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Effect of Weir Height on Flow Features of Duckbill Weir

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ABSTRACT

Duckbill weirs do not have a straight crest in the direction perpendicular to the flow. The plan view of the weir consists of multiple and broken linear crests that increase its effective length. The advantages of this type of weirs are their higher discharge capacity, easy aeration as well as low fluctuations of water surface at the weir upstream. In this study, discharge coefficient of the duckbill weir is investigated numerically. Numerical modeling is carried out by Fluent v. 6.2. The simulated velocity and pressure field are coupled by using "Piso" method. Reynolds governing equations, turbulence k –ε model, and the Volume of Fluid (VOF) model are numerically solved to define pressure and velocity. Also a few equations are proposed to define the relationship of discharge coefficients with some dimensionless hydraulic Parameters. Results showed that as the height of weir is increased, the discharge coefficient increases and the value of discharge coefficient is constant after H/P = 0.3 and is fixed on 0.47. Also the increase in weir height has a significant effect on the increase in the duckbill weir on discharge coefficient, which is an important factor in designing these weirs. Equation 8, with error value of 0.01695, is presented as the best equation to estimate the discharge coefficient over duckbill weirs.

1. Introduction

Weirs and gates are used for controlling the water level in the irrigation channels. Weirs are common structures to regulate water surface and flow control in water conveyance channel and hydraulic structures. One of the effective and economical methods to increase the efficiency of weirs is the utilization of labyrinth weirs whose length increase with modification of plan form and therefore flow discharge will be increased. Generally, they are made in trapezoid, triangular and rectangular forms that are shown in Figure 1.

The duckbill weir is one of the most commonly used structural arrangement, because in majority of conditions, it is the most economical one, providing optimum discharge capacity in relation to lengths of structure and amount of construction material. Plan of duckbill weir, is shown in Figure 2.

Discharge coefficient of duckbill weirs is obtained from equation 1.

$$Q = \frac{2}{3} C_d \sqrt{2g}\, L H^{1.5} \qquad (1)$$

In which, C_d is discharge coefficient, L is the effective length of weir, g is the gravity acceleration and H is the head on the weir crest. C_d depends on the geometry of the channel and weir [1].

Over the years, a lot of researches have been conducted on labyrinth weirs. Hey and Taylor (1970) studied multi-dimensional weirs with sharp-edge crest.

Khorchani and Blanpain (2011) defined discharge coefficient of lateral multi-dimension weirs and presented an equation for discharge coefficient computation [3].

Crookston et al. (2012) performed a numerical simulation on multi-dimension labyrinth weirs.

Shaghaghian and Sharifi (2013) tried to investigate the characteristics of flow in triangular labyrinth weirs through FLUENT Software. Their results showed that numerical model of FLUENT was highly capable of simulating flow field in labyrinth weirs. Therefore, the values of other hydraulic characteristics of flow can be extracted from the numerical model for various parts of the model such as fluid volumetric fraction, flow rate in longitudinal cross section and flow depth, dynamic pressure values and total flow pressure, flow speed vectors, and flow lines.

Emiroglu and Kisi (2013) predicted discharge coefficient in trapezoidal labyrinth side weirs using ANFIS.

Seamons (2014) modeled the effects of varying certain labyrinth weir geometric design parameters to determine the effects on discharge efficiency.

Gupta *et al.*, (2015), investigated the effect of weir's height on flow performance on the sharp crested

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*Corresponding author's email: *Somayehemami70@gmail.com* rectangular-plan form weir. In this paper, the results of experimental investigation presented on 24 different sharp crested rectangular plan form weir models which as manufactured from mild steel plates to show the effect of crest height on flow performance with the various crest lengths.

Bilhan *et al*., (2016) examined discharge capacity of labyrinth weirs with and without nappe breakers as an experimentally.

Roushangar *et al*., (2017) modeled discharge coefficient of normal and inverted orientation labyrinth weirs using machine learning techniques.

Roushangar *et al*., (2017) applied support vector machine to determine discharge coefficient of labyrinth and arced labyrinth weirs.

Haghiabi *et al*., (2017), predicted discharge coefficient of triangular labyrinth weirs using adaptive neuro fuzzy inference system.

Emami *et al*., (2017), investigated the effect of the geometric parameters of duckbill weir on the discharge coefficient numerically.

In recent years, with rapid advances in numerical models, researchers have used a numerical model to solve the equations of fluid flow.

Overvall, expanding the results to the real conditions in addition to the high cost of laboratory tests is limited as well as changing effective parameters. Today, CFD software has won a special place among researchers to investigate the flow conditions of fluid dedication. In this study, the effect of height of duckbill weir is investigated on discharge coefficient by using fluent software. The aim of this study is numerical examination of the effect of duckbill weir height on discharge coefficient. This study aimed to specify a range of mentioned parameters in which the weir discharge coefficient is constant.

