

Performance Improvement of Broad Crested Weirs

Bahzad M.A. Noori,

Inam A.K. Juma,

Dept. of Water Resources,
College of Engineering,
University of Mousl.

Dept. of, Civil Engineering,
College of Engineering,
University of Dohuk.

Abstract

In order to improve the performance of broad crested weirs, forty weir models were manufactured and tested and two hundred thirty six experiments were conducted in a laboratory horizontal channel of 10m length, 0.3m width and 0.45m depth for a wide range of discharges. The performance of broad crested weir was improved by introducing an upstream face slope, rounding upstream corner and capping the upstream corner with a semi-cylinder in order to reduce the effect of flow separation. Analysis of experimental results showed that introducing an upstream slope face to square edge broad crested weir improved the performance and gave higher values of discharge coefficient. Rounding upstream corner increased the values of discharge coefficient and improved the performance of the weir. Also, capping the upstream corner with semi-cylinder improved the performance of the weir and gave higher values of discharge coefficient. Two empirical equations were obtained to estimate the value of discharge coefficient in terms of effective head to crest height ratio, upstream corner radius to crest height ratio and radius of cap to crest height ratio with high correlation coefficients.

تحسين أداء هدارات القمة العريضة

بهزاد محمد علي نوري
قسم هندسة الموارد

انعام علي قاسم
قسم الهندسة المدنية

المائية

كلية الهندسة/ جامعة

كلية الهندسة/ جامعة دهوك

الموصل

الخلاصة

لتحسين أداء الهدارات ذات القمة العريضة تم إنشاء واختبار أربعين نموذجاً منها، و إجراء مائتان و ستة وثلاثون تجربة في قناة مختربية أفقية ذات طول 10م وعرض 0.3 م وعمق 0.45م و لمدى واسع من التصارييف. لقد تم تحسين قمة الهدار العريضة بوضع ميل مقدم للهدار وجعل زاوية مقدم الهدار مستديرة وتلبيس نصف اسطوانة على زاوية مقدم الهدار وذلك لتقليل تأثير انفصال خطوط الجريان. اظهر تحليل النتائج المختربية ان وجود ميل مقدم الهدار ادى الى تحسين أداء الهدار واعطى قيم أعلى لمعامل التصريف. كما أن جعل زاوية مقدم الهدار مستديرة زادت من قيم معامل التصريف وحسنت أداء الهدار عريض القمة وكذلك تلبيس نصف اسطوانة على زاوية مقدم الهدار حسن من أداء الهدار وأعطى معاملات تصريف أعلى. لقد تم الحصول على معادلتين وضعيتين لحساب قيمة معامل التصريف بدلالة نسبة الشحنة الفعالة فوق القمة الى ارتفاع القمة ونسبة نصف قطر استدارة زاوية المقدم الى ارتفاع القمة ونصف قطر اسطوانة التلبيس الى ارتفاع القمة وبمعاملات ارتباط عالية.

Notation

The following symbols are used in this paper:

C_D	= dimensionless weir discharge coefficient,
f_1 to f_5	= signify function of,
g	= acceleration due to gravity,
H_1	= upstream head above crest,
H_e	= effective upstream head above crest,
L	= weir length,
P_1	= weir height ,
P_2	= height of semi-cylinder crest above bed,
q	= flow rate over the weir per unit width,
R_1	= radius of the upstream corner of the weir,
R_2	= radius of semi-cylinder cap,
Re	= Reynolds number,
S	= upstream weir face slope, and
ν	= kinematics viscosity.

Introduction

Broad crested weirs are low cost and simple overflow structures widely used for flow measurements in field and laboratory channels. Moreover, broad crested weirs have an advantage of good range of flow rates and high modular limit. For square edge upstream corner, a separation zone appears as a dead water zone and consequently decreasing the effective head above the crest, rounding this zone, or rounding the upstream corner increases the discharge coefficient and decreases the silt deposition at upstream face especially for small weir heights (Ramamurthy et al., 1988;Gogus et al., 2006).

The characteristics of flow over broad crested weirs have attracted the attention of many investigators to obtain empirical equations for the estimation of discharge coefficients (Tracy, 1957; Rao and Rao, 1973; Achters et al., 1978; Sarker and Rhodes, 2004; Gonzalez and Chanson,2007). Based on the boundary layer theory, Hall (1962) derived an expression for the free flow and submerged conditions of square edge broad crested weirs. The corner separation of square edge broad crested weir was analyzed by Moss (1972) concluding that the length of separation zone is 77% of head above crest and its height is 15% of head above crest. Hydraulic features of flow over square edge broad crested weirs with vertical upstream face were studied experimentally by Crabbe (1963) and Hager et. al. (1994).

Govinda Rao and Muralidhar (1963) classified weirs as broad crested weirs if the ratio of head above crest (H_1) to weir length (L) is greater than 0.1 and less than 0.4, while, Singer (1964) went to a limit as wide as $0.08 < H_1/L < 5.6$. Rao and Shukla (1971) studied experimentally the effect of finite crest length on discharge characteristics of broad crested weirs with square and elliptical upstream corners. Ramamurthy et al. (1988) gave a condition that the upstream corner of broad crested weir is considered sharp if the radius of curvature at this corner is less than 9.4% of weir height. Johnson (2000) conducted experiments on flat-topped and sharp-crested weirs presenting his results in the formation of a single curve to estimate the discharge coefficient values. The effect of upstream face inclination on the characteristics of rectangular broad crested weirs was studied by Replogle (1978), Clemmens et al. (1984) and Bos et al. (1984) giving design tables for a wide range of variables.

