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Research paper

Experimental investigation of the discharge coefficient of labyrinth weirs with asymmetric cycles

Hossein Elahifar[1], Omid Tayari[2], Najme Yazdanpanah[1] and Mehdi Momeni[3]

[1]*Department of Water Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran*
[2]*Department of Civil Engineering, Tehran North Branch, Islamic Azad University, Tehran, Iran*
[3]*Department of Civil Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran*

This study investigated the discharge coefficient in asymmetric rectangular labyrinth weirs. A dimensional analysis was carried out which showed that the discharge coefficient is a function of dimensionless parameters, such as the ratio of asymmetric widths of left and right cycles (w_L/w_R), the ratio of the total hydraulic head to the weir height (H_t/P), and the weir length ratio (B/w_{avg}). The experimental results for the discharge coefficient were found to decline as w_L/w_R increased or B/w_{avg} decreased. For $w_L/w_R = 1.19$, the ratio $B/w_{avg} = 2.76$ improves the discharge coefficient by nearly 12.7% compared to $B/w_{avg} = 3.1$. For $w_L/w_R = 1.42$, the ratio $B/w_{avg} = 2.76$ improves the discharge coefficient by nearly 34.2% compared to $B/w_{avg} = 3.1$. For $w_L/w_R = 1.70$, the ratio $B/w_{avg} = 2.76$ improves the discharge coefficient by nearly 30% compared to $B/w_{avg} = 3.1$.

CORRESPONDENCE
Omid Tayari

EMAIL
tayari@iauk.ac.ir

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INTRODUCTION

As hydraulic structures, labyrinth weirs effectively control flow in channels, rivers, and dams. In hydraulic terms, nappe interference downstream of labyrinth weirs improves aeration compared to linear weirs. Besides improving the water quality, aeration reduces the probability of negative pressure and cavitation, decreasing dam maintenance costs (Wormleaton and Soufiani, 1998; Wormleaton and Tsang, 2000; Emiroglu and Baylar, 2005). The main uses of the labyrinth weir, as defined by JafariNodooshan (2010), are to limit the width of the weir, limit the height of the water table upstream of the weir, limit the expansion of the usable capacity of the dam reservoir, and make changes. Several studies have shown that a nonlinear weir design is the solution to achieving high-efficiency, economical structures. The intricate flow pattern and the multitude of uncertainties involved in the hydraulics of labyrinth weirs have led to this design being used in several physical models.

Because of nappe interference at the weir outlet, a smaller discharge coefficient than that of a linear weir of equal duration can be achieved (Hay and Taylor, 1970). In cases where the weir location imposes restrictions on the width of the structure or the water level upstream, labyrinth weirs are effective and economical solutions to increase the discharge capacity (Sangsefidi et al., 2015). Bahrehbar et al. (2018) studied the discharge coefficient in labyrinth weirs of different geometries using FLOW-3D and an experimental model. They made an attempt at numerical investigation using FLOW-3D and the k-ε turbulence model with a 300-mm wide, 400-mm deep conduit, and four different discharge capacities (5, 10, 15, and 20 L/s). They experimented with trapezoidal, square, triangular, and piano-key labyrinth weirs and showed that the triangular labyrinth weir offers the highest discharge coefficient and that the discharge coefficient decreases in all models by increasing the H_t/P ratio. Furthermore, they claimed that the numerical and experimental results were consistent, and that the best H_t/P ratio is maintained within the 0.14–0.42 range, where a peak discharge coefficient of 1.24 can be obtained.

Esmailzadeh et al. (2018) compared numerical and experimental modeling in estimating the discharge coefficient of labyrinth weirs. His research showed that the emission factor decreases as the water pressure ratio (H_t/P) increases, indicating that a natural trend has been established for labyrinth weir efficiency. Moreover, the range of discharge coefficients was above the standard range for discharge coefficients, i.e. $1 < C_d < 0$, which indicates the high hydraulic efficiency of this type of weir. Safarzadeh et al. (2019) studied the effects of the hydraulic head on the distribution of discharge capacity over the crest, and the behaviour of streamlines, on an asymmetric piano-key weir. The higher discharge capacity of a piano-key weir compared to that of a linear weir of the same width was attributed to the extended crest. Parvaneh et al. (2016) studied the discharge coefficient of an asymmetric, triangular labyrinth side weir by the nonlinear partial least-squares (PLS) method. Using data from more than 200 experiments, the authors proposed a nonlinear equation to determine the emission factors of an asymmetric triangular labyrinth weir based on dimensionless geometric and hydraulic specifications. They claimed the proposed relations offer much higher accuracy than their predecessors.

