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PERFORMANCE ENHANCEMENT IN DISCHARGE MEASUREMENT BY COMPOUND BROAD CRESTED WEIR WITH ADDITIVE MANUFACTURING

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ABSTRACT

Manufacturing compound weirs for exact discharge measurement has been a challenge, according to studies so far. The length of the weir crest (L), weir height, and weir width all affect the efficacy of compound broad crested weirs as flow monitoring devices. As a result, the flow characteristics of a given flume are determined by changes in weir geometry, particularly the discharge coefficient (C_d), which varies proportionally with the h/L ratio. For varying h/L levels, many researchers have maintained an average range of C_d. The experimental and Computational Fluid Dynamics simulations for measuring discharge by compound broad crested weir are presented in this work. Validation in the results is achieved using CFD FLOW 3D software. For enhanced accuracy in free surface simulations, the model uses the renormalized group (RNG) approach with the volume of fluid (VOF) method. Laboratory models were employed in an attempt to analyse and validate the CFD model. The model is fabricated using PVC material first and later resorted to additive manufacturing for targeting accurate discharges. The shape of the compound broad crested weir was modified to achieve constant C_d by comparing three-dimensional computational fluid dynamics models to experimental measurements. The performance of the CBC weir for precise measurement of a wide range of discharges is confirmed by numerical simulations and experimental measurements, with a reasonably constant design input value of discharge coefficient of 0.6. When compared to empirical methods, CFD-based weir geometry optimization produces more exact model predictions. Moreover, manufacturing this optimized model with 3D printing technology using Poly Lactic Acid plastic material has validated the weir performance with accurate estimates between theoretical, experimental and CFD outputs.

Keywords: Additive manufacturing, 3D printing, Compound Broad Crested Weir, Discharge coefficient, Flow 3D, CFD

INTRODUCTION

Sharp and broad crested weirs have piqued the curiosity of researchers in the past and even more recently. Researchers like [Akers et al. (1978), RangaRaju (1981)] who provided observations on discharge characteristics of finite crest length weirs, have been studying open channel flow measurement for a long time. Discharge relations for flow estimates with cross section shapes such as rectangular, triangular, trapezoidal, and truncated triangular have also been investigated, as well as relevant empirical discharge equations for various weirs (Boiten & Pitlo,1982; Hager & Schwalt, 1994; Gogus et al., 2016; Swamee, 1988). The Kindsvater-Carter equation (Kindsvater and Carter, 1959) was designed to provide a single dependable, precise approach for modelling all rectangular weirs (suppressed, partially contracted, and fully contracted). [Kulin & Compton (1975)] described a rating system for partially contracted 90 degree and totally contracted V notch weirs with a range of 25-100 degrees that may also be used to fully side suppressed, partially contracted, and fully contracted rectangular weirs. [Bos (1989)] The head-discharge equations for broad-crested weirs and long-throated flumes of various cross sections have been proposed. If viscosity and surface tension are ignored, the discharge coefficient is a function of the weir head to length ratio, h/L [Horton (1907)]. The studies on discharge relations for rectangular broad crested weirs conducted by (Azimi & Rajaratnam, 2009; Salmasi et al., 2012; BijanKhan, 2014) with the goal of investigating the effects of the 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 are reported in the literature. In the realm of open channel hydraulics, researchers have recently used mathematical software and soft computing technologies, typically for compound weirs. (Hinge et al., 2011) provided the calibration of a compound weir with a short reach in the presence of a hydraulic jump. Under difficult flow conditions, the commercial software FLUENT 6.3.26 provided excellent prediction of upstream flow depths for the given flow rates. Researchers all around the world are interested in applying soft computing algorithms to predict discharge in compound channels with respect to compound sharp crested weirs. (Zahiri et al., 2013; Zahiri & Azamathulla, 2014) used several soft computing technologies such as linear genetic programming and M5 model trees to validate the experimental and conventional approach of linear combination of theoretical equations of basic weirs. Mathematical models were investigated, and they showed strong prediction of discharge coefficients with an error of less than 3.8 percent, as well as enhanced outputs from mathematical and soft computing techniques. Hinge et al. (2010) and Hager and Schwalt (1994), for example, have made similar approaches.

The discharge coefficient is proportional to the head over weir in all of the above investigations. Savage & Johnson (2001) combined 2D and 3D physical models with Flow 3D simulations to determine the discharge coefficient for an ogee spillway. The results of the 2D model were satisfactory. On a contact tank, Khan et al. (2006) used the STAR-CD tool to plot velocity vs. length graphs. The drag coefficient was calculated from the experimental Head-Discharge curve, and the link between drag coefficient and permeability coefficient was discovered. Kulkarni & Hinge (2017; 2020) conducted considerable experimental work and concluded that the compound broad crested weir model can be employed as a discharge measurement device while keeping C_d constant. With a few more physical model combinations, the current study endeavour attempts to validate the experimental results presented therein. In this work, we provide the results of the research that led to the new idea of keeping a consistent C_d value regardless of the head over weir. The literature review based on CFD to open channel flow, encouraged the use of 3D modeling technique for application of discharge measurement in open channel flow. Previous research has shown that the Flow 3D simulation technique is promising, but it has yet to be fully investigated in the realm of broad crested weir applications. In the 1990s, 3D printing processes were thought to be only suited for the manufacture of functional or aesthetic prototypes, and fast prototyping was a more relevant phrase. Today, 3D printing techniques have improved in precision, repeatability, and material range to the point where some 3D printing processes are regarded viable as an industrial production technology, and the phrase additive manufacturing can be used interchangeably with 3D printing. One of the most appealing features of 3D printing is the capacity to create extremely complicated forms or geometries, and a digital 3D model or CAD file is required to manufacture any 3D printed object. Owing to the complex weir geometry of compound broad crested weir, it was decided to manufacture model cast using additive technique.

