

Numerical Modeling of Sharp-Crested Triangular Plan Form Weirs Using FLUENT

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Abstract

Weirs are hydraulic structures used for measuring flow rate. Triangular labyrinth weir is a kind of non-linear weirs which are used to control free flow passing over weirs in low width. Accordingly, the present paper attempted to investigate the characteristics of flow in triangular labyrinth weirs through FLUENT Software. In this regard, using GAMBIT Model, geometrical and grid generation conditions of flow was created for flow field solution. Using numerical model of Fluent, boundary conditions and flow field conditions were implemented for the model. Meshing conditions is for about 300 thousands cells with at most about 11% error. In the next test, simulation error is decreased about 30% through minimizing the size of computational cells and flow field solution for 580 meshes and the maximum depth simulation error reaches to 8%. Re-decreasing the cells' size and the limited number of about 1 million computational cells causes that simulation error approaches to 7%. Through more careful computational cells selection and given to hardware limitations during simulation time, about 580 thousands cells with average size of 20 mm were selected. It is due to the fact that smaller selection leads to the increase of flow field modeling time up to 2 times more than time. Numerical model of FLUENT is highly able to simulate flow field in labyrinth weirs.

Keywords: Flow Measurement, Fluent, Labyrinth, Numerical Modeling, Open Channel, Triangular Plan

1. Introduction

Labyrinth weirs consist of walls connected in a plan in the form of triangles, trapezoid, and other shapes. Their crest axis is indirect. This type of weirs, in a constant width, relative to weirs with direct crown, have longer crest and higher discharge passes through them under load or equivalent height. They also have a better performance in low hydraulic loads; however, their hydraulic efficiency is gradually decreased as a result of increasing load, leading to the decrease of their water transmissivity.

Due to discharge passing in them under low hydraulic load and the need of less space than other types, labyrinth weirs are generally considered economic structures.

Labyrinth weirs which are also known as spiral weirs have various types. In terms of apparent form, they are divided into labyrinth and piano key weir types. Although most of the existing labyrinth weirs have trapezoid shapes or isosceles triangles in plan, which are due to their simpler implementation, there are other shapes such as rectangular (piano key weir) and U-shape. Figure 1 shows some instances of plan for labyrinth weirs in various states. Principally, labyrinth weirs are used in regions which have limitation in terms of place and total width increase of weir location and/or have had limitations for flood in terms of space capacity and additional volume increase well as for modifying and increasing existing weir capacity.

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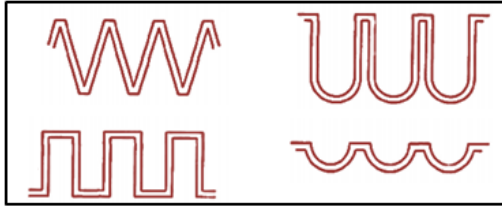


Figure 1. Various labyrinth weirs including triangular, U-shape, rectangular, and semi-circle plan.

According to dams' destruction reports, one-third of dams' destruction is due to low discharge capacity of weirs. Therefore, International Commission of Large Dams (ICOLD) has recommended that large dams' weirs are rechecked to make sure of their security. Hence, to design weirs, floods should be considered with larger return period which causes the increase of weir's width as well as the increase of weirs construction cost. Accordingly, to decrease costs, designers have attempted to minimize confidence coefficient necessary for weirs' dimensions and simplify their structure. As mentioned earlier, using non-linear weirs is one of the best strategies in this regard. Labyrinth weirs or multi-dimensional weirs are one of the oldest types of non-linear weirs. So far, various studies have been conducted on labyrinth weirs and each of them has investigated a certain parameter of these weirs.

Hey and Taylor¹ was the first person who studied multi-dimensional weirs with sharp-edge crest. Hey and Taylor also performed the most comprehensive study on multi-dimensional weirs. Darvas² employed many results of the studies on two dams' model (Verona and Own) to form a number of design curves. Mayer³ performed some experiments to investigate factors affecting labyrinth weirs discharge in Bartlett's-Ferry Project. Tullis⁴ studied models for designing Standley Lake's labyrinth weir.

