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An Experimental Study of Flow over Rectangular Broad Crested Weir

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ABSTRACT

The main objective of this study was to investigate the flow behavior of the broad crested weir (BCW) and establish a new formula describing the discharge coefficient. In the present work, an experimental study has been carried out on twenty-five BCW physical models with various geometrical configurations and surface roughness conditions too.

Accordingly, the analysis highlights that discharge coefficient (Cd) values are directly proportional to the total head (H) acting on the broad crested weir for a fixed value of weir length (Lw) and increase with the decrease of weir surface roughness. The results showed (H/Lw) is the most studied effective BCW dimensionless ratio that significantly influences the discharge coefficient. An increasing H/Lw from 0.15 to 0.35 leads to noted discharge coefficient values increasing up to 28.39%. As consequence, a new formula with a more compact and short form of expression has been developed for the BCW discharge coefficient prediction. Moreover, a reasonable agreement was noticed between the present study results and the previous research-developed models with errors of less than 10%. Considering the proposed discharge coefficient formula, the optimum hydraulic design of the new BCW model can be successfully facilitated by the extrapolation of characteristics of the idealized scale.

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Keywords: *Discharge Coefficient; Hydraulic Design; Physical Models; Surface Roughness.*

1. Introduction

A broad crested weir (BCW) is generally considered one of the most popular hydraulic structures for flow measurement and controlling the water surface level in open channels (Rahmanshahi, et al. 2018).

The most complex factor that affects the discharge capacity of BCW is the discharge coefficient value (Ritz, et al. 1998). The estimation of the BCW discharge coefficient is generally based on two main approaches. The first one assumed the discharge coefficient of BCW is a function of the relative height of the weir upstream wall. While the second approach assumed that the BCW discharge coefficient depends only on the relative length of the threshold and not a function of wall height (Gogus et al. 2006). Hager et al. (1994) developed an empirical formula for BCW discharge coefficient prediction. This study illustrated that the discharge coefficient mainly depends on the relative weir length L/H, thus, the effects of viscosity and surface tension may be neglected.

Azimi et al. (2009) conducted a wide range of experimental programs to investigate the discharge coefficient (Cd) formula in rectangular broad-crested weirs with different geometry. The output of this study clarified flow patterns and governing relationships in the hydraulics of rectangular broad weirs.

Jalil et al. (2014) experimentally derived an empirical formula for the prediction of broad-crested weir discharge coefficients. The results showed that the performance of the broad crested weir is inversely proportional to the ratio of roughness to the weir height and the increase of the total head to the length.

Albayati et al. (2016) conducted an experimental study to derive an empirical equation for the broad-crested weir discharge coefficient. This study indicated that the discharge coefficient can be obtained experimentally as a function of the non-dimensional total head of the approaching flow

Rhodes et al. (2004) implemented a unique laboratory program that focuses on rectangular broad crested weirs with measurements of free-surface profile over a laboratory scale. The study compared their experimental results with numerical procedures by aiding computer software.

2. Aim and Research Significance

The significance of the current work arises from the fact of successful weirs usage feasibility as one of the important hydraulic structures for controlling water depth and discharge. Thus, the aim of this research was to experimentally investigate the influence of various broad crested weir characteristics as dependent variables on the discharge coefficient as an independent variable. Consequently, the research is concerned with developing a new proposed equation for accurate broad crested weir discharge coefficient determination. The practical application of the research output can be useful for practical hydraulic engineers, especially in the case of the unavailability of an exact common discharge relation and discharge coefficient of broad crested weirs.

3. Dimensional Analysis

Dimensional analysis was implemented by using Buckingham's theorem to discover the relationships among the different measurements and their changes as well as the interaction between all dependent variables. However, it is utilized to describe the free flow over the broad crested weir, the parameter that affects the BCW discharge coefficient (C_d), and the determination of the different dimensionless group terms. Geometry parameters which can be described as shown in Fig. 1 were; Height of the broad crested weir (p), Head over the (H), weir length (Lw), Weir width (B), Radius of the upstream face of the weir crest (r), Roughness diameter size (D100), and Gravitational acceleration (g).

