INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 7, Issue 2, 2016 pp.169-178
Journal homepage: www.IJEE.IEEFoundation.org

Experimental investigation of compound side weir with modeling using computational fluid dynamic

Saleh I. Khassaf[1], Ali N. Attiyah[2], Hayder A. Al-Yousify[2]

[1] Civil Engineering Department, University of Basrah, Iraq.
[2] Civil Engineering Department, University of Kufa, Iraq.

Abstract
Side weirs, also known as lateral weirs, are flow diversion devices widely used in irrigation as a head regulator of distributary and escapes, land drainage, and urban sewage systems. The modeling of side weir is a sophisticated problem in the hydraulic engineering. The coefficient of discharge over side weirs were investigated by many of the researchers experimentally and theoretically. In this study, the coefficient of discharge over the two compound side weirs (Rectangular and Semi-Circle) were modeled by using Computational Fluid Dynamic (CFD) to describe the flow characteristics in subcritical flow conditions. (Flow-3D) program was used to determine the numerical uncertainty of the simulation results. The simulation results were compared with experimental observations, and good agreements were obtained between the both results.

Keywords: Experimental channel; Side weir; Water discharge; CFD analysis.

1. Introduction

Weirs are a small overflow-type dams commonly used to raise the level of a river or stream and cause a large change of water level behind them. It is likely that the flow discharge exceeds the capacity of a channel or river and, thus, a control structure such as side weirs should be employed to protect the system against overflow. Conventional side weirs are installed in the channel side wall, parallel to the flow direction and at a desired height so that when the water level rises to the weir height, some portion of flow would be deviated laterally. Occasionally, side weirs as a mean of water diversion can be used, as well. Recently, many researchers investigated the discharge coefficient of side weirs theoretically, experimentally, or numerically. Rahimpour M. et al. [7] used experimental and theoretical evidence to estimate the best discharge of trapezoidal side weir under subcritical flow conditions. Aydin M. C. [2] studied the water surface profiles of the (triangular labyrinth side weirs) to describe the flow characteristics in the case of sub-critical flow, using CFD with Fluent code. Aydin, M. C. et al. [3] studied the discharge capacity of triangular labyrinth side weir with one cycle by using VOF method with fluent code. They compared the discharge coefficients found from CFD results with experimental data of Aydin et al. [3]. Hoseini, S. H. et al. [5] Computational Fluid Dynamic (CFD) model together with laboratory model of rectangular broad-crested side weir were used for determining the discharge coefficient of the rectangular broad-crested side weir located on the trapezoidal channel. Zahiri A. et al. [10] developed an empirical equation to find the discharge coefficient for compound rectangular side weir using experimental data well as the final job of the dimensions of analysis. Baghers, S. et al. [4]

indicated that the discharge coefficient of side weirs, estimated using the traditional weir formula, was related closely to the upstream Froude number by a power correlation. Moreover, the influences of the other parameters, such as (h_1/P, h_1/b, and b/B) on C_d were found to be negligible.

There is considerable interest, particularly in rectangular side weirs. De Marchi in (1934) was one of the first researchers to provide equation for flow over rectangle side weirs, as shown in equation (1).

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

where: Q is the discharge in the main channel, C_d is coefficient of discharge, *L* is width of side weir, g is acceleration due to gravity, h is the flow depth above side weir. In which total flow over side weir Q is in m^3/s, the discharge coefficient C_d is dimensionless; the width of side weir L and h is in meters.

Zahiri A. et al. [10] used Eq. (1) to estimate the discharge coefficient of compound rectangular side weir, and he proposed the following equation for subcritical flow condition:

$$C_m = 0.412 - 0.0551 Fr_1 + 0.00168 \left(\frac{L}{y_1}\right)^{1.1789} + 0.1063 \left(\frac{\overline{W}}{y_1}\right)^{2.1065} \qquad (2)$$

where: Fr_1: upstream Froude number in the main channel at the upstream of weir, y_1: depth of flow on the upstream end of the side weir in the main channel centerline, L: length of the side weir, $\overline{W}$: crest weighted height

According to this point, there is a great similarity with the present research studied in terms of finding the discharge coefficient of compound side weir located in straight open channels. The present research determine discharge coefficient of compound side weirs located in straight open channels in the subcritical flow condition by using CFD simulations with Flow-3D program, and the simulation results are compared with the experimental results.

2. Experimental work

The laboratory channel used in this study is shown in Figure 1. The channel structure is a glass fiber modeled with steel stiffness which has an 18.6 m length, 0.5m width and 0.5 m depth, and the bed of the channel was maintained at a horizontal slope during all the tests.

Figure 1. The experimental channel Abbas, H. A. [1].