In the present investigation, the main objective is to study the effects of upstream sloping face in order to reduce the dead water region in the upstream approach, rounding of the upstream top corner of the weir and capping the upstream separation zone with semi-cylinder on the characteristics of flow above broad crested weirs.

Theoretical Considerations

The broad crested models are based on the following assumptions: flow upstream of weir is steady, sub-critical and two dimensional; the effects of flow surface tension and viscosity are eliminated. For rectangular broad crested weir assuming the critical flow on the weir crest, the equation for flow rate is written as (Boiten, 2002):

$$q = C_D \times \frac{2}{3} \times H_e \sqrt{\frac{2}{3} g H_e} \dots\dots\dots(1)$$

where,

q = flow rate over the weir per unit width,

C_D = dimensionless weir discharge coefficient,

H_e = effective upstream head above crest including approach velocity head

$$= H_1 + \frac{q^2}{2g(P_1 + H_1)^2} ,$$

H₁ = upstream head above crest,

P₁ = weir height, and

g = acceleration due to gravity.

For a free flow over broad crested weir with square or rounded upstream corner, a functional relationship can be written as follows(see Figs(1a) to (1d)) :

$$f_1(q, H_e, P_1, R_1, g, S, \nu) = 0 \dots\dots\dots(2)$$

where,

R₁ = radius of the upstream corner of the weir,

S = upstream weir face slope, and

ν = kinematic viscosity.

Using Buckingham Pi-theorem and after certain permissible manipulations, Eq.(2) becomes:

$$C_D = \frac{q}{\frac{2}{3} H_e \left(\frac{2}{3} g H_e \right)^{\frac{1}{2}}} = f_2 \left(\frac{H_e}{P_1}, \frac{R_1}{P_1}, S, R_e \right) \dots\dots\dots(3) \text{ where,}$$

R_e = Reynolds number.

Reynolds number will have very large values and hence its effect on C_D will be very little, therefore, R_e can be dropped and Eq.(3) can be written as:

$$C_D = f_3 \left(\frac{H_e}{P_1}, \frac{R_1}{P_1}, S \right) \dots\dots\dots(4)$$

For rectangular broad crest weirs with upstream sloping face, Eq.(4) can be expressed as:

$$C_D = f_4 \left(\frac{H_e}{P_1}, S \right) \dots\dots\dots(5)$$

Another method of improving the efficiency of the crest is to introduce a semi-cylinder of radius R₂ at the upstream separation zone (see Fig.1e), consequently, for this case, Eq.(5) can be written as:

$$C_D = f_5 \left(\frac{H_e}{P_2}, \frac{R_2}{P_2}, S \right) \dots\dots\dots(6)$$

where,

P₂ = height of cylinder crest above bed.

Experimental Setup And Procedure

In order to check the validity of the proposed relationships, an intensive experimental program was carried out by testing different models of broad crested weirs of different cases. These models were tested in a horizontal glass walled tilting channel of 10m length, 0.3m width and 0.45m depth. A moveable carriage with a point gauge was mounted on brass rails at the top of channel sides. Forty weir models were manufactured and tested each having a specific condition. The first model was rectangular with square edge upstream and downstream of 0.45m length and 0.15m height (Fig. (1a)). For the following four models, the upstream face was given slopes(S) of (0.5H:1V), (1H:1V),(2H:1V),and (3H:1V), i.e., $S=2,1,0.5$ and 0.33 respectively (Fig.(1b)). In the following five models the upstream corner was rounded to radii (R_1) =1.5cm, 6cm, 9cm, 12cm and 15cm respectively (Fig. (1c)) and keeping the upstream face vertical. For models eleven to fifteen the upstream face slope was kept (0.5H: 1V, $S=2$) and the upstream corner radius (R_1) changed five times from 1.5cm to 15cm (Fig.(1d)). In the models sixteen to twenty, the upstream edge was capped with semi-cylinder of radius (R_2) =1cm and the upstream slope (S) was varied five times from (0H: 1V) to (3H: 1V), see Fig. (1e). For the remaining models radius of semi-cylinder (R_2) was changed to 2cm, 3cm, 4cm and 5cm and for each radius the upstream face slope was varied five times from vertical (0H:1V) to (3H:1V) as shown in Fig.(1e). Details of the tested weir models and the experimental program are shown in Table (1).

Analysis Of Results

Upstream Face Slope

A way of improving the performance of broad crested weir is to introduce an upstream face slope to the upstream square edge. The effect of upstream face slope on the behavior of broad crested weirs was studied by testing five weir models of different cases, the first weir model was broad crested with vertical upstream face(square edge), i.e., with slope(0H:1V), while, the other four were of slopes(0.5H:1V),(1H:1V),(2H:1V) and (3H:1V). Fig.(2) shows the experimentally determined relationships between C_D and H_o/P_1 for the five cases studied showing that C_D increases with the increase of H_o/P_1 for all slopes and existence of upstream slope gives higher values of discharge coefficient(C_D).

From Fig.(2) one may conclude that an upstream face slope of (0.5H:1V or $S=2$) is quite enough to give high values of C_D among other slopes. This means that upstream slope flatter than (0.5H:1V) will not give improvement to the value of discharge coefficient and will be more expensive in construction.

