Effect of Compound Weir and below Circular Gate Geometric Characteristics on its Discharge Coefficient

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Abstract

Weirs and gates can be combined together in one device to minimize sedimentations, depositions and floating materials problems, so that water could pass over the weir and below the gate simultaneously. The purpose of this paper is to explore the discharge coefficient C_d variations for different geometric characteristics of a combined hydraulic measuring device consists of compound weir, which have two rectangular notches with trapezoidal notch between them and circular sluice gate installed on the weir bottom. For this purpose, 316 experimental runs were carried out to determine the discharge coefficient. Three circular gate diameters d, beside the absence of the gate case (0, 8, 12, and 15 cm), three values for the lower notch width W_2 and height z of the compound weir of 5, 7, and 9 cm, and 6, 9, and 11 cm respectively, were tested as geometric characteristics. For each experimental set – up, six operating water heads were applied and the corresponding actual discharges were determined. The results show that the discharge coefficient C_d increases as the hydraulic and geometric parameters h/H, and W_2/W increase, while the decreasing in C_d values is attributed to the increase of the geometric parameters z/H and d/H. The results were presented in curves showing the C_d and all the mentioned parameters relationships.

Keywords: Compound flow; compound weirs; circular gate; weir flow; gate flow; physical model.

1- Introduction

One of the classic methods for measuring the flow rate in irrigation and drainage networks is to create a control section and develop the discharge - head relationship by constructing a hydraulic device in the flow path. These devices can operate on the basis of hydraulic principles of flow through a hole such as circular gates and principles governing flow such as overflows with different geometric sections. The most common flow measurement devices that used for controlling, adjusting the flow in irrigation channel and diverting the flow from a main channel to a secondary channel are weirs and gates. When the weirs and gates combined together in one device, new hydraulic condition is appeared which is different with the hydraulic condition of using weir or gate individually. The function of the combined device may be similar to that of weirs or gates as a discharge measurement device, and also, it will minimize each deposition upstream of weirs and minimize the needed maintenance as most of the floating materials and sediments will pass through this combined device. Mahmoudi et al [1] developed equations to estimate the flow rate through the overflow-valve device in different flow conditions. This device, despite its simplicity in form, is associated with complexity in estimating discharge. Also, Ferro [2] reported the results of an investigation carried out to establish the stage – discharge relationship for a flow simultaneously discharging over and under a sluice and broad crested gate. Al-Hamid et al. [3] used a compound weir consists of triangular weirs above rectangular contracted gates and contracted rectangular weirs above triangular gates to discuss the effect of hydraulic and geometrical parameters on the combined discharge and the results were presented as discharge equations. It was found that significant errors were produced for the prediction of the combined discharge through the use of common discharge coefficients. Negm et al. [4] carried out experimental runs to discuss the characteristics of combined flow over a sharp-crested rectangular weir and through a gate structure below the weir. The results showed that the geometrical and hydraulic parameters have a significant effect on the discharge, and within the limitations of the experimental setup, their discharge formula was used under a free-flow condition. Negm et al. [5] conducted an experimental investigation to study the characteristics of the combined flow over contracted sharp crested rectangular weirs and below contracted sharp crested rectangular gate. A laboratory flume of (0.305 m * 0.305 m * 9.00 m) dimensions was used to conduct the experiments using nineteen models on a horizontal bed and eighteen models for sloping beds. Abbas et al. [6] investigated the coefficient of discharge C_d for combined hydraulic measuring device consists of compound weir (have two rectangular notches with trapezoidal notch between them) and below semicircular sluice gate. It was found that, the value of C_d varies from 0.427 to 0.543. Al-Saadi [7] presented the results of an experimental study on the hydraulic characteristics of weirs and combined weirs under multi cases, these cases were (rectangle weir, V-notch weir, semicircular weir, rectangular combined weir with a rectangular gate, V-notch combined weir with a rectangular gate, semi-circular combined weir with a rectangular gate, and semicircular combined weir with a semi-circular gate). Abdulabbas et al [8] conducted experimental runs to investigate the scour hole dimensions downstream the combined devices which consist of weir and gate. Twelve models have been designed and every model is formed from composite weir consists of two geometric shapes and three types of gates which are rectangular, semi-circular and triangular in shape, where multi factors were studied to find out the effect of changing geometry for both weir and gate, discharge flowing in the flume and particle size of bed material on the dimensions of scour hole. The experiments were conducted in a laboratory channel with dimensions of 18 m length, 1 m width and 1 m depth. Saleh and Abbas [9] investigated the discharge coefficient for combined device consists of compound weir have two rectangular notches with trapezoidal notch between them and semicircular sluice gate to study the effect of the compound weir and gate geometric characteristics on the discharge coefficient. Fifteen models were constructed and manufactured of Plexiglas sheet of 3 mm thickness with beveled edges to 2 mm thickness for this purpose. Eltoukhy and Mohammad [10] studied experimentally the velocity distributions downstream compound weirs. The results showed that the vertical and longitudinal velocity distributions increase with water head and with plastic bed case. The velocity distributions decrease for larger wide weir and higher downstream water depth. Rafi et al [11] implemented experimental runs in the hydraulic laboratory considering hydraulic and geometrical variables to investigate the overlapping between weir and gate having a parabolic shape. They reported that the weir and gate cross sectional area of flow have significant effect on coefficient of discharge of combined hydraulic structure. It is also very necessary to consider the effect of geometrical parameters on the coupled parabolic weir over flow and gate under flow rate. Also, the results proved that the weir and gate parabolic shape more efficiency as compared with regular shape. Samani and Mazaheri [12] presented a new physically based approach for estimating the stage discharge relationship of combined flow over the weir and under the gate for semi submerged and fully submerged conditions.

The present paper aims to study the effect of geometric characteristics of a weir equipped with lower circular gate on its discharge coefficient. The considered compound device is not previously reported in the available literature.

2. Theoretical Analysis

The combined free flow over a sharp crested compound weir and the below circular gate is sketched in Figs. 1 and 2. The theoretical discharge equation for sharp crested compound weir Q_{wth}, which consists of two rectangular notches and trapezoidal notch between them, may be written as follows:

$$Q_{wth} = \frac{2}{3}\sqrt{2g}\,W_2(z^{1.5}) + \frac{2}{3}\sqrt{2g}\,W_1 h_1^{1.5} + \frac{2}{3}\sqrt{2g}\,W_2\left(h_2^{1.5} - h_1^{1.5}\right) + \frac{8}{15}\sqrt{2g}\tan\theta\left(h_2^{2.5} - h_1^{2.5}\right) \quad (1)$$

Where; Q_{wth}: the theoretical discharge over the compound weir, h, h_1, and h_2: the height of water above the upper, middle and lower notches of the compound weir, z: is the height of the lower notch, W_1: width of the upper notch of the compound weir. W_2: width of the lower notch of the compound weir. g: the gravitational acceleration. ɵ: the angle of the crest of the compound weir.