The channel has been developed to do the laboratory experiments, and divided into two crossings by using glass of thickness 10mm (main channel and a discharge collection channel). The main channel dimensions are 12 m length, 0.3m width, and 0.50m depth. Collection channel dimensions are 0.19 m width and 0.50 m depth, and situated parallel to the main channel. The side weir is placed on the wall between the crossings and at a distance 9 m from the upstream of channel. Two Standard weirs have been used to measure the discharge, one of them is V-notch sharp crested weir located in the upstream while the other one has been put in the downstream of the channel and made from steel. Pair of adjustable instrument rails is fitted on the top of the channel sides through the working section, all the depth measurement are carried by using point gage (± 0.1 mm accuracy) put on wheel which can move to any position above the working section transversely and horizontally. The development of channel is shown in Figures 2, 3, 4.

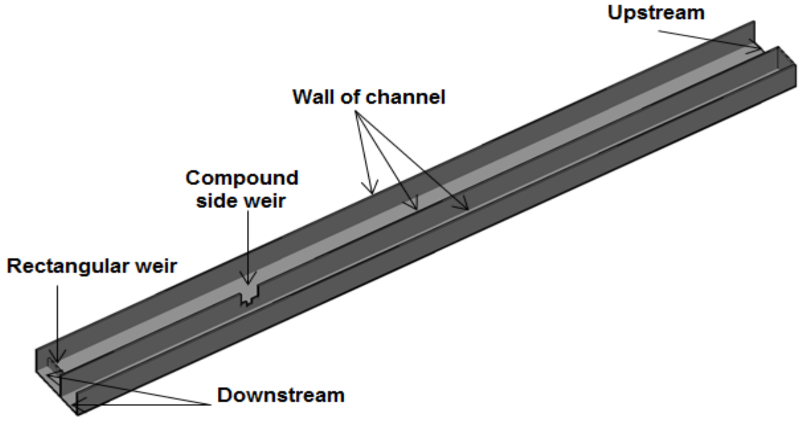

Figure 2. Sketch of channel.

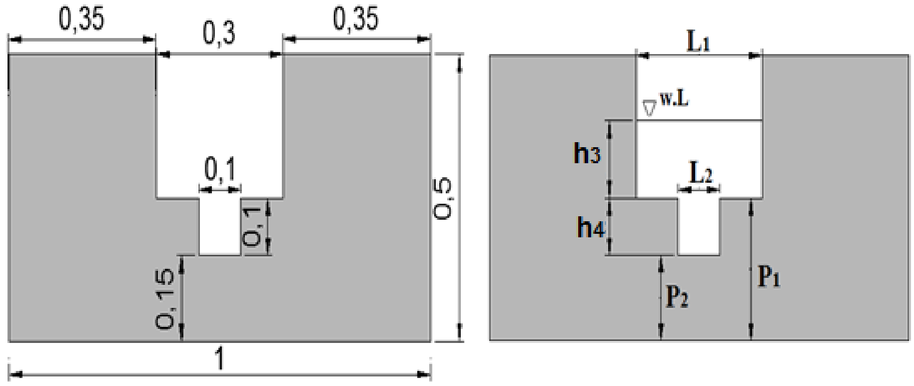

Figure 3. Compound rectangular - Rectangular side weir.

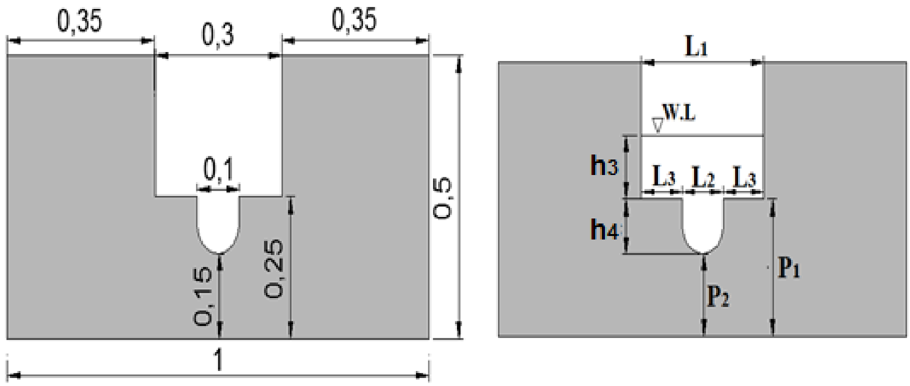

Figure 4. Compound rectangular - Semi-circle side weir.

3. The discharge coefficient of side weirs (Cd)

The discharge coefficient (**Cd** $_{\text{measured}}$) was computed by using De-Marchi's equation (Eq. 1) as shown below.

$$Q = \frac{2}{3}\, C_d\, L_1 \sqrt{2g}\, h_1^{\;1.5} + \frac{2}{3}\, C_d\, L_2 \sqrt{2g}\, h_2^{\;1.5} \tag{3a}$$

Simplifying the above equation will yield the following equation:

$$Q = \frac{2}{3}\, C_d \sqrt{2g}\, \left(L_1 h_1^{\;1.5} + L_2 h_2^{\;1.5}\right) \tag{3b}$$

The results of (C_d) from this equation are shown in Table 1.

