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AN ENERGY PERSPECTIVE OF COMPOSITE BROAD CRESTED WEIR FOR MEASURING ACCURATE DISCHARGE

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ABSTRACT

This paper reports the computational fluid dynamics and experimental fluid dynamics studies conducted for the measurement of release by a composite broad-crested (CBC) weir. Studies conducted thus far depict that manufacturing composite weirs for precise discharge measurement is a demanding field. The performance of composite broad crested weirs as flow measuring devices depends on the weir width (b), height of the weir and upstream flow over the weir crest (h). Thus, a change in the geometry of the weir for a given flume will determine the flow characteristics, mainly the discharge coefficient (C_d), which changes according to the h/b ratio. At present, researchers have maintained an average range of C_d for various h/b ratios. This study is related to CFD investigations regarding hydraulic properties to determine optimized weir geometry. FLOW 3D deploys accuracy in free surface simulations where the model employs a renormalized group (RNG) approach with volume of fluid (VOF). To validate the CFD model, laboratory models were used. In this research, flow depth parameters on the weir crest and velocity distribution on a composite broad-crested weir were evaluated. The experimental observations were used to validate the 3-D CFD models, and then the geometry of the composite broad-crested weir was optimized to obtain a constant C_d. The results of both the performance of the CBC weir for precise measurement of a wide range of discharges are confirmed by numerical models and experimental observations by fairly maintaining a constant design input value of the discharge coefficient of 0.6. Compared to empirical methods, optimization of the weir geometry through CFD definitely yields the correct model prediction. Furthermore, additive manufacturing of this optimized model with poly lactic acid plastic material validated the weir performance with accurate estimations between theoretical, experimental, and CFD outputs. The applications of the proposed method from the energy aspect are highlighted.

Keywords: Composite Broad Crested Weir, Coefficient of Discharge, Flow 3D, 3D printer, Energy

INTRODUCTION

Sharp crested and broad crested weirs have raised the interest of researchers in the past and in recent years. Open channel flow assessment has long been researched by scholars such as Ackers et al. (1978) and Ranga Raju (1981), who published findings for the flow properties of finite crest length weirs. Discharge relations for flow estimations with cross-section forms such as rectangular, triangular, trapezoidal, and truncated triangular have been studied, and adequate empirical discharge formulas for these weirs have been presented (Boiten and Pitlo, 1982; Swamee, 1988; Hager and Schwalt, 1994; Gogus et al. 2016). The Kindsvater-Carter equation (Kindsvater and Carter, 1959) was created to provide a trustworthy, exact method for modeling all rectangular (suppressed, partially contracted, and completely contracted) weirs. Kulin and Compton (1975) established a rating technique for partially contracted 90 degree and wholly contracted V notch weirs between 25 and 100 degrees, which can also be used on entirely suppressed, partially contracted, and fully contracted rectangular weirs. Head-discharge calculations for wide weirs and long flumes with different cross sections were proposed (Bos, 1989). If viscosity and surface tension are not taken into account, the discharge coefficient is determined by the weir head above the crest to length ratio, h/b (Horton, 1907). Based on critical flow theory, an expression for the coefficient of discharge for a streamlined broad-crested weir was constructed, accounting for boundary layer formation (Harrison, 1967). Laboratory measurements conducted by Gogus et al. (2006) found that the global coefficient of discharge for a composite broad-crested weir is less than that of a simple broad-crested weir with the same crest height and lengths. Salmasi et al. (2012) and Bijankhan et al. (2014) conducted research on discharge relations for rectangular broad crested weirs with the goal of investigating the effects of lower weir crest width and step height of broad crested weirs with rectangular composite cross sections on the values of the discharge coefficient (C_d) and approach velocity coefficient. Researchers have recently used mathematical software and soft computing methodologies in the domain of open channel hydraulics, notably for composite weirs. Hinge et al. (2010) demonstrated how to calibrate a composite weir with a small reach in the presence of a hydraulic jump. Under difficult flow conditions, the forecast of upstream flow depths using the commercial software FLUENT 6.3.26 for the specified flow rates was found to be excellent. Forecasting discharges in composite channels using soft computing methods has captured the interest of academics worldwide. Zahiri and Azamathulla (2014) used several soft computing technologies, such as linear genetic programming and the M5 model tree, to confirm the experimental and conventional approach of the linear combination of theoretical equations of simple weirs. Azamathulla et al. (2016) stated that support vector machine techniques are equally useful for predicting the side weir discharge coefficient. Optimization techniques such as PSO were investigated by (Parsaie et al., 2018) for determining C_d of a cylindrical weir gate. Mathematical models were explored, and they also displayed good discharge coefficient prediction with errors of less than 3.8 percent, with improved outputs produced by mathematical and soft computing techniques. The discharge coefficient is related to the head over the weir, according to all previous studies. Savage and Johnson (2001) used 2D and 3D physical models with 3D flow simulations to determine the discharge coefficient for an ogee spillway. The 2D model produced satisfactory results. Khan et al. (2006) created velocity versus length graphs on a contact tank using the STAR-CD tool. These graphs were made at three different depths: top, middle, and bottom. The CFD STARCD model was shown to accurately reflect the velocity field. The FLOW3D program was used to design a rectangular sharp crested weir with C_d as a function of head over a weir-to-weir height (Rady, 2011). The C_d from various heads estimated from various head over weir-to-weir height ratio relationships was found to be within a 3% error. It also highlighted the advantages of utilizing "Flow-3D" as a tool for assessing velocity vectors and pressure patterns over rectangular sharp crested weirs. The head was plotted using flow rate v/s FLUENT, and the experimental and numerical findings corresponded well. Simulation of C_d values for a circular labyrinth weir with and without a nappe breaker using FLOW3D was investigated (Omer et al., 2018). The experimental and CFD results were extremely close, with only a 4% average difference. FLOW-3D's applicability to broad crested porous weirs has been examined (Safarzadeh and Mohajeri, 2018), where using the experimental head-discharge curve, the drag coefficient was computed, and the relationship between the drag coefficient and the coefficient of permeability was identified. Kulkarni and Hinge (2021) recently discussed the use of composite weirs for accurate measurements using additive manufacturing and numerical analysis. Achour and Amara (2022) proved that the ratio h/B *(weir head to width ratio)* accounts for 23.5% as an average effect in the calculation of the discharge coefficient C_d and hence of the flow rate Q. Similar efforts conducted on rectangular and triangular channels using broad crested and thin crested sills shed light upon hydraulic jump characteristics in surface flow hydraulics (Achour et al., 2022a, 2022b, 2022c). The current study is an attempt to validate the experimental results achieved by the authors and referenced in the literature, using a few more physical model combinations. In this study, we have highlighted the investigations that were carried out to demonstrate the novel concept of maintaining a constant value of C_d regardless of the head over weir. The current research is focused on the design, fabrication, and testing of a composite broad-crested weir with a fairly constant discharge coefficient that may be used as a discharge measurement device after the head discharge relation has been experimentally established. The key applications of the proposed weir from an energy standpoint are then discussed in greater detail.

