The Overshot Gate as a Flow-Measuring Device

Jihan M. Qasim

Department of Water Resources Engineering, College of Engineering, University of Duhok,
Kurdistan Region – F.R. Iraq

Abstract—**The overshot gate is a commonly used adjustable overflow weir for regulating the upstream water level in open channels. The amount of gate movement is proportional to the water level change. However, to effectively manage the water flow, it is also important for operators to accurately measure the flow rate in the channel. This study examines an overshot gate installed at the end of a laboratory flume to estimate the flow rate under various free flow conditions. This study investigates different gate angles ranging from 9.6° to 90° to evaluate their impact on the flow properties and the discharge coefficient. The analysis of the results indicates that the maximum flow rate values can be achieved with gate inclinations from 15.5° to 47.2° with relatively lower head; the inclined alignment of the gate decreases the effective gate height which consequently increases the gate efficiency. The use of the overshot gate is advantageous over the normal gate when channel depth is limited and higher discharge is required at relatively lower head. In this study, at the highest gate inclinations, the water surface is significantly stable having the lowest values of the approach Froude number. In addition, the head to gate height ratio decreases with raising the gate due to the reduced vertical contraction of the channel. Finally, this paper proposes an empirical equation for estimating the discharge coefficient based on the gate inclination, which demonstrates good accuracy in the specified range.**

Index Terms—**Overshot gate, Leaf gate, Inclined thin-plate weir, Pivot weir, Discharge coefficient, Discharge measurement.**

I. Introduction

The overshot gate, also known as the leaf gate, or pivot weir, is an overflow adjustable weir that consists of a rectangular leaf hinged to the channel bed, and chained to a cable hoist that lowers and raises the gate to the desired height. The gate is popular for controlling the upstream water level in the channels and has been found very easy to operate and understand. The gate is raised to raise the water level and lowered to lower the water level. The amount of gate movement is proportional to the water level change (Stringam et al., 2012). In irrigation districts, the gate delivers nearly constant flow rates for the turnouts regardless of the flow rate in the main canal. It is known to handle surges in the flow with limited depth changes (U. S. Department of the Interior Bureau of water, 2001).

The first overshot gate patent was granted to R.A. Lang in 1890, the device did not incorporate much of today's irrigation requirements, as cited in (Stringam et al., 2012; Stringam, 2010; Stringam and Gill, 2012). The overshot gate has been the subject of few studies and published works. The available published investigations agree on very few details of the discharge characteristics of this hydraulic structure due to the differences in experimental equipment and technique. Thin-plate weirs inclined toward downstream, similar to overshoot gates, were used in some research works. Wahlin and Replogle (1994) performed tests on a laboratory model gate and a prototype gate. Empirical equations were developed to determine the flow rate of a ventilated free-flow gate valid for gates angle between (16.2°–63.4°) and for the upstream head to gate height less than unity. Weyer (2000; 2002), Qoi, Krutzen and Weyer et al. (2003), Eurén (2004), Mareels et al. (2005), Eurén and Weyer (2006), Ooi and Weyer (2007; 2008), Ooi, Foo and Weyer (2011), and Aleem, Muhammad, and Nasir (2014) studied the overshot gates located along irrigation channels, system identification models were presented to predict the head over the gates, and significant potential for substantial water savings was demonstrated. Prakash and Shivapur (2003; 2004), Shivapur, Mulangi and Swamy (2009), and Prakash, Ananthayya and Kovoor (2011) studied the variation of the discharge coefficient of an inclined rectangular sharp-crested weir with the normal position of the weir. They also analyzed the flow over inverted triangular, rectangular notch weirs, and compound notch-weir consisting of two triangular sections with different vertex angles inclined at (15°, 30°, 45°, and 60°) with the vertical plane. Discharge equations were established in terms of the head to crest height, and the inclination angle. Mohammed and Mohammed (2011) studied and compared the inclined side weir with crest angles (0, 4°, 8°, and 12°) against and in the flow direction, and obtained an equation for the discharge coefficient. Nikou, Monem, and Safavi (2016) experimentally investigated the free and submerged flow over pivot weirs with angles between (20°–90°) with different side contractions. Two discharge equations were used, the first one was Kindsvater-Carter's equation, and the second one was derived from energy and critical depth equations. For the free flow condition, the equations were accurate within ±15 and ±10%, respectively. For submerged flow condition, however, the accuracy was within ±30% and ±20%. Bijankhan, Asce, and Ferro (2018) applied

