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Review Article

Geometric and Hydraulic Properties of Arced Labyrinth Weirs

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Abstract

Weirs serve a critical role in dam safety. Numerous reservoirs' flood projections used in hydraulic design have risen in magnitude in recent years. As a result, many current spillways are no longer adequate since they do not fulfill current discharge capacity standards. Labyrinth weirs are frequently used to rehabilitate existing fixed width spillways. Weirs come in a variety of shapes and sizes, including labyrinth, linear, piano key, and more. Labyrinth weirs enhance the weir crest length for a given width, which increases the weir flow capacity. The majority of labyrinth weirs are designed in linear designs. An Arced cycle layout can boost the discharge capacity and hydraulic efficiency of a labyrinth weir. The article cites an arced geometric layout for labyrinth weirs, as well as nomenclature for arc-specific geometric variables. Experimental studies in the literature are presented by discussing and comparing.

Keywords: *Arced labyrinth weir, Discharge coefficient, Spillways.*

1. Introduction

Water management and transportation are essential to human civilization. Hydraulic structures are becoming increasingly important as infrastructure ages and development develops. Due to a greater emphasis on dam safety and revised and higher predicted maximum flood flows, many spillways are determined to require rehabilitation or replacement. The flow control structure in many existing spillways is a sort of weir. Weirs are hydraulic structures that are used for a variety of purposes, including flow rate measurement, flood control, water storage, grade control, and flow diversion, and changing the flow regime in a canal or river. Weirs are also widely employed as spillway control structures. Weirs play an important role in dam safety and account for a major amount of dam building expenditures. They are among the structures that are used to measure and manage water flow. Weirs with insufficient discharge capacity are one of the leading causes of dam failure. The need to expand the discharge capacity of existing dams has grown as probable maximum flood occurrences have been revised. The indirect axis in plan that is repeated regularly distinguishes the labyrinth weirs. The length and shape of a weir's crest determine how much water can flow through it. When compared to linear weir constructions, a labyrinth weir (see Figure 1) is a linear weir folded in plan view; these structures offer various advantages.

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Labyrinth weirs increase the flow capacity for a given upstream head by increasing the crest length for a certain channel width. These weirs require less free board in the upstream reservoir than linear weirs, facilitating flood routing and increasing reservoir storage capacity at base flow circumstances (weir height may be increased). Labyrinth weirs are a popular design choice for increasing flow capacity and regulating upstream water levels due to their hydraulic efficiency.

An arced cycle layout in a reservoir can boost discharge capacity by better aligning the labyrinth weir cycles to the oncoming flow. Therefore, many researchers have conducted studies on labyrinth weirs and there is still an interest in this type of weir (Tullis *et al*., 1995; Crookston *et al*., 2010; Emiroglu *et al*., 2014; Borghei *et al*., 2016). A labyrinth spillway capacity is known to be sensitive to both the amplitude and direction of approach flows (Copeland & Fletcher, 2000). According to Falvey, if the labyrinth alignment had been curved to align labyrinth cycles perpendicular to incoming streamlines, turbulent flow, flow separation, and unstable nappe aeration at the weir crest would have been decreased, resulting in a more efficient weir (*Hydraul. Des. Labyrinth Weirs*, 2002). By optimizing the orientation of the labyrinth weir cycles to the oncoming flow, an Arced cycle layout can boost discharge capacity. Case studies for labyrinth weirs with nonlinear cycle configurations provide useful but restricted information (e.g., inlet section, labyrinth weir direction, and nonuniform approach circumstances).

