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The Relation Between the Coefficient of Discharge and Different Hydraulic and Geometric Parameters for a Vertical Drop Structure Using CFD

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Abstract

This study shed light on the most important dissipation energy structures which exposed for the vertical drop of water. The case study in this research is built on the base of Sarda fall type specifications. The models were simulated by ANSYS of fluid fluent software (Computational Fluid Dynamic).

Five suggested models differ from each other with a height of drop (y_{dr}) equals 0.25m, 0.35 m, 0.45 m, 0.55 m and 0.65 m. are used. Each model is tested under five values of inlet velocities (V_u) which are 0.4 m/s, 0.5 m/s, 0.6 m/s, 0.7 m/s and 0.8 m/s as a requirement to build the CFD model. The main aim of this study is to derive a non – dimensional relationship between the coefficient of discharge (C_d) for the flow over the crest of the drop and the other hydraulic and geometric parameters such as the depths of flow upstream the drop (y_{up}), depth of water in the middle of cistern (y_{ci}), depth of water after the cistern and downstream the structure (y_{do}) and Froude number downstream the structure (F_r). All these parameters were processed in Buckingham theorem to obtain a non – dimensional parameters and then subjected them in SPSS v25 to get the non – dimensional formula. This equation is the first one that calculates the coefficient of discharge over a broad crested weir (crest of the drop) based on several hydraulic and geometric variables, unlike the traditional equations for calculating the value of C_d. This relation indicates a positive relation between C_d and the other parameters (i.e. y_{up}, y_{ci}, y_{do} and F_r) and this also was confirmed by the results of laboratory experiments for the purpose of verifying the results of the model. The coefficient of determination (R^2) was developed from the relationship yielded a good correlation.

Keywords: Vertical drop, Coefficient of discharge, Froude number, CFD, Fluid fluent

INTRODUCTION

There are very little researches available in the field of analysing the hydraulic performance of vertical canal drop, especially those researches published recently. Most of the available research dates back to the 1950s and 1960s.

Arora, K. R. (2018) defined the canal drop as a structure constructed across a channel for lowering the water level and bed level also. Because of the drop of the water level at the fall, the potential energy of the flow is converted to a kinetic energy, which may damage the downstream floor by scouring action.

The important types of falls which were used previously and recently are Ogee type, Rapid type, stepped type, Falls of Trapezoidal notch, Vertical drop type (Sarda), Falls of Straight glacis type and English (Baffle) falls.

Ayoub, N. S and Hamad, A. M. (2022) introduced a numerical study for a free flow over a broad – crested weir with different slopes of upstream and downstream faces using the software of computational fluid dynamics (Flow – 3d, version 11.0.4). the researchers configure four weirs with different slopes in upstream and downstream slopes to investigate the effect of the shape of weirs on the value of the coefficient of discharge (C_d), the trend of upstream energy grade line and the flow velocity of depth - averaged using multi values of flow. The results of simulation showed that the difference between numerical and experimental values of upstream head was ranged between 0 to 9.6 %. As an important conclusion, the study proves that when the slope upstream face reduced by 50 % and 70.5 %, the values of C_d increased by 9.5 % and 13.2 % respectively and the value of energy grade line (static pressure) decreased by 4.3 % and 8.7 % respectively. The results showed also there is no influence for changing the slope of downstream face.

Mazumder S. K. (2012) and Mazumder S. K. (2017) considered that the conventional practice of design of canal drops along length of inlet and outlet canal transitions are offered to improve performance. Mazumder represents that its very costly in addition that its hydraulic performance is not quite good. Experimental works and analytical solution were undertaken by the researcher to find an economical and innovative design method. The optimum ratio of flow and optimum transition length are found to be economic and good in performance. An optimum design of stilling basin with rapidly diverging wing walls and reverse slope floor which acts as an energy dissipater and the recommendation of expanding the transition is needed.

