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Comparative study of experimental and CFD analysis for predicting discharge coefficient of compound broad crested weir

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ABSTRACT

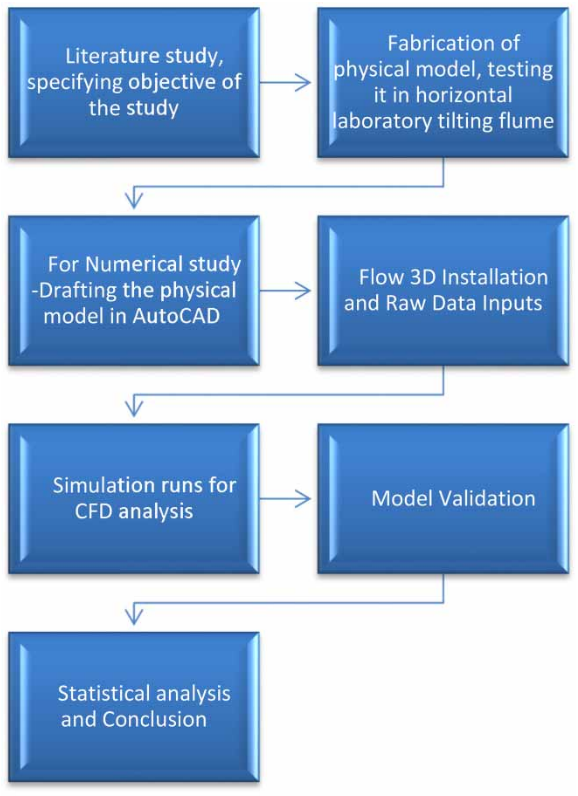
Present study highlights the behavior of the weir crest head and width parameter on the discharge coefficient of a compound broad crested (CBC) weir. Computational fluid dynamics model (CFD) is validated with laboratory experimental investigations. In the discharge analysis through broad crested weirs, the upstream head over the weir crest (h) is crucial, where the result is mainly dependent upon the weir crest length (L) in the transverse direction to flow, water depth from channel bed. Currently, minimal investigations are known for CFD validations on compound broad crested weirs. The hydraulic research for measuring discharge numerically is carried out using FLOW 3D software. The model applies renormalized group (RNG) using the volume of fluid (VOF) method for improved accuracy in free surface simulations. Structured hexagonal meshes of cubic elements define discretized meshing. The comparative analysis of the numerical simulations and experimental observations confirm the performance of the CBC weir for precise measurement of a wide range of discharges. Series of CFD model studies and experimental validation have led to constant range of discharge coefficients for various heads over the weir crest. The correlation coefficient of discharge predictions is 0.999 with mean error of 0.28%.

Key words: compound weir, FLOW 3D, flow measurement, numerical technique, open channel

HIGHLIGHTS

- The Head-Discharge relation is established for discharge measurement using a compound broad crested weir, experimentally and numerically.
- Assessment of head over the weir crest for different step widths of the proposed weir on the discharge coefficient is executed.
- Experimental and CFD results of weir performance demonstrate good agreement between the theoretical discharges by traditional rectangular weir formulae keeping Cd constant.

GRAPHICAL ABSTRACT



NOMENCLATURE

(B)	Lower width of the weir crest in transverse flow direction
(Q_{th})	Theoretical discharge calculated using traditional rectangular weir formula
(Q_{expt})	Experimental discharge using volumetric measurement technique
(Q_{CFD})	Discharge simulated by FLOW 3D, CFD software
(L)	Length of the weir in longitudinal direction of flow
(y)	Lower weir height
(y_2)	Depth of water flow corresponding to intermediate weir height
(b)	Intermediate crest width of the weir in the transversal flow direction
(h)	Upstream head over the weir crest
(C_d)	Coefficient of discharge
(lps)	Liters per sec, unit for discharge
CBC	Compound broad crested weir