MANUFACTURING COMPOSITE BROAD CRESTED WEIR USING 3D PRINTING TECHNOLOGY

A broad crested weir is a simple device for measuring discharge in various forms and widths of channels. A broad-crested weir is a flat-crested barrier with a crest length greater than the flow thickness, resulting in parallel streamlines and hydrostatic pressure distribution. Unnecessary fluctuations in the value of C_d may cause design ambiguity, resulting in heavy buildings. It also results in losses owing to contraction, friction, and transitional effects. As a result, to make the most use of available water resources, an effective low-cost structure for discharge measurement must be conceived, produced, and tested. To estimate the discharge rate utilizing hydraulic structures, an empirically designed, experimentally proven, and numerically confirmed relationship between the head and discharge must be devised. With this in mind, the current project focuses on the development of a novel composite broad crested weir for discharge measurement. The innovative method of maintaining a constant discharge coefficient is utilized, which accurately measures a wide range of discharges regardless of the weir head. Experiments were carried out in a 2.5 meter long, 20 centimeter wide, and 30-centimeter-deep laboratory tilting flume. C_d was altered between 0.55 and 0.67 in prior trials, and the current broad crested weir model was adjusted to provide the best discharge measurement findings. The following tasks are the focus of this research report. Manufacturing volumetric discharge measurement assembly for the experimental set up.

- Fabrication of new composite broad crested weir using 3D printing technique and modification of this model toward better prediction of C_d.
- Establishing an experimental head-discharge rating for a modified composite weir.
- Verification and comparison of experimental results through CFD simulation and statistical approach against theoretical input.

The tilting flume used for the laboratory study had an orifice meter for discharge measurement. It was proposed that accurate estimations of the flow rate over a weir are possible using volumetric flow measurements imparting a fraction of the total flow (Hager and Schwalt, 1994). Hence, the fabrication and installation of a volumetric discharge measurement apparatus was one of the tasks undertaken for this study. For the given flume discharge capacity, a 125 liter tank was cast in a metal alloy that was later powder coated.

The tank was calibrated, and a measuring scale was attached to it to obtain readings of the amount of water collected in it. A sliding frame arrangement was attached to the collection tank to direct water from the flume into the measuring tank. The time period required (in sec) to collect 100 liters of water in this tank was recorded. Dividing the volume of water collected by the time required (in sec) is reported as the experimental discharge. A pump attached to this assembly is operated upon after taking the readings, and water is redirected to the sump tank for the next set of observations. The composite broad crested weir under inquiry was built step by step with SOLIDWORKS and 3D viewer software. 3D printing technology was used to create the model. The phrase "3D printing" refers to a variety of procedures in which material is combined or solidified under computer control to produce a three-dimensional item. These techniques often stack material (such as liquid molecules or powder grains) together. PLA (poly lactic acid) plastic was used to produce the models. It comes in the form of a filament with a diameter of 1.75 mm at first. It took 1.5 mm that had metal balls (5 mm diameter and 58 gm each) inside. The prototype could withstand the flow of water because there was enough space between the balls. The filament was spread out in layers and was rendered later by combining the layers. The accuracy of 3D printing designs is very high, and the time it takes to create is also less (approximately 22 hrs required). The design was built waterproof by covering the sides and bottom with a rubber sheet that was 3 mm thick. However, this did not change the shape of the weir.

Figure 1: Fabrication of the volumetric measurement assembly

Figure 2: 3D printer with fused deposition discharge modeling technique

Figure 3: CBC Weir Model Casted with Poly Lactic Acid Plastic material

To improve C_d prediction, 3D printing technology was used to modify a freshly cast composite broad-crested weir. According to the initial inquiry (Trial 1), the discharges were not correctly targeted based on each step size of the composite weir model. The first target was to meet the design parameters for a lower step height, i.e., a discharge of 2 lps equal to a 6.57 cm lower step. To achieve this purpose, the first step was modified by greatly expanding the model's base width. The make and cut procedure was used, in which the model base width was symmetrically lowered by 1 mm on both sides, followed by trial runs. After finding the closest discharge value for a reduced step size, the model was tested in the laboratory (Trials 2 and 3) using a full set of discharge values ranging from low to high. For each performance, C_d values were computed. Additional modifications to each step height can be made until the design parameter of $C_d = 0.6$ is obtained.

EXPERIMENTAL AND NUMERICAL STUDY

To improve C_d prediction, a series of laboratory tests were carried out to experimentally construct a head-discharge link for the redesigned composite broad-crested weir. The geometry of the composite broad crested weir model is based on the design proposed in (Hinge et al., 2010), which included the construction of a rectangular broad crested stepped weir at the end of the horizontal apron to constrain the building of a distinct hydraulic jump within the basin. It has not been properly examined whether a composite broad crested weir can be used as a discharge monitoring device while maintaining a reasonably constant C_d. Kulkarni and Hinge (2020) present the current CBC weir's experimental setup, trial runs, and brief results analysis. The experiment was carried out in accordance with the directions provided in the USBR water measuring manual, 2001. The photographs below show a set of trial composite broad crested weir models made with PVC material and subsequently cast with poly lactic acid plastic material using additive manufacturing for testing reasons.