The present study deals with the design, fabrication and testing of compound broad crested weir manufactured with additive technique which performs efficiently maintaining nearly constant value of discharge coefficient. Such hydraulic structures can be effectively used as discharge measurement device on field after establishing head discharge relation. By far, the novel approach reported in this paper, with precise manufacturing of compound broad crested weir which measures wide range of discharges leading to nearly close discharge coefficients is first of its kind.

MATERIAL AND METHODS

The broad crested weir is a simple device that can be used to estimate discharge in any channel shape. A broad-crested weir is a flat-crested structure with a crest length greater than the flow thickness, allowing streamlines to be parallel to the crest invert and pressure distribution to be hydrostatic. Unnecessary variations in the value of C_d can lead to design ambiguity, leading in high-cost heavy constructions and water discharge losses due to contraction, friction, and transitional losses. As a result, for appropriate utilization of existing water resources, an efficient low-cost structure for discharge measurement must be designed, manufactured, and tested. To measure discharge rate using hydraulic structures, a well-established head-discharge relationship must be devised empirically, tested experimentally, and numerically confirmed. With this in mind, the current research focuses on a new compound broad crested weir construction for discharge measurement. The new method of keeping a constant discharge coefficient is used, allowing for accurate measurement of a wide range of discharges regardless of head over weir. Experiments are conducted in a 2.5 m long, 20 cm wide, and 30 cm deep horizontal tilting flume in a laboratory. C_d was measured in the range of 0.55 to 0.65 in previous experiments. Subsequently the present broad crested weir model is modified for suiting best results for discharge measurement.

Initially the model was fabricated with PVC sheet. Proper treatment was given to this model for arriving at results as per theoretical design. Further it was decided to explore the model manufacturing by additive 3D printing technology, where it was fabricated using Poly Lactic Acid plastic material. The performance of proposed broad crested weir model is then validated by CFD Flow 3D technique and experimental analysis, having some statistical base.

Research Methodology

In the earlier investigations carried out, the experimental performance of compound broad crested weir manufactured with PVC material, had the discharge coefficients (C_d) in the range of 0.518 to 0.648. To arrive at the nearest C_d value of 0.6 which is the input design parameter, the geometry of PVC model was given logical treatment to lower base width. For achieving this, the make and cut approach was used. It was reduced to 10.3 cm from 10.5 cm in earlier testing. This enabled the C_d value lying in the range 0.546 to 0.67. In next trail, PVC model base width was fabricated with 10.2 cm, further reducing the base width by 0.5 mm on each side symmetrically. This led to closer proximity of 0.6 value, however with much deviation in the range observed. The PVC model studies revealed the fact, that since the discharge from weir is proportional to the h/L, fabrication error in the geometry of weir may lead to deviated results. Hence, to achieve accuracy in model fabrication additive manufacturing approach was undertaken. It was decided to use 3D printing technology to modify a freshly casted compound broad crested weir model in order to improve C_d prediction. Initially, the CBC weir model was casted by 3D printing technology as per theoretical design. It was tested in laboratory to evaluate the performance for discharge measurement. Depending upon the results, the model was modified again and response noted. The different trails for laboratory testing and model fabrication proved difficult and time consuming. Hence, it was decided to resort to CFD application for optimizing the results with respect to constant discharge coefficient, which is novel objective of current research work. Flow-3D was used for this purpose. The discharges were not appropriately targeted according to the step size of the compound weir model, according to the first investigation (Trial 1) done with a 3D printing model. The first goal was to achieve the design's specifications for a lower step height, i.e. a discharge of 2 lps equating to a 6.57 cm lower step size. To do this, the first step was corrected by expanding the model's base width somewhat. The model base width was lowered by 1 mm on both sides symmetrically using the make and cut method. Once the nearest value of discharge obtained for lower step size, the model was again tested (Trial 2 & Trial 3) with one full rigorous set from low to high discharge values in the laboratory set up. For each performance the C_d values were also computed. Further amendments can be made for each step height till the design parameter of $C_d = 0.6$ is obtained.

Experimental Study

Series of laboratory studies were undertaken to establish Head- Discharge relationship for the modified compound broad crested weir experimentally towards better prediction of C_d. The geometry of Compound broad crested weir model is based upon the design mentioned in Hinge et al. (2010) who proposed a new design of hydraulic jump type stilling basin where a rectangular broad crested stepped weir was developed at the end of horizontal apron to constrain the formation of clear hydraulic jump within basin. However, the possibility of using compound broad crested weir model as discharge measuring device by maintaining C_d fairly constant has not been explored extensively. The experimental set up working details, trial runs conducted with brief result analysis is reported in Kulkarni and Hinge (2020). The experiment is executed as per guidelines given in USBR water measurement manual. Photographs given below show series of trial compound broad crested weir models fabricated initially with PVC material and later modified to use of Poly lactic acid plastic material casted with 3D printing technology for testing purpose. The compound broad crested weir models were rigorously tested in the laboratory using horizontal tilting flume for the wide range of discharge capacity. The details about theoretical discharge predictions referred here using traditional rectangular weir formula can be obtained in authors another paper published (Kulkarni and Hinge, 2017). Figure 1 and 2 shown below are the compound broad crested weir models casted with PVC material, before and after the modification in the weir geometry.