Odgaard A. J. et al. (2013) introduced a non – dimensional relationship to describe the flow inside a baffle – drop structure which is represents one of conveyance structures used to transport urban storm water to underground storage tunnels. The researchers conducted a number of laboratory experiments to analyze many hydraulic parameters testing them to ensure the validity of results that may be used in the design. The derived formula relates between number of key variables such as design discharge, diameter of the shaft, spacing between baffles and the vertical wall position that divides the shaft in both dry and wet conditions.

Salmasi F. (2011) investigated physical models of a drop to dissipate the energy of flow. Three values of drops heights have been made from Plexiglas to determine the effective parameters on the phenomenon and they have been attached with two existing laboratory flumes. Several tests were conducted on physical models to measure the required parameters to calculate the required energy dissipation value. Results showed that the energy dissipation depends on the drop height and the value of flow. A nonlinear regression between effective parameters using a model has been developed statistically to predict the energy dissipation in vertical drops. An approach of artificial neural networks (ANN) was used to develop an explicit procedure to estimate the loss of energy at drops. The response of this network was predicted the RMSE and R^2 as 0.0085 and 0.977 respectively.

Farouk M. and Elgamal M. (2012) investigated the hydraulic performance of single drop and multi-drop structures and by re-analyzing the empirical equations that calculate the dissipation of energy. Then, a numerical investigation was conducted by the computational fluid dynamic (CFD) to evaluate the hydraulic performance of multi – stepped channel and single vertical drop using the technique of the volume of fluid (VOF). It was found that the (CFD) is able to simulate the hydraulic performance with high reality of both cases.

Sholichin M. and Akib S. (2010) conducted a laboratory work to create a hydraulic jump downstream vertical and sloped drop structure. The effectiveness of the jump was measured by drop number (D). The other objective was to develop the mathematical model for the sloped and vertical drop structure. Results showed that the D equation could estimate the length of drop (Ld) and the length of hydraulic jump (Lj) for vertical drop structures. These equations have non-linear regression with a range between 60% - 87% and relative error ranged between 5% - 13%.

The main aim of this study is to formulate a non-dimensional relation between the coefficient of discharge and other hydraulic and geometric parameters of a vertical drop by the help of CFD software. It is the first time that the relationship between the discharge coefficient and the rest of the hydraulic parameters of flow over and within a vertical drop has been addressed, as the derived equation can be used to measure the discharge passing within this structure in addition to the basic function of dispersing the flow energy.

DIMENSIONAL ANALYSIS

To derive a dimensionless expression that describes a relationship between the coefficient of discharge (C_d) and other dimensionless parameters (y_{dr}, y_{up}, y_{ci}, y_{do}, F_r), the Buckingham method can be used as a tool to obtain these parameters, the equation consists of:

$$\therefore\ C_d = f\left(\frac{y_{up}}{y_{dr}}, \frac{y_{ci}}{y_{dr}}, \frac{y_{do}}{y_{dr}} F_r\right) \quad (1)$$

Where $\frac{y_{up}}{y_{dr}}$ is non – dimensional upstream water level at the inlet of the model, $\frac{y_{ci}}{y_{dr}}$ is non – dimensional water depth in the middle of the cistern, $\frac{y_{do}}{y_{dr}}$ is non – dimensional downstream water level after cistern and F_r is Froude Number at downstream of the drop after cistern.

COMPUTATIONAL FLUID DYNAMIC MODELS

The CFD model is based on Fluid Flow (Fluent) software package as a high performance of fluid dynamics simulation program that has been used to characterize and solve wide range of open channel flow cases.

Geometry

Figure 1 shows the Computational Fluid Dynamics model as a first step to build the model using space claim and the final editing of the geometry was done by design modeler.

Setup of the Mesh

Figure 2 shows the method of multi- zone that was used in the numerical analysis by the technique of the finite element. The dimension of each cell in the mesh 0.01 m in each direction.