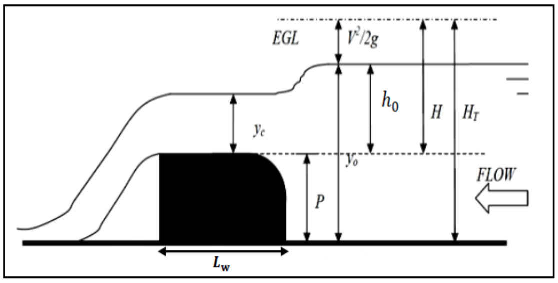

Fig.1 Definition sketch of a Broad Crested Weir

Therefore, the discharge capacity can be expressed as follows:

$$Q = f\,(H\,,L\,,r\,,B\,,P,D_{100}\,,g\,,\rho\,,\mu,\sigma\,) \qquad (1)$$

Meanwhile, the viscosity (μ) and the surface tension (σ) can be considered a neglected effect due to the values of the test heads that exceed thirty mm [10].

the following π terms can be considered, and the general form of the discharge coefficient as an independent variable can be written as follows:

$$C_d = f\,\left(\left(\frac{H}{L},\frac{H}{P},\frac{H}{r},\frac{H}{B},\frac{L}{D_{100}},\frac{D_{100}}{P}\right)\right) \qquad (2)$$

4. Experimental Program

4.1 The Laboratory Flume

Fig.2 illustrates the present study laboratory rectangular flume with a length of 5.6 m long, a width of 30 cm, and 60 cm deep. Static point gauges (±0.2 mm) were installed at the top of the centerline of a flume for measuring the water level. The device was equipped with a mechanical jack to adjust the slope to create and study subcritical, critical, and supercritical flow regimes. The discharge was measured with a flow meter.

Fig.2 Experimental flume

After setting up the laboratory models, water was pumped to the laboratory flume and the required parameters, including the level of water and discharge rate, were measured.

The twenty-five broad crested weirs models were manufactured from wood with varnish coating and covered by a uniform of sand and gravel mixtures, Fig. 3. Each model had 12 cm height and 9.4 cm width with various values of length (L =0.15, 0.20, 0.25, 0.30 and 0.35 m respectively). In each model, the surface roughness that is represented as the sieve diameter has five different values: D100 = 1.62 mm, D100 = 2.36 mm, D100 = 4.75mm, and D100 = 5.78 mm.

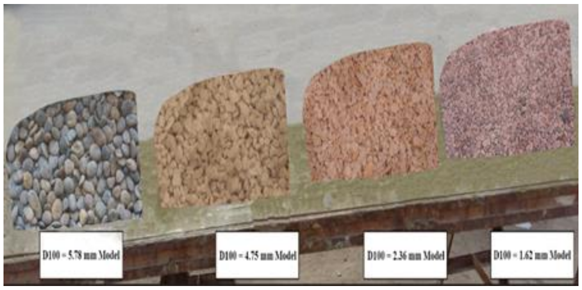

Fig.3 Models with various roughness conditions

4.2 The Experimental Setup and Procedure

First, flow meter readings are checked and calibrated with a quantitative method (flow volume broad-crested). In each run, the selected broad-crested weir physical model is installed in the middle of the flume length. Consequently, water is supplied from the upstream entrance through a pipe. The discharge in the channel is controlled by a valve before it reaches the entrance tank. After the entrance, water passes through a rectangular channel and exits over the broad crested weir down into the measurement tank and this circulation continues.

5. Test Results and Discussion

5.1 Head-Discharge Rating

In Fig 4, head-discharge rating data for various weir lengths as well as different surface roughness conditions have been presented.