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Corresponding author's e-mail: jihan.mahmood@uod.ac

experimental and numerical simulations to study the effect of the inclination angles ranging within (30°–90°) on the stage-discharge formula of rectangular weir. It was found that the discharge capacity for 30° inclination increases by about 8.2% compared with that of the normal weir. In addition, the study concluded that flow through the normal weir is not sensitive to the inclination angle in the interval $54° \leq \theta \leq 90°$. Azimfar, Hosseini, and Khosrojerrdi (2018) proposed analytical equations to estimate the discharge coefficient of a pivot weir based on the Bernoulli and momentum equations with relative errors within ±5% and ±10% for the free and submerged flow conditions, respectively. Bijankhan and Ferro (2020) investigated the factors affecting submerged flow conditions for the pivot weir and proposed a stage-discharge formula with a mean absolute relative error of 6.4%.

In the present study, it is aimed to examine the reliability of the adjustable overshot gate, which is usually used only to control the water level in a laboratory flume that is built-in with the gate at its downstream end, for estimating the flow rate. The present work differs from the earlier studies in that a greater number of inclination angles are experimentally investigated and, as a result, a greater amount of data are obtained that allows for a more comprehensive analysis of the hydraulic characteristics of the structure under different flow conditions.

II. METHODOLOGY

To achieve the objective of this study, an approach to the gate flow problem is found through using a combination of analysis of the underlying empirical laws and laboratory experiments. The experimental program is organized to measure the flow properties in the neighborhood of this hydraulic structure. The relationships between the various parameters are investigated.

For any flow-measuring device, the head-discharge equation has a discharge coefficient C_d and a velocity coefficient of the approach flow C_v, or their combination. The accuracy of the measurement depends to a great extent on the variation of these coefficients. The discharge over a vertical thin-plate weir can be calculated using a modified form of the Kindsvater-Carter equation which is also valid for a vertical overshot gate (Wahlin and Replogle, 1994):

$$Q = C_e \frac{2}{3}\sqrt{2g}\; b_e\; h_e^{3/2} \tag{1}$$

$$b_e = b_c + K_b \tag{2}$$

$$h_e = h_1 + K_h \tag{3}$$

where Q = Discharge over the gate, C_e = Effective discharge coefficient, g = Acceleration due to gravity, b_e = Effective width of gate, b_c = Width of the control section, K_b = Empirical constant from Fig. 1 dependent on (b_c/B) that describe the boundary geometry, B = Width of the rectangular approach channel h_e = Effective head on the gate, h_1 = Piezometric head measured upstream from the gate, and K_h = 0.001 m is constant regardless of the flow rate and the gate height where K_b and K_h have little effect on the flow rate at high heads.

By modifying the gate width and the head approaching the structure, the combined effects of viscous and surface tension forces are accounted for (Carter, 1956; Shen, 1981). An advantage of (1) is that the effect of approach velocity is incorporated and need not be included in the study. This procedure is valid for $h \geq 3$ cm, $h/p \leq 2$, $p \geq 10$ cm, and $b_c \geq 15$ cm (Kulin and Compton, 1975).