Gebhardt et al. (2017) compared side weirs with labyrinth weirs at the Ilmenau River and employed an empirical stage–discharge relation for side weirs and trapezoidal, rectangular, and triangular labyrinth weirs for free- and submerged flow conditions. According to this study, thanks to its longer crest the labyrinth weir can pass more fluid than the side weir for a smaller hydraulic head, at the cost of a higher upstream head during floods. Furthermore, the side weir offers better performance with a submerged flow. Karimi et al. (2019) examined flow over an asymmetric triangular labyrinth weir at different orientations in an experimental study. The flow characteristics for the asymmetric triangular weir show that the asymmetric labyrinth weir has a higher emission factor than the symmetric labyrinth weir, because more ridges are orthogonal to the flow. In other words, the discharge capacity of the asymmetrical configuration is improved by 50% compared to the symmetric weir.

Bonakdari et al. (2020) estimated the discharge capacity of the labyrinth weir using gene expression programming (GEP). Using the ratio of crest height to the hydraulic head over the weir (w/y or P/y), the ratio of crest length to channel width (L/W), the ratio of crest length to hydraulic head (L/y), Froude number (Fr), and vortex angle (θ), they presented a numerical relation by the GEP method (Eq. 1). The study showed the vortex angle θ to be the least significant among the studied models for estimating the discharge coefficient (C_d). Moreover, it was found that using all parameters in Eq. 1 simultaneously is necessary to estimate the discharge coefficient. Further, Eq. 2, derived by nonlinear regression (NLR), was also presented to estimate the discharge coefficient. In the end, their results showed GEP to be more accurate than NLR.

$$C_d = \exp\,[F - L/b + 1.8] - \exp\,[1 - \exp\,[w/y]] + w/y \times \exp\,[0.034\, L/y\,(\theta - 1)] + 1 - [w/y + \exp\,[L/b + 1.58\, F - \theta + 1.79]] \tag{1}$$

$$C_d = 0.466 + 0.338\,(p/y) - 0.183\,(L/W) - 0.022\,(L/y) + 0.31\,F + 0.12\sin(\theta) \tag{2}$$

In summary, previous studies have focused primarily on symmetric linear labyrinth weirs, indicating that perhaps little research has been done on asymmetric linear labyrinth weirs. In this study, we focused on the asymmetrical width of the labyrinth weir (two-cycle) and the length of the lateral ridge. This was an experimental attempt to investigate the effects of the ratio of asymmetric widths of the left and right cycles (w_L/w_R) and the weir length ratio (B/w_{avg}) on the discharge coefficient and the hydraulic performance of labyrinth weirs.

MATERIALS AND METHODS

The experiments were carried out in an experimental flume at the Hydraulics Laboratory of Khuzestan Province, Iran. The rectangular flume measured 800 mm in length, 600 mm in width, and 600 mm in height. The flume walls were made of clear glass to show the water-surface profile and flow conditions. The flume was equipped with an underground water supply tank, a 90° triangular weir for discharge measurement, a honeycomb, a 50 L/s submersible pump, and a constant head tank, and had a horizontal fixed bed. Figure 1a shows the plan and longitudinal profile of the experimental flume used for the study. Water was first delivered from the underground supply to the head tank elevated to a 600 mm height by the 6” submersible pump, and from where it was sent toward the flume via PE pipes. Inflow to the flume was controlled using a valve placed before the inlet tank, letting the flow into the conduit and over the weir slowly and at a low discharge rate before returning to the underground tank via the downstream conveyance pipe for recirculation. The experimental flume and its installations are depicted in Fig. 1b.