Peter⁵ studied aeration performance of triangular planform labyrinth weirs. Using artificial neural network, Khorchani and Blanpain⁶ computed discharge coefficient of lateral multi-dimension weirs and presented an equation for discharge coefficient computation. Bilhana⁷ employed various models based on artificial neural networks of discharge coefficient in lateral weirs located on channels' bend. In this regard, 7963 experiments performed on hydraulic model were analyzed. Crookston⁸ performed numerical simulation on multi-dimension labyrinth weirs. This study was defined based on physical modeling results on a rectangular flume under laboratory conditions. Then, 3-dimension simulation of flow was performed on the weir using Flow 3D Software.

Naseri⁹ attempted to compare discharge coefficient of labyrinth weirs for different cape shape and lengths. In this study, using laboratory observations, discharge coefficient properties were investigated for different crest length and cape shapes. He concluded that semi-circle cape has the highest discharge coefficient. Banihashemi¹⁰ investigated various methods of hydraulic labyrinth weirs design and presented benchmark method of designing and effective parameters. Carollo¹¹ also investigated output flow in triangular labyrinth weirs. Using a physical model in laboratory flume, they constructed triangular labyrinth weirs with different geometrical characteristics. Aminoroayaei¹² studied the hydraulic parameters such as pressure; velocity and depth of flow chute spillway and flip buckets.

2. Geometrical Structure of Labyrinth Weirs Using GAMBIT

GAMBIT Software is for geometrical construction and grid generation of numerical model through which user can depict and generate grid considered model with the most details and highest accuracy. Selecting the type of grid depends on the considered problem application. During the selection of grid type, some items such as flow analysis time and computational cost should be taken into account. At this stage, the geometry of existing models should be depicted with predetermined scales. In general, grid generation in GAMBIT is performed as following:

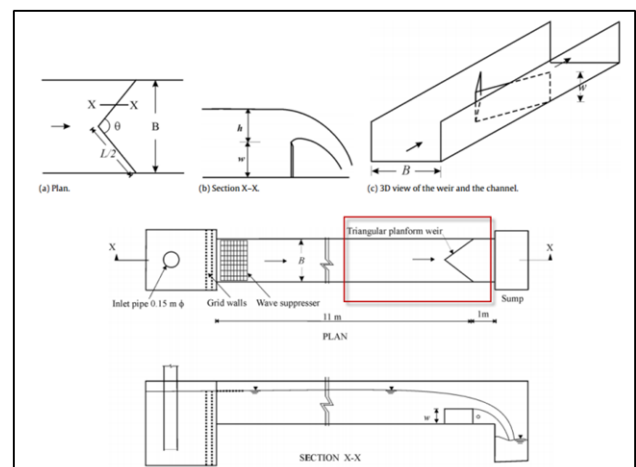


Figure 2. The geometrical characteristics of triangular labyrinth weir in laboratory studies.

- Producing the geometry of problem using generation tools.

- Generating the grid of constructed geometry.
- Determining boundary conditions.

Saving GAMBIT file with *.dbs suffix and getting results through FLUENT Software with *.msh format

The generated geometry characteristics include 3m-channel length in line with X axis, 0.27m-channel width in line with Z axis, 0.41m-channel height in line with Y axis, and 2m-distance of triangular labyrinth weir from input. Figure 2 shows the geometry of the primary model constructed for numerical model. The geometrical characteristics of the weir have been shown according to laboratory studies.

After generating the geometrical framework of the produced model, the geometrical model should be gridded or meshed. There are various tools for grid generation. Default options of Quad and Map are used to create an organized mesh. Creating an organized mesh is possible in four-side pages. In pages with more than four sides, appropriate sides should be changed into one side. Additionally, the number of opposite sides' divisions is equal. It is important to determine the size of grid springs. Large size of spring leads to the decrease of FLUENT's computation accuracy. On the contrary, excessive decrease in springs' size causes to the increase of time required to implement FLUENT¹³.