Table 1. The measured and calculated values for the discharge coefficient.

Q_{1act}	Compound side weir					
	Rectangle			Semi-circle		
	Cd measured	Cd Calculated	% error	Cd measured	Cd Calculated	% error
33	0.942	0.936	0.64	0.97	0.965	0.52
30.5	0.915	0.916	0.11	0.944	0.948	0.42
28	0.901	0.902	0.11	0.923	0.926	0.33
25.5	0.885	0.884	0.11	0.907	0.909	0.22
23	0.864	0.866	0.23	0.88	0.881	0.11
20.5	0.85	0.84	1.18	0.86	0.86	0
18	0.815	0.812	0.37	0.836	0.835	0.12
15.5	0.789	0.79	0.13	0.804	0.803	0.12
13	0.739	0.737	0.27	0.762	0.764	0.26

For the Compound side weir, the increasing of discharge leads to the increasing of discharge coefficient values, also it can be concluded that the discharge coefficient of Compound Semi-Circle side weir is greater than the discharge coefficient of Compound Rectangle side weir when using the same discharge, as shown in Figure 5.

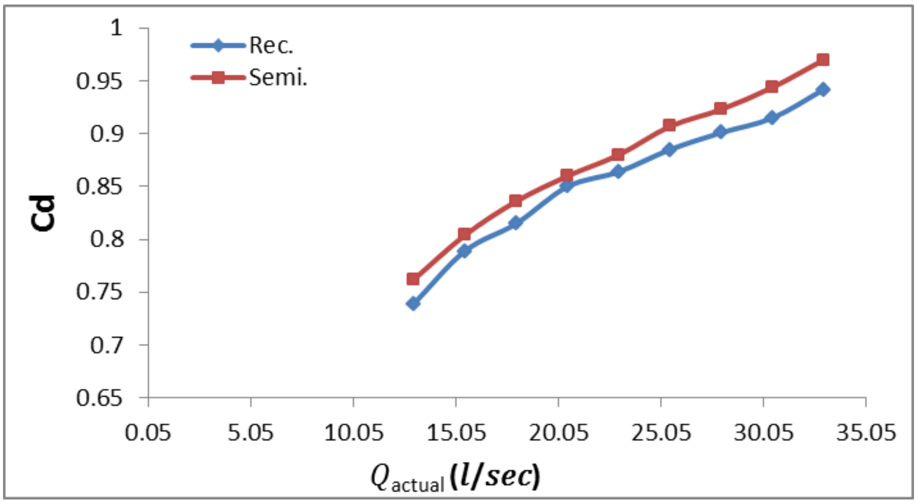

Figure 5. Variation of C_d versus Q_{actual} for compound side weir.

By using the dimensional analysis technique for compound side weir gives the following dimensionless parameters:

- For Compound Rectangle side weir

$$C_d = f\left(Fr, \frac{L_1}{y_1}, \frac{L_2}{y_1}, \frac{\bar{P}}{y_1}, \frac{B}{y_1}\right) \tag{4}$$

- For Compound Semi-Circle side weir

$$C_d = f\left(Fr, \frac{L_1}{y_1}, \frac{D}{y_1}, \frac{\bar{P}}{y_1}, \frac{B}{y_1}\right) \tag{5}$$

A relationship has been drawn between each parameter and the coefficient of discharge as shown in Figures 6, 7, 8, 9 and 10. In Figure 6, the discharge coefficient extrusive proportion to the Froude number while in other figures it is inversely proportion to the rest of the dimensionless parameters. The coefficient of discharge (C_d) for Compound Semi-Circle side weir is greater than the coefficient of discharge (C_d) for the Compound Rectangular side weir at the same dimensionless parameters and same discharge.

Empirical correlations were developed to predict discharge coefficient (cm) for compound (rectangular and semi-circle) side weirs according to experimental data as well as the final function of the dimensionless analysis. Using a computer program (SPSS), several attempts have been conducted to find a better relationship between the discharge coefficient and dimensionless parameters, thus it was obtained the following equations.

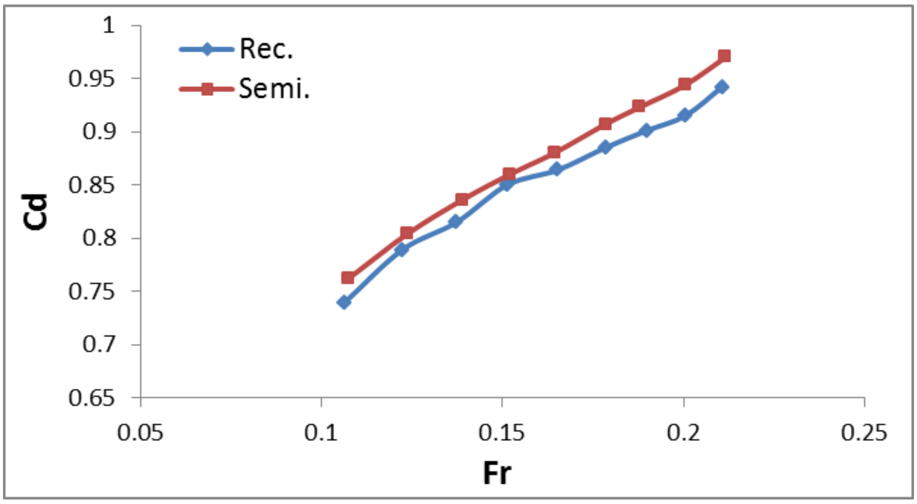

Figure 6. Variation of C_d versus Fr for Compound side weir.

