International Journal of Civil Engineering and Technology (IJCIET)
Volume 7, Issue 4, July-August 2016, pp. 314–328 Article ID: IJCIET_07_04_027
Available online at
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

DETERMINATION OF DISCHARGE COEFFICIENT FOR FLOW OVER ONE CYCLE COMPOUND TRAPEZOIDAL PLANFORM LABYRINTH WEIR

Anees K. Idrees, Riyadh Al-Ameri and Subrat Das
School of Engineering,
Deakin University, 3216 Australia

ABSTRACT

Weirs are common structure to regulate discharge and flow control in water conveyance channels and hydraulic structures. labyrinth weirs considered one of economical and effective methods to increase the efficiency of weirs that crest length of weirs increasewithout a related increase in structure width.Therefore, flow discharge will be increase. Compared to use compound weir, there are some benefits including the simultaneous passage of floating materials such as wood, ice, etc. Also, sedimentations are pass through compound weir. The trapezoidal Labyrinth weir is one of the combined models. In present study 15 physical models that discussion effect changes sidewall angle of labyrinth weir on discharge coefficient of flow over and through the compound trapezoidal one cycle Labyrinth weir. Also, it is developed design curves with various shapes and configurations. The research showed here mainly objectives at determining the coefficient of discharge for flow-over trapezoidal labyrinth weir by performing tests at wide range of values of side wall angles (α) from 6° to 35° and compound linear weir to be compared.

Key words: Trapezoidal Plan Form Weir, Coefficient of Discharge, Nappe, Flume

Cite this Article: Anees K. Idrees, Riyadh Al-Ameri and Subrat Das, Determination of Discharge Coefficient For Flow Over One Cycle Compound Trapezoidal Planform Labyrinth Weir. *International Journal of Civil Engineering and Technology*, 7(4), 2016, pp.314–328.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4

1. INTRODUCTION

Labyrinth weirs were considered one of the interesting shapes of hydraulic structures because it is a linear weir in plan-view, while it is more complex than linear weir behaviour. Labyrinth weirs have been used to increase discharge efficiency over the weir, compared with traditional weirs, without varying the overall width and overall upstream head(Crookston 2010). The flow capacity of a labyrinth weir depends on the total head over the crest, the coefficient of the crest and the effective crest length. The crest coefficient depends on different variables of geometry, such as the weir height, the crest shape in planform, head over the crest, apex shape and sidewall angle and sidewall thickness of the weir. The geometric labyrinth weir parameters are illustrated in Figure (1).Early studies were conducted to provide initial visions about the behaviour of labyrinth weirs. However, because each study had limited scope, it provided insufficient information for the general design of labyrinth weirs. Taylor, (1968) conducted the first study on the labyrinth weirs that was typically related to the characteristics of weirs. This study provided sufficient information for a general design of labyrinth weirs. Hay and Taylor (1970) conducted an experimental study by using a trapezoidal, rectangular, and triangular labyrinth weir. They reported outcomes using the changing flow magnification ratio, Q/Qn, described as the ratio between the labyrinth weir discharge, Q, according to a given head h and the discharge, Qn, flow discharge by the linear weir for the same head value. Houston, (1982) conducted a model study of the Ute dam labyrinth spillway, and found that the diagram constructed by Hay and Taylor (1970) was not reliable. Cassidy et al., (1985) stated that for maximum heads, the diagram of Hay and Taylor (1970) was used to produce discharge 20 – 25 % less than those measured on their hydraulic labyrinth weir model.Tullis et al., (1995) suggested a relationship for designing labyrinth weirs. A sidewall angle α, varying from 6° to 35°, was used and the crest shape was used a quarter round of the upstream side. The authors determined regression equations to calculate the coefficient of discharge, these equations were dependent on the variation of the coefficient of discharge (Cd), with both the ratio of total head and weir height (HT/P) and a different sidewall angle α. Ghare et al., (2008) proposed a methodology for the best possible hydraulic design of trapezoidal labyrinth weir utilizingregression analysis and also suggested a mathematical model for finding the optimum value of the coefficient of discharge for labyrinth weirs. Tullis and Crookston, (2008) developed the Tullis method, involving an improvement to the design curve for a labyrinth sidewall angle of 8 degrees. Ghodsian, (2009) used dimensional analysis for finding a relationship for modelling the outflow procedure of a triangular labyrinth weir. Khode and Tembhurkar, (2010) carried out a study on trapezoidal labyrinth weirs. They conducted assessment and analysis to compare coefficients of discharge using the two methods from (Lux III, 1984) and Tullis (1995).Khode et al., (2012) carried out a study on flow characteristic over trapezoidal labyrinth weirs by using physical models having a range of sidewall angles of 8^0 to 30^0.Crookston et al., (2012) developed six models of α = 15° trapezoidal labyrinth weirs. Three of these models kept constant values of P, Ac, tw, α and varied values of w, N, and lc. Their results were explained as increases in the Ac / lc ratio, while there is a significant decrease in cycle efficiency. Crookston et al., (2012) examined three physical models of labyrinth weirs to investigate the effects of differing the width ratio (w/P) on discharge efficiency. Recently some researchers have turned to the study of new types of labyrinth weirs for obtaining the best hydraulic performance. From these models are labyrinth weirs which contain one stage or notch. However, this will give more accurate information for understanding the flow characteristics of notched and staged labyrinth weirs. In addition, it will help the engineers in estimating and replacing the structure more efficiently and accurately. Dabling and Crookston, (2012)investigated the discharge efficiency of the labyrinth weirs that have used stage and notch sections of crest.Dabling et al., (2013) investigated the hydraulic performance of labyrinth weirs that consist of two crest elevation as a function of the various staged labyrinth weir configurations (e.g. staged wall height, location and stage length).Mirnaseri and Emadi, (2014) examined five physical models of rectangular labyrinth weir with gate. They investigated effect height and effective length of weir with different slope of flume on coefficient of discharge through flow over and under the compound rectangular labyrinth weir -gate. In the present study conducted to investigate effect the range sidewall angle 6^o to 35^o and linear for comparing. The design curves were obtained from experimental data and relationship between coefficient of discharge and dimensionless term HT/P of one cycle compound labyrinth weir.