The overshot gate is hydraulically similar to a sloping rectangular sharp-crested weir. To account for the inclination of the overshot gate, C_a is introduced such that:

$$Q = C_a C_e \frac{2}{3}\sqrt{2g}\; b_e\; h_e^{1.5} \tag{4}$$

Setting the discharge coefficient $C_d = C_a\, C_e$, (1) becomes:

$$Q = C_d \frac{2}{3}\sqrt{2g}\; b_e\; h_e^{1.5} \tag{5}$$

The present study seeks establishment of an empirical formula for estimating C_d as a function of θ, the angle of gate inclination to the direction of flow, as shown in Fig. 2.

III. LABORATORY WORKS

The experimental tests are carried out in the Hydraulic Laboratory of the College of Engineering, University of Duhok using a horizontal rectangular flume having a working length of 500 cm, 30 cm width, and 45 cm depth. The tested

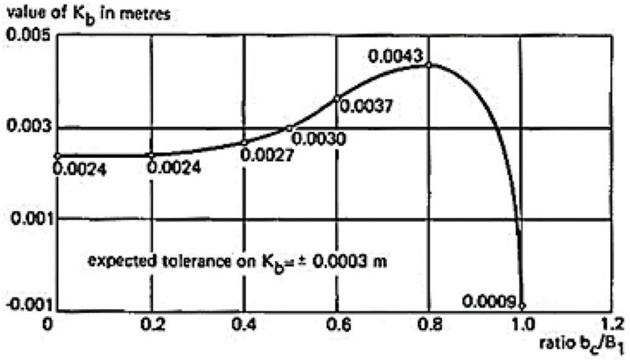

Fig. 1. Values of Kb versus bc/B (Bos, 1989).

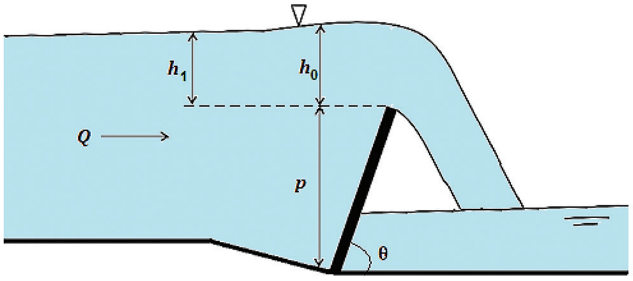

Fig. 2. Definition sketch of the overshot gate.

overshot gate is located at the end of the flume. In the outlet of the flume, a part of the bed is sloping at an angle of 16.7° just upstream of the gate, as shown in Fig. 3. The gate is 29.7 cm wide, 60 cm high, and 0.6 cm thick.

For the purpose of flow ventilation, eight plastic hoses of 6 mm in diameter at space of 3 cm with their openings 24 cm below the top of the gate were fixed on the downstream face of the gate, as shown in Fig. 4. This precaution ensures that sufficient supply of air is maintained to the air pocket beneath the flow nappe so that the nappe is entirely free from the gate body after passing the gate. Otherwise, the pressure in the air pocket is reduced causing undesirable effects, such as, jet vibration resulting in an unsteady flow due to inconsistent air supply to the air pocket; and increased curvature of the overfalling jet resulting in increased discharge coefficient C_d values. If the discharge Q is fixed, the head h measured over the gate is reduced, and if the head h is fixed, the discharge is increased (Bos, 1989).

Different tilting angles of the gate θ were investigated ranging from 9.6° to 90° (normal position). Different flow rates were applied in free flow conditions, such that the top of gate is above the downstream water level. This is always the case for the laboratory channel we consider since the water drops out of the channel just after passing the gate. The flow rate and the head over the crest were recorded in each experiment. Ten experimental tests were accomplished for each value of θ, as shown in Table I. Thus, 260 experiments were made on the gate including flow rates from 0.00148 to 0.03318 m^3/s with heads varying from 0.01645 up to 0.13725 m. The rate of flow was measured by an electromagnetic flow meter, and the water surface elevations were measured using point gauges.

