Characteristics and Prediction of Simultaneous Flow Over Broad-Crested Weirs and Through Culverts

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Abstract: The problem of culvert overtopping with water is investigated. In this case, where the culvert cross sectional area is not sufficient to drain the incoming flood, the ordinary solution is either to replace the old culvert with a bigger capacity one or to add new vents to the original. An alternative solution is to use the top of the existing culvert as a broad-crested weir and modify (raise) the road approaches to act like an Irish Road.

An experimental study has been conducted to simulate the overtopped flow case. In this case a part of the flow will go through the culvert vents and the rest will overtop it. The flow depth at the downstream side is taken greater than the culvert height (submerged flow). The characteristics of these simultaneous flow cases are analyzed. The effect of flow and geometrical parameters of the structure are presented and explained. Discharge prediction model has been developed by means of multiple linear regression technique. The results of the developed model have agreed with an independent data set.

Keywords: Open channel hydraulics, Hydraulic structures, Discharge measurement structures, Flood drainage, Culvert, Broad-crested weir.

1 Introduction

Culverts and broad-crested weirs are hydraulic structures that could be used for measuring the flow rate in open channels. The characteristics of flow through culvert are very complicated because they are controlled by many variables including the entrance geometry, slope, roughness, size, approach and tailwater conditions. The flow through culverts may be partly or completely full. In the former case, the culvert flow is treated as open channel flow while the later case, the flow is dealt as closed conduit flow. Closed conduit may occur even when the outlet is not submerged when the culvert is sufficiently long to be treated as hydraulically long culvert. This study concerns with the flow through culvert when both inlet and outlet are submerged. Classifications of culvert flow are treated in Chow (1959) and in more details in Herschy (1978) and French (1985). Comprehensive investigation on culvert for discharge measurements may be found in Benson (1968) and Bodhaine (1968). Early studies on the flow through different pipe and box culverts are due to Yarnell et al. (1926). Mavis (1942) tested the flow through a round smooth pipe culvert. Corrugated and concrete pipe culverts were tested by Straub and Morris (1950a,b,c) and by Straub et al.

(1953a,b). Standard box culverts were tested by Shoemaker and Clayton (1953). The hydraulic behavior of the commonly used pipe culverts was conducted at the United State Bureau of standards as reported by French (1955, 1956 and 1957). Carter (1957) prepared rough design charts to distinguish between hydraulically short and hydraulically long culverts. Li and Patterson (1956) gave a reasoning for self priming hydraulically short culverts with submerged inlet to flow full. They mentioned that the water rises to the top mainly due to the formation of the hydraulic jump or the backwater effect at the outlet or due to a standing surface wave developed inside the culvert barrels.

On the contrary to the flow through culvert, the flow over weirs is simple and the structure itself is one of the simplest measurement device with the advantage of easy construction, easy installation and structure stability. However, broad-crested weirs may be less accurate in measuring flow rate compared to other accurate devices because of the variable value of the discharge coefficient. British Standards Institute (1965) and USBR (1967) could be consulted for the specification of broad-crested weirs and installation procedures for accurate measurements.

Investigations of free and submerged flow over broad-crested weir were done by Woodburn (1932), El-Kateb (1974), Bos (1976), Bos et al. (1984), French (1986) and Ramamurthy et al. (1988). The features of the two dimensional free flow over weirs of rectangular cross section with sharp as well as streamlined corners were presented by Surya Rao and Shukla (1971) based on an experimental study. Flow separation at the upstream edge of a square edged broad-crested weir was analyzed by Moss (1972). Rao and Rao (1973), Replogle (1978), Ackers et al (1978) and Swamee (1988) studied the broad-crested from discharge coefficient point of view in order to provide empirical expressions for the discharge coefficient. Hager and Schwalt (1994) investigated experimentally the flow features over broad-crested weirs with vertical upstream walls and sharp-crested corners.

A contracted broad-crested weir is one where the weir width is smaller than that of the channel. Compared to the suppressed broad-crested weirs, the contracted one has not been studied adequately yet. Hall (1972) analyzed discharge characteristics of broad crested weirs using boundary layer theory. He proposed a theoretical relation for the discharge over the contracted broad-crested weirs. Muralidhar (1965) conducted some studies on free flow over broad-crested weirs with contractions. Based on a semi-theoretical approach, a discharge relation for flow over suppressed and contracted broad-crested weir has been presented by Ranja Raju and Ahmed (1973).

Negm and Alshaikh (1997) investigated the characteristics of flow over contracted broad-crested weirs for different contraction ratios in the range $0.508 \leq b/B \leq 1.0$ at constant $P/L=0.375$ with $0.1 \leq h_w/L<0.5$ (b being the width of the contracted weir, B is the channel width, P is the height of the weir, L is the length of the weir and h_w is the head of water above the weir). They developed an expression for estimating the discharge coefficient and the velocity coefficient. Saleh et al. (1998) extended the study of Negm and Alshaikh by testing broad-crested weirs of b/B=0.607 and different P/L in the range of 0.375 to 0.50.

The characteristics of simultaneous flow over broad-crested weir combined with box smooth culvert of sharp-edges both at entrance and exit are investigated in this study. A prediction equation is developed in terms of the flow, boundary and geometrical parameters of the structure using the multiple linear regression.