Figure 1. Lake Brazos Labyrinth Weir (Waco, Texas)

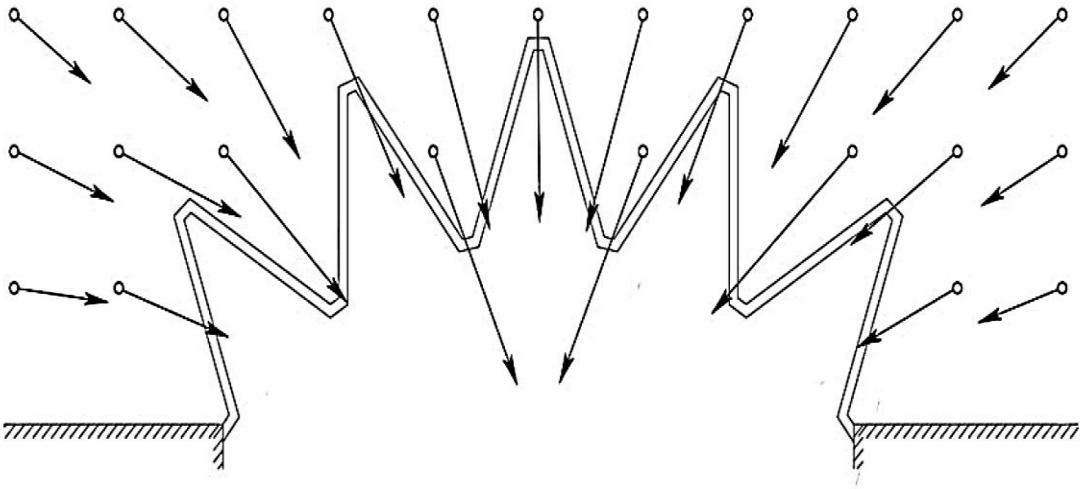

Figure 2. The flow velocity vector field of an arced labyrinth weir (Crookston & Tullis, 2012)

Curved or arced labyrinth weir prototype spillways can be seen at Avon Dam in Australia, Kizilcapinar Dam in Turkey, and Weatherford Dam in Texas.

The discharge efficiency of multiple labyrinth weir geometries incorporating various numbers of Arced and non-arced labyrinth weir cycles in tandem was recently assessed by Page *et al*. (2007) for Mara Cristina Dam (Castellón, Spain) (YerTutucu1). They found that using an Arced cycle arrangement to better align the cycles to the approach flow boosted discharge efficiency.

Similarly, Cookston *et al*., (2010) suggested that the cycle structure can also be arced to better align the cycle orientations with the reservoir's approaching flow conditions and extend the weir crest length. The downstream cycle geometry distinguishes arced labyrinth cycles. Optimizing the inlet section can generally improve the weir discharge capacity (Crookston *et al*., 2010). Crookston and Tullis (2012) then showed the flow direction of the arced design to the weir with velocity vectors in Figure 2 (Crookston & Tullis, 2012).