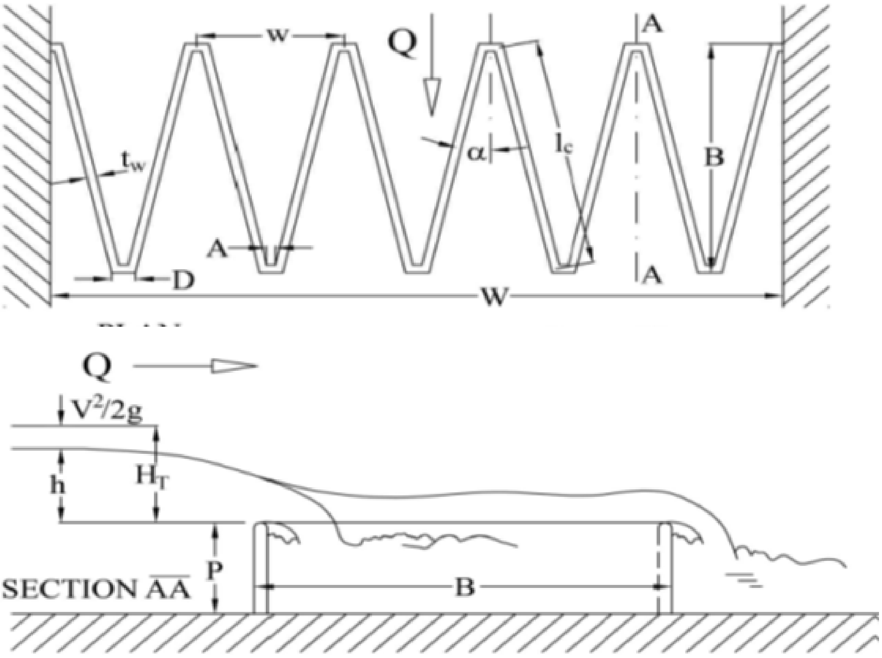

Figure 1 The geometric labyrinth weir parameters

2. MATHEMATICAL EQUATION FOR COMPOUND LABYRINTH WEIR

The flow over labyrinth weir is three dimensional and does not readily fit into mathematical description and hence the discharge function is found through experimental studies and analysis. The capacity of labyrinth weir is a function of total head, the effective crest length and the crest coefficient. The crest coefficient depends on the total head, weir height, thickness, crest shape, apex configuration and angle of side wall. To simplify the analysis, the effect of viscosity and surface tension could be neglected by selecting model and velocity of sufficient magnitude. With this assumption only important parameter is the gravitational acceleration which is the ratio of specific weight and density of fluid. For the practical reasons, it is more suitable to represent the crest coefficient as non- dimensional parameter. The crest coefficient is dependent on the same variable influencing a linear weir plus the configuration of the labyrinth at its apex and the angle of the labyrinth. To compute the discharge coefficient for compound labyrinth weir, the following equation may be obtained by discharge over crest labyrinth weir and the discharge through the groove of weir that can be expressed as

$$Q_{theo} = Qgtheo + Q_{wtheo} \qquad (1)$$

Where: Q_{gtheo}, $Q_{wtheo}$are theoretical discharge through the groove and over crest of weirrespectively which can be expressed as follows

$$Q_{wtheo} = \frac{2}{3}\sqrt{2g} * L_c * H_T^{1.5} \qquad (2)$$

Where, $H_T = h_o + \frac{V^2}{2g}$, HT: total head, ho: head over crest of weir. V: velocity, g: gravitation acceleration

$$Q_{gtheo} = \left[\frac{4}{3} * \sqrt{\frac{2g}{3}} * b_1 * H_T^{1.5} + \frac{32}{25} * \sqrt{\frac{2g}{5}} * \tan\frac{\theta}{2} * H_T^{1.5}\right] \qquad (3)$$

