Measurement of discharge in open channels: A case study of laboratory discharge calibration model

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Measurement of Discharge in Open Channels: A Case Study of Laboratory Discharge Calibration Model

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Abstract. In order to obtain an identical implementation in the field, flow testing is frequently conducted by creating physical models in the laboratory to describe the actual flow in the field with physical models in the laboratory; thus, a series of calibration tests are required. In this study, the equation obtained from the results of the threshold calibration has been conducted. The equation formed from the three calibrated thresholds includes the triangular threshold (weir#2), the discharge equation Q = 0.0144 h^2.5726 (l/s) the r^2 value 0.9918, and the rectangular threshold (weir#1) has the discharge equation Q = 0.378 h^1.9223 (l/s) the r^2 value is 0.9507. The discharge coefficient obtained is Cd = 2.0729 h^0.622 for the triangular threshold (weir#2) and Cd = 4.5172 h^1.1414 at the rectangular threshold (weir#1).In the calibration process, the accuracy of the obtained results is highly dependent on the accuracy and precision at the time of measurement, and in addition to the completeness and suitability of the equipment and facilities required for the calibration, In small discharge, the measurement must be conducted because smaller calibrated discharge leads to higher error rate.

INTRODUCTION

To supply irrigation water, an irrigation network is deemed pivotal that functions properly and is measurable. An excellent and measurable water transportation process requires a channel equipped with measuring structures to control and regulate the overall water supply.

A basic understanding of the capacity of a drainage system provides a solid knowledge to enable performing a more scientific approach, achieve reasonable control, and start saving water without compromising water supply requirements. All irrigation needs to know the application system of water flow measurement in inches per hour or inches per irrigation [1].

Flow testing is frequently performed with physical modeling to describe the actual flow. In proving it, the flow rate is measured correctly, and it is pivotal to calibrate the flow with a model scale measuring building, constructed with accurate and careful measurement results, to generate an accurate flow calibration results for identical implementation in the field.

The flow meter structure is a hydraulic structure installed in the open/closed channel with a free water level in the case of a decrease in discharge from the measured upstream water level [2]. A sharp rectangular threshold, utilized as a discharge control, an opening with a thin metal or bulkhead, is placed perpendicular to the surface of the approach channel boundary [3].

This research was conducted to determine the performance of the sharp threshold measuring instrument against water runoff through it, determine the graph formed and the water level through it, and obtain identical equations based on the measurement results of the model. The benefits include the understanding towards the calibration method for the measurements based on general flow height.

METHODS

A good water measuring system will support accurate water usage calculations, enabling the water supply fulfilling an optimal level in the destination area [4]. Other laboratory experiments have investigated the hydraulics of weirs and culverts of downstream slope weirs. The upstream water level rises when the tailwater level is below the peak elevation, the flow in the culvert is submerged, and the discharge decreases due to the increase in the tailwater water level [5].

A sharp threshold of this experiment is formed with a triangular threshold and rectangular threshold, thereby generating the Equation 1 and Equation 2 approach as follows Figure 1.

According to Figure 1 (a), $\tan\frac{\emptyset}{2} = \frac{Y}{X}$; because $\emptyset = 90^o$, so

$Q = Cd \,.\, A \,.V$, $\quad Y = X \tan\frac{\emptyset}{2}$, $\quad A = ½\, Y \,.\, X \,.\, 2 = Y \,.\, X$

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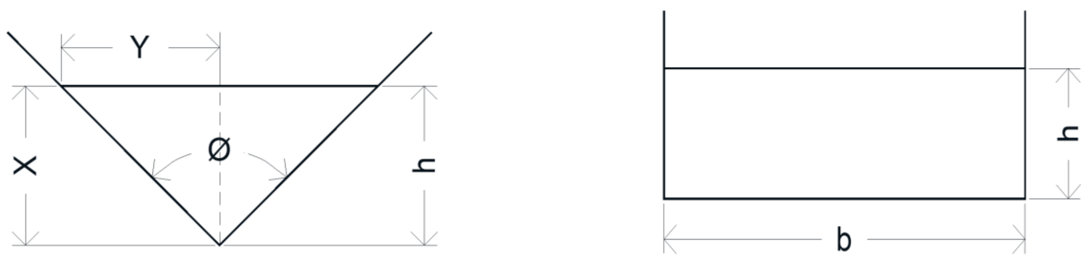
$$A = X^2 \tan\frac{\emptyset}{2} \quad \text{and } X = h, \text{ So } A = h^2 \tan\frac{\emptyset}{2}.$$
$$V = \sqrt{2gh}, \quad \text{And then } Q = Cd.\ h^2 \tan\frac{\emptyset}{2}.\sqrt{2gh}$$
$$Q = Cd.\ h\ .\ \tan\frac{\emptyset}{2}.\sqrt{2g}$$
$$Cd = \frac{Q}{h\ \tan\frac{\emptyset}{2}.\sqrt{2g}} \qquad (1)$$