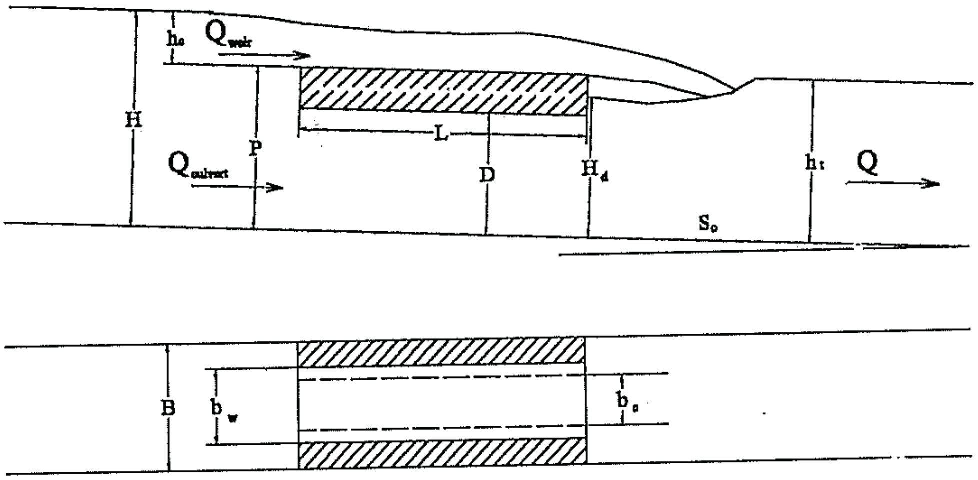

Figure 1. Definition sketch for simultaneous flow through culvert and over broad-crested weir

2 Theoretical Background

Figure 1 shows a definition sketch for the proposed structure with the symbols of variables defined as follows: density of water, ρ, gravitational acceleration, g, the bottom slope, S_o, the combined discharge of the structure, Q, the head of water over the broad-crested weir, h_w, head of water at inlet of the culvert, H, the height of the culvert barrel, D, the depth just downstream the culvert, H_d, the tailwater depth downstream the culvert, H_t, the width of the weir, b_w, the width of the culvert vent, b_c, the flume width, B, the length of the culvert, L, and the weir height p.

Thus the functional form for the flow rate can be written as follows:

$$\begin{pmatrix} \rho, g, S_o, Q, h_w, H, D, H_d, H_t, b_w, \\ b_c, L, B, P \end{pmatrix} = 0 \quad (1)$$

The following form could be written using the principles of the dimensional analysis:

$$\frac{Q}{D^2\sqrt{gD}} = f\begin{pmatrix} S_o, \frac{h_w}{D}, \frac{H}{D}, \frac{H_d}{D}, \frac{H_t}{D}, \frac{b_w}{D}, \\ \frac{b_c}{D}, \frac{L}{D}, \frac{B}{D}, \frac{P}{D} \end{pmatrix} \quad (2)$$

The bottom slope, S_o, the height of the culvert, D, the length of the culvert, L, the weir height, P, and the flume width, B, are all kept constants during the experimental work. In Eq.(2), the effect of viscosity is neglected as the temperature was mostly constant. The effect of H_d/D could be neglected as H_d is a function of H_t. Taking H_t/D equals S to denote the submergence ratio. The effect of h_w is included in H. Eq.(2) can be simplified as follows:

$$\frac{Q}{D^2\sqrt{gD}} = f\left(\frac{H}{D}, \frac{b_w}{D}, \frac{b_c}{D}, S\right) \quad (3)$$

The non-dimensional discharge $Q_{nd}=Q/D^2\sqrt{gD}$ of equation (3) will be computed using the experimental data and different plots will be prepared to discuss the effect of H/D, S, b_w/D and b_c/D on it.

3 Experimental Tests and Setup

A horizontal rectangular flume 30.5 cm wide, 31 cm high and 9.5 m long is used. The flume is equipped with a tail gate to control the tailwater depth. A centrifugal pump lifts water from underground sump to the flume inlet. Water runs through the flume then returns back to the sump tank via a measuring tank.

The tested model consisted of a contracted broad-crested weir combined with a one vent box culvert with the same total length, L, from entrance to exit of L=40 cm. The weir width varied from 10 cm to 18 cm. The height of the culvert barrel was kept constant to D=6 cm while the width of the vent was varying also from 10 cm to 18 cm. The bottom slope of the structure was kept constant to S_o=0.006. Appendix 1 shows the details of the experimental data and experimental conditions of the present study. The flow condition was such that the flow at both inlet and outlet of the culvert are submerged and the culvert is flowing full. Always, the approaching discharge to the structure is more than the capacity of the culvert and thus a flow over the weir is expected. The measurements taken include the flow depth at 40 cm upstream from the culvert and just downstream the culvert to ensure flow over the weir. The tailwater depth was recorded several times for each discharge to account for the effect of submergence.

Discharges were measured by a pre-calibrated V-notch installed in a measuring tank located below flume outlet at its downstream end and is connected directly to underground sump tank. Water depths are measured using a precise point gauge (up to ±0.1 mm accuracy) mounted on a carriage.

