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Characterization of Free Surface Hydraulics Flow Over Sharp-Crested Weir in a One-Dimensional HEC-RAS Model

Mohd Adib Mohammad Razi[1]*, Mohd Shalahuddin Adnan[1], Siti Nazahiyah Rahmat[1], Mohd Azlan Mohd Yusoff[1], Hartini Kasmin[1]

[1]Micro-pollutant Research Centre,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA

*Corresponding Author

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Abstract: The current study aimed to determine the flow changes when the uses of weir hydraulic structure in an open channel hydraulic system. An experiment was conducted by using an open channel structure at the Hydrology System Station, Micro-pollutant Research Centre (MPRC), Universiti Tun Hussein Onn Malaysia (UTHM). Two (2) different types of sharp-crested weir structures which are semi-circular and triangular weir are analyzed. The experiment is conducted at same initial flow rate which is 0.270m3/s for both types of weirs. All the data required in analysis of flow characteristic such that yo, y1, y2, y3, H and Q for upstream and downstream of weirs structure was recorded. The main objective was to evaluate the flow water surface profile and energy grade line downstream of weir using Hydraulic Model (HEC-RAS). Analysis of data was conducted for physically measured and using HEC-RAS model. The results revealed that the flow at downstream had lower Fr of 0.150 compared to upstream when uses of weirs. The relationship between downstream velocity and upstream flow shows the higher the upstream flow rate, the lower the downstream velocity. HEC-RAS result shows that the upstream energy grade elevation had higher percentage difference of 24.4% from physical analysis for semi-circle weir. HEC-RAS was an effective instrument for analyzing of flow behavior in open channel and capable in evaluating the flow characteristics changes when the uses of hydraulic structure in open channel.

Keywords: flooding, sharp-crested weir, flow characteristic, HEC-RAS model

1. Introduction

The application of fluid mechanics for the management of water issues are called hydraulic engineering [1]. The open channel flow represents a critical point from the civil engineering point of view. This is because in the cause of flood the water quality is going down due to the mixing with the environmental pollutants. The flooding is representing a very subjective issue for human life. In many of the countries the hydraulic structures are constructed in order to minimize the destructives caused by the flooding. The hydraulic structure is constructed to transmit discharges, control flow as well as to maintain water levels in streams and channels [2]-[4]. For example, weir is one of the structures that use for control flood which is very useful in lowland area such as agriculture area in West of Johor.

In the flood season, the river flow show complexity stream status causing an erosion by high velocity. Therefore, in order to reduce the problems associated with the flooding, a determination for the changes of flow characteristics and the influence of hydraulic structure in open channel changes should be conducted. The most common model used for this purpose is 1-Dimensional (1D) model [5], [6]. The HEC-RAS model allows the water depth to be computed at each open channel section during the inline structure [7].

**Corresponding author: adib@uthm.edu.my*

The floods caused at the catchment area depended on heavy rainfall and fail drainage systems. The drainage systems most applicable in urban area compare to swale system. The floods at Batu Pahat is take place due to the trench size needed which is small. Similar at Kota Tinggi and Segamat the floods are associated with high rainfall recorded as recorded in 2006 and early 2007 which has affected more victims.

The present study investigated one dimensional HEC-RAS for analyzing the flow characteristics down the stream over the weir inline structure [7], [8]. The current work was performed by using two (2) different type of weir structure included semi-circular and triangular sharp-crested weir. The data analysis was conducted using the 1D-hydraulic model of HEC-RAS. The discharge conditions were analyzed into steady flow data. The study computed the flow specific energy and energy loss using the related equations as well. Therefore, the flow changes and their characteristics are addressed and profiled.

2. Materials and Methods

2.1 Experimental Setup

The open channel structure completed with the reservoir was used in the present work. Water was supplied from storage reservoir using a pump and thus the diverted discharged evacuated to an open channel. Fig. 1 shows the schematic plan view of the experimental set up. The frontal weir with fully contracted sides is used as a controlling hydraulic structure of the study. The schematic plan view for the channel section is presented in Fig. 2. The location of upstream flow meter is located 16.5 m before the weir whereas downstream flow meter is 30.0 m after the weir structure.