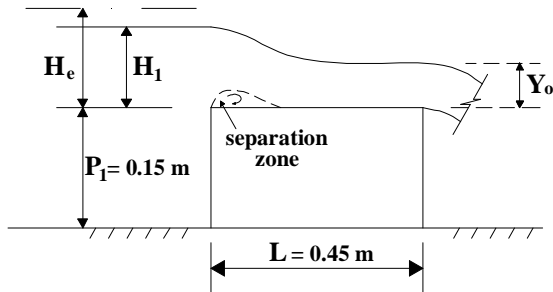


Fig. (1a) Flow over square edge weir with vertical upstream face (Model 1)

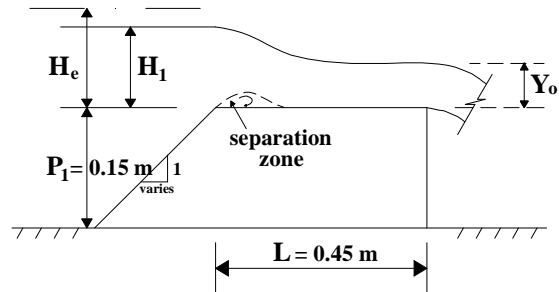


Fig. (1b) Flow over inclined upstream face weir (Models 2-5)

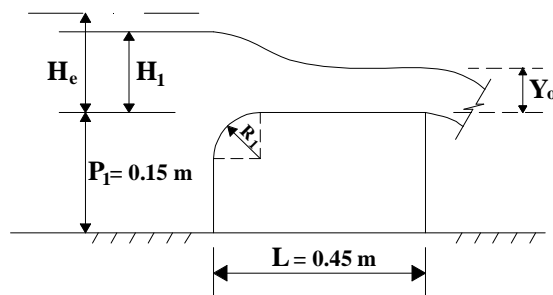


Fig. (1c) Flow over round edge weir with vertical upstream face (Models 6-10)

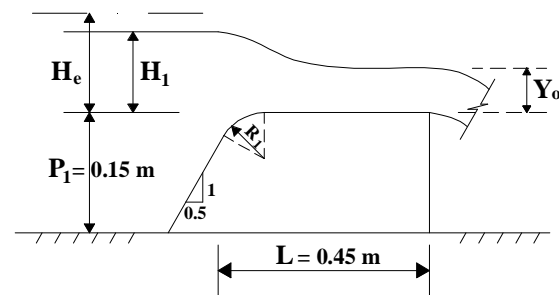


Fig. (1d) Flow over rounded edge and inclined upstream face weir (Models 11-15)

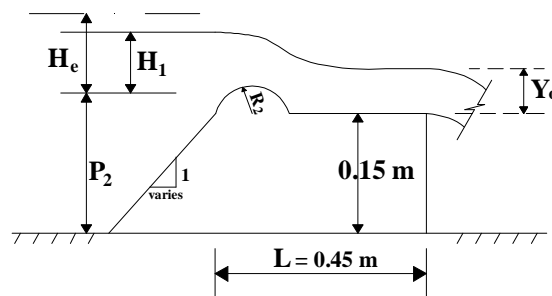


Fig. (1e) Flow over capped edge weir with inclined upstream face (Models 16 - 40)

Fig. (1) Definition sketches showing different cases tested

Noori: Performance Improvement of Broad Crested Weirs

Model No.	Run No.	Corner Radius R₁ (cm)	Range of Effective Head H_e (cm)	Range of Flow Rate q m³/(sec.m) *10⁻³	U.S. Face Slope (S)
1	1-5	0	5.85 – 11.03	19.81 - 55.15	0H:1V
2	6-11	0	3.36 – 9.26	8.89 - 42.62	0.5H:1V
3	12-16	0	5.75 – 10.84	19.81 - 55.15	1H:1V
4	17-21	0	5.76 – 10.94	19.81 - 55.15	2H:1V
5	22-26	0	5.75 – 10.94	19.81 - 55.15	3H:1V
6	27-32	1.5	3.36 – 9.21	8.89 - 42.62	0H:1V
7	33-38	6	3.21 – 8.82	8.89 - 42.62	0H:1V
8	39-44	9	3.19 – 8.67	8.89 - 42.62	0H:1V
9	45-50	12	3.21 – 8.67	8.89 - 42.62	0H:1V
10	51-56	15	3.19 – 8.65	8.89 - 42.62	0H:1V
11	57-62	1.5	3.35 – 9.16	8.89 - 42.62	0.5H:1V
12	63-68	6	3.19 – 8.77	8.89 - 42.62	0.5H:1V
13	69-74	9	3.16 – 8.64	8.89 - 42.62	0.5H:1V
14	75-80	12	3.18 – 8.62	8.89 - 42.62	0.5H:1V
15	81-86	15	3.19 – 8.62	8.89 - 42.62	0.5H:1V
Model No.	Run No.	Cap Radius R₂ (cm)	Range of Effective Head H_e (cm)	Range of Flow Rate q m³/(sec.m) *10⁻³	U.S. Face Slope (S)
16	87-92	1	3.31 – 8.85	8.89 - 42.62	0H:1V
17	93-98	1	3.31 – 8.83	8.89 - 42.62	0.5H:1V
18	99-104	1	3.26 – 8.80	8.89 - 42.62	1H:1V
19	105-110	1	3.24 – 8.79	8.89 - 42.62	2H:1V
20	111-116	1	3.29 – 8.81	8.89 - 42.62	3H:1V
21	117-122	2	3.25 – 8.79	8.89 - 42.62	0H:1V
22	123-128	2	3.25 – 8.78	8.89 - 42.62	0.5H:1V
23	129-134	2	3.24 – 8.77	8.89 - 42.62	1H:1V
24	135-140	2	3.21 – 8.73	8.89 - 42.62	2H:1V
25	141-146	2	3.21 – 8.74	8.89 - 42.62	3H:1V
26	147-152	3	3.21 – 8.6	8.89 - 42.62	0H:1V
27	153-158	3	3.21 – 8.78	8.89 - 42.62	0.5H:1V
28	159-164	3	3.23 – 8.60	8.89 - 42.62	1H:1V
29	165-170	3	3.11 – 8.57	8.89 - 42.62	2H:1V
30	171-176	3	3.16 – 8.58	8.89 - 42.62	3H:1V
31	177-182	4	3.21 – 8.72	8.89 - 42.62	0H:1V
32	183-188	4	3.21 – 8.71	8.89 - 42.62	0.5H:1V
33	189-194	4	3.20 – 8.70	8.89 - 42.62	1H:1V
34	195-200	4	3.16 – 8.67	8.89 - 42.62	2H:1V
35	201-206	4	3.21 – 8.66	8.89 - 42.62	3H:1V

