Developing CAD tools to determine optimal dimensions of thin-crusted weirs

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Abstract. Weir is an important hydraulic structure functioning to tap, measure, and control water discharge through it. In general, the relationship between discharge and water level involves many variables subjected to some constraints. These situations make finding the optimum dimensions of weirs takes time and may generate mistakes in computation processes. The objectives of this study are to develop tools in the form of computer programs to determine the optimal dimensions of thin-crusted weirs subjected to expected discharges and to produce text files that store the resulted data readable by common CAD readers. These tools are expected capable to obtain fast and accurate weir’s dimensions and accelerate design processes. As a result, the tools have been built to determine the optimum dimensions of four weir types (full-rectangular, partial-rectangular, trapezoidal, and triangular). The programs are written interactively in Visual Basic Language available in MS Excel. The outputs are displayed in graphics and can be saved in an SCR file readable by any CAD software. These programs are easy to use and can reduce a significant time to get the optimum dimensions and may help to accelerate weir designs. The tools are practical to use and are sharable to any interested parties.

1. Introduction

Hydraulic structures play an important part in the development of water resources. There are many types of structures with their functions. One of them is a weir which is used to mainly measure water discharge passing through a water channel or a river. There many types of weirs with their specifications. There are thin-plate and long-base weirs. Within the thin plates, the commonly used are full-rectangular, partial-rectangular, trapezoidal, and triangular weirs [1,2]. A selection to determine the right type of weir needs considerations so that the selected weir can function effectively.

The instructional design of weirs is available elsewhere. Among others, such as promoted by Haseeb Jamal [3] on how to design weirs with considering conditions for stability & maximum stresses. While CCLYNCH & Associate [4] listed 13 design requirements thoroughly listed to ensure accurate discharge measurement.

In general, a weir is a contracted structure to restrict the flowing water so that the water thickness \((h)\) is homogeneous with its width. The relation of the water discharge \((Q)\) commonly takes the form of \(Q = Kh^n\) [3] where \(K\) is the contraction coefficient and \(n\) is 1.5 for full rectangular, partial rectangular and trapezoidal weirs, and 2.5 for the triangular weir. Since \(h\) is measured, determining the right value of \(K\) is important to get precise estimates for \(Q\). The coefficient is dependent on the type and dimension of the weir. It can be found through experimental works as well as estimated by models [6-8]. Most models calculate \(K\) from weir dimensions with complicated constraints that need an iterative computation to meet the constraints.

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2. Materials and Methods
Four types of weirs are presented here since they are most used to measure water discharge in water canals. They are in the forms of the full-rectangular weir (FRW), partial rectangular weir (PRW), trapezoidal or Cipoletti weir (CPW), and triangular weir (TAW). There are quantizable information on these weir types with their formula to estimate the passing through water discharges. However, in this paper, the weirs presented by [8] are referred here since they are provided with complete formulations especially on how to determine their restriction coefficients. These weirs are described as follows.

2.1. Full Rectangular Weir
Figure 1 shows a sketch of the full-rectangular weir which its width is B and height is H. With its crest-height is D, and the water level is h, water discharge over the crest can be estimated using the following equations and constraints.

\[
Q = KBh^3 \\
K = 107.1 + \left(\frac{0.177}{h} + 14.2 \frac{h}{D}\right) (1 + \varepsilon) \quad (1a) \\
\varepsilon = \begin{cases} 
0 & \text{if } D \leq 1 \\
0.55(D - 1) & \text{if } D > 1 
\end{cases} \quad (1b) \\
B \geq 0.50 \quad (1c) \\
D \geq 0.30 \quad (1d) \\
h \leq \frac{B}{4} \leq 0.80 \quad (1e) \\
D \geq 0.30 \quad (1f) \\
h \leq 0.45 \sqrt{b} \quad (1g)
\]

Where, Q is water discharge (m³ mnt⁻¹), and K is the contraction coefficient as a function of h and D (m).