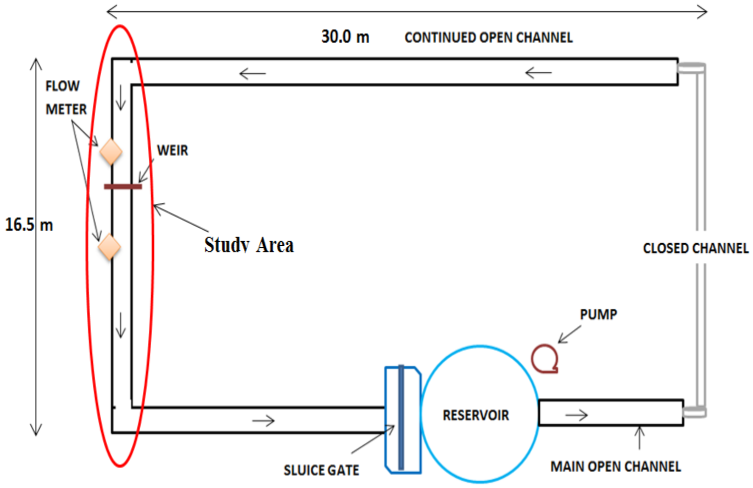


Fig. 1 - Schematic plan view of experimental set-up channel

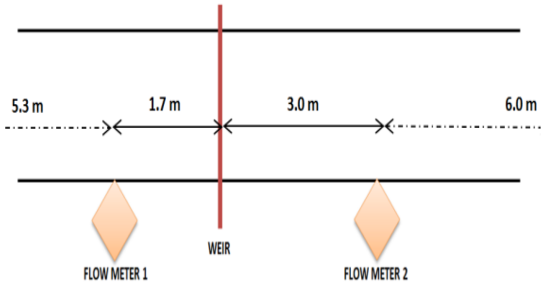


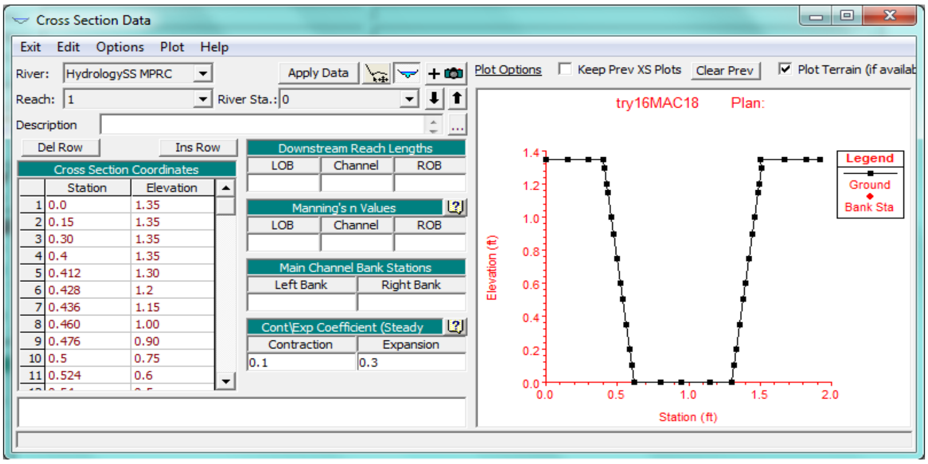
Fig. 2 - Schematic plan view of study section

The main function of the weir plate is to free the flow over the weir from bottom boundary effects and thus the weir section controls the flow rate [9]-[11]. In the current study, a semi-circular and triangular sharp-crested weir was used which is an opening of the weir plate is half circle notch and V notch. These weirs were made of steel plates with the particular size to fit the trapezoidal channel. The assumptions are the trapezoidal open channel used is a prismatic channel which has constant cross-section, dimension, and side slope along the channel. Then, water flow will be flowing in the channel with same pressure as at the beginning of experiment. The bed surface of channel was smooth, no friction factor was concern along the channel section under study. The bottom slope of the channel was 0.00024 as measured using the Manning's equation. The Manning's roughness coefficient was fixed along the channel with the value of n = 0.017 as for surface characteristic of concrete line [12].