INTRODUCTION

A weir is an obstruction in an open channel that constricts the flow and causes it to fall over a crest. A broad crested weir has the advantage that it operates effectively with higher downstream water levels than a sharp crested weir. According to the United States Bureau of Reclamation (USBR 2001), broad crested weirs are specially shaped weirs that can be designed to fit more complicated channel cross sections better than other weirs, and the shape of the control section can be selected considering the range of variations of the discharge and head. Sharp crested and broad crested weirs have been areas of interest for past investigation and research carried out even recently. Open channel flow measurement was studied by investigators like Ackers *et al.* (1978); Rangaraju (1981), where observations on discharge characteristics of finite crest length weirs were presented. The investigations carried out are discharge relations for flow estimation with cross section shape, such as rectangular, triangular, trapezoidal, and truncated triangular, and useful empirical discharge equations for these weirs have also been proposed by researchers like Boiten & Pitlo (1982); Swamee (1988); Hager & Schwalt (1994); Gogus *et al.* (2016). To provide a single reliable, accurate method to model all rectangular weirs (suppressed, partially contracted, and fully contracted), the Kindsvater-Carter equation was developed (Kindsvater & Carter 1959). The rating method for partially contracted 90 degree and fully contracted V notch weirs between 25 and 100 degrees which can as well be applied to fully side suppressed, partially contracted, and fully contracted rectangular weirs is reported by (Kulin & Compton 1975). Bos (1989) put forth the head-discharge equations for broad-crested weirs and long-throated flumes of various cross sections. Horton (1907) stated if the effects of viscosity and surface tension are neglected, discharge coefficient is function of weir head above crest to length ratio, h/L. Harrison (1967) derived an expression for coefficient of discharge for a streamlined broad-crested weir based on critical flow theory, allowing boundary layer development. Laboratory experiments conducted by Gogus *et al.* (2006) demonstrate that the global discharge coefficient for a compound rectangular broad-crested weir is lower than that of a simple rectangular broad-crested weir having the same crest height and crest length. Literature reports the studies conducted on discharge relations for rectangular broad crested weirs (Azimi & Rajaratnam 2009; Salmasi *et al.* 2012; Bijankhan *et al.* 2014) with the aim to investigate the effects of width of the lower weir crest and step height of broad crested weirs with rectangular compound cross sections on the values of discharge coefficient (C_d) and approach velocity coefficient. Recently, researchers have used mathematical software and soft computing tools in the field of open channel hydraulics, typically for Compound weirs. The calibration of compound weir under short reach in presence of hydraulic jump was given by Hinge *et al.* (2011). For the given flow rates the prediction of upstream flow depths was found excellent using commercial software FLUENT 6.3.26 under complex flow conditions. Predictions of discharge in compound channels with respect to compound sharp crested weirs using soft computing tools has gained fancy of researchers all over. Zahiri & Azamathulla (2014) validated the experimental and conventional method of linear combination of theoretical equations of simple weirs by applying different soft computing tools like linear genetic programming, M5 model tree. Mathematical models were explored as well which exhibited good prediction of discharge coefficients with error within 3.8 percent with improved outputs given by mathematical and soft computing techniques. In all the investigations carried OUT above it is seen that the discharge coefficient is proportional to head over weir. Savage & Johnson (2001) investigated the discharge coefficient for ogee spillway where 2D and 3D physical models were compared with Flow 3D simulations concluding that 2D model gave satisfactory result. Khan *et al.* (2006) applied STAR-CD tool for velocity verses length graphs on contact tank. These graphs were plotted at 3 different depths- top, middle, low. It was concluded that CFD STARCD model simulated the velocity field very well. Rady (2011) applied FLOW3D software was applied to rectangular sharp crested weir where C_d is function of head over a weir to weir height. It was found that C_d from various head estimated from various head over weir to weir height ratio relationship was within a ±3% error. It also highlighted the advantages of using 'Flow- 3D' as s tool for examining velocity vectors and pressure pattern over rectangular sharp crested weirs. Omer *et al.* (2018) simulated C_d values by FLOW3D for circular labyrinth weir with and without nappe breaker. The experimental and CFD results obtained were close with just 4% average variation. FLOW3D application to broad crested porous weirs was explored by Safarzadeh & Mohajeri (2018). From experimental Head-Discharge curve, the drag coefficient was obtained and the relationship between drag coefficient and coefficient of permeability was found out. Man *et al.* (2019) dealt with the analysis of different turbulence flow models on scouring pit of bridge-pier using Flow 3D software. An assessment of turbulence model adopted with the parameters of the Melville experiment to estimate the maximum scour-depth was performed. The results of the scour development of large eddy simulation (LES) turbulence model were found to be more satisfied than the Renormalized group (RNG) turbulence model and close to the prior experiment results. Aydin (2016) demonstrated the effect of sill on overall performance of rectangular side weir which is placed at various locations. Investigation was carried out using CFD ANSYS Fluent version 12 along with the physical model for determining the sill effect. Recently metaheuristic technique like Grey Wolf Optimization is employed by Roushangar *et al.* (2021) to minimize cross sectional area of composite trapezoidal and compound channel, giving in depth analysis of flow parameters. This signifies the topic selected for present study under current scenario. An overview of the empirical formulae proposed by investigators for prediction of discharge for different types of weirs published in literature is given in Table 1 below.

The discharge equations proposed through literature study, indicate that discharge coefficient (C_d) changes proportionally with H/L ration. It means it is proportional to head over weir. In this paper, authors have revealed the investigations carried out in an effort to propose the novel idea of maintaining constant value of C_d irrespective of the head over weir. The present study deals with the design, fabrication and testing of compound broad crested weir having discharge coefficient values exactly equal to design input parameter which can be used as discharge measurement device after establishing head discharge relation experimentally and numerically.

Table 1 | Discharge equations for different types of weirs

Sr. No.	Type of weir	Discharge equation
1.	Rectangular	$\mathrm{Q} = \frac{2}{3} C_d \sqrt{2\mathrm{g}} L H^{3/2}$
2.	Triangular	$\mathrm{Q} = \frac{8}{15} C_d \sqrt{2\mathrm{g}} \tan \theta H^{5/2}$
3.	Trapezoidal	$\mathrm{Q} = \frac{2}{3} C_d \sqrt{2\mathrm{g}} H^{3/2}\ (L_1 + \frac{4}{5} \tan \theta H_1)$
4.	Sharp crested	$Q = C_d L_e H_e^{3/2}$
5.	Broad Crested	$Q = C_d L \sqrt{2g}\ \sqrt{H\mathrm{h}^2 - \mathrm{h}^3}$
6.	Ogee Shaped	$\mathrm{Q} = \frac{2}{3} C_d \sqrt{2\mathrm{g}} L H^{3/2}$
7.	Suppressed	$\mathrm{Q} = \frac{2}{3} C_d \sqrt{2\mathrm{g}} L (H_1\ - H_2)^{3/2}$
8.	Contracted	$\mathrm{Q} = \frac{2}{3} C_d \sqrt{2\mathrm{g}} L H^{3/2}$

MATERIALS AND METHODS

A broad crested weir is a hydraulic structure for estimation of discharge in open channels of different cross-sections. Hydraulically, a broad-crested weir has crest length large compared to the flow thickness. To measure discharge rate by means of hydraulic structures, a well-established relationship of head and discharge is needed which can be determined empirically in the laboratory. Too much variation in the value of $\mathrm{C_d}$ may lead towards design ambiguity resulting in high cost heavy structures as well as loss in water discharged due to contraction, frictional and transitional losses. Hence an efficient low cost structure for discharge measurement is to be designed, fabricated and tested for effective use of available water resources. The literature review based on CFD encouraged the use of 3D modelling technique for application of discharge measurement in open channel flow. Past researches exhibit that FLOW 3D simulation technique is promising one but has not been explored that much in field of broad crested weir baring examples of quite a few. This study is an attempt to showcase the results/outputs generated from FLOW 3D as against the experimental values for compound broad crested weir which is fabricated using the theoretical parameters and evaluated for efficiency based on experimental and numerical technique. The following objectives are undertaken towards finalization of this research paper:

1. To simulate compound broad crested weir in FLOW 3D software.
2. To Compare and validate FLOW 3D simulation results with experimental measurements of the physical model.
3. To optimize the compound broad crested weir geometry which sustains wide range of flows with constant coefficient of discharge.