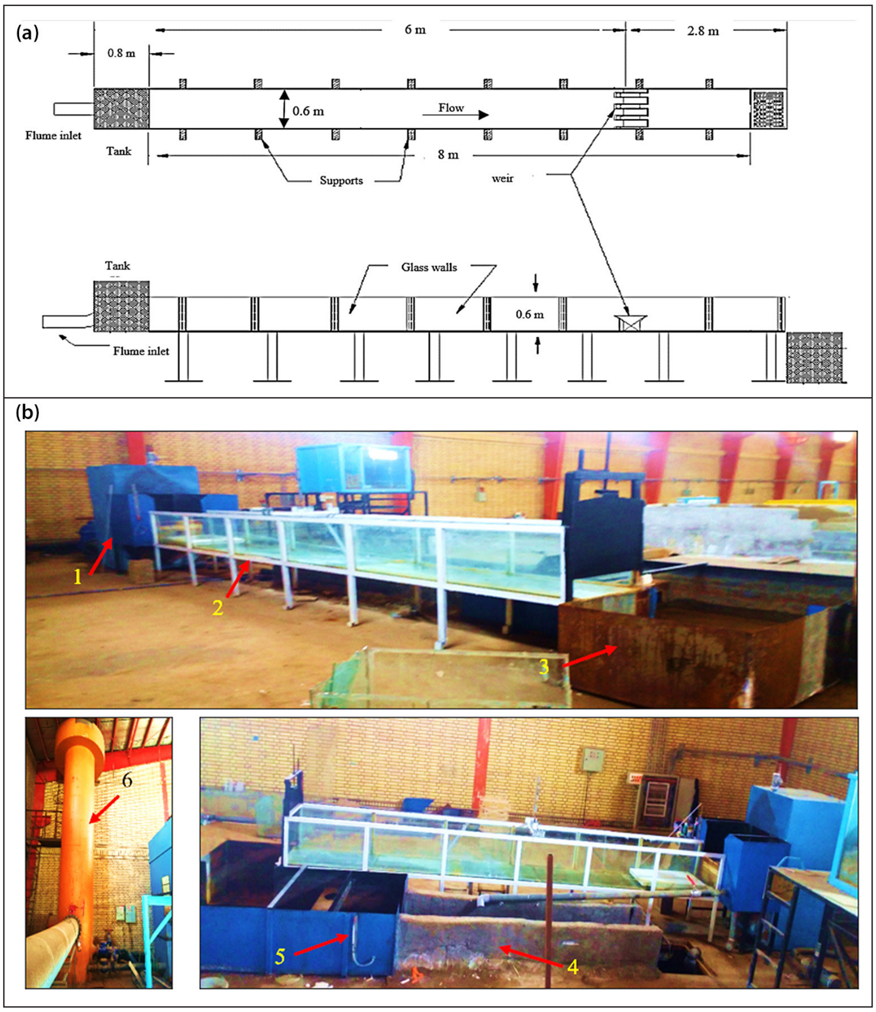

Figure 1. (a) The plan and longitudinal profile of the experimental flume, (b) flume and supporting installations: inlet tank (1), experimental flume (2), outlet tank (3), underground tank (4), manometer (5), head tank (6)

The hydraulic conditions were recorded upstream, over, and downstream of the weir at different discharge rates. The inflow to the flume was measured using a V-notch weir. The weir models prepared and studied were made of 3-mm plexiglas (Fig. 2). Details of the design of asymmetric labyrinth weirs are presented in Table 1.

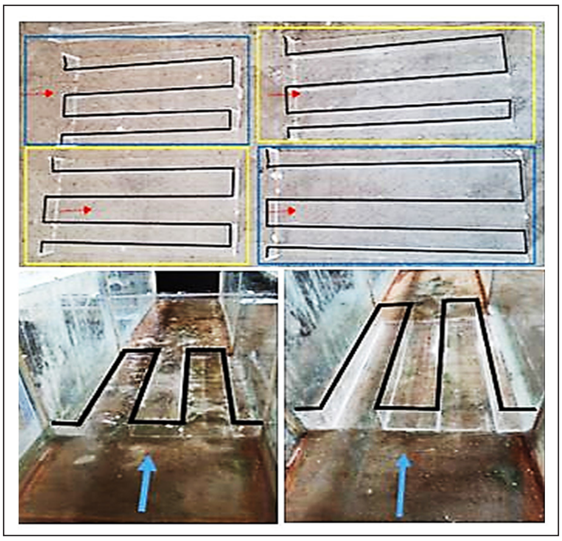

Figure 2. Some of the asymmetric rectangular labyrinth weir models (upper: plan, down: flow direction)

Studies show that submergence has the same effects in labyrinth weirs as in linear weirs. Provided that the tailwater level does not surpass the weir crest, submergence does not affect the weir's hydraulic performance; otherwise, the weir simply becomes an excrescence baffling the flow. In separate studies, Hay and Taylor (1970) and Tullis et al. (2007) have warned against using the labyrinth weir design under severe submergence. According to Anderson and Tullis (2013), the critical parameters in designing a labyrinth weir are as presented in Fig. 3.

Dimensional analysis

The accurate characterization of three-dimensional flow in labyrinth weirs is a complicated task. Energy, momentum, and continuity equations, as well as parameters such as the weir geometry, crest shape, local submergence, nappe interference passing over the weir, non-parallel streamlines, pressure beneath the nappe, whether a cavity forms behind the nappe, and effects of surface tension and viscosity, among others, should be all combined in single relation. Introduced by Tullis et al. (1995), Eq. 3 is the general formula to calculate the discharge capacity of weirs.

$$Q = C_d \frac{2}{3}\sqrt{2g}LH_t^{\frac{3}{2}} \tag{3}$$

where Q represents the weir's discharge capacity, L is the total crest length, g is the gravitational acceleration, H_t denotes the total hydraulic head, and C_d is the dimensionless discharge coefficient,