2.2 Procedure of Modeling Weir in HEC-RAS

The parameter considered was the cross section of the channel. The trapezoidal channel cross section was determined and then was set in the geometric data edit for cross section. An example of cross section entry is depicted in Fig.3(a). In the cross-section input entry, the data including distance in the channel, Manning's roughness coefficient, main channel bank station and cross section coordinates especially were the significant parameter needed in designing the channel geometries.

The channel cross section data was input for several times called the river station. This trapezoidal open channel was used as a prismatic channel. Hence, the cross section at every river station was same along this study channel section. The weir hydraulic structure was set under inline structure data at geometry data input. The weir structure was designed based on the dimension of weir plate itself. Therefore, the coordinate was plotted based on the station and elevation for the weir when placed in the open channel structure. The inline structure data input in HEC-RAS model is presented in Fig. 3(b).



River: HydrologySS MPRC

Reach: 1

River Sta.: 0

Cross Section Coordinates

	Station	Elevation
1	0.0	1.35
2	0.15	1.35
3	0.30	1.35
4	0.4	1.35
5	0.412	1.30
6	0.428	1.2
7	0.436	1.15
8	0.460	1.00
9	0.476	0.90
10	0.5	0.75
11	0.524	0.6

Downstream Reach Lengths

LOB	Channel	ROB

Manning's n Values

LOB	Channel	ROB

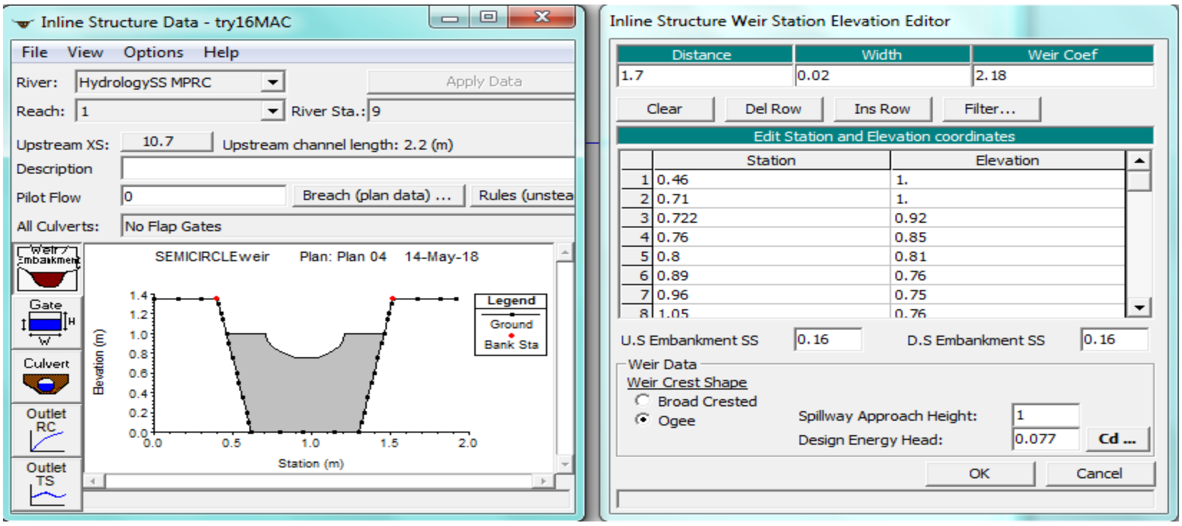
Main Channel Bank Stations

Left Bank	Right Bank

Cont\Exp Coefficient (Steady

Contraction	Expansion
0.1	0.3

(a)



River: HydrologySS MPRC

Reach: 1

River Sta.: 9

Upstream XS: 10.7

Upstream channel length: 2.2 (m)

Pilot Flow 0

All Culverts: No Flap Gates

Distance	Width	Weir Coef
1.7	0.02	2.18

Edit Station and Elevation coordinates

	Station	Elevation
1	0.46	1.
2	0.71	1.
3	0.722	0.92
4	0.76	0.85
5	0.8	0.81
6	0.89	0.76
7	0.96	0.75
8	1.05	0.76