Where, $H_T = h_l + \frac{V^2}{2g}$, HT: total head, h1: head over crest of groove, b1: groove width

$$Q_{gact} = Cd_g * Q_{gtheo} \qquad (4)$$

$$Q_{wact} = Cd_w * Q_{wtheo} \qquad (5)$$

Where, $Q_{gact,}$ $Q_{wact}$are actual discharge through the groove and over crest of weir respectively.

$$Q_{act} = Cd_g\left[\frac{4}{3} * \sqrt{\frac{2g}{3}} * b_1 * H_T^{1.5} + \frac{32}{25} * \sqrt{\frac{2g}{5}} * \tan\frac{\theta}{2} * H_T^{1.5}\right] + Cd_w\left[\frac{2}{3}\sqrt{2g} * L_c * H_T^{1.5}\right] \qquad (6)$$

Where, $Cd_{g,}$ Cd_w are discharge coefficient for the groove and the weir respectively. For the compound discharge through the groove and over weir can be expressed as following:

$$Q_{act} = Cdc\left[\frac{4}{3} * \sqrt{\frac{2g}{3}} * b_1 * H_T^{1.5} + \frac{32}{25} * \sqrt{\frac{2g}{5}} * \tan\frac{\theta}{2} * H_T^{1.5} + \frac{2}{3}\sqrt{2g} * L_c * H_T^{1.5}\right] \qquad (7)$$

3. EXPERIMENTAL SETUP

3.1. INSTRUMENTATION

The present study conducted at the Deakin University civil lab, the tilting rectangular laboratory flume with dimensions (7.5 cm width, 25 cm depth and 500 cm length) is composed of acrylic panels for the walls and a steel framework. It contains one jack for bed slope, adjusted manually, for this study the longitudinal bed slope is set to zero. Flexible pipe supplies the water to the flume with diameter 2 in (5 cm) as shown in Figure (2). In the downstream flume exit, there is a sluice gate to control and regulate the tail water level. The source of the water is a tank with capacity 250 L. The water is pumped by a pump with a flow rate between 10 - 150 L/min. Water depths are measured using point gauges located (3h) upstream of the weir. The location of the weir is 1 m from the inlet point. Staff gauges fixed on the flume walls were used for verification of point gauges. Water flow rates are measured by using a digital flow meter. Water temperatures were taken with a thermometer with a range of 58°F to 302°F and readable to ±0.05°F. A movable pointer gauge, with an accuracy of 0.1 mm, fixed on the flume side rails was utilised to measure water depths. Also, a digital camera was used to document weir flow behaviour.

Figure 2 Tilting rectangular laboratory flume at Deakin University civil lab.

3.2. MODEL DESCRIPTION

Experimental work conducted on 15 model configurations. The models were fabricated of wood with thickness 0.5 cm and painted with pigments as explain in figure (3). All models were trapezoidal compound labyrinth weirs. Tables (1) show the physical model test program. Each model was tested in normal and reverse flow orientation. Crookston and Tullis, (2011) noted that when the outside apexes of a labyrinth weir fix to the flume wall at the upstream or starting region of the apron, it is called a “normal orientation”, see Figure (4). While, when apexes fix to the flume wall at the downstream end of the apron, it is called an “inverse orientation.