Setup of the Model

The transient VOF simulation based on solving 3-D Reynolds-averaged Navier–Stokes equations, including sub-grid models for air entrainment, evaluation of density and drift-flux. Eulerian phases are: air as a primary phase and the second is water liquid (Dong, Z. et al. 2019). The force of surface of continuum model and the phase localization of compressive scheme are the base of interaction phase (ANSYS I. 2013; Kuzmin, D).

The used viscous model is the standard k - epsilon with standard wall functions that represents more adopted in open channel flow researches because it gives the best turbulence model and satisfy a good agreement with experimental and field data. The models were categorized into five according to the height of drop (25 cm, 35 cm, 45 cm, 55 cm and 65 cm) which locates at 0.6 m after the chosen reach at upstream. The other components of the canal fall are shown in figure 3. All models are tested under five values of inlet velocity from upstream side (0.4 m/s, 0.5 m/s, 0.6 m/s, 0.7 m/s and 0.8 m/s.

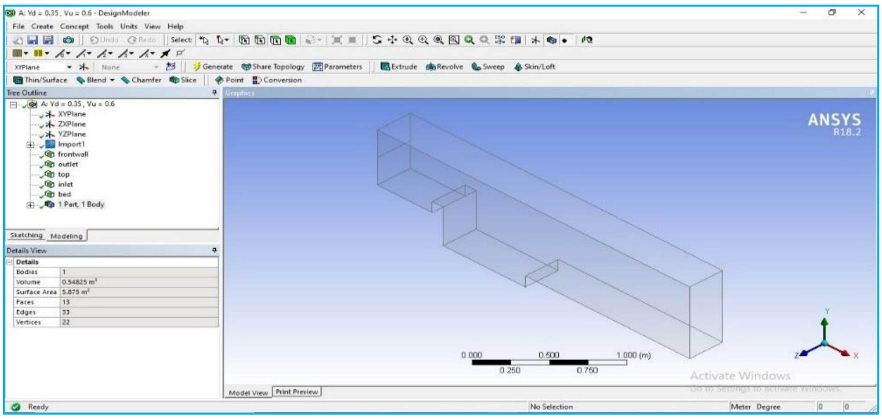

Figure 1. Three-dimensional geometry by design modeler

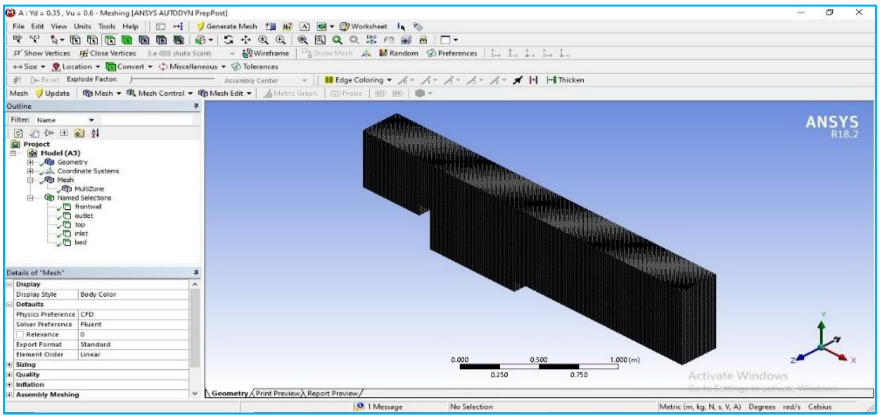

Figure 2. Creating the mesh by multizone method

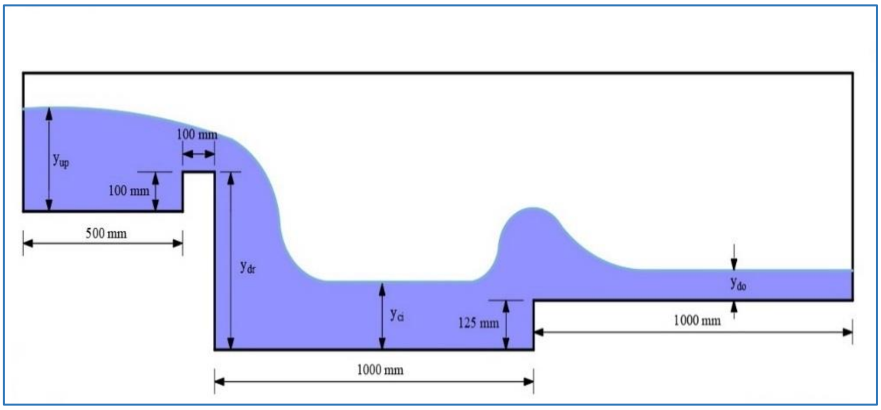

Figure 3. A typical geometry of CFD model

The effect of each parameter in the derived formula should be investigated to find the most sensitive parameter and influence on the value of the coefficient of discharge.

RESULTS AND DISCUSSION

The results of all runs conducted by ANSYS 18.2 for all models are illustrated in table 1 as follows:

Table 1: Output of CFD models

Model No.	V_u (m/s)	C_d	yup (cm)	yci (cm)	ydo (cm)	F_r
1	0.4	1.82	23.05	23.12	9.88	0.96
	0.5	1.85	26.02	26.13	11.5	1.08
	0.6	1.97	27.25	28.09	13.25	1.09
	0.7	2.15	28.55	29.46	14.32	1.19
	0.8	2.34	29.23	30	14.95	1.3
2	0.4	1.88	23.13	25	8.44	1.21
	0.5	1.95	25.63	27.1	10.15	1.28
	0.6	2.12	26.67	29.1	11.52	1.31
	0.7	2.31	27.76	30.1	12.3	1.44
	0.8	2.56	28.23	30.6	12.65	1.61
3	0.4	2	23.15	26	7.57	1.43