U.S Embankment SS 0.16

D.S Embankment SS 0.16

Weir Data

Weir Crest Shape

○ Broad Crested

● Ogee

Spillway Approach Height: 1

Design Energy Head: 0.077

(b)

Fig. 3 – (a) Cross section entry input in HEC-RAS, and (b) Weir design input in HEC-RAS software

The HEC-RAS software is a one-dimensional (1D) river analysis that capable to compute the steady flow water surface profile and displaying the critical depth elevation. Therefore, in steady flow computational results, the flow rate Q and the condition of flow which was the boundary condition of flow will be the most important parameter to run and compute flow in HEC-RAS. Two profiles were used for separating the steady flow with weir and another one is for without weir structure.

After setting the steady flow data, the steady flow boundary conditions were considered. The known water surface was used in this work, since the flow depths upstream and downstream of weir were based on the collected data from experiment done. The parameter was measured before run and compute the analysis data. The data were saved first and then run for the steady flow data. The computational results were view under water surface profile computation, energy grade line as well as profile output table. Additionally, X-Y-Z perspective plot and a number of output graphs also had been computed by HEC-RAS [13].

3. Results and Discussion

3.1 State of Flow

Flow states over both semi-circle and triangular sharp crested weirs are shown in Table 1. The parameters of the process of hydraulic geometry of open channel flow and water flow analysis are used to obtain a series of cross-sections along the open channel structure for HEC-RAS input. The flow parameter data such as hydraulic depth, flow top width and flow area are important in analysis of flow state manually by equation.

Table 1 - Flow state over semi-circular and triangular weirs

Flow Data	**Semi-Circular Weir**			**Triangular Weir**		
	Upstream Flow	**Downstream Flow**		**Upstream Flow**	**Downstream Flow**	
		Downstream 1	**Downstream 2**		**Downstream 1**	**Downstream 2**
Flow Rate, Q (m^3/s)	0.286	0.244	0.259	0.274	0.271	0.270
Flow Depth, y (m)	$y_1 = 0.856$	$y_2 = 0.781$	$y_3 = 0.803$	$y_1 = 0.831$	$y_2 = 0.827$	$y_3 = 0.827$
Velocity, V (m/s)	V = 0.409	V = 0.387	V = 0.399	V = 0.403	V = 0.403	V = 0.402
Froude number, *Fr*	*Fr* = 0.153 (subcritical flow)	*Fr* = 0.150 (subcritical flow)	*Fr* = 0.153 (subcritical flow)	*Fr* = 0.153 (subcritical flow)	*Fr* = 0.153 (subcritical flow)	*Fr* = 0.152 (subcritical flow)

The results been found that the value of Fr was 0.153 before the semi-circle weir, while decreasing to 0.150 at downstream just after the weir. Moreover, it was revealed that the value of Fr is 0.153 before and just after the triangular weir, whereas decreased to 0.001 at 3.0 meter downstream of weir. The flow after the both weir structure was in the subcritical state as same as before the weir since the Fr was less than 1. The flow regime for flow with semi-circle weir structure is subcritical flow. Additionally, upstream flow over both types of weirs structures is in M1 profile because of the critical depth (y_c) is lower than normal depth y_o, while upstream depth y1 is higher than y_o. Meanwhile, the occurrence of flow profile flow for flow weir downstream is M2 profile since y_o is bigger than y2 and y3. Weirs are commonly used to control the flow rates of rivers during periods of high discharge. V will be increases as depth of flow reduces if the length of the channel is very long and steep. In this case, weir is functioning for control the flow and in the same time will control the velocity.

3.2 Critical Depth Analysis

Determination of the critical depth (y_c) was conducted to plot the position of E_{min}. The flow critical depth was solved by using the graphical method with respect to the normal depth of data collected from the conducted experiment. The analysis result for y_c is presented in Table 2 while the solving for determination of flow critical depth y_c, by plotting y against A^3_c/T_c is depicted in Fig. 4. Based on the graph y against A^3_c/T_c there was no hydraulic jump was recorded after the weirs structure since downstream flow depths which are y_2 and y_3 do not bypass the y_c value.