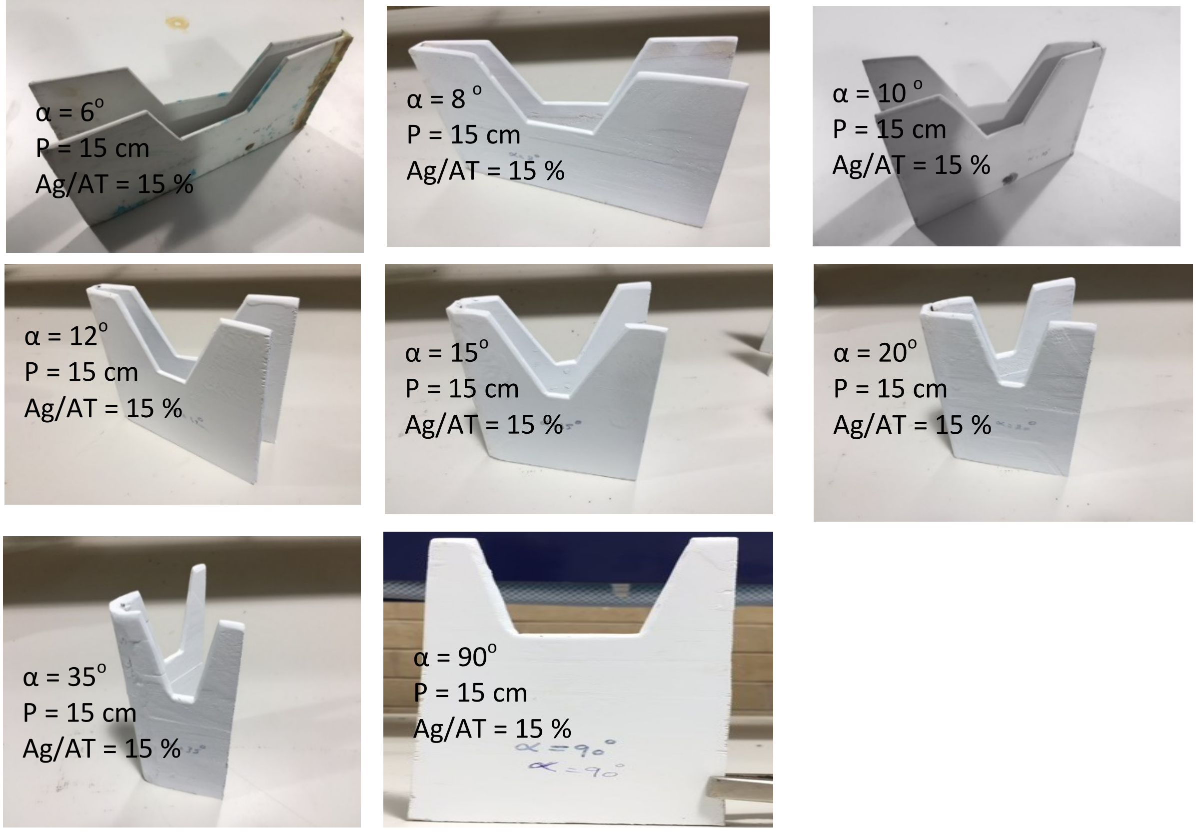

Figure 3 Shows the tested models

Table 1: Physical model test program

Model	α degree	P (cm)	B (cm)	Lc-cycle (cm)	N	Ag= groove area for two legs cm^2	A_T = total area for two legs cm^2	Ag/A_T	Crest shape	Type	Orientation
1	6	15	28.5	58.4	1	129.1	861.0	15%	HR	Trap.	Normal & Reverse
2	8	15	21.5	44.3	1	97.5	650.0	15%	HR	Trap.	Normal & Reverse
3	10	15	17.2	35.9	1	78.5	523.6	15%	HR	Trap.	Normal & Reverse
4	12	15	14.3	30.3	1	65.9	439.4	15%	HR	Trap.	Normal & Reverse
5	15	15	11.4	24.7	1	53.3	355.4	15%	HR	Trap.	Normal & Reverse
6	20	15	8.5	19.1	1	40.8	271.9	15%	HR	Trap.	Normal & Reverse
7	35	15	4.6	12.1	1	25.0	166.8	15%	HR	Trap.	Normal & Reverse
8	90	15	-	7.4	-	16.7	111.0	15%	HR	Trap.	-

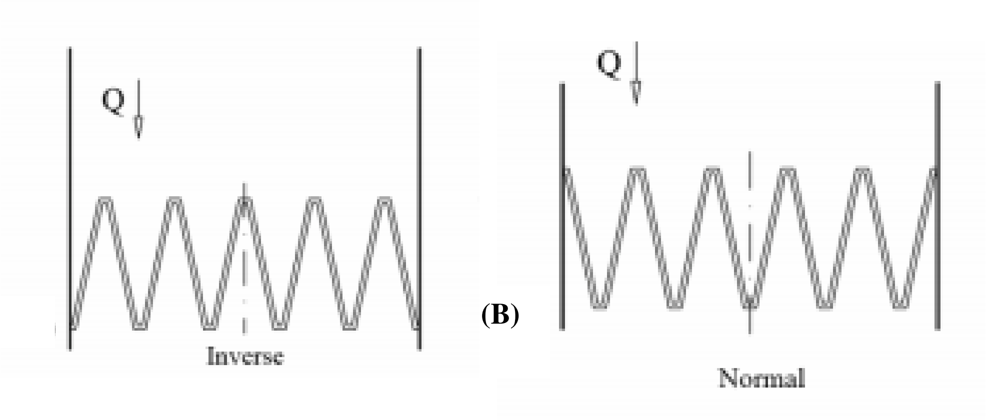

Figure 4 Labyrinth Weir Orientations (Crookston and Tullis, 2011)

4. RESULTS AND DISCUSSIONS

Experimental work is conducted investigate the characteristics of discharge of compound labyrinth weirs under free flow conditions. The examinations are carried out on the one-cycle trapezoidal compound labyrinth weir models with half round crest and various sidewall angles 6^o to 35^o for the first group. The sidewall angle for α (90° linear) were also included for comparison. The second group conducted the examinations on labyrinth weirs with sidewall angle 20^o to investigate the effect of height of weir and groove area on the coefficient of discharge. There were 10 readings carried out for each tested weir geometry (150 total). The discharge was adjusted for each test in the range between 15 L/min to 150 L/min.