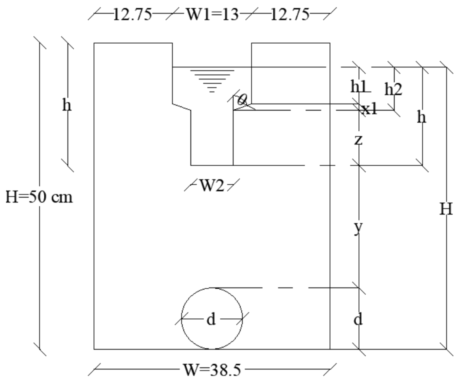

Fig. 1 Sketch of the combined weir

Fig. 2 Model sample of combined weir

On the other hand, the theoretical discharge through the circular gate Q_{gth} may be written as:

$$Q_{gth} = \frac{\pi}{4} d^2 \sqrt{2g\left(h + y + \frac{d}{2}\right)} \quad (2)$$

Where: Q_{gth}: the circular gate theoretical discharge, d: the circular gate diameter, and y is the distance between the lower notch sill and the circular gate.

The total theoretical discharge Q_{th} is calculated by combining the two equations 1 and 2 as follows;

$$Q_{th} = Q_{wth} + Q_{gth} \quad (3)$$

And hence, the actual discharge Q_{act} can be written as;

$$Q_{act} = C_d \times Q_{th}$$

$$= \quad Cd \quad \left(\frac{2}{3}\sqrt{2g}\, W_2 (z^{1.5}) + \frac{2}{3}\sqrt{2g}\, W_1 h_1^{1.5} + \frac{2}{3}\sqrt{2g}\, W_2 \left(h_2^{1.5} - h_1^{1.5}\right) + \frac{8}{15}\sqrt{2g} \tan\theta \left(h_2^{2.5} - h_1^{2.5}\right) + \frac{\pi}{4} d^2 \sqrt{2g\left(h + y + \frac{d}{2}\right)}\right) \quad (4)$$

The functional relationship of the discharge coefficient C_d can be written as;

$$C_d = f(H, h, h_1, h_2, Z, y, d, b, W_1, W_2, g, \rho, \mu, \sigma) \quad (5)$$

Where: b: is the flume width (38.5 cm), ρ: the water density, μ: dynamic viscosity, σ: surface tension.

Based on Eq. (5) and employing Buckingham π – theorem the following relationship was obtained;

$$C_d = f\left(\frac{W_2}{W},\ \frac{h}{H},\ \frac{z}{H},\ \frac{H}{d},\ R_e,\ W_e\right) \tag{7}$$

In which R_e and W_e are Reynolds and Weber numbers respectively and assumed to be neglected for combined devices at tested parameters.

3. Experimental Setup and Methodology

The experimental runs were carried out in the Hydraulics Laboratory, Benha Faculty of Engineering, Benha University, Egypt. A zero slope flume with smooth concrete bed and Plexiglas walls was used for achieving the purpose of this paper. The flume has width of 0.4 m, height of 0.6 m, and a length of 15.0 m as shown in Fig. 3. A pump was used to pump water from the ground tank of dimensions (5.5, 4.4, and 1 m) to the flume, using control valve to control the pumped discharge. The flume has an adjustable tailgate at the downstream end to produce the desired flow conditions. The pumped discharge was measured by calibrated flow meter and point gauge was used for measuring the water levels.

The experimental run procedure was devised to accurately determine the head–discharge relationship across multiple compound weir and circular gate geometric characteristics. The following steps were followed for each experiment

1- Set up the first compound weir without circular gate and turn on the pump to pump water into the flume with adjusting the controlling valve for the required head and recording the corresponding discharge.
2- Adjust the controlling valve to have new head and also record the corresponding discharge five times.
3- Repeat steps 1 and 2 for lower weir part height z of 6 cm with three widths of 5, 7, 9 cm.
4- Repeat step 3 for two another values of z of 9 and 11 cm.
5- Repeat steps from 1 to 4 using circular gate diameters of 8, 12, and 15 cm.
6- After each run the pump should be turned off.

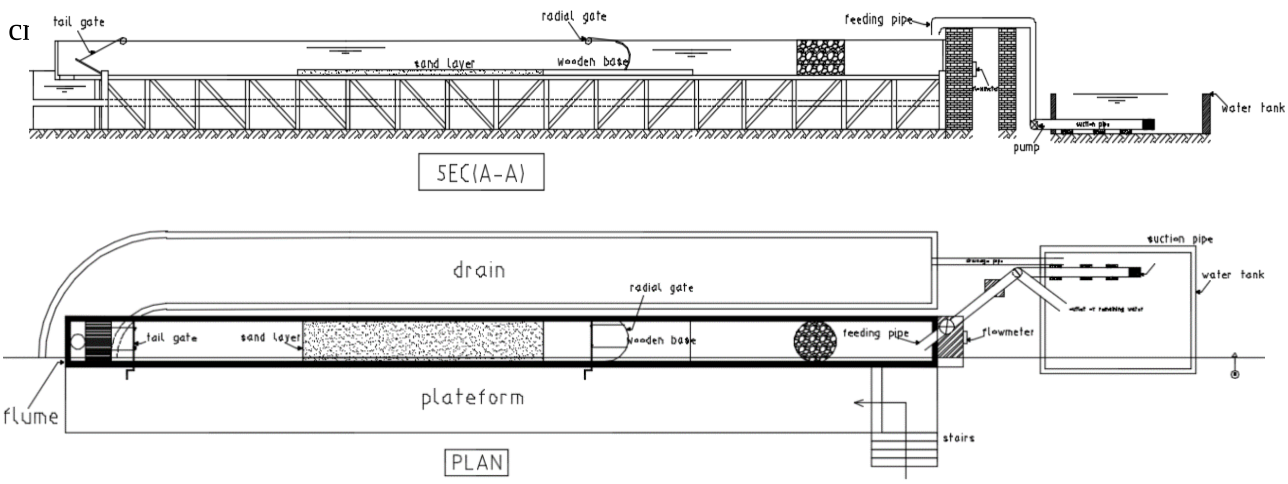

Fig. 3 Plan and elevation of the flume layout

the lower notch width W_2 of 5, 7, and 9 cm Which, in turn, uses six values for the water head for each W_2 value.