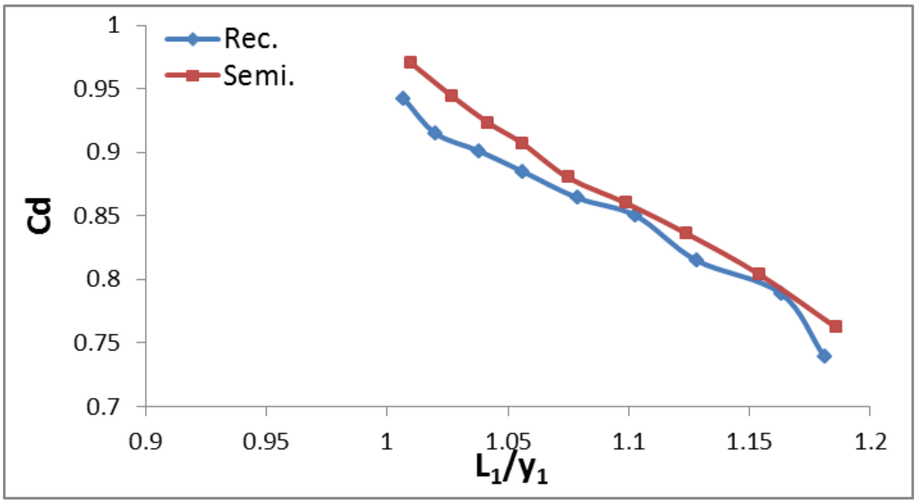

Figure 7. Variation of C_d versus L_1/y_1 for compound side weir.

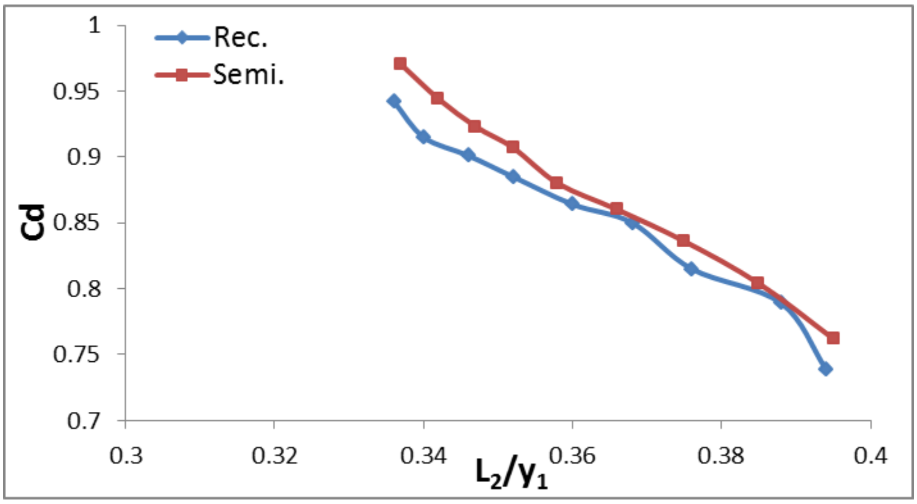

Figure 8. Variation of C_d versus for compound side weir.

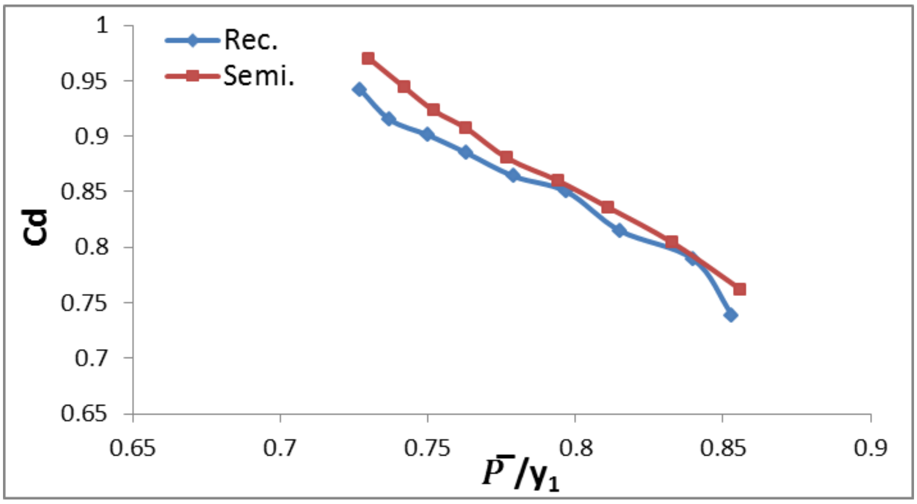

Figure 9. Variation of C_d versus $\overline{P}/y_1$ for compound side weir.

