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A Laboratory Investigation on Flow Rate Coefficient for Compound Weir

Nur Aina Atirah Othman[1], Zarina Md Ali[1]*, Noor Aliza Ahmad[1]

[1]Department of Civil Engineering, Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

*Corresponding author

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Abstract: The application of the weir can be used to determine the flowrate in an open channel. Thus, the coefficient of flow rate is an important consideration when using weirs because its value is dependent on the shape of the weir. Compound weirs are an appropriate structure for rivers with low flow levels during the dry season and high flow levels during the rainy season. The objective of the study is to determine the flowrate coefficient, C_d using a combination of rectangular-triangular (V-notch) shape weir. An experimental study using nine models of compound weirs with different measurements of V-notch angle, θ (30°, 50°, and 80°) and width of rectangular weir, L (0.1 m, 0.12 m and 0.15 m). Result shows the highest and lowest value for C_d is 0.47 (Model 2 at water level, H = 0.076 m) and 0.11 (Model 8 at water level, H = 0.025 m, respectively. The most efficient combination is a compound weir with a V-notch angle of = 50o and a rectangular shape width of L = 0.1 m. The correlation between C_d and H, and Q_{exp} and Q_{theory} shows good relationship between variables, except for Model 7. It is show that the flowrate and characteristics of the weir influence the flowrate coefficient, C_d. In conclusion, the value of the flow rate coefficient, Cd, can be determined for both high and low water flows prior to its application on the actual site. The hydraulic structure must therefore conform to a precise discharge value as a design criterion. If the discharge is overestimated, the structure may collapse, and if it is underestimated, the structure may not last long due to its inherent fragility.

Keywords: Compound weirs, flowrate coefficient, experimental study, rectangular-triangular weir

1. Introduction

Weirs are structures that form a barrier across the width of a river, altering the flow characteristics and usually resulting in a change in river level, as well as allowing flow rates to be measured as a function of depth. The most common shapes for weirs are rectangular, trapezoidal, and triangular (V-notch); however, each of these shapes has drawbacks and is not ideal in all situations [1]. Among these shapes, the V-notch has an easy structure and can accurately measure flow in a natural or manmade channel.

Compound weirs are made up of various types of weirs. Compound sharp-crested weirs are becoming more popular due to their simplicity, ease of maintenance, and high flow measurement precision. However, compound weirs are appropriate for dams with low flow levels during the dry season and high flow levels during the rainy season. A compound weir may be an appropriate solution in situations where flow rates are expected to vary greatly [2][3]. The V-notch is made for situations with low flow, while the rectangular weir is used to measure flows that are higher. The designed hydraulic structure must fulfil the design requirement, which is an accurate value of discharge. If the discharge is overestimated, the structure may fail; if the discharge is underestimated, the structure may fail due to weakness. [4].

Numerous laboratory studies on compound weirs have been conducted to determine performance using rectangular and triangular weir shapes or combinations of these shapes [5–15]. The models of sharp-crested weirs were mostly used

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*Corresponding author: zarinaa@uthm.edu.my in the experiments. According to the findings of their research, the flow characteristics and geometry of the weir and channel influence the flowrate coefficient.

Therefore, experimental study is needed to determine coefficient of the flowrate, C_d, of compound weirs with different sizes of openings. This allows for accurate observations of streams with a wide variety of flow rates. The objectives of this study are to determine the coefficient of flow rate, C_d of compound weirs (rectangular – triangular) and to correlate the relationship between the Q_{theory} and Q_{exp} and between coefficient of flow rate, $C_{d,}$ and height of water, H. Compound weirs were created by combining rectangular and triangular (V-notch) cut-outs. This study can be used to determine the value of Cd for high and low water flows before it is used at the site. It is possible to manage the water flow of the drainage system by determining the necessary coefficient of flow rate, C_d. This raises the water level, allowing water to be redirected by the canal to the agricultural field due to the difference in head.