4 Analysis and Discussions

The non-dimensional discharge, Q_{nd}, given by equation (3) was evaluated using the experimental data. The relationships between Q_{nd} and H/D in accordance with Eq.(3) were plotted in Figures 2, 3 and 4 with one parameter rather than H/d as third parameter keeping the other two unchanged. Figure 2 presents the relationships between Q_{nd} and H/D at constant b_w/D=1.4 and S is increasing from 3 in Fig.2a to 4 in Fig.2d with bc/d as third parameter having values of 1.667, 2.0, 2.333, 2.667 and 3.0. It is clear that the values of Q_{nd} increase with the increase of H/D at fixed values of S, b_w/D and b_c/D. This is because the head upstream the inlet is a major contribution of the differential head affects the discharge. At constant H/D, it is observed that increasing the ratio b_c/D, causes a corresponding increasing in the Q_{nd} which means that wider vents at constant height pass more discharges. Particularly, e.g. in Fig.2a, the Q_{nd} line for b_c/D=3.0 is higher than that for b_c/D=2.667 and more higher than that for 2.333, ..etc.

Similarly, Figure 3 shows the relationship between Q_{nd} and H/D at constant values of b_c/D=3.0 and S=3, 3.667 and 4.0 with b_w/D as third parameter having values of 1.8, 2.2, 2.6 and 3.0. As discussed above, the discharge increases with the increase of

