International Journal of Civil Engineering and
Geo-Environmental

Journal homepage:http://ijceg.ump.edu.my
ISSN:21802742

INVESTIGATION OF WATER LEVEL PROFILE AND STAGE-DISCHARGE CURVE IN LABYRINTH WEIRS

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ARTICLEINFO

Keywords:
Water surface profile
Labyrinth weir
Stage-discharge curve

A B S T R A C T

Labyrinth weirs are among the important hydraulic structures for regulating the water level and discharge in channels, rivers and dams reservoirs. Labyrinth weirs are used in regions where there is no enough space for increasing the weir width. Many factors affect labyrinth weirs. Ratio of head to weir height is one of the most important ones which is addressed. in this research via use of a numerical model investigating water level profile and stage-discharge curve in labyrinth weirs with triangular, trapezoidal and curved planform shapes. It was observed that in a fixed head, discharge from a curved weir is higher than trapezoidal weir which is higher than triangular one. This difference in performance is for long heads is too small. In practice there is no significant difference in discharge of these weirs in high heads. Weirs with H/P>0.9, have the same performance and the shape does not influence the discharge.

1.0 Introduction

For flow of excess water from upstream to downstream in dams, weirs are applied. Weir is one of the crucial components of the dams in a way that the breakage in dams is attributed to the failure of their weirs. The performance of these weirs in abnormal circumstances is an important factor in security of dams. Therefore, weir is one of the main parts of dam construction or any other water-related project. The weirs are hydraulic structures constructed for variety of purposes. Among them labyrinth weirs are important hydraulic structures for regulating the water level and control of water flow in channels, rivers and dam reservoirs. The axis of crest in this type of weir is non-linear, and in a given width, they have higher crest length among the conventional linear weirs. The aim of this study is to the water level profile and investigate the stage-discharge curves in labyrinth weirs with triangular, trapezoidal and curved planform shapes.

2.0 Types of labyrinth weirs

Falvey expressed the application of the labyrinth weirs as the energy dissipaters which are used by aeration or de-aeration of the flow. Magalhães andLux, have presented a brief explanation on the properties of labyrinth installations. The distinguished property of the labyrinth weirs is that their planform shapes are not linear. The most important ones are listed as follows:

- U-shaped or rectangular
- V-shaped or triangular (figure 1)
- Trapezoidal shaped

In figure 2, W is the cycle width (m), P is the weir height (m), B is the length of lateral wall (m), α is the angle of the lateral wall (degree), a is the half of cape width (m), H is the total upstream head on the weir (m) $H=h+V^2/2g$ and n is the number of cycles. Figure 3 shows a schematic view of the diagonal, duck-billed and labyrinth weirs.

Figure 1: Triangular labyrinth weir of hydraulic power plant of Ohau C in New Zealand

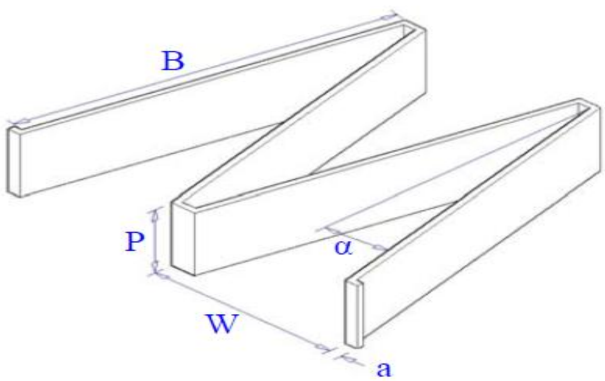

Figure 2: A two-cycle labyrinth weir and the important parameters

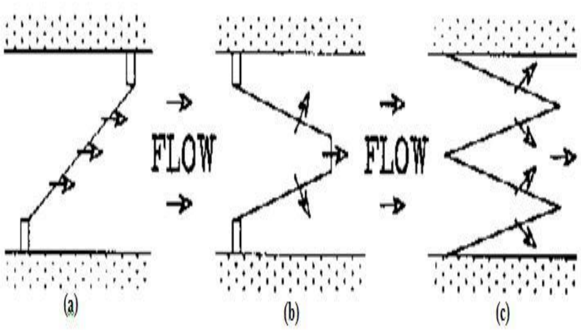

Figure 3: Some of nonlinear weirs a) diagonal weir, b) duck-billed weir and c) labyrinth weir