IV. Results and Discussion

For each gate height, the actual discharge against effective head h_e is drawn in Fig. 5 *a* through *f*. The smaller p is that the flatter is the gate which allows for more discharge to pass over it. At very small inclination angles such as when p is 10 and 12 cm (corresponding to θ values of 9.6 and 11.5°), the gate hydraulically behaves like a free overfall, which is also found by Bijankhan and Ferro, 2020. At this stage, the sloping part of the channel outlet accelerates the water flow until the gate is further raised. When p is between 14 and 44 cm, for a given head value, the discharge decreases with the increase of gate height with a small variation which could be due to measurement uncertainties. This observation also agrees with (Prakash and Shivapur, 2004).

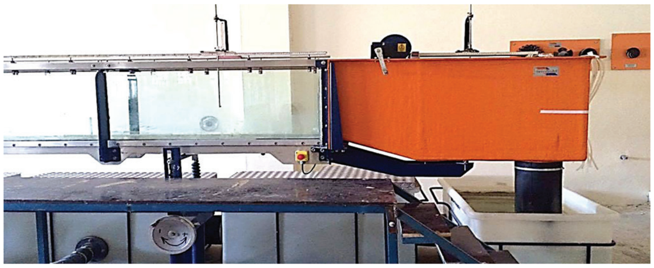

Fig. 3. Location of the overshot gate in the laboratory flume.

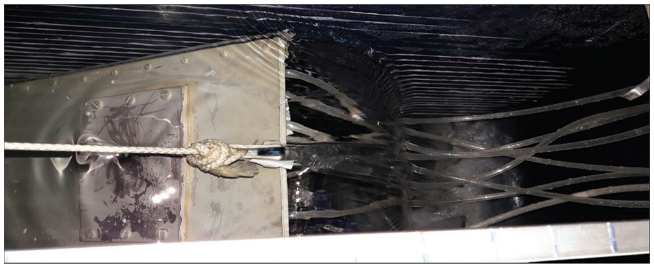

Fig. 4. Ventilation of the overshot gate.

However, when p is between 46 and 54 cm, Q_{act} increases with the increase of p which may be attributed to the fact that the increased gate inclination reduces the lower nappe. At p between 56 and 60 cm, lower flow rates can pass over the gate since raising the gate causes the water level to rise until the gate is completely vertical, and thus, the structure operates under minimum required head to avoid overflow of the approach channel.

It is worth mentioning that uncertainties in the head measurement in the present laboratory work may be attributed to the water surface fluctuations due to turbulent flow with Reynold's number Re ranging from 9000 to 72000, and the fact that the crest of the gate does not exactly resemble the crest of a sharp-crested weir. The percentage error in the head measurement for each gate inclination is presented in Fig. 6 with an average of 6.75% for the entire experimental program.

The relationship between inclination angle of the gate and the actual discharge is shown in Fig. 7. For each value of

TABLE I

Scope of the Experimental Variations

P (cm)	θ (°)	Number of tests	Range of Q (m^3/s)	
			From	To
10	9.6	10	0.01465	0.02346
12	11.5	10	0.01484	0.02342
14	13.5	10	0.01536	0.03302
16	15.5	10	0.01537	0.03318
18	17.5	10	0.01536	0.03301
20	19.5	10	0.01542	0.03311
22	21.5	10	0.01525	0.03286
24	23.6	10	0.01535	0.03279
26	25.7	10	0.01528	0.03285
28	27.8	10	0.01504	0.03268
30	30	10	0.01537	0.03286
32	32.2	10	0.01523	0.03283
34	34.5	10	0.01524	0.03268
36	36.9	10	0.01516	0.03274
38	39.3	10	0.01522	0.03276
40	41.8	10	0.01502	0.03267
42	44.4	10	0.01499	0.03051
44	47.2	10	0.01019	0.01899
46	50.1	10	0.01026	0.01919
48	53.1	10	0.01028	0.01909
50	56.4	10	0.00522	0.01395
52	60.1	10	0.00521	0.01398
54	64.2	10	0.00420	0.00862
56	69	10	0.00207	0.00425
58	75.2	10	0.00148	0.00278
60	90	10	0.00142	0.002775