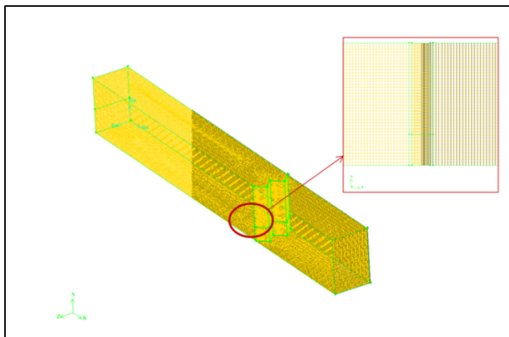


Figure 3. Meshing the geometrical model of triangular labyrinth weirs using GAMBIT.

Table 1. Boundary conditions applied on geometrical boundaries of channel and triangular labyrinth weir

Geometry	Boundary conditions
Channel and weir body	Wall
Boundary between air above water and atmosphere	Symmetry
Water input boundary	Fluid height
Water output boundary	Out flow

In this grid generation, organized mesh has been employed and more fine meshes have been used in areas with stronger gradient of hydraulic parameters and flow turbulent. The final geometry model selected for modeling base and various tests has 580 meshes in the entire grid. Figure 3 shows grid generation for the geometrical model.

At this stage, boundary conditions are implemented on the model according to the laboratory model. Here, it should be noted that in FLUENT, there is the possibility of changing boundary conditions created in GAMBIT. Various boundary conditions can be defined in GAMBIT. Boundary conditions determined for triangular labyrinth weir has been presented in Table 1.

3. Numerical Modeling of Flow in Triangular Labyrinth Weirs using FLUENT

To ensure the convergence between the results and hydraulic characteristics of flow for each of modeling performed in various time reiterations, output discharge values of the numerical model have been compared with laboratory results¹⁴. Accordingly, reiterations less than 1000, the difference between numerical results and laboratory results is higher than 40%. Therefore, reiterations have been increased up to 8000. Investigating flow discharge values including flow depth, flow rate in input boundary area and downstream depth of triangular labyrinth weir reveals that the difference has been decreased up to at most 17%. To make sure of the accuracy of the results, the number of solutions' reiteration, 42000 reiteration s have been implemented for each model. Comparing input and output discharge of the model also shows total convergence of discharge values.

To investigate the accuracy of the selected grid generation in FLUENT, three different grid generations have been used such that, for a model with the conditions of flow height on weir and discharge, 40 mm and 6.8 l/s have been used, respectively. Gridding models have been used based on grid generation with cube and rectangle structure in all numerical model spaces. Table 2 shows relative size of gridding cells, total number of applied cells, and numerical modeling time.

As shown in Table 2, meshing conditions is for about 300 thousands cells with at most about 11% error. In the next test, simulation error is decreased about 30% through

Table 2. Various field gridding conditions for appropriate model gridding selection

Run No.	Charcterstic Mesh			Exp Model		Fluent Model		Error%	
	No. cell	D cell(mm)	Time Run (s)	h (mm)	Q (Lit/s)	h(mm)	Q (Lit/s)	h	Q
Run 1	300,000	30 mm	10172	40	6.8	35.4	7.44	11.5	-9.41
Run 2	580,000	20 mm	25298	40	6.8	43.3	7.18	-8.25	-5.59
Run 3	1,100,000	10 mm	59423	40	6.8	42.8	7.13	-7	-4.85

minimizing the size of computational cells and flow field solution for 580 meshes and the maximum depth simulation error reaches to 8%. Re-decreasing the cells' size and the limited number of about 1 million computational cells causes that simulation error approaches to 7%. Through more careful computational cells selection and given to hardware limitations during simulation time, about 580 thousands cells with average size of 20 mm were selected. It is due to the fact that smaller selection leads to the increase of flow field modeling time up to 2 times more than time. In computational fluids dynamic problems, these parameters determine the number of computational field cells. With respect to the selection of type, size and number of computational cells of flow field, Table 3 shows flow numerical modeling for 5 models with geometrical and hydraulic characteristics of those models selected from these experiments.