4. Results and Discussion

The effect of the hydraulic parameters $\frac{h}{H}$, $\frac{W_2}{W}$, $\frac{z}{H}$, $\frac{H}{d}$ on C_d was investigated in this section.

4.1 Discharge Coefficient Variation C_d with the water head ratio *h/H*

Firstly the discharge coefficient C_d variation with the water head ratio *h/H* was discussed. Through the analysis of all experimental runs, it was found that for constant circular gate diameter ratio *d/H*, lower notch width ratio W_2/W, and lower notch height *h/H*, the discharge coefficient C_d increases as the water head ratio *h/H* increases. The increase in *Cd* in all circular gate diameters beside the case of no circular gate (*d* = 0) has the same trend, Figs 4 to 15. For example for *d/H* = 0.24, *z/H* = 0.18 and W_2/W = 0.18 increasing *h/H* from 0.18 to 0.278 results in increasing in *Cd* from 0.4978 to 0.569, which means that 54.44% increasing in *h/H* results in 14.3% increasing in C_d. The range of the discharge coefficient C_d and its average values for different *h/H* are for *d/h* = 0 *Cd* ranges from 0.5096 to 0.9124 with average value of 0.711, for *d/h* = 0.16 *Cd* ranges from 0.4548 to 0.7134 with average value of 0.584, for *d/h* = 0.24 Cd ranges from 0.4562 to 0.6537 with average value of 0.5549, for *d/h* = 0.3, *Cd* ranges from 0.3905 to 0.5809 with average value of 0.4857.

4.2 Discharge Coefficient Variation C_d with the Lower Notch Width Ratio W_2/W

Also, Figs 4 to 19 show that for constant circular gate diameter ratio *d/H*, water head ratio *h/H*, and lower notch height ***z***/*H*, the discharge coefficient C_d increases as the lower notch width increases for all circular gate diameters beside the case of absence of the circular gate (d = 0). For instance for d/H = 0.24, h/H = 0.3, and z/H = 0.18, the discharge coefficient C_d