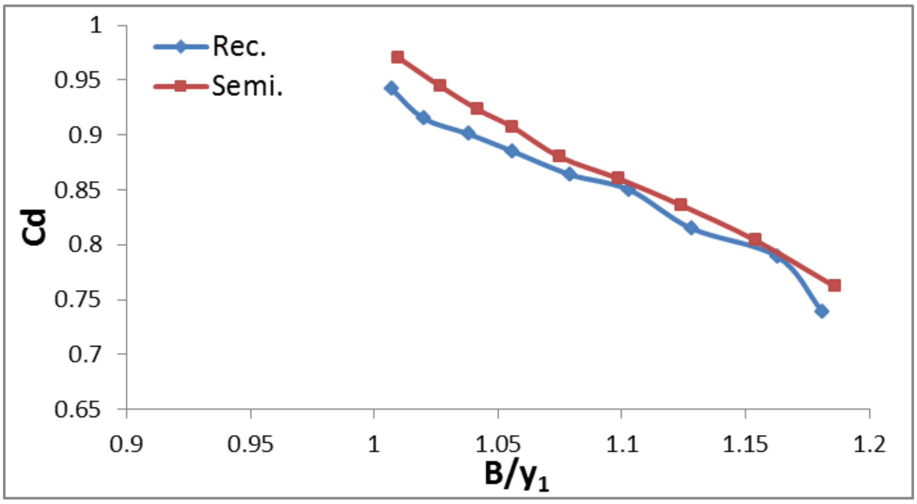

Figure 10. Variation of C_d versus B/y_1 for compound side weir.

Compound Rectangular side weir: the following formula is found with Determination coefficient is (R^2= 0.995).

$$C_d = 3.529 + 3.058Fr^{0.548} - 4.646\left(\frac{B}{y_1}\right)^{-0.388} + 4.931\left(\frac{P}{y_1}\right)^{-0.461} - 4.646\left(\frac{L_1}{y_1}\right)^{-0.388} - 0.092\left(\frac{L_2}{y_1}\right)^{-1.2} \quad (6)$$

Compound Semi-Circle side weir: the following formula is found with Determination coefficient is (R^2= 0.998).

$$C_d = 0.242 + 2.142Fr^{0.515} - 0.571\left(\frac{B}{y_1}\right)^{-1.089} + 0.806\left(\frac{P}{y_1}\right)^{-0.776} - 0.571\left(\frac{L_1}{y_1}\right)^{-1.089} - 0.047\left(\frac{D}{y_1}\right)^{-1.016} \quad (7)$$

After finding a formula to calculate the discharge coefficient for two shapes of compound side weirs, the discharge coefficient has been calculated and the results putted in Table 1. A relationship has been plotted between the discharge coefficient calculated from these equations and the discharge coefficient that measured from equation (3), as shown in Figures 11 and 12. From these figures, the Determination coefficient (R^2) is seen to be not less than 0.995, and there is symmetry and convergence in the results of each other and that is a good thing in the selection of those equations. In addition, the error percentage of discharge coefficient between the calculated and measured values is calculated using equation (8) and the range is found to be between (0% - 1.18%) for shapes of compound side weirs.

$$\%\ error = \frac{C_{d\text{measured}} - C_{d\text{calculated}}}{C_{d\text{measured}}} * 100 \quad (8)$$

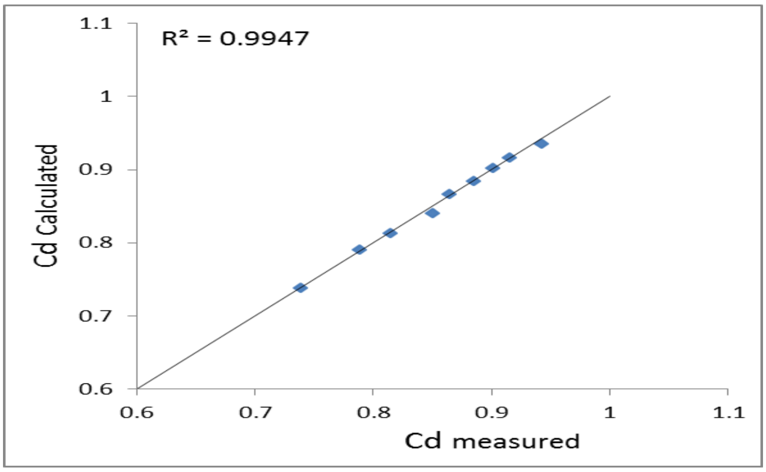

Figure 11. Comparison of measured and calculated values of C_d for compound rectangle side weir.