2. Materials and Methods

Multiple experiments on the compound (rectangular-triangular) weir were conducted at the Fluid Laboratory, Faculty of Civil Engineering and Built Environment. The equipment and experimental procedures are discussed further below.

2.1 Experimental Equipment

The compound weir (Fig. 1) was created in nine thin plate models with specific measurements. Table 1 displays the dimensions of weir models with various V-notch angles, θ (30°, 50°, and 80°) and rectangular widths, L. (0.10 m, 0.12 m, and 0.15 m). The constant values for these models are: (1) length of the weir, B is 0.25 m, (2) height of the weir from the datum, P is 0.06 m, (3) height of the weir sample, 0.16 m, and (4) thickness of the weir plate, 3 mm.

The hydraulic bench (Fig. 2) serves as a short-distance channel, complete with a small water tank and a pump that re-channels water through a pipe and back into the water tank. The outlet in the reservoir base is linked to a piezometer, which is used with a timer to measure the flow rate.

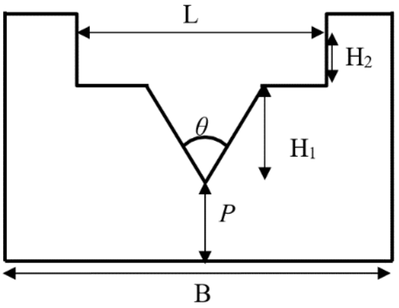


Fig. 1 - Sketch of compound (rectangular-triangular) weir

Fig. 2 - Hydraulic bench

Table 1 - Dimensions of the weir model

Model	1	2	3	4	5	6	7	8	9
Triangular angle, θ	30	50	80	30	50	80	30	50	80
Rectangular Width, L (m)	0.10	0.10	0.10	0.12	0.12	0.12	0.15	0. 15	0.15

2.2 Experimental Procedures

The laboratory safety procedure was identified and followed before, during, and after the experiment. After that, the equipment must be inspected to ensure that it is in good working order. The experiments were carried out using nine different measurement of weir plates, with the height of the water and the duration of the flow being recorded. The procedure for this experiment is as follows: A weir model was placed on a hydraulic bench, and the gap between the weir model and the hydraulic bench was filled with plasticine. The control valve was then adjusted for the highest level of water in the tank. The data measured involved the height of water, H_1 and H_2, time to flow, T, at a volume of 3 liters (collected in the volumetric tank). These steps were carried out several times by increasing the control valve to increase the water level for each compound weir model.

2.3 Equations

The Bernoulli equation is commonly used to solve the force and energy problem that is frequently encountered in engineering practise, and it provides the theoretical foundation for solving hydraulic calculations in actual engineering [16]. These equations were applied and were very significant in this study. The related equations are;

i. Experimental flow rate, Q_{exp}

$$Q_{exp} = V/t \tag{1}$$

where, V = volume = 3 Liters and t = time (s)

ii. Theoretical flow rate

$$Q_{theory} = \frac{8}{15} C_d \sqrt{(2g)} \tan\frac{\theta}{2} H_1^{\frac{5}{2}} + \frac{2}{3} C_d \sqrt{2g} L H_2^{\frac{3}{2}} \tag{2}$$

Where, C_d = coefficient of flow rate, g = gravitational acceleration, H_1 = the height of water in V-notch, H_2 = the height of water in rectangular weir, θ = V- shape angle, L = width of rectangular weir

Then, the coefficient of flow rate, C_d is the ratio of the actual flow rate that goes through the gauge compared to the theoretical flow rate. The equation can be written as:

$$C_d = \frac{\text{Actual flow}}{\text{Theoretical flow}}$$

$$C_d = \frac{Q_{exp}}{Q_{theory}} \tag{3}$$

R-squared and linear regression are useful in determining the strength of a relationship between two variables, allowing one value to be predicted in a model. Almost all studies involving the strength of the relationship between variables and other variables employ this statistical technique [17].

