Discharge coefficient for trapezoidal side weir

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Abstract The designed length of the rectangular side weirs sometimes becomes too long that makes it non-practical from the engineering point of view. In order to decrease the length of channel opening with the desired water height, this study focuses on applying trapezoidal geometry for side weirs. The discharge coefficient needs to be found experimentally for any kinds of trapezoidal side weirs. For this study experimental tests have been carried out for trapezoidal side weir in order to obtain the discharge coefficient. The main dimensionless variables for the tests include: Upstream end Froude number ($F_1$), $w/y_1$, $L/L_0$, $L'/L$, $w/L'$ and $\sin(\alpha)$. Finally, the relationship for DeMarchi’s coefficient in subcritical flow for trapezoidal side weir is presented based on the non-dimensional parameters of weir and flow. Eventually, all the data points are within ±10% limit, which shows the accuracy of the results of this study.

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1. Introduction

A wide variety of different structures is employed to mitigate any extreme flooding event. In some ways, side weirs are the most popular structure to make a diversion in flood flow. Several of the large regions in floodplain areas resorted to the use of side weirs [5,12,18]. These structures help the flood flow deviate from the main stream to non-hazard zone without any significant side effects compared to other mitigations such as dams or retention ponds. In some sections of the rivers or irrigation channels, the discharge might be increased and exceeded the discharge capacity of the channel. In contrast with the normal approaches, operation of the side weirs causes spatially varied flow. Using of side weirs causes the transverse variations of the free surface profile and the velocity distribution.

There were numerous studies on normal weirs, which are perpendicular to the direction of the main stream. In that situation, upstream depth and the crest length are the most significant parameters for weir discharge. Side weirs as control structures are framed in the side of a channel and steer the lateral flow to lateral channel. There are different types of side weirs with similar definitions and different applications and hydro-specifications and behaviour [1].

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Nomenclature

\[ B \] channel width (m);
\[ C_M \] De-Marchi coefficient of discharge (–);
\[ C_d \] discharge coefficient (–);
\[ E \] specific energy (m);
\[ F \] Froude number (–);
\[ g \] gravitational acceleration (m/s²);
\[ L \] opening length of side weir (m);
\[ L' \] effective length of trapezoidal side weir (m);
\[ Q \] channel discharge (m³/s);
\[ Q_w \] weir outflow discharge (m³/s);
\[ x \] flow direction (–);
\[ y \] water depth in main channel (m);
\[ z \] side angle (degree)

\[ \theta \] head angle of the trapezoidal labyrinth side weir (degree);
\[ \Phi \] varied flow function (–);
\[ \sigma \] surface tension;
\[ S_c \] slope of the main channel bed (–);
\[ \rho \] mass density of the fluid (–);
\[ \mu \] dynamic viscosity of the fluid (–).

Subscripts

1, 2 upstream and downstream conditions for the weir, respectively

\[ L = \frac{3}{2} \frac{B}{C_M} (\Phi_2 - \Phi_1) \quad (3) \]

where subscripts 1 and 2 present the upstream and downstream end of the weir in the channel. A large number of the studies have been conducted to obtain discharge coefficient for side weirs rely upon De-Marchi context. Table 1 provides a summary of empirical relationships to determine discharge coefficient for sharp crest conventional side weirs Eqs. (4)–(12).

Different approaches have been applied to determine discharge coefficient for side weirs. For instance, Ghodsian studied behaviour of the rectangular side weir under the conditions of supercritical flow [13]. Photometry was used by Khorchani and Blanpain with a full-scale experiment using digital cameras [17]. Since the crest length has the greatest influence on the discharge capacity among parameters based on previous studies, the effective length was introduced by researchers [20]. By using the idea of the duckbill spillway [11] crest length can be increased while the opening length can still be kept constant by folding the weir into more sections. Different duckbill and labyrinth side weirs were designed with various shapes and presented in the recent decade. Studies show that most of the designed labyrinth side weirs could perform better than conventional side weirs. Table 2 illustrate the sketch of each type of recent side weirs presented in the literature.

