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Experimental Analysis of Flow over Rectangular Sharp-Crested Compound Weirs

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Abstract

Compound weirs can be used as flexibly adjustable structures to regulate the flow and the flow distribution over the cross-section. Examples are found in rivers to create additional resistance in one side of the river bifurcations. It is done to distribute the discharge among the branches properly. They are placed at the flood plains and become active only during flooding. Therefore, the expected flow type over the weirs is generally submerged, unlike the modular weir flow which has been studied a lot in the literature. In this study, an experimental campaign was conducted to understand how flow over compound weirs consisting of 12 sections, differs from the flow over uniform weirs. The analyses were conducted under modular and submerged weir conditions to gain a comparative understanding. Configurations of the compound weirs are important as they may lead to horizontal and vertical contraction of flow at various degrees. In this study, nine compound weir configurations were used to include flow variety and a wide range of applications. The experiments were conducted in a 3-meter-wide, 20-m-long rectangular horizontal flume at the Water Lab of Delft University of Technology. Flow depths at the upstream and downstream sides of the weirs were recorded along with the flow rates. Six discharge values were used to include the effect of discharge variations in the results. The measurement results were compared with the standard formulas from the literature to estimate flow rates over uniform rectangular sharp-crested weirs. Experimental data showed strong deviations from the model in submerged cases and moderate to slight deviations in modular cases. The observed deviations showed dependence on weir configurations and discharge. This indicates that discharge coefficients and head losses cannot be treated per weir section, but should be considered in interaction with neighboring sections.

Keywords: Weir; Submerged weirs; Compound weirs; Sharp-crested weirs; Experimental study

1. INTRODUCTION

Several types of weirs varying in shape and length are used to measure, divert or control flow in open channel flows. Rectangular sharp-crested weirs have been used widely for flow rate measurement or flow diversion purposes. Compound sharp-crested rectangular weirs have been used for flow diversion purposes when located at the flood plains close to the river bifurcations. They become active during flooding. This means that most of the time the downstream flow depth is high enough to affect the flow over the weir. Then, the weir becomes submerged. A general understanding of the flow behavior at compound weirs is still not complete (Wessels and Rooseboom, 2009). Therefore, in this study, we analyze both of the cases: (1) Submerged weir flow; when downstream conditions affect the weir flow (2) Modular weir flow; when downstream flow depth is not high enough to have that influence on the flow over the weir. Modular weir flow over a rectangular sharp-crested weir was studied and reliable formulas were proposed for uniform (full-width) weirs (Rehbock, 1929, Bos 1989). The flow equation of them were estimated by writing an energy equation from upstream to the weir section by assuming that pressure over the weir was hydrostatic. According to it, the unit discharge over the weir, q, can be calculated with the given formula:

$$q = (2/3)C_d\sqrt{2g}h_0{}^{3/2} \quad [1]$$

where, C_d is the weir coefficient associated with neglected terms in derivation like energy losses and h_0 is the upstream flow depth relative to the weir crest

Weir coefficient, C_d, has been defined by Rehbock (1929) as a function of h_0 to the weir height, P, ratio. Later, Kindswater and Carter (1957) modified it for contracted weirs. For submerged weir flow, on the other hand, that kind of reliable approach could not be proposed. Among the proposed methods, the Vilemonte method has been used widely (Vilemonte 1947). This method included the effect of downstream water level on flow rate over the weir as a reducing agent. This reduction was applied by a function, φ, which was defined as a function of the submergence rate, S. S was defined as downstream to upstream energy head ratio which were estimated relative to the weir crest. The reduction function takes the following form:

$$\varphi = \sqrt{1 - S^{1.5}} \quad [2]$$

Then, the unit discharge passing through the submerged weir, q_s, becomes:

$$q_s = \varphi q \quad [3]$$

In this study, flow over compound weirs, which are composed of rectangular sharp-crested weirs, were analyzed. In order to achieve this, an experimental plan was developed covering a series of compound weir configurations, six discharges and two modes of flow (modular and submerged). The experiments were conducted at the Water Lab of Delft University of Technology. At each tested submerged case, flow depths upstream and downstream were recorded along with the discharge. At the modular cases, only upstream flow depths were recorded with the discharges. The discharge values were modeled by using the Rehbock (1929) and Vilemonte (1947) formulas. In these models, each weir gate was assumed to work individually and the formulas were applied to each of them separately. Then, the total discharge carrying capacity of each weir was estimated by adding up the calculated flow rates at each gate.

