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Effect of Bed Flume Contraction on Discharge Coefficient of Composite Weir-Gate Structure

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Abstract-The present work is concerned with the impact of bed flume contraction on discharge coefficient of composite hydraulic structure which consists of trapezoidal weir and trapezoidal gate as compared with the normal case of flume without bed contraction. It is very important to investigate the effect of bed flume contraction on hydraulic parameters which control the hydraulic response of regime especially in downstream region. Some experimental work is carried out to study the effect of many factors on the discharge coefficient and these factors are; Froude number, Reynolds number, discharge quantity, flow velocity, and average downstream water depth of hydraulic regime. It was found that nonlinear water surface profile occurs in downstream of regime in case of bed flume contraction as compared with linear water surface profile in case without bed flume contraction. Also, the interfere between over flow velocity and under flow velocity reflects on hydraulic response of the whole system.

Keywords- *Discharge Coefficient, Bed Flume Contraction, Weir-Gate Structure*

I. Introduction

Hydraulic structures often have a design that makes a contracted stream achieving the least cost structure necessary as long as the location is technically feasible. The cross section's hang works on disturbing the flow in both the contracted reach and near to it from upstream and downstream. This change over a specified reach in the channel's cross section, slope and, and/or alignment is named local transition. These channel transitions are mainly used in minimizing and avoiding excessive loss of energy, eliminating cross waves, resulting turbulence and ensuring safety for both structure and downstream channel reach, see e.g. (Hinds, 1928), (Ippen, 1950) and (Engelund and Petersen, 1953). In addition, the local channel transition has the possibility of changing flow regime in channel at particular locations through or beyond the transition depending on factors such as the incoming flow rate, contraction ratio and length. Flow through transition each either is subcritical, critical or supercritical. These flow types are preceded by subcritical flow upstream of the transition and may or may not be followed by a supercritical flow.

A review of the literature ended up showing that there have been many studies concerning channel contraction that have been published [1-14]. An experimental investigation was carried out by (Kindsvater et al., 1953) and (Kindsvater and Carter, 1955) addressing the effects that different types of contractions have on discharge characteristics. Various design for channel transition (contraction and expansion) were tested by (Formica, 1955) and the main results of that work were presented in (Chow, 1959).

The effect of thin plate contraction placed normal to channel axis was investigated by (Vallentine, 1958). Data that included different regimes of flow was covered in his observations. (Laursen, 1970), on the other hand, identified the different types of flow through studying the contraction coefficient at sudden expansion in bridge locations. The contraction coefficient was found to vary between 0.7 for about 30% of the contraction ratio and 1.0 for no contraction. (Hager and Dupraz, 1985) obtained the coefficient of contraction in terms of the contraction ratio, the inlet angle of the contraction and the length ratio of the contracted reach through deriving a theoretical equation. The assumption was that flow passes in its critical state through the contracted length. They also verified an expression for the contraction coefficient experimentally. One observation about this equation was that it slightly overestimates the contraction coefficient compared to the experimental measurements.

(Alsamman, 1989) was investigating the effects that inlet angle of transition, contraction ratio and transition length ratio have on the contraction coefficient, basing it off experimental data where the contraction is asymmetric and the upstream flow is subcritical and flow passes in a critical state through transition length. The conclusion was that the contraction coefficient decreases with the decrease of contraction ratio and the increase of transition inlet angle from 30o to 90o. In addition, it was noted that transition outlet angle has an insignificant effect on contraction coefficient. Also, relative transition length, L/b, had no remarkable effect on contraction coefficient in cases where L/b is greater than 5, where b is flow width within the transition.

The Laser Doppler Velocimetry (LDV) was used by (Attia and Ibrahim, 2000) for the purpose of studying the effect of channel contraction on turbulence characteristics. It was concluded that turbulence intensities located upstream of the contraction would be high for smaller contraction ratios (b/B) than for bigger ones. The turbulence intensities increase with decreasing contraction ratio within the contraction and they are larger in the location of the downstream expansion for smaller contractions. In recent times, the effects of asymmetric both sudden and gradual transition on discharge characteristics represented by the discharge coefficient and relative energy loss when the flow through the contraction length happens to be transitional from subcritical to supercritical was experimentally investigated by (Negm, 2001, 2002a, and 2002b).