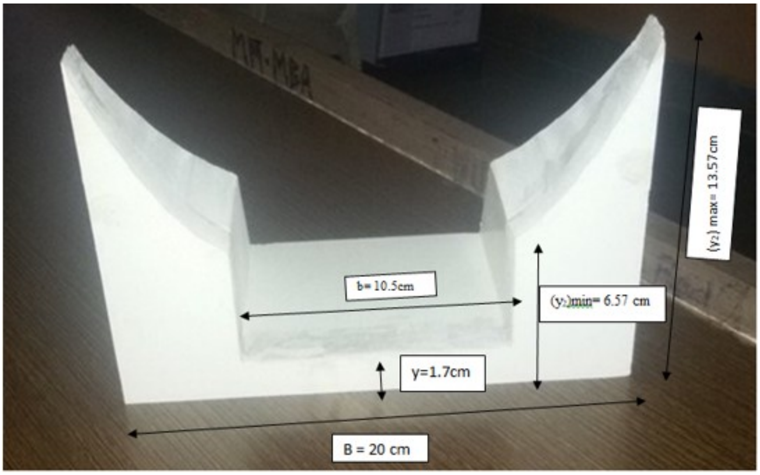

Figure 4: PVC Composite Broad Crested Weir

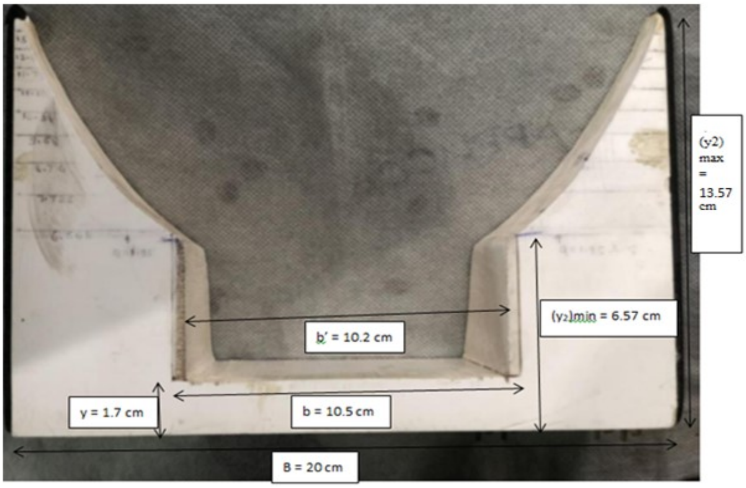

Figure 5: Modified PVC CBC Weir

The above cast composite broad crested weir models were carefully evaluated in the laboratory using a horizontal tilting flume for a wide range of discharge capacities. Kulkarni and Hinge (2017) described a thorough assessment of experimental data acquired on a PVC-cast weir model. In the same paper, the theoretical discharge predictions referred to herein are calculated using the classic rectangular weir formula.

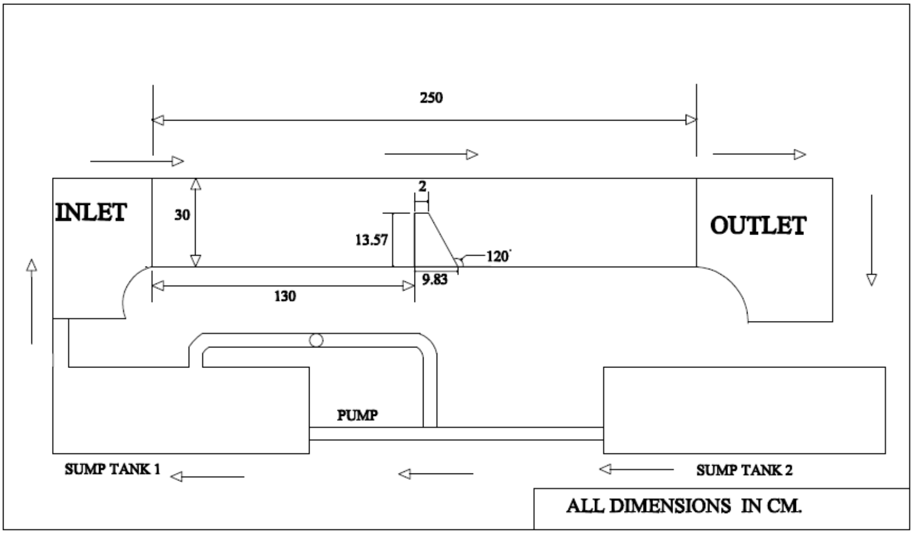

Figure 6: Laboratory Experimental Set Up (Reprinted from Kulkarni and Hinge, 2020)

According to the results of the experimental investigation, the model created using 3D printing technology resulted in an exact discharge measurement with a standard deviation of 2.378 compared to 2.607 in prior trials. Furthermore, at a 95 percent confidence level in the discharge estimates, the R2 between the experimental and theoretical discharges was discovered to be 0.999. Furthermore, with values ranging from 0.55 (min) to 0.6 (max), with the majority of values being near 0.6, as input parameters, an improved estimation of the discharge coefficient with lower variance was produced. A literature study based on CFD to open channel flow advised the use of 3D modeling techniques for discharge assessment in open channel flow. Previous research has demonstrated that the Flow 3D simulation technique is promising, but it has yet to be thoroughly examined in the context of large crested weir applications. This study compares the results/outputs of CFD applications of Flow 3D simulations to the physical model behavior as well as theoretical inputs.

Numerical Model

FLOW-3D solver version 10.1.1.05 win64 2013 produced 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 program that includes unique modules designed for hydraulic engineering applications. The Volume of Fluid Method is used by Flow 3D. (VOF). The VOF model is well suited to free surface flow applications (Samadi and Arvanaghi, 2014). It is based on the idea that two or more fluids should not be combined. This is a two-phase technique in which the grid models both the water and the air. The approach is based on the idea that each cell contains a fraction of water (F) that is 1 when the element is completely filled with water and 0 when the element is completely filled with air. The element contains the free water surface if the value is between 1 and 0.

Grid Generation and Resolution

In Flow 3D, the weir was created by entering an STL file. Solid objects in STL files are designated by cubes. AutoCAD application is used to convert the solid model into STL format. A single nonuniform mesh block was used to discretize the domain network. The evolution of time was employed as a means of easing into the final steady state. A 3-D grid with 30,000 cells in the x, y, and z dimensions was produced, as depicted in the figure below. Each cube's volume was designated as 5 cm^3, resulting in a cell size of 1.7 cm. In the following experiments, solid object surfaces in STL files are approximated by cubes. One uniform mesh block was used to discretize the domain. The temporal evolution was used as a relaxation to the final steady state. A three-dimensional grid with 3,50,000 cells in the x, y, and z directions was generated. Each cube's volume was set as 0.04 x 0.04 x 0.04 m, i.e., 0.000064 m^3, resulting in a cell size of 4 mm. The mesh resolution was constant for the simulated geometry. A structured mesh with 4-mm resolution for the selected region of 0.7 m in the x-direction was implemented initially. The mesh grid was placed from 1.00 m to 1.70 m, where the weir model was at 1.20 m to 1.29 m from the origin. Steady-state convergence was achieved after 6.00 seconds of stimulation time, which corresponds to a computational time of approximately 6 to 7 h for fluid elevation. In such a manner, 10 fluid elevations were recorded as mentioned in Tables 1 to 3 using the system running on Windows 10 Single Language with a 4-core Intel® Core™ i5-7400 CPU @ 3.00. With this hardware, the proposed weir was simulated for different cell counts of 35000, 51000, 2 lakh, 3 lakh, and 5 lakh. To explore the target further to optimize the solution, the model was simulated with 7 lakh mesh counts. However, it was observed that the results deviated from the expected output. In this way, the grid sensitivity is used to refine the meshes that display the closest possible output. The performance that gave close results to the targeted discharge value (C_d = 0.6) was retained.