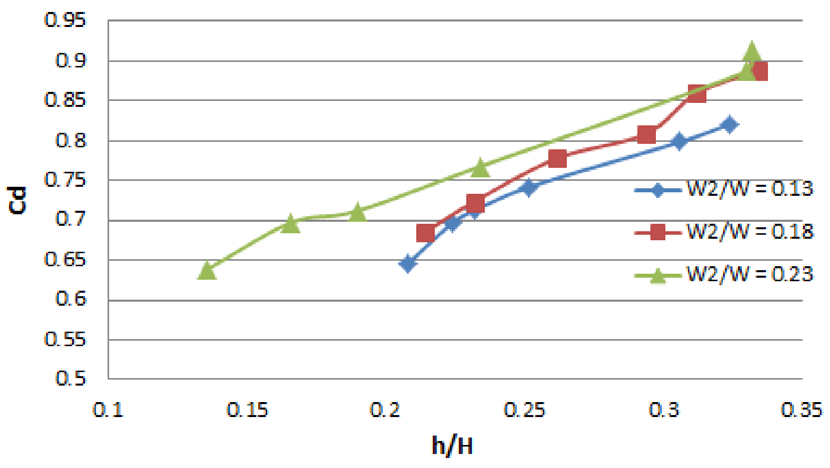

Fig. 4 Variation of C_d with Water Head, z/H = 0.22, d/H = 0

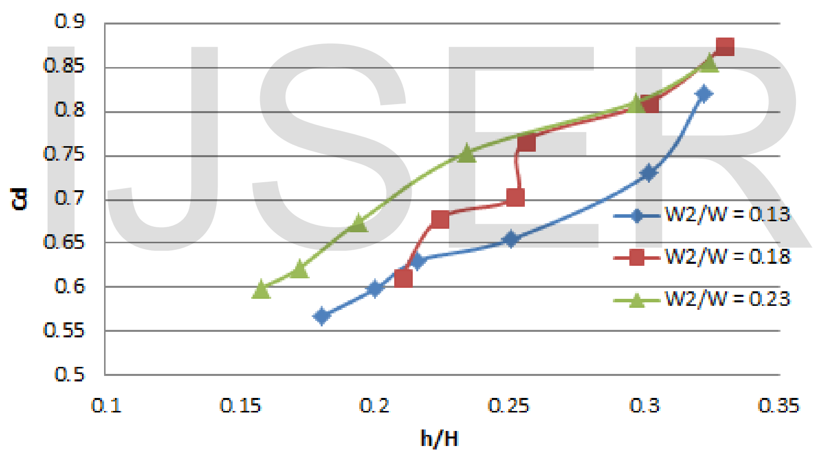

Fig. 5 Variation of C_d with Water Head, z/H = 0.18, d/H = 0

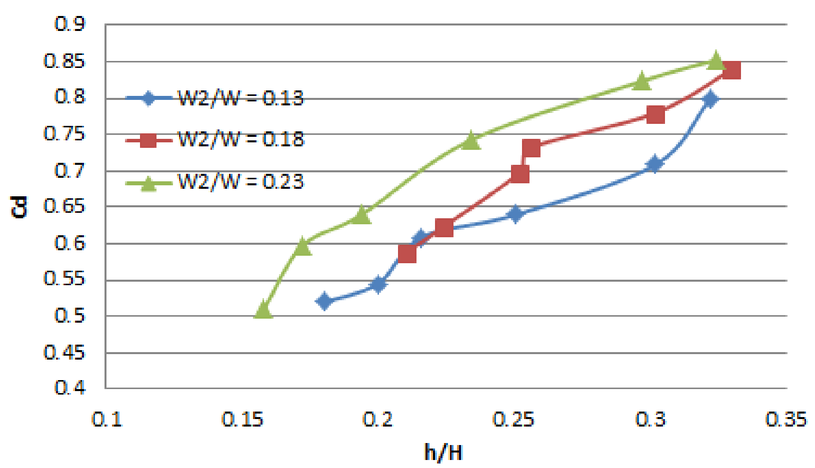

Fig. 6 Variation of C_d with Water Head, z/H = 0.12, d/H = 0

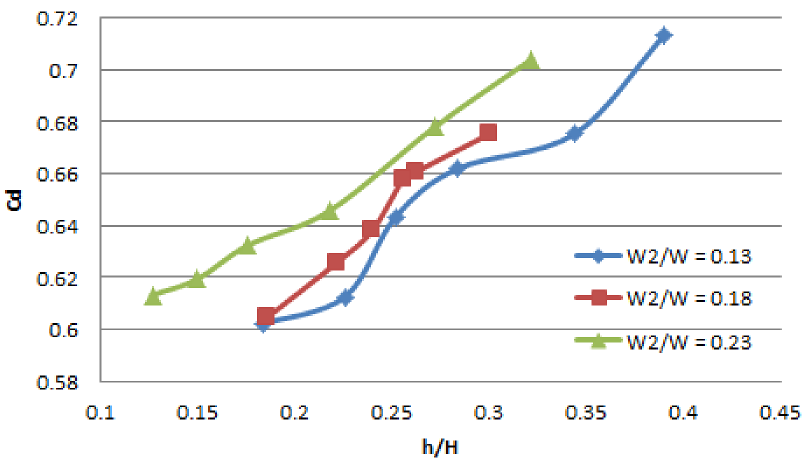

Fig. 7 Variation of C_d with Water Head, z/H = 0.22, d/H = 0.16

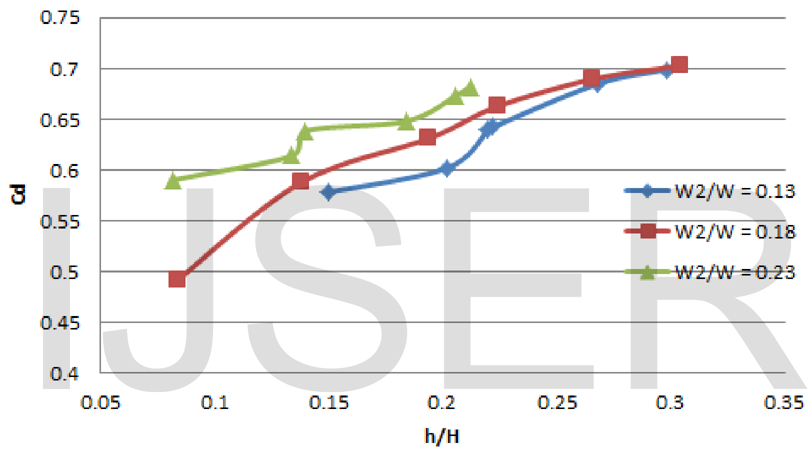

Fig. 8 Variation of C_d with Water Head, z/H = 0.18, d/H = 0.16

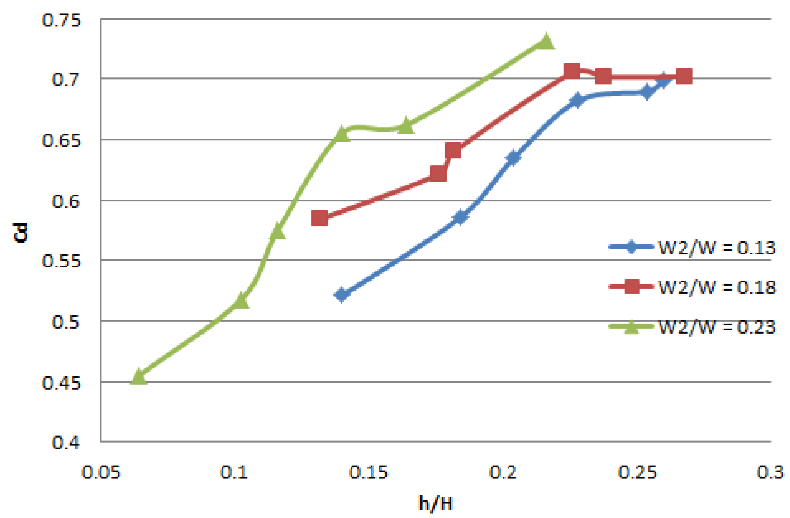

Fig. 9 Variation of C_d with Water Head, z/H = 0.12, d/H = 0.16