Table 3. Geometrical and hydraulic characteristics selected from laboratory model for calibrating and measuring the accuracy of numerical model results

Run No.	θ	W (mm)	h (mm)	Q (Lit/s)	Cd	b (m)
1	90	102.9	14	1.5	0.789	0.08
2	90	102.9	25	3.4	0.758	0.12
3	90	102.9	40	6.8	0.716	0.16
4	90	102.9	54	9.6	0.655	0.08
5	90	102.9	69	12.1	0.572	0.12

The results of the above modeling have been extracted

using FLUENT and used to compute discharge in triangular labyrinth weirs by considering discharge coefficient identical. This method is based on presenting an equation to estimate discharge coefficient of flow passing through the model. To compute discharge in triangular labyrinth weirs, the following equation is employed¹⁵:

$$Q = \frac{2}{3} C_d \sqrt{2g} L H^{3/2} \quad (1)$$

As observed in Equation (1), the increase of H which is a function of flow discharge of the weir, leads to the increase of flow discharge as well. To investigate the numerical and laboratory results, flow discharge coefficient has been obtained according to the above equation. Table 3 shows laboratory and numerical values extracted from the numerical model. Here, the accuracy of the numerical model results for various discharge values is measured. Then, the results obtained from the numerical model are compared to the laboratory model results. Given to the laboratory and numerical results, mean and variance of errors have been calculated through the following equation and the obtained value has been used as a benchmark for accuracy measurement.

$$E_i = \frac{(Q_i)_{Num} - (Q_i)_{Exp}}{(Q_i)_{Exp}} \times 100 \quad (2)$$

Where E_i indicates i^{th} relative discharge error; $(Q_i)_{Num}$ indicates the i^{th} discharge computed by the numerical

Table 4. Comparing numerical modeling error and laboratory results

Run No.	Experimental Model			Fluent Model			Error%	
	h (mm)	Q (Lit/s)	Cd	h (mm)	Q (Lit/s)	Cd	h (mm)	Q (Lit/s)
1	14.00	1.50	0.79	13.80	1.56	0.82	1.43	-4.00
2	25.00	3.40	0.76	26.20	3.47	0.70	-4.80	-2.06
3	40.00	6.80	0.72	43.30	7.18	0.68	-8.25	-5.59
4	54.00	9.60	0.66	55.10	10.20	0.68	-2.04	-6.25
5	69.00	12.10	0.57	70.20	12.80	0.59	-1.74	-5.79

model and $(Q_i)_{Exp}$ indicates i^{th} observed laboratory discharge.

In table 4, the laboratory and numerical results of flow discharge have been presented. Based on Equation (2), error percentage of the numerical modeling relative to laboratory studies has been shown. As seen in the table, the maximum error of numerical modeling for flow depth modeling and output discharge are 8.25% and 6.22%, respectively. These values are acceptable.

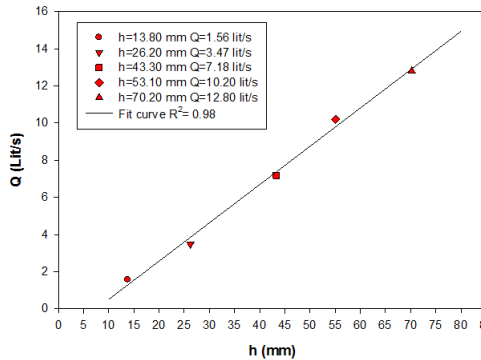


Figure 4. Diagram of the changes of output discharge of numerical model boundary to laboratory model.

According to fitness measurement performed using Sigma plot Software, the results has determination coefficient of 0.96 for numerical and laboratory discharge (Figure 4).

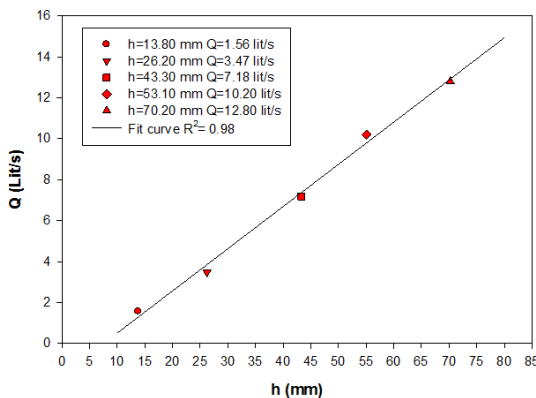


Figure 5. Diagram of discharge change in numerical model relative to flow height changes on weir.