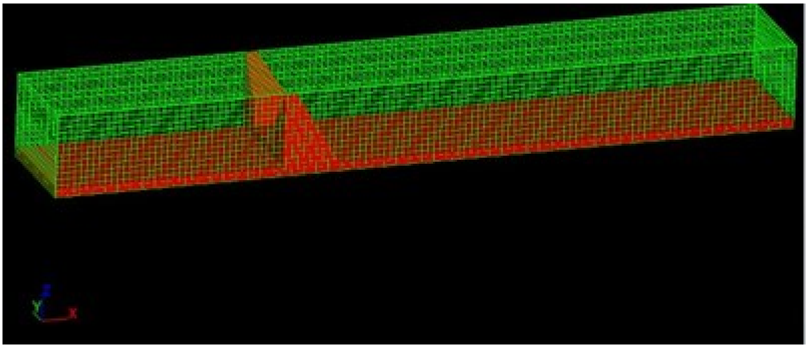

Figure 7: Meshing and Grid Generation

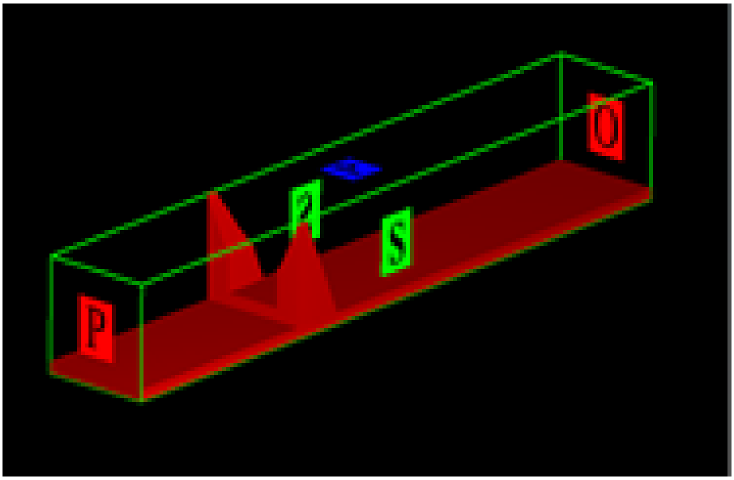

Figure 8: Boundary configuration

Conditions of Boundary

The boundary conditions for side borders were classed as "symmetry," suggesting that similar flow exists on both sides of the wall and hence no drag. The x-direction boundary requirement was "specified stagnation pressure." Using this method, Flow 3D may represent numerous flow elevations beginning from a static pressure state. In the x direction outlet, a continuous border outflow condition is examined. This meant that the flow will continue uninterrupted through the border. The boundary conditions on the x, y, and z planes are depicted in Fig. 8.

RESULTS AND DISCUSSION

The calculation with Flow 3-D produced a grid with 1, 20,811 active cells when the boundary conditions and meshing were selected. A steady state condition was discovered after a calculation time of 229 seconds. The turbulent flow model in Flow 3D modeling has five schemes: large eddy simulation (LES), Renormalization Group (RNG), two equations (k-), one equation turbulent energy (k), and Prandtl's mixing length theory. The RNG turbulence model was used to execute CFD by Flow 3D simulations, which resulted in discharge values ranging from 1.99 lps (lower value) to 10 lps (higher value). Figs. 9 and 10 illustrate the 3D image of flow created by Flow 3D simulation for high and low discharges.

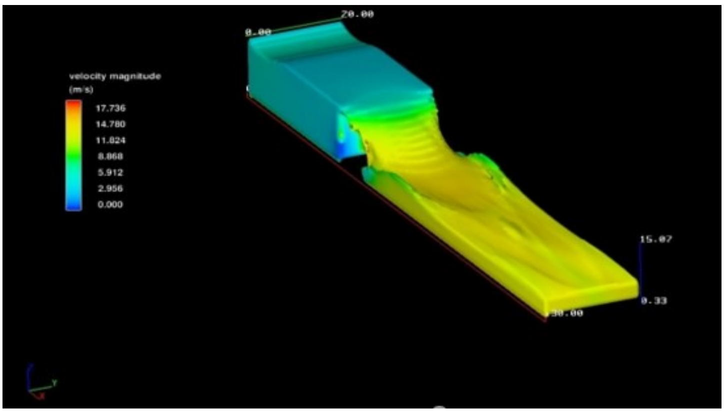

Figure 9: Flow 3D simulation for CBC weir: maximum *Q* = 10 lps

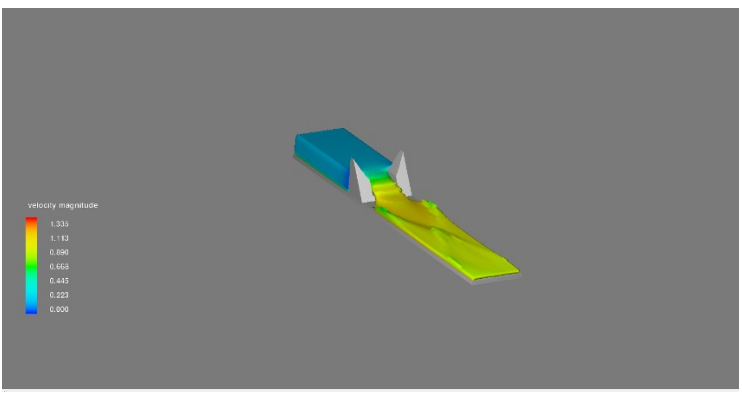

Figure 10: Flow 3D simulation for CBC weir: minimum *Q* = 2 lps

The readings acquired after operating the flume for various discharge capacities are shown in Table 1. As the step height and tread change, the partial discharge for each step is estimated using classic rectangular weir calculations for the observed head determined empirically. The actual discharge is volumetrically assessed by running the flume through several ranges (10 lps to 2 lps). The curving part above the base rectangular weir is formed by connecting the midpoints of many rectangular steps to remove sharp edges and corners and avoid cavitation. The cumulative discharges for different steps are calculated using the standard rectangular weir formula, which includes the width difference between each rectangular step and matching head. The experimental values for the CBC weir model cast with PVC material were determined in the laboratory and compared to CFD simulations for the same model geometry. The behavior of the experimental and CFD findings was then compared to the theoretical model parameters, yielding a concise study. The head discharge relationship for the tested models is shown below.

