Discharge Coefficients for Different Types of Side Weirs

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ARTICLE INFO

Article History:
Received: 14/05/2017
Accepted: 12/04/2018
Published: 01/06/2018

Keywords:
Side weir
Discharge coefficient
Labyrinth weir
Open channel flow

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ABSTRACT

Side weirs are extensively used with open channel structures for different purposes such as; raising water level for irrigation and drainage purposes, also to divert a course of excess flow from rivers or channels during the occurrence of flood which is consider the main problem during the wet seasons. In the present study a series of 18 manufactured laboratory models of different types of side weirs are investigated through a total of 160 test runs. Subcritical flow regime was tested on the side weirs that installed inside the prismatic rectangular main channel. Five different types of side weirs are used namely linear crest of normal rectangle with (θ = 90°), an oblique rectangle which inclined its crest with flow direction by (θ = 75°, 60° and 45°). Triangular labyrinth with apex angles (δ=90° and 120°), Semi-hexagonal labyrinth with wall angles (Z=30° and 64.7°) and Semi-circular labyrinth side weirs. Dimensional analysis for different parameters which influence the behavior of models were carried out, then the equations outlined from multivariable regressions. For this purpose a statistical software called (SPSS V.22.0) was applied. Finally De Marchi's assumption of constant specific energy along the side weir was checked and approved, moreover the results shows that the coefficient of discharge in labyrinth side weir cross-sections are greater than of the linear crests of rectangular models.

INTRODUCTION

Free surface flow are affected by the value of Froude number, if this value is changed gradually then the phenomenon is called spatially varied flow (SVF). Side weir is a hydraulic structure used for diverting flow from the main channel into the side channel whenever the water surface rises above the side weir crest, and the flow overflows over it freely under gravity. Their hydraulic behavior is complex and exhibition to change due to different free surface profiles along the side weir. (De Marchi, 1934) is one of the earliest investigators who gave equations for the flow over side weirs on the basis of a constant specific energy along this structure. (Collinge, 1957) studied experimentally the discharge capacity of side weirs. (Subramanya and Awasthy, 1972) and (Ranga Raju et al., 1979) concluded that the De Marchi equation can be used and they presented different equations for calculation of discharge coefficient in terms of upstream Froude number for subcritical flow conditions. (May et al., 2003) indicated that the flow condition in the main channel at the upstream and downstream of a side weir can have a major influence on the behavior of the flow on the weir itself. There are numerous application that related to the side weirs can
commonly highlighted in hydraulic engineering applications namely irrigation systems such as flood control structure, and in sanitary engineering practice to disperse storm flow in the combined sewer system. The main purpose of this study is to predict the discharge coefficient for different types of side weirs especially when the weir length increased while the width of the lateral opening is kept constant.

**Theoretical Consideration:**

The SVF equation can be derived basing on energy or momentum principle which described the flow condition within the main channel, dynamic equation for SVF is expressed by:

\[
\frac{dy}{dx} = \frac{S_0 - S_f - \frac{\alpha Q}{g A^2} \frac{dQ}{dx}}{1 - \frac{\alpha Q^2 T}{g A^3}}
\]

where; \( y \) is the depth of flow, \( x \) is the distance along the side weir from upstream end, \( S_0 \) is the main channel slope, \( S_f \) is friction slope, \( \alpha \) is kinetic energy correction factor, \( Q \) is discharge in channel, \( \frac{dQ}{dx} \) is discharge per unit length of side weir, \( g \) is the acceleration due to gravity, \( A \) is the cross sectional area of flow and \( T \) is the top width of the channel section.

In accordance of De Marchi’s approach of constancy in specific energy between upstream and downstream ends of the side weir, the parameters that affected on the flow over rectangular cross-section was explained in Figure (1). The discharge through an elementary strip (dx) was:

\[
\frac{-dQ}{dx} = \frac{2}{3} C_m \sqrt{2g} (y - p) \frac{3}{2}
\]

Discharge coefficient for flow passing over the side weir was proposed as:

\[
C_m = \frac{3B}{2L} (\phi_2 - \phi_1)
\]

In which \( \phi_1 \& \phi_2 \) are varied flow functions at sections 1 & 2 expressed as:

\[
\begin{align*}
\phi_1 &= \frac{2E_1 - 3p}{E_1 - p} \sqrt{\frac{E_1 - y_1}{y_1 - p}} - 3\sin^{-1}\sqrt{\frac{E_1 - y_1}{E_1 - p}} \\
\phi_2 &= \frac{2E_2 - 3p}{E_2 - p} \sqrt{\frac{E_2 - y_2}{y_2 - p}} - 3\sin^{-1}\sqrt{\frac{E_2 - y_2}{E_2 - p}}
\end{align*}
\]

Where : \( B \) is main channel width, \( E_1 \& E_2 \) is specific energy heads at upstream and downstream ends of the side weir respectively (i.e. sections 1&2), \( y_1 \& y_2 \) is water depths at upstream and downstream ends of the side weir respectively, \( L \) is length of the side weir, and \( p \) is side weir height.