	0.5	2.1	25	28.05	8.85	1.53
	0.6	2.31	25.7	29.7	9.7	1.63
	0.7	2.57	26.65	30.62	10.37	1.79
	0.8	2.84	27.12	30.9	10.6	2.02
4	0.4	2.08	23.15	27.1	6.7	1.72
	0.5	2.23	24.5	29.58	7.82	1.8
	0.6	2.45	25.17	30.57	8.41	1.99
	0.7	2.73	26.08	31.62	8.8	2.24
	0.8	3.04	26.45	32	8.97	2.52

5	0.4	2.16	23.15	28.17	6.18	1.93
	0.5	2.32	24	30.36	7.1	2.04
	0.6	2.56	24.88	31.72	7.72	2.23
	0.7	2.94	25.37	32.38	7.98	2.53
	0.8	3.31	25.5	32.5	8.2	2.78

The results showed that when the inlet velocity (V_u) increases, the values of all depths of flow and the coefficient of discharge (C_d) for the same model are increased. While at a specific value of inlet velocity, the value of any depth of flow (i.e. y_{up}, y_{ci} and y_{do}) is decreased when the value of drop height (y_{dr}) increases due to the increase in the value of momentum flux and depending on the principle of increasing the velocity of the falling object with increasing height of fall.

Non – Dimensional parameters and the derived formula

Typically, in regression problems, one of the variables which are often called the response (dependent) variable, it has a special significance and is indicated by y. The other parameters $x_1, x_2, \ldots, x_k$, are called explanatory (independent) variables that are used in the prediction of the values of y and the trend of formula 2 (Ruckstuhl, A. F. 2010; Leite, M. T. 2020):

$$Y = f\,(x_1, x_2, \ldots\ldots, x_k; \Theta) \tag{2}$$

Where $\Theta = f\,(\alpha, \beta)$ and can be expressed in equations as:

$$y = \alpha\, x^{\beta} \tag{3}$$

According to equation 1 and depending on the results listed in tables 1, 2 and 3, and by applying 80 %, the following formula is derived by SPSS version 25 to describe the non – dimensional relationship between the coefficient of discharge (C_d) and the other non – dimensional parameters as follows:

$$C_d = 0.282 - 3.33 * \frac{y_{up}}{y_{dr}} + 3.378 * \frac{y_{ci}}{y_{dr}} + 0.557 * \frac{y_{do}}{y_{dr}} + 1.044 * F_r \tag{4}$$

The coefficient of determination (R^2) is equal to 0.935.