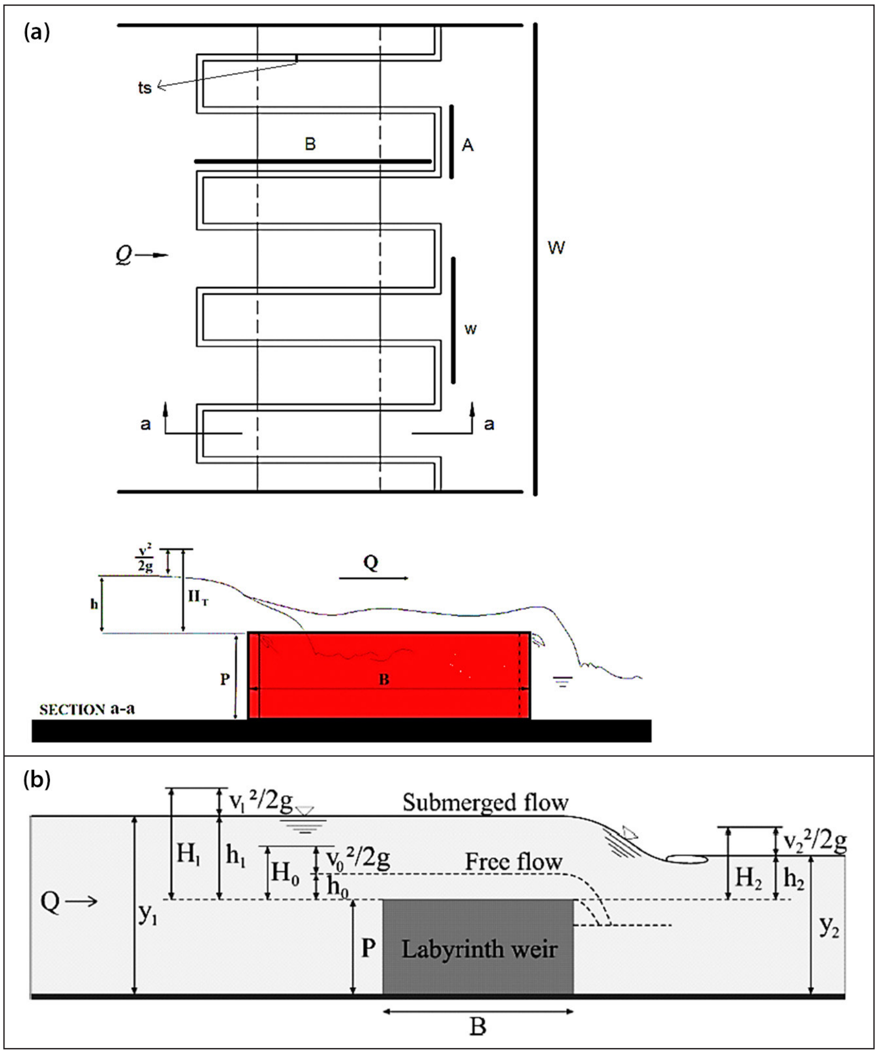

Figure 3. (a) Geometrical parameters of the labyrinth weir; (b) hydraulic parameters of the labyrinth weir (Anderson and Tullis, 2013); *w* is the weir cycle width, *P* is the weir height, t_s is the weir wall thickness, *B* represents the lateral crest length, *A* is the nose width, and *W* is the total weir width

Table 1. Geometrical and hydraulic characteristics of the asymmetric labyrinth weirs

Test no.	Discharge no.	P (mm)	N	t_s (mm)	B/w_{avg}	w_{avg} (mm)	w_L/w_R	w_R (mm)	w_L (mm)	W (mm)	B (mm)	ID model	Weir type
36	12	100	2	3	2.76	290	1.19	265	315	580	800	1	Asymmetric rectangular labyrinth weir
36	12	100	2	3	2.93	290	1.19	265	315	580	850	2	
36	12	100	2	3	3.1	290	1.19	265	315	580	900	3	
36	12	100	2	3	2.76	290	1.42	240	340	580	800	4	
36	12	100	2	3	2.93	290	1.42	240	340	580	850	5	
36	12	100	2	3	3.1	290	1.42	240	340	580	900	6	
36	12	100	2	3	2.76	290	1.70	215	365	580	800	7	
36	12	100	2	3	2.93	290	1.70	215	365	580	850	8	
36	12	100	2	3	3.1	290	1.70	215	365	580	900	9	

which is determined via experimentation. The effective parameters regarding the discharge coefficient of labyrinth weirs are presented in Eq. 4.

$$C_d = f\ (Q, B, S, w_L, w_R, W, w_{avg}, t_s, P, N, H_t, g, \mu, \rho, \sigma) \quad (4)$$

where the discharge coefficient C_d is a function of discharge rate Q, length of the lateral crest B, bottom slope S, the left cycle width w_L, the right cycle width w_R, average width of left and right cycles w_{avg}, the total weir width W, weir wall thickness t_s, weir height P, number of cycles N, total hydraulic head H_t, gravitational acceleration g, dynamic viscosity μ, fluid density ρ, and the fluid surface tension σ. In the dimensional analysis, ρ, P, and Q were considered repeating variables. The dimensionless parameters are, therefore, expressed in Eq. 5.