Table(1): Details of the tested weir models

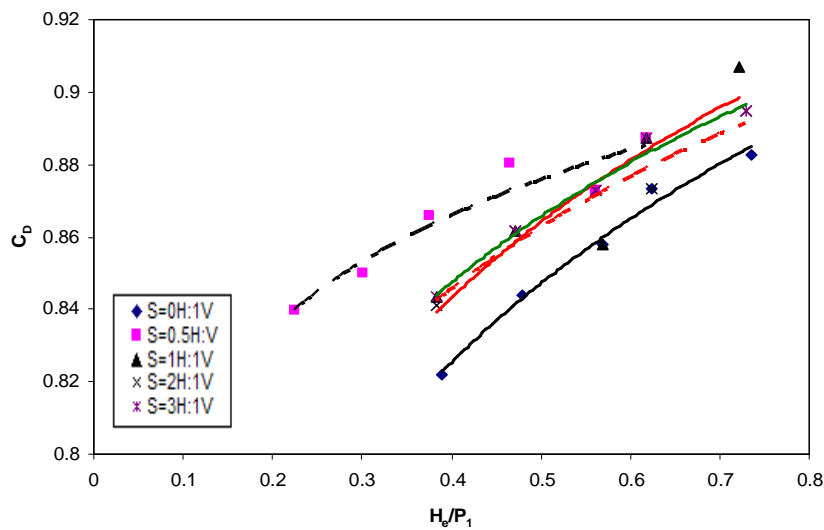


Fig.(2) Variation of C_D with H_e/P_1 for different upstream weir face slopes

Rounding Upstream Top Corner

One of the main objectives of this study is to determine the effect of rounding upstream top corner on discharge coefficient. Eq.(4) indicates that one can find the effect of H_e/P_1 and R_1/P_1 on C_D by conducting tests on weir models for which the slope(S) is held constant. The effect of rounding the upstream corner of the square edge broad crested weir is to increase the coefficient of discharge by reducing very much flow separation at the crest which is the primary source of energy loss. Fig.(3) shows the effects of H_e/P_1 and R_1 on C_D by holding the upstream face vertical. From Fig.(3) one may observe that C_D increases significantly with the increase of H_e/P_1 . Also, it can be observed that when R_1 is greater than or equal to 9cm, the discharge coefficient reaches peak values which means that the flow separation is nearly vanished and further rounding beyond $R_1 = 9\text{cm}$ does not alter the flow characteristics. The variation of average values of C_D with R_1/P_1 is shown in Fig.(4) indicating that the average value of C_D reaches the highest value when R_1/P_1 is equal to 0.6 and greater, this means that well rounding is reached. Fig.(5) shows the variation of C_D with H_e/P_1 for upstream face slope (0.5H:1V) and rounding the upstream top corner. In Fig.(5), it is shown that C_D increases with the increase of H_e/P_1 and well rounding of the top corner gives higher values of C_D . The variation of average values of C_D with R_1/P_1 for round upstream top corner and upstream face slope (0.5H:1V) is shown in Fig.(6) showing slightly higher values of C_D compared with those of weirs without slope and peak values of C_D were obtained when R_1/P_1 reaches 0.6 and greater.