According to Figure 1 (b);

$$Q = Cd\ .\ A\ .\ V$$
$$A = b\ .\ h$$
$$V = \sqrt{2gh}, \text{ And then } Q = Cd.\ b.h.\ \sqrt{2gh}$$
$$Q = Cd.\ b\ .\ h^{3/2}.\sqrt{2g}$$
$$Cd = \frac{Q}{b\ h^{3/2}\sqrt{2g}} \qquad (2)$$



(a) (b)

FIGURE 1. (a) V-notch cross-section model, (b) Rectangular cross-section model
(*source: own drawing*)

In an analysis for different types of flow, the flow equation with free-flow conditions, discharge through a sharp threshold could be approximated by the following Equation 3.

$$Q = Cd\ h^n \qquad (3)$$

In which: Q = discharge through the sharp threshold, Cd = discharge coefficient, h = water height of sharp threshold, and then n = exponent of water height h, A = cross-section area, V = velocity, and g = gravitational acceleration.

Sharp flow presents as one of the most useful basic applications of hydraulic theory, both in introducing students to the theoretical process of hydraulics and in providing one of the most widely applied formulas for practical application [6]. The calibrated equation developed on a flume by combining the principles of Pi theory with a laboratory-scale physical model, designed for trapezoidal, rectangular, and circular channels [7].

In another research, the application of v-notch threshold was accurate at low discharges between 5 and 10 l/s, and at discharges between 15 and 35 l/s, the quadrangular threshold was accurate [8]. Thin plate weirs are commonly applied for measuring flumes, enabling accurate flow measurements with simple instruments. The calibration formulas of such devices depend on several empirical coefficients, encouraging the requirement to obtain a novel and accurate physical data to complement the existing evidence [9].

The outflow process of the triangular crested weir was studied employing dimensional analysis and incomplete similarity theory, theoretically concluded, and the test conducted according to the literature [10]. Measurements employing PIV technology indicate that spatial resolution is an essential factor in measurement accuracy in estimating the dissipation rate.

Optimal results are achieved if the interrogation area is not too large (sampling phenomenon) or too small (noise in measurement data). The effect of the number of samples applied in the ensemble average is also considered [11]. The height and width of the weir plate become the two parameters characterizing the head-discharge relationship. Laboratory experiments are conducted by measuring the discharge and the head over the weir for variable weir heights and widths [12]. The analytical solution is additionally performed for establishing the water surface profile along the side weirs in a triangular channel. The solution, which yields a direct computation of the flow profile, should be a valuable tool for the evaluation and design of side weirs in triangular channels [13].

Preparations that must be performed before research activities on flow discharge include the preparation of a design scheme model and flow system by measuring the structure. The design model scheme for open and closed flow applied in this study is illustrated in Figure 2, as follows.

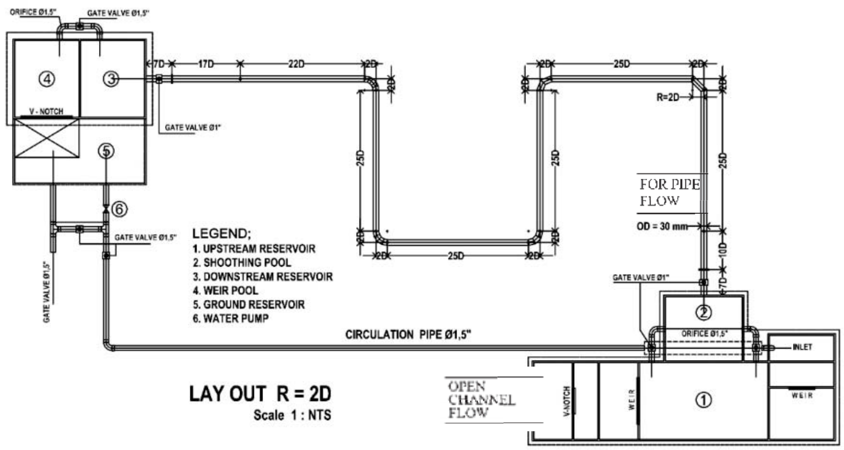


FIGURE 2. Plan model schematic for discharge calibration [14]