Figure 5 also shows laboratory discharge values based on water height in triangular labyrinth weir extracted from numerical simulation results.

Considering the performed modeling, in numerical model of FLUENT, using fluid height values on weir

(h) and height values of triangular labyrinth weir (w), dimension-free equation can be presented for labyrinth weirs. Using these equations, discharge coefficient is obtained. Figure 6 shows the values of discharge changes relative to dimension-free parameter (h/w).

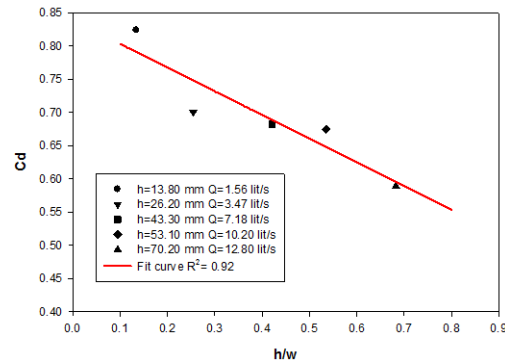


Figure 6. Diagram of discharge changes based on geometrical and hydraulic characteristics (h/w).

Based on the obtained fitting of the information resulted by the numerical model, discharge coefficient equation for triangular labyrinth weir can be stated as flowing:

$$C_d = 0.839 - 0.357 \left(\frac{h}{w} \right) R^2 = 0.92 \quad (3)$$

As observed in the above equation, determination coefficient of the equation equals 92% (which is at a good level, near to 1) using linear fitness.

Here, the most important hydraulic parameters affecting flow field of triangular labyrinth weirs are discussed. In the following, hydraulic parameters including fluid volumetric fraction, flow rate, flow pressure, speed vectors, and flow lines are presented in various cross sections. As seen in Figure 7, flow on weir has falling form. In the figure, 1 is for water fluid volumetric fraction and zero is for air fluid volumetric fraction.

Another important hydraulic parameter in flow numerical modeling is flow rate. Figure 8 shows flow rate values in longitudinal line of flow. As seen in the figure, due to the principle of lack of slip, fluid rate on weir crest equals to wall, i.e. zero (rate near to wall equals zero since No Slip option has been selected in FLUENT) and causes to the formation of boundary layer with very low thickness. Finally, rate boundary layer reaches to its maximum level and decreased as a result of height

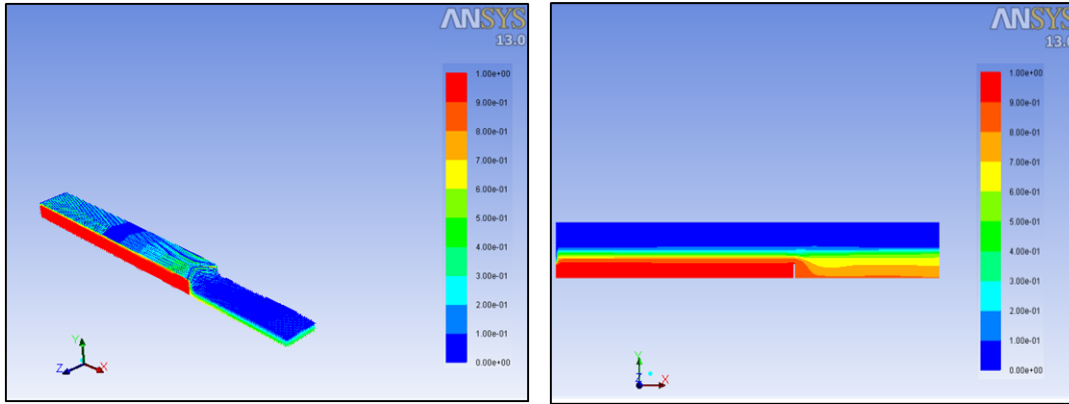


Figure 7. Fluid volumetric fraction values in 3D simulation of flow in labyrinth weirs.

increase to reach its minimum extent at flow free level¹⁶. In the following Figure 9, flow rate values have been shown for central axis of the channel n longitudinal line as well as in latitudinal line for various cross sections such as weir, weir place and after weir.