Table 1: Experimental, theoretical, CFD head-discharge calculations, PVC model: b = 10.2 cm

Step no.	Depth of water (design) (cm)	Depth of water (from expt) (cm)	Theoretical Q (lps)	Experimental Q (lps)	CFD Q (lps)	$C_{d(expt)} = [Q_{(expt)}/Q_{(th)}] \times 0.6$ (expt approach)	$C_{d\,(CFD)} = [Q_{(CFD)}/Q_{(th)}] \times 0.6$ (CFD approach)	Comment (CFD predictions)
10	13.57	13.598	9.2	10.35	10	0.675	0.65	Overprediction of Q values
9	13	13.032	8.4	9.32	9.38	0.665	0.67	
8	12.413	12.442	7.6	8.417	8.73	0.66	0.689	
7	11.78	11.824	6.8	7.127	6.98	0.628	0.61	
6	11.1	11.148	6	6.015	5.3	0.6	0.53	Under prediction of Q values
5	10.38	10.42	5.2	5.153	4.8	0.595	0.553	
4	9.58	9.592	4.4	4.18	4.4	0.57	0.6	Predictions near to design input value of $C_d = 0.6$
3	8.714	8.736	3.6	3.34	3.5	0.55	0.583	
2	7.725	7.729	2.8	2.57	2.74	0.55	0.587	
1	6.568	6.562	2	1.95	1.99	0.585	0.597	

Table 2: Experimental, theoretical, CFD head - discharge calculations for 3D printed model cast – Trial I, b = 10.5 cm

Step no.	Water Depth (expt) (cm)	Collection Time for 100 liters (sec)	$Q_{(expt)}$ (lps)	$Q_{(th)}$(lps) for relevant step no.	$C_d = [Q_{(expt)}/Q_{(th)}] \times 0.6$	$Q_{(CFD)}$(lps)	$C_d = [Q_{(CFD)}/Q_{(th)}] \times 0.6$
10	13.57	10.96	9.118	9.2	0.594	9.24	0.602
9	13	12.3	8.127	8.4	0.5805	7.66	0.547
8	12.413	13.65	7.322	7.6	0.578s	6.95	0.548
7	11.78	16.08	6.216	6.8	0.548	6.18	0.545
6	11.1	18.84	5.307	6	0.5307	5.42	0.542
5	10.38	22.53	4.438	5.2	0.512	4.6	0.531
4	9.58	27.37	3.654	4.4	0.498	4.08	0.556
3	8.714	33.52	2.983	3.6	0.497	3.44	0.573
2	7.725	46.92	2.131	2.8	0.456	2.45	0.525
1	6.568	54.05	1.85	2	0.55	1.73	0.519

The current study compares theoretical, experimental, and flow 3D simulation findings for several composite broad crested weir designs, and the performance is evaluated. Discharge estimation is demonstrated in terms of the coefficient of discharge values obtained by all the approaches studied for different composite broad-crested weir model casts.

Table 3: Experimental, theoretical, CFD head - discharge calculations for 3D printed model cast – Trial II (after treating model): b = 10.3 cm

Step no.	Water Depth (expt) (cm)	Collection Time for 100 liters (sec)	$Q_{(expt)}$ (lps)	$Q_{(th)}$(lps) for relevant step no.	$C_d = [Q_{(expt)} / Q_{(th)}] \times 0.6$	$Q_{(CFD)}$ (lps)	$C_d = [Q_{(CFD)}/Q_{(th)}] \times 0.6$
10	13.57	10.87	9.19	9.2	0.599	9.63	0.62
9	13	12	8.33	8.4	0.594	8.59	0.61
8	12.413	13.29	7.52	7.6	0.594	7.68	0.6
7	11.78	15	6.67	6.8	0.588	6.66	0.587
6	11.1	17	5.88	6	0.588	5.88	0.588
5	10.38	20	5	5.2	0.576	4.97	0.573
4	9.58	24	4.47	4.4	0.568	4.15	0.566
3	8.714	30.04	3.33	3.6	0.555	3.36	0.56
2	7.725	39.4	2.54	2.8	0.544	2.61	0.559
1	6.568	51.2	1.95	2	0.585	1.886	0.565

The velocity profile of the composite broad crested weir generated by FLOW 3D at a maximum discharge capacity of 10 lps, with the corresponding upstream depth of flow, is shown below.

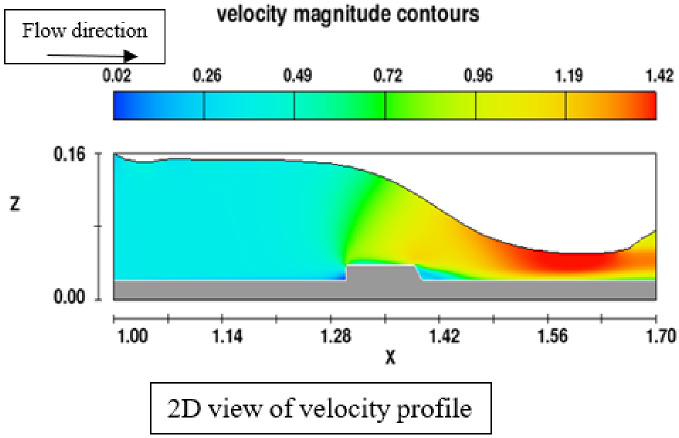

Figure 11: Velocity Profile for a Maximum Discharge of 10 lps

The theoretical and experimental model's head discharge relationship and its performance for CFD simulations for various discharge ranges with varying base width geometries are presented in Figs. 12 to 14 below.