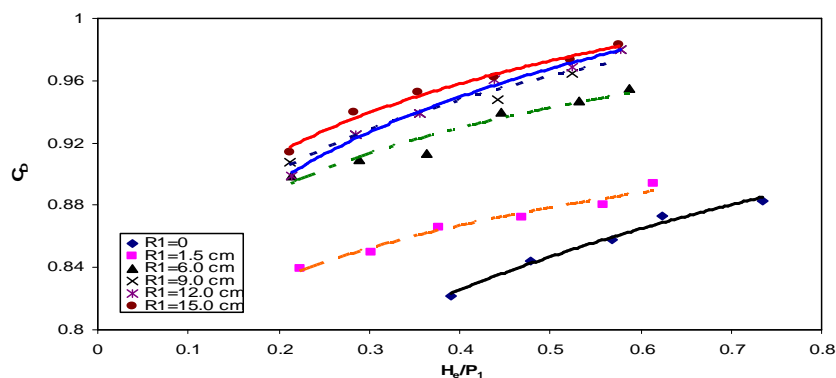


Fig.(3) Variation of C_D with H_e/P_1 for different values of R_1 and vertical upstream weir face

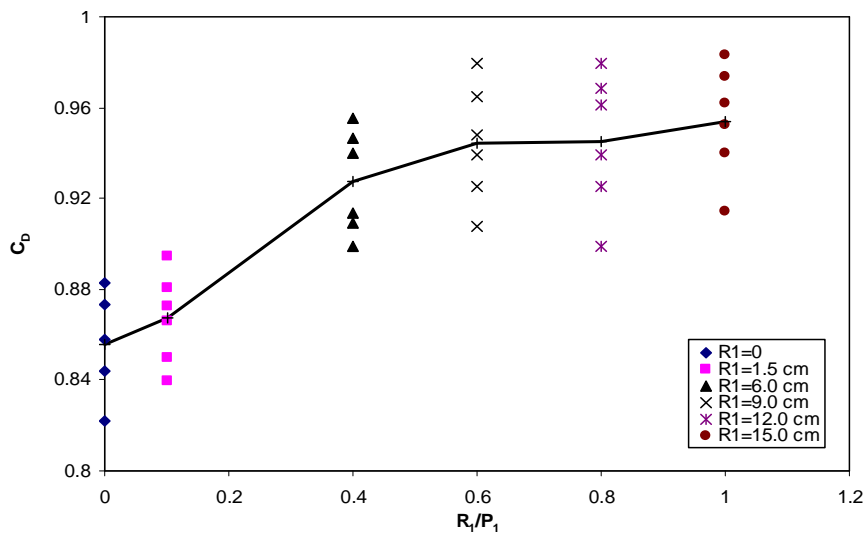


Fig.(4) Variation of average values of C_D with R_1/P_1 for vertical upstream weir face

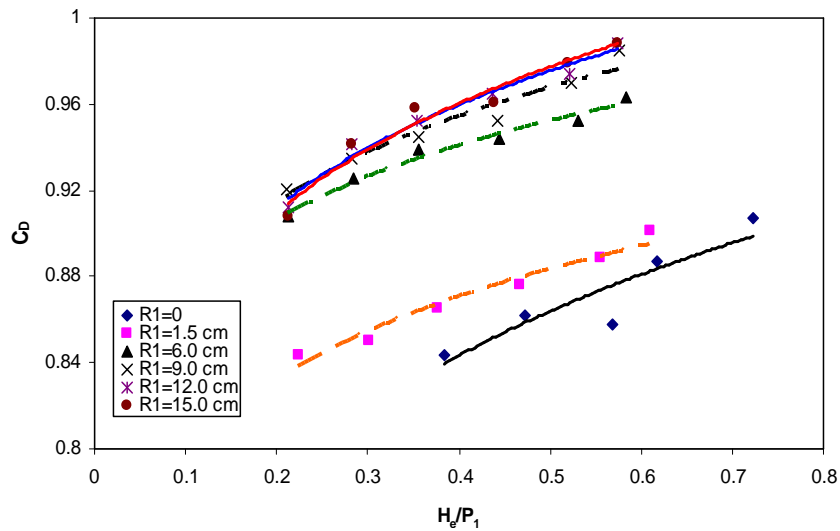


Fig.(5) Variation of C_D with H_e/P_1 for different values of R_1 and upstream weir face slope (0.5H:1V)

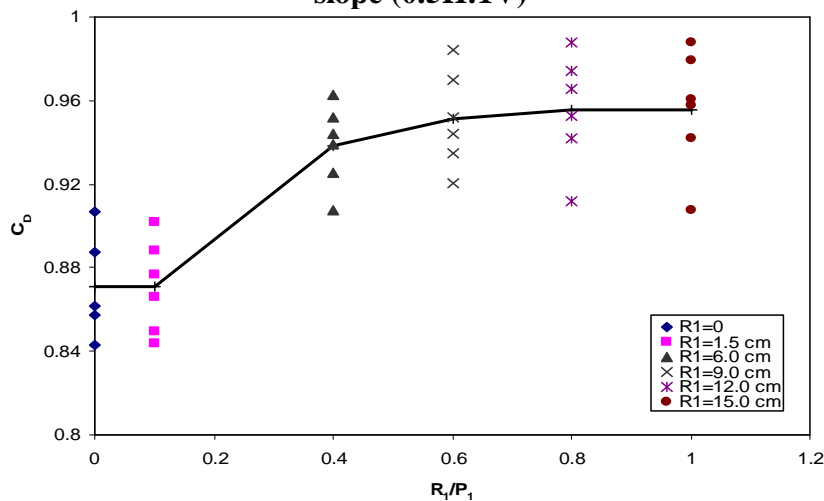


Fig.(6) Variation of average values of C_D with R_1/P_1 for upstream weir face slope (0.5H:1V)