One of the most common and fundamental basis for designing of side weirs is De-Marchi’s approach. Different geometries of side weirs imitate the assumption of constant specific energy across the weir for subcritical flow [4]. Eq. (1) could be applied for rectangular channel in the case of spatially varied flow.

\[ x = \frac{3B}{2C_M} \Phi(y, E, w) + \text{Const.} \quad (1) \]

where \( C_M \) is the De-Marchi coefficient (or side weir discharge coefficient) which represents the performance of the side weir and \( x \) represents the length in flow direction, \( B \) is the constant channel width. With regard to Eq. (2), \( y \) is the flow depth, \( E \) is the specific energy, \( w \) is the weir height and \( \Phi \) is a varied flow function defined as follows:

\[ \Phi(y, E, w) = \frac{(2E - 3w)}{(E - w)} \times \left( \frac{E - y}{y - w} \right)^{\frac{1}{2}} - 3 \sin^{-1} \left( \frac{E - y}{E - w} \right)^{\frac{1}{2}} \quad (2) \]

By using Eq. (3), the design detail of side weir could be determined due to the expected \( C_M \) value for conventional side weir. It is clear that the amount of weir height and weir length (opening length) could be designed for required outflow discharge (\( Q_w \)) [25].

| \( C_M \) | \( 0.622 - 0.222F_1 \) | (4) |
| \( C_M \) | \( 0.432 \sqrt{\frac{3F_1}{1 + F_1}} \) | (5) |
| \( C_M \) | \( 0.81 - 0.6F_1 \) | (6) |
| \( C_M \) | \( 0.485 \sqrt{\frac{3F_1}{1 + F_1}} \) | (7) |
| \( C_M \) | \( 0.45 - 0.22F_1 \) | (8) |
| \( C_M \) | \( 0.33 - 0.18F_1 + 0.49w/y_1 \) | (9) |
| \( C_M \) | \( 0.71 - 0.41F_1 + 0.22w/y_1 \) | (10) |
| \( C_M \) | \( 0.7 - 0.48F_1 - 0.3w/y_1 + 0.06L/B \) | (11) |
| \( C_M \) | \( [1 + 0.333(L/B) - 0.105(L/B)^2] \times [1 + 0.034(w/y_1) - 0.491(w/y_1)^3 + 0.421(w/y_1)^5] \times [0.348 + 0.22(F_1) - 0.203(F_1)^2 + 0.303(F_1)^3 - 0.168(F_1)^4] \) | (12) |

Table 1: Former studies on \( C_M \) values for conventional side weir.

Table 2: Sketch of each type of recent side weirs presented in the literature.
<table>
<thead>
<tr>
<th>Type of labyrinth side weirs</th>
<th>Sketch of different labyrinth side weirs</th>
</tr>
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<tbody>
<tr>
<td>Triangular labyrinth side weirs with one cycle [20,7,2]</td>
<td></td>
</tr>
<tr>
<td>Triangular labyrinth side weirs with two cycles [20,2]</td>
<td></td>
</tr>
<tr>
<td>Semi-elliptical labyrinth side weir [16]</td>
<td></td>
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<tr>
<td>Trapezoidal labyrinth side weir [8]</td>
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In 2010, Emiroglu and Kaya worked on a special type of trapezoidal labyrinth side weir which was the combination of one main trapezoidal side weir and two side rectangular shapes. Fig. 1 illustrates the detailed design of their study. The width of each rectangular is equal to the half apex width [8].

However, they concluded that, this type of trapezoidal labyrinth side weir has higher performance rather than conventional side weirs, but slightly higher than triangular labyrinth side weir. Most of the aforementioned researcher, who made an experiment on geometrical labyrinth side weirs, introduced new effective parameters. The new parameter that made an important role in discharge coefficient was side or head angle. Emiroglu and Kaya [8] mentioned that the discharge coefficient $C_d$ increased with reduction in sidewall angle.