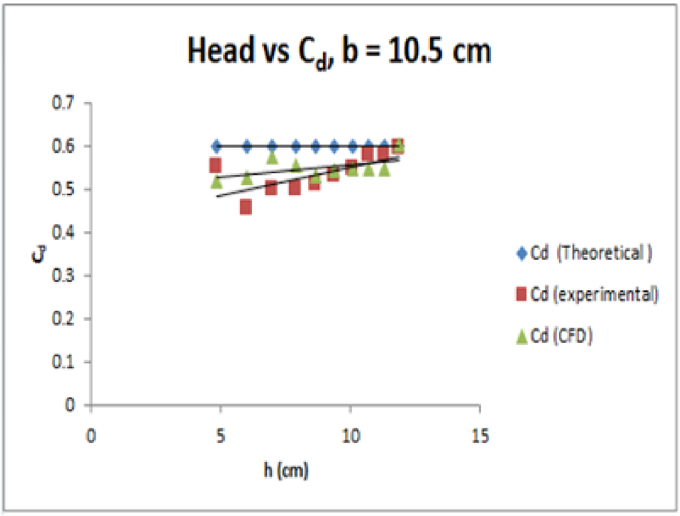

Figure 12: Experimental, Theoretical and CFD Variations of Head (h) vs. Discharge coefficient C_d, b = 10.5 cm

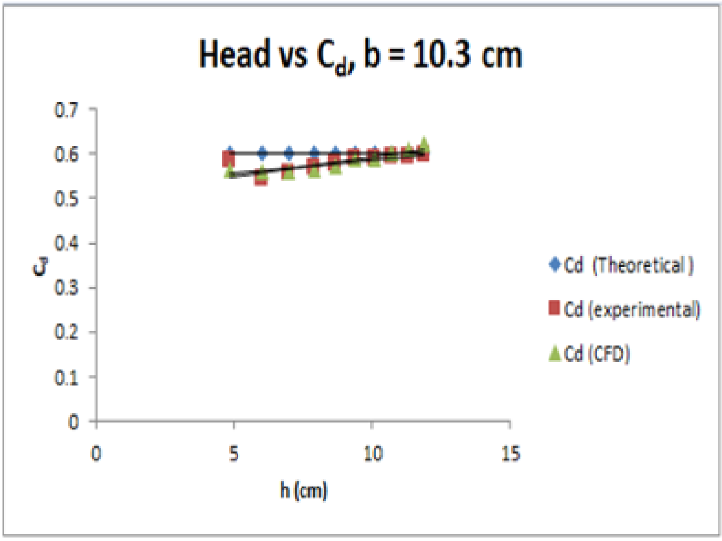

Figure 13: Experimental, Theoretical and CFD Variations of Head (h) vs. Discharge coefficient C_d, b = 10.3 cm

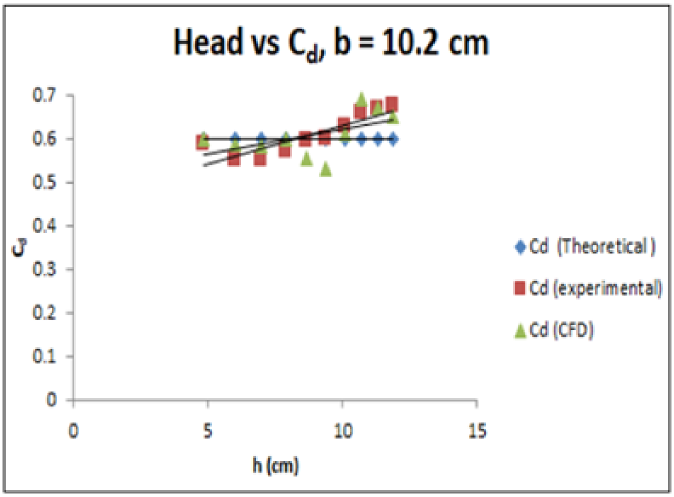

Figure 14: Experimental, Theoretical and CFD Variations of Head (h) vs. Discharge coefficient C_d, b = 10.2 cm

The coefficient of discharge was estimated for various ranges using a CBC weir modified base width of 10.3 cm and yielded the following values, as shown in Table 4.

Table 4: Comparison chart for y_2 vs. C_d values – 10.3 cm model

Step no.	Water Depth (cm)	Theoretical C_d	Experimental C_d	CFD C_d
10	13.57	0.6	0.599	0.62
9	13	0.6	0.584	0.61
8	12.413	0.6	0.594	0.6
7	11.78	0.6	0.588	0.587
6	11.1	0.6	0.588	0.588
5	10.38	0.6	0.576	0.573
4	9.58	0.6	0.568	0.566
3	8.714	0.6	0.555	0.56
2	7.725	0.6	0.544	0.559
1	6.568	0.6	0.585	0.565

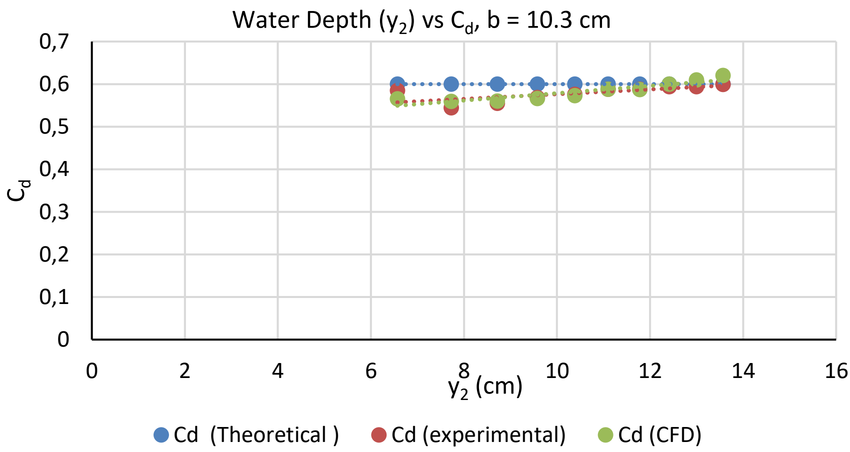

Figure 15: Variation in water depth (y_2) and C_d.