Capping Upstream Corner

Capping upstream corner with a semi-cylinder at the zone of flow separation is to eliminate the effect of flow separation at crest (Fig. (1e)). The variation of C_D with H_e/P_2 for different values of semi-cylinder radius ($R_2 = 1\text{cm}, 2\text{cm}, 3\text{cm}, 4\text{cm}$ and 5cm) is shown in Fig.(7) from which one may observe that the value of C_D increases with the increase of both H_e/P_2 and R_2 values. The variation of average values of C_D with R_2/P_2 is plotted in Fig.(8) showing that the average value of C_D reaches the highest value at $R_2/P_2 = 0.17$. This means that the effect of stream lines separation vanishes when the value of R_2/P_2 reaches 0.17 after which it remains nearly constant. The effect of sloping upstream face on the discharge coefficient is studied by testing models of constant radius of semi-cylinder cap with different upstream face slopes. Figs (9) to (13) show the variation of C_D with H_e/P_2 for different slopes and semi-cylinder radii ($R_2 = 1\text{cm}, 2\text{cm}, 3\text{cm}, 4\text{cm}$ and 5cm , respectively). These figures show that the upstream face slope has very little effect on the improvement of discharge coefficient and flow characteristics. This means that the parameter (S) can be dropped from Eq.(6).

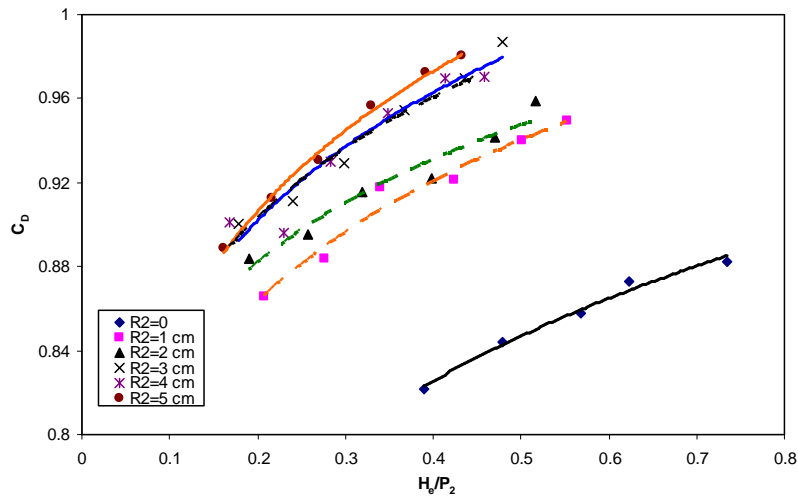


Fig.(7) Variation of C_D with H_e/P_2 with different values of R_2 and vertical upstream weir face

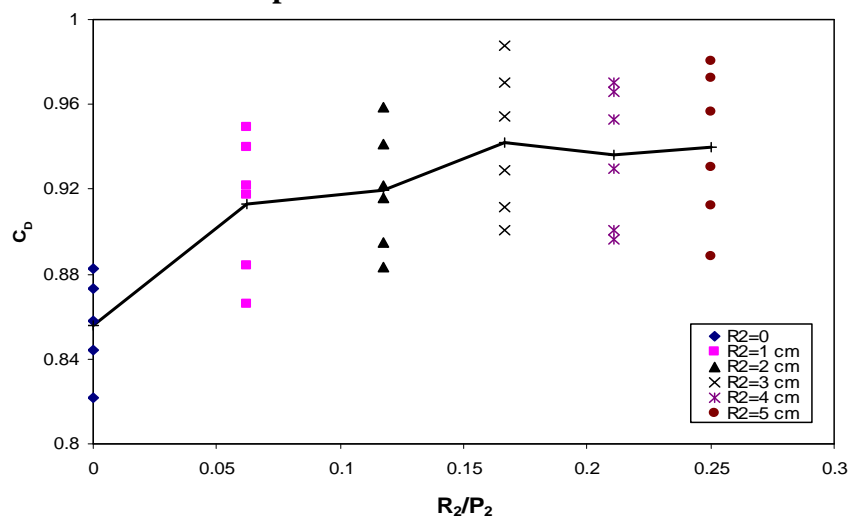


Fig.(8) Variation of average values of C_D with R_2/P_2 for vertical upstream weir face

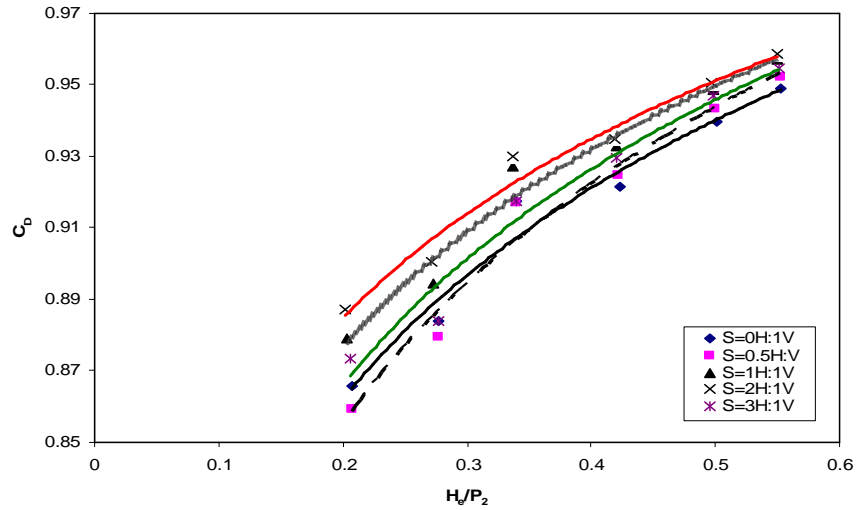


Fig.(9) Variation of C_D with H_e/P_2 for different upstream weir face slopes and $R_2=1\text{cm}$