**Fig.1. Sketch of flow over rectangular side weir in:**

(a) Longitudinal section, (b) Top view.

Buckingham’s \( \pi \) theorem was used for evaluation of the variables controlled the flow over the side weir. As sketched in Figure (2), the expected factors which affecting the discharge coefficient for different types of side weirs was expressed in general relation as:

\[
C_m = f \left( L, L_c, p, B, V_1, y_1, \rho, g, \Theta, \delta, Z \right)
\]

**Fig.2. Definition sketch for different side weir models.**

Discharge coefficient for different type of side weirs in term of dimensionless pi terms was expressed as:

\[
\begin{align*}
C_m &= f \left( Fr_1, \frac{p}{y_1}, \frac{L}{B} \right) \quad \text{Normal Rectangular.} \\
C_m &= f \left( Fr_1, \frac{p}{y_1}, \frac{L}{B}, \frac{L}{L_c}, \Theta \right) \quad \text{Oblique Rectangular.} \\
C_m &= f \left( Fr_1, \frac{p}{y_1}, \frac{L}{B}, \frac{L}{L_c}, \delta \right) \quad \text{Triangular Labyrinth.} \\
C_m &= f \left( Fr_1, \frac{p}{y_1}, \frac{L}{B}, \frac{L}{L_c}, Z \right) \quad \text{Semi-hexagon Labyrinth.}
\end{align*}
\]
\[ C_m = f \left(Fr_1, \frac{P}{\gamma_y}, \frac{L}{B}, \frac{L_c}{L} \right) \]  
Semi-Circular Labyrinth.

**MATERIALS AND METHODS**

Methodology of experimental program was conducted in the laboratory of civil engineering department belonging to the college of engineering/Salahaddin University. The laboratory flume has a rectangular prismatic section which its dimensions were 12m length, 0.5m wide and 0.5m deep. The width of the flume was divided into two passage channels as shown in Figure (3), one for the main channel of width (B=0.2m) while (B=0.294m) was the side channel width and the lateral openings of the side weir was taken as (L= 0.2, 0.25 and 0.3m), the side weirs are usually considered as short structures with (L/B ≤ 3.0), and the longitudinal slope of the flume was set to zero (horizontal) for all tests.

![Fig.3. Flume dividing: a) Top view, b) laboratory view.](image)

The experimental program was carried out through investigation on five different types of side weirs as shown in Figure (4). The weirs were normal rectangular (\(\theta=90^\circ\)), oblique rectangular (\(\theta=75^\circ\), 60\(^\circ\) and 45\(^\circ\)), triangular labyrinth (\(\delta=120^\circ\) and 90\(^\circ\)), semi-hexagonal labyrinth (\(Z=64.5^\circ\) and 30\(^\circ\)), and semi-circular labyrinth (\(r = L/2\)). Side weirs were installed at a distance of 2.2m from the downstream end of the main channel. These models were investigated through 160 test runs with different flow rates, the flow starting from very low rate controlled via a manually operated small valve, and the flow rate was gradually increased. Eight to ten runs was conducted on each side weir models.

![Fig.4. Different side weir models and their position.](image)

Total discharge entering the main channel \((Q_1)\) was measured through a v-notch weir equation \((Q_1=0.0194 \ h^{2.4015})\) which calibrated by (Bahar, 2015) and a point gauge of a vernier scale with an accuracy of 0.05mm was used to measure the water depth(h) above the v-notch weir. It was fixed to zero level corresponding to the level of v-notch weir crest. Whereas the discharge \((Q_2)\) at the downstream of the main channel was measured by installing the standard rectangular weir at 2.2m away from downstream end of the side weir. According to (British standard institute, 1965) for a rectangular weir, the discharge at the downstream of the main channel can be calculated by Rehbock formula: \((Q_2 = \frac{2}{3} C_d \sqrt{2gh} \ b \ he^{1.5})\). The coefficient of
discharge was determined: \( C_d = 0.602 + 0.083 \frac{h_d}{p} \), and \( h_e = h_d + 0.0012 \)
Where: \( C_d \) is the discharge coefficient, \( p \) is the weir height, \( h_e \) is the effective head above the standard rectangular weir and \( h_d \) is the depth of water measured at the upstream of standard rectangular weir.