2. METHOD

The tests were carried out at a horizontal flume of 20-m-length, 3-m-width rectangular, with a smooth bed and 0.25 cm high steel side walls. The schematized weir structure employed in this study was based on a prototype scaled 1:20 and has 12 notches (openings), each with a width of 23 cm (Figure 1). The wooden buttresses between them were 2 cm thick. Using thin plates, the weir structure was built to accommodate different weir heights. It was put 10 meters from the inlet, in the middle of the flume. A honeycomb straightened the flow, while foam barriers at the intake suppressed surface water waves. The downstream flow depth was controlled by a tilting vertical tailgate. The flow was steady throughout the tests. The flow rates were recorded by using an acoustic flow meter installed at the inlet pipe. Two laser altimeters, one 3 meters upstream and the other 5 meters downstream of the weir, were used to record the stages. Each of the nine compound weir layouts was evaluated for six discharge values ranging from 20 to 70 l/s in increments of 10 l/s. Table 1 provides the weir configurations in numerical form. These values were then added by the threshold values, which were roughly 3 mm at each weir opening. The combinations were chosen to cover a variety of applications and flow types. Modular and submerged cases were each tested. In order to maintain consistent downstream flow conditions in each case, the tailgate was used in the vertical position at the submerged weir cases. The flow type at the upstream was always subcritical throughout the tests with Froude numbers ranging from 0.027 to 0.414.

Table 1. Weir heights (P_i) for each weir configuration (all dimensions in cm)

Configuration	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}
C1	0	0	0	0	0	0	0	0	0	0	0	0
C2	10	10	10	10	10	10	10	10	10	10	10	10
C3	15	15	15	15	15	15	15	15	15	15	15	15
C4	15	10	15	10	15	10	15	10	15	10	15	10
C5	15	15	10	15	15	10	15	15	10	15	15	10
C6	15	15	15	15	10	10	10	10	5	5	5	5
C7	15	15	10	10	5	5	5	5	10	10	15	15
C8	20	20	15	10	5	0	0	20	20	20	20	20
C9	5	5	10	10	15	15	15	15	10	10	5	5

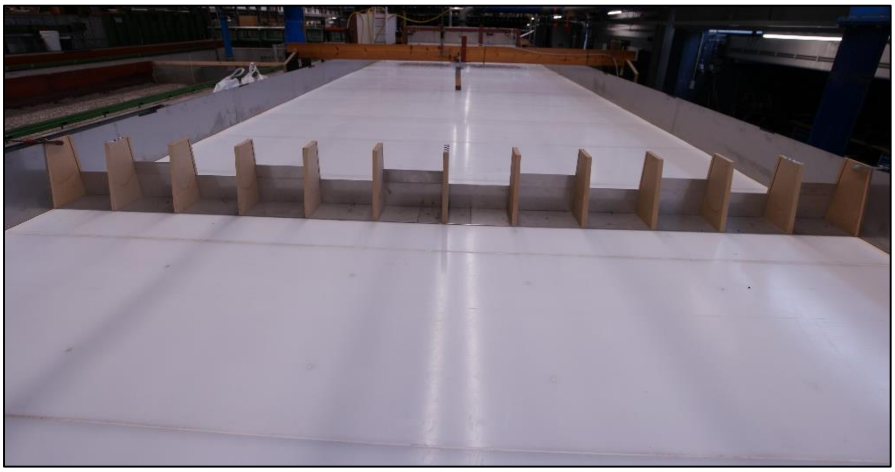

Figure 1. Flume view from the downstream of the weir structure (Weir configuration in figure is C4)

3. RESULTS

When the tested discharges are the same, the modular test results demonstrate that designs with greater blocking weir areas have higher h_0. Very non-uniform configuration C8 did not exhibit this behavior, most likely as a result of horizontal flow constriction or non-flowing gates brought on by high weirs. The same weir area shared by C6, C7, and C9 has about the same h_0 at the same discharge. C2 likewise has the same weir area, but its h_0 values were larger because each of the configurations previously discussed included a few non-flowing gates. Using observed upstream water levels, Equation (1) was used to simulate the discharge for the modular weir scenarios. $C_d = 0.6 + 0.066\left({}^{h_0}/_{P}\right)$ was used as suggested by Kindswater and Carter (1957). As the lowest portions of C8 and C1 have gates without a weir which do not fall within the C_d formulation, we believe that C_d=0.5 is provided by the strong local contraction. In order to compare the discharges produced by the model with the data, a comparison graph is shown in Figure 2. Percentage error, %ε, was used to compare the modeled and measured discharges. The equation for it is given below:

$$\%\varepsilon = \left[\frac{Q_{model} - Q_{measured}}{Q_{measured}}\right] * 100 \qquad [4]$$