Moreover, Eq. (13) was provided for this type of combined trapezoidal side weir.

$$C_d = \left[ 1.063 \times (L/B)^{0.002} - 0.069 \times (L/L)^{0.074} + 0.0045 \times (w/y_1)^{5.209} - 5.195 \times \left( \sin \left( \frac{\theta}{2} \right) \right)^{38.754} + 0.003F_2^{5.802} \right]^{22.104} \tag{13}$$

On the other hand, the performance of the labyrinth is reduced by increasing the water head ($y_1 - w$) on the weir edge while this matter has been mentioned by Falvey [11]. The flow over labyrinth weirs can be complicated by the interference of the jets from adjacent crests. The degree of impact increases as the angle between the crests decreases and as the flow depth over the crest increases. This interference could significantly reduce the efficiency of labyrinth weirs. For labyrinth weir, Parvaneh et al. [24] have discussed this difficulty for labyrinth side weirs [11,24].

Doubtless, improving the efficiency of side weirs would be expected from the new designs. Since the previous design of trapezoidal labyrinth side weir is the combination of rectangular and trapezoidal, therefore, the aim of this paper was to introduce and evaluate the performance of pure trapezoidal labyrinth side weirs with one cycle on flow diversion with respect to the conventional and other labyrinth side weirs. For analysis of results the approach of spatially varied flow, has been conducted.

### 1.1. Dimensional analysis

There are different parameters involved in achieving the discharge coefficient ($C_d$) for labyrinth side weirs. The physical characteristics of the experiment conditions could be mentioned such as the width of the channel ($B$), the width of the trapezoidal labyrinth side weir ($L$), the slope of the main channel bed ($S_o$), the Manning roughness coefficient of the main channel ($n$), the head angle of the trapezoidal labyrinth side weir ($\theta$), the weir crest length (effective length ($L^e$)), and crest height ($w$). Furthermore, effective flow characteristics were mentioned by studies such as flow depth at the upstream end of the side weir ($y_1$), flow velocity at the upstream end of the side weir ($V_1$), acceleration due to gravity ($g$), dynamic viscosity of the fluid ($\mu$), surface tension ($\sigma$), and mass density of the fluid ($\rho$).

Based on Borghei et al. the effect of slope is negligible. Moreover, the effect of $n$, $\sigma$ and $\mu$ on discharge coefficient for elementary flow particle is not considerable. Since the minimum knob height over the side weir is less than 30 mm in this study, the “We” number is less than 9 and the effect of surface tension is negligible.
According to Buckingham’s method (π theorem) to develop physical model, the following related variables in Eq. (14) should be investigated [22].

\[ f(C_M, y_1, L, L', w, V_1, g, \rho, B, \sin(\alpha)) = 0 \]

(14)

\[ x = \left( \frac{\theta}{2} \right) \]

(15)

The governing variables are \( g, \rho \) and \( y_1 \) using basic dimensions. 7 Non-dimensional arguments \( (\pi_1, \pi_2, \ldots, \pi_7) \) have been presented. All of the three governing variables are repeated in all arguments with different exponents and the other variables are presented as a forth variable in each argument. Table 3 illustrates the arguments due to related variables.

However, it is possible to combine various dimensionless arguments. For instance the \( \pi_1/\pi_4 = L'/B, \pi_2/\pi_4 = w/L', \pi_3/\pi_3 = L'/L \) and \( \pi_5/\pi_6 = F_1/\sin(\alpha) \) so that, Eq. (16) is the dimensionless equation in a functional form.

\[ C_M = f\left( \frac{L'}{B}, \frac{L'}{L}, \frac{w}{w}, \frac{F_1}{L'}, \sin(\alpha) \right) \]

(16)

This equation has been applied to current research. \( F_1 \) is the Froude number at the upstream end of the side weir at the channel centre which was applied in previous studies.