Analysis of non – dimensional parameters

Figure 4 shows the relation between non dimensional upstream water level and the coefficient of discharge.

It is clear that the relation is positive within the same model. Also, it has been noticed that when the value of drop height (y_{dr}) increase, the value of C_d increases also in general when it's compared with the other models. The reason refers to the decrease in the value of (Q_{th}) if it was taken into consideration there is an approximate stability of the actual discharge values. Also, it is noticed that when (y_{up}/y_{dr}) in the maximum value as a group, the values of C_d as a group also will be within minimum due to the effect of the value of drop height (y_{dr}).

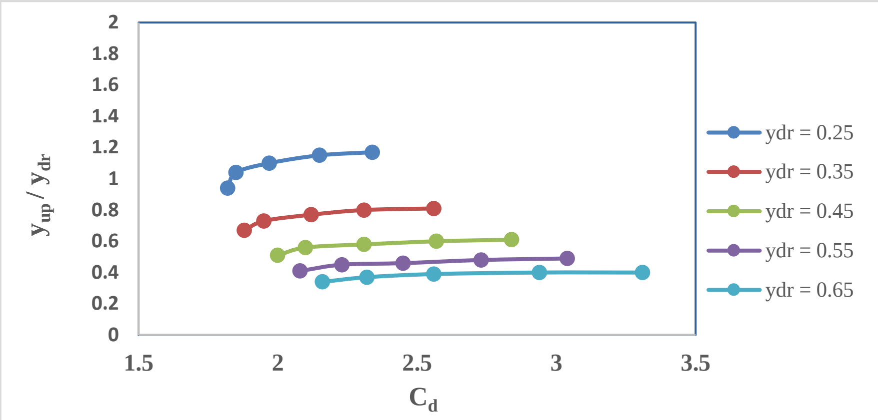

Figure 4. The relation between C_d and non-dimensional upstream water level

The same behaviour and interpretation remain for the trends of curves in the figures 5 and 6 because when the height of drops increase, the values of flow velocity in all sections of the domain will increase also and that means decreasing the depths of flow after the fall.