In this study, it is imperative to note the measuring structure used and the flow system. Other equipment includes gauges and rulers, point gauges, flow guides, stopwatches, measuring tubs, measuring tubes, and forms to fill in observation and crew data. Physical models in the laboratory are urged to be equipped with a ground reservoir, sharp threshold with meter-scale, triangular and rectangular thresholds. The flow regulator employs a distribution pump containing the required capacity. Water from the ground reservoir is channeled by a pump to the initial holding tank (Figure 3 on the left) then after passing through the tranquilizer blade the water flows past the rectangular threshold (Figure 3 on the right) and continues to flow into the stabilizer tank. From the stabilizer tank, the overflow of water is controlled by a triangular threshold (Figure 4 on the right). Meanwhile, the water from the water stabilizer tank is channeled into the pipeline network and then exits in the sinking basin downstream of the pipe and then the water is continued to flow to the calming tank and is measured by a triangular threshold (Figure 4 on the left) downstream of the pipe before the water flows back to the ground reservoir.

initial water storage tank (wst) rectangle threshold after wst

FIGURE 3. Rectangular sharp threshold
(source: own documentation)

triangle threshold downstream of the piping triangle threshold downstream of the weir

FIGURE 4. Triangular sharp threshold
(source: own documentation)

Testing the flow capacity of a threshold is conducted, thereby measuring the flow rate that flows at that threshold to control the amount of flow that passes through the threshold according to the required provisions. The process of testing this flow capacity is conducted in stages according to the procedure [15]to obtain data from observations about the flow capacity that passes through the tested sharp threshold; thus, data records are obtained to study the flow properties and obtain the coefficient values of the sharp threshold flow capacity.

RESULTS AND DISCUSSION

As aforementioned, the results of the implementation of model calibration measurements, the data obtained after analysis was applied as a reference in measuring the flow passing above the calibrated threshold. Based on the discharge simulation results from the laboratory model, data obtained from observations on each of the observed thresholds include a rectangular threshold in the upstream part, a triangular threshold in the downstream of the tranquilizer basin, which is upstream of an open channel, and a triangular threshold in the downstream part of the sinking basin as the part of an open channel. Furthermore, the observed data from the flow calibration test is described in the subsequent discussion.

Flow Calibration Results At Sharp Threshold Triangular

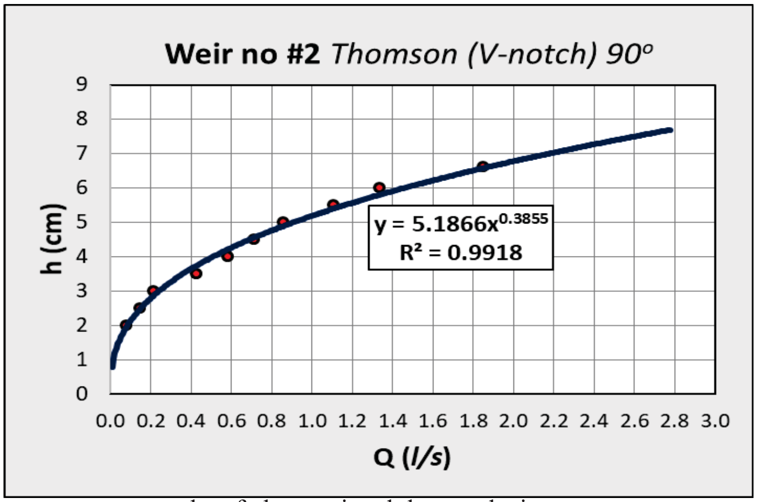
Observational data on the sharp triangular threshold was continued with data analysis to obtain relevant and accountable observation results. Furthermore, observations and calculations of the discharge flowing above the triangular threshold are described in the following Table 1.