The present study used the equations (7) to calculate the compound coefficient of discharge. The term Cdc can be affected by weir geometry (e.g., P, α, A, w, tw, and crest shape), weir abutments, flow conditions (e.g. HT, local submergence, approaching flow angle and nappe interference), and nappe aeration conditions (Crookston and Tullis, 2012).Figures (5), (6)show the relationship between the compound discharge coefficient Cdc (α°) with dimensionless term HT/P for normal and inverse orientation with half round crest. In general, it can be noticed that there is a maximum value for the compound discharge coefficient in each of the curves, then followed by the long depression limb. For all angles $\alpha° = 90^o, 35^o$, and 20^o at $H_T/p = 0.2$, the compound discharge coefficient slightly increased because the flow nappe was the sudden removal of the air cavity behind the nappe (Crookston and Tullis, 2011). Then the compound discharge coefficient reduces with increasing HT/P because the flow nappe from adjacent crestscollide with each other, resulting in a non-aerated nappe (e.g., HT/P = 0.35 for $\alpha = 15^o$), also see figures (7), (8).

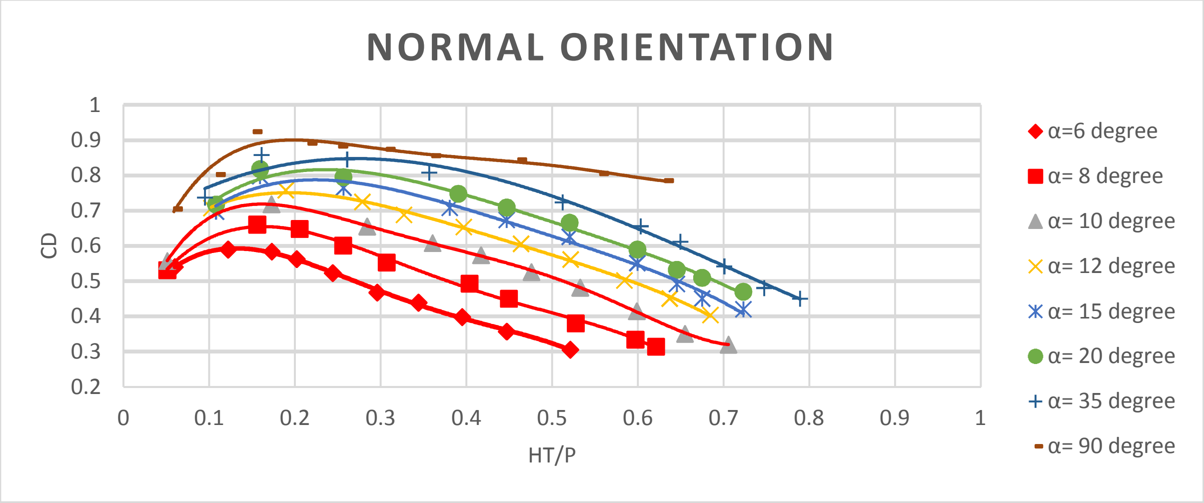

Figure 5 Values of Cdc versus Ht/P for half round trapezoidal compound labyrinth weir

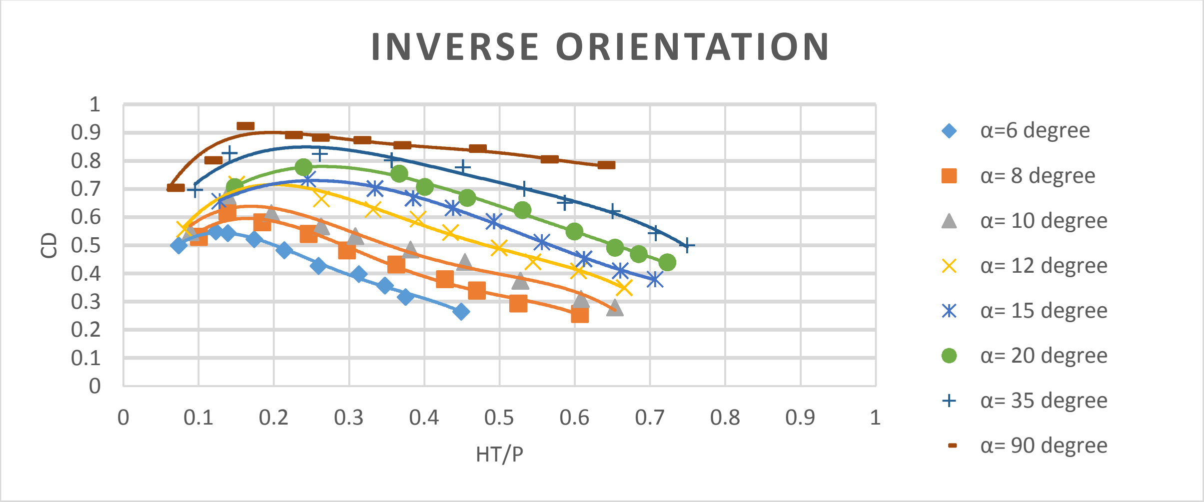

Figure 6 Values of Cdc versus Ht/P for half round trapezoidal compound labyrinth weir