$$C_d = f\ (B/P, t_s/P, w_L/P, w_R/P, w_{avg}/P, N, H_t/P, S, gP^5/Q^2, \mu P/\rho Q, W/P, \sigma/\rho P) \quad (5)$$

Some of these dimensionless parameters, namely the bottom slope S, weir wall thickness t_s/P, total weir width W/P, and the number of cycles N, were eliminated since they remained constant. Moreover, given the turbulent nature of the flow and the considerable depth of flow in the channel, the effects of the Reynolds ($\mu P/\rho Q$) and Weber number ($\sigma/\rho P$) were also ignored. The effects of gravitational acceleration gP^5/Q^2, which represents the Froude number, were considered in the dimensionless parameter H_t/P. The left (w_L/P) and right (w_R/P) widths were combined to produce a dimensionless and varying parameter, i.e. width ratio of the left and right cycles (w_L/w_R). Furthermore, combining the lateral crest length (B/P) and the average width of the left and right cycles (w_{avg}/P) produced the dimensionless variable B/w_{avg}. Provided that the flow remains in the turbulent regime and the hydraulic head over the weir does not drop below a certain level (based on the minimum and maximum hydraulic heads, the Reynolds number varies from 7 000 to 85 000) and the Weber number varies between 6 149 and 15 890, the effects of viscous force and surface tension can be ignored. In this regard, most references, including the American Society of Civil Engineers (ASCE, 2000), recommend a minimum 25 mm hydraulic head for this purpose. After dropping the dimensionless constants, Eq. 6 was presented as the final equation to calculate the discharge coefficient in the present study:

$$C_d = f(w_L/w_R, H_t/P, B/w_{avg}) \quad (6)$$

where C_d denotes the coefficient of discharge, H_t/P is the total hydraulic head ratio (total hydraulic head to the weir height), w_L/w_R is the width ratio of the left and right cycles, and B/w_{avg} is the weir length ratio (ratio of the lateral crest length to the average length of the weir cycle). Table 1 presents the geometrical and hydraulic specifications of the asymmetric labyrinth weirs studied here.

RESULTS AND DISCUSSION

The hydraulic performance of an asymmetric rectangular labyrinth weir was experimentally investigated considering several dimensionless parameters, namely, the ratio of asymmetric widths of the left and right cycles (w_L/w_R), the ratio of the total hydraulic head to the weir height (H_t/P), and the weir length ratio (B/w_{avg}).

Effect of w_L/w_R on the hydraulic performance of the asymmetric rectangular labyrinth weir

All parts of Figs 4a, b, and c suggest that increasing the hydraulic head causes a decline in the discharge coefficient. On average, in the hydraulic head (H_t/P) range of 0.05 to 0.3, the different asymmetric labyrinth weirs had distinct hydraulic performances in all parts of Fig. 4, and in terms of reaching full aeration at small hydraulic head ratios, asymmetric labyrinth weirs can be said to have a high discharge coefficient. Moreover, based on each one's design parameters, the weirs display excellent hydraulic performance at small hydraulic head ratios. It can be concluded that a small water pressure ratio is characteristic of a good asymmetric labyrinth weir design. Asymmetric labyrinth weirs with different length ratios show similar hydraulic performance on average from a water level of 0.3. This is because local submergence occurs throughout the top of the weir, which in turn floods the weir and significantly reduces hydropower performance. In this regard, it should be noted that increasing the hydraulic head exacerbates the nappe interference in discharge from the outlet keys, causing a considerable energy loss and undermining the weir's hydraulic performance. On the other hand, it must be noted that in all parts of Figs 4a, b and c, the discharge coefficient decreases (for different length ratios B/w_{avg}) as the ratio of asymmetric widths of the left and right cycles (w_L/w_R) is reduced.

Effect of B/w_{avg} on the hydraulic performance of the asymmetric rectangular labyrinth weir

All parts of Fig. 5 are suggestive of a reduction in the discharge coefficient by increasing the hydraulic head ratio. The same effects as Fig. 5b appear in Figs. 5a and c but at a gentler slope, showing the hydraulic balance of the weirs. In other words, a weir is said to be in hydraulic balance when it transits from full aeration to drowning over a gentle slope. In this case, the negative impacts of energy loss are also reduced, although the situation is somewhat different in Fig. 5b. From another perspective, it is safe to say that increasing the weir length ratio (B/w_{avg}) reduces the discharge