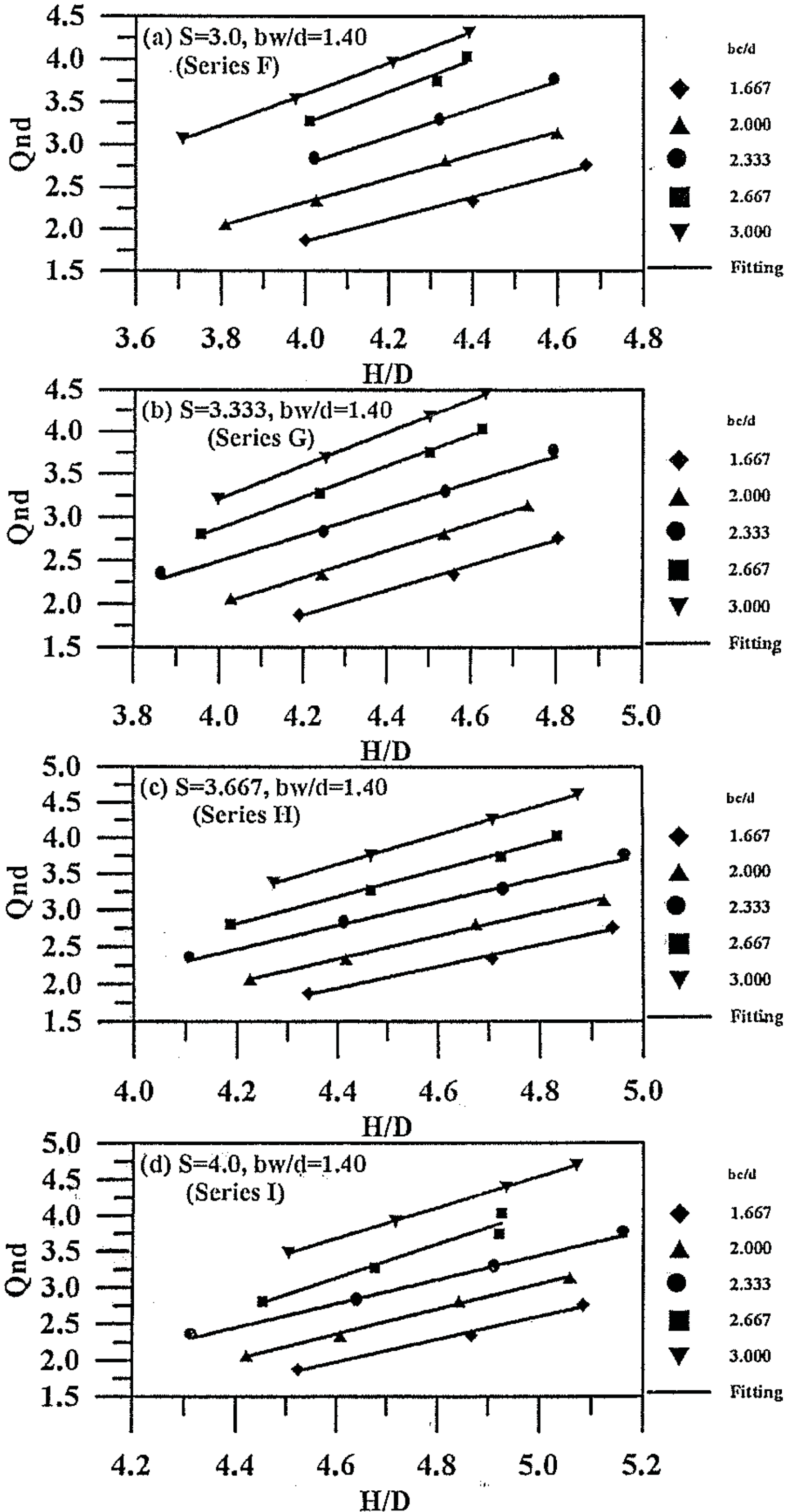

Figure 2. Effect of b_c/d on the relationship between H/D and Q_{nd}

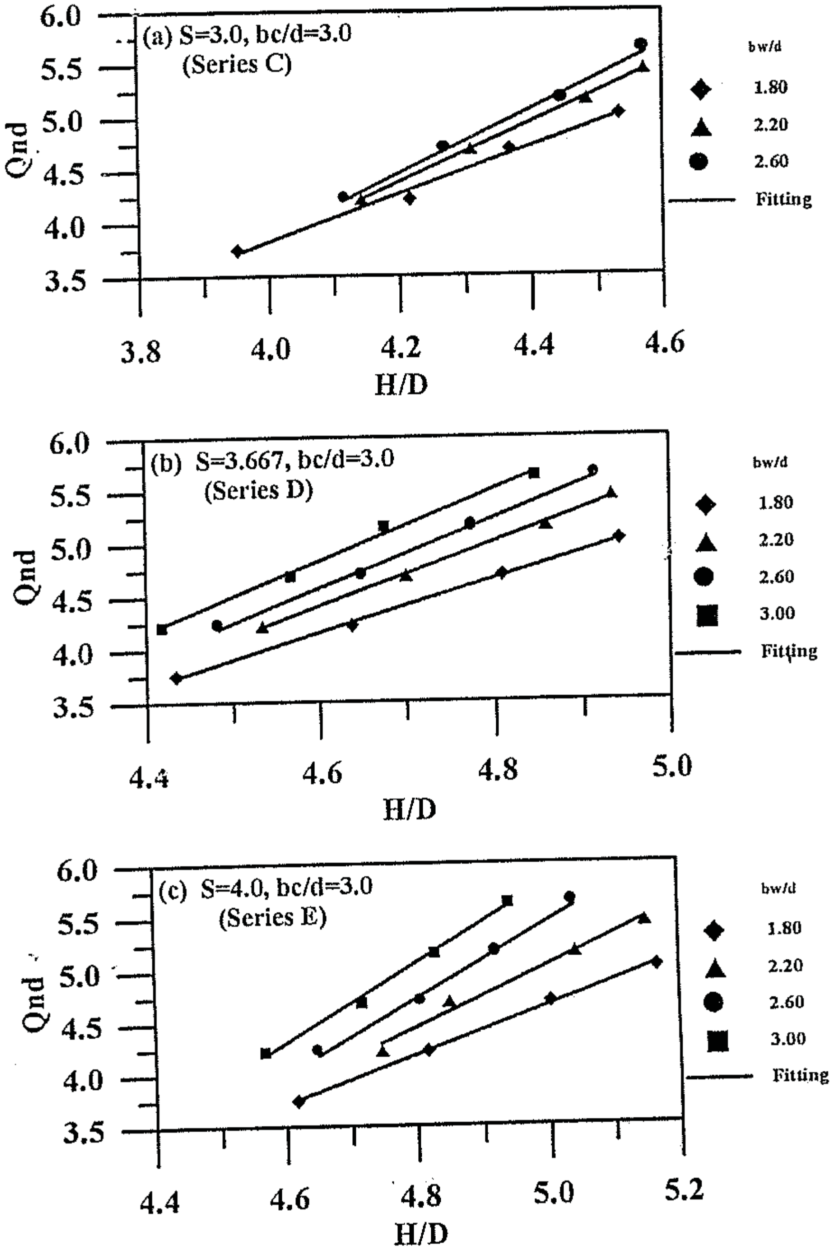

Figure 3: Effect of b_w/d on the relationship between H/D and Q_{nd}

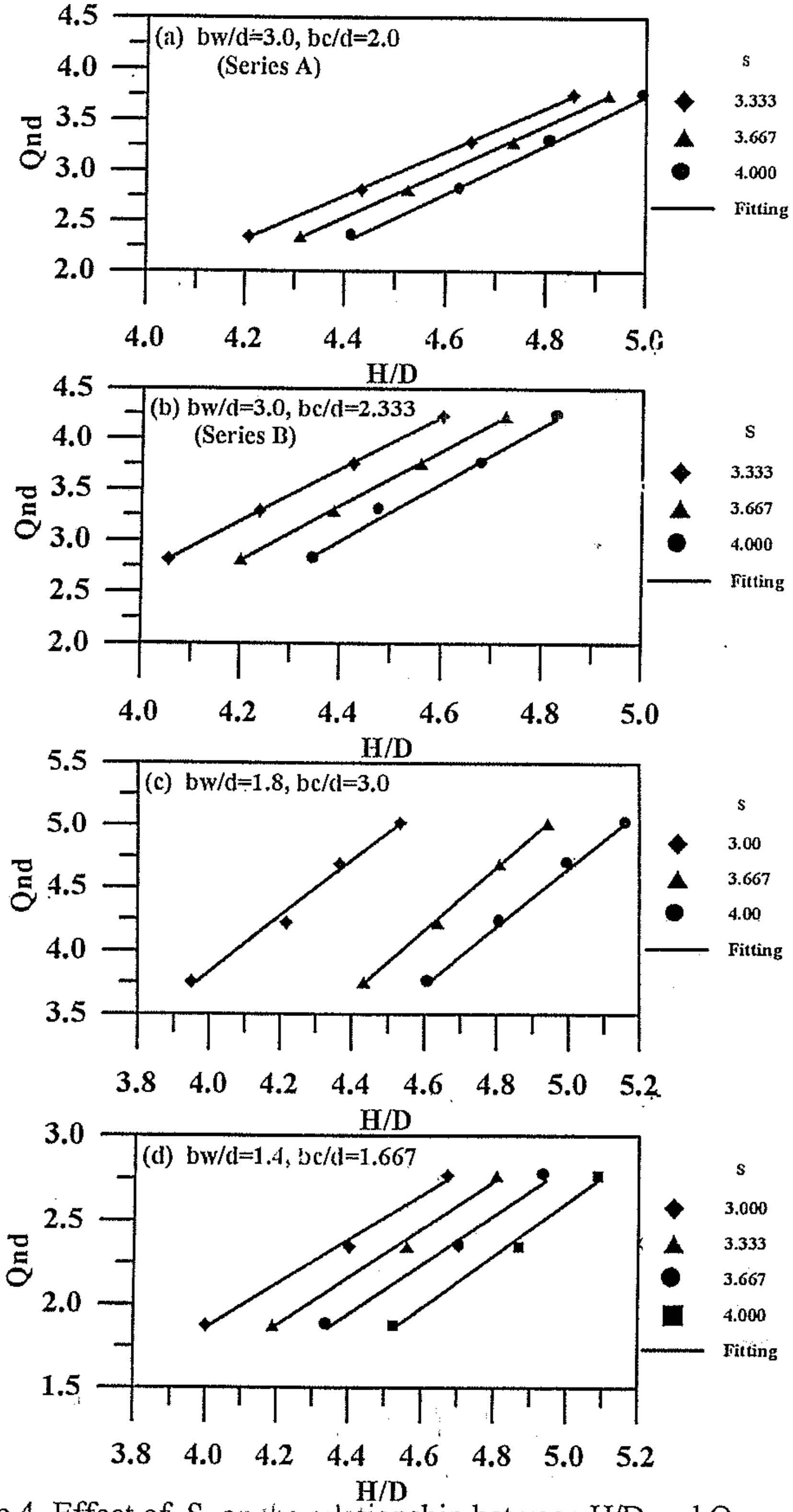

Figure 4. Effect of S on the relationship between H/D and Q_{nd}

b_w/D, it means that for constant d the more wider the weir the more discharge will be.

Figure 4 shows the relationship between Q_{nd} and H/d for constant values of b_w/D and b_c/D with S as third parameter having values of 3.0, 3.333, 3.667 and 4.0. It is clear that increasing the submergence causes a decrease in the discharge because of the increase of downstream water level results a backwater yielding a smaller differential head on the culvert and consequently, the discharge is reduced. Particularly, in Figure 4b, the line having S=4.0 is lower than the line having S=3.333.

5 Prediction of Discharge

One main point in dealing with discharge measurement structures, is the determination of discharge. The discharge could be predicted if the measurements were used to calibrate a properly regression model. Many models were tested in order to select the most valid one. The model that gives the best results is;

$$Q_{nd} = -0.074 + 0.225\left(\frac{H}{D}\right)^2 - 1.059S + 1.33\left(\frac{b_w}{D}\right) + 0.819\left(\frac{b_c}{D}\right) - 2.329\left(\frac{b_w}{b_c}\right) \quad (4)$$

Equation (4) has a coefficient of determination of 0.973 and standard error of estimate =0.177. Figure 5 shows the comparison between the values of Q_{nd} from measurements and the predicted values from Eq.(4). Figure 6 shows the comparison between the prediction of Eq.(4) and the measured values for series F as a typical example. The predicted values are very close to the measured ones with a mean relative error of 0.039.

6 Conclusions

An experimental investigation was conducted concerning the discharge characteristics of simultaneous flow over broad-crested weirs and through box culverts. It was found that the relative upstream head H/D, the submergence ratio S, the weir width ratio b_w/D, culvert width ratio b_c/D and the weir width/culvert width ratio b_w/b_c are the main factors affecting the dimensionless discharge. The discharge always is the main factor affecting the structure volume, it increases with the increase of H/D and decreases with the increase of S assuming all other parameters are constants. However, at fixed values of H/D and S, the discharge increases with the increase of either b_w/D and/or b_c/D. Non-dimensional discharge prediction equation was developed to predict the discharge of the simultaneous flow over the broad-crested weir and through the box culvert. The prediction of the equation agreed well with the measurements against a percentage mean relative error of less than 4%.