3. Results and Discussion

The experiments were carried out for 14 to 16 trials to collect data on nine different weir models, which are summarized in Table 2. The results show that the minimum and maximum water heights that can be recorded are 0.025 m (Model 7 and 8) and 0.079 m (Model 1), respectively. While the average of water height ranged between 0.049 m and 0.058 m. When comparing all models, the height of the water decreases as the V-notch angle and rectangular length of the weir increase, for example, the maximum level for model 3 is 0.005 m lower than Model 2, but still higher than Model 6.

Table 2 - Experimental results for compound weirs

Model		1	2	3	4	5	6	7	8	9
Height of water, H = $H_1 + H_2$ (m)	Min	0.029	0.027	0.026	0.028	0.026	0.028	0.025	0.025	0.025
	Max	0.079	0.076	0.071	0.078	0.075	0.068	0.077	0.070	0.066
	Ave	0.057	0.056	0.051	0.057	0.053	0.050	0.058	0.053	0.049
Q_{exp} (x 10^{-3} m^3/s)	Min	0.025	0.028	0.038	0.023	0.021	0.038	0.012	0.012	0.051
	Max	0.691	0.862	0.779	0.767	0.763	0.826	0.783	0.804	0.872
	Ave	0. 283	0.347	0.368	0.294	0.313	0.355	0.309	0.325	0.395
Q_{theory} (x 10^{-3} m^3/s)	Min	0. 091	0.132	0.216	0.083	0.120	0.216	0.063	0.109	0.196
	Max	1.812	1.854	2.007	1.896	2.017	1.964	2.319	1.869	2.005
	Ave	0.760	0.926	1.114	0.802	0.875	1.036	1.034	0.950	1.082
C_d	Min	0.27	0.21	0.18	0.28	0.18	0.18	0.19	0.11	0.26
	Max	0.4	0.47	0.41	0.41	0.41	0.42	0.35	0.43	0.44
	Ave	0.35	0.34	0.29	0.34	0.32	0.30	0.28	0.29	0.34

Furthermore, the Q_{exp} and Q_{theory} varied from 0.283 x 10^{-3} m^3/s to 0.395 x 10^{-3} m^3/s, and from 0.76 x 10^{-3} m^3/s to 1.114 x 10^{-3} m^3/s, respectively. The calculated minimum and maximum value for Q_{theory} are 0.063 x 10^{-3} m^3/s and 2.017 x 10^{-3} m^3/s, respectively, while the minimum and maximum values recorded by Q_{exp} are 0.012 x 10^{-3} m^3/s and 0.862 x 10^{-3} m^3/s, respectively, both of which are less than Q_{theory}.

3.1 Coefficient of Flow Rate, C_d

According to Table 2, the minimum and maximum values for the flow rate coefficient, C_d, are 0.11 (Model 8) and 0.47 (Model 2), respectively, while the average value ranged from 0.28 to 0.35. As a result, Model 1 has the best optimum value of C_d 0.35. Apart from Models 7-9, the average C_d decreases as the V-notch angles increase, while the width of the rectangular weir, L, remains constant.

The distribution of Cd is shown in Fig. 3 based on the number of experiment trials performed on nine compound weir models. At the maximum water heights of the experiment trials, the C_d ranged between 0.34 and 0.47, with Model 7 recording the lowest value at H = 0.077 m. The best value of C_d for L = 0.10 m and 0.15 m is 0.47 and 0.44, respectively at θ = 50°. While for L = 0.12 m, the best value of C_d is 0.42 at θ = 80°.