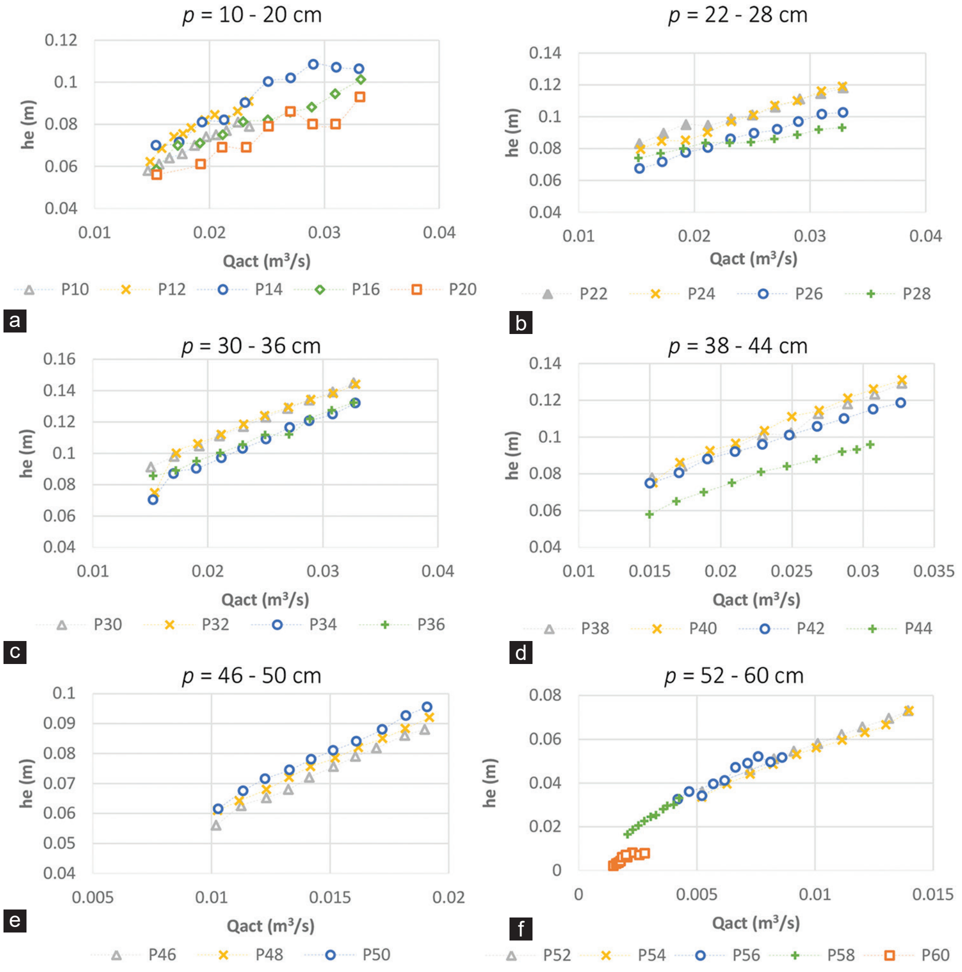

Fig. (a-f) 5. Variation of Q_{act} with h_e.

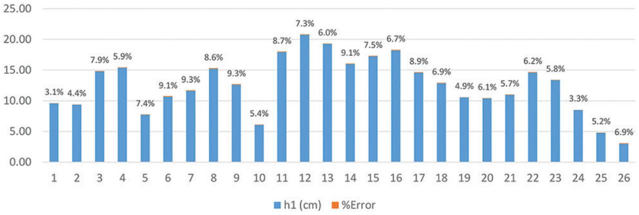

Fig. 6. Average percentage error in h_1 for each θ.