3.0 Application

One of the main problems in hydraulic analysis of weirs is the discharge coefficient which is related to the discharge capacity of the weir. This characteristic of the weir is under the influence of various parameters among which the ratios of the head to the height of the weir, shape and length of the crest are more effective. Therefore, revision of different parts of the constructed dams for insuring about the efficiency of them is of particular importance. When the maximum flood of the design is increased and the capacity of the existing installation is not adequate, there are 3 solutions: 1- increasing the volume of the dam reservoir, 2- increasing the capacity of weir without changing the dam reservoir volume or 3- a combination of these two. On the other hand, in many cases, the accessible space is not enough for increasing the width of weir. For addressing this problem, the labyrinth weir was introduced by experts. If the weir crest has a zigzag form, this is a labyrinth weir. In this way, due to the increase of the length of weir crest, the discharge capacity would be increased.

4.0 Flow in labyrinth weir

The discharge of a labyrinth weir can be directly increase by the length of crest. However, this is only true for labyrinth weirs working under low heads. Lux andHinchliff believed that by increasing upstream head, the flow pattern will be continuously varied via 4 main phases including completely aerated, semi-aerated, transmitted and compressed. In completely aerated phase, the flow freely passes through the entire crest of the weir. For this phase, the nappe of flow and the depth of tail water have no impact on the discharge capacity of the labyrinth weirs, which acts like the linear weirs with similar vertical cross section. By increasing the head, due to convergence of the opposite water layers and the tail waters with higher depths are relatively aerated. Aeration process becomes difficult due to collision of the water nappes which results in decrease of discharge coefficient. Along each lateral wall of the downstream, a stable air bubble flow would be created. By further increase of upstream head and tail water depth, the nappes would be compressed in different locations. The stable air bubbles would be divided into smaller bubble in a way that they periodically move along the lateral walls toward upstream which leads to instability in water layer. This condition is the start of transmission phase whose observation is difficult in lab. However, the transmission region could be simply defined as the change in slope of discharge coefficient curve. Finally, if the flow consists of a non-aerated layer, it would be included in compressed phase and no air would be removed from water. If the head above the crest is more than the height of the labyrinth weir, the complete floating will occur. In this case the efficiency will decrease rapidly and will get close to the efficiency of a linear crest with a length equal to the width of the channel or shot.

5.0 Research in designing the labyrinth weir

Taylor (1968) conducted an extensive research with 24 models on the triangular, trapezoidal and rectangular labyrinth weirs. He investigated two edges: sharpe and semi-circle. Darvas (1971) presented an initial discharge equation. Lux and Hinchliff (1985) presented a different discharge coefficient, $C_{d\text{-}Lux}$ which included the vertical face ratios (W/P) and a shape constant (k). Magalhães and Lorena (1989) introduced curves similar to those presented by Darvas for the sharp edged labyrinth weirs and recommended a dimensionless discharge coefficient, $C_{d\text{-}M\&L}$. Emiroglu et al. (2010) studied the discharge coefficient of the single- cape triangular labyrinth weir in the range of $22.5^{\circ}<\alpha<75^{\circ}$. They used this weir as the lateral weir in the direct channels. Amanian (1987) conducted experiments on linear and triangular labyrinth weir and concluded that by increasing of the head, due to drowning, the discharge would decrease. Waldron (1994) performed a physical modeling of linear and trapezoidal weirs in a channel. All the weirs had quadrant edges placed closely perpendicular to the flow direction. Willmore (2004) tested the trapezoidal double-cape labyrinth weirs in a rectangular laboratory flume with t_w=36.96 mm. Table 1 listed the tested geometries of the labyrinth weirs.