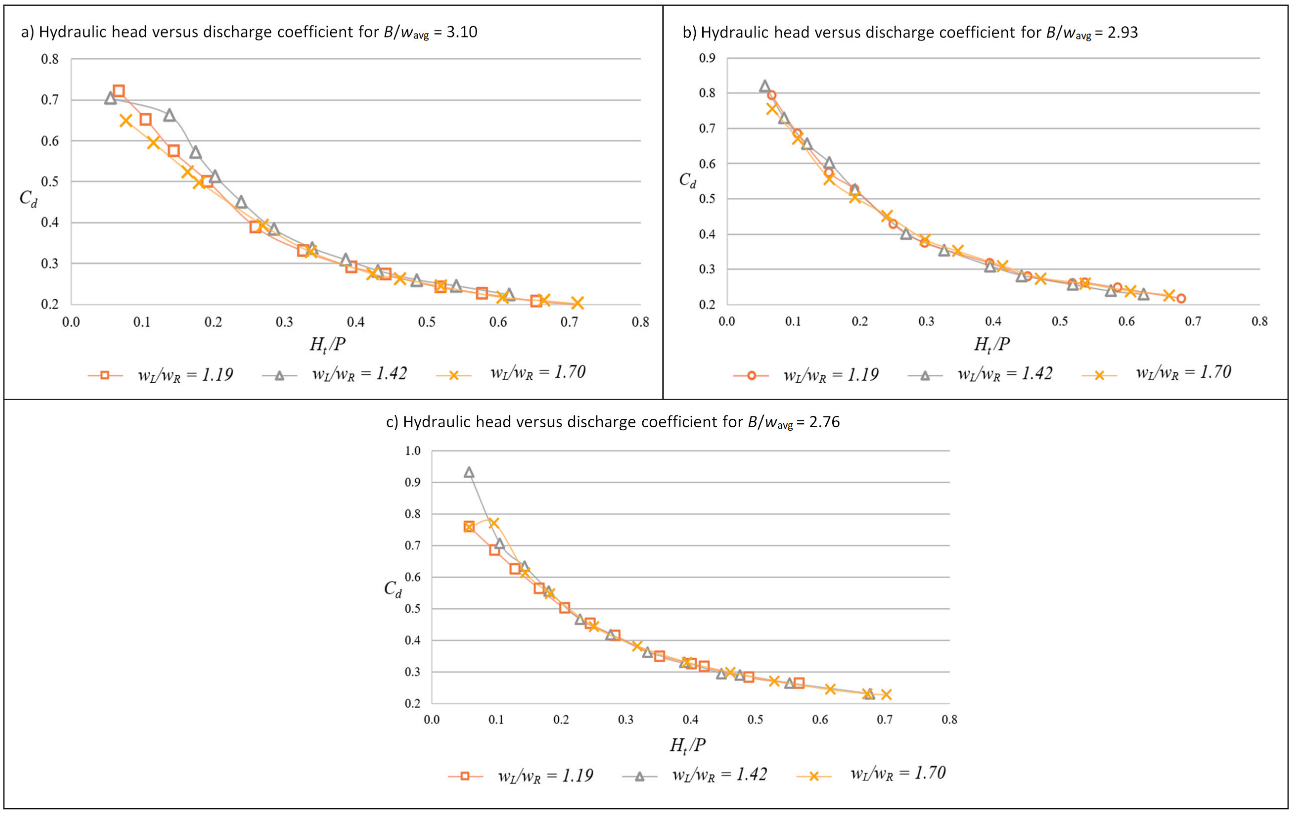

Figure 4. Hydraulic head versus discharge coefficient at asymmetric cycle width ratios, for three different length ratios