θ, the value of Q_{act} is taken as the mean value of the whole range of the measured values of Q_{act}. Maximum values of flow rates are possible in the cases when θ is about 13.5° through 47.2°. Accordingly, the free board of the channel may be reduced in these cases for a more economical design (Shivapur, Mulangi and Swamy, 2009). The values of θ smaller than 13.5° exhibit characteristics of instability due to the intermittent clinging of the nappe to the gate surface. Similar behavior is observed at very low heads on almost all gate angles. This may be attributed to that the streamlines are no longer parallel and converge further when compared to the vertical gate. On the other hand, laboratory investigations show that for a given head value, the discharge decreases with the increase in gate inclination. It was also indicated in (Prakash and Shivapur, 2004) that lower gate angles allow for higher discharges. Fig. 7 also shows that the discharge capacity of the gate decreases at the values of θ greater than 47.2°, as mentioned earlier, and reaches its minimum at θ = 90°.

The discharge coefficient is also a form of the Froude number (Kindsvater, 1964). Froude number is a dimensionless parameter that refers mainly to the amount of the velocity. From the laboratory data, Q_{act} can be plotted against the upstream Froude number, Fr_1, for each gate inclination. There is a unique Fr_1 value for each flow state; this relation is given in Fig. 8. There is a clear trend for Fr_1 with each different discharge level. The result appears sensitive to the gate inclination, it indicates the water surface stability especially at the highest gate inclinations where the lowest values of Fr_1 are encountered.

The discharge coefficient C_d determines the ratio between the actual and the theoretical discharge. The variation of Q_{th} with Qact for every value of θ is presented in Fig. 9 where it may be noticed that the values of C_d are high at the relatively smaller gate angles.

The ratio of the head to gate height h_1/p is a primary geometric ratio that describes the degree of vertical contraction of the channel. The upper and lower nappe profiles are a function of h_1/p (Carter, 1956). Its variation with the gate

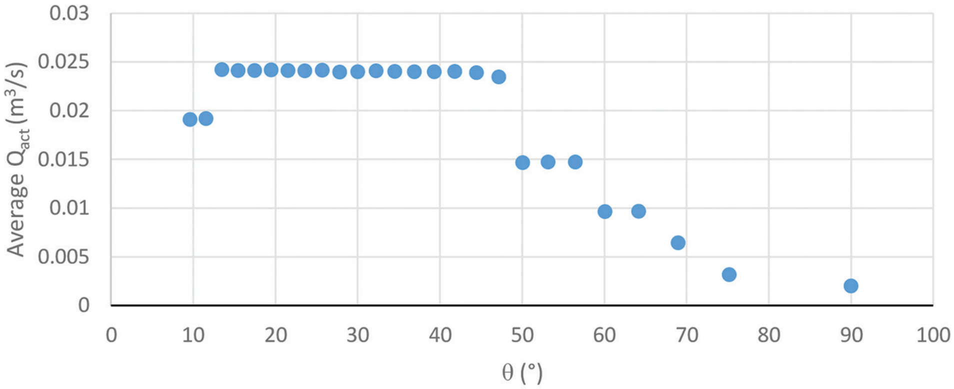

Fig. 7. Variation of Q_{act} with θ.

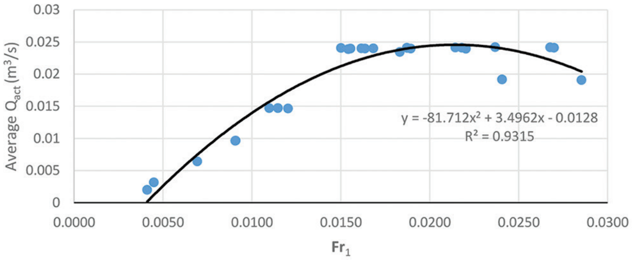

Fig. 8. Variation of Q_{act} with Fr_1.