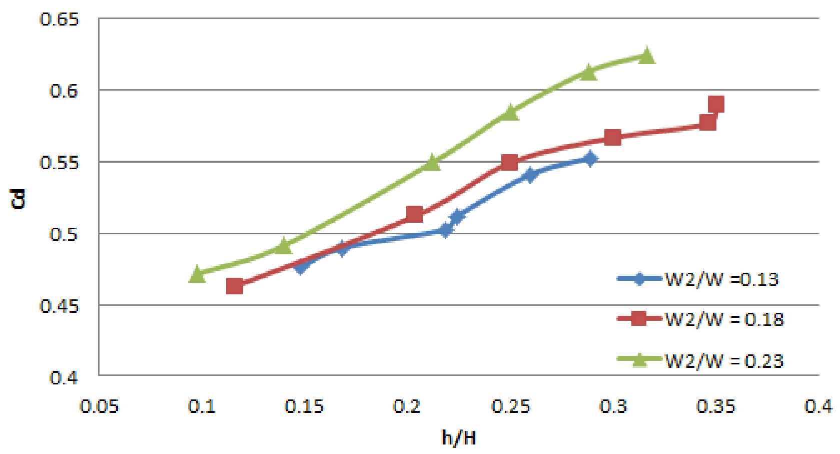

Fig. 10 Variation of C_d with Water Head, z/H = 0.22, d/H = 0.24

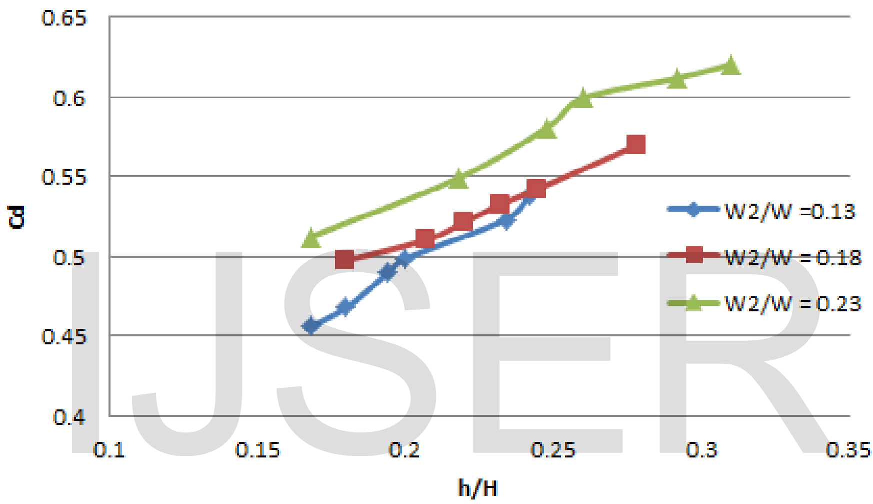

Fig. 11 Variation of C_d with Water Head, z/H = 0.18, d/H = 0.24

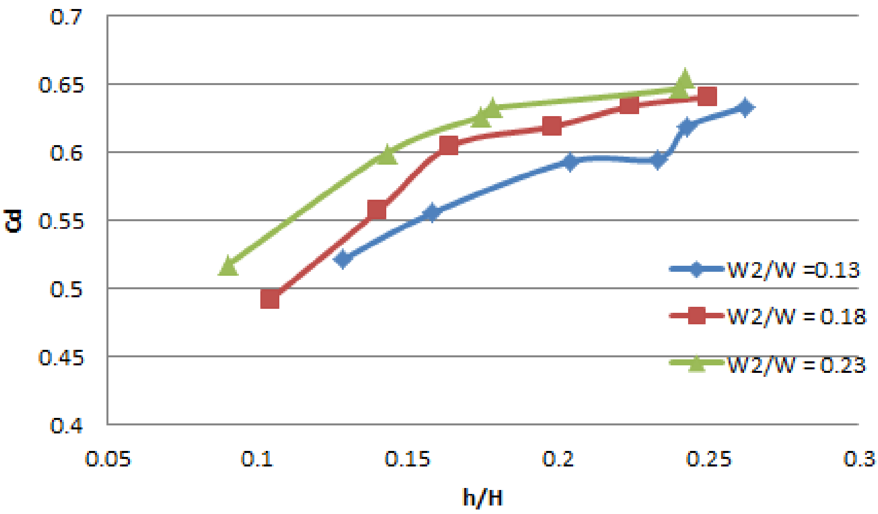

Fig. 12 Variation of C_d with Water Head, z/H = 0.12, d/H = 0.24

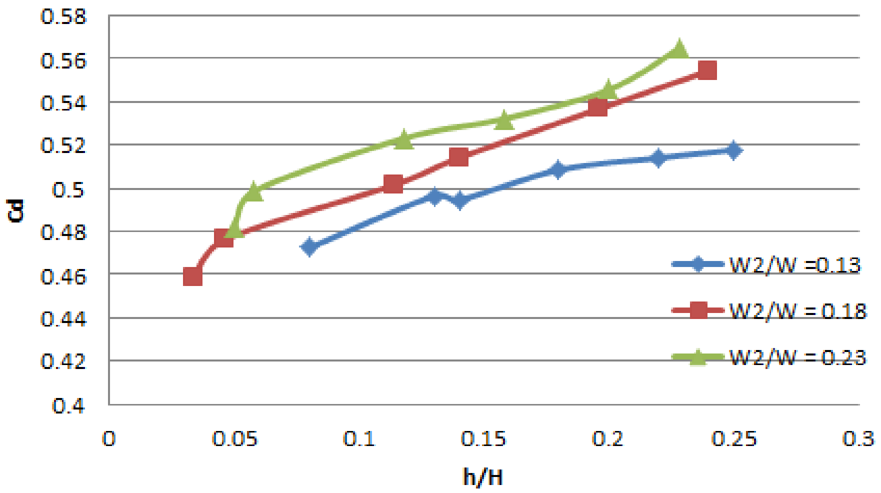

Fig. 13 Variation of C_d with Water Head, z/H = 0.22, d/H = 0.3

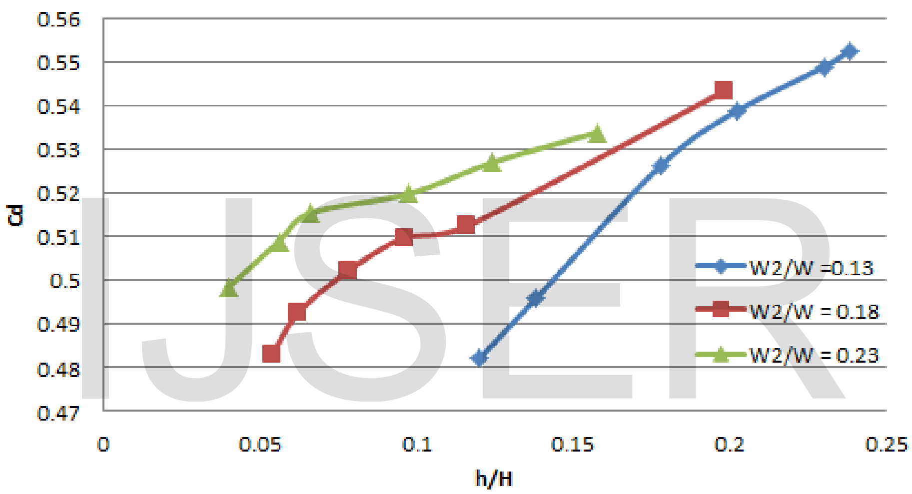

Fig. 14 Variation of C_d with Water Head, z/H = 0.18, d/H = 0.3

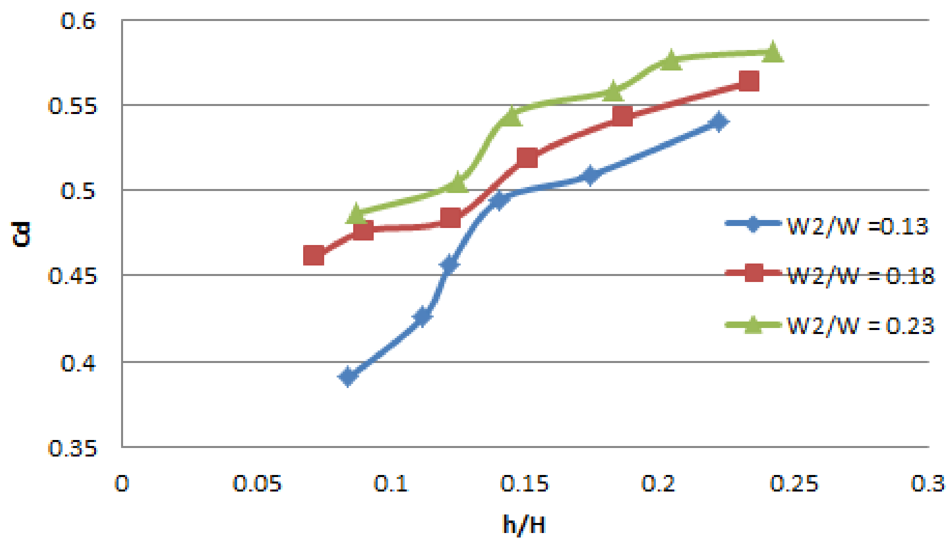

Fig. 15 Variation of C_d with Water Head, z/H = 0.12, d/H = 0.3