Table 2 - Analysis data for flow critical depth y_c

y_c	A^3_c/T_c
0.6	0.116
0.4	0.0326
0.35	0.0216
0.30	0.0134
0.20	0.00388
0.15	0.00162

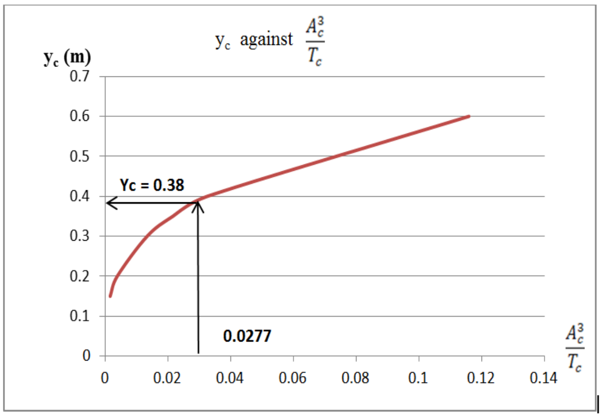


Fig. 4 - Graphical method of critical depth determination

The flow is in subcritical state along the channel because the flow depth pass the critical depth, due to the critical flow which occurs at the critical state which when the Froude number, Fr is equal to 1. Therefore, the specific energy, E for each flow depth has been determined as shown in the Fig. 5 and Fig. 6.

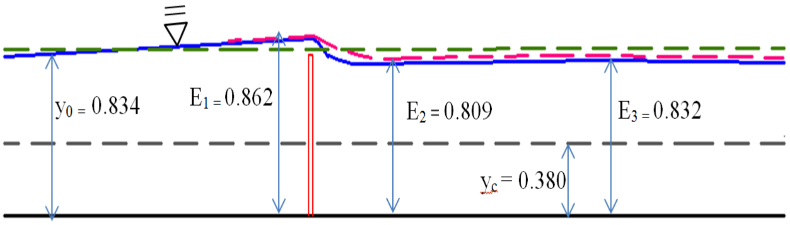


Fig. 5 - Energy grade line of flow over semi-circle sharp crested weir

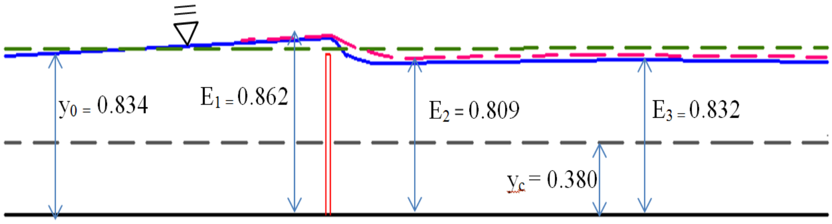


Fig. 6 - Energy grade line of flow over triangular sharp crested weir

The results also revealed that there were small differences between the flow specific energy at the upstream and downstream of channel when the flow passes over the triangular weir. E value of flow before the triangular weir was higher compared to E2 and E3 which both were same at specific energy of 0.835 (Fig. 6). Thus, there is also an energy loss (EL) occurs when the flow pass over the triangular weir and it was only a small value. The energy loss and percentage difference of specific energy for flow with triangular weir structure is illustrated in Table 3. Hence, the percentage difference for specific energy for case of triangular weir is 0.48% which is 5.67% lower compared to semi-circle flow case.