To perform the experimentation, compound broad crested weir was fabricated according to design proposed by Hinge *et al.* (2010). They proposed a new design of hydraulic jump type stilling basin where a rectangular broad crested stepped weir was developed at the end of a horizontal apron to constrain the formation of a clear hydraulic jump within the basin. The current study exhibits the possibility of using a compound broad crested weir model as a discharge measuring device by maintaining $\mathrm{C_d}$ fairly near to the design input value, which is the novelty of the present study conducted. The validation of the physical model through experimental and numerical output proves the workability of this weir model. The design of the compound broad crested weir involves multiple step rectangular cross sections such that discharge coefficient ($\mathrm{C_d}$) is 0.6, maximum and minimum discharges of the flume being 10 lps to 2 lps respectively. The various parameters of a compound broad crested weir model are shown in Figure 1. This compound broad crested weir model was designed and fabricated using PVC sheet for the preliminary trial (original model) and tested in a laboratory horizontal tilting flume of 2.5 m length, 20 cm width and 30 cm deep, fabricated from transparent toughened glass and stainless steel. An elaborate experimental work regarding discharge measurement by compound broad crested weir structure concluded that compound broad crested weir model can be used as discharge measurement device maintaining $\mathrm{C_d}$ constant. The details of experimental layout, model set up, lab runs execution can be found in Kulkarni & Hinge (2020). The experimental work details are not being highlighted in the present context, rather a comparative overview of laboratory and CFD output is discussed herein.

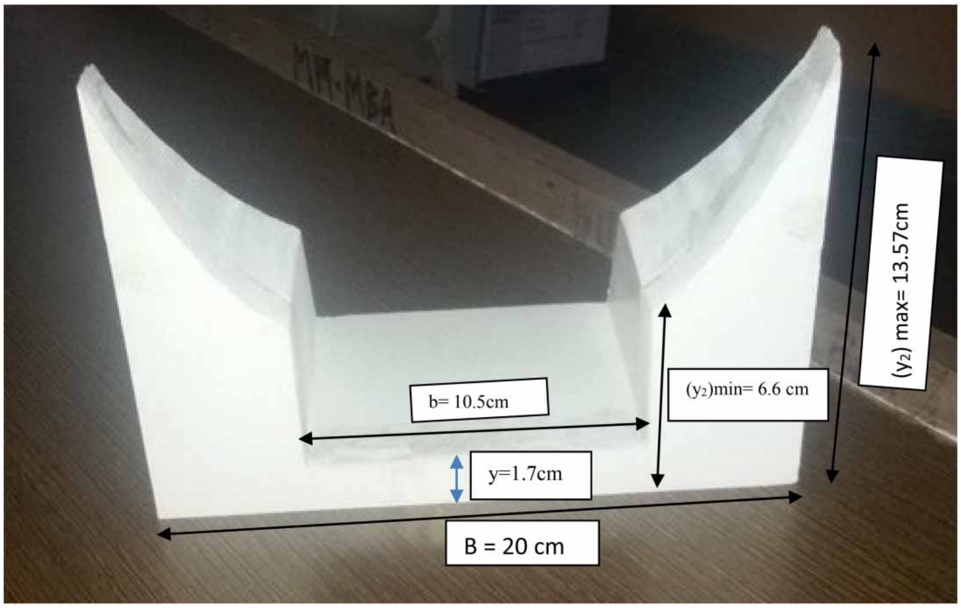


Figure 1 | Original Compound Broad crested weir model (PVC cast).

Numerical model

CFD codes are structured around the numerical algorithms that can tackle fluid flow problems. In order to provide easy access to their solving power all commercial CFD packages include three main elements to input the problems and to examine the results, which are a pre-processor, a solver, and a post processor.

The present model is implemented using numerical code, which is widely used in hydraulic applications. The CFD model used here for simulating the free surface flow over the weir was FLOW-3D solver version 10.1.1.05 win 64 2013 developed by Flow Science, Inc., in the USA. FLOW-3D uses the Volume of Fluid Method (VOF). The VOF model is ideally suited to applications involving free surface flows (Samadi & Arvanaghi 2014). It is set on the principle that two or more fluids are not mixed together. This is a two phase approach where both the water and air are modeled in the grid. The method is based on the concept that each cell has a fraction of water (F), which is 1 when the element is totally filled with water and zero (0) when the element is filed with air. If the value is between 1 and 0, the element contains the free water surface. Figure 2 shows the 3D view of the compound broad crested weir model ready for input in FLOW-3D.

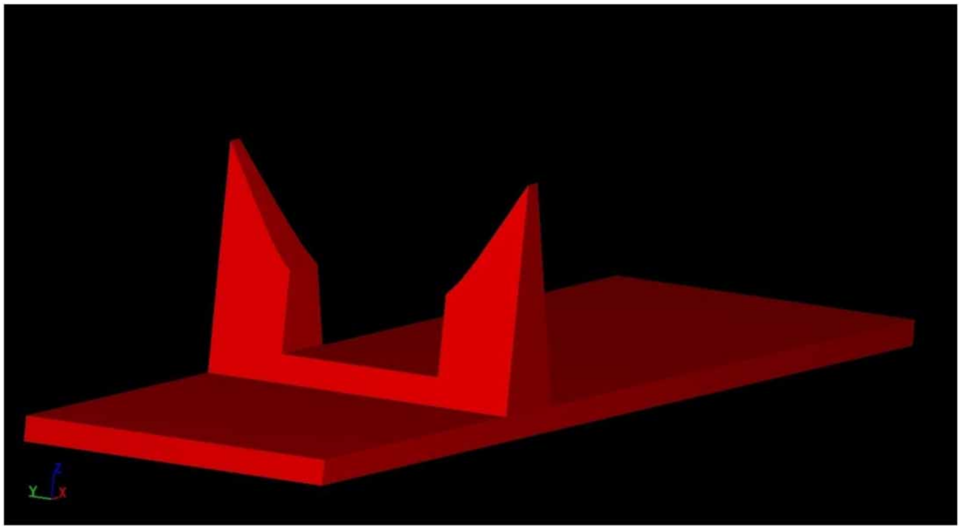


Figure 2 | 3D model of compound broad crested weir.