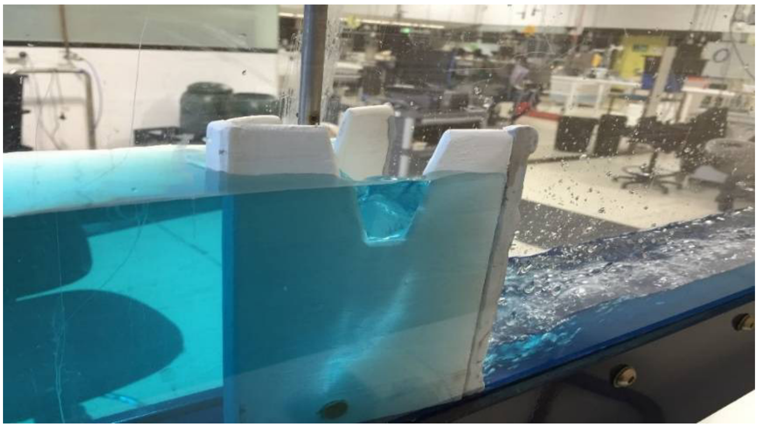

Figure 7 Explain effect of nappe interference before the submerge with α°= 20°.

Figure 8 Nappe interference in adjacent crest that observe collisions with each other with α°= 15°.

Compound discharge coefficient increases with increasing sidewall angle (α°) because that reduces the length of the crest for limit width of weir, hence decreasing the effect region of the nappe interference, see figure (9).

To represent the data in equation form, the set of curves in figures (5), (6) are shown in tables (2), (3); it is found that 4th degree polynomial fit by regression analysis is good to get the relationship between Cdc and HT/P. These equations are valid for width of apex $t \leq A \leq 2t$, $HT/P \leq 0.75$, crest shape is a half round. This relationship can be expressed as equation (8).

$$Cdc = A_4E^4 + A_3E^3 + A_2E^2 + A_1E^1 + A_O \quad (8)$$

For E = HT/P

The value of Cdc does not differ significantly with a variation of α. So that, each of the equations can be utilised for angles close to those listed. In the case where the angles vary by more than about ± 1° from those explained in tables (2), (3), a new regression equation should be developed or the data interpolated from figures (5), (6) (Tullis et al., 1995).

Table 2 Polynomial equations for set of curves representing the relationship between Cdc& HT/P with normal orientation.

Model	α degree	Orientation	Polynomial equation	R2
1	6	Normal	Cdc = -33.349 E 4 + 46.815 E 3 - 23.232 E 2 + 3.9778 E + 0.3753	0.9984
2	8	Normal	Cdc = -22.398 E 4 + 36.61 E 3 - 21.339 E 2 + 4.4195 E + 0.3588	0.9954
3	10	Normal	Cdc = -11.809 E 4 + 22.164 E 3 - 15.285 E 2 + 3.7637 E + 0.4059	0.9922
4	12	Normal	Cdc = -9.8403 E 4 + 17.734 E 3 - 12.113 E 2 + 2.9717 E + 0.5148	0.9979
5	15	Normal	Cdc = -10.246 E 4 + 19.662 E 3 - 14.325 E 2 + 3.9135 E + 0.4345	0.9842
6	20	Normal	Cdc = -8.5122 E 4 + 17.213 E 3 - 13.268 E 2 + 3.825 E + 0.4529	0.9862
7	35	Normal	Cdc = -8.8315 E 4 + 17.637 E 3 - 13.403 E 2 + 3.8652 E + 0.4892	0.9894
8	90	Normal	Cdc = -28.464 E 4 + 45.875 E 3 - 26.261 E 2 + 6.0126 E + 0.4303	0.9147

Table 3 Polynomial equations for set of curves representing the relationship between Cdc& HT/P with normal orientation

Model	α degree	Orientation	Polynomial equation	R2
1	6	Inverse	Cdc = -68.343E4 + 84.085E3 - 36.97E2 + 5.8907E + 0.2383	0.9928
2	8	Inverse	Cdc = -32.076E4 + 52.432E3 - 30.01E2 + 6.193E + 0.1788	0.9849
3	10	Inverse	Cdc = -29.835E4 + 48.559E3 - 27.831E2 + 5.8217E + 0.2395	0.9706
4	12	Inverse	Cdc = -23.802E4 + 42.348E3 - 27.098E2 + 6.5241E + 0.194	0.9838
5	15	Inverse	Cdc = -0.6401E4 + 5.5786E3 - 7.8215E2 + 2.9366E + 0.3999	0.9984
6	20	Inverse	Cdc = -6.3118E4 + 15.129E3 - 13.537E2 + 4.4531E + 0.3001	0.9954
7	35	Inverse	Cdc = -12.358E4 + 23.581E3 - 16.885E2 + 4.7369E + 0.3998	0.974
8	90	Inverse	Cdc = -28.464E4 + 45.875E3 - 26.261E2 + 6.0126E + 0.4303	0.9147

Figure 9 Effect of increasing length of crest on reducing nappe interference, then increasing compound discharge coefficient for α°= 8°,α°= 20°.