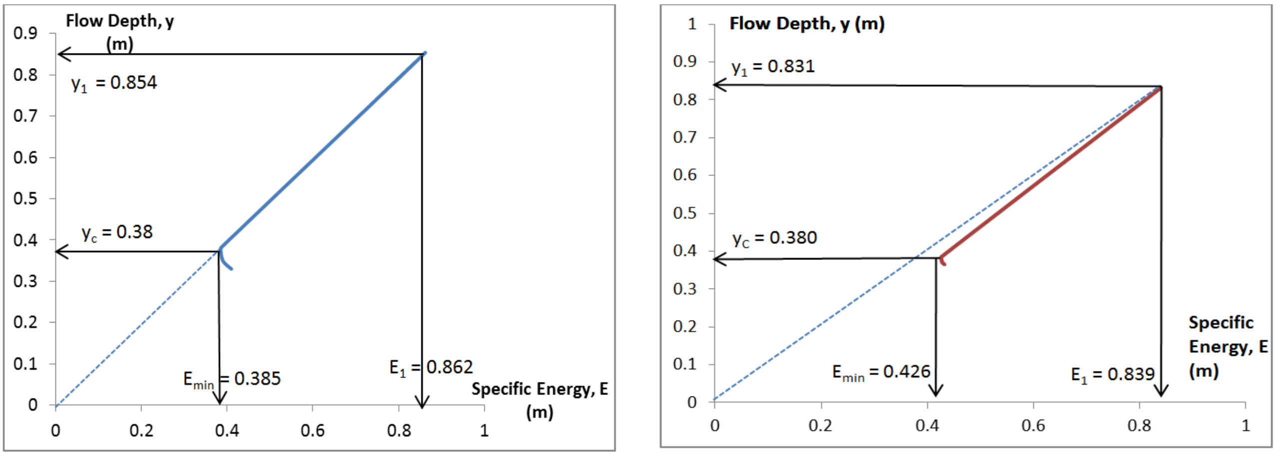
Table 3 - Energy loss and specific energy percentage difference

	Semi-Circular Weir		Triangular Weir	
	Upstream weir	Downstream weir	Upstream weir	Downstream weir
Flow rate, Q (m^3/s)	0.284	0.255	0.274	0.271
Specific Energy, E (m)	0.862	0.809	0.839	0.835
Energy Loss, E_L (m)	0.053		0.004	
Percentage difference of specific energy (%)	6.15		0.48	

3.3 Relationship of Velocity and Flow Rate

Flow velocities at downstream after the weir structure were measured by Manning's equation. The lowest flow velocity obtained in this case study was 0.388 m/s that occur when the flow rate was highest that at 0.286 m3/s. The results in Fig. 7(a) shows that the velocity decreased when the flow rate increased. Meanwhile, for triangular sharp-crested weir as shown in Fig. 7(b), the relationship between flow velocity and flow rate are constant.

In addition, velocity percentage differences are measured as to compare the effectiveness of both weirs in reducing flow rate. As shown in Table 4, for semi-circular weir and Q at 0.286m3/s, velocity percentage differences of upstream and downstream is 5.12% that is bigger than triangular weir which only 1.99%. From this relationship analysis, it can be said that, semi-circular weir has more effectiveness in reducing the flow rate of open channel flow than a triangular sharp crested weir.



(a) (b)

Fig. 7 – (a) Specific energy diagram for flow over semi-circle weir, (b) Specific energy diagram for flow over triangular weir

Table 4 - Summary data for upstream flow rate and downstream velocity for both weirs type

Semi-Circle Weir			
Downstream Velocity, V_2 (m/s)	0.391	0.390	0.388
Upstream Velocity, V_1 (m/s)	0.407	0.408	0.409
Upstream Flow Rate, Q_1 (m^3/s)	0.284	0.285	0.286
Velocity Percentage Difference (%)	3.93	4.41	5.12
Triangular Weir			
Downstream Velocity, V_2 (m/s)	0.395	0.395	0.395
Upstream Velocity, V_1 (m/s)	0.399	0.402	0.403
Upstream Flow Rate, Q_1 (m^3/s)	0.270	0.272	0.274
Velocity Percentage Difference (%)	1.00	1.74	1.99

3.4 Relationship of Flow Rate and Total Head

Apart from the velocity-flow rate relationship, flow rate against total head also one of the relationships that can proved the effect of notch in changed the flow characteristics in term of reducing the flow rate or flow discharge. Based on Table 5, both types of weir show the increased in upstream flow rate, the increased the total head. As the head of flow above the weir crest is increasing, it shows that the flow rate at the downstream area is reduced correspondingly.