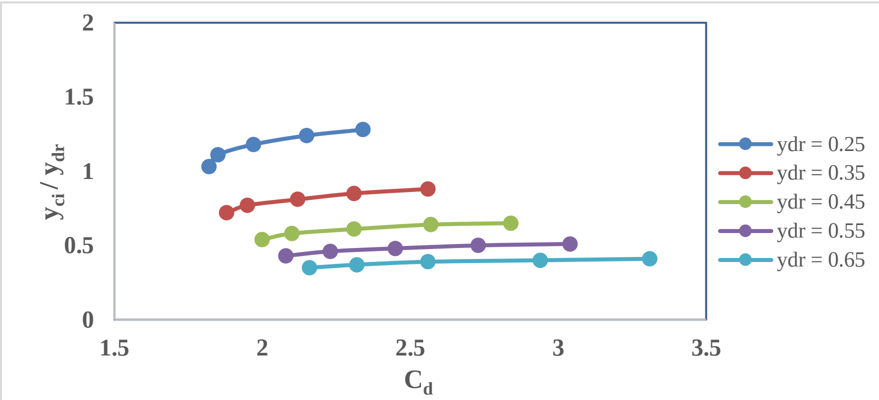

Figure 5. The relation between C_d and non-dimensional cistern water level

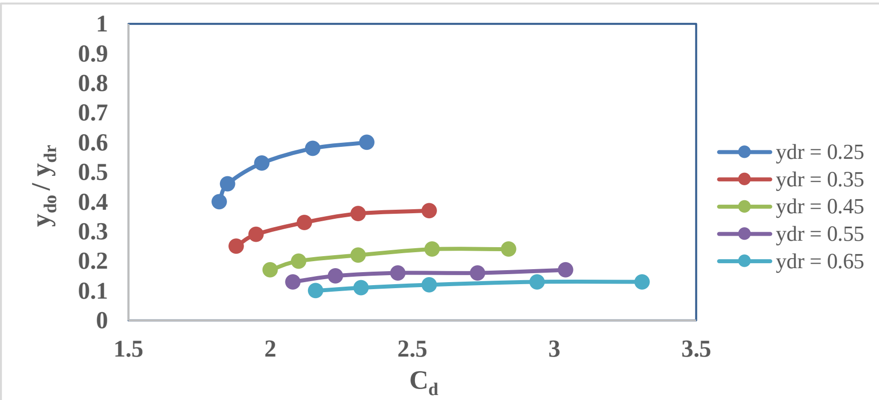

Figure 6. The relation between C_d and non-dimensional downstream water level

While, in figure 7, the trend is different when it was observed that the relation is negative in general when it is compared with figures 4, 5 and 6. It had been noticed that when the value of drop height (y_{dr}) increase, the value of C_d increases also when it's compared with the other values in the other models and that is refers to the same reason of decreasing in the value of theoretical discharge. Also, it was observed that when (F_r) in the maximum value as a group, the values of C_d as a group also will be within maximum due to the effect of the value of drop height (y_{dr}) and increasing the flow velocity and the value of momentum as shown in figure 7.

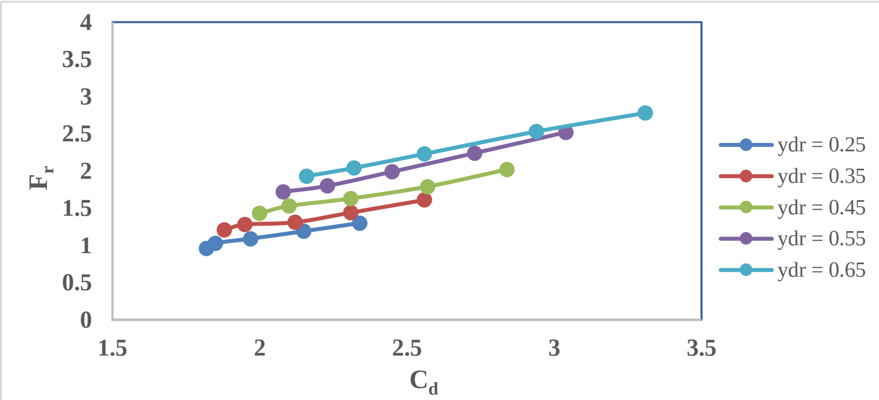

Figure 7. The relation between C_d and Froude number

Accuracy test according to Experimental Work

To ensure the validation of formula (4), the comparison between the results of CFD analysis will be compared with the others obtained from experimental work which was conducted for two suggested models (1 and 2) fabricated from Plexiglas material. The models were fixed to a laboratory flume with dimensions of 30 cm wide, 60 cm height and 15 m long at 5 meters from the upstream tank. The results of laboratory work as shown in table 2:

Table 2: Experimental results applied on model #1 and Model #2

Model No.	Q_{act} (m^3/s)	V_u (m/s)	C_d	yup (cm)	yci (cm)	ydo (cm)	F_r
1	0.028	0.4	1.88	23.13	23.15	9.93	0.96
	0.038	0.5	1.81	26.12	26.18	11.58	1.07
	0.047	0.6	1.99	27.32	28.2	13.33	1.08
	0.057	0.7	2.14	28.6	29.53	14.5	1.17
	0.066	0.8	2.33	29.31	30.06	15.13	1.28
2	0.028	0.4	1.83	23.33	25.06	8.66	1.18
	0.038	0.5	1.9	25.67	27.12	10.2	1.26
	0.047	0.6	2.1	26.77	29.17	11.64	1.3
	0.057	0.7	2.3	27.82	30.19	12.47	1.42
	0.066	0.8	2.54	28.34	30.66	12.78	1.59