1.2. Experimental setup

All the experiments for this study were conducted in Hydraulic Laboratory of Tabriz University, Tabriz, Iran. Fig. 2 sketches the experimental setup. It was equipped with eight metres rectangular flume with 0.80 m width and 0.50 m height. The slope of the channel was considered zero in all the experiments. There is a series of stabilizing plates. The side weir was set far enough from downstream of the channel to let fully developed turbulent flow occurs in the approach channel. The side weirs’ model was made of 2 mm thickness steel plates. Water was pumped from the main tank to the Flume. The overflow from side weir was diverted to the inferior reservoir tank. A rectangular spillway was installed there to measure the outflow discharge \( (Q_w) \). The downstream discharge \( (Q_2) \) was measured using standard rectangular spillway with the average accuracy of 2% and the maximum accuracy of 2.5% using limnimeter. The flow depth of the downstream could be adjusted by using an adjustable valve at the end of the Flume. The water surface profile could be measured by digital point gauge placed on the upper edge of the flume. For most researches the presumption is used that, the flow at the channel centre is more stable than at the bank of the weir. Thus, the data at the upstream end of the side weir at the channel centre had been used by them [1,27,28,9,8,10]. However, in this study water profile in both of the centre line (line 1 in Fig. 3) and the bank of the side weir line (line 2 in Fig. 3) is taken every 0.05 m.

Fig. 4 illustrates that the water surface in the centre line is smoother than the bank of the side weir. It indicates that...
the effect of water diversion in side weirs has less influence on centre line rather than closer situations to the bank of side weirs.

Table 4 describes the range of variables for the experimental tests. The depth of water over the side weir was always kept more than the requirement for omitting the surface tension effects (more than 30 mm [21]). As shown in the table, 90 tests were conducted for Trapezoidal side weirs with one cycle. The range of the variables has been chosen in order to be more practical. For instance by choosing the lowest value as 30° for α, the head angle becomes 60° which is mentioned as the smallest practical angle by studies [24,20]. Moreover, the extension of weir into the side channel should be practical.

The design system for trapezoidal side weirs is based on 3 fixed ratios for \( L/L' \). As a result, for all side weirs with \( \alpha = 30 \), \( L/L' = 0.7 \) and with \( \alpha = 45 \), \( L/L' = 0.8 \) and with \( \alpha = 60 \), \( L/L' = 0.9 \) have been used. This system tries to provide longer oblique part rather than horizontal to use its advantages unless for small angles (\( \alpha = 30 \)). When the head angle (\( \theta \)) decreases the side angle (\( \alpha \)) becomes sharper than before. Therefore, the diversion of flow is increased for the side wall of trapezoidal side weirs. Thus, with sharper side angle,

**Figure 4** The water surface profile for opening length (a) 1 m in bank of side weir (ys); (b) 1 m in centre line (yc); (c) 0.8 m in bank of side weir (ys); (d) 0.8 m in centre line (yc); (e) 0.6 m in bank of side weir (ys); (f) 0.6 m in centre line (yc).
longer horizontal crest is needed to provide enough space for flow diversion and prevents any vortex in side weir area (Fig. 5). On the other hand, it helps control the knob length to make side weirs more practical.

2. Experimental results and discussions

2.1. Energy constancy

In accordance with De-Marchi assumption the energy should be constant along the side weir. For all the tests the energy at both sides of the weir was calculated. The Coriolis coefficient was considered equal to one according to Olivito et al. [23]. The energy in the upstream end ($E_1$) and downstream end ($E_2$) was calculated by Eq. (17). The average error ($RE$) for energy differences in this study achieved by Eq. (18) is equal to 0.41%.

$$E = y + \frac{Q^2}{2gB^2} y^2$$  \hspace{1cm} (17)

$$RE = \frac{100}{n} \times \frac{\sum |\Delta E|}{E_i}$$  \hspace{1cm} (18)

$n = \text{number of experiments}$

$E_1$ and $E_2$ were calculated using the Coriolis coefficient $\alpha = 1$. The average error ($RE$) for energy differences in this study achieved by Eq. (18) is equal to 0.41%.

$E = y + \frac{Q^2}{2gB^2} y^2$

$RE = \frac{100}{n} \times \frac{\sum |\Delta E|}{E_i}$

$n = \text{number of experiments}$

El-Khashab and Smith [6], reported 5% for the energy loss for the conventional side weirs [6]. Fig. 6 shows the state of energy error versus $F_1$. Hence, the De-Marchi equation was used for further calculations on the trapezoidal side weirs.