3.5 HEC-RAS Analysis

At each cross section, HEC-RAS uses several parameters such as channel station (cross-section) number, left and right bank station locations, Manning's roughness coefficients and channel contraction and expansion coefficients. After that, for the flow data and the condition of boundary open channel system are needed to produce a steady flow data that contains two different profiles which are without weir and with weir structure. The hydraulic analysis of steady flow simulation that performed by using different flow rate value shows difference elevation of water surface profile (WSP) for with and without weirs. Table 6 shows the flow water surface profile (WSP) plot without weir structure shows that it is higher at downstream when compared to flow that is with semi-circular and triangular weir flow. Meanwhile, flow at upstream of weir is relatively high when there is uses of the semi-circular sharp crested weir.

Other than that, Table 7 shows the comparison of the energy grade line (EGL) of flow between without and with semi-circular and triangular weirs. The result obtained shows that there is energy loss when flow down the stream. The energy grade line is higher than the water surface elevation which also known as hydraulic grade line. Additionally, EGL of flow over triangular weir is it had low energy loss when compared to the flow over semi-circular weir. It can be concluded that weir hydraulic structure will affects on the flow characteristic at downstream of channel and for triangular weir it is much essential for low flow rate of water.

Moreover, the other HEC-RAS output result can be determined from the profile output Table 6. From the output table, it can be said that the value of Froude number at weir downstream and upstream is in subcritical state which is 0.15 (Fr < 1). From the HEC-RAS analysis, it can be said that the flow characteristics are changed, and it shows a slightly differences from the physical analysis. Therefore, the percentage difference is determined. The different between HEC-RAS and physical analysis are shown as Table 7.

Table 5 - Summary data of flow rate and total head for flow over both weirs type

Semi-Circle Weir			
Q weir (m^3/s)	0.284	0.285	0.286
Head, H (m)	0.0667	0.0747	0.0797
$H^{3/2}$ (m)	0.0172	0.0204	0.0225
Triangular Weir			
Q weir (m^3/s)	0.270	0.272	0.274
Head (m)	0.278	0.382	0.385
$H^{3/2}$ (m)	0.232	0.236	0.239

Table 6 - Water surface profile and energy grade line HEC-RAS output for both weirs type

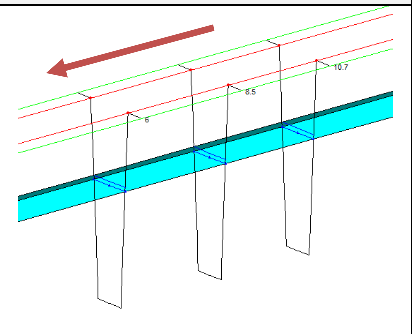
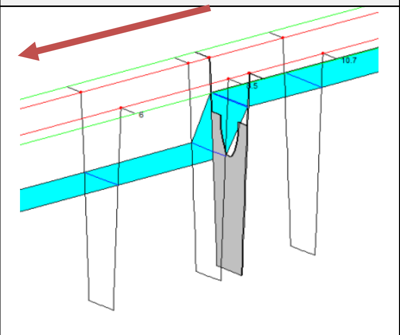
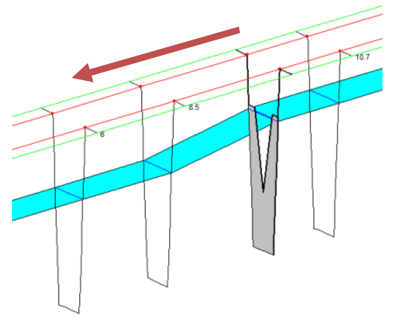
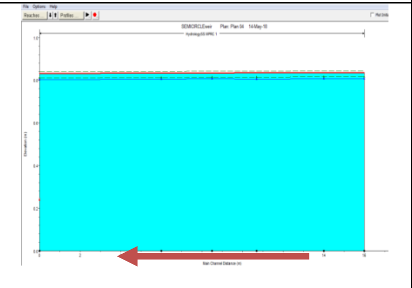
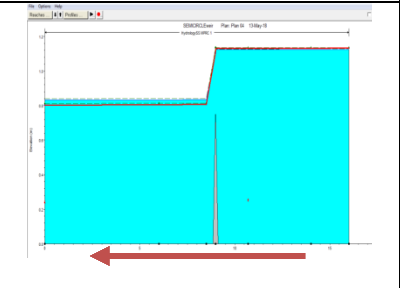
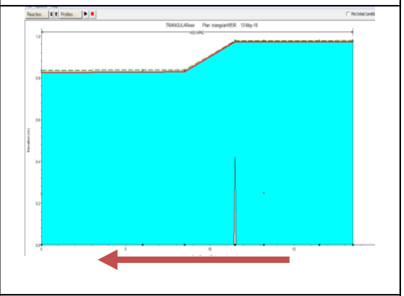
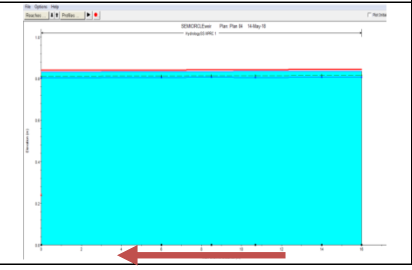
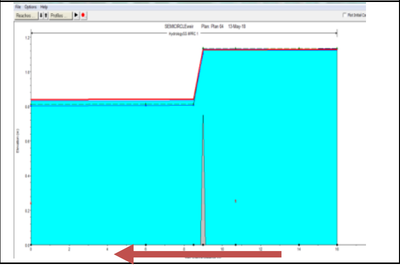
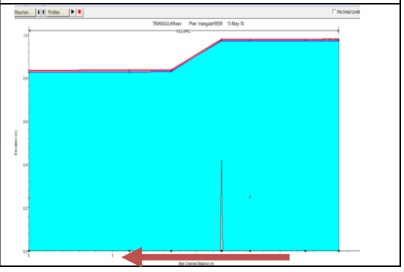
	Without Weir	**Semi-Circular Weir**	**Triangular Weir**
X-Y-Z Perspective Plot			
Water Surface Profile			
Energy Grade Line			