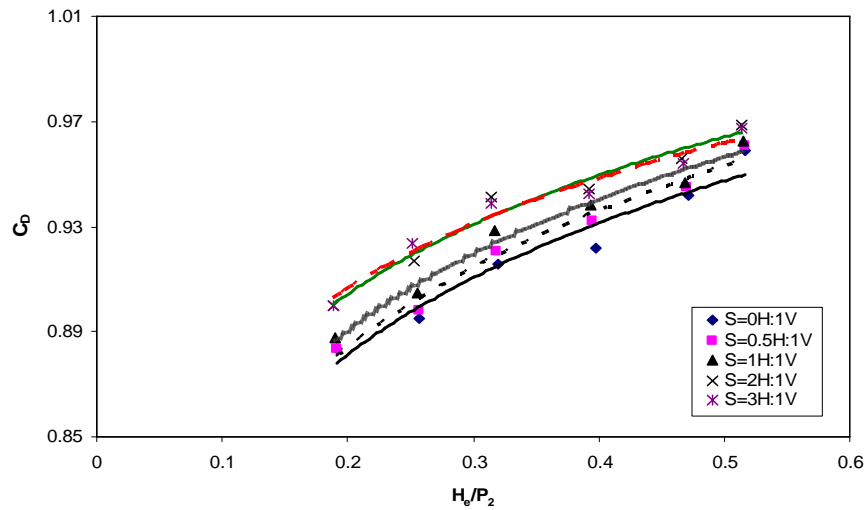


Fig.(10) Variation of C_D with H_e/P_2 for different upstream weir face slopes and $R_2=2\text{cm}$

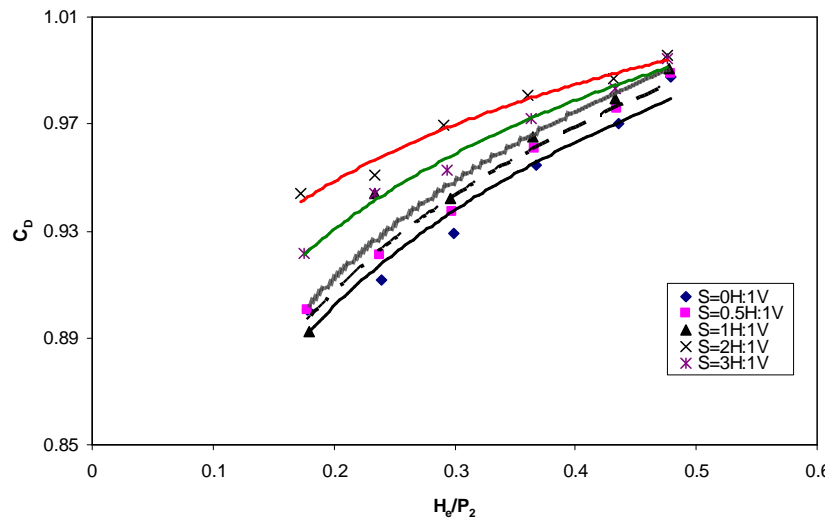


Fig.(11) Variation of C_D with H_e/P_2 for different upstream weir face slopes and $R_2=3\text{cm}$

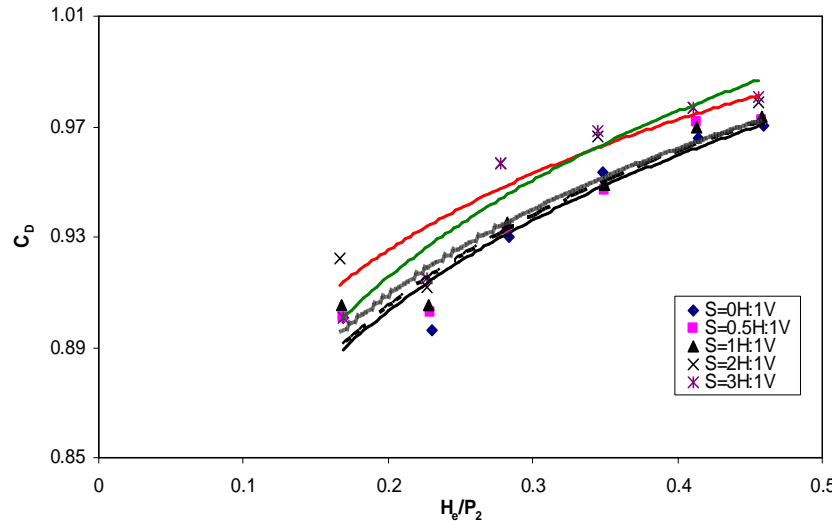


Fig.(12) Variation of C_D with H_e/P_2 for different upstream weir face slopes and $R_2=4cm$