Mesh and boundary conditions

The model was drafted in AutoCAD-3D and was converted into a Stereo Lithography (.stl) file which was imported in software. The mesh resolution was constant for simulated geometry. The boundary conditions were defined as the pressure inlet, outflow, symmetry and walls as shown in Figure 3. In such a manner, 10 fluid elevations were recorded as mentioned in the table, using the system running on Windows 10 Single Language having a 4-core Intel® Core™ i5–7400 CPU @ 3.00 GHz. Boundary conditions were labeled as 'symmetry' for side boundaries, which implies that identical flow occurs on both sides of the boundary and hence there is no drag. In the x-direction the boundary condition was 'specified stagnation pressure'. With this algorithm, FLOW-3D is able to model various flow heights beginning at a stagnation pressure state. A continuative boundary outflow condition, at the outlet of x direction, is considered. This represented a smooth continuation of the flow through the boundary. Boundary conditions on x, y, z plane are shown below in Figure 3(a) and 3(b).

Grid generation

The weir step in Flow 3D was performed by importing a Stereo Lithography (.stl) file. In STL files, solid object surfaces are approximated by cubes. The domain was discretized using one uniform mesh block. The evolution in time was used as a relaxation to final steady state. FLOW-3D has a structured and orthogonal grid with rectangular (2D) and hexahedral cells (3D). The border between the geometry and the water is defined by the Fractional Area Volume Obstacle Representation (FAVOR) method or Volume of Fluid (VOF) method. Figure 3(a) shows a longitudinal profile of the grid used in FLOW-3D. As shown in figure, a three dimensional grid with 30,000 cells in the x, y, z directions was created. The volume of each cube was designated as 5 cm^3, which resulted in the cell size of 1.7 cm.

With these specified conditions, the calculation with FLOW-3D had a grid with 1, 20,811 active cells. After a computation time of 229 seconds, a steady state condition was found. In the present FLOW-3D modeling, the RNG turbulence model was used to perform CFD simulations, which resulted in following values as shown in Table 2.

Figure 4 below shows the 3D view of flow generated through FLOW-3D simulation for high and low discharges respectively.

The velocity profiles and discharges obtained for high and low upstream depth of flows of compound broad crested weir section according to CFD simulations are shown below in Figure 5(a) and 5(b). The velocity head for upstream and downstream flow condition is well simulated according to the discharge condition. It is clearly evident from the velocity profile that even for high discharges, the proposed weir operates under non submergence indicating smooth flow transition upstream to the downstream end of the channel section.

RESULTS AND DISCUSSION

This section gives the analysis of theoretical, experimental and CFD simulations obtained for various discharge rates for the compound broad crested weir model, tabulated in Table 3. The theoretical discharge is calculated by the traditional rectangular weir formula, modified for the current broad crested weir with multiple rectangular steps (Equation (1)). The details are

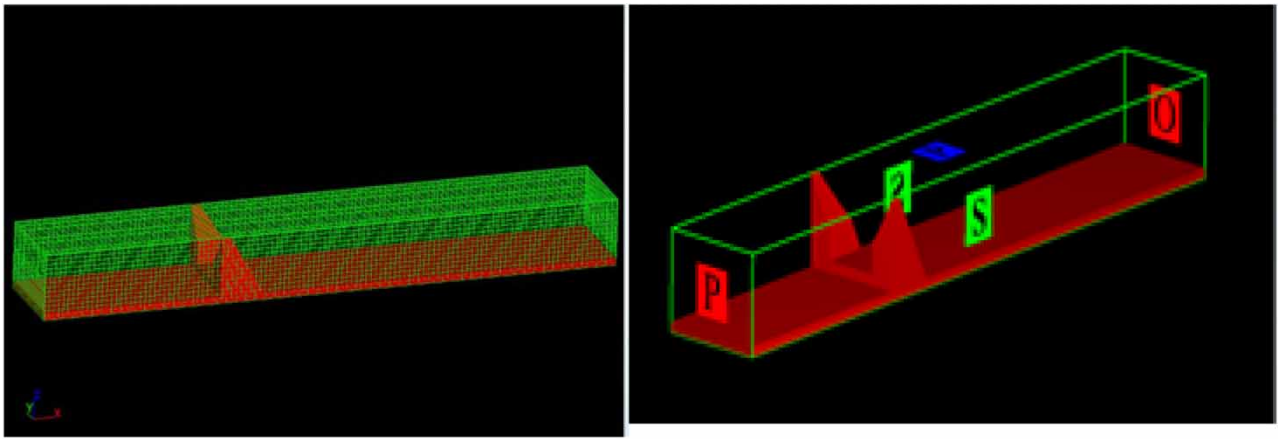


Figure 3 | Numerical model details: (a) meshing, grid generation, (b) boundary conditions.