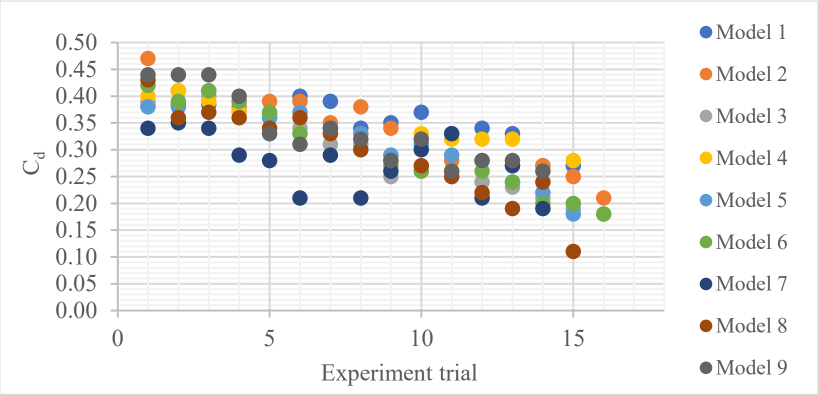
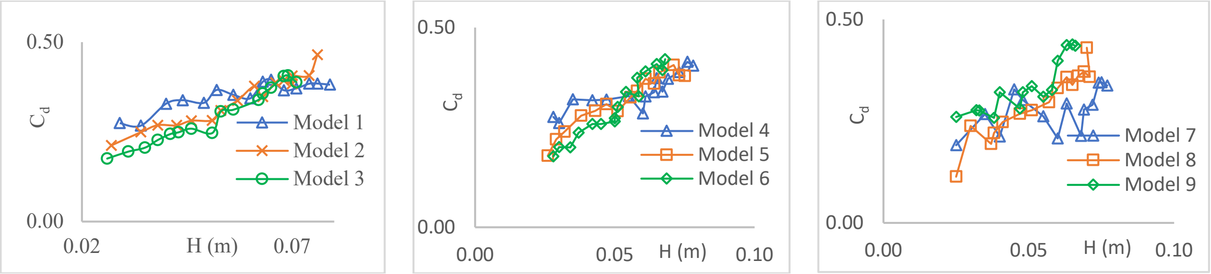


Fig. 3 - Distribution of coefficient of flowrate, C_d

3.2 Relationship Between Coefficient of Flow Rate, C_d and Height of Water, H

Figure 4 depicts the relationship between C_d and water height, H, where the value of C_d varies across all models. Model 7 has the weakest relationship with 0.29, which has large value fluctuations in Fig. 4. (c). Meanwhile, Table 3 shows the R^2 value of the linear equation Y = mX + c, where Y = C_d and X = H.

The results show that the V-notch angle, θ = 30°, has a moderate relationship with Models 1 and 4, however a poor correlation with Model 7. For V-notch angle, θ = 50°, both variables exhibit a strong relationship with $R^2 \geq 0.9$ at Models 2, 5, and 8. Lastly, for V-notch angle, θ = 80°, there is a good relationship with $R^2 \geq 0.94$ at Models 3 and 6, but moderate correlation at Model 9. This demonstrates that the V-notch angle, θ = 50°, is the best angle of V-notch when compared to rectangular weir widths, L (0.1 m, 0.12 m, and 0.15 m). Therefore, Model 3 is the best model in terms of variable correlation, while Model 6 has the highest increment among models, with m = 5.98. In conclusion, $R^2 > 0.9$ indicates that Models 2, 3, 5, 6, and 8 have a good relationship between C_d and H.



(a) Model 1 to 3 (b) Model 4 to 6 (c) Model 7 to 9

Fig. 4 - Relationship between coefficient of flow rate, C_d and height of water, H according to compound weir models

Table 3 - Derived equation between C_d and H

Model	1	2	3	4	5	6	7	8	9
Equation, Y=mX + c	Y=2.22x +0.2245	Y=4.57x +0.0801	Y=5.26x +0.0239	Y=2.34x +0.2054	Y=4.00x +0.1064	Y=5.98x +0.0031	Y=1.75x +0.1758	Y=5.05x +0.0279	Y=4.35x +0.1223