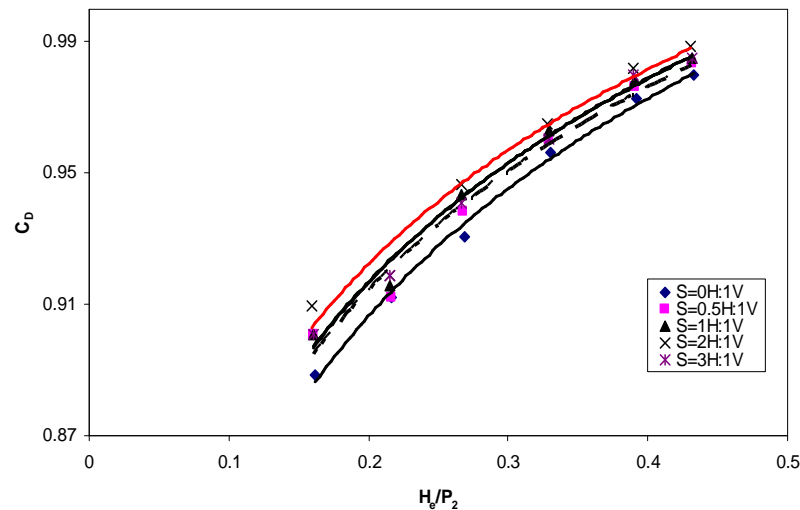


Fig.(13) Variation of C_D with H_e/P_2 for different upstream weir face slopes and $R_2=5cm$

Empirical Expressions of Discharge Coefficient

All experimental results of broad crested weirs of round upstream corner and vertical upstream face were used as input data in a regression analysis computer program to obtain an empirical power expression for the variation of C_D with both (H_e/P_1) and (R_1/P_1) :

$$C_D = 1.0256 \left(\frac{H_e}{P_1} \right)^{0.0694} \left(\frac{R_1}{P_1} \right)^{0.04377} \dots\dots\dots(7)$$

with a correlation coefficient =0.9856. The relation between C_D values predicted by Eq.(7) and values observed experimentally is plotted in Fig.(14) showing good agreement. For all data of capped weirs, another empirical power expression was obtained for the variation of C_D with both (H_e/P_2) and (R_2/P_2) for vertical upstream face using the same computer program as:

$$C_D = 1.114 \left(\frac{H_e}{P_2} \right)^{0.0918} \left(\frac{R_2}{P_2} \right)^{0.0392} \dots\dots\dots(8)$$

with a correlation coefficient =0.9645. A comparison between C_D values predicted by Eq.(8) and observed values experimentally is shown in Fig.(15) showing good agreement.

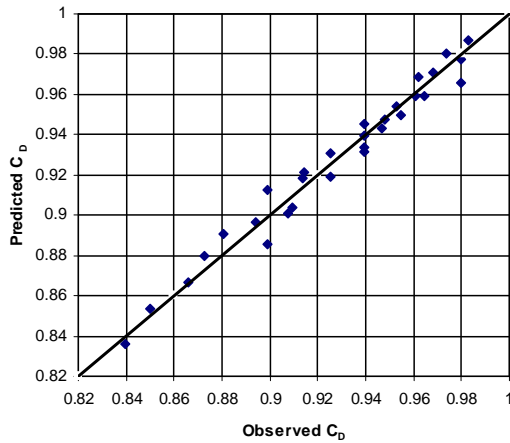


Fig.(14) Variation of predicted values of C_D with observed ones for round upstream corner and vertical upstream face weirs

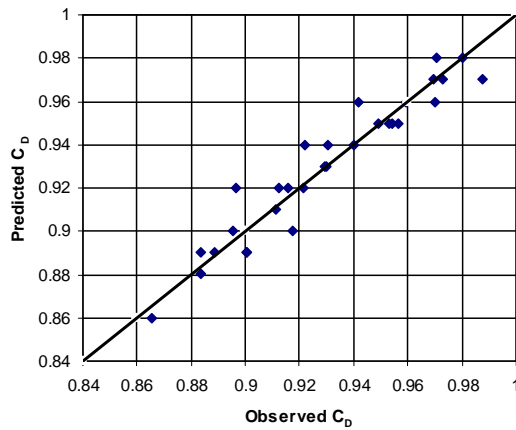


Fig.(15) Variation of predicted values of C_D with observed ones for capped upstream corner and vertical upstream face weirs

Conclusions

Within the limits of the experimental data of the present investigation, the following main conclusions can be summarized as:

1. Square edge broad crested weir can be well improved and the discharge coefficient is increased by introducing an upstream face slope of 0.5H:1V and this value of slope is quite enough to give high values of discharge coefficient(see Fig.(2)).
2. Rounding upstream top corner well reduces the flow separation at the crest and consequently reduces the energy loss and improves the performance of broad crested weirs. The value of C_D increases with the increase of R_1/P_1 values reaching its highest value when R_1/P_1 values are equal or greater than 0.6 (see Figs(3) and(4)).
3. Capping the upstream corner of the weir with semi-cylinder also eliminates the effect of flow separation and improves the performance of crest. The value of C_D increases with the increase of R_2/P_2 values reaching its highest value when R_2/P_2 values reach 0.17 (see Fig.(8)). The upstream face slope had very little effect on the improvement of discharge coefficient and performance of the weir.
4. Two empirical power expressions were obtained, one for round upstream corner weirs to estimate discharge coefficient (C_D) in terms of effective head to crest height ratio (H_e/P_1) and upstream corner radius to crest height ratio (R_1/P_1) with a correlation coefficient = 0.9856 as shown in Eq.(7), while, the second expression for capped upstream corner weirs to estimate (C_D) in terms of effective head to crest height ratio(H_e/P_2) and cap radius to crest height ratio (R_2/P_2) with a correlation coefficient = 0.9645 as shown in Eq.(8).

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