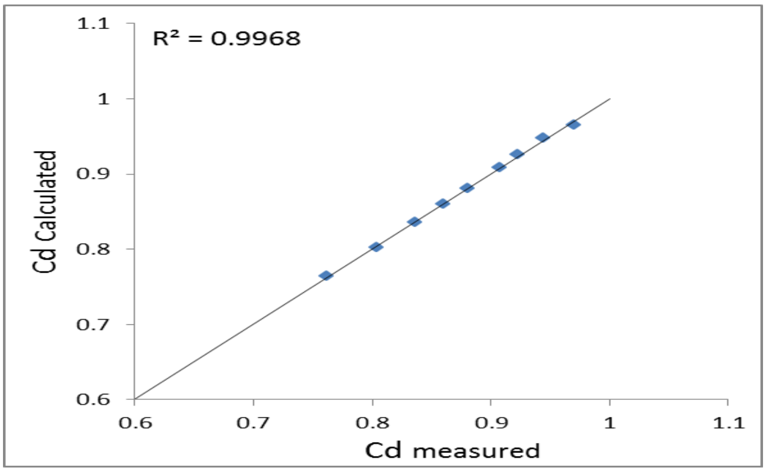

Figure 12. Comparison of measured and calculated values of C_d for Compound Semi-Circle side weir.

4. CFD model

Computational Fluid Dynamics (CFD) is a branch of numerical modeling that has been developed for solving problems involving fluid flow. This includes applications involving fluid-solid interaction, such as the flow of water in a river or over and around hydraulic structures. Therefore, there is considerable interest in the applicability of CFD to model fluid flow.

Many codes are available for modeling **CFD**, such that **FLOW-3D**, **ANSYS** and **CFX**. The (**FLOW-3D 10.0.1)** which is a computational fluid dynamic (**CFD**) tool has been used for the present work.

CFD allows the users to obtain flow information at any point in the flow domain rather than just at selected locations where instruments are installed, as in physical modeling. The benefits of using CFD have created interest in the software and a desire on the part of hydraulics engineers to verify the full capability of numerical models.

Governing equations for this program are the Navier Stokes equation. These equations describe how they relate to pressure, velocity, temperature, and density of a moving fluid. Independently, equations were derived by G.G. Stokes, in England, and M. Navier, in France at 1800. The equations are extensions of the Euler equations [8].

5. Results of CFD and comparison with experimental results

After using Computational Fluid Dynamic (CFD) depending on the experimental data by (Flow-3D) program, the results from program as shown in Figure 13 and these results putted in Table 2. The relationships of the calculated values of the discharge coefficient are drawn from the proposed equations between the experimental results and the results obtained from CFD. Moreover, relationships have been drawn between values of Froude number and coefficient of discharge for each experimental and CFD results as shown in Figures 14 and 15.

As seen in these figures, the CFD and the experiment values are close to each other in a large proportion, also the Determination coefficient is (R^2=0.9753) for two shape used in the present study and this is a good indicator. In addition, the results are symmetrical and convergent from the drawn line with angle 45 and this is a perfect index. Additionally, to evaluate the accuracy between experimental and CFD results the percentage of error values ranged between (0.96% - 5.7%).