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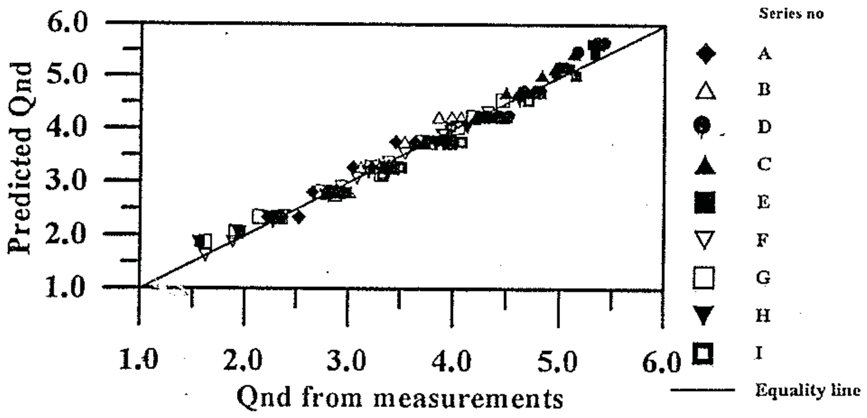

Figure 5. Comparison between Q_{nd} from measurements and Q_{nd} from Eq.(4) for all series

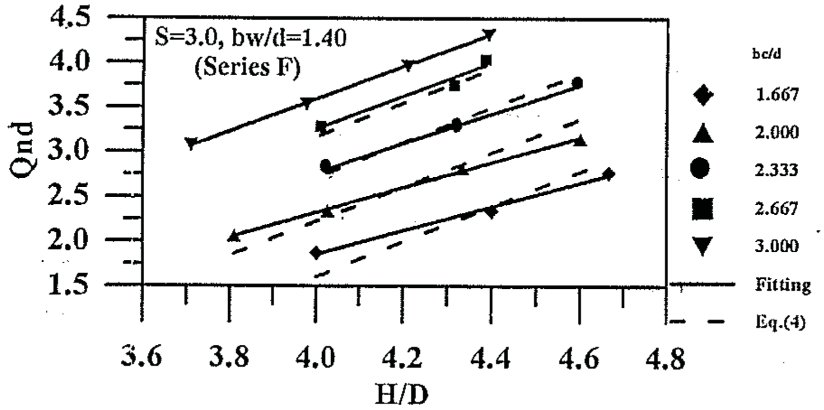

Figure 6. Comparison between Q_{nd} from measurements and Q_{nd} from Eq.(4)

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8 Notations

The following symbols are used in the present paper

b_w is the width of the contracted broad-crested weir,

b_c is the width of the culvert vent,

B is the channel width,

D is the height of the culvert,

g is the gravitational acceleration,

h_w is the head of water above the weir,

H is the depth of water 40 cm upstream the culvert inlet,

H_d is the depth of water just downstream of the culvert,

H_t is the tailwater depth downstream the culvert,

L is the length of the weir or the length of the culvert,

P is the height of the weir,

Q is the combined discharge of the structure,

Q_c is the discharge through culvert,

Q_{nd} is combined the discharge,

Q_w is the discharge over the weir,

S is the submergence ratio,

S_o is the bottom slope,

μ is the dynamic viscosity of water and

ρ is the density of water.

Appendix 1

Experimental conditions and experimental data of the present study

Series	b_w (m)	b_c (m)	H/D	Q_{nd}	S	b_w/D	b_c/D	b_w/b_c
A1	0.180	0.120	4.100	2.347	3.000	3.000	2.000	1.500
A1	0.180	0.120	4.782	3.755	3.000	3.000	2.000	1.500
A1	0.180	0.120	4.335	2.816	3.000	3.000	2.000	1.500
A1	0.180	0.120	4.567	3.286	3.000	3.000	2.000	1.500
A2	0.180	0.120	4.312	2.347	3.667	3.000	2.000	1.500
A2	0.180	0.120	4.525	2.816	3.667	3.000	2.000	1.500
A2	0.180	0.120	4.733	3.286	3.667	3.000	2.000	1.500
A2	0.180	0.120	4.923	3.755	3.667	3.000	2.000	1.500
A3	0.180	0.120	4.812	3.286	4.000	3.000	2.000	1.500
A3	0.180	0.120	4.630	2.816	4.000	3.000	2.000	1.500
A3	0.180	0.120	4.417	2.347	4.000	3.000	2.000	1.500
B1	0.180	0.140	3.890	2.816	3.000	3.000	2.333	1.286
B1	0.180	0.140	4.303	3.755	3.000	3.000	2.333	1.286
B1	0.180	0.140	4.482	4.224	3.000	3.000	2.333	1.286
B1	0.180	0.140	4.100	3.286	3.000	3.000	2.333	1.286
B2	0.180	0.140	4.200	2.816	3.667	3.000	2.333	1.286
B2	0.180	0.140	4.387	3.286	3.667	3.000	2.333	1.286
B2	0.180	0.140	4.558	3.755	3.667	3.000	2.333	1.286
B2	0.180	0.140	4.725	4.224	3.667	3.000	2.333	1.286
B3	0.180	0.140	4.683	3.755	4.000	3.000	2.333	1.286
B3	0.180	0.140	4.350	2.816	4.000	3.000	2.333	1.286
B3	0.180	0.140	4.833	4.224	4.000	3.000	2.333	1.286