In order to check the accuracy of the above standard equation, the flow through the side weir was sited to be turn off and the results of mass balance for several test runs shows that the maximum error in the discharge measurements between inlet and outlet of the main channel not exceeded 6.04%. Then the flow passing over the side weir (\( Q_w \)) was measured as (\( Q_w = Q_1 - Q_2 \)).

RESULTS AND DISCUSSION

Specific energy values at the side weir entry (\( E_1 \)) and side weir exit (\( E_2 \)) was calculated and plotted in Figure (5) which illustrated that the specific energy between two ends of side weirs has a linear variation. The best intercept fit line among all models includes high correlation coefficient. This finding means that the energy differences was a small fraction which considered as no significant effect. (Jaaffar, 2010) estimated the energy difference to be less than 1% in for the rectangular cross-section of side weirs with different crest lip shapes, while (Raju et al., 1979) obtained mean value of 2%, (Khameneh et al., 2014) obtained the energy difference to be less than 1% for semi-circle labyrinth side weir. In the present study, the average error of energy difference was found to be between (1-2) %. This finding was adopted with De Marchi’s assumption in which the specific energy should be considered as constant in the main channel between upstream and downstream ends of the side weir.

Variations of De-Marchi’s discharge coefficient (\( C_m \)) with upstream Froude number (\( F_r_1 \)) for different side weir models was shown in Figure (6), which revealed that by increasing the Fr1 a decrease in \( C_m \) values will produced. This pattern was familiar by (Subramanya and Awasthy, 1972) were obtained a similar tendency for the aforementioned relation. Flow with low velocity value, good efficiency of the side weir flow was obtained, while increasing the flow velocity leads to creating vortexes which made a return flow area especially in labyrinth side weirs were consequently decreased the flow capacity over the side weirs. For an oblique rectangular side weir (Fig.6.a) with different inclination angles as (\( \theta = 45^\circ, 60^\circ \) and \( 75^\circ \)), and (L/Lc) ratio as (0.707, 0.866 and 0.966) with keeping the side weir height as 0.1m. It was noted that the lowest oblique angle (\( \theta = 45^\circ \)) will give higher value of Cm in comparison with the other oblique angles due to its longer crest length which leads to serve more lateral flow above the side weir. Similar results was founded for triangular and semi-hexagonal labyrinth side weirs (Fig.6.b,c), in which the longer side weir crest length provide greater efficiency than the other crest lengths.
The relations of $C_m$ against ratio of $p/y_1$ for different side weirs was shown in Figure (7). Results pointed out grow up in $C_m$ values with increasing the ratio of $p/y_1$. This revealed the majority and sensitivity of the measurement of upstream side weir water depth ($y_1$).

In the Figure (8), the variation of $L/B$ ratio on $C_m$ values was revealed. For different lateral openings of rectangular and triangular side weirs, a slight effect was seen. In other words, the lateral opening inside channel width has no significant effect on the performance of the side weir in terms of discharge coefficient.

Comparison between different types of side weirs was shown in Figure (9), results indicated that for different lateral openings ($L=0.2,0.3m$) the normal rectangular side weir has lower efficiency in terms of its discharge capacity, while the semi-hexagonal model provided higher $C_m$ values when ($Fr_1<0.2$). Increasing flow rate ($Fr_1>0.2$), leads the triangular labyrinth weir to be a little bit performance. In other words, the discharge passed over labyrinth weirs was greater than that discharge over the normal and oblique rectangular weirs, this was due to longer crest length that allow more lateral flow into the side channel.
In order to find which shape of labyrinth weirs was better, taking into account the increasing of the weir crest length (Lc), the head length (Lh) should be focused on and considered as an important parameter in the hydraulic design aspects. Therefore semi-hexagonal labyrinth side weir model was found to be better than the other models due to its smaller head length (Lh = 0.086m). Whereas, semi-circle and triangle weirs has longer head lengths as (both Lh = 0.1m). Similarly, the same conclusion for the side weirs with the lateral opening L = 0.3m was adopted. Additionally, the labyrinth side weirs capacity were founded to be 1.27 times higher than the capacity of rectangular side weir.