2.2. Partial Rectangular Weir
Figure 2 shows a sketch of the partial-rectangular weir which its width is B and height is H. With its crest-height is D and width is b, and the water level is h, water discharge over the crest can be estimated using the following equations and constraints.

\[
Q = Kb h^3 \\
K = 107.1 + \frac{0.177}{h} + 14.2 \frac{h}{D} + \varepsilon \quad (2a) \\
\varepsilon = -25.7 \sqrt{\frac{(B-b)h}{DB}} + 2.04 \sqrt{\frac{B}{D}} \quad (2b) \\
0.5 \leq B \leq 6.30 \quad (2c) \\
0.15 \leq D \leq 5.50 \quad (2d) \\
0.15 \leq b \leq 5.0 \quad (2e) \\
\frac{bd}{B^2} \geq 0.06 \quad (2f) \\
0.03 \leq h \leq 0.45 \sqrt{b} \quad (2g)
\]

Where, Q is water discharge (m³ mnt⁻¹), K is the contraction coefficient as a function of h, D, and B (m).
2.3. Triangular Weir
Figure 3 shows a sketch of a 90-degree triangular weir which its width is \( B \) and height is \( H \). With its lower crest-height is \( D \) and width is \( b \), and the water level is \( h \), water discharge over the crest can be estimated using the following equations and constraints.

\[
Q = K h^2
\]

\[
K = 81.2 + \frac{0.24}{h} + \left( 8.4 + \frac{12}{\sqrt{D}} \right) \left( \frac{h}{b} - 0.09 \right)^2
\]

(3a)

\[
0.50 \leq B \leq 1.20
\]

(3b)

\[
0.10 \leq D \leq 0.75
\]

(3c)

\[
0.07 \leq h \leq 0.26
\]

(3d)

\[
h \leq \frac{B}{3}
\]

(3e)

For \( B > 1.20 \) and \( D > 0.75 \):

\[
0.07 \leq h \leq h'
\]

(3f)

\[
h' = \min(h'_1, h'_2)
\]

(3i)

\[
h'_1 = \frac{1}{4}(B - 0.20)
\]

(3j)

\[
h'_2 = \frac{2}{3}D
\]

(3k)

Where, \( Q \) is water discharge (m\(^3\) m\(^{-1}\)), \( K \) is the contraction coefficient as a function of \( h, D, \) and \( B \) (m).

2.4. Trapezoidal/Cipoletti Weir
Figure 4 shows a sketch of a trapezoidal (known also as Cipoletti) weir which its width is \( B \) and height is \( H \). With its crest-height is \( D \), lower crest-width \( L \), and the water level is \( h \), water discharge over the crest can be estimated using the following equations and constraints [1].

\[
Q = KLh^2
\]

(4)

The upper crest-width \( b \) is determined when the water level reaches a maximum height \( (h_x) \) with the outer slope is 4 resulted in the following equation.

\[
b = L + \frac{h_x}{2}
\]

(4a)

Furthermore, \( K \) and other constraints are calculated using Eq. 2a–Eq. 2g.

2.5. Solutions
Equations 1, 2, 3, and 4 were written in the form of Visual Basic (VB) functions and subjected to the constraints were solved using Solver which is available in MS Excel. The algorithms were arranged to determine optimum dimensions such as \( D, h, b \) or \( L \). In general, there are four algorithms in every interface. The first algorithm is to determine \( B, D, h, \) and \( b \) or \( L \) to match with a given \( Q \) and subjected to the given constraints. The second algorithm is to produce a rating curve that relates \( Q \) with \( h \). This is done by an optimization process. Based on the resulted dimensions, the corresponding weir was drawn and plotted in the form of graphics in MS Excel and then the data was saved to SCR files that are readable by CAD Software for further refinements.
3. Results and Discussion

3.1. Computer Programs

Table 1 shows 4 computer programs each based on Eq 1, Eq 2, Eq 3, and Eq 4 in the form of functions (namely, FRWeir, PRWeir, CPWeir, and TAW) written in MS Visual Basic Editor. Every function is to calculate $Q$ or $K$ with 4 inputs of $B$, $D$, $h$, and $s$, and additional one input of $L$ for CPWeir. The input $s$ is to select whether the output is $Q$ where $s = 1$, or the output is $K$ where $s = 2$.