The labyrinth weir orientations examined in this study are summarised in Table (1). Falvey, (2003) explained that a labyrinth weir can be placed in the "inverted" or "normal" positions. As shown in figures (5), (6), the values of Cdc are not significantly different for labyrinth weirs located in the flume with both weir orientations. Because the data is collected from one cycle weir, therefore the number of apex in both orientations is equal. Then the nappe interference has less effect. Figure (10) explains the Comparison of Average, minimum, and maximum for Cdc values with sidewall angle (α), according to weir orientation for half round trapezoidal compound labyrinth weirs. Table (4) is a description of statistical analysis for the compound coefficient of discharge, according to different flow orientations and sidewall angles for labyrinth weirs. The statistical results show that $\alpha = 20^o$ is the best angle for normal orientation, based on coefficient of variance (CV) that gave less value 18.8 %. While, in the inverse orientation the $\alpha = 35^o$ was best angle for coefficient of variance (CV) 16.7% compared with others.

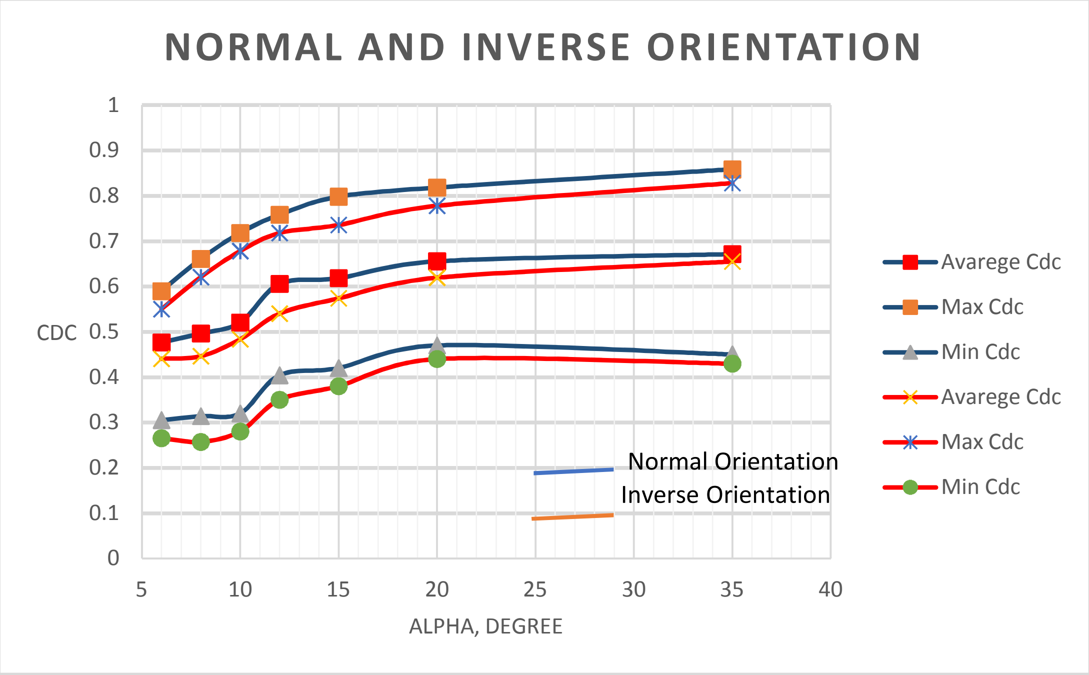

Figure 10 Comparison between Cdc values with angle of sidewall according to weir orientation for half round trapezoidal compound labyrinth weir

Table 4 Description of statistical analysis for compound coefficient of discharge according to different of flow orientation and angle of side wall for labyrinth weir

Normal Orientation						
Alpha, degree	**Average (Cdc)**	**Max (Cdc)**	**Min (Cdc)**	**Standard Deviation (Cdc)**	**Variance (Cdc)**	**Coefficient of Variance C.V= Stdev/mean x 100 %**
6	0.477	0.59	0.306	0.1	0.01	20.9
8	0.497	0.661	0.314	0.125	0.016	25.2
10	0.521	0.718	0.32	0.129	0.017	24.8

Normal Orientation						
12	0.606	0.758	0.405	0.122	0.015	20.1
15	0.619	0.798	0.42	0.133	0.018	21.5
20	0.656	0.818	0.47	0.123	0.015	18.8
35	0.672	0.858	0.45	0.148	0.022	22
Inverse Orientation						
Alpha, degree	**Average (Cdc)**	**Max (Cdc)**	**Min (Cdc)**	**Standard Deviation (Cdc)**	**Variance (Cdc)**	**Coefficient of Variance C.V= Stdev/mean x 100 %**
6	0.441	0.55	0.266	0.103	0.011	23.4
8	0.446	0.621	0.257	0.125	0.016	28.1
10	0.484	0.678	0.28	0.131	0.017	27
12	0.54	0.718	0.35	0.117	0.014	21.6
15	0.574	0.736	0.38	0.127	0.016	22.1
20	0.62	0.778	0.44	0.123	0.015	19.9
35	0.655	0.828	0.43	0.116	0.013	16.7