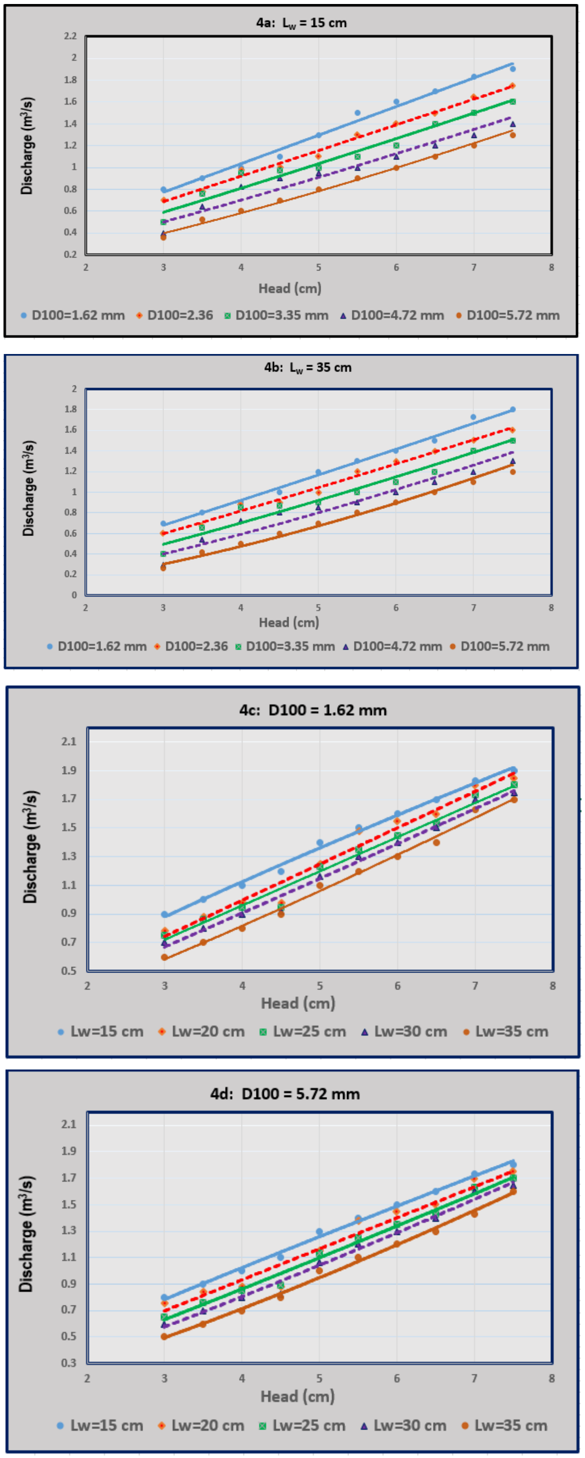

Fig.4 Head-discharge curves for various lengths and surface roughness conditions

Generally, the data plotted show that the discharge over a broad crested weir has a direct proportion to water head over the weir. As a head-over weir increases from 3 cm to 7.5 cm, a noted increase in the discharge percent over weirs models, with various roughness conditions up to 33.24% and 39.76% for weir length equal to 15 cm and 35 cm

5.2 Effect of Weir length on the Discharge Coeff.

The dimensional analysis for the variables affecting the Cd value of weirs [10] indicates that the value (H/Lw) (Where H is the head of the water above the weir and Lw is the length of the weir), has a major influence on Cd value. However, C_d is plotted against (H/Lw) for different weir lengths under the same surface roughness as shown in Fig. 5