Throughout, turbulent flow was established for entire weir flow depths, indicating no possibility of submergence of the proposed weir even at higher discharges. After experimenting with PVC models with C_d values ranging from 0.518 to 0.648, the design was produced utilizing additive manufacturing technology to increase precision. C_d ranges from 0.456 to 0.594 in trial 1 of the newly cast CBC weir model. To come closer to the desired discharge range with respect to each weir step, the model was handled by removing 1 mm width from each side for a lower step height, bringing it down to 10.3 cm from 10.5 cm previously. This test showed a C_d value ranging from 0.544 to 0.599. Furthermore, the correlation coefficient found between the experimental discharge and theoretical discharge was 0.999, with a standard deviation of 2.378. To investigate CFD simulations, Flow 3D software was employed, which produced reasonable findings that corresponded to the theoretical design. These FLOW3D results were compared to experimental results, and the accuracy level of both outputs was determined to be well within the error range of 5% specified in the literature. The above relationship shows that there is good agreement between theoretical discharges calculated using classic rectangular weir formulas and experimental and CFD discharges for various ranges. When compared to the theoretical and practical approaches, the discharge levels predicted by FLOW3D were slightly higher. According to CFD, the discharge coefficient should be in the range of 0.61 to 0.65, as opposed to the design input value of 0.6 for the CBC weir model. Thus, in the context of the current study, the range of discharge coefficients and discharges agree well with the input design parameters. The weir width parameters tested were 10.5 cm, 10.3 cm, and 10.2 cm. The experimental discharge values and CFD discharges were compared to the theoretical discharges derived using the classic linear combination technique of the traditional rectangular weir formula. The CFD analysis for 10.3 cm yields the most accurate result in the prediction of discharge values, with a mean absolute error of 1.77% and an R^2 of 0.999. The discharge coefficient is presented below for the experimental and CFD studies (Table 5). The sampling errors for 90%, 95% and 99% confidence levels are reported below, with p values for T statistics being 0.27% and 1.69% for experimental and CFD C_d, respectively. The C_d mean value of approximately 0.58 using both methodologies, compared to the design input of 0.6, demonstrates that the weir model accurately predicts discharges with nearly 95% confidence.

Table 5: Statistical details for the discharge coefficient (C_d) of the composite broad-crested weir

Parameter (C_d)	Mean	Std. deviation	T statistic	Sampling error for Confidence level		
				90%	95%	99%
Experimental	0.5791	0.018193	0.27%	0.0105	0.0130	0.0187
CFD	0.5828	0.021719	1.69%	0.0126	0.0155	0.0223

Application of the Proposed Composite Broad Crested Weir from an Energy Perspective

The following are the unique advantages of the proposed composite weir that make it different from other hydraulic structures. A governor, which is the main controller of the hydraulic turbine, is installed in every hydroelectric facility. It regulates the flow of water through the turbine. The governor regulates the inflows into the turbines based on the electrical load demand. It detects the turbine's rotating speed (RPM) and modifies the flow into the turbines such that the RPM remains constant. An increase in RPM indicates that the turbine is underloaded, and the governor restricts the flow to the turbine. Overload is indicated by a drop in RPM, which causes the governor to allow more flow to the turbine. This proposed broad crested weir will measure the discharges effectively for various head variations as per the load capacity required for hydropower generation. This composite weir can be installed as an additional flow measuring device to verify and cross check the rate of flow released by the governor as per the load demand requirement.

Energy dissipation strategies are critical everywhere energy transitions from high to low and vice versa. Substantial energy is generated at the power plant's outlet, which must be dissipated to avoid losses caused by turbulence and slash. Initially, the proposed composite broad crested weir was tried for this purpose [13]. This weir can disperse energy generated by a hydraulic jump caused by a lack of tail water. As a result, the proposed composite weir could be an alternative configuration for the stilling basins employed for energy dissipation.

Another application of the proposed weir can be reported at the canal outlets where sluice gates are installed for controlling the flow. This often creates a shooting type of flow that needs to be calm down, exhibiting tranquil flow conditions. This method is found to be suitable to fulfil the purpose. According to the USBR water measurement manual, for the current proposed weir, the modular limit is high, approximately 0.8. Hence, this composite broad-crested weir has added advantages over other hydraulic structures, such as sharp-crested weirs.

CONCLUSION

- The CFD technique was used to affirm the head discharge rating created for the composite rectangular broad crested weir over various discharge ranges.
- For experimental output, the variance in C_d for the original composite weir model cast using additive manufacturing technology is found to be in the range of 0.45 to 0.594. Furthermore, this object was treated to a step width of 10.3 cm, with C_d ranging from 0.54 to 0.599. CFD reveals that the discharge coefficient is in the range of 0.559 to 0.62, as opposed to the theoretical CBC weir model's design input value of 0.6.
- The mean absolute error between the discharge predictions and the Flow 3D simulation for the CBC weir model with b = 10.3 cm is 1.77%. The “R” value in the discharge predictions is 0.99 for the physical and CFD models. Mean interval estimates of almost 0.58 for the discharge coefficient reveal that the proposed weir model is almost 95% accurate in predicting discharges for various ranges.
- The current study clearly demonstrates the correctness of the geometry achieved by 3D printing the broad crested weir with PLA material, which has significantly reduced the variance range of the discharge coefficient. This performance was not previously attained in the model cast with PVC material.

- As a result, FLOW 3D accurately simulates the theoretical and actual results for obtaining discharge through a composite broad crested weir. This approach may be an effective tool to be utilized for 3D CFD computing. Investigating the stepwise treatment given to weir geometry using a make and cut approach will result in a constant value of the discharge coefficient, which is the novelty of the present study. From an energy standpoint, the unique advantages of discharge measurement by the proposed composite broad-crested weir are also highlighted.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ACKERS P., WHITE W.R., HARRISON A.J.M. (1978). Weirs and flumes for flow measurement, Wiley, New York, USA.

AMIR HOSSEIN A., RAJARATNAM N. (2009). Discharge characteristics of weirs of finite crest length, Journal of Hydraulic Engineering, Vol. 135, Issue 12, pp. 1081-1085.

ACHOUR B., AMARA L. (2022). Accurate discharge coefficient relationship for the crump weir, Larhyss Journal, No 52, pp. 93-115.

ACHOUR B., AMARA L., MEHTA D., BALAGANESAN P. (2022a). Compactness of Hydraulic Jump Rectangular Stilling Basins Using a Broad-Crested Sill, Larhyss Journal, No. 51, pp. 31-41.

ACHOUR B., AMARA L., MEHTA, D. (2022b). Control of the hydraulic jump by a thin crested sill in a rectangular channel, new experimental consideration, Larhyss Journal, No 50, pp. 31-48.

ACHOUR B., AMARA L., MEHTA, D. (2022c). New theoretical considerations on the gradually varied flow in a triangular channel, Larhyss Journal, No. 50, pp. 7-29.

AZAMATHULLA H.M., HAGHIABI A.H., PARSAIE A. (2016). Prediction of side weir discharge coefficient by support vector machine technique, Water Science and Technology: Water Supply, Vol. 16, Issue 4, pp. 1002-1016.

BIJANKHAN M., Di STEFANO C., FERRO V., KOUCHAKZADEH S. (2014). New stage discharge relationship for weirs of finite crest length, Journal of Irrigation and Drainage Engineering, Vol. 140, Issue 3, 06013006.