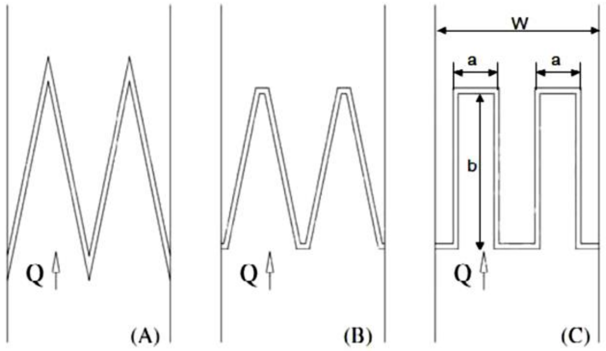

Figure1. Labyrinth weirs A: Triangular, B: Trapezoidal and C: Rectangular

W: channel width, a: apex width and b: apex length (top view)

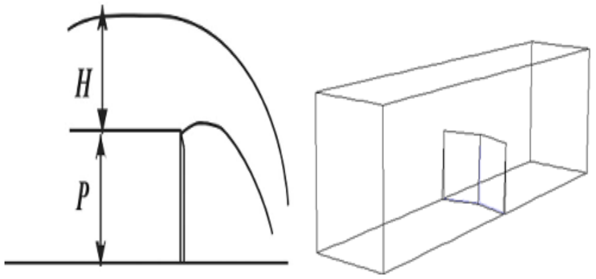

Figure2. Plan of duckbill weir

2. Materials and methods

2.1. Numerical Simulation

Numerical modeling involves solving Navier- Stokes equations based on mass consistency and momentum law for moving the fluid.

These equations are expressed as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_i}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}\left(\rho\overline{u_i{}'u_j{}'}\right) \qquad (3)$$

Where, ρ= fluid density, u= velocity components, x= space dimension, t= time, p=hydrostatic pressure, μ= dynamic viscosity, $\overline{u_i{}'u_j{}'}$= Reynolds stress tensor and δ_{ij}= crooner delta.

There are different methods to solve RANS. In this study, k-ε RNG turbulence model is used which is defined as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \qquad (5)$$

where k= kinetic energy, ε= energy dissipation rate, G_k= turbulence kinetic energy generation due to mean velocity gradient, G_b= kinetic energy due to floatation and Y_M= turbulence Mach number.

In order to simulate the flow over the duckbill weir, channel length, width and height were 4.5, 0.5 and 0.6 m respectively. Gambit software v 2.4.6 was used for modeling. Gambit software is one of the best to model the geometry. This software has a set of commands for rapid organization of 2D and 3D geometries. It also includes structured and unstructured meshes.

In this study, we used Quad-Map element for the meshing of model geometry and Hex-Map element for the meshing of all volumes.

Meshing of the geometrical model of duckbill weir using Gambit is shown in Figure 3.

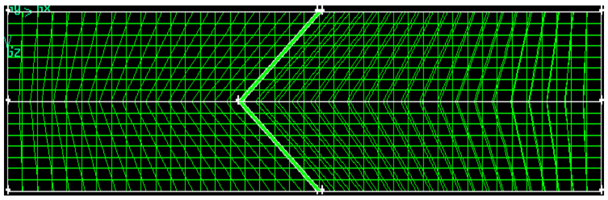

Figure3. Meshing of the geometrical model of duckbill weir using GAMBIT

Also**,** numerical modeling is carried out by Fluent v. 6.2. Fluent software is the best and most powerful processing and post-processing software in computational fluids dynamics (CFD). This software has the ability to support structured and unstructured meshes and it is also written by C programming language. The simulated velocity and pressure field are coupled by using "Piso" method. Reynolds governing equations, turbulence k –ε model, and the Volume of Fluid (VOF) model are numerically solved to define pressure, velocity and the free surface flow profiles.

As numerical simulation continues, discharge of flow is calculated as the product of flow velocity and cross section. Discharge coefficient can be obtained by Equation (1).

2.2. Dimensional analysis

The discharge passing over the weir depends on several parameters, which is mathematically expressed by equation (6):

$$C_d = f\,(H_d, L_e, P, W, \theta, y) \qquad (6)$$

Where H_d is total head over the weir crest, W is weir width, P is weir height, θ is the vertex angle and y is flow depth. A dimensional analysis is performed with Π Buckingham method to find a relation between the discharge coefficient and other parameters as stated above. The following is the mathematical expression of this relation.

$$C_d = f\left(F_r, \frac{H_d}{P}, \frac{L_e}{P}, \frac{y}{P}, \frac{H_d}{w}, \frac{y}{w}, R_e, \frac{L_e}{w}, \theta, W_e\right) \qquad (7)$$

$$\Longrightarrow \qquad C_d = f\left(\frac{H_d}{P}, \frac{L_e}{P}, \theta, R_e, W_e\right)$$

According to Equation (7), discharge coefficient depends on $(\frac{H_d}{P}, \frac{L_e}{P}, \theta)$ and dimensionless numbers of Reynolds and Weber. For modeling the river, it is suggested that if the minimum depth of water is 0.03 m, the effect of surface tension can be neglected. As in this study, the minimum water height on weir is 0.03 m and the minimum discharge rate is 10 l/s, so Reynolds and Weber numbers can be ignored.