In the present study, the effects of horizontal channel downstream contraction on discharge coefficient of composite hydraulic structure which consists of trapezoidal weir and trapezoidal gate are investigated based on experimental observations. This study concentrated on overlapping between hydraulic characteristics and geometrical dimension.

II. Fundamentals of Fluid Mechanics

The flow-rate through combined hydraulic structure for the free flow case, is represented by the summation of both weir and gate flow-rates.

$$Q_{theoretical} = Q_{weir} + Q_{gate} \quad (1)$$

To calculate the theoretical flow – rate through weir (Streeter, 1983)

For rectangular weir:

$$Q_{weir} = \frac{2}{3}\sqrt{2g}\ L\,h^{3/2} \quad (2)$$

For triangular weir:

$$Q_{weir} = \frac{8}{15}\sqrt{2g}\ \tan\frac{\emptyset}{2}\ h^{5/2} \quad (3)$$

$$Q_{weir} = Q_{triangular\ weir} + Q_{rectangular\ weir} \quad (4)$$

$$Q_{weir} = \frac{8}{15}\sqrt{2g}\ \tan\frac{\emptyset}{2}\ h^{5/2} + \frac{2}{3}\sqrt{2g}\ L\,h^{3/2} \quad (5)$$

To calculate the theoretical flow rate through gate:

From continuity equation (Streeter, 1983):

$$Q = V\,A \quad (6)$$

$$Q_{gate} = Q_{triangulat} + Q_{rectangular} \quad (7)$$

$$Q_{gate} = V\,A_{triangular} + V\,A_{rectangular} \quad (8)$$

$$Q_{gate} = V\left(A_{triangular} + A_{rectangular}\right) \quad (9)$$

$$V = \sqrt{2gH} \quad (10)$$

For free flow:

$$H = d + y + h \quad (11)$$

$$Q_{act} = c_d\,Q_{theoretical} \quad (12)$$

To estimate the total actual flow rate that passes through composite hydraulic structure:

$$Q_{actual} = \frac{8}{15}\,c_d\sqrt{2g}\ \tan\frac{\emptyset}{2}\ h^{5/2} + \frac{2}{3}\,c_d\sqrt{2g}\ L\,h^{3/2} + c_d\,V\left(A_{triangular} + A_{rectangular}\right) \quad (13)$$

H: Upstream water depth

h: Water head above sharp crest weir

y: Vertical distance between weir and gate

d: Water depth at gate opening

A: Flow cross- sectional area that crossing the gate

L: Width of rectangular notch

V: Flow velocity of water that crossing the gate

c_d : Coefficient of discharge

To estimate Froude Number (Fox and McDonald, 1994)

$$F_r = \frac{V}{\sqrt{gy}} \quad (14)$$

Where, V: flow velocity, g: gravity acceleration, y: stream water depth.

To calculate the Reynolds Number of the regime (Negm et al., 2002)

$$R_e = \frac{V\,d_d}{\upsilon} \quad (15)$$

d_d : Downstream water depth

υ: Kinematic viscosity of water

III. Experimental Work

The experiments were carried out in a rectangular glass sided flume with a dimension of 200cm length, 15cm depth and 7.5cm width. The discharge is measured using the volume method while the average water depth is measured by the scales fixed in the wall of the flume. Figure (1) shows the combinations shapes which considered in the present work. Table (1) reviews dimensions of the trapezoidal models that fabricate from wood material as well as the length of side obstructions that represent the bed contractions. Table (2) reviews selected information that was obtained from experimental study performed in laboratory. The following procedures are adopted in laboratory test (Qasim et. al., 2018).

1- The slope of the flume is always in horizontal position.

2- The models were fixed into flume at distance 80cm from the beginning of the flume.

3- The free flow condition is satisfied by removing the tail gate from the channel.

The above procedure was repeated for all models.