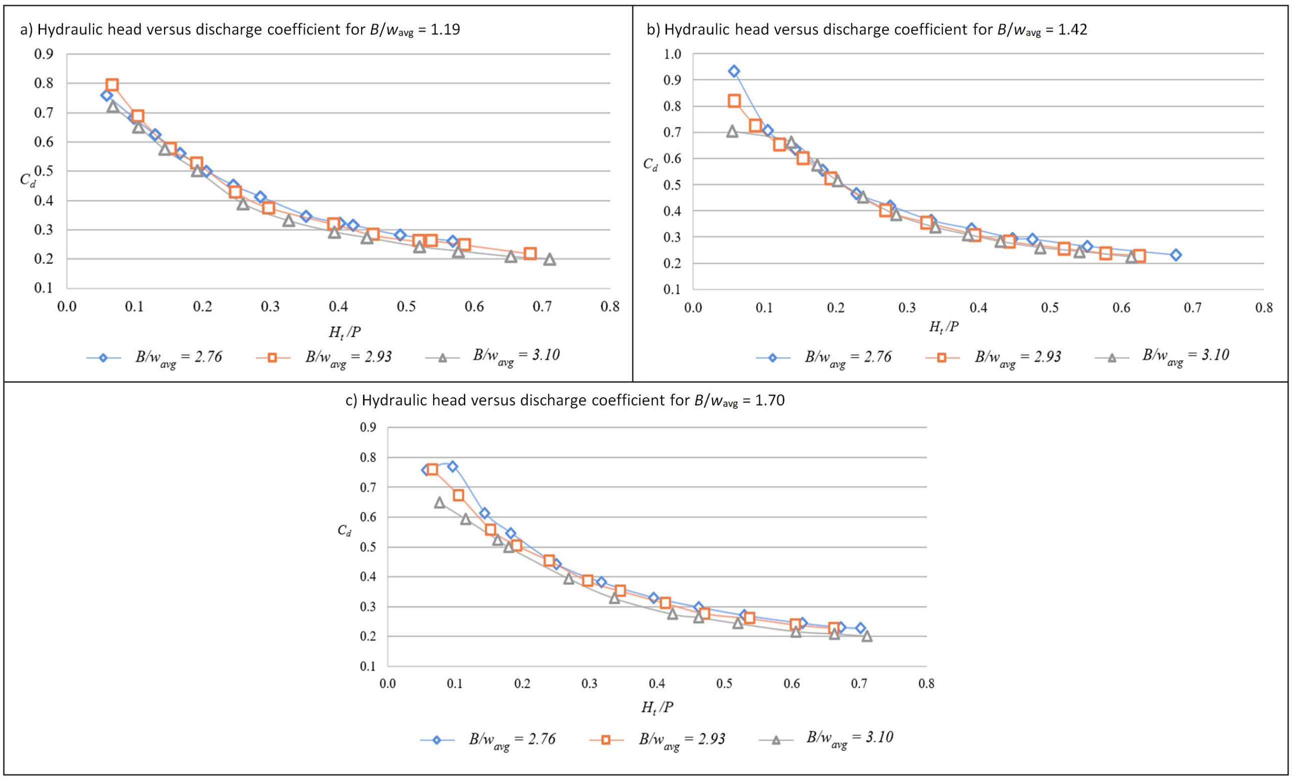

Figure 5. Hydraulic head versus discharge coefficient at asymmetric cycle width ratios, for three different length ratios

coefficient (for any w_L/w_R) in terms of the higher hydraulic head; therefore, the increased volume and interference of nappes discharging from the outlet key of the asymmetric labyrinth weir. On average, the discharge coefficient varied within the range of 0.8 to 0.2 and had a decreasing trend. According to Fig. 5a, the weirs have a similar hydraulic performance during aeration, whereas Figs. 5b and c are indicative of distinctive performances in this stage and at small hydraulic head ratios ($H_t/P < 0.2$). The entire Fig. 5 consistently shows that the weirs are drowned when the hydraulic head rises above $H_t/P > 0.2$, in which case the weir crest undergoes local submergence across its length, and the energy loss compromises the hydraulic performance.

Determination of discharge coefficient by statistical analysis

To determine the discharge coefficient of Labyrinth weirs we used SPSS software for statistical analysis, which is an applied software with the ability of function approximation between two variables or more. Various functions were extracted for the dependent variable (C_d) about independent variables (H_t/P, w_L/w_R,B/w_{avg}) to reach the best equation. In Fig. 6a, b, c, the matrix scatter plot, regression standardized residual, and histogram are presented for each independent variable (H_t/P, w_L/w_R, B/w_{avg}) against the dependent variable (C_d).

Considering Fig. 6, two equations were fitted. The results are presented in Tables 2 and 3, where one can also see the statistical features of the equations.

The discharge coefficient equation for Model 2, as presented in Table 2, has the best fit with the plot, data, and highest R^2 value, as seen in Table 3. Model 2 has an acceptable correlation with a simpler form and can be used when the downstream parameters are not available.

CONCLUSION

The hydraulic performance of an asymmetric rectangular labyrinth weir was investigated experimentally based on dimensionless parameters w_L/w_R, H_t/P, and B/w_{avg}. In brief, the experimental results were suggestive of a decrease in the discharge coefficient as the hydraulic head rose, regardless of the parameters investigated (w_L/w_R and B/w_{avg}). The discharge coefficient was found to decline at a lower asymmetric width ratio (w_L/w_R) or a higher weir length ratio (B/w_{avg}). Thus, the lowest