Series	b_w (m)	b_c (m)	H/D	Q_{nd}	S	b_w/D	b_c/D	b_w/b_c
C1	0.108	0.180	4.533	5.022	3.000	1.800	3.000	0.600
C1	0.108	0.180	4.367	4.694	3.000	1.800	3.000	0.600
C1	0.108	0.180	3.950	3.755	3.000	1.800	3.000	0.600
C1	0.108	0.180	4.217	4.224	3.000	1.800	3.000	0.600
C2	0.132	0.180	4.572	5.445	3.000	2.200	3.000	0.733
C2	0.132	0.180	4.483	5.163	3.000	2.200	3.000	0.733
C2	0.132	0.180	4.308	4.694	3.000	2.200	3.000	0.733
C2	0.132	0.180	4.142	4.224	3.000	2.200	3.000	0.733
C3	0.156	0.180	4.448	5.163	3.000	2.600	3.000	0.867
C3	0.156	0.180	4.272	4.694	3.000	2.600	3.000	0.867
C3	0.156	0.180	4.117	4.224	3.000	2.600	3.000	0.867
C3	0.156	0.180	4.575	5.632	3.000	2.600	3.000	0.867
D1	0.108	0.180	4.808	4.694	3.667	1.800	3.000	0.600
D1	0.108	0.180	4.433	3.755	3.667	1.800	3.000	0.600
D1	0.108	0.180	4.637	4.224	3.667	1.800	3.000	0.600
D1	0.108	0.180	4.942	5.022	3.667	1.800	3.000	0.600
D2	0.132	0.180	4.533	4.224	3.667	2.200	3.000	0.733
D2	0.132	0.180	4.700	4.694	3.667	2.200	3.000	0.733
D2	0.132	0.180	4.933	5.445	3.667	2.200	3.000	0.733
D2	0.132	0.180	4.858	5.163	3.667	2.200	3.000	0.733
D3	0.156	0.180	4.650	4.694	3.667	2.600	3.000	0.867
D3	0.156	0.180	4.917	5.632	3.667	2.600	3.000	0.867
D3	0.156	0.180	4.775	5.163	3.667	2.600	3.000	0.867
D3	0.156	0.180	4.483	4.224	3.667	2.600	3.000	0.867
D4	0.180	0.180	4.417	4.224	3.667	3.000	3.000	1.000
D4	0.180	0.180	4.567	4.694	3.667	3.000	3.000	1.000
D4	0.180	0.180	4.675	5.163	3.667	3.000	3.000	1.000
D4	0.180	0.180	4.847	5.632	3.667	3.000	3.000	1.000
E1	0.108	0.180	5.167	5.022	4.000	1.800	3.000	0.600
E1	0.108	0.180	5.003	4.694	4.000	1.800	3.000	0.600
E1	0.108	0.180	4.617	3.755	4.000	1.800	3.000	0.600
E1	0.108	0.180	4.817	4.224	4.000	1.800	3.000	0.600
E2	0.132	0.180	5.042	5.163	4.000	2.200	3.000	0.733
E2	0.132	0.180	4.850	4.694	4.000	2.200	3.000	0.733
E2	0.132	0.180	4.747	4.224	4.000	2.200	3.000	0.733
E2	0.132	0.180	5.150	5.445	4.000	2.200	3.000	0.733
E3	0.156	0.180	5.042	5.632	4.000	2.600	3.000	0.867
E3	0.156	0.180	4.808	4.694	4.000	2.600	3.000	0.867
E3	0.156	0.180	4.650	4.224	4.000	2.600	3.000	0.867
E3	0.156	0.180	4.925	5.163	4.000	2.600	3.000	0.867
E4	0.180	0.180	4.717	4.694	4.000	3.000	3.000	1.000
E4	0.180	0.180	4.650	4.224	4.000	3.000	3.000	1.000
E4	0.180	0.180	4.830	5.163	4.000	3.000	3.000	1.000
E4	0.180	0.180	4.942	5.632	4.000	3.000	3.000	1.000
F1	0.084	0.100	4.000	1.877	3.000	1.400	1.667	0.840
F1	0.084	0.100	4.400	2.347	3.000	1.400	1.667	0.840
F1	0.084	0.100	4.667	2.769	3.000	1.400	1.667	0.840
F2	0.084	0.120	3.808	2.065	3.000	1.400	2.000	0.700
F2	0.084	0.120	4.025	2.347	3.000	1.400	2.000	0.700
F2	0.084	0.120	4.333	2.816	3.000	1.400	2.000	0.700
F2	0.084	0.120	4.600	3.145	3.000	1.400	2.000	0.700
F3	0.084	0.140	4.025	2.816	3.000	1.400	2.333	0.600
F3	0.084	0.140	4.325	3.286	3.000	1.400	2.333	0.600
F3	0.084	0.140	4.600	3.755	3.000	1.400	2.333	0.600
F4	0.084	0.160	4.008	3.286	3.000	1.400	2.667	0.525