TABLE I. THE TESTED MODEL DIMENSIONS AND DETAILS OF SELECTED DIFFERENT LENGTH OF SIDE OBSTRUCTIONS (S.O)

Model No.	S.O Length (cm)	h_u (cm)	y (cm)	d (cm)	H (cm)
1	Without	1	5	2	9
2	80	1	5	2	9
3	100	1	5	2	9
4	Without	2	4	2	8
5	80	2	4	2	8
6	100	2	4	2	8
7	Without	1	3	3	7
8	80	1	3	3	7
9	100	1	3	3	7

TABLE II. RESULTS OF THE SELECTED EXPERIMENTAL MODELS

Model Case	Average h_d (cm)	Fr_{down}	Fr_{up}	R_N	V (m/sec)	$Q_{act.}$ (l/sec.)	Q_{theo} (l/sec.)	Cd
1	2.625	0.543	0.085	7242	0.895	0.543	0.879	0.618
2	3.200	0.432	0.091	7762	0.959	0.582	0.879	0.662
3	2.875	0.510	0.092	7787	0.962	0.584	0.879	0.664
4	3.875	0.409	0.137	9771	1.207	0.732	1.004	0.730
5	4.062	0.421	0.152	10801	1.335	0.810	1.004	0.807
6	3.875	0.448	0.151	10724	1.325	0.804	1.004	0.801
7	3.312	0.493	0.160	9309	0.666	0.698	1.300	0.537
8	4.250	0.355	0.168	9748	0.698	0.731	1.300	0.563
9	3.812	0.408	0.164	9524	0.682	0.714	1.300	0.550

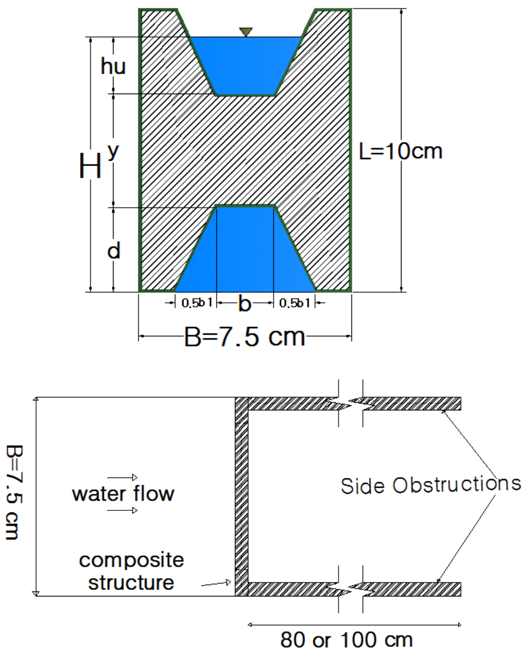

Figure 1. Definition sketch for the composite structure and contraction bed flume

Thirty Six models were tested (12 without bed contraction, 12 with bed contraction equal to 80 cm, and 12 with bed contraction equal to 100 cm) involving the following limitations: 2≤ y ≤5cm, 2≤ d ≤ 4cm, b=2 cm, 1≤ h_u ≤ 3. The bed flume contractions (side obstruction) cross sectional area equal to 5mmx10mm. Models of composite structures and bed flume contraction are made of wood sheet 5mm thick beveled along all the edges at 45^0 with sharp edges of thickness 1mm (Qasim et. al., 2018). Models of composite structures are fixed to flume using plexiglass supports, whereas the bed flume side obstructions are fixed in place by sticks along the bed of each side of the flume. The selection of the flume and model material was based on the available laboratory facilities. In each test, combined flow rate, $Q_{act.}$, head over the weir, h_u, downstream flow depth, h_d, and upstream flow depth, H, are measured under free flow conditions.

IV. RESULTS AND DISCUSSION

A composite weir-gate hydraulic structure is commonly used in irrigation system work so it is very important to study the interaction between this structure and flume or open channel due to significant interaction between over flow rate and under flow rate which reflects on the hydraulic behavior of regime. The target of this work based on study of the effect of bed flume contraction on the required functionality of composite hydraulic structure as compared with normal condition. The discharge coefficient for free flow condition are plotted versus Froude number for downstream of regime in figure (2) It is clear from figure that all points concentrated at $F_r = 0.5$ and distributed around it regardless the value of discharge coefficient. This means that the flow velocity is low and gravity force is dominant and this occurs when Froude number is less than unity. The bed flume contraction does not have any influence on the relationship between discharge coefficient and Froude number because of Froude number depends on flow velocity and water depth.