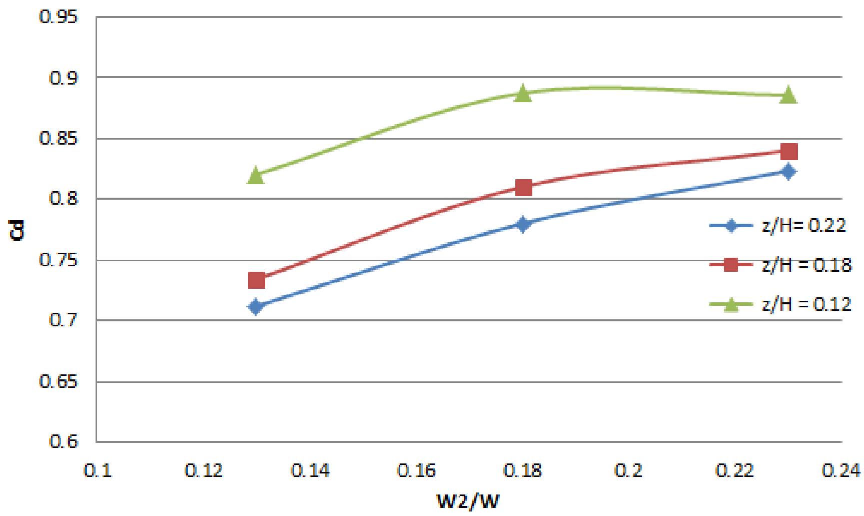

Fig. 16 Variation of C_d with W_2/W, for h/H = 0.32, d/H = 0

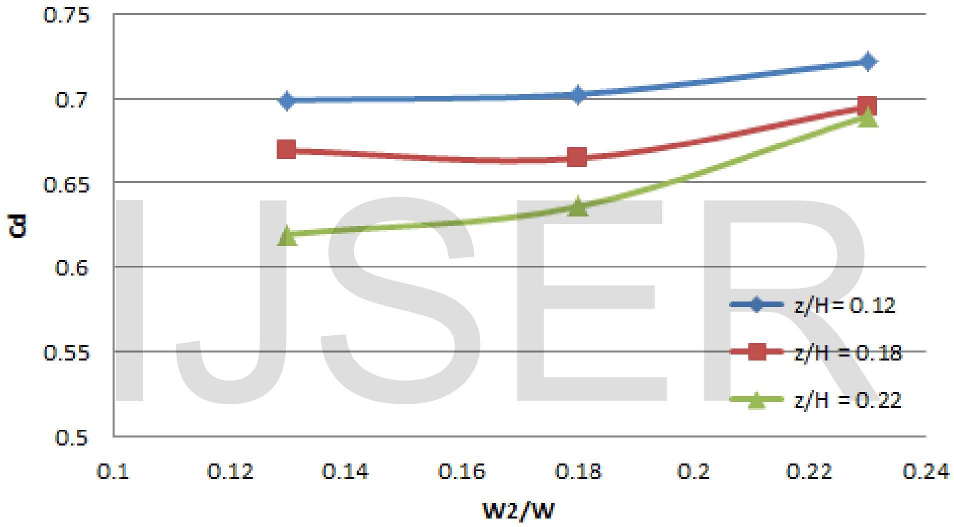

Fig. 17 Variation of C_d with W_2/W, for h/H = 0.3, d/H = 0.16

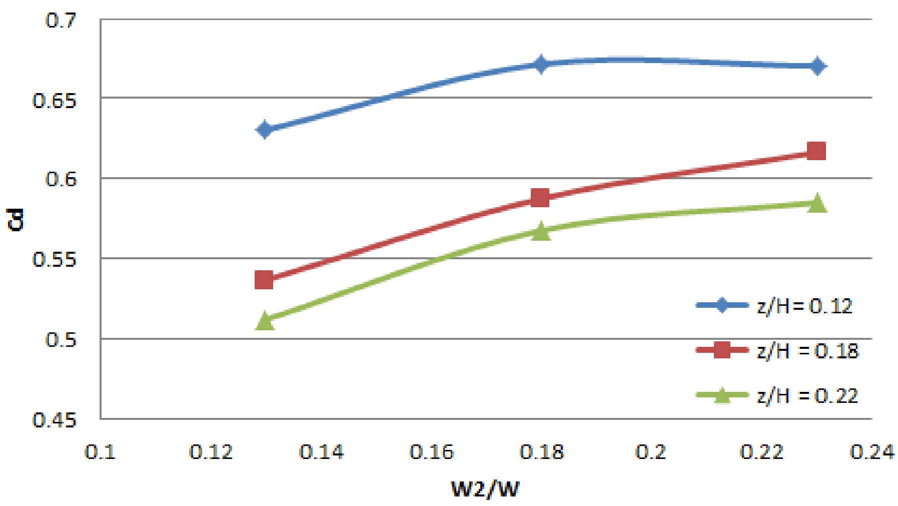

Fig. 18 Variation of C_d with W_2/W, for h/H = 0.3, d/H = 0.24

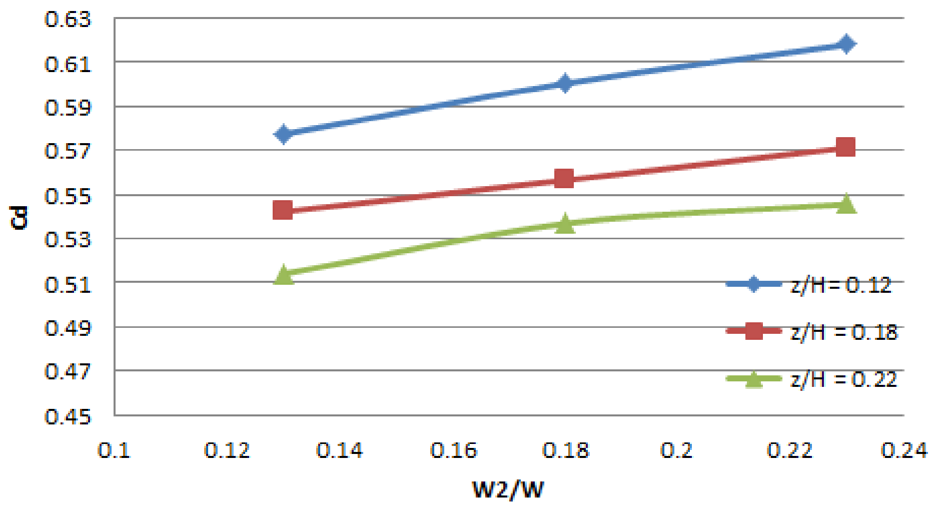

Fig. 19 Variation of C_d with W_2/W, for h/H = 0.3, d/H = 0.3

increases from 0.5366 to 0.6162 as the lower notch width ratio W_2/W increases from 0.13 to 0.23, this means that *Cd* increases by 14.8% as a result of 76.92% increasing in W_2/W.