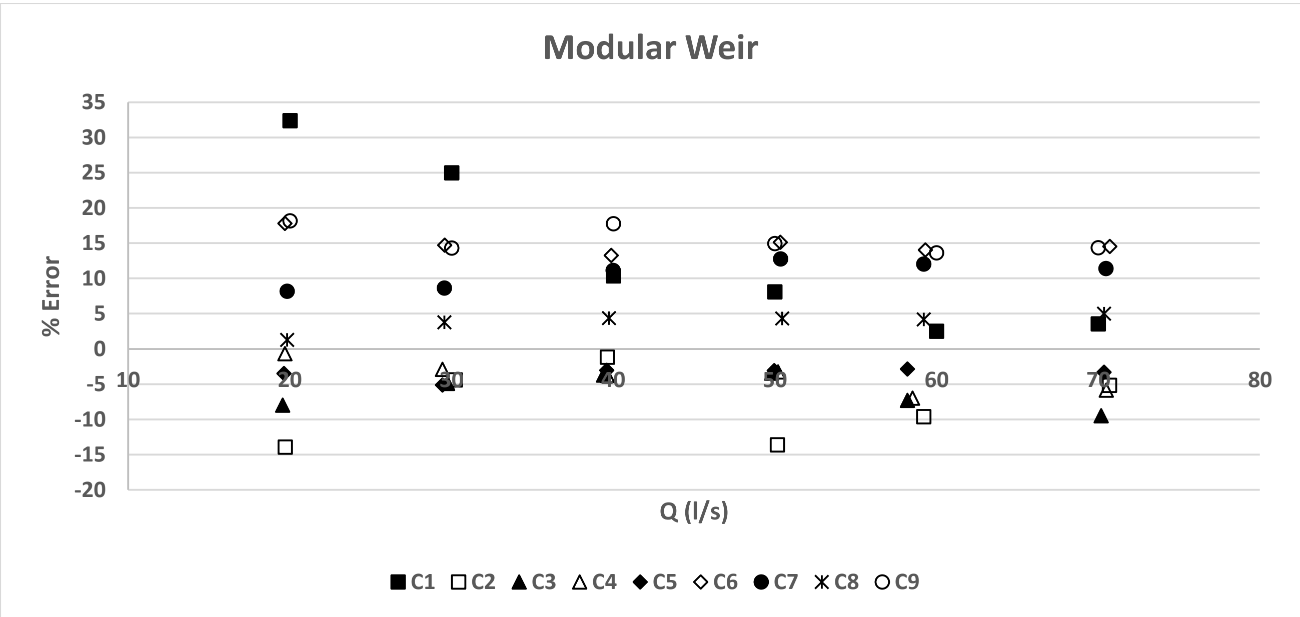

Figure 2. Comparison of measured and modeled (Eqn. 1) discharges at modular weir cases.

Configurations like C3, C4 and C5 produce small errors with a maximum absolute error of 7%. However, the error amounts were larger for the remaining configurations. Configuration C1 produced the largest errors. The downstream flow depths were also measured in cases of submerged weirs. Despite all cases having the same tailwater conditions, C8 produced the smallest records, while the others were often near to each other. Due to the significant horizontal contraction upstream and the development of water jets at the two fully open gates, the decreasing free surface level at C8 suggests that the weir flow is still having an impact at the downstream stage measurement location. The maximum and minimum h_0 were measured for C3 and C1, respectively, with the same discharge. In contrast to the modular cases, the submerged cases had a reduced interval between recordings. For the identical discharges, C2 had relatively similar h_0 values to the C6, C7, and C9 examples, in contrast to modular weir cases. In submerged weir cases, C6, C7, and C9 do not have any non-flowing gates, making the effective weir area the same. The Vilemonte (1947) method (Eqn. 2 and 3) was used to model the discharges. The percentage errors produced by the model are given in Figure 3. It is seen that the method developed very large errors in most of the configurations. The percentage errors have a tendency of reducing when discharge increases. The smallest errors are observed at C3 with a maximum absolute percentage error of 10%. Then, C8, C5 and C4 produced the least amount of errors in the remaining group. C1 resulted in the highest errors having the smallest of all being 45% when Q= 70 l/s and highest of all being 270% when Q= 20 l/s.