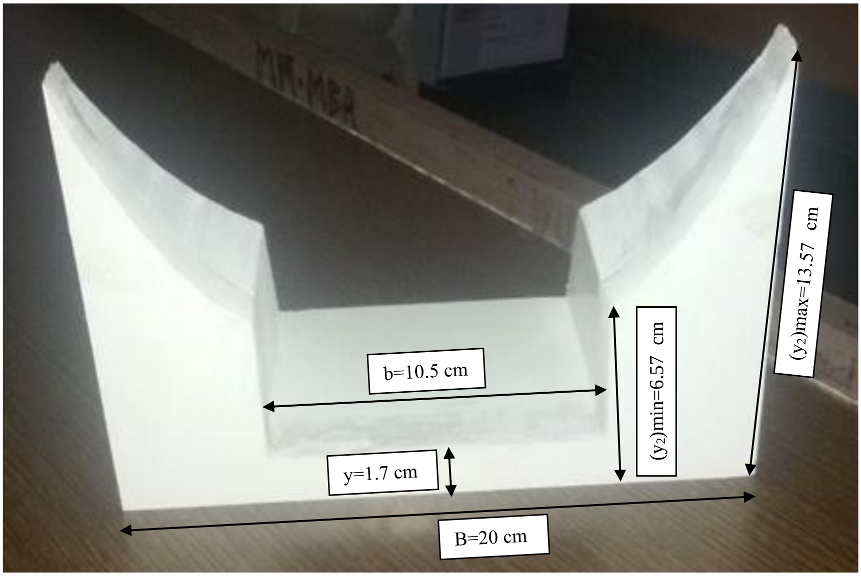

Figure 1: Compound Broad Crested Weir Casted with PVC material (original, trial 1)

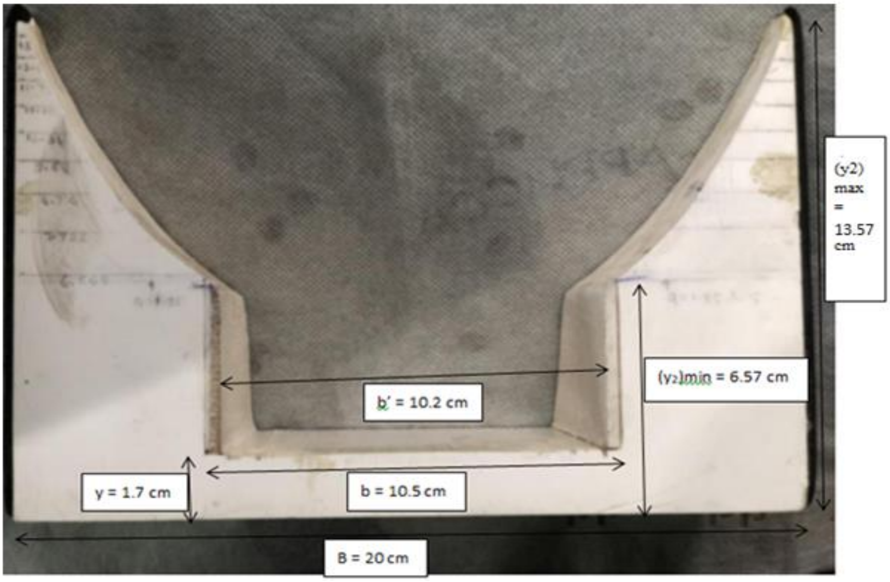

Figure 2: Modified Compound Broad Crested PVC Weir casted with PVC Model (Trial 2)

Additive Manufacturing of Compound Broad Crested Weir using 3D Printing Technology

Fused Deposition Modeling (FDM), a material extrusion technique, is the most widely used 3D printing method. Metal Powder Bed Fusion has recently gained popularity as a result of the widespread use of metal parts in the 3D printing industry. Unlike the traditional machining method, which removes material from a stock item, or the ancient casting and forging procedures, 3D Printing creates a three-dimensional object from a computer-aided design (CAD) model by gradually adding material layer by layer. The phrase "3D printing" initially referred to a procedure in which inkjet printer heads deposit a binder material onto a powder bed layer by layer. In current work, SOLIDWORKS and 3D viewer software is used to design and fabricate the compound broad crested weir model, which was given a progressive treatment. 3D printing technology was used to create the model. PLA (Poly Lactic Acid) Plastic, which is originally in the form of filament with a diameter of 1.75mm, was used to make the model. While fabricating the model, 1.5mm spacing was created between metal balls (5mm dia. and 58gm each ball) to ensure that the model could resist the flow of water. Filament was inserted in layer form, and a model was created by combining layers. The accuracy of 3D printing design is very good, and the fabrication time is also very short. The model was made waterproof by using rubber sheet of 3mm thickness at the sides and bottom part, however without disturbing the weir geometry. The term 3D printing covers a variety of processes in which material is joined or solidified under computer control to create a three-dimensional object, with material being added together (such as liquid molecules or powder grains being fused together), typically layer by layer.

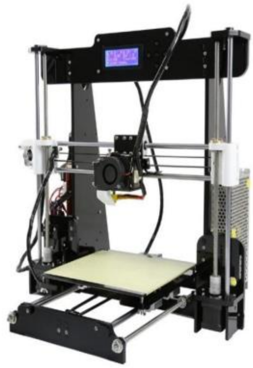

Figure 3: FDM printer

Figure 4: CBC Weir Model Casted with PLA Plastic material fixed inside the tilting flume

FDM printer can formulate the models using materials like PLA, Wood, PVA, Nylon etc. In the current study, compound broad crested weir model is manufactured using Poly Lactic Acid (PLA) material adhering to the specifications given below:

Table 1: Specifications of FDM printer

XY Axis Positioning Accuracy	0.012mm
Z Axis Positioning Accuracy	0.004mm
Print Color	Single Color
Extruder Dia.	0.4mm (Custom Options: 0.5/0.3/0.2mm)
Print Precision	0.1-0.4mm
Layer Resolution	0.1mm
Printing Speed	100mm/s
Maximum Print Size	220*220*230mm
Nozzle Temperature	Recommended: 210℃, Maximum 250℃
Heating Plate Temperature	50-110 ℃ (Adjustable)
Heating Plate Material	Aluminum
Filament Materials	PLA, ABS, HIPS, WOOD, PVA, Nylon
Filament Dia.	1.75mm
3D Printing Software	CURA
Power Supply	DC 12V/20A (default EU plug)