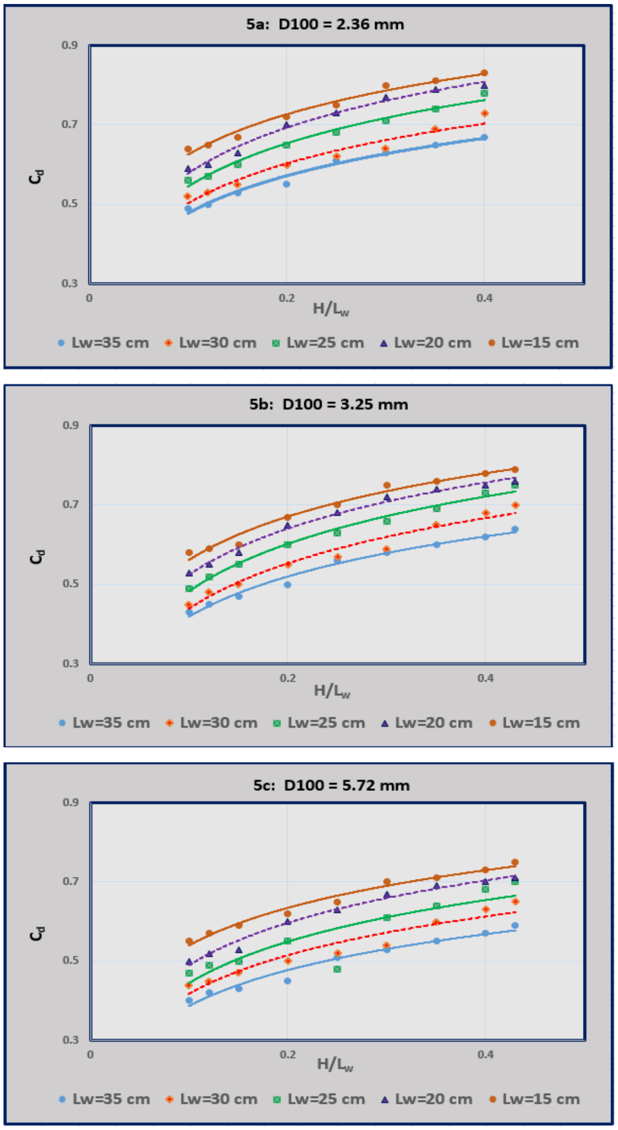

Fig.5 Variation of discharge coefficient with various BCW lengths

It is clear from these Figures that there is an increase in C_d values with the increase of the rate of (H/Lw). These Figures show also, that the Cd values vary directly in proportion to the weir length. At D100 equal 2.36mm, when (H/Lw) increased from 0.15 to 0.45, the discharge coefficient increases up to 28.18%, 28.64%, 29.57%, 29.67%, and 28.89% for Lw equal 15 cm, 20cm, 25 cm, 30 cm and 35cm respectively. While at D100 equal 5.72mm, a relatively slight increasing in Cd values was noted by 24.37%, 24.54%, 24.76%, 24.97%, and 25.08% for Lw equal 15 cm, 20cm, 25 cm, 30 cm and 35cm respectively in the same mentioned (H/Lw) range.

5.3 Effect of Surface Roughness on Discharge Coefficient

Fig.6 describes the relationship between (H/Lw) and the discharge coefficient of different surface roughness conditions at each of the same weir crest experiment models’ lengths.

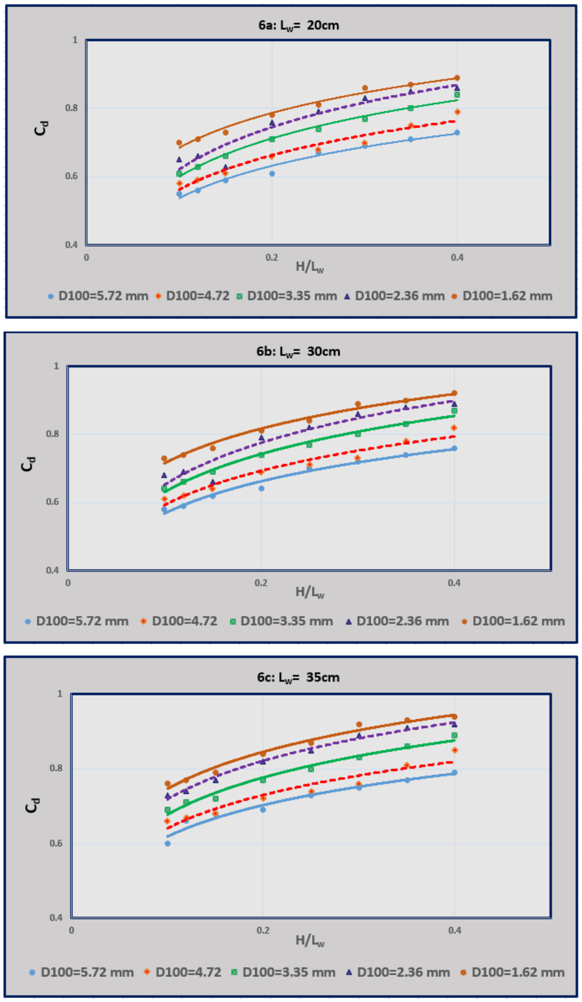

Fig.6 Variation of discharge coefficient with weir surface roughness conditions

From Fig. 5 it is obvious that for various experiment weirs lengths values, a relatively gradual increase in discharge coefficient was noted. Considering weir model length equals 20 cm, when H/Lw increases from 0.15 to 0.45, the average discharge coefficient increases up to 23.14%, 23.73%, 24.02%, 24.34%, and 24.62% for D100 equaling 1.62 mm, 2.36 mm, 3.35 mm, 4.72 mm, and 5.72 respectively. On the other hand, increasing weir length to 35 cm, the average discharge coefficient increases up to 23.46%, 24.59%, 24.84%, 25.06%, and 25.22% for D100 equaling 1.62 mm, 2.36 mm, 3.35 mm, 4.72 mm, and 5.72 respectively. In addition, these figures show that the Cd values are decreases with the increase in surface roughness, and this is attributed to the fact that an increase in the roughness of the surface will lead to an increase in the head of the water.