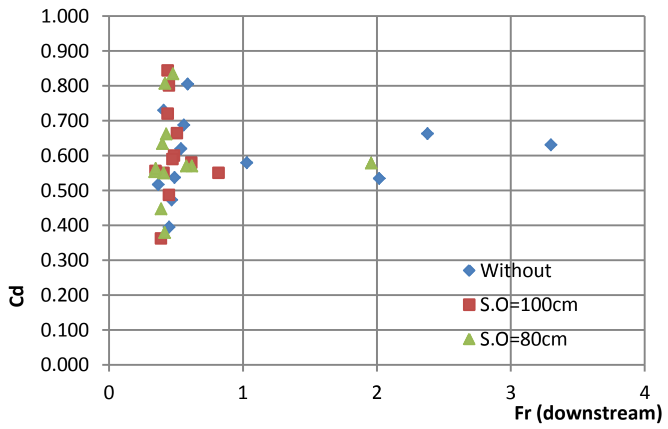

Figure 2. Variation of Coefficient of Discharge with downstream Froud Number

Figure (3) shows the discharge coefficient plotted versus Reynolds number. It is clear from this figure as Reynolds number increases the discharge coefficient decreases because of both of them depend on flow velocity. Reynolds number is directly proportional with velocity while discharge coefficient is inversely proportional with velocity. So this variation of flow velocity will reflect on the relationship between the non-dimensional parameter regardless of the bed flume contraction.

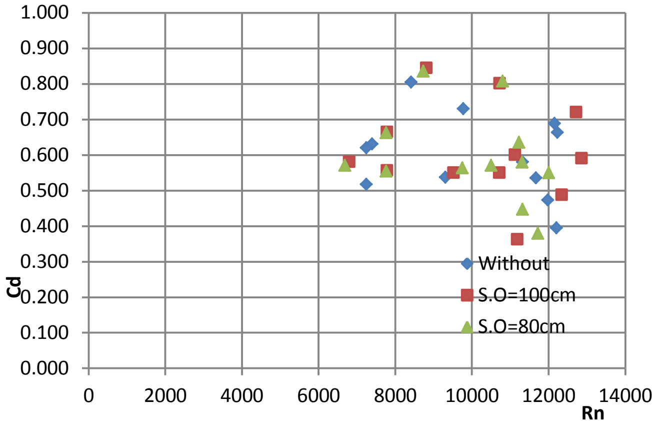

Figure 3. Variation of Coefficient of Discharge with Reynold's Number

Figure (4) shows the variation between the discharge coefficient and the measured discharge. It is clear from this figure as discharge increases the discharge coefficient will increase in the case of without bed flume contraction while in case of bed flume contraction the discharge coefficient will decrease when discharge increases and this obvious from the figure because of reduction in cross sectional area of flow in case of bed flume contraction and this leads to an increase in water flow velocity which is directly proportional with discharge and inversely proportional with discharge coefficient this reduction will reflect on the relationship.

The discharge coefficient for free flow condition are plotted versus velocity in figure (5) It is obvious from this figure that the relationship is complex due to interaction between over flow velocity from weir and under flow velocity from gate. Also the existence of longitudinal obstacle at the bed flume will share on complexity of relationship as compared with bed flume without contraction.

Figure (6) shows the relationship between discharge coefficient and Froude number at upstream of regime. All values of Froude number are less than unity then the gravity force will dominate at the upstream regime and lead to low flow velocity regardless the existence of bed flume contraction. The variation in relationship depends on water depth and flow velocity. The flow velocity is directly proportional with Froude number and inversely proportional with discharge coefficient and this will reflect on the relationship.

Figure (7) shows the relationship between discharge coefficient and average downstream water depth of regime. The discharge coefficient values increase with increase in depth of water in downstream regime especially with the existence of bed flume contraction. The discharge coefficient and downstream water depth are considered independent.