Table 2 | Comparison of step heights and discharge values for theoretical and CFD output – (preliminary study – original CBC weir)

Sr. No.	y_2 (th) (cm)	y_2 (CFD) (cm)	Q_{th} (lps) for corresponding step size	Q_{CFD} (lps)
1	6.568	6.560	2	1.9906
2	7.725	7.717	2.8	2.9428
3	8.714	8.706	3.6	3.7509
4	9.580	9.593	4.4	4.5953
5	10.380	10.383	5.2	5.403
6	11.100	11.103	6.0	6.2923
7	11.780	11.773	6.8	7.153
8	12.413	12.403	7.6	8.1367
9	13.00	12.997	8.4	9.2317
10	13.57	13.557	9.2	10.008

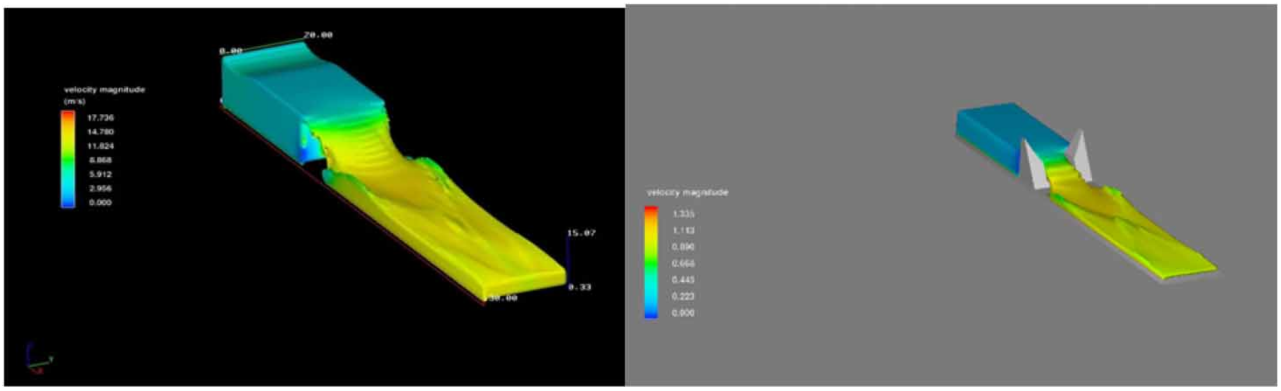


Figure 4 | CFD simulation for max discharge ($y_2 = 13.557$ cm, $Q_{max} = 10$ lps) and min discharge ($y_2 = 6.56$ cm, $Q_{min} = 2$ lps).

reported as per author's previous study mentioned in Kulkarni & Hinge (2017).

$$Q_{\text{pred}} = \frac{2}{3} C_d \sqrt{2g}\, b' \,(y_2 - y)^{\frac{3}{2}} \tag{1}$$

where, $C_d = 0.6$, $y = 1.7$ cm, y_2 ranging from (y_2) max $= 13.57$ cm to (y_2) min $= 6.57$ cm considering different steps/rise having rectangular shape with $b' = (B - b)$ (Figure 1) for bottom rectangular weir and further goes on changing according to each step rise and tread till (y_2) max is finally reached. For the experimental study conducted for a physical compound broad crested weir model in a horizontal tilting flume, the head above the weir crest for corresponding step heights ranged from 13.43 cm to 7.38 cm. The behavior of experimental and CFD studies were then compared to the theoretical model parameters and brief analysis was obtained.

The empirical relation developed for CFD discharge values with respect to head over weir crest is depicted in Figure 6 below. The head discharge rating curves were developed based on the readings obtained from theoretical, experimental and CFD inputs. Since the range of head over weir values was different for the experiment conducted (13.43 cm–7.38 cm) as compared to CFD (13.57 cm–6.568 cm), a best fit second-degree polynomial equation was derived for the rating curves and then again a head-discharge relationship was derived from the developed equations freezing the required head parameter for different step heights. This enabled the determination of discharge coefficients for various discharge ranges, but maintaining the same upstream head over the weir crest for all the approaches. The values predicted from theoretical, experimental and CFD rating equations were based upon graphical interpolation best fit curve technique, the following discharges as shown in Table 4 were obtained for corresponding heads.

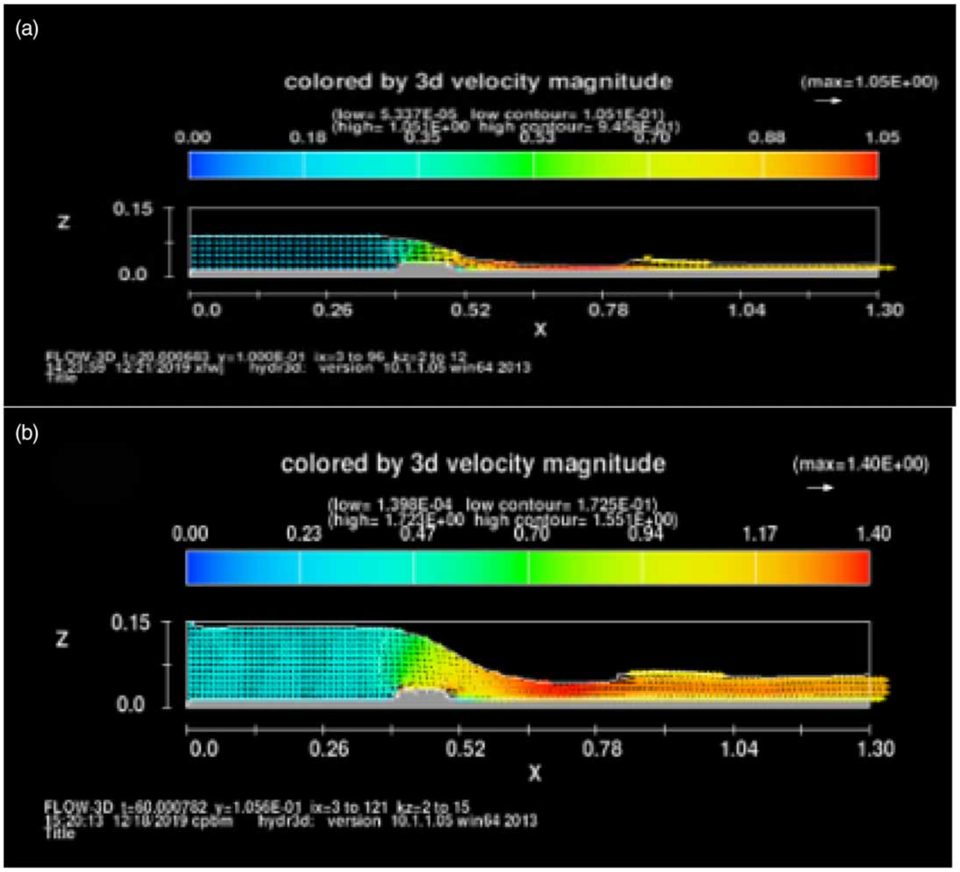


Figure 5 | (a, b) velocity profiles corresponding to max discharge (10 lps) and min discharge (2 lps).