2.3. Discharge equation for duckbill weir

In order to determine the discharge coefficient equation on the duckbill weir, nonlinear regression was used. To obtain the best equation, different functions for C_d as the dependent variable in relation to independent variables as (H/P, L, θ), some equations were derived for C_d.

Equation 8, shows that an example of the estimated functions for C_d.

$$C_d = 0.0948 \left(\frac{H}{P}\right)^{-0.249} \theta^{0.374} \qquad (8)$$

Above equation, with error value of 0.01695, was presented as the best equation to estimate the discharge coefficient over duckbill weirs. The application range of this equation is $45^\circ \le \theta \le 180^\circ$ and $0.1 \le \frac{H}{P} \le 0.67$.

3. Results and Discussion

3.1. Geometric Characteristic of Simulated models

The characteristic of all examined models are presented in Table 1.

Table1. Geometric characteristic of simulated models

Height (H) (m)	Height of weir(P) (m)	H/P	Length
0.03-0.2	0.05-0.3	0.2-1.33	1
0.03-0.2	0.05-0.3	0.2-1.33	1
0.03-0.2	0.05-0.3	0.2-1.33	1
0.03-0.2	0.05-0.3	0.2-1.33	1
0.03-0.2	0.05-0.3	0.2-1.33	1

Figure 4, represents dimensionless height of weir effect on discharge coefficient. As can be seen in this figure, the discharge coefficient increases by the increase in the height of weir and the value of discharge coefficient is constant after H/P= 0.3 and is fixed on 0.47.

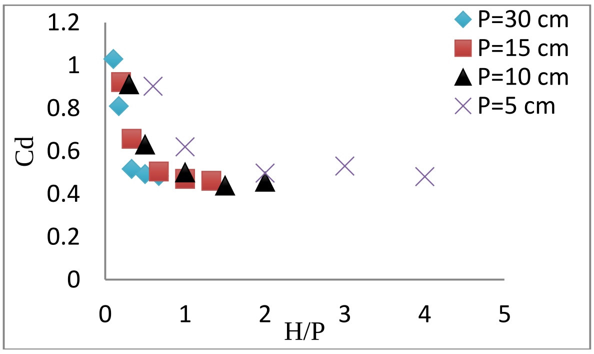

Figure4. The numerical results of C_d at various H/P (P=30, 15, 10, 5 cm)

As shown in Figure 4, the discharge coefficient increases with the height of weir, for a certain H/P due to interference of the jets.

As is evident in Figure 4, discharge coefficient variation with H/P at different heights; has two separate sections; upstream and downstream sections of curve. In upstream section of curve, it can be seen that the discharge coefficient increases with H/P variations. In this section of curves, the interference in the jets not so noticeable. Almost in whole length of duckbill weir crest, the flow is discharged freely with no serious interference by the layers.

Over the time, downstream section of curve begins to increase the interference of the flow layers and the discharge coefficient starts to decrease by increasing H/P value. In this section of curve, at first, all curves have a steep slope, but the slope of curves decreases by increasing H/P. so that, at a specified range of H/P, the discharge coefficient reaches a constant value. The tests were numerically performed on four different heights of duckbill weirs. The ranges of the complete data are given in Table 2.

Table2. Data collected in the present study

No.	L (m)	H (m)	P (m)	H/P	C_d	Q ($m^3 S^{-1}$)
W1	1	0.03	0.3	0.1	0.902	0.015804
W2	1	0.05	0.3	0.17	0.619	0.026709
W3	1	0.1	0.3	0.33	0.497	0.048278
W4	1	0.15	0.3	0.5	0.453	0.084403
W5	1	0.2	0.3	0.67	0.451	0.127835
W6	1	0.03	0.15	0.2	0.911	0.014132
W7	1	0.05	0.15	0.33	0.63	0.021691
W8	1	0.1	0.15	0.67	0.5	0.047064
W9	1	0.15	0.15	1	0.438	0.080629
W10	1	0.2	0.15	1.33	0.457	0.12176
W11	1	0.03	0.1	0.3	0.921	0.013978
W12	1	0.05	0.1	0.5	0.657	0.0208
W13	1	0.1	0.1	1	0.504	0.04669
W14	1	0.15	0.1	1.5	0.47	0.07514
W15	1	0.2	0.1	2	0.461	0.120703
W16	1	0.03	0.05	0.6	1.03	0.01384
W17	1	0.05	0.05	1	0.809	0.020436
W18	1	0.1	0.05	2	0.517	0.04641
W19	1	0.15	0.05	3	0.492	0.074625
W20	1	0.2	0.05	4	0.484	0.119119

According to Figure 5, it can be seen that duckbill weir with vertex angle of 30°, passes more discharge than normal weir. It can be related to the fact that duckbill weirs have longer length and therefore, they pass more discharge through themselves.