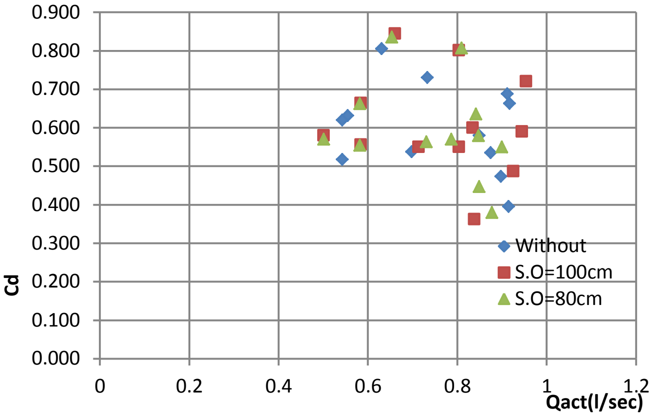

Figure 4. Variation of Coefficient of Discharge with Measured Discharge

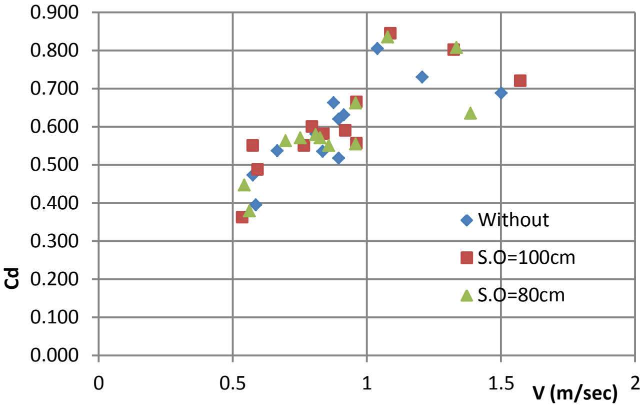

Figure 5. Variation of Coefficient of Discharge with Velocity

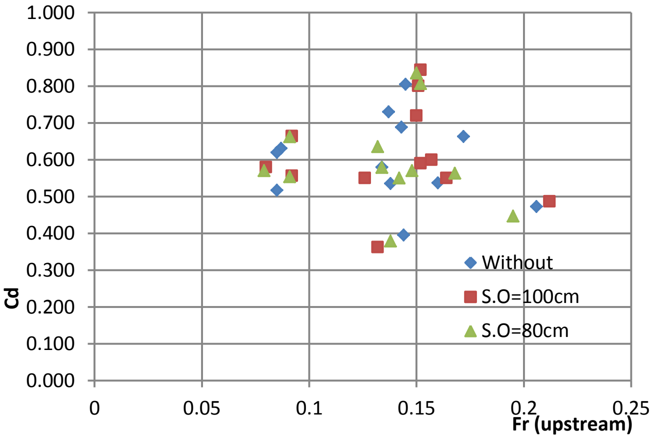

Figure 6. Variation of Coefficient of Discharge with upstream Froud Number

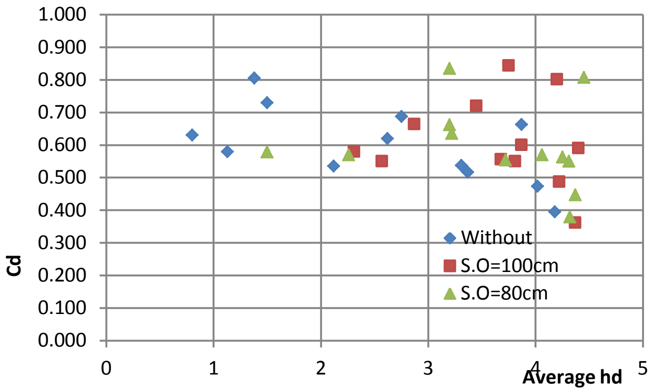

Figure 7. Variation of Coefficient of Discharge with Average downstream Depth of Water