VALIDATION OF DATA

The comparison between the Cd prototype dams is achieved with Cd estimated from equations in table 2. There are eight prototype dams having labyrinth weir have been used for validation. Table.5 shows the comparison of Cd prototype dam from previous published by(Khode et al., 2011) and Cdc estimated from equations in table 2. The estimated value of coefficient of discharge have been calculated using regression equations in table 2, The intermediate values of discharge coefficients have been calculated by interpolating discharge coefficients of close side wall angles. Table 5 shows that the Cd of prototype dam calculated by (Khode et al., 2011)and Cdc estimated from equations in table 2.The different was between ± 6 %.

Table 5 Comparison between the Cd of prototype dam calculated by (Khode et al., 2011) and Cdc estimated from equations in table 2

Location	**Sidewall angle**	**Weir Height (m)**	**Total Head (m)**	**Head to Weir Height Ratio (HT/P)**	**Number of Cycles**	**Total Crest Length (m)**	**Prototype dam flow (m3/sec)**	**Cd Prototype Dam calculated by (Khode et al., 2011)**	**Cdc Estimated from Eq. in table 2**	**% Diff. between Cd Prototype Dam and Cdc Estimated from Eq. in table 2**
Avon Dam, Australia.	27.5	3.05	2.16	0.71	10	265	1420	0.572	0.539	-5.86
Bartletts Ferry, U.S.A.	14.5	3.43	2.44	0.71	20.5	1441	6796	0.419	0.415	-0.95
Boardman, USA.	19.44	3.53	1.8	0.51	2	109.2	387	0.497	0.525	5.72
Carty, USA.	19.4	2.76	1.8	0.65	2	109.2	387	0.497	0.526	5.85
Dungo, Angola.	15.2	4.3	2.4	0.56	4	115.5	576	0.454	0.475	4.72
Hyrum, USA.	9.14	3.66	1.82	0.50	2	91.44	262	0.395	0.411	3.98
Navet, Trinidad	23.6	3.05	1.68	0.55	10	137	481	0.546	0.562	2.96
Ute Dam, U.S.A.	12.15	9.14	5.8	0.63	14	1024	15574	0.369	0.387	4.78

5. CONCLUSION

Labyrinth weirs have gained greater common application in the world due to their inherent advantage in linking with flow increase and structural stability. They can pass unexpected discharging floods over structure safely. The design is appropriate for utility at sites where the head over crest is limited or the weir width is limited by the topography. The labyrinth weir is considered a successful solution for increase in the storage capacity. The following conclusions are drawn:

1. Coefficient of discharge values were obtained from the design curves based on experimental data from the flume on labyrinth weirs of sidewall angle 6,8,10,12,15,20,35,90 degrees and half round crest
2. The compound coefficient of discharge firstly increases when the head reaches maximum value and then decreases gradually.
3. The compound coefficient of discharge is minimum for a sidewall angle of 6^o and increases with increasing the sidewall angle under restricted width of weir.
4. Regression analysis is a good selection to estimate compound coefficient of discharge for rang α between 6^o to 90^o when the HT < 0.75.
5. The impact of labyrinth weir orientation was evaluated. The present study indicates that weir orientation does not significantly affect efficiency of discharge.
6. The statistical results show that the $\alpha = 20°$ is the best angle for normal orientation based on the coefficient of variance (CV) that gave less value 18.8 %. While, in the inverse orientation the $\alpha = 35°$ was the best angle for the coefficient of variance (CV) 16.7%, compared with others.
7. The different between discharge coefficient of Prototype dam calculated by (Khode et al., 2011)and estimated discharge coefficient from equations in table 2 was between ± 6%.

ACKNOWLEDGEMENTS

The authors would like to express them sincere thanks to the government and Ministry of higher education and Scientific Research in Iraq for providing the financial cover for the study (scholarship for PhD student Anees Kadhum Idrees). They acknowledge the technical assistance of civil lab staff in school of Engineering and Built Environment (Deakin University).

NOTATIONS:

H_T= Total upstream head on weir
P = Weir height
W = Total width of Labyrinth weir
w = Width of one cycle of labyrinth
C_{dc} = Compound coefficient discharge
A = Inside apex width
l = Length of one cycle (2L1+A+D)
L = Effective length of labyrinth =N (2L2+2A)
t = Wall thickness
α = Angle of side edge or labyrinth angle
N = Number of cycle
B = Length of labyrinth apron
L1 = Actual length of a single leg of the labyrinth weir
L2 = Effective length of a leg of the labyrinth weir.

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