Table 3 | Step height vs head over weir comparison chart (theoretical, experimental, CFD approach – original CBC weir model)

Sr. No.	y_2 (cm) theoretical	y_2 (cm) CFD	y_2 (cm) experimental	Head above weir crest (y_2-y), h (cm) theoretical	Head above weir crest CFD (cm)	Head above weir crest (y_2-y), h (cm) experimental
1	6.568	6.56	7.388	4.868	4.86	5.688
2	7.725	7.717	8.94	6.025	6.017	7.24
3	8.714	8.706	9.97	7.014	7.006	8.27
4	9.589	9.593	10.96	7.889	7.893	9.26
5	10.38	10.38	11.64	8.68	8.68	9.94
6	11.107	11.103	12.096	9.407	9.403	10.396
7	11.78	11.77	12.52	10.08	10.07	10.82
8	12.41	12.403	13.07	10.71	10.703	11.37
9	13	13	13.436	11.3	11.3	11.736
10	13.57	13.56	13.54	11.87	11.86	11.84

Head discharge relation generated through graphical interpolation is depicted in Figure 7 below. From the relative plot it can be seen that numerical (CFD) discharges are in sync with the theoretical range for lower head values. As the head increases, discharge simulated numerically is over predicted. For experimental values, the discharge generated for lower head values lies below the theoretical range, then it is exactly equal to the theoretical value, where C_d of 0.6 is almost obtained, further for last 2, 3 steps (towards high discharge) the experimental discharge increases as compared to the theoretical discharge.

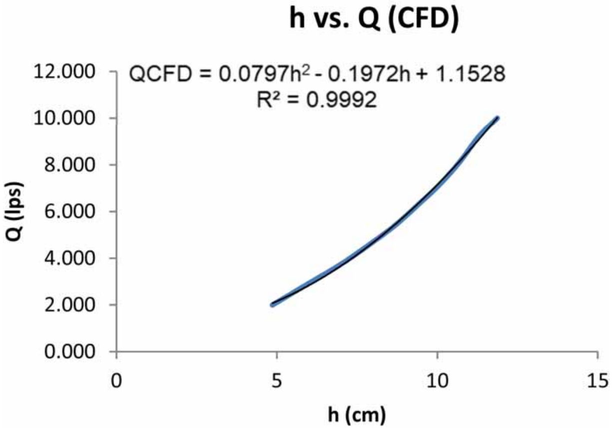


Figure 6 | Head-discharge rating curve for CFD analysis (original CBC weir).

Table 4 | Discharges predicted for different crest heads (graphical approach – original CBC weir)

Sr. No.	y_2 (cm)	Head above weir crest (y_2-y), h (cm)	Q_{th} (lps) for corresponding step size	Q_{expt} (lps)	Q_{CFD} (lps)
1	6.568	4.868	2.006362	1.7726	2.08152
2	7.725	6.025	2.793892	2.3976	2.85783
3	8.714	7.014	3.592716	3.16404	3.69058
4	9.589	7.889	4.396016	4.02057	4.55732
5	10.38	8.68	5.200214	4.93904	5.44589
6	11.107	9.407	6.004676	5.90393	6.35052
7	11.78	10.08	6.805163	6.90022	7.26305
8	12.41	10.71	7.603101	7.92266	8.18271
9	13	11.3	8.392988	8.95894	9.10133
10	13.57	11.87	9.195242	10.0324	10.0415

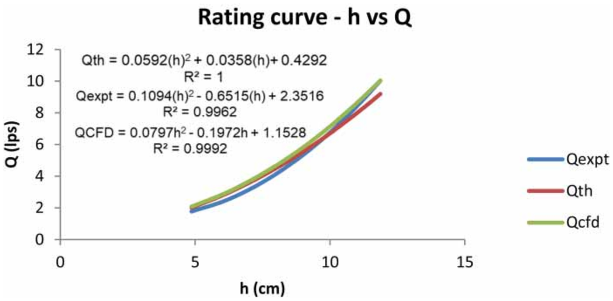


Figure 7 | Head discharge rating curve for theoretical, experimental and CFD (graphical approach – original CBC weir model).

This plot of head and discharge clearly indicates that by virtue of some logical approach indicating the experimental, theoretical, numerical behavior of a compound broad crested weir, there has to be proper treatment given to the model geometry, which will function in accordance with the input design parameter of $C_d = 0.6$. Thus, the discharge coefficient can be a constant entity irrespective of head over the weir, where a vast range of discharges can be investigated with the same model.

The coefficient of discharge was calculated for various ranges and resulted in the values as shown in Table 5 below. The theoretical discharge coefficient is 0.6, which is the input design parameter for the compound broad crested weir model. As

Table 5 | Comparison of C_d values – original compound broad crested weir

Sr. No.	y_2 (cm)	C_d (theoretical)	C_d (experimental)	C_d (CFD)
1	6.568	0.6	0.53	0.6225
2	7.725	0.598	0.514	0.6137
3	8.714	0.598	0.528	0.6163
4	9.580	0.599	0.548	0.6220
5	10.380	0.6	0.569	0.6283
6	11.100	0.6	0.59	0.6346
7	11.780	0.6	0.608	0.6404
8	12.413	0.6	0.625	0.6457
9	13.00	0.599	0.64	0.6506
10	13.57	0.599	0.654	0.6552

against this input, the experimental C_d is found to be varying in the range of 0.514–0.654. CFD interpretation states that C_d lies in between 0.61 and 0.655 for the same weir model. The plot of weir step height against the discharge coefficient is shown in Figure 8 below. Though the experimental and numerical discharge coefficients vary from the theoretical value, they are actually lying in close limits to the target, which is a positive output towards the weir model behavior.