4.1 Effect of Lower Notch height Ratio *z/H* on the Discharge Coefficient C_d

Oppositely, the analysis of the experimental results show that for constant circular gate diameter ratio *d/H*, water head ratio *h/H*, and lower notch width W_2/W, the discharge coefficient C_d decreases as the lower notch height increases, Figs 20 to 23. It was found that for d/H = 0.3, h/H = 0.3, and W_2/W = 0.18, increasing of the lower notch height ratio *z/H* from 0.12 to 0.22 leads to decreasing in the value of C_d from 0.6 to 0.5389, which means that the discharge coefficient C_d has 11.34% decreasing as a result of 83.33% increasing in the lower notch height ratio *z/H*.

4.2 Effect of the Circular Gate Diameter Ratio *d/H* on the Discharge Coefficient C_d

Figs 24 and 25 show that, the presence of circular gate below the compound weir has an effect on the overall discharge coefficient C_d for the same values of water head ratio *h/H*, lower notch width W_2/W, and the lower notch height *z/H*. It was found that increasing the circular gate diameter ratio *d/H* results in decreasing in the value of the discharge coefficient C_d. For example, changing the value of *d/H* from 0.16 to 0.3 leads to decreasing of C_d value from 0.655 to 0.566, this means that 87.5% increasing in *d/H* results in 15.7% decreasing in the value of C_d.