2.2. Effect of different parameters on the out flow

Former studies on the conventional side weir show the effect of 3 main parameters for developing discharge coefficient ($C_M$) (Borghei et al. [1,15,14]). These parameters are $F_1$, $w/y_1$, $L/B$. Previously the effect of $F_1$ was the main contribution to $C_M$ value [19,3,25,30]. Based on this study the effect of Froude number in the upstream end is reverse. It means, the secondary flow with regard to the lateral flow is affected by increasing the velocity of flow, which is presented by Froude number ($F_1$). However, in this type of side weir, the increase of the Froude number causes the deduction of the separate zone and reversed flow near the downstream end, as Fig. 7 illustrated that the Froude number has a descending order with discharge coefficient ($C_M$) under the control of side angle ($\alpha$). Fig. 7 illustrates the effect of flow in different knob length, which is considered in this study.

Therefore, the parameter with the combination of $F_1$ and $\sin(\alpha)$ is preferable. The behaviour of discharge coefficient versus $F_1/\sin(\alpha)$ has been investigated in Fig. 8. The results in Fig. 8 indicate the values of discharge coefficient grow up with increasing the values of the $F_1/\sin(\alpha)$. Based on Fig. 8, the slope of the increasing is similar for weirs with lower height rather than weirs with $w = 15$ cm. However, higher values for $L/B$ cause less increasing gradient for discharge coefficient side weirs and higher weirs (15 cm) get better $C_M$ rather than lower one (10 cm).

To study the effect of $w/y_1$ on discharge coefficient of trapezoidal side weir Fig. 9 shows the values of $C_M$ versus $w/y_1$. The data indicate the reduction of $w/y_1$ by increasing the $C_M$ values. However, the experiments with higher height of the weir could achieve higher $C_M$. Fig. 9 illustrates the effect of $L'/L$ with the $C_M$ corresponding to the same $w/y_1$ values.

Table 4 Description of variables in the experimental tests.

<table>
<thead>
<tr>
<th>Height of weir $w$ (cm)</th>
<th>Opening length $L$ (cm)</th>
<th>$\alpha$ (°)</th>
<th>$F_1$</th>
<th>$Q_1$ (lit/s)</th>
<th>Number of conducted test</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,10</td>
<td>60</td>
<td>30–45–60</td>
<td>0.1–0.3</td>
<td>20–30</td>
<td>30</td>
</tr>
<tr>
<td>15,10</td>
<td>80</td>
<td>30–45–60</td>
<td>0.2–0.4</td>
<td>20–35</td>
<td>30</td>
</tr>
<tr>
<td>15,10</td>
<td>100</td>
<td>30–45–60</td>
<td>0.2–0.4</td>
<td>30–40</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 5 The flow direction in trapezoidal side weir for this study (a) out flow view and (b) inside view.
Another parameter which is not favoured by the previous studies is \( \frac{w}{L} \). The relation between \( \frac{w}{L} \) and discharge coefficient \( (C_M) \) has been depicted in Fig. 10. Since the study considered three side angles as \( \alpha = 30 \), \( \alpha = 45 \) and \( \alpha = 60 \), the results of comparison are split by these angles. However, based on three different \( \frac{L}{B} \), the ascending gradient for \( \frac{L}{B} = 1.25 \) is significantly bigger than other values. Furthermore, discharge coefficient \( (C_M) \) increases significantly with an increase in \( \frac{w}{L} \).

The study tries to use an empirical correlation to predict the discharge coefficient by trapezoidal side weir with the mentioned non-dimensional parameters. Eq. (19) presents the best correlation based on non-dimensional analysis.

\[
C_M = \left( 1.35 \times \left( \frac{w}{L} \right)^{0.81} + 0.384 \times \left( \frac{L}{B} \right)^{0.372} + 0.059 \times \left( \frac{F_1}{H_{o,m}} \right)^{2.24} 
- 1.37 \times \left( \frac{\alpha}{\text{deg}} \right)^{0.76} \right) \times \left( 0.979 + 0.755 \times \left( \frac{L}{B} \right) \right) 
\]

(19)

The results from Eq. (19) in terms of calculated values for \( C_M \) should be compared with the actual measured values. It seems, from Fig. 11 and, that the calculated parameter produces precise results within \( \pm 10\% \) range.