CFD Analysis

Numerical Model and Grid Generation

The FLOW-3D solver version 10.1.1.05 win64 2013 developed by Flow Science, Inc. in the United States was used to simulate the free surface flow over the weir. Flow-3D is a commercial CFD programme designed specifically for hydraulic engineering applications. The Volume of Fluid Method (VOF) is used in Flow 3D. For situations involving free surface flows, the VOF model is ideal [Samadi and Arvanaghi (2014)]. It is based on the notion of avoid mixing two or more fluids. Both the water and the air are modelled in the grid in this two-phase technique. The approach is based on the idea that each cell has a fraction of water (F), which is 1 when the element is completely filled with water and 0 when the element is filled with air. If the value is between 1 and 0, the element contains the free water surface. The weir was created in Flow 3D by importing an STL file. Solid object surfaces are approximated by cubes in STL files. The solid model was converted to STL format using the AutoCAD application. One non-uniform mesh block was used to discretize the domain. The final steady state was relaxed using the development of time. A three-dimensional grid with 30,000 cells in the x, y, and z dimensions was produced, as illustrated in the picture. Each cube was assigned a volume of 5 cm^3, resulting in a cell size of 1.7 cm.

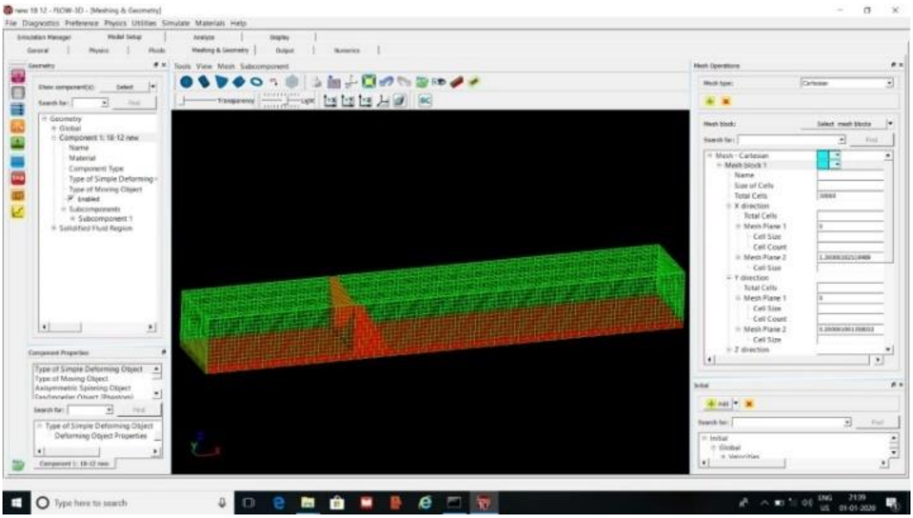

Figure 5: Meshing and Grid generation

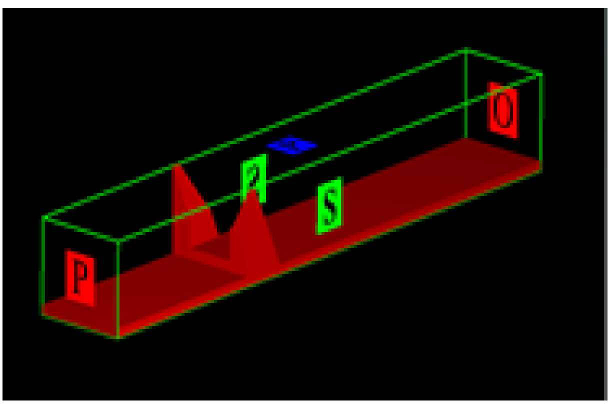

Figure 6: Configurations of boundary

Boundary conditions

For side borders, boundary conditions were classified as "symmetry," implying that identical flow occurs on both sides of the barrier and hence no drag. The boundary condition in the x-direction was "defined stagnation pressure." Flow 3D can represent multiple flow heights starting at a stagnation pressure state using this approach. At the outlet of the x direction, a continuous boundary outflow condition is examined. This indicated that the flow will continue to flow smoothly through the boundary. Figure 6 depicts the boundary conditions in the x, y, and z planes.

RESULTS AND DISCUSSION

The calculation with Flow 3-D had a grid with 1, 20,811 active cells due to the set boundary conditions and meshing. A steady state condition was discovered after a calculation time of 229 seconds. Large eddy simulation (LES), Renormalization Group (RNG), the two equations (k-), one equation turbulent energy (k), and Prandtl's mixing length theory are the five techniques used in Flow 3D modelling. Flow 3D simulations using the RNG turbulence model resulted in discharge levels ranging from 1.99 lps (lower value) to 10 lps (higher value). The 3D view of flow generated through FLOW3D simulation for high and low discharges are shown in figure 7 below.