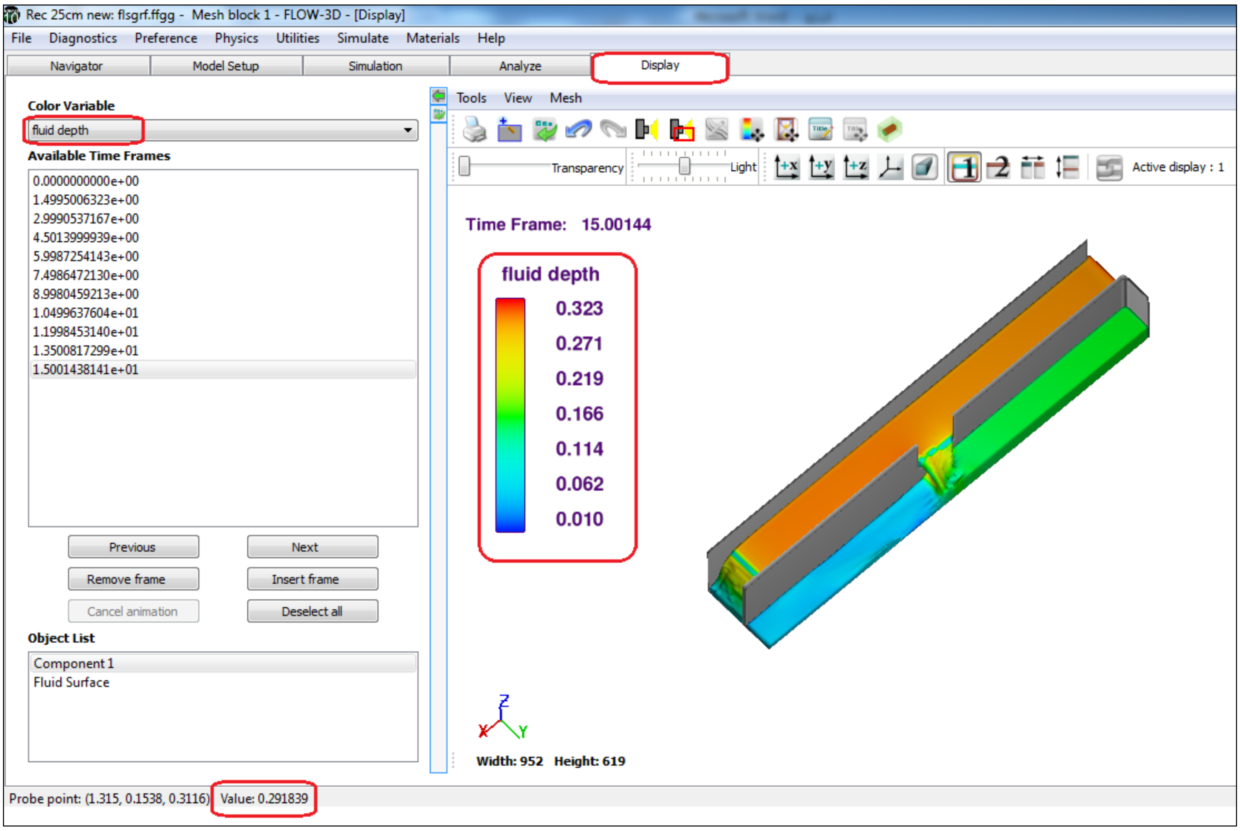

Figure 13. The results of the flow-3D program.

Table 2. CFD results of Compound side weir and percent error of C_d between Exp. and CFD results.

Q_{1act}	Compound side weirs					
	Rectangle			Semi-circle		
	Cd (CFD)	Cd (EXP)	% error	Cd (CFD)	Cd (EXP)	% error
33	0.945	0.936	0.96	0.992	0.965	2.8
30.5	0.954	0.916	4.15	0.98	0.948	3.38
28	0.917	0.902	1.66	0.937	0.926	1.19
25.5	0.903	0.884	2.15	0.924	0.909	1.65
23	0.884	0.866	2.08	0.898	0.881	1.93
20.5	0.865	0.84	2.98	0.88	0.86	2.33
18	0.829	0.812	2.09	0.847	0.835	1.44
15.5	0.813	0.79	2.91	0.816	0.803	1.62
13	0.779	0.737	5.7	0.774	0.764	1.31

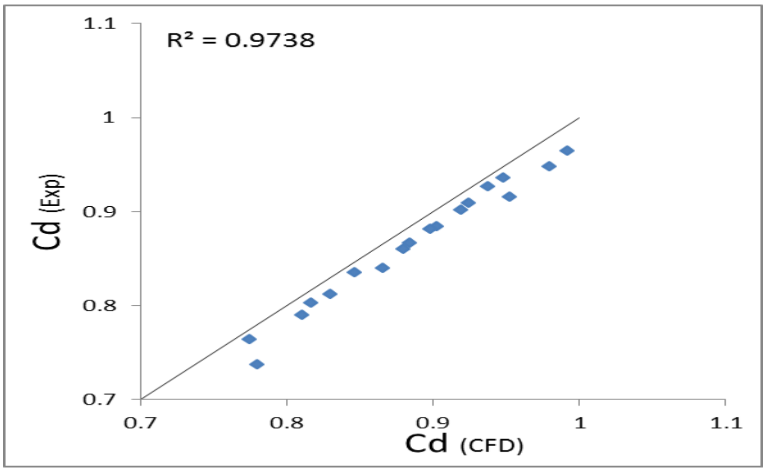

Figure 14. Comparison of the discharge coefficient values for Compound side weir.

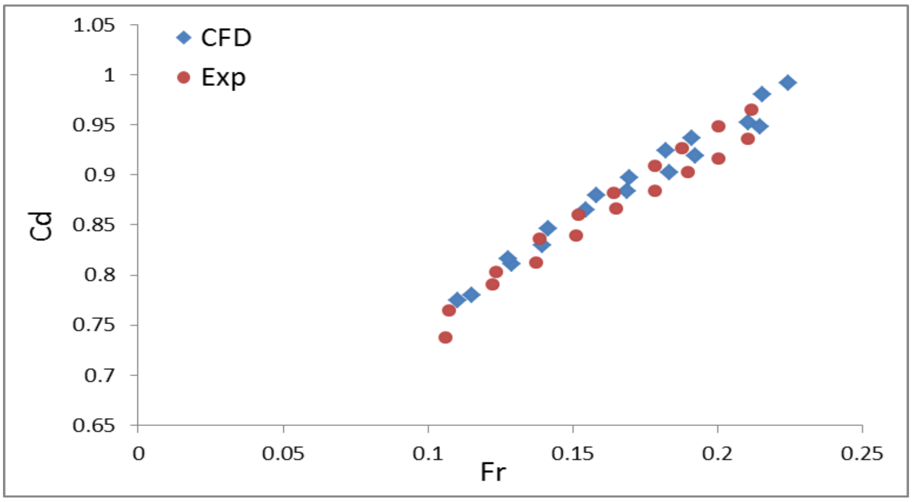

Figure 15. Comparison of C_d against the Froude number for compound side weir.