TABLE 1. Analysis result of triangular sharp threshold calibration (weir #2)

No	Overflow (h) cm	Duration (t) s	Observation		(Q) l/s		Cd	No	Overflow (h) cm	Duration (t) s	Observation		(Q) l/s		Cd
			(h) cm	(V) m3	obs	average					(h) cm	(V) m3	obs	average	
1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
		21.320	3.435	0.002	0.099					9.239	10.846	0.007	0.723		
1	2.00	23.170	3.389	0.002	0.090	0.082	0.923	6	4.50	8.759	10.271	0.006	0.722	0.716	3.593
		24.210	2.205	0.001	0.056					9.141	10.462	0.006	0.704		
		17.710	4.353	0.003	0.151					6.049	8.840	0.005	0.899		
2	2.50	17.490	4.169	0.003	0.147	0.149	1.346	7	5.00	8.060	11.135	0.007	0.850	0.860	3.885
		17.950	4.353	0.003	0.149					8.240	11.135	0.007	0.832		
		17.660	6.393	0.004	0.223					6.053	10.750	0.007	1.093		
3	3.00	18.390	6.486	0.004	0.217	0.217	1.636	8	5.50	6.114	11.328	0.007	1.140	1.110	4.556
		19.340	6.673	0.004	0.212					5.793	10.319	0.006	1.096		
		11.363	8.177	0.005	0.443					5.854	13.074	0.008	1.374		
4	3.50	11.689	8.036	0.005	0.423	0.431	2.778	9	6.00	5.835	12.490	0.008	1.317	1.338	4.556
		11.746	8.130	0.005	0.426					5.725	12.295	0.008	1.322		
		8.739	8.177	0.005	0.576					5.260	15.333	0.009	1.794		
5	4.00	9.069	8.651	0.005	0.587	0.584	3,296	10	6.60	4.297	13.660	0.009	1.956	1.851	6.331
		9.340	8.935	0.005	0.589					5.576	16.325	0.010	1.802		

Source: *Analysis result*

Based on the results of measurement data on the triangular threshold at the downstream of the pipe, then a regression analysis was carried out which obtained a comparison between the overflow height above the triangular threshold and the amount of discharge shown in Figure 5.



results of observational data analysis on triangle threshold

FIGURE 5. h and Q triangular sharp threshold - weir#2 (*source: analysis result*)

Flow Calibration Results At Sharp Threshold Rectangular

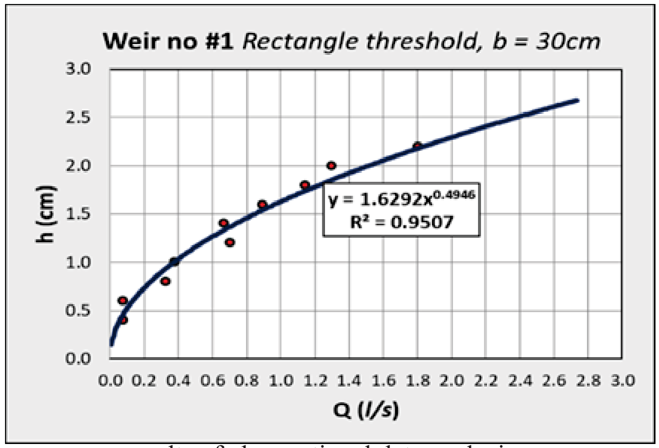
Another observation includes the sharp threshold of the rectangle to obtain the expected modeling results. Further, the observations and calculations of the flow rate on the rectangular sharp threshold model are additionally presented, as shown in following Table 2.

TABLE 2. Analysis result of rectangular sharp threshold calibration (upstream)

No	Overflow (h) cm	Duration (t) s	Observation		(Q) l/s		Cd	No	Overflow (h) cm	Duration (t) s	Observation		(Q) l/s		Cd
			(h) cm	(V) m3	obs	average					(h) cm	(V) m3	obs	average	
1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
		23.420	2.650	0.002	0.070					7.120	7.800	0.005	0.674		
1	0.40	22.730	3.590	0.002	0.097	0.079	0.236	6	1.40	6.930	7.517	0.005	0.668	0.669	0.304
		22.890	2.559	0.002	0.071					6.170	6.673	0.004	0.666		
		22.090	3.343	0.002	0.093					5.500	7.706	0.005	0.862		
2	0.60	23.970	3.161	0.002	0.081	0.081	0.130	7	1.60	7.280	10.846	0.007	0.917	0.893	0.332
		26.400	2.887	0.002	0.067					6.950	10.175	0.006	0.901		
		11.540	6.860	0.004	0.366					5.000	9.030	0.006	1.112		
3	0.80	16.220	8.745	0.005	0.332	0.325	0.343	8	1.80	4.870	9.316	0.006	1.177	1.144	0.357
		18.180	8.272	0.005	0.280					5.680	10.558	0.006	1.144		
		12.90	7.800	0.005	0.372					5.630	12.005	0.007	1.312		
4	1.00	12.250	6.860	0.004	0.345	0.380	0.286	9	2.00	8.120	16.524	0.010	1.252	1.298	0.345
		12.030	8.272	0.005	0.423					2.400	5.184	0.003	1.329		
		5.700	6.580	0.004	0.710					3.910	9.983	0.006	1.571		
5	1.20	7.630	8.840	0.005	0.713	0.702	0.402	10	2.20	5.430	16.027	0.010	1.816	1.804	0.416
		7.11	7.894	0.005	0.683					6.340	20.864	0.013	2.025		