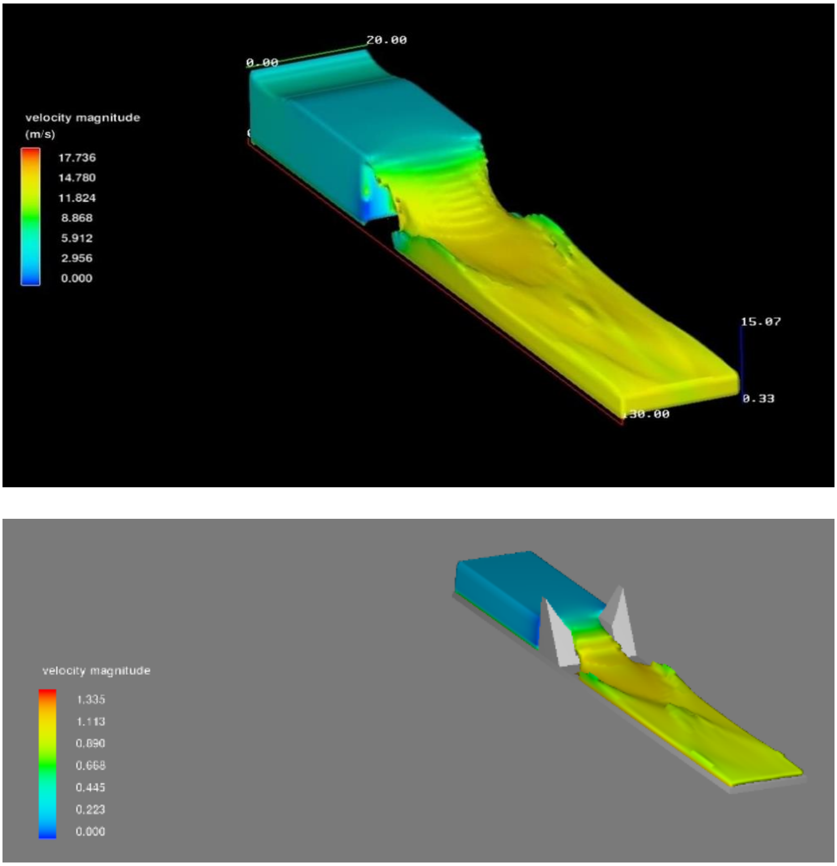

Figure 7: Flow through compound broad crested weir in Flow 3D for max & min discharge (y_2 = 13.557 cm, Q_{max} = 10 lps) max to (y_2 = 6.56 cm, Q_{min} = 2 lps) min

The readings obtained after running the flume for various discharge capacities using PVC material are tabulated below, (table 2). As the step height and tread change, classic rectangular weir formulae are used to determine the partial discharge for each step, which is then calculated for the observed head recorded empirically. The actual discharge is volumetrically assessed by running the flume through several ranges (10 lps to 2 lps). The curved component of the weir above the base rectangular weir is made by combining the midpoints of successive rectangular steps to eliminate sharp edges and corners and eliminate the risk of cavitation. Consequently, despite the fact that there seems to be a curve above the rectangular weir, the cumulative discharges for different steps are calculated using the usual rectangular weir formula.

Table 2: Head – Discharge Calculations (Experimental vs Theoretical vs CFD approach for PVC model), b = 10.5 cm

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 (cm) CFD	Head above weir crest (y_2-y), h (cm) Experimental	Q_{th} (lps)	Q_{expt} (lps)	Q_{CFD} (lps)
1	6.568	6.56	7.388	4.868	4.86	5.688	2	1.773	2.082
2	7.725	7.72	8.94	6.025	6.017	7.24	2.8	2.398	2.858
3	8.714	8.71	9.97	7.014	7.006	8.27	3.6	3.164	3.691
4	9.589	9.59	10.96	7.889	7.893	9.26	4.4	4.021	4.557
5	10.38	10.4	11.64	8.68	8.68	9.94	5.2	4.939	5.446
6	11.107	11.1	12.096	9.407	9.403	10.396	6	5.904	6.351
7	11.78	11.8	12.52	10.08	10.07	10.82	6.8	6.9	7.263
8	12.41	12.4	13.07	10.71	10.703	11.37	7.6	7.923	8.183
9	13	13	13.436	11.3	11.3	11.736	8.4	8.959	9.101
10	13.57	13.6	-	11.87	11.86	-	9.2	10.03	10.04

The experimental values were determined in laboratory for the CBC weir model casted with PVC material and compared with the CFD simulations for the same model geometry. The behavior of experimental and CFD results were then compared to the theoretical model parameters and brief analysis were obtained. In the current research, comparison of theoretical, experimental and FLOW 3D simulation results for different compound broad crested weir casted with PVC and PLA plastic material by additive manufacturing is undertaken and the performance is evaluated. The head discharge relationship for the models tested are given below.

Table 3: Head – Discharge Calculations (Experimental vs Theoretical vs CFD approach) –Broad crested weir model casted by 3D printing technology – Trial I (before treating model), b = 10.5 cm

Sr. No.	y_2 (expt) (cm)	Time to collect 100 litters (sec)	Q_{expt} (lps)	Q_{th}(lps) for corresponding step size	$C_d = [Q_{expt}/Q_{th}] \times 0.6$	Q_{CFD} (lps)	$C_d = [Q_{CFD}/Q_{th}] \times 0.6$
1	6.568	54.05	1.85	2	0.55	1.73	0.519
2	7.725	46.92	2.131	2.8	0.456	2.45	0.525
3	8.714	33.52	2.983	3.6	0.497	3.44	0.573
4	9.580	27.37	3.654	4.4	0.498	4.08	0.556
5	10.380	22.53	4.438	5.2	0.512	4.60	0.531
6	11.100	18.84	5.307	6.0	0.5307	5.42	0.542
7	11.780	16.08	6.216	6.8	0.548	6.18	0.545
8	12.413	13.65	7.322	7.6	0.578	6.95	0.548
9	13.00	12.30	8.127	8.4	0.5805	7.66	0.547
10	13.57	10.96	9.118	9.2	0.594	9.24	0.602

Table 4: Head – Discharge Calculations (Experimental vs Theoretical vs CFD approach) –Broad crested weir model casted by 3D printing technology – Trial II (after treating model, reducing 1 mm at lower step height from each side), b = 10.3 cm