The Discharge coefficient \( (C_M) \) that is calculated from Eq. (19) is substituted into Eq. (3). The depth of flow \( (y) \) is taken as the flow depth at the upstream end of the side weir at the channel centre \( (y_1) \) to estimate the Energy in the Upstream end \( (E_1) \) and downstream end \( (E_2) \) for Eq. (2) based on the outflow discharge \( (Q_w) \). Therefore, by using Eqs. (2), (3) and (19) the total flow over the side weir \( (Q_w) \) can easily be obtained.

Eventually, to measure how well Eq. (19) predicts the actual value of the discharge coefficient, the sum of squares’ terminology has been used. This terminology tries to define the variability in the data by using \( R^2 \). In the current study, the ratio of \( R^2 \)-squared is equal to 0.903, which shows a precise correlation between measured and calculated discharge coefficient \( (C_M) \). Since the RMSE indicates the goodness of the fit related to high discharge coefficient values, this study tries to apply another important criterion such as Normalized Root Mean Square Error (NRMSE). Eq. (20) shows the terminology of Normalized Root Mean Square Error (NRMSE).

\[
NRMSE = \sqrt{\frac{\sum (F(x) - f(x))^2}{\sum (f(x) - \bar{f})^2}} 
\]

(20)

![Figure 6](image1) State of Error of the Energy versus \( F1 \) to approve energy constancy among side weir.

![Figure 7](image2) \( C_M \) versus different \( F1 \) with \( \alpha = 30 \), \( \alpha = 45 \) and \( \alpha = 60 \) and different knob length.
where $F(x)$ is the predicted (or calculated) value and $f(x)$ is the average of the measured values. Accordingly, the value of NRMSE for this study is 0.31. The NRMSE decreases as the accuracy of the correlation increases. Thus this value shows high accuracy for the results of this study.

Figure 8  The effect of $F/\sin(x)$ on discharge coefficient of trapezoidal side weir with different $L/B$.

Figure 9  The effect of $w/y$ on discharge coefficient of trapezoidal side weir.
The performance of trapezoidal side weir is significantly higher than conventional side weirs. Furthermore, this type of side weir achieved slightly better results compared with triangular side weirs. However, the smaller knob length for this type of side weirs makes it more practical rather than others. Fig. 12 illustrates the comparison and preference of trapezoidal side weir versus other types such as conventional and triangular side weirs.

3. Conclusion

Based on the results from laboratory experiments, by changing a normal side weir to a trapezoidal side weir the efficiency of the weir improves considerably. The effect of the dimensionless parameters $F_1$, $w/y_s$, $L/B$, $L/L_0$, $w/L_0$ and $\sin (a)$ on discharge coefficient has been investigated precisely. From a practical point of view, trapezoidal side weirs have been tested.

Figure 10  $C_M$ versus different $w/L_0$ with $a = 30$, $a = 45$ and $a = 60$ and different $L/B$.

Figure 11  Calculated discharge coefficient by Eq. (19) versus measured discharge coefficient.

Figure 12  Comparison of $C_M$ values for trapezoidal labyrinth side weir with the values obtained from the former equations.
experimentally with one cycle. Therefore, an empirical correlation was developed for calculating $C_M$ with a different combination of effective non-dimensional variables. The main findings can be summarized as follows:

- Application of trapezoidal side weir with one cycle decreases the knob length in contrast to triangular labyrinth side weirs with one cycle with the same effective length ($L^*$);
- The efficiency of a trapezoidal side weir is greater than a conventional side weir.
- The error analysis for the measured values showed a good correlation with the results illustrated in Figs. 11.
- The side angle of the trapezoidal side weirs can act as a control parameter. It means that when $\alpha$ is between 30° and 60°, the less values for $\alpha$ present the higher values for $C_M$.
- Increasing the height of trapezoidal side weirs leads to increase of the $C_M$.
- Higher amount of $L/B$ issues the higher $C_M$ for most of the tests.
- The $F_1/\sin (\alpha)$ and $C_M$ are in the ascending order with each other.

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