Performance evaluation of original CBC weir model

The observed data set of discharge values for various heads over the weir crest has the correlation coefficient as 0.9966, with standard deviation as 2.32. Since the value of standard deviation is low with a high correlation coefficient, it is observed that the sample is well representative for overall population; it is relevant and less scattered around the mean. The relative average error between discharge predictions with FLOW-3D simulation is 4.96%, which is found to be less than the predictions made by graphical interpolation technique (5.33%). After the experimentation with the PVC compound broad crested weir model, it is observed that the discharge coefficient values lie within more or less the same limits in range with the numerical simulation. The correlation coefficient between experimental discharge and theoretical discharge obtained was 0.99 with standard deviation in the discharge coefficient being 0.0502. The correlation coefficient between the CFD discharge and theoretical discharge obtained was 0.99 with standard deviation of C_d being 0.0146. The main objective of this study is to explore the CFD simulation FLOW-3D technique for predicting discharges in open channel. Flow 3D yielded reasonable results matching to the theoretical design. These results given by FLOW-3D are compared to experimental results as well and the accuracy level of both the outputs was found to be well within the error range stated in the literature. The sensitivity analysis for discharge coefficient parameter (C_d) for experiment and the CFD approach is mentioned in Table 6.

The above statistics demonstrate that there is good agreement between the theoretical discharges by traditional rectangular weir formulae as well as experimental and CFD discharges for various ranges. The discharge values predicted by FLOW-3D

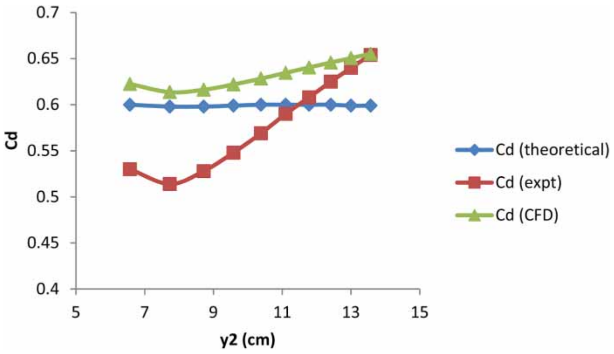


Figure 8 | Variation of C_d against depth of flow.

Table 6 | Statistical analysis for experimental and CFD approach – original CBC weir model

					Performance index		
Parameter (C_d)	Prediction range	Mean	RMSE	Standard deviation	Median	Skewness	Model R
Experimental	Min 0.514 Max 0.654	0.5806	0.416	0.050207	0.5795	0.121322	0.9931
CFD	Min 0.6137 Max 0.6552	0.63293	0.444	0.014628	0.63145	0.220238	

simulation for the original compound weir are towards the slightly higher side compared to the theoretical and experimental approach. The NRMSE for experimental and CFD outputs is found to be 0.07427 and 0.0745 respectively. However, very little skewness of the predicted value suggests that with further improvement in the mesh geometry and more sensitive grid generation, the discharge coefficients may lie near the target input value or even match within the experimental range. Thus, in the context of the present study conducted, the range of discharge coefficient values and discharge predictions for wide range are in good agreement with the input design parameters.

Further to reach still closer to the targeted discharge values, the model was given treatment in CFD to improvise the weir geometry, which can maintain the input value of $C_d = 0.6$ throughout. Rigorous trial and error approach with over 75 model geometries and 500 simulations resulted in the final geometry of a compound broad crested weir with lower base width modified to 11.8 cm instead of 10.5 cm earlier. Likewise, treatment was given to every step height, modifying the base width until theoretical discharge was simulated exhibiting a constant discharge coefficient of 0.6. The step heights for the rectangular stepped weir were rather kept intact, thereby freezing the head over the weir crest for each step. This finalized model was casted using 3D printing technology and tested in the laboratory for validating the weir performance. The head–discharge readings obtained for this modified compound weir geometry are given in Table 7.

Empirical predictive model for discharge estimation

In the earlier experimentation conducted with the original compound model cast, the majority of the C_d values are lying above 0.5 and for high discharges also C_d is near to 0.6, which is the input parameter given for design of the weir model under investigation. The head-discharge relationship developed for the modified weir model for estimation of discharge is demonstrated by Figure 9. This study indicates a good fit amongst the predicted values of discharge corresponding to different head values, with R^2 of 0.9997. In the earlier trials, mean error was found to be nearly 5.33%, which is now reduced to 0.28% after treating the model geometry for improving accuracy. The standard deviation for the discharges obtained by the newly casted compound broad crested weir is 2.387 (CFD) and 2.264 (experimental) respectively, with around maximum data

Table 7 | Head discharge observations (experimental and CFD approach) for modified compound weir geometry

Sr. No.	Head over weir, h (expt) (cm)	Time to collect 100 litres (sec)	Q_{expt} (lps)	Q_{CFD} (lps)	Q_{th} (lps) for corresponding step size	C_d (expt approach)=[Q_{expt}/Q_{th}]×0.6	C_d (CFD approach)	Remarks
1	4.87	49.79	2.006	2.01	2	0.6	0.6	Exact prediction of discharge values. C_d remains constant for various flow ranges
2	6.03	35.502	2.82	2.82	2.8	0.596	0.6	
3	7.01	27.784	3.59	3.6	3.6	0.594	0.6	
4	7.89	22.622	4.42	4.39	4.4	0.602	0.6	
5	8.68	19.134	5.22	5.19	5.2	0.602	0.6	
6	9.41	16.554	6.03	5.97	6	0.598	0.6	
7	10.08	14.682	6.806	6.78	6.8	0.596	0.6	
8	10.78	13.152	7.602	7.68	7.6	0.596	0.61	
9	11.31	11.81	8.47	8.53	8.4	0.6	0.61	
10	11.87	10.822	9.24	9.45	9.2	0.6	0.62	