Sr. No.	y_2 (expt) (cm)	Time to collect 100 liters (sec)	Q_{expt} (lps)	Q_{th}(lps) for corresponding step size	$C_d = [Q_{expt}/Q_{th}] \times 0.6$	Q_{CFD} (lps)	$C_d = [Q_{CFD}/Q_{th}] \times 0.6$
1	6.568	51.20	1.95	2.0	0.585	1.886	0.565
2	7.725	39.40	2.54	2.8	0.544	2.61	0.559
3	8.714	30.04	3.33	3.6	0.555	3.36	0.56
4	9.580	24.00	4.47	4.4	0.568	4.15	0.566
5	10.380	20.00	5.0	5.2	0.576	4.97	0.573
6	11.100	17.00	5.88	6.0	0.588	5.88	0.588
7	11.780	15.00	6.67	6.8	0.588	6.66	0.587
8	12.413	13.29	7.52	7.6	0.594	7.68	0.6
9	13.00	12.00	8.33	8.4	0.594	8.59	0.61
10	13.57	10.87	9.19	9.2	0.599	9.63	0.62

The velocity profile and discharge simulated by FLOW 3D obtained for high discharge i.e. 10 lps with respective upstream depth of flow of compound broad crested weir section is shown below:

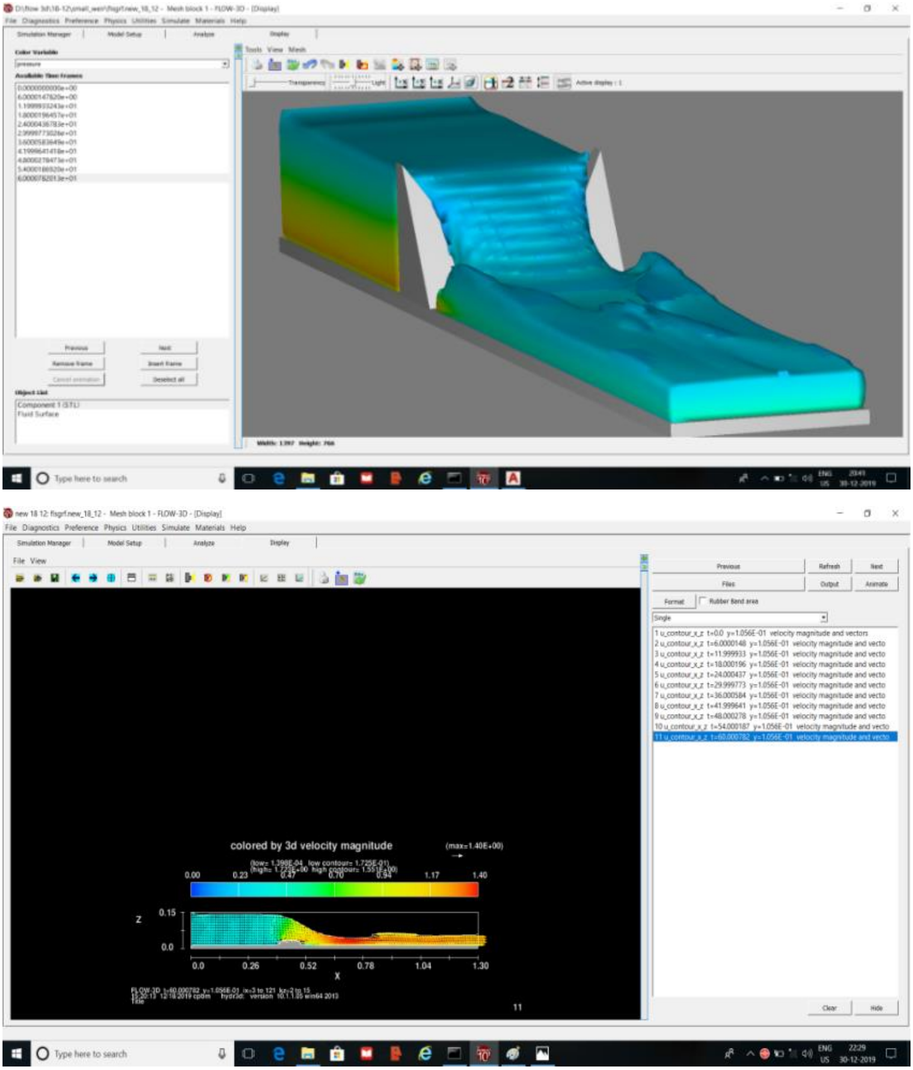

Figure 8: FLOW 3D Simulation for 10 lps Discharge with Velocity profile

The head discharge relationship established for theoretical, experimental model and its performance for CFD simulations for various discharge ranges with different compound broad crested models casted are shown below in figure 9 below.