Table 1: Summary of different geometries tested on labyrinth weir

Researcher	Edge type	Plan shape of weir
Hey and Taylor (1970)	Sharpe semi-circle edge	Triangular, trapezoidal, rectangle
Darvas (1971)	Large Quadrant $R_{crest}=t_w$	Trapezoidal
Hinchliff and Huston (1984)	Sharp, Quadrant $R_{crest}= t_w/2$	Triangular, trapezoidal
Lux and Hinchliff (1985) Lux (1989,1984)	Quadrant $R_{crest}= t_w/2$	Trapezoidal
Magalhães and Lorena (1989)	Shortened peak $R_{crest}= t_w/2$	Trapezoidal
Tullis et al. (1995)	Quadrant $R_{crest}= t_w/2$	Trapezoidal
Melo et al. (1995)	Large Quadrant $R_{crest}= t_w/2$	Trapezoidal
Tullis et al (2007)	Semi-circle	Trapezoidal
Emiroglu et al. (2010)	Sharpe edge	Triangular

6.0 Effective factors on performance of labyrinth weir

Many factors affect the performance of the discharge coefficient in the labyrinth weirs. Among them, the head to height ratio H/P is of significant importance. Although due to creation of relative vacuum by increasing of head, higher discharge coefficients are expected; because of flow mixing, discharge would be decreased. Ratio of the cape width to the height of weir, W/P, was addressed by Taylor in 1968. He recommended that W/P>2. In practice, the lowest required thickness of the walls considering structure design and analysis would be determined. According to investigations on the hydraulic parameters using physical model some recommendation were made about this ratio. For instance, Tullis et al. and Willmore have introduced P/t_w=6 and 8, respectively.

7.0 Numerical modeling

FLOW-3D is versatile software in fluid dynamics produced and supported by Flow Science Inc. This software is designed for research on 1-2- and 3 dimensional behavior of fluid dynamic. FLOW-3D is a computer program with variety of abilities. The user, by entering the data, can select different models for presenting wide variety of flow phenomenon. In this software differentiation and finite volume approximation is used for temporal and spatial calculation of variations in motion equations. In this model which is composed of a 40×40 cm channel with a length of 7.32 m (the weir is located at 5.2 m distance for upstream), two computational blocks are used for simulation (Figure 4). The number of the second blocks is far smaller than the other block as due to use of Cartesian coordination existence of a different geometry for optimized simulation of this model, another block was also applied.

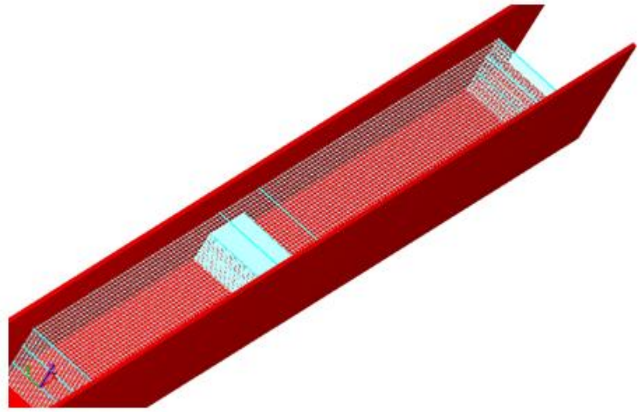

Figure 4: Gridding in the presented numerical 3-D model

Generally, each block is consisted of 6 boundary faces. In Flow-3D model, for the rigid boundaries the wall law, w, is used. The boundaries of the free water level follow the symmetry law of S and 2 input and output boundaries of the upstream and downstream follow the constant discharge Q and constant pressure laws, respectively (Figure 5).
For solving the governing equations of the flow, RNG turbulence model and the algorithm of solving pressure equations GMRES with 0.01 s time-step were applied.