BILHAN O., AYDIN M.C., EMIROGLU M.E., MILLER C.J. (2018). Experimental and CFD Analysis of Circular Labyrinth Weirs, Journal of Irrigation and Drainage Engineering, ASCE, Vol. 144, Issue 6, 04018007.

BOITEN W., PITLO H.R. (1982). The V- shaped broad-crested weir, Journal of Irrigation and Drainage Engineering, Vol. 108, Issue 2, pp. 142-160.

BOS M.G. (1989). Discharge Measurement Structures. 3rd edition, International Institute for Land Reclamation and Improvement, Publication 20, Wageningen, The Netherlands.

FARZIN SALMASI, SANAZ POORESCANDAR, ALI HOSSEINZADEH DALIR, DAVOOD FARSADI ZADEH, 2012. Discharge relations for rectangular broad crested weirs, Journal of Agricultural Sciences, No 17, pp. 324-336.

GOGUS M., DEFNE Z., OZKANDEMIR V. (2006). Broad-crested weirs with rectangular compound cross sections, Journal of Irrigation and Drainage Engineering, Vol. 132, Issue 3, pp. 272–280.

HAGER W.H., SCHWALT M. (1994). Broad – crested weir, Journal of Irrigation and Drainage Engineering, Vol. 120, Issue 1, pp. 13 - 25.

HARRISON A.J.M. (1967). The streamlined broad-crested weir, Proceedings of the Institution of Civil Engineers, Vol. 38, pp. 657-678.

HINGE G.A., BALKRISHNA S., KHARE K.C. (2010). Improved Design of Stilling Basin for Deficient Tail Water, Journal of Basic and Applied Scientific Research, Vol. 1, Issue 1, pp. 31-40.

HINGE G.A., BALKRISHNA S., KHARE K.C. (2011). Experimental and Numerical Study of Compound Broad Crested Weir, International Journal of Fluids Engineering, Vol. 3, Issue 2, pp. 197-202.

HORTON R.E. (1907). Weir experiments, coefficients, and formulas, Dept. of the Interior, U.S. Geological Survey, Water-Supply and Irrigation Paper 200. Government Printing Office, Washington, D.C.

ISSAM A. AL-KHATIB, MUSTAFA GOGUS (2014). Prediction models for discharge estimation in rectangular compound broad-crested weirs, Flow Measurement and Instrumentation, Vol. 36, pp. 1-8.

KHAN L.A., WICKLEIN E.A., TEIXEIRA E.C. (2006). Validation of a Three-Dimensional Computational Fluid Dynamics Model of a Contact Tank, Journal of Hydraulic Engineering, American Society of Civil Engineers, ASCE, Vol. 132, Issue 7, pp. 741- 746.

KINDSVATER C.E., CARTER R.W. (1959). Discharge Characteristics of Rectangular Thin-Plate Weirs, Paper No 3001, Transactions, American Society of Civil Engineers, ASCE, No 124.

KULIN G., COMPTON P.R. (1975). A Guide to Methods and Standards for the Measurement of Water Flow, Special Publication 421, National Bureau of Standards.

KULKARNI K.H., HINGE G.A. (2017). Compound Broad Crested Weir for Measurement of Discharge – A Novel Approach, Proceedings, International Conference organized by Indian Society of Hydraulics – ISH HYDRO. 21 – 23 Dec 2017, India, pp. 678 – 687.

KULKARNI K.H., HINGE G.A. (2020). Experimental study for measuring discharge through compound broad crested weir, Flow Measurement and Instrumentation. Elsevier, Vol. 75, Paper 101803. https://doi.org/10.1016/j.flowmeasinst.2020.101803

KULKARNI K.H., HINGE G.A. (2021). Performance Enhancement in Discharge Measurement by Compound Broad Crested Weir with Additive Manufacturing.Larhyss Journal, No 48, pp. 169-188. http://larhyss.net/ojs/index.php/larhyss/index

KULKARNI K.H., HINGE G.A. (2021). Comparative study of experimental and CFD analysis for predicting discharge coefficient of compound broad crested weir. Water Supply – Water Science and Technology, IWA Publishing, Vol 22, No 3, pp. 3283-3296. https://doi.org/10.2166/ws.2021.403

MUSTAFA GOGUS, ISSAM A. AL-KHATIB, AHMET E. ATALAY, JUMANA I. KHATIB (2016). Discharge prediction in flow measurement flumes with different downstream transition slopes, Flow measurement and Instrumentation, Vol. 47, pp. 28-34.

PARSAIE, A., AZAMATHULLA, H.M., HAGHIABI, A.H. (2018). Prediction of discharge coefficient of cylindrical weir–gate using GMDH-PSO, ISH Journal of Hydraulic Engineering, Vol. 24, Issue 2, pp. 116-123.

RANGA RAJU K.G. (1981). Flow through open channels, McGraw-Hill, New York.

REDA M. ABD EL-HADY RADY (2011). 2D 3D Modeling of flow over sharp crested weir, Journal of Applied Sciences Research, Vol. 7, Issue 12, pp. 2495-2505.

SAFARZADEH A., MOHAJERI S.H. (2018). Hydrodynamics of Rectangular Broad-Crested Porous Weir, Journal of Irrigation and Drainage Engineering, ASCE, Vol. 144, Issue 10, 04018028

SAMADI A., ARVANAGHI H. (2014). CFD Simulation of Flow over Contracted compound Arched Rectangular Sharp Crested Weirs, International Journal of Optimization in Civil Engineering, Vol. 4, Issue 4, pp. 549-560.

SAVAGE B.M., JOHNSON M.C. (2001). Flow Over Ogee Spillway: Physical and Numerical Model Case Study, Journal of Hydraulic Engineering, ASCE, Vol. 127, Issue 8, pp. 640-649.

SWAMEE P.K. (1988). Generalized rectangular weir equations, Journal of Hydraulic Engineering, ASCE, Vol. 114, Issue 8, pp. 945–952.

The United States Bureau of Reclamation (USBR) Water Measurement Manual, Chapter 7 – Weirs. U.S. Government Printing Office, Washington, DC 20402. 2001. Retrieved from http://www/usbr.gov/pmts/hydraulics_lab/pubs/wmm

ZAHIRI A., AZAMATHULLA H.M. (2014). Comparison between linear genetic programming and M5 tree models to predict flow discharge in compound channels, Neural Computing and Application, Vol. 24, No. 2, pp. 413-420.