R^2	0.78	0.94	0.96	0.72	0.93	0.94	0.29	0.9	0.76

*where Y = Cd and X = H

According to Fig. 5, all models show that as H increases, so does the value of Cd, even though Model 7 recorded some data that is far from the average value. All models, except Model 7 ($C_d = 0.34$) achieved $C_d \geq 0.4$ at H = 0.07 m, while at H = 0.03 m, all models achieved $C_d = 0.23 \pm 0.03$ except Model 3. Most of the value of C_d is scattered between 0.2 and 0.4, however when $H \geq 0.06$ m, the value of C_d begins to increase more than 0.4. As the study was carried out in a short-distance channel with a height of less than 0.17 m, the value of C_d cannot be recorded at more than 0.47 as there is insufficient channel height to raise the water level in the channel. Using the equation in Table 3, C_d can be determined for any value of H, for example, if H = 0.1 m, value of $C_d = 0.55$ using Y = 5.26x +0.0239 (equation Model 3).

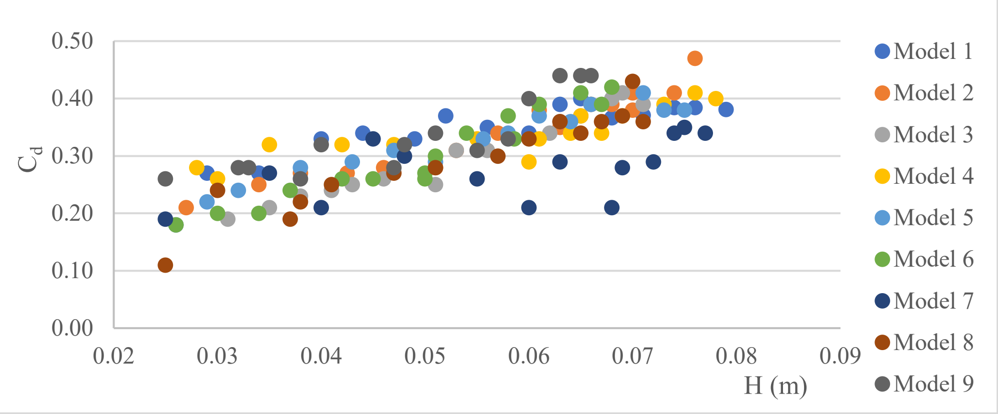


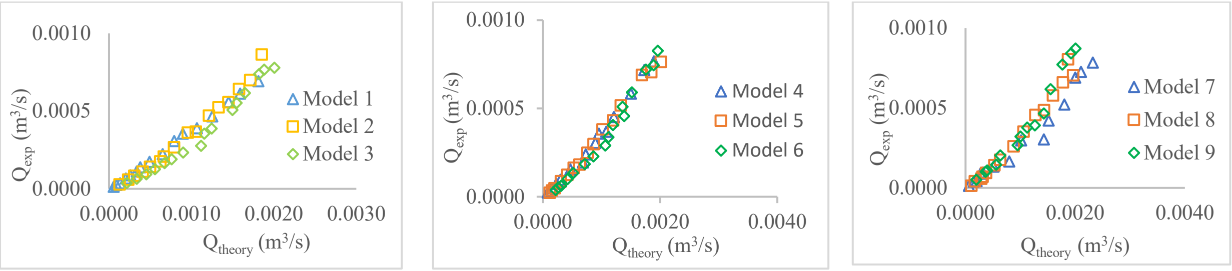
Fig. 5 - Distribution of coefficient of flow rate, C_d versus height of water, H

3.3 Relationship Between the Q_{theory} and Q_{exp}

Based on the width of the rectangular weir, L, Fig. 6 depicts the relationship between theoretical flow rate, Q_{theory}, and experimental flow rate, Q_{exp}. Figure 5 (a) shows that the V- shape angles, θ = 50° and θ = 30° had the highest and lowest values of Q_{exp}, with 0.000862 m^3/s and 0.000691 m^3/s, respectively. Meanwhile, the highest and lowest values of Q_{theory} are at θ = 80° and θ = 30°, respectively, with values of 0.002007 m^3/s and 0.001812 m^3/s. According to Figure 5 (b), V-notch, = 80° had the highest Q_{exp}, with a value of 0.000826 m^3/s, and = 50° had the lowest, with 0.000763 m^3/s. In contrast, the highest and lowest of Q_{theory} were obtained by θ = 50° and θ = 30° with values of 0.002017 m^3/s and 0.001896 m^3/s, respectively.