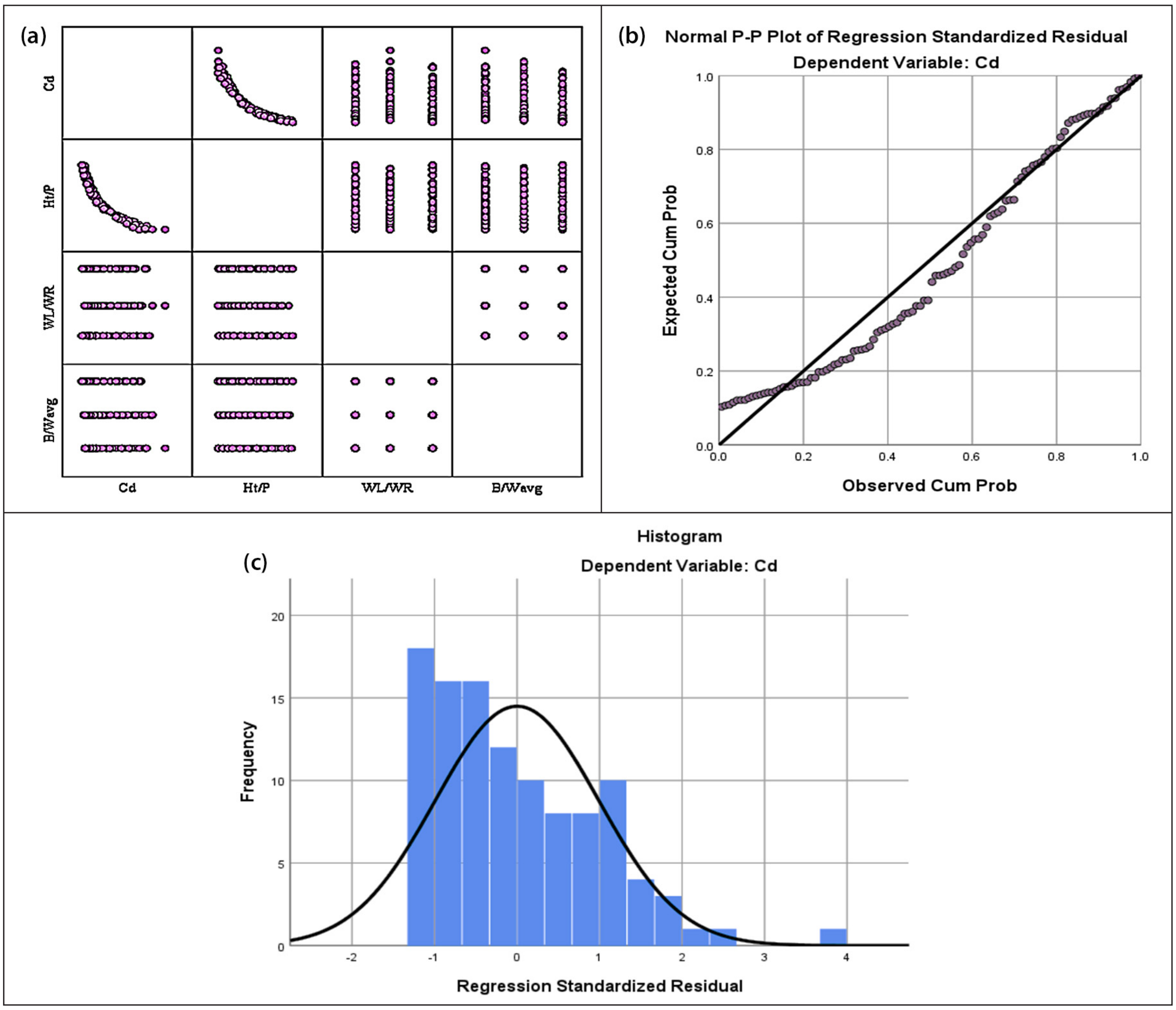

Figure 6. Matrix scatter plot (a) and regression standardized residual (b) and histogram (c)

Table 2. Presented equation by using the SPSS for determination of discharge coefficient

Model	Equation
1	$C_d = -0.864\ H_t/P + 0.714$
2	$C_d = -0.1\ B/w_{avg} - 0.86\ H_t/P + 1.004$

Table 3. Statistical parameters for presented equations

Model	R	R^2	Adjusted R^2	Std. error	F change	df1	df2	Sig. F change	Durbin-Watson
1	0.929	0.863	0.861	0.06749	665.859	1	106	0.000	
2	0.932	0.869	0.866	0.06635	4.668	1	105	0.033	0.451

discharge coefficient was achieved in the asymmetric labyrinth weir by reducing w_L/w_R and increasing B/w_{avg}. The reason lies in the impacts of hydraulic factors, such as the transition from full aeration stage into partial aeration and then drowning, at which point the hydraulic function of the weir is reduced to that of a protuberance baffling the flow. The interference of nappes flowing over the outlet keys and downstream is another factor that compromises the weir's hydraulic performance and causes energy loss. In quantitative terms, for w_L/w_R = 1.19, the ratio B/w_{avg} = 2.76 improves the discharge coefficient by nearly 12.7% compared to B/w_{avg} = 3.1. For w_L/w_R = 1.42, the ratio B/w_{avg} = 2.76 improves the discharge coefficient by nearly 34.2% compared to B/w_{avg} = 3.1. For w_L/w_R = 1.70, the ratio B/w_{avg} = 2.76 improves the discharge coefficient by nearly 30% compared to B/w_{avg} = 3.1. From the results, an equation for determining the C_d coefficient was developed using regression analysis.

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