The experimental results and CFD results can be compared also using two methods as follows:

5.1 Mean standard error

A mean standard error has been used in order to find the rapprochement between the experimental results and the results of the CFD using the following formula:

$$MSE = \frac{100}{N} \sum_{n=1}^{n} \left| \frac{C_d\,(\mathrm{Exp}) - C_d\,(\mathrm{CFD})}{C_d\,(\mathrm{Exp})} \right| \quad (9)$$

where: *MSE*: Mean Standard Error, *N*: Number of the predicted values.
In this method, the result of men standard error (MSE) for compound rectangle side weir is (2.742%) and for compound semi-circle side weir is (1.961%).

5.2 Root mean squared error
The root mean square error calculation is a well-known and frequently used method of error analysis. It accurately depicts the magnitude of deviations of estimated (measured or calculated) value from the actual value sought [6]. The RMSE has the same units as the measured and calculated data. Smaller values indicate better agreement between the measured and the calculated values [9].

$$RMSE = 100\sqrt{\frac{\sum_{i=1}^{n}[C_d(\mathbf{Exp}) - C_d(\mathbf{CFD})]^2}{N}} \tag{10}$$

The result of Root men standard error (RMSE) for compound rectangle side weir is (2.504%) and for compound semi-circle side weir is (1.961%)
From the previous two methods, the comparison between experimental and CFD results are found to be the highest value for Mean Standard Error is (2.742) and for Root Mean Squared Error is (2.504), a small percentage and this means that there is a clear convergence between these results.

6. Conclusions
In the present research, the following points have been concluded:

1. The discharge coefficient of compound Semi-Circle side weir greater than that of compound Rectangular side weir.
2. The derived formula for the coefficient of discharge C_d for compound (rectangle and semi-circle) side weirs have been developed by using the dimensional analysis techniques , this formulas were restricted to the laboratory data .
3. The software Flow – 3D is used to model the experimental data using Computational Fluid Dynamic (CFD). Significant corresponding has been found between the experimental results and the results obtained from (CFD), and the percentage error between these results is (0.96% - 5.7%).

References

[1] Abbas, H. A., (2014). "A Study of flow over different opening of combined weir and below gates", Thesis Master of Hydraulic Structures (Civil Engineering), Kufa University, Iraq.
[2] Aydin, M. C., (2012). "CFD simulation of free-surface flow over triangular labyrinth side weir", Advances in Engineering Software, No.45, pp.159-166.
[3] Aydin, M. C., Emiroglu, M.E., (2013) "Determination of capacity of labyrinth side weir by CFD", Flow Measurement and Instrumentation, No.29, pp.1-8.
[4] Bagheri, S., Kabiri-Samani, A. R., Heidarpour, M., (2014). "Discharge coefficient of rectangular sharp-crested side weirs. Part I: Traditional weir equation", Flow Measurement and Instrumentation, No.35, pp.109-115.
[5] Hoseini, S. H. et al., (2013). "Determination of Discharge Coefficient of Rectangular Broad-Crested Side Weir in Trapezoidal Channel by CFD", International Journal of Hydraulic Engineering, No.2 (4), pp. 64-70.
[6] Johnson, L., L., (1995). "A Comparison of Methods for Estimating RMS Error: A "Brute Force" Approach Versus a Mathematically-Elegant Approach, as Applied to the Calculation of a Specific Retrieval Error for a Limb-Scanning Microwave Radiometer-Spectrometer", M. Sc. Thesis, the Faculty of the School of Engineering Air Education and Training Command AFIT/GAP/ENP/95D- 10.
[7] Rahimpour, M., Keshavarz, Z., Ahmadi, M., (2011). "Flow over trapezoidal side weir ", Flow Measurement and Instrumentation, No.22, pp.507-510.
[8] Manikandan, M., Prasad, S. U., Suvarna, A. A., Bhat, A., Nair, V. and Shivakrishna, G., (2014). "External Aerodynamic Analysis of TATA Nano using Numerical Tool" International Journal of Current Engineering and Technology, E-ISSN 2277-4106, P-ISSN 2347-5161.
[9] Scheaffer, R., L., (2011). "Probability and Statistics for Engineer", brooks/Cole, USA.
[10] Zahiri, A., Azamathulla, H.M., Bagheri, S., (2013). "Discharge coefficient for compound sharp crested side weirs in subcritical flow conditions", Journal of Hydrology, No.480, pp.162-166.