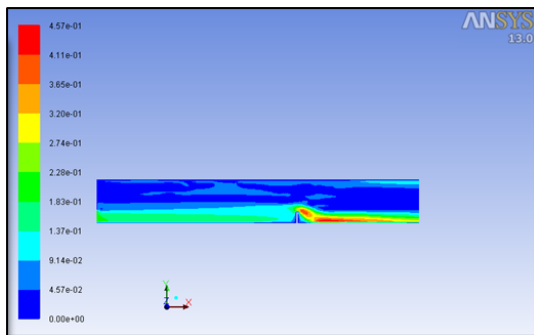


Figure 8. Numerical modeling results of flow rate in longitudinal line.

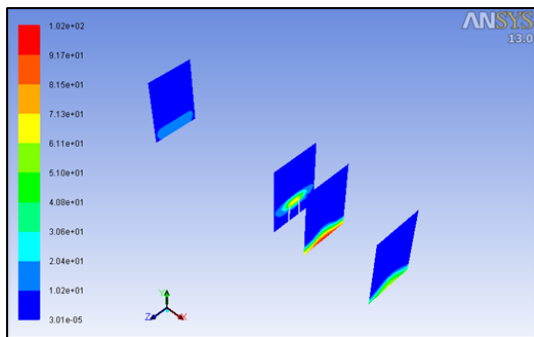


Figure 9. Flow rate values in various transverse cross sections of the numerical model.

Figure 10 shows flow dynamic pressure values in longitudinal line of flow. As seen, the maximum dynamic pressure values belong to weir's crest. Afterwards, the

maximum dynamic pressure for landing place and during falling flow formation is formed on the channel bed.

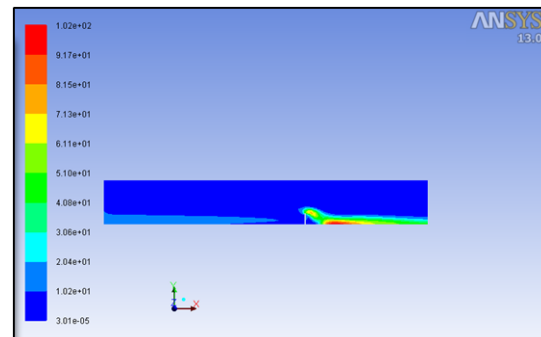


Figure 10. Dynamic pressure values of various longitudinal cross sections of the numerical model.

As shown in Figure 10, the maximum dynamic pressure occurs in sharp-edge part of weir and flow falling jet part.

5. Conclusion

Meshing conditions is for about 300 thousands cells with at most about 11% error. In the next test, simulation error is decreased about 30% through minimizing the size of computational cells and flow field solution for 580 meshes and the maximum depth simulation error reaches to 8%. Re-decreasing the cells' size and the limited number of about 1 million computational cells causes that simulation error approaches to 7%. Through more careful computational cells selection and given to hardware limitations during simulation time, about 580 thousands cells with average size of 20 mm were selected. It is due to the fact that smaller selection leads to the increase of

flow field modeling time up to 2 times more than time. In computational fluids dynamic problems, these parameters determine the number of computational field cells. The maximum error of numerical modeling for flow depth modeling and output discharge are 8.25% and 6.22%, respectively. These values are acceptable. Numerical model of FLUENT is highly able to simulate flow field in labyrinth weirs. Accordingly, the values of other hydraulic characteristics of flow for various parts of the model such as fluid volumetric fraction, flow rate in longitudinal cross section and flow depth, dynamic pressure values and total flow pressure, flow speed vectors, and flow lines can be extracted from the numerical model.

6. References

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