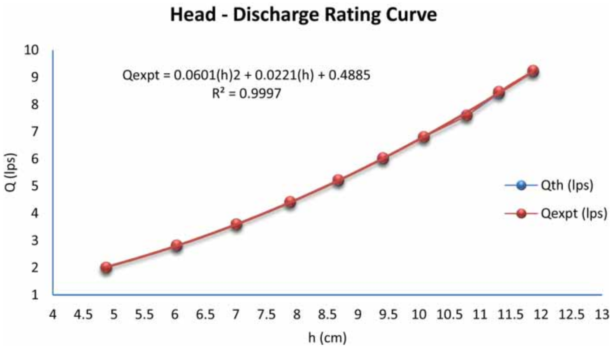


Figure 9 | Head-discharge rating curve for constant discharge coefficient – modified CBC weir.

points being close to the design value of the discharge coefficient. The above parameters demonstrate that there is good agreement between the theoretical discharges by traditional rectangular weir formulae and the experimental discharges for various ranges. The prediction model for discharge maintaining constant C_d is defined by Equation (2) for the compound weir casted by 3D printing technology and tested in a horizontal laboratory flume.

$$Q_{\text{expt}} = 0.0601\,(h)^2 + 0.0221\,(h) + 0.4885 \tag{2}$$

A study conducted by Al-Khatib & Gogus (2014) exhibited the discharge models for rectangular compound broad crested weirs and suggested the variation in discharge coefficient ranging from 0.58 to 1.0 with a mean error of 4.85% between the measured and predicted discharge values. With the current numerical and experimental trials, we have attempted an investigation of a compound broad crested weir and observed that the discharge coefficient is constant (value of 0.6) for high to low flow ranges. The correlation coefficient of the predictive model is high (0.999) with less error in discharge estimations. Hence, a wide range of variation in calculating discharge coefficients is squeezed down with decent accuracy.

The main objective of this study was to investigate the flow through a compound broad crested weir using physical and numerical models for different upstream heads over the weir crest and weir crest width conditions. The innovative concept of achieving constant C_d for various discharge ranges comprising different heads over the weir was implemented. The optimized numerical model was validated by comparing the results with physical model study. The error estimation in prediction of discharge values was found within a 3%–5% limit in earlier trials conducted by experimental and CFD approach. This was further minimized to a meagre 0.28% with optimized model geometry through the numerical technique imparting refined

Table 8 | Range of Froude number, Reynold's number and Weber number

	Dimensionless parameter		
Head over weir crest, h (cm)	**Froude number**	**Reynold's number**	**Weber number**
4.87	0.237	6,236.629	14.989
6.03	0.188	7,136.42	16.10
7.01	0.206	8,861.576	23.238
7.89	0.240	11,367.07	36.398
8.68	0.238	12,217.112	40.349
9.41	0.257	13,943.827	51.153
10.08	0.263	15,247.426	59.254
10.78	0.274	16,707.77	69.463
11.31	0.283	18,035.734	79.272
11.87	0.293	19,417.187	90.235

meshing and grid resolution satisfying objective no. 3 stated in the earlier part of this paper. Further, accuracy in compound weir model fabrication was gained with high resolution additive manufacturing technology.

Characteristic dimensionless parameters like the Froude number, Reynold's number and Weber number were evaluated for the present study conducted (Table 8). The range of Froude number suggest that the flow is subcritical throughout the variation from low to high discharge. Turbulent flow is maintained across the entire discharge range. A Weber number greater than unity for different flow variations confirms that the surface tension effect is negligible.

The main contribution of the present research work is that the investigations for the compound broad crested weir are carried out with the novel approach of the discharge coefficient being the main input design parameter. The innovation highlighted through various studies conducted and reported herein, is that the authors have revealed the investigations carried out in an effort to propose the novel idea of maintaining constant C_d irrespective of the head over the weir. The other advantages of the proposed compound weir are the availability of low crest height in the design model, which will permit the passage of sediments through high and low discharges thereby ensuring the accuracy of the rating curve. In case of perennial canals, lower weir height will ensure undisrupted passage of fishes, which in turn will maintain ecological equilibrium. Artificial fish ladders need not be provided. The experimental and CFD results obtained in comparison to theroetical design are also encouraging. The results are useful for practical hydraulic engineers, especially in the case of unavailibilty of common discharge relation and discharge coefficient of compound weir. By referring to the head-discharge rating curve, an engineer can know the discharge corresponding to head over a CBC weir, irrespective of the weir geometry and coefficient of discharge for various flow ranges.

CONCLUSION

1. The head discharge relationship established for a compound rectangular broad crested weir for various discharge ranges was validated by CFD technique. A three dimensional simulation software FLOW-3D was used for this purpose.
2. Original theoretical compound weir model depicts the relative average error between discharge predictions with FLOW-3D simulation as 4.96%, which is found to be less than the predictions made by the graphical interpolation technique, which is 5.33%.
3. The standard deviation in the C_d parameter for the CFD simulation model is less, i.e. 0.0146 compared to the experimental output of 0.0502.
4. The correlation coefficient for physical and CFD studies for the modified compound weir model is high, around 0.999 with error in discharge predictions being 0.28% compared to the accuracy limits of about ±3–5% stated in the literature so far.
5. Discharge coefficient by experimental and CFD approach is maintained constant and equal to design input value of 0.6.

Thus, the proposed CBC weir can be operated for various discharge ranges by maintaining constant discharge coefficients. Good agreement between the theoretical, experimental and CFD simulation results for obtaining discharge through compound broad crested weir ascertains the fact that CFD model can be used as an effective tool towards modeling flow through compound broad crested weir.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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