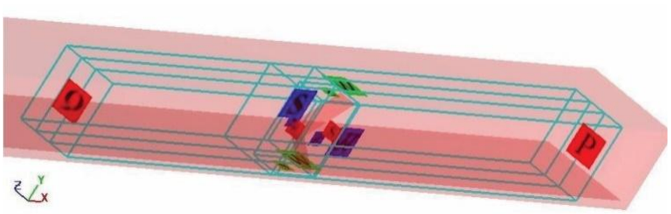

Figure 5: Boundary conditions employed in the models.

Characteristics and planform of each tested model is as the followings (Figures 6 and 7):

a) Sharp-edge labyrinth weirs with triangular plan and central angle of 90 degree.
L=0.566m , P=0.1m
b) Sharp-edge labyrinth weirs with trapezoidal plan.
L=0.566m , P=0.1m
c) Sharp-edge labyrinth weirs with curved plan.
L=0.566m , P=0.1m

The steps taken for modeling the weirs and obtaining the output from Flow3D are listed as the followings:

a) Calculation of the weir's dimensions according to angle and its location in channel
b) Modeling of weir in Auto Cad
c) Calling Auto Cad file in Flow3D
d) Entering the flow properties such as density, viscosity and …
e) Meshing the channel and weir (meshes in weir are far smaller than channel)
f) Running the software and receiving the required output

In order to make the flow falling type, the critical depth of the water was considered in downstream which is obtained from .

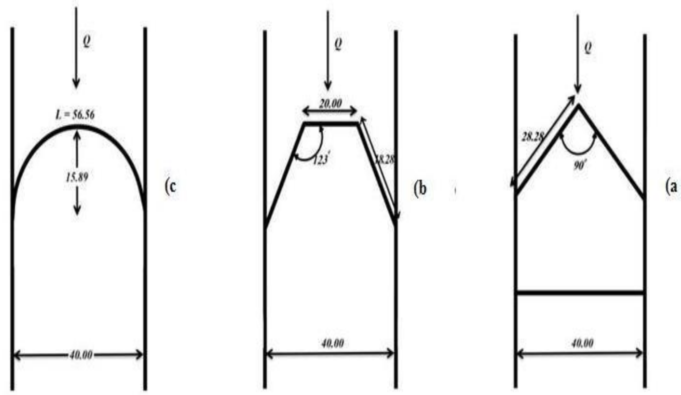

Figure 6: Weirs planform a) Triangular, b) Trapezoidal and c) Curved (All dimension in cm.)

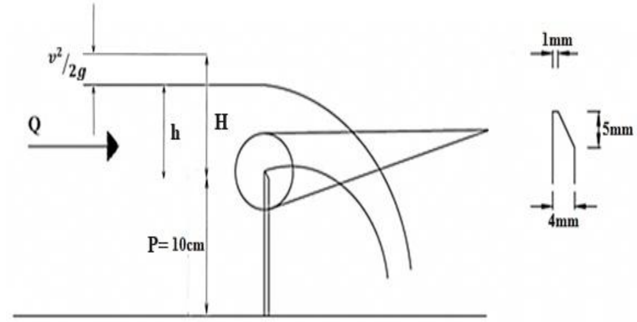

Figure 7: X-X section of weirs wall

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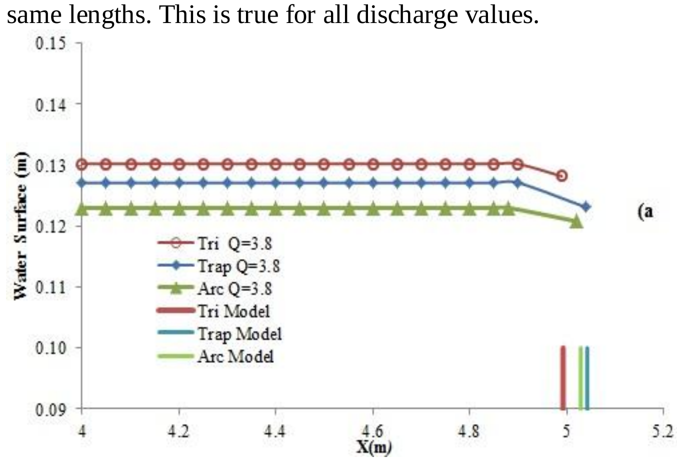
8.0 Comparing the water level profile in different geometries

One of the main characteristics of weirs is the variation of head as a function of discharge. In figure 8 the alternation of water level profile is shown for two discharges of 3.8 and 21.2 l/s. As it can be seen, the head for the weir with curved planform has the least value in comparison with the other two weirs with the same lengths. This is true for all discharge values.