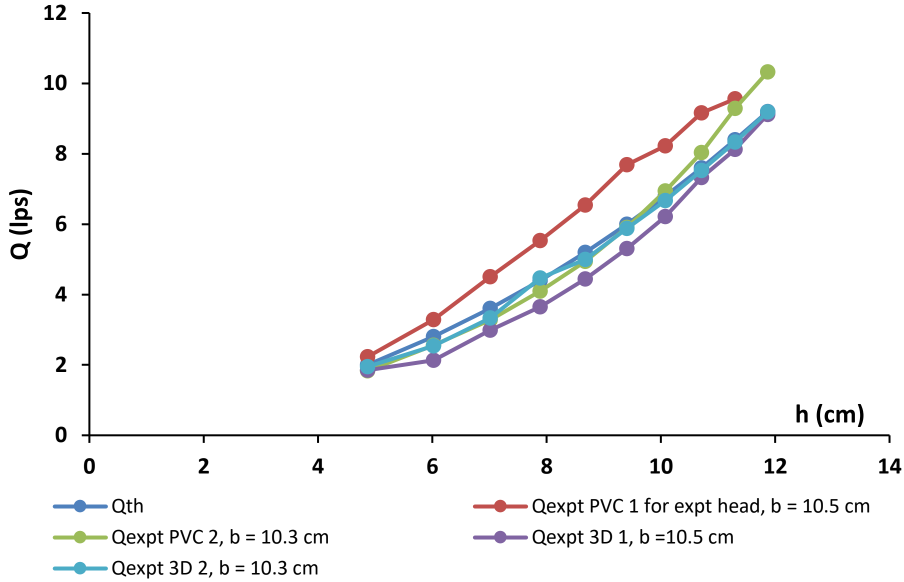

Figure 9: Head Discharge Rating Curve for PVC and 3D printed models

The coefficient of discharge was calculated for PVC models - original and modified (PVC 1 and PVC 2), along with CBC weir model casted with 3D printing technology – original and modified (3DP1 and 3DP2) various ranges and resulted in the following values (Table 5). The plot resulted in the comparison of Cd values obtained for different models casted as against the input design value (Fig. 10).

Table 5: Comparison of C_d values – for PVC and 3D printing model cast

y_2 (cm)	C_d (input)	C_d PVC 1, b=10.5 cm	C_d PVC 2, b=10.3cm	C_d 3DP1, b=10.5cm	C_d 3DP2, b=10.3cm
6.568	0.6	0.524	0.549	0.55	0.585
7.725	0.6	0.518	0.547	0.456	0.544
8.714	0.6	0.566	0.546	0.497	0.555
9.58	0.6	0.569	0.56	0.498	0.568
10.38	0.6	0.592	0.57	0.512	0.576
11.1	0.6	0.6408	0.591	0.5307	0.588
11.78	0.6	0.638	0.612	0.548	0.588
12.413	0.6	0.648	0.63	0.578	0.594
13	0.6	0.637	0.66	0.5805	0.594
13.57	0.6	-	0.67	0.594	0.599

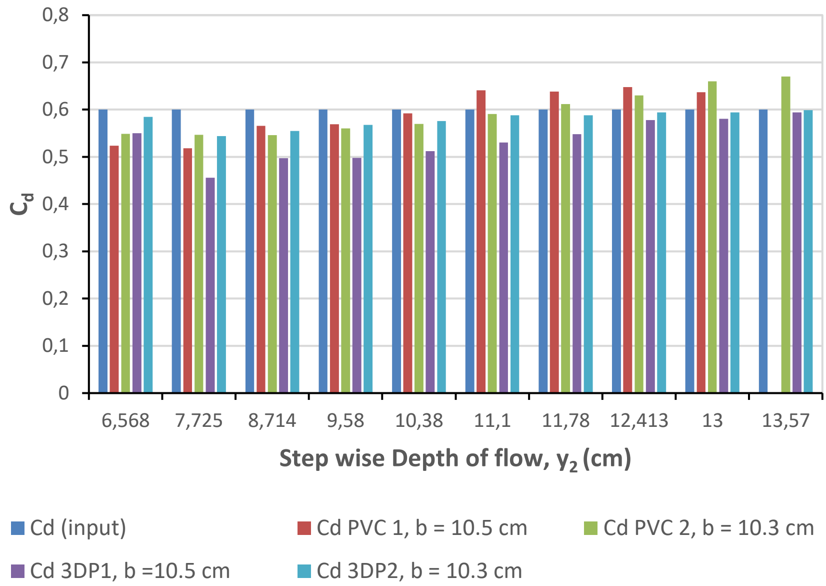

Figure 10: Step wise depth of water (y_2) vs. C_d.

Fully turbulent flow was developed for entire weir flow depths with no sign of weir submergence even under high discharges, throughout. After the experimentation with PVC models, which related C_d in range of 0.518 to 0.648 the design was fabricated using 3D printing technology to improve accuracy. With trial 1 of newly casted CBC weir model, C_d varies in between 0.456 to 0.594. To reach closer to the targeted discharge values, model was treated by reducing 1mm width from each side for lower step height i.e., making it now to 10.3 cm instead of 10.5 cm earlier. This test conducted yielded the value of C_d in between 0.544 to 0.599. Also, the correlation coefficient between experimental discharge and theoretical discharge obtained was 0.999 with standard deviation of 2.378. To explore CFD simulations FLOW 3D software was used, which yielded reasonable results matching to the theoretical design. These results given by FLOW 3D were compared to experimental results as well and the accuracy level of both the outputs was found to be well within the error range of ± 5% stated in literature. Above relation demonstrates that there is good agreement between the theoretical discharges by traditional rectangular weir formulae as well as experimental and CFD discharges for various ranges. Thus, in the context of present study conducted, the range of discharge coefficients and discharges are in good agreement with the input design parameters. The weir width parameters considered for testing were 10.5 cm, 10.3 cm, 10.2 cm respectively. Experimental discharge values and CFD discharges obtained were compared against the theoretical discharges obtained from conventional method of linear combination technique of traditional rectangular weir formula. The discharge coefficient for experimental and CFD analysis is given below (Table 6). The C_d mean value with experimental and CFD approaches is quite near to the design input of 0.6 reveal that the weir model predicts the discharges accurately.

The comparitive experimental discharges for CBC weir casted with 3D printing technology – original (3DP1) and modified (3DP2) as against the theoretical discharge for head over different rectangular steps is shown in Table 6 below. The head discharge rating curve for models casted with 3D printing technology is shown in Fig. 11. The calibrated curve shows good amount of agreement in thoretical and experimental discharge values with correlation coefficient almost 0.99.