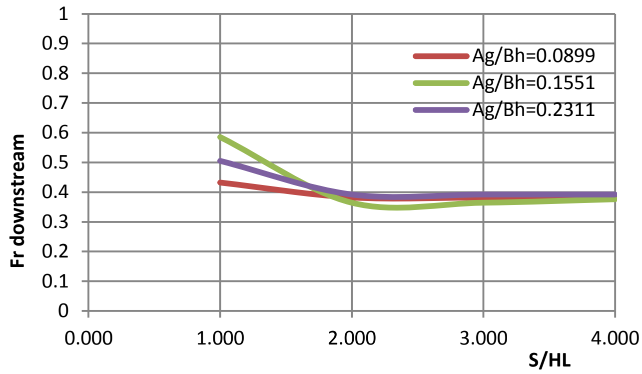

Figure 9. Profile of downstream Froud Number along the downstream Channel for Aw/BH=0.0899 and S.O=80cm

Figure (8) shows the variation in water surface profile at downstream of regime with Froude number. The values of water depth at downstream (S) are non-dimensionalized by division of the total depth of composite hydraulic structure (HL). It is obvious from this figure that linear water surface profile in the case of without bed flume contraction while nonlinear water surface profile occurs at downstream in case of existence bed flume contraction. Figure (9) shows the variation in nonlinear water surface profile at downstream of regime with Froude number for different cross sectional area of flow that crosses the gate. The cross sectional area of flow that cross the gate is non- dimensionalized by division by (Bh) where B is width of flume and h is the head above the sharp crested weir.

Table (3) reviews the variation in values of discharge quantity and coefficient of discharge for different values of cross sectional area of flow that cross the gate. It is clear from this table that the discharge and discharge coefficient increase with the increase in flow that pass the gate of composite hydraulic structure and some fluctuation occurs due to overlapping between over flow velocity and under flow velocity. The cross sectional area of flow that passes the gate is non-dimensionalized by division of the hydraulic cross sectional area (BH).

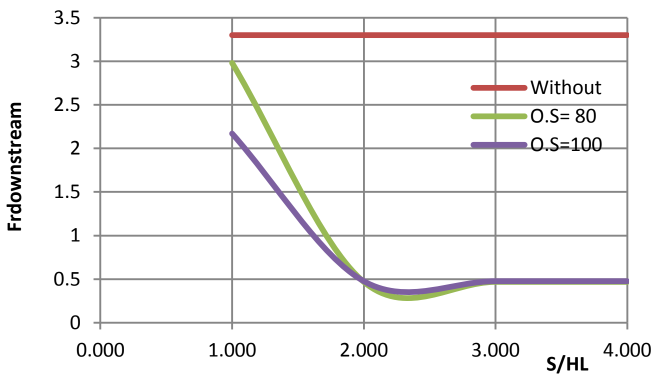

Figure 8. Profile of downstream Froud Number along the downstream Channel for Ag/BH=0.0899 and Aw/BH=0.0384

TABLE III. VARIATION OF ACTUAL DISCHARGE AND COEFFICIENT OF DISCHARGE WITH AREA OF GATE FOR AW/BH=0.0899

Ag/BH	$Q_{act.}$ (l/sec)			C_d		
	Without	S.O =80cm	S.O =100cm	Without	S.O =80cm	S.O =100cm
0.0899	0.543	0.582	0.584	0.517	0.554	0.556
0.1551	0.875	0.900	0.964	0.535	0.550	0.590
0.2311	0.915	0.879	0.830	0.395	0.379	0.362

V. CONCLUSIONS

The following points are apparent from the present work

1- Froude number has a vital role in describing the flow velocity level and the force the developed in regime.

2- Reynolds number represents a good parameter in describing the relationship between turbulent flow and discharge coefficient of composite hydraulic structure.

3- The measured discharge has a major impact in evaluating the value of discharge coefficient.

4- Hydraulic characteristics and geometrical dimension have a major effect on relationship between discharge coefficient and flow velocity.

5- Discharge coefficient and water head depth at downstream are considered independent parameters.

6- Linear water surface profiles are existent when there is a bed flume without contraction while the nonlinear water surface profile exists with the existence of bed flume contraction.

7- Bed flume contraction has a direct and indirect influence in hydraulic response of regime.

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