Keep in mind that the results of the calculation are only acceptable when the constraints as stated before have been justified. Once the input variables have been optimized, the function then can be used to estimate $Q$ based on $h$ to obtain a rating curve.

3.2. Interfaces

Table 2, Table 3, Table 4, and Table 5 show the interfaces displaying the inputs and the outputs each for FRW, PRW, CPW, and TAW. Every interface contains four parts as follows:

1) The first part shows data input-output. Cell B3 to be filled with the targeted $Q$, C3 is calculated $Q$ by the model, and D3 is the absolute Error between the targeted and calculated $Q$. Other inputs are channel dimensions of $B$ ($B_6$) and $H$ ($B_7$). Followed by crest’s dimensions ($D$, $h$, $b$, $L$) to be found subject to their constraints. These dimensions are optimized using SOLVER to minimize the Error. Crest’s area $A$ is then calculated based on the optimized dimensions.

2) The second part shows a rating curve displaying the relation of $Q$ and $h$ which is interpolated by a power function.

3) The third part shows XY data with its point numbers used to draw a graph (schematic picture) displaying the dimensions of the channel, weir, and the water level. This graph is to verify whether the resulted weir with its optimal dimensions has met with the expected structure before exporting the resulted dimensions to a CAD reader.

4) The fourth part shows 2 buttons which are ExportToSCRFile and ImportSCRFile.

a) ExportToSCRFile is to read and arrange the XY data (B17-G17 downward) and necessary commands to draw lines in ASCII format that can be read by any common CAD.
reader. As shown from J18 downward, the first command is LINE to draw the weir’s crest and followed by another LINE to draw the channel’s wall. This XY data is then saved in the form of an SCR file with a specific filename in a folder/drive. The filename can be written in J15. The computer program is listed in Table 1 in the form of a subroutine named ExportData.

b) ImportSCRFile is to retrieve the data with the same filename which has been saved previously to make sure that the data has been structurally arranged as expected. The retrieved data is then arranged in J18 downward. The computer program is listed in Table 1 in the form of a subroutine named ImportData.

Table 2. Interface for FRW

Table 3. Interface for PRW

Table 4. Interface for CPW

Table 5. Interface for TAW

3.3. Finding the Optimum Dimensions

To find optimal dimensions of the weirs that can deliver maximum value of Q, one needs to give a targeted Q and the dimensions of the channel (B and H). For an example, with B=1 m and H=1 m, we set Q=10 m³/min and obtained D=0.33 m and h=0.19 m for FRW (Table 2); D=0.50 m and h=0.28 m for PRW (Table 3); and D=0.49 m and h=0.32 m for CPW (Table 4). And with B=2 m and H=2 m, D=1.29 m and h=0.43 m (Table 5).
Figure 5 shows the resulted weirs designs with the optimal dimensions (the unit is in decimetre) drawn using AutoCAD, and the corresponding rating curves. The rating curve is different from each other, but all precisely follow a simple power function. To select which one is the most material-efficient among the weir’s types, one may choose the smallest area of the weir’s crest. In this example, the crest area of FRW is 0.33 m², PRW 0.61 m², CPW 0.54 m², and TAW 3.26 m². Here, CPW results in the smallest crest area than the others. While TAW is effective for a wider and deeper channel.

(a). FRW  
(b) PRW  
(c) CPW  
(d) TAW

**Figure 5. Optimal Dimensions and the Corresponding Rating Curves with Q=10 m³ m⁻¹**

4. Conclusions
Computer programs have been built to determine the optimum dimensions of four weir types (full-rectangular, partial-rectangular, trapezoidal, and triangular). The programs are written interactively in visual basic in MS Excel. The outputs are displayed in graphics and can be saved in an SCR file readable by AutoCAD software. These programs are easy to use and can reduce a significant time to get the optimum dimensions and may help to accelerate weir designs.

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