Table 6: Head – Discharge Calculations – Compound Broad crested weir model casted by 3D printing technology

Head over weir, h (cm)	Qth (lps)	Qexpt 3DP1 (lps)	Qexpt 3DP2 (lps)
4.868	2	1.85	1.95
6.025	2.8	2.131	2.54
7.014	3.6	2.983	3.33
7.889	4.4	3.654	4.47
8.68	5.2	4.438	5
9.407	6	5.307	5.88
10.08	6.8	6.216	6.67
10.71	7.6	7.322	7.52
11.3	8.4	8.127	8.33
11.87	9.2	9.118	9.19

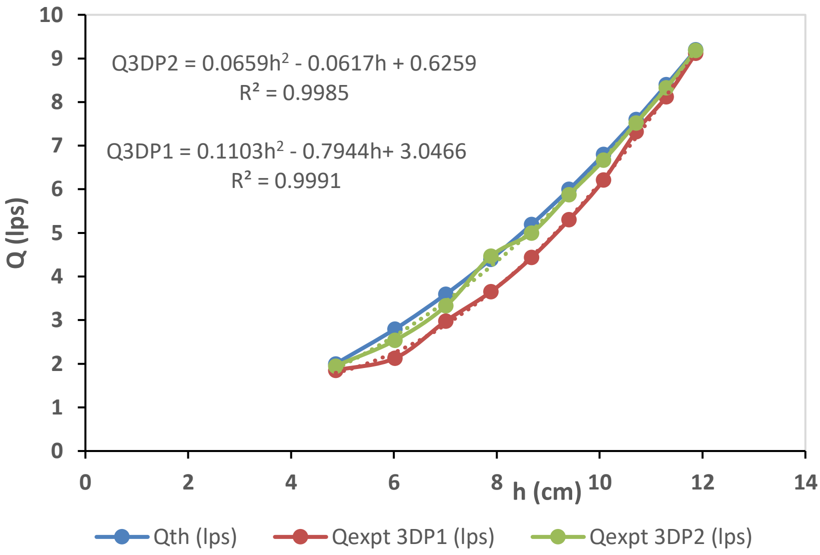

Figure 11: Head Discharge Rating Curve for CBC Weir casted with 3D Printing

The performance validation of proposed CBC weir with different approaches was justified using some error and statistical equations. The error estimation between experimental and theoretical inputs were calculated by applying the following checks in form of Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) as given below.

$$\text{RMSE} = \sqrt{\left(\frac{1}{n}\sum_1^n (Q_{expt} - Q_{th})^2\right)} \quad (1)$$

$$\text{MAPE} = 100 \times \frac{1}{n}\sum_1^n \left|\frac{Q_{expt} - Q_{th}}{Q_{th}}\right| \text{-} \quad (2)$$

After the experimental investigation, it was concluded that the model fabricated with 3D printing technology led to precise discharge measurement with standard deviation being reduced to 2.378 as compared to 2.6 in prior trials with PVC material. Also, R^2 between experimental and theoretical discharges was found to be 0.999 with 99% confidence level in the discharge estimates. Further, an improved estimation of discharge coefficient was obtained with less variation with values lying in the range from 0.55 (min) to 0.6 (max), with majority values lying near to 0.6, given as input parameter. It is observed that the study conducted for 10. 3 cm with additive manufacturing gives the most accurate result in the prediction of discharge values with mean absolute error of 3.24% and R^2 of 0.999 as against 7.842% and 4.26 % for PVC models and CFD models respectively. The root mean square error for 3D printing model is also less, 0.151 as against 0.512 and 0.22 for PVC and CFD models. This analysis proves that additive manufacturing has resulted in precise discharge measurement by compound broad crested weir for wide range of discharges. Accurate estimates when compared to PVC material demonstrates the enhanced behavior of the proposed model.

Table 7: Statistical details for manufacturing compound broad crested weir with PVC, 3D Printing and CFD Approach

Parameter (Q)	Range of Discharge Coefficient (C_d), Min - Max		Std. deviation	RMSE	MAPE (%)	Correlation Coefficient (Parameter Q)
	original	Modified				
PVC results	0.518 - 0.648	0.546 - 0.67	2.595829	0.512	7.842	0.9959
3D printing results	0.45 - 0.594	0.544 - 0.599	2.378233	0.151	3.243	0.9991
CFD Simulation	0.597- 0.652	0.559 - 0.62	2.4467298	0.22	4.26	0.998601015

CONCLUSION

- Compound broad crested weir is manufactured with traditional method and additive manufacturing technique where the head discharge relation is established experimentally.
- The CFD validation of compound broad crested weir is accomplished for wide range of discharges using Flow 3D a three-dimensional simulation software.
- For experimental output, the discharge coefficient for the original compound broad crested weir model cast using 3D printing technology varies between 0.45 and 0.594. This 3D printed object was also subjected to a step width of 10.3 cm, with improved estimation in discharge coefficient ranging from 0.54 to 0.599.
- In all the approaches deployed, the CBC weir model manufactured with 3D printing technology demonstrates the least root mean square error of 0.151 and least mean average absolute error of 3.243 with high correlation coefficient of 0.999.
- The accuracy of geometry attained by producing the compound broad crested weir model utilizing 3D printed technology and Poly Lactic Acid plastic material, has greatly reduced the variation range of discharge coefficient. This epic level of achievement as against theoretical design was not attained in the PVC model cast.

Thus, the performance of proposed weir is greatly enhanced by adapting additive manufacturing process. FLOW 3D fairly simulates the theoretical and experimental results for obtaining discharge through compound broad crested weir which can be used as an effective tool towards three dimensional CFD computing. Further exploring the step wise addition and cutting in weir geometry with trial-and-error approach will definitely result in constant value of discharge coefficient which is the novel objective of current research.

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