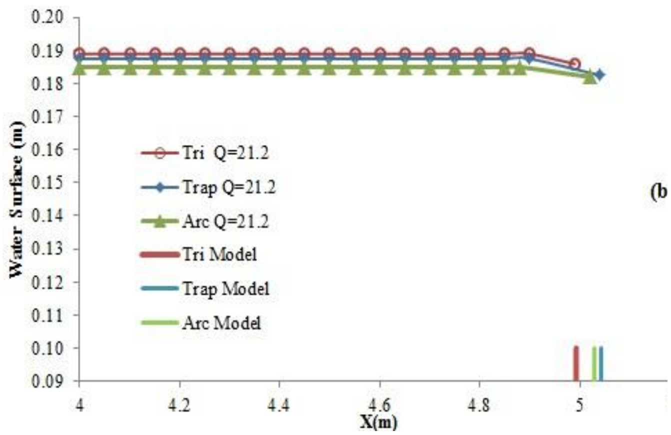


Figure 8: water level profile in different plan weirs with the same length of 0.566 m a) 3.8 l/s and b) 21.2 l/s discharge

9.0Comparison of stage-discharge curve for different planform shapes

Regarding figure 9 it can be observed that the stage-discharge curves follows the same trend in triangular, trapezoidal and curved shape weirs in a way that by increasing the discharge, the head would increase as well. However as the results show, discharge variation in a constant head for the triangular weir has the lowest value while curved shape weir has the highest variation. The difference in performance is small and approaches to zero in large heads. Therefore, in practice there is no significant difference in the discharge of these weirs in high heads. In the other words, the weirs with H/P>0.9 have similar performances due to the occurrence of drowning state and the difference in shapes does not induce any significant changes in discharge.

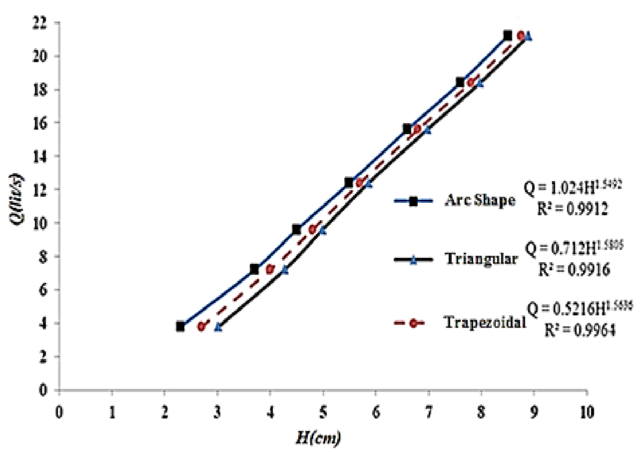


Figure 9: Stage-discharge curve in weirs with different planform shapes with identical length of 0.566 m

10. Conclusion

Labyrinth weirs are used where there is no enough space for increasing the weir width. Many factors can affect the labyrinth weirs but the most important one is the ratio of H/P. The main results of this research are:

a) In labyrinth weirs, by increasing the discharge, the efficiency decreases. In very low discharges, due to the existence of surface tension forces, the capacity of weir decreases.
b) The head value has the lowest quantity in curved shape weir in comparison to triangular and Trapezoidal ones with the same length in constant discharge.
c) In a constant head, the value of discharge in curved shape weir is higher than triangular and trapezoidal ones. The difference in performance is small in large heads and approaches to zero. Therefore, in practice there is no significant difference in the discharge of these weirs in high heads and the weirs with H/P>0.9 have similar performances due to the occurrence of drowning state and the difference in shapes does not induce any significant changes in discharge.

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