Source: *Analysis result*

Figure 6 explains the data analysis of the measurement results from the data calibration conducted as illustrated above. In general, the calibration observations obtained from each threshold have different dynamics according to the object's condition. The analysis results indicate a good match because the r^2 value is above 90% and even close to 100%. The results of the formulated equation has been suitable to be applied, indicated by the value of r^2 approaching 100%.



results of observational data analysis
on rectangle threshold

FIGURE 6. h and Q rectangular sharp threshold in upstream (*source: analysis result*)

The following Table 3 presents a complete description of each sharp threshold, comprising the results of the analysis related to the discharge equation formed and the value of the discharge coefficient obtained.

TABLE 3. Analysis report and equation model

No.	Threshold type	Position	r-square	Equation* (l/s)	Cd**	Notes
1.	Triangular threshold (upstream open channels model)	downstream of weir	0,9918	Q = 0,0144 h^2,5726	Cd = 2,0729 h^0,622	
2.	Rectangular threshold (upstream reservoir)	upstream (after water inlet)	0,9507	Q = 0,378 h^1,9223	Cd = 4,5172 h^1,1414	

* equation 3, ** equation 1 and 2
Source: *Analysis result*

The following Table 4 indicates the implementation results based on the equations built from the graph of the calibration measurement results.

TABLE 4. Calculation report based on the built equation

No.	Overflow (cm)	Discharge (Q) l/s		No.	Overflow (cm)	Discharge (Q) l/s	
		Weir #1	Weir #2			Weir #1	Weir #2
		Q=0.378 h^1.9223	Q=0.0144 h^2.5726			Q=0.378 h^1.9223	Q=0.0144 h^2.5726
1.	0.40	0.06488	0.00136	11.	2.40	2.03588	0.13693
2.	0.60	0.14152	0.00387	12.	2.60	2.37471	0.16824
3.	0.80	0.24610	0.00811	13.	2.80	2.73849	0.20357
4.	1.00	0.37800	0.01440	14.	3.00	3.12708	0.24311
5.	1.20	0.53676	0.02302	15.	3.20	3.54035	0.28702
6.	1.40	0.72200	0.03422	16.	3.40	3.97819	0.33546
7.	1.60	0.93342	0.04825	17.	3.60	4.44046	0.38860
8.	1.80	1.17073	0.06532	18.	3.80	4.92708	0.44659
9.	2.00	1.43371	0.08566	19.	4.00	5.43793	0.50959
10.	2.20	1.72216	0.10947	20.	4.20	5.97293	0.57774

Source: *Analysis result*

CONCLUSIONS

Based on the analysis and discussion of the measurement resultsregarding the calibration results, it is expected that it provides an important note that could be considered for further related research, which are as follows. The accurate resultsis deemedpivotal to have complete tools and equipment following measurement needs. High accuracy and precision are required in the measurement and reading process. The results obtained from this calibration process are as follows;

- ✓ The triangular threshold downstream of the spillway (weir#2) has an excellent data distribution because it coincides with the graph line with the value of r-square = 0,9918.
- ✓ The upper rectangular threshold of the model (weir #1) has a good data distribution and slightly coincides with the graph line with r-square = 0.9507. At the threshold of a quadrilateral, when the measured discharge is more significant, the tendency is that the error value will be smaller.

1. The equation formed by the two calibrated thresholds is the triangular threshold (weir#2), the discharge equation Q = 0,0144 h^2,5726 (l/s), and the rectangular threshold (weir#1) is the discharge equation Q = 0,378 h^1,9223 (l/s).
2. The discharge coefficient value obtained is Cd = 2,0729 h^0,622 for the triangular threshold (weir#2) and Cd = 4,5172 h^1,1414 at the rectangular threshold (weir#1).

In the process of performing the calibration, the accuracy of the results obtained are highly dependent on the accuracy and precision in measuring and recording data by laboratory personnel/teams, the completeness and suitability of the equipment and facilities for calibration; thus, if the discharge is slight, the measurement must be carefully conducted, as smaller calibrated discharge generates higher error rate.

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