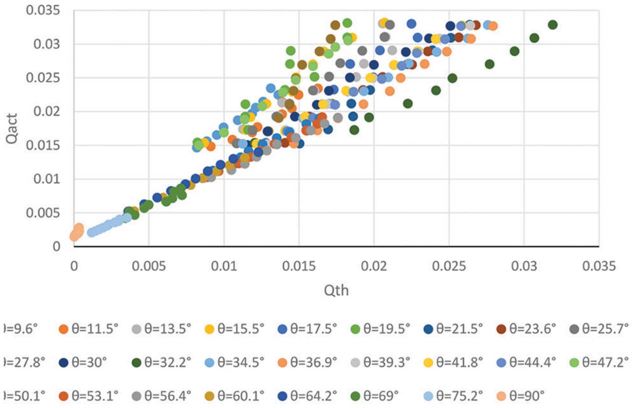

Fig. 9. Variation of Q_{th} with Q_{act}.

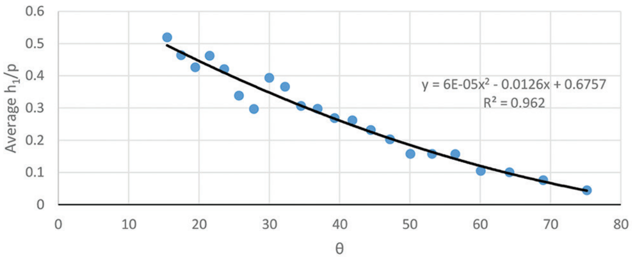

Fig. 10. Variation of h_1/p with θ.

inclination is shown in Fig. 10. The trend obviously declines with a considerable consistency as the vertical contraction of the channel decreases with raising the gate.

For estimating the C_d values, a cubic equation is proposed as the function of θ, such that:

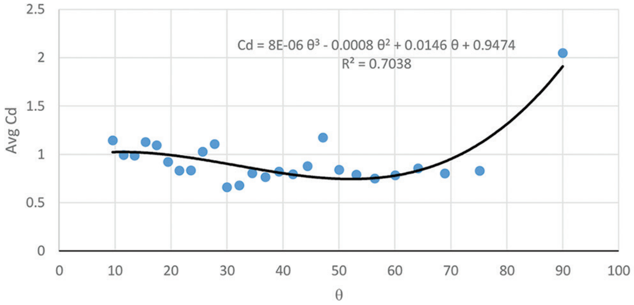

Fig. 11. Variation of C_d with θ.

$$C_d = 0.000008\theta^3 - 0.0008\theta^2 + 0.0146\theta + 0.9474 \qquad (6)$$

The empirical formula is valid within the ranges of θ = (9.6°–90°), Q = (0.00148–0.03413) m³/s. As a result, the overshot gate is reliable as a flow-measuring device. Fig. 11 displays this relation with the mean square error MSE = 0.0287 and the root mean square error, RMSE = 0.17.

V. CONCLUSION

With the increase in water demand and decrease in water resources, the issue of water measurement increasingly attains importance. In the present work, it is aimed to examine the measurement capability of the overshot gate equipped at the downstream end of a laboratory flume. A wide range of gate angles are investigated under different free flow conditions. From analyzing the performance of the gate, the following conclusions may be drawn:

1. At the maximum gate inclination, the structure operates under minimal applicable heads and thus lower flow rates pass over the gate. In addition, the water surface is significantly stable having the lowest values of the approach Froude number.
2. At very small inclination angles, the gate behaves hydraulically like a free overfall. The flow exhibits characteristics of instability and the recurrent clinging to the gate surface, that is, the water nappe becomes in close contact with the downstream face of the gate and resists separation.
3. For a given discharge, the head over the crest increases with the increase in gate height, then it starts to decrease. The

head to gate height ratio decreases with raising the gate due to the reduced vertical contraction of the channel.

4. An empirical formula for estimating C_d is proposed for application within a broader range of θ than the formulae in the literature with acceptable accuracy, which makes the overshot gate reliable as a flow-measuring device.

For future research, there is potential for improvement in the gate performance using deeper laboratory channel than in the present study. This would allow for a wider range of discharges at the maximum gate inclination without causing the flow to overtop the channel sides.

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