In order to find the relation between the dependent and the independent dimensionless parameters, SPSS software was applied for each weir geometry and two empirical equations as multivariable linear and multivariable power regressions was examined as shown in Tables (1&2) respectively. The calculated values of Cm from the empirical equation was compared with actual Cm values of experimental runs as shown in Figure (10).

Table (1) Multivariable Linear Regression for different side weir models.

| Side Weir Name          | Multivariable Linear Regression                                                                 | R²  |
|-------------------------|-------------------------------------------------------------------------------------------------|-----|
| Normal & Oblique        | \( C_m = a + b(F_r) + c(L/\beta) + d_1(L_c/\delta) + e_1(\sin \beta, \delta, Z) \)             | 0.754 |
| Rectangular              | \( C_m = 0.955 + 0.062(F_r) + 0.666(p/\gamma) - 0.064(L_c/\beta) + 0.018 \sin \beta \)        | 0.795 |
| Labyrinth               | \( C_m = 0.162 - 0.935(F_r) + 0.337(p/\gamma) - 0.31(L_c/\beta) - 0.247(L_c/\delta) - 0.068(\sin Z) \) | 0.8241 |
| Rectangular Inclined     | \( C_m = 0.106 + 1.057(F_r) + 2.061(p/\gamma) - 2.994(L_c/\beta) + 3.306(L_c/\delta) \)        | 0.8498 |

Table (2) Multivariable power Regression for different side weir models.

| Side Weir Name          | Multivariable power Regression                                                                 | R²  |
|-------------------------|-------------------------------------------------------------------------------------------------|-----|
| Normal & Oblique        | \( C_m = 0.791 - 0.014(F_r)^{-0.486} - 0.123(p/\gamma)^{0.274} - 0.024(L_c/\beta)^{0.217}(L_c/\delta)^{-1.013}(\sin \beta)^{0.219}(\sin Z)^{-0.937} \) | 0.8071 |
| Rectangular              | \( C_m = -7.316 + 3.799(F_r)^{-0.445} - 5.682(p/\gamma)^{-0.031} - 1.5980(\sin^{0.1064}(L_c/\delta)^{-1.161} \) | 0.8817 |
| Labyrinth               | \( C_m = -0.781 + 9.295(F_r)^{0.083} - 6.061(p/\gamma)^{-0.323} - 0.574(L_c/\beta)^{-0.061}(L_c/\delta)^{-0.006}(\sin^{0.879}Z)^{-0.96} \) | 0.8827 |
| Semi-hexagonal Labyrinth| \( C_m = 10.615 - 15.444(F_r)^{-0.807} - 25.603(p/\gamma)^{-0.347} + 10.532(L_c/\beta)^{0.406} + 0.106(L_c/\delta)^{-1.746} \) | 0.8584 |
Multivariable power regressions was found to be more suitable with higher correlation coefficient than the linear one. Therefore the equations of this regression was used for calculating $C_m$ of different side weir geometries then compared with the other investigator as shown in Figure (11). Results of the discharge coefficient ($C_m$) value in the present study was found to be higher than the values obtained by (Subramanya and Awasthy, 1976) for normal rectangular side weir. While it was found to be lower than that of (Kaya N., 2010) values for triangular labyrinth side weir and the experimental discharge coefficient ($C_m$) value was found to be almost in agreement with the obtained values by (Khameneh et al., 2014).

**CONCLUSIONS**

The conclusions was summarized as:

1. Results of this study were coincide with De Marchi assumption for constant specific energy between side weir entry and exit. The maximum value of average error in energy difference for different types of side weirs was found to be not more that 1.56%.

2. De Marchi's discharge coefficient ($C_m$) was found to be decreased with the increasing in ($Fr_1$) values and decreased with decreasing in ($p/y_1$) values. Whereas ($C_m$) increased with decreasing an oblique angle of rectangle weir ($\theta$), apex angle of triangular labyrinth weir ($\delta$) and side wall angle for semi-hexagonal labyrinth side weirs ($Z$).

3. Experimental tests show that the labyrinth side weirs had better performance due to its longer weir crests and the discharge coefficient of labyrinth side weir was found to be 1.27 times more than that of the rectangular side weir.

4. Several empirical equations for discharge coefficient for different types of side weirs
were predicted. Multivariable power regression models with higher correlation coefficient ($R^2$) was found to be more applicable than the multivariable linear regressions.

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