for a culvert length of 10 ft.

CONCLUSIONS

This study has shown that the submerged flow analysis used for flow measuring flumes and weirs can be applied to free surface outlet control flow in culverts. Also, discharge ratings for horizontal culverts can be graphically shown on a single plot. Such a plot covers the three flow conditions investigated in this study, which are inlet control, free surface outlet control, and submerged outlet control.

The results of this study have clearly shown that culverts can definitely be used as flow measuring structures in irrigation systems. Thus, existing culverts could be utilized for providing discharge measurements. Also, small culverts could be employed as portable flow measuring devices.

The assumption that n_1 = 1.5 was used to simplify the analysis. Further study should be undertaken to remove this assumption from the flow analysis. Then, generalized discharge ratings could be developed for a wide variety of inlet, barrel, and outlet culvert geometries.

NOMENCLATURE

A	=	Cross-sectional area of flow
C	=	Inlet control flow coefficient
C_1	=	Free surface subcritical flow coefficient
C_3	=	Submerged outlet flow coefficient
D	=	Pipe diameter, in ft
g	=	Gravitational acceleration, in fpc
TW	=	Tailwater depth at culvert outlet, in ft
H	=	Difference in water levels upstream and downstream
H_e	=	Specific energy, in ft
H_e	=	Head increment, in ft
HW	=	Headwater depth, the vertical distance from the culvert invert, in ft
HW + z	=	Upstream water surface elevation above invert of culvert outlet, in ft
k	=	Empirical free surface inlet control coefficient
L	=	Length of culvert, in ft

TABLE 2. SUMMARY OF DISCHARGE RATINGS FOR INLET CONTROL, FREE SURFACE OUTLET CONTROL, AND SUBMERGED OUTLET CONTROL FOR THE 12-in. DIAMETER CORRUGATED METAL PIPE

Culvert length, L	Barrel slope, S_o	Inlet control $Q = C(HW)^{n_1}$		Free surface outlet control $Q = \frac{C_1(HW+z-TW)^{n_1}}{[-\log(TW/(HW+z))]^{n_2}}$			Submerged outlet control $Q = C_3H^{n_3}$	
ft	ft/ft	n_1	C	n_1	n_2	C_1	n_3	C_3
5	0.0000	1.500	1.999	1.500	1.040	1.680	0.50	4.337
	0.0333	1.500	2.244	1.500	1.040	1.440		
	0.0667	1.500	2.319	1.500	1.040	1.250		
	0.1167	1.500	2.324	1.500	1.040	1.080		
10	0.0000	1.500	1.727	1.500	1.040	1.460	0.50	3.762
	0.0167	1.500	2.060	1.500	1.040	1.325		
	0.0333	1.500	2.221	1.500	1.040	1.220		
	0.0583	1.500	2.288	1.500	1.040	1.100		
20	0.0000	1.500	1.506	1.500	1.040	1.330	0.50	3.032
	0.0083	1.500	1.773	1.500	1.040	1.180		
	0.0167	1.500	1.984	1.500	1.040	1.100		

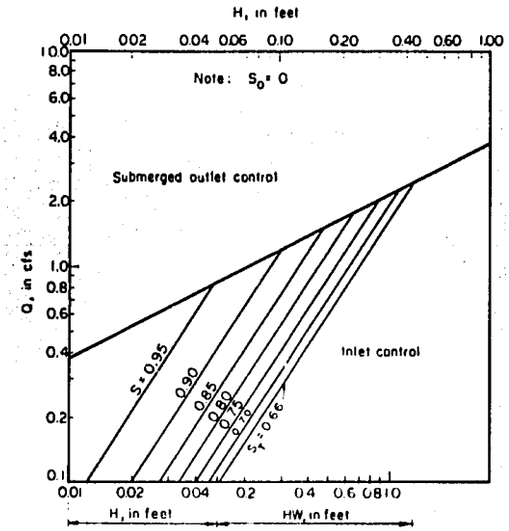

FIG. 9 Discharge ratings for horizontal experimental culvert 10 ft long.

n_1 = Inlet control flow exponent

n_2 = Free surface subcritical flow exponent

n_3 = Submerged outlet flow exponent

Q = Flow rate, in cfs

S = Submergence, which is the ratio of a downstream flow depth to an upstream flow depth, but using a common datum such as the culvert outlet

S_o = Barrel slope, in ft per ft

S_t = Transition submergence, which is the value of submergence at which a change in tailwater depth creates a change in the headwater depth

y_c = Critical depth, in ft

z = Vertical distance from invert at the culvert outlet (reference datum) to the invert at the culvert inlet, in ft

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