To test the validity of formula (4), values of C_d will be compared with the others obtained from formula (4). The difference percentage between two sets of results as shown in table 3:

Table 3: Percentage of difference between experimental data and the results of formula (4)

Model No.	V_u	C_d from Experimental Work	C_d from Formula 4	Percentage of Difference %
1	0.4	1.79	1.58	13.3
	0.5	1.81	1.72	5.24
	0.6	1.99	1.88	5.86
	0.7	2.14	2.01	6.47
	0.8	2.33	2.12	9.91
2	0.4	1.83	1.86	1.62
	0.5	1.9	1.94	2.07
	0.6	2.05	2.09	1.92
	0.7	2.3	2.23	3.14
	0.8	2.54	2.41	5.4

Accuracy Test According to the Other CFD Data

The other comparison is conducted between the results of formula (4) and 20 % of the CFD results which are not used in non – linear regression, were applied in the formula to compare the two sets of the results:

Table 4: Percentage of difference between CFD data and the results of formula (4)

V_u	C_d from CFD	C_d from formula 4	Percentage of Difference %
0.4	2.16	2.4	10.1
0.5	2.32	2.49	6.86
0.6	2.56	2.7	5.03
0.7	2.94	3.01	2.49
0.8	3.31	3.31	0.01

Both of tables 3 and 4 show a good compatibility between the results of CFD and the other obtained from formula derived from non- linear regression.

SENSITIVITY ANALYSIS

Sensitivity analysis is a technique to test the quality of a proposed model or improve the quality of an inference based on the model (Saltelli, A. 2010; Nguyen, A. T. and Reiter, S. 2015).

Table 5 shows the sensitivity analysis for each non-dimensional parameter and the effect ratio for each parameter as a percent:

Table 5: The effect ratio for each parameter in formula 4

Parameters	y_{up}/y_{dr}	y_{ci}/y_{dr}	y_{do}/y_{dr}	F_r
Effect Ratio %	30.1	29.7	79.6	95.8

As seen from table 5, the non-dimensional downstream water level is the more parameter effect on the value of C_d.

CONCLUSIONS

The following conclusions are formulated based on the results and according to the parameters values implemented in the research:

- According to the results of sensitivity analysis were illustrated in table 3, the non-dimensional downstream water level represents the most influence parameter on the value of C_d and Froude number ranked second.

- The percentage of variation in values of ($\frac{y_{up}}{y_{dr}}$) with respect to the values of C_d ranged from 17.7 % to 24.5 % where it was observed that the lowest percentage was when the value of drop height is maximum. While the highest percentage was recorded at the minimum value of y_{dr}. The same behaviour still constant for the relations between ($\frac{y_{ci}}{y_{dr}}$ vs. C_d) and ($\frac{y_{do}}{y_{dr}}$ vs. C_d) when the percentage of variation ranged between 17.2 % to 24.31 % and 30 % to 50 % respectively.

- The relation between the percentage of variation of the values of Froude Number and drop height is positive. The minimum value of variation was 35.5 % at the value of y_{dr} equal to 0.25 m, while the maximum variation was 44.1 % at maximum drop height which is equal to 0.65 m.

- The values of percentage of difference of C_d obtained from the simulation of CFD and the others that resulted from formula (4) ranged between 0.01 % to 10.1 %. The high level of agreement between two sets of results was obtained when the velocity of flow increases and turbulence occurs.

RECOMMENDATIONS

- Studying the effect of rounded crest and to what extent the value of C_d may be affected by the new shape when it was compared with the rectangular crest.
- Making a dentated crest and then studying the influence of the new shape on the flow regime and the value of the coefficient of discharge.

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