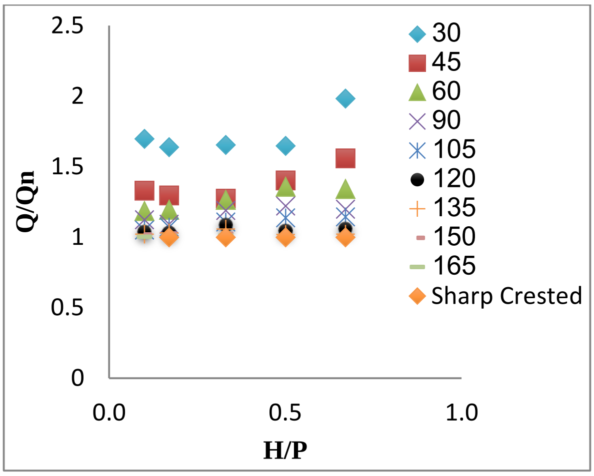

Figure5. Comparision of the discharge of duckbill weirs with normal weir

Variation of flow discharge is shown in Figure 6 based on height of water over the duckbill weirs (H) with different height compared with normal weir. This figure indicates that, discharge (Q) increases as the value of H over duckbill weir is increased.

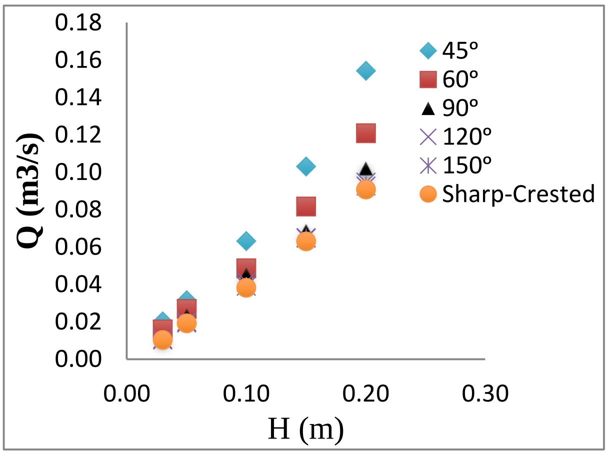

Figure6. Variation of Q with H for duckbill weirs

With the increases in height and θ angle over duckbill weir and due to the reduction of the effective length of weir, the discharge decreased from the duckbill weirs. Generally, it can be expressed that the length of duckbill weirs compared with normal weir (standard weir) has an important role in discharge passes over the weir.

The predicted values of C_d at various observed values of C_d are shown in Figure 7.

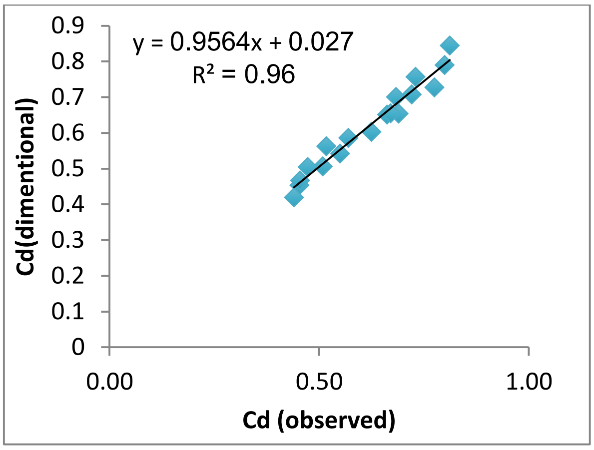

Figure7. The predicted values of C_d at various observed values of C_d

4. Conclusions

In this study, we investigated the effect of height on discharge coefficient of duckbill weir. The results showed that the discharge coefficient increases with the height of weir and the value of discharge coefficient is constant after H/P =0.3 and is fixed at 0.47. Also, the efficiency of the duckbill weir increases with the value of H. As well, discharge coefficient increases with the height of weir for constant H/P, but this increase in the discharge coefficient in higher at downstream section of curves where, there are interference by the jets than at upstream section of curves where there are no interferences by the jets. According to the results, discharge passes of duckbill weirs were compared with normal weirs, reflecting the efficiency of duckbill weirs. Also, Equation 8 can be used to obtain the discharge coefficient with error value of 0.01695, on the duckbill weir.

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