5.4 Developing Discharge Coefficient Formula

In this study, the specific conducted experimental data from twenty-five BCWs physical models were utilized to develop the discharge coefficient formula. However, an empirical formula for discharge coefficient determination was suggested. Moreover, the multiple regression analysis was applied to the experimental results to associate BCW that affects the Cd into one general formula; the following equation the deduced empirical formula.

$$C_d = -2.031 + 0.614\,(H/Lw)^{0.543} + 0.708\,(H/D100)^{0.404}$$

$$R^2 = 0.94 \qquad (3)$$

From equation (3), it can be easily inferred that the discharge coefficient of a BCW is primarily close to a power-exponential function.

5.5 Comparing with Previous Studies

Many previous empirical formulas have been investigated for estimating the orifices discharge coefficients. To ensure the overall accuracy of the present study’s developed formula, various statistical measures are applied to compare the present study’s discharge coefficients equation with the corresponding previous studies’ discharge coefficients determination equations, Table 1. However, three statistical measures: relative error percentage (RE); root mean square errors (RMSE), and mean absolute errors (MAE) were used to evaluate the result accuracies selected for implementing these required comparisons and evaluation between the current study and other researchers’ BCWs discharge coefficients equations.

Table 1 Comparing with Previous Studies Statistics

Compared Researchers	***Equation***	***RE***	***RMSE***	***MAE***
Hagar et al. [4]	$C_d = \mathbf{0.419\ \{1- 2/9\ [1+(H/Lw)^4\ ]\}}$	7.75%	6.23%	5.06%
Azimi et al. [5]	$C_d = \mathbf{0.309\ (H/Lw) + 0.796}$	5.34%	8.18%	6.44%
Jalil et al. [6]	$C_d = \mathbf{0.\ 86\ (H/Lw) - 49.606(H/Ks)}$	3.15%	4.09%	5.11%
Albayati et al. [7]	$C_d = \mathbf{0.1\ (H/Lw) + 0.93}$	3.25%	5.74%	6.33%

It is clear that the equation by Jalil et al. [6] and Albayati et al. [7] consistently resulted in estimations closest to the present study compared to the other two equations. Meanwhile, according to various applied evaluating statistical measures results, it is obvious that all the compared research results with the current study tend to represent a good compliance with an error less than 10%.

6. Conclusions

The finding from this research may have practical applications, especially when performing BCW hydraulic design that is based on its characteristics to increase discharge capacity. The following main conclusions may be drawn:

-The present study evaluates the effect of the broad crested weir’s characteristics on their flow discharge by using twenty-five experimental physical laboratory models.

-The discharge coefficient, Cd, tends to have a direct proportion to H/Lw, in particular when weir surface roughness conditions decrease as well as weir length increases.

-Accordingly, an increase in H/Lw values with the increase in the weir length led to increasing in Cd value up to 28.18%, 28.64%, 29.57%, 29.67%, and 28.89% for Lw equal 15 cm, 20cm, 25 cm, 30 cm and 35cm respectively at D100 equal 2.36 mm. While with increasing D100 to 5.72mm, a relatively slight increase in Cd values was noted by 24.37%, 24.54%, 24.76%, 24.97%, and 25.08% for Lw equal 15 cm, 20cm, 25 cm, 30 cm and 35 cm respectively.

- Meanwhile, the discharge coefficient values decrease with the increase in the surface roughness. Results show that for weir model length equals 20 cm, when H/Lw increases from 0.15 to 0.45, the average discharge coefficient increases up to 23.14%, 23.73%, 24.02%, 24.34%, and 24.62% for D100 equaling 1.62 mm, 2.36 mm, 3.35 mm, 4.72 mm, and 5.72 respectively. On the other hand, increasing the weir length to 35 cm, the average discharge coefficient increases up to 23.46%, 24.59%, 24.84%, 25.06%, and 25.22% for D100 equaling 1.62 mm, 2.36 mm, 3.35 mm, 4.72 mm, and 5.72 respectively.

-Additionally, a new empirical formula has been developed to facilitate accurate broad crested weir discharge coefficient estimation.

-Meanwhile, by referring to the study outcomes, the water authorities can easily evaluate the discharge capacity through various BCW for each particular situation.

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