Furthermore, graphs in Figure 5 (c) show that the highest and lowest Q_{exp} values were at = 80° (0.000872 m^3/s) and = 30° (0.000783 m^3/s), respectively. Meanwhile, the highest and lowest values of Q_{theory} are at = 30° and 50°, respectively, with values of 0.002319 m3/s and 0.001869 m3/s.

These graphs depict the direct proportional between Q_{theory} and Q_{exp}, with Q_{theory} always being greater than Q_{exp}. As a result, as the Q_{exp} increases, so will the Q_{theory}. Nevertheless, Model 7 demonstrates a fluctuating relationship between these variables. Therefore, a comparison between Q_{exp} and Q_{theory} is required to validate the value of the coefficient of flow rate, Cd, for estimating the flow rate at the field site.



(a) L = 0.1 m

(b) L = 0.12 m

(c) L = 0.15 m

Fig. 6 - Comparison between Q_{exp} and Q_{theory} for nine models

Table 4 displays the linear equation Y = mX + c, as well as the R-squared (R^2) value. Y = mX + c equation was used in conjunction with the expressions Y = Q_{exp} and X = Q_{theory}. All the models have positive values for the gradient m, between 0.39 and 0.46, and the R^2 values ranged from 0.96 to 1.00. This demonstrates the strength of the relationship that exists between the two variables.

Table 4 - Equation from relationship of Q_{exp} and Q_{theory}, and R-squared

Model	1	2	3	4	5	6	7	8	9
Y=mX + c	$Y=0.39x$ $-1x10^{-5}$	$Y=0.46x$ $-8x10^{-5}$	$Y=0.44x$ $-1x10^{-05}$	$Y=0.41x$ $-4x10^{-5}$	$Y=0.41x$ $-4x10^{-5}$	$Y=0.44x$ $-1x10^{-4}$	$Y=0.33x$ $-3x10^{-5}$	$Y=0.41x$ $-6x10^{-5}$	$Y=0.46x$ $-1x10^{-4}$
R^2	1.00	0.98	0.97	0.99	1.00	0.97	0.96	0.98	0.96

4. Conclusion

In conclusion, study on nine compound weir models reveals that the width of the rectangular weir, L, and the V-notch angle, influence the value of C_d. The highest value for C_d is 0.47 which characteristics weir, L = 0.10 m, $\theta = 50^o$ (Model 2) at H = 0.076 m. Meanwhile, the lowest value of C_d is 0.11 which characteristics weir, L = 0.15 m, $\theta = 50^o$ (Model 8) at H = 0.025 m. However, this study was unable to achieve Cd ≥ 0.47 because the experiments could not raise the water level higher than 0.08 m, thus the equation between C_d and H can be used to estimate value of C_d by given H. Furthermore, when compared to all model results, the most effective combination of V-notch angle, = 50^o, and rectangular shape width, L = 0.1 m. Except for Model 7, the correlation between Cd and H, and Q_{exp} and $Q_{theory,}$ shows good relationships between variables. Before being used at the actual site, the value of C_d can be determined using this study for high and low water flows. It is possible to manage the drainage system's water flow or raise the water level, allowing water to be redirected by the canal to the agricultural field due to the difference in head, by determining the necessary flowrate coefficient, C_d. The installation of a compound weir in the dam will improve water flow control. Furthermore, this study can be used as a guide and reference point for future researchers studying the flowrate coefficient of rectangular-triangular weirs.

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