Table 7 shows the difference between Semi – Circular weir and triangular weir in terms of energy grade line and Froude number. The analysis shows for energy grade elevation that Semicircular weir give a high percentage difference which is 24.4% compare with triangular weir which is 14.4%.

Table 7 - Comparison of physical and HEC-RAS analysis on both types of weirs

	Semi- Circular Weir			**Triangular Weir**		
	Physical Analysis	**HEC-RAS Analysis**	**Percentage Difference (%)**	**Physical Analysis**	**HEC-RAS Analysis**	**Percentage Difference (%)**
Energy grade elevation, E_1	0.862	1.140	24.4	0.839	0.980	14.4
Energy grade elevation, E_2	0.809	0.810	0.12	0.835	0.840	0.60
Energy grade elevation, E_3	0.832	0.810	2.64	0.835	0.840	0.60
Upstream Froude Number	0.153	0.120	21.6	0.153	0.120	21.6
Downstream Froude Number	0.150	0.150	0	0.152	0.150	1.32

4. Conclusion

HEC-RAS result shows that the flow at downstream of channel was changed and different when there is used of the sharp-crested weirs. Water surface profile and energy grade line (EGL) are evaluated by 1D hydraulic model, HEC-RAS. Water surface flow at upstream of weir is relatively high when there is uses of the semi-circular sharp crested weir. Then, there is energy loss when flows down the stream because the downstream EGL is lower than upstream. Additionally, it is preferable to have a semi-circular weir at the open channel structure in order to control the flood. It is found that the semi-circular weir had high tendency to dissipate the energy and shorten it [8]. Therefore, this semi-circular weir is very applicable as outlet control structure at pond body which is it provide a controlled overflow of flows and thus reducing the flood impact. Besides, the tendency of the flow downstream weirs to be uniform is quicker for weirs with the bigger openings area. Hence, it can be said that triangular weir is preferable in irrigation system as it makes open channel such as rivers more navigable and controlling flooding. In triangular weir case, the result of different between before used of weir and after weir was relatively the same. Result obtained from HEC-RAS is in two-decimal place and it is affecting in the percentage difference between HEC-RAS output and the physical analysis. As a recommendation, the authorities play an important role to analyze the open channel structure depth and area in order to prevent floods and manage water from reservoirs. The result of analysis is very helpful for a mitigation of flood event since the HEC-RAS model are used for flood management [13]

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