Series	b_w (m)	b_c (m)	H/D	Q_{nd}	S	b_w/D	b_c/D	b_w/b_c
F4	0.084	0.160	4.313	3.755	3.000	1.400	2.667	0.525
F4	0.084	0.160	4.387	4.037	3.000	1.400	2.667	0.525
F5	0.084	0.180	3.708	3.286	3.000	1.400	3.000	0.467
F5	0.084	0.180	3.975	3.755	3.000	1.400	3.000	0.467
F5	0.084	0.180	4.208	4.224	3.000	1.400	3.000	0.467
F5	0.084	0.180	4.392	4.553	3.000	1.400	3.000	0.467
G1	0.084	0.100	4.188	1.877	3.333	1.400	1.667	0.840
G1	0.084	0.100	4.558	2.347	3.333	1.400	1.667	0.840
G1	0.084	0.100	4.803	2.769	3.333	1.400	1.667	0.840
G2	0.084	0.120	4.025	2.065	3.333	1.400	2.000	0.700
G2	0.084	0.120	4.242	2.347	3.333	1.400	2.000	0.700
G2	0.084	0.120	4.533	2.816	3.333	1.400	2.000	0.700
G2	0.084	0.120	4.733	3.145	3.333	1.400	2.000	0.700
G3	0.084	0.140	3.867	2.347	3.333	1.400	2.333	0.600
G3	0.084	0.140	4.250	2.816	3.333	1.400	2.333	0.600
G3	0.084	0.140	4.542	3.286	3.333	1.400	2.333	0.600
G3	0.084	0.140	4.800	3.755	3.333	1.400	2.333	0.600
G4	0.084	0.160	3.953	2.816	3.333	1.400	2.667	0.525
G4	0.084	0.160	4.237	3.286	3.333	1.400	2.667	0.525
G4	0.084	0.160	4.500	3.755	3.333	1.400	2.667	0.525
G4	0.084	0.160	4.625	4.037	3.333	1.400	2.667	0.525
G5	0.084	0.180	3.993	3.286	3.333	1.400	3.000	0.467
G5	0.084	0.180	4.250	3.755	3.333	1.400	3.000	0.467
G5	0.084	0.180	4.500	4.224	3.333	1.400	3.000	0.467
G5	0.084	0.180	4.633	4.553	3.333	1.400	3.000	0.467
H1	0.084	0.100	4.342	1.877	3.667	1.400	1.667	0.840
H1	0.084	0.100	4.707	2.347	3.667	1.400	1.667	0.840
H1	0.084	0.100	4.942	2.769	3.667	1.400	1.667	0.840
H2	0.084	0.120	4.225	2.065	3.667	1.400	2.000	0.700
H2	0.084	0.120	4.417	2.347	3.667	1.400	2.000	0.700
H2	0.084	0.120	4.675	2.816	3.667	1.400	2.000	0.700
H2	0.084	0.120	4.925	3.145	3.667	1.400	2.000	0.700
H3	0.084	0.140	4.112	2.347	3.667	1.400	2.333	0.600
H3	0.084	0.140	4.417	2.816	3.667	1.400	2.333	0.600
H3	0.084	0.140	4.733	3.286	3.667	1.400	2.333	0.600
H3	0.084	0.140	4.972	3.755	3.667	1.400	2.333	0.600
H4	0.084	0.160	4.187	2.816	3.667	1.400	2.667	0.525
H4	0.084	0.160	4.467	3.286	3.667	1.400	2.667	0.525
H4	0.084	0.160	4.725	3.755	3.667	1.400	2.667	0.525
H4	0.084	0.160	4.833	4.037	3.667	1.400	2.667	0.525
H5	0.084	0.180	4.273	3.286	3.667	1.400	3.000	0.467
H5	0.084	0.180	4.467	3.755	3.667	1.400	3.000	0.467
H5	0.084	0.180	4.708	4.224	3.667	1.400	3.000	0.467
H5	0.084	0.180	4.875	4.553	3.667	1.400	3.000	0.467
I1	0.084	0.100	4.523	1.877	4.000	1.400	1.667	0.840
I1	0.084	0.100	4.867	2.347	4.000	1.400	1.667	0.840
I1	0.084	0.100	5.083	2.769	4.000	1.400	1.667	0.840
I2	0.084	0.120	4.420	2.065	4.000	1.400	2.000	0.700
I2	0.084	0.120	4.607	2.347	4.000	1.400	2.000	0.700
I2	0.084	0.120	4.842	2.816	4.000	1.400	2.000	0.700
I2	0.084	0.120	5.058	3.145	4.000	1.400	2.000	0.700
I3	0.084	0.140	4.317	2.347	4.000	1.400	2.333	0.600
I3	0.084	0.140	4.642	2.816	4.000	1.400	2.333	0.600
I3	0.084	0.140	4.917	3.286	4.000	1.400	2.333	0.600
I3	0.084	0.140	5.167	3.755	4.000	1.400	2.333	0.600

Series	b_w (m)	b_c (m)	H/D	Q_{nd}	S	b_w/D	b_c/D	b_w/b_c
I4	0.084	0.160	4.452	2.816	4.000	1.400	2.667	0.525
I4	0.084	0.160	4.675	3.286	4.000	1.400	2.667	0.525
I4	0.084	0.160	4.920	3.755	4.000	1.400	2.667	0.525
I4	0.084	0.160	4.925	4.037	4.000	1.400	2.667	0.525
I5	0.084	0.180	4.503	3.286	4.000	1.400	3.000	0.467
I5	0.084	0.180	4.717	3.755	4.000	1.400	3.000	0.467
I5	0.084	0.180	4.933	4.224	4.000	1.400	3.000	0.467
I5	0.084	0.180	5.070	4.553	4.000	1.400	3.000	0.467