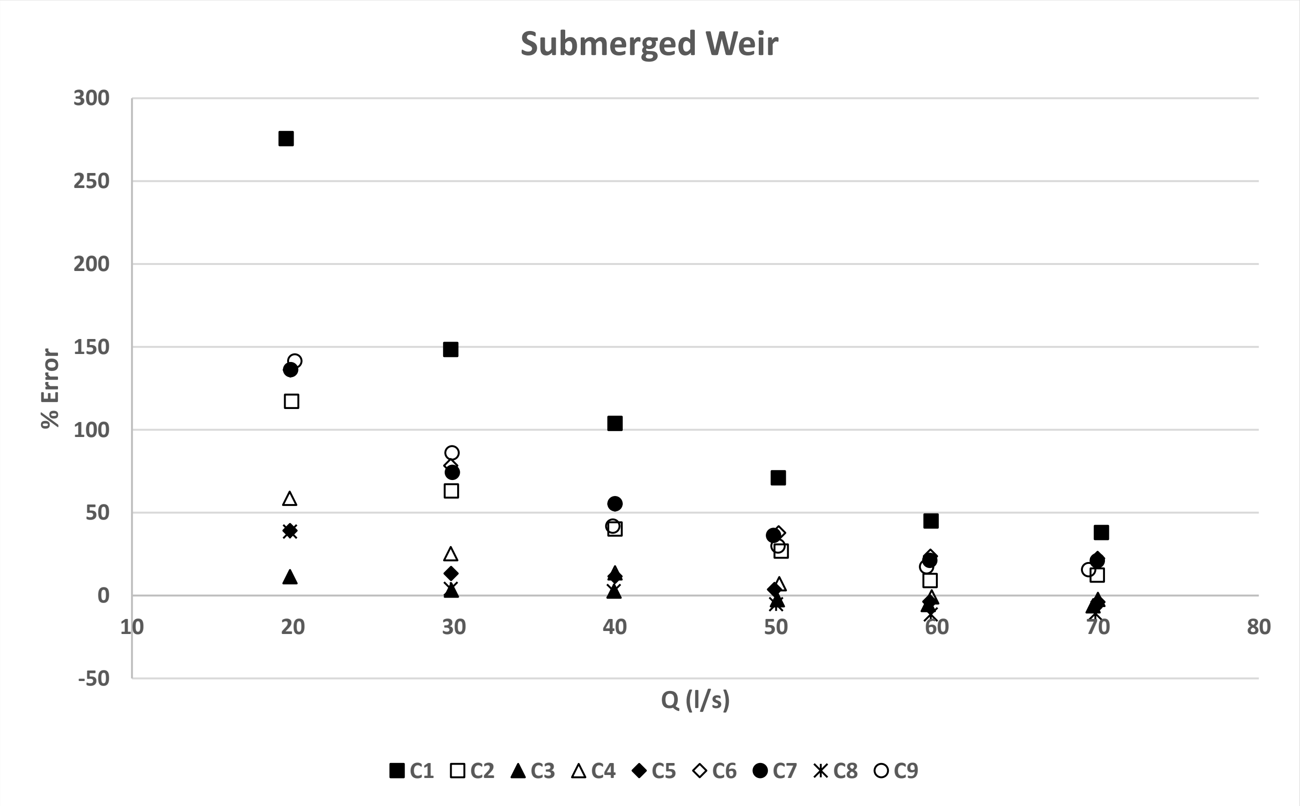

Figure 3. Comparison of measured and modeled (Eqns. 2 and 3) discharges at submerged weir cases.

4. CONCLUSIONS

Nine weir configurations with different total weir areas and weir uniformity were used to investigate the flow over compound weirs under modular and submerged weir settings. The resistances of the weirs were observed to be proportional to the weir area in the tested designs when there were flows at each weir gate and when weir non-uniformity is not at high levels. Standard weir formulas that were tested for uniform weirs at modular and submerged weir types were used to model flow over compound weirs by assuming each weir opening works independent of the rest of the configurations. The model tested for modular weir cases (Rehbock 1929) showed moderate to low deviations at most of the configurations independent of the tested flow rate. The tested model for submerged weir cases (Vilemonte 1947) can be regarded as successful at only one configuration over the nine tested ones. In some of the cases, the model resulted with errors larger than 100%. In the submerged weir model, the absolute percentage errors decreased at each configuration when discharges increase. To conclude, the performances of both of the models were poor which means that the traditional models cannot provide answers for compound weirs. Especially in highly contracted cases, the modelling approach requires a better representation of the physics and at least two-dimensional models should be tested to include the horizontal contraction effects.

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