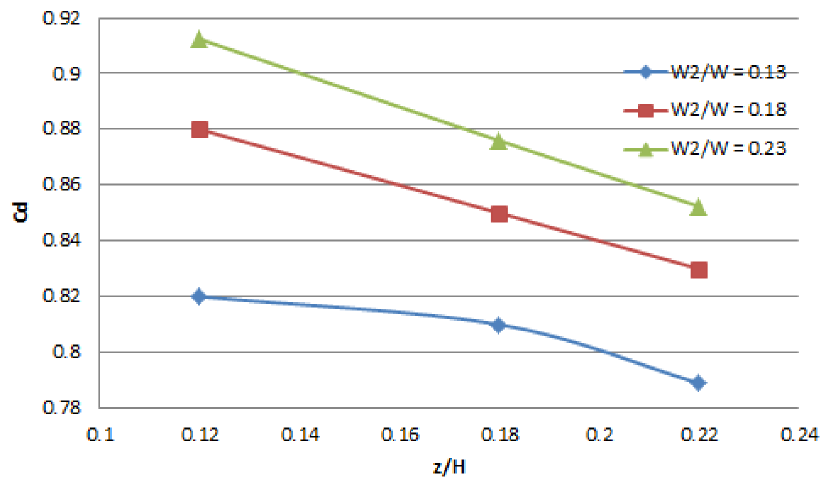

Fig. 20 Variation of C_d with *z/H*, for *h/H* = 0.32, *d/H* = 0

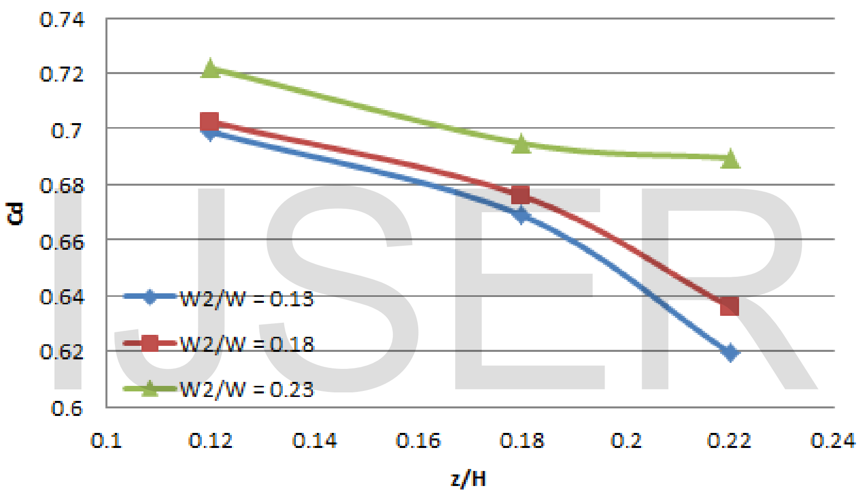

Fig. 21 Variation of C_d with *z/H*, for *h/H* = 0.3, *d/H* = 0.16

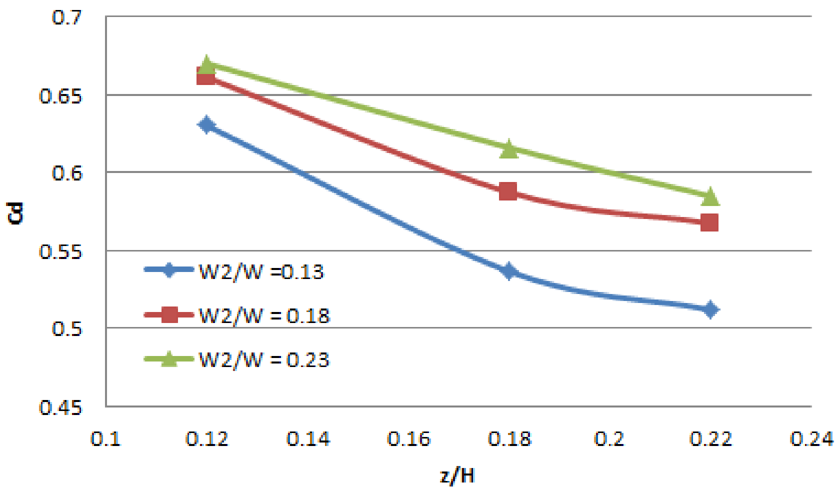

Fig. 22 Variation of C_d with *z/H*, for *h/H* = 0.3, *d/H* = 0.24

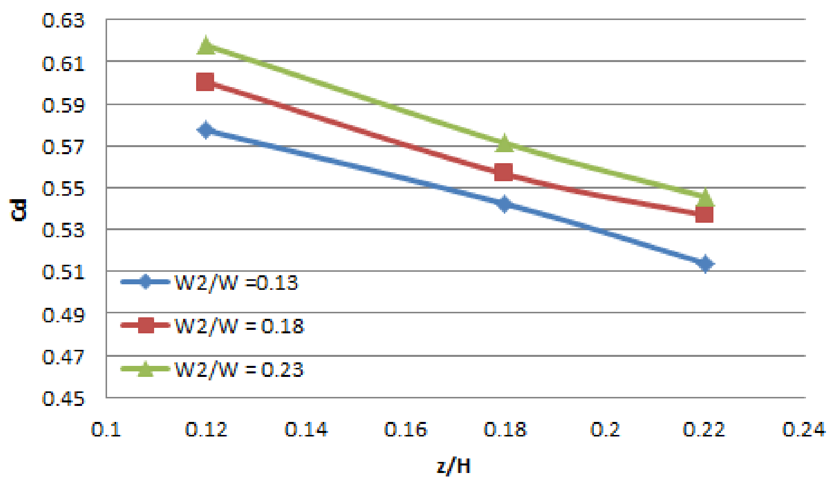

Fig. 23 Variation of C_d with *z/H*, for *h/H* = 0.3, *d/H* = 0.3

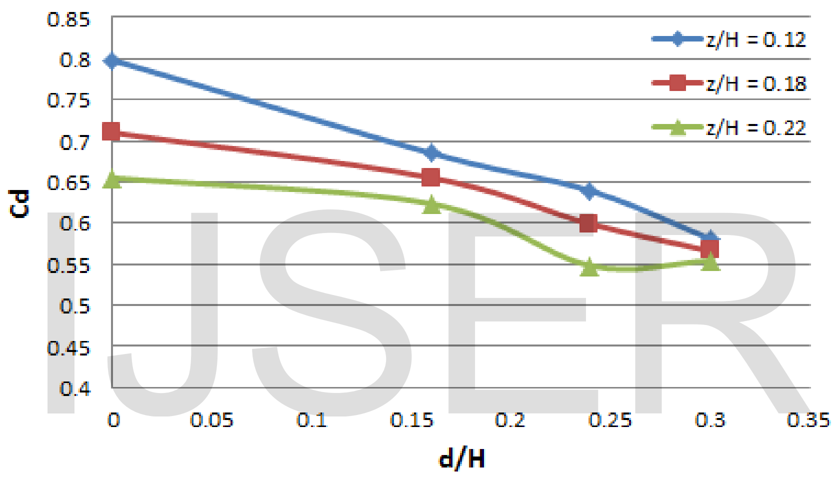

Fig. 24 Variations of discharge coefficient C_d with the circular gate diameter ratio *d/H* for W_2/W = 0.18 and *h/H* = 0.25

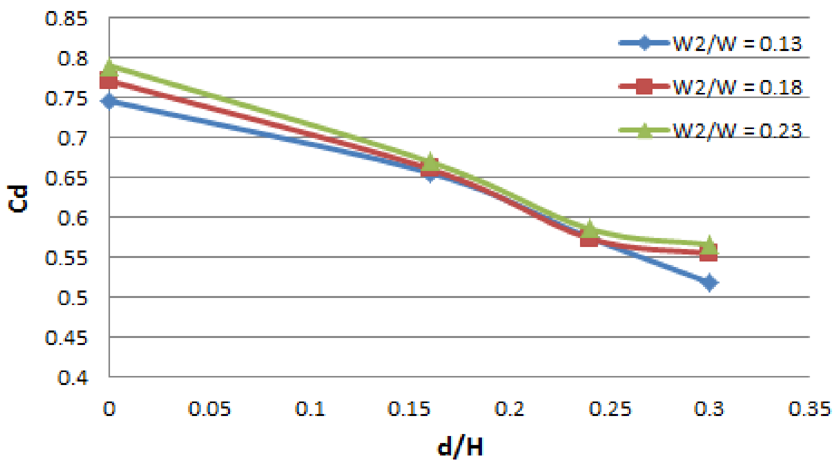

Fig. 25 Variations of discharge coefficient C_d with the circular gate diameter ratio *d/H* for *z/H* = 0.22 and *h/H* = 0.25

5. Conclusions

Based on the analysis of the experimental results the following main conclusions were concluded:

1- There are effects of the compound weir with below circular gate geometric characteristics on the discharge coefficient C_d.

2- For all experimental results, the coefficient of discharge C_d increases as the hydraulic water head h increases with the same trend.

3- As the width of the lower notch of the compound weir W_2 increases for constant values of water head *h*, circular gate diameter *d*, and lower notch height *z*, the discharge coefficient C_d also increases.

4- Increasing the lower notch height *z* for the same water head *h*, circular gate diameter *d*, and the lower notch width W_2, results in decreasing the discharge coefficient C_d.

5- The circular gate diameter *d* increasing results in decreasing of C_d for the same lower notch of the compound weir W_2, lower notch height *z*, and water head *h*.

Notations

C_d: discharge coefficient (-).
d: The circular gate diameter (L).
g: The gravitational acceleration (LT^{-2}).
h: Total head (L).
h_1, h_2: height of water above the upper and middle notches of the compound weir (L).
W: Width of the flume (L).
W_1: Width of the upper rectangular notch (L).
W_2: Width of the lower rectangular notch (L).
Q_{th}: Free combined theoretical discharge (L^3T^{-1}).
Q_{act}: Actual discharge (L^3T^{-1}).
Q_{wth}: Compound weir theoretical discharge (L^3T^{-1}).
Q_{gth}: Circular gate theoretical discharge (L^3T^{-1}).
R_e: Reynolds's number (-).
W_e: Weber number (-).
X: Height of the crest (L).
Y: Distance between the lower edge of weir crest and the gate top (L).
Z: Height of the lower notch of the compound weir (L).
μ: Dynamic viscosity ($ML^{-1}T^{-1}$).
ρ: Water density (ML^{-3}).
σ: Surface tension (MT^{-2}).
ɵ: The angle of the crest for trapezoidal notch (-).

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