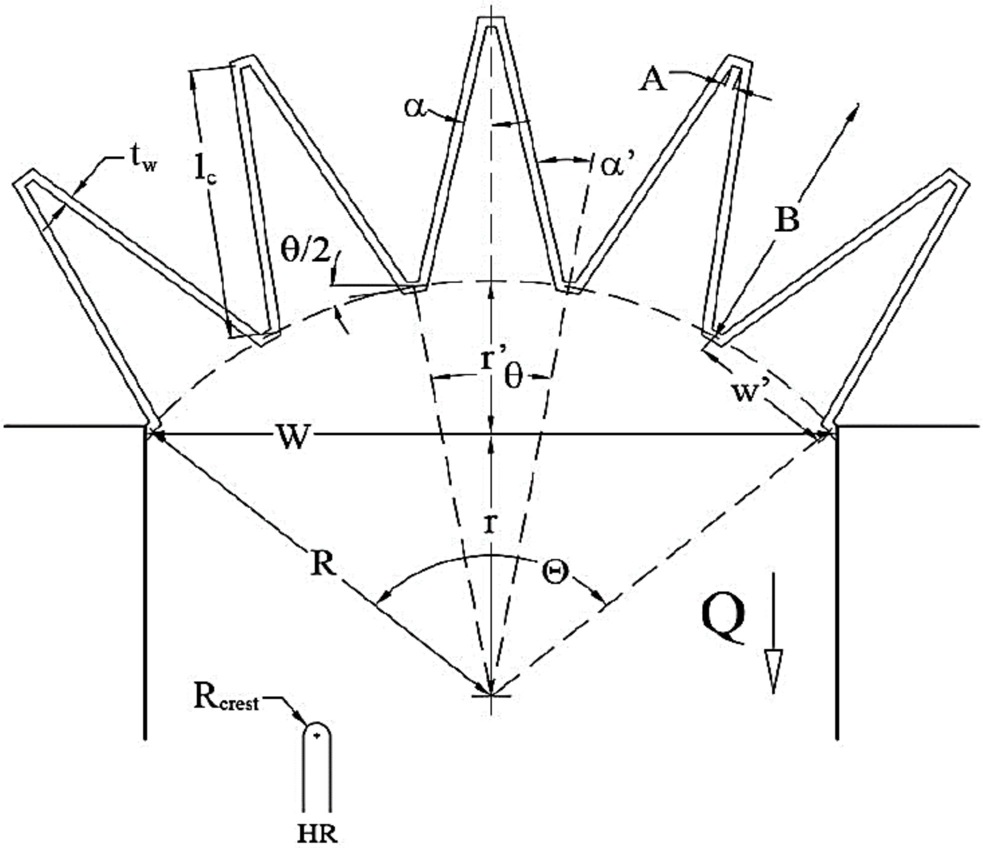

Figure 3. Arced labyrinth weir (Crookston & Tullis, 2012)

2. Geometric Layout of Arced Labyrinth Weirs

An arced labyrinth weir is a cycle architecture in which the downstream apexes follow the arc of a circle. A nomenclature is created for the arc labyrinth weir with complex geometry (see Figure 3).

The geometric specifications of an arced labyrinth weir include:

A Upstream interior apex length
l_c Centerline length of the sidewall
L_c Length of weir
$L_{c\text{-}cycle}$ Length of one complete cycle
N Number of cycles or trapezoidal folds
Q Volume flow rate
r Height of a segment from the channel's opening to arc circle's center
r' Height of a segment from the channel's opening to perpendicular downstream apex
R Arced radius, $R=(W^2/4 + r'^2)^{1/2}$
t_w Wall thickness at crest
w' Cycle arc width, $w'=W'/N$
W Downstream channel width
α Sidewall angle
α' Upstream sidewall angle, $\alpha'=\alpha + \theta/2$
θ Cycle arc angle, $\theta=\Theta/N$
Θ Central arc angle, $\Theta=W'/R$

3. Hydraulic Properties

It is quite difficult to accurately describe a three-dimensional flow in Labyrinth weirs. Because weir geometry, crest form, local submergence, interference of flow layers over a weir, non-parallel flow lines, pressure under nappe, presence or absence of an air pocket behind nappe, effects of surface tension and viscosity, and other parameters are all taken into account, a mathematical formulation is required.

The conventional Poleni equation can be used to compute the head-discharge relationship for arced labyrinth weirs.

The equation as follows:

$$Q = \frac{2}{3} C_d L_c H^{3/2} \sqrt{2g}$$

where Q is the discharge passing over the weir, L_c is the crest length, H is the total head upstream, g is acceleration constant of gravity and C_d is discharge coefficient.

3.1. Relationship between the head and the discharge

The arched weir discharge coefficients are highest when the water head on the weir is low. As the H/P ratio rises, it will decrease and eventually approach a constant value. Table 1 presents several operating features related to the different arced labyrinth weir.

Table 1. Comparison of different arced labyrinth weirs

Number of cycle	Range of H/P	Discharge (l/s)	Discharge coefficient	Type of labyrinth weir	Researcher
4	0.19-1.02	2-20	0.70-0.87	Triangular	(Monjezi *et al.*, 2018)
5,7,10	0.10-0.90	88-433	0.32-0.72	Trapezoidal	(Christensen *et al.*, 2012)
5	0.14-0.95	5-50	0.40-0.66	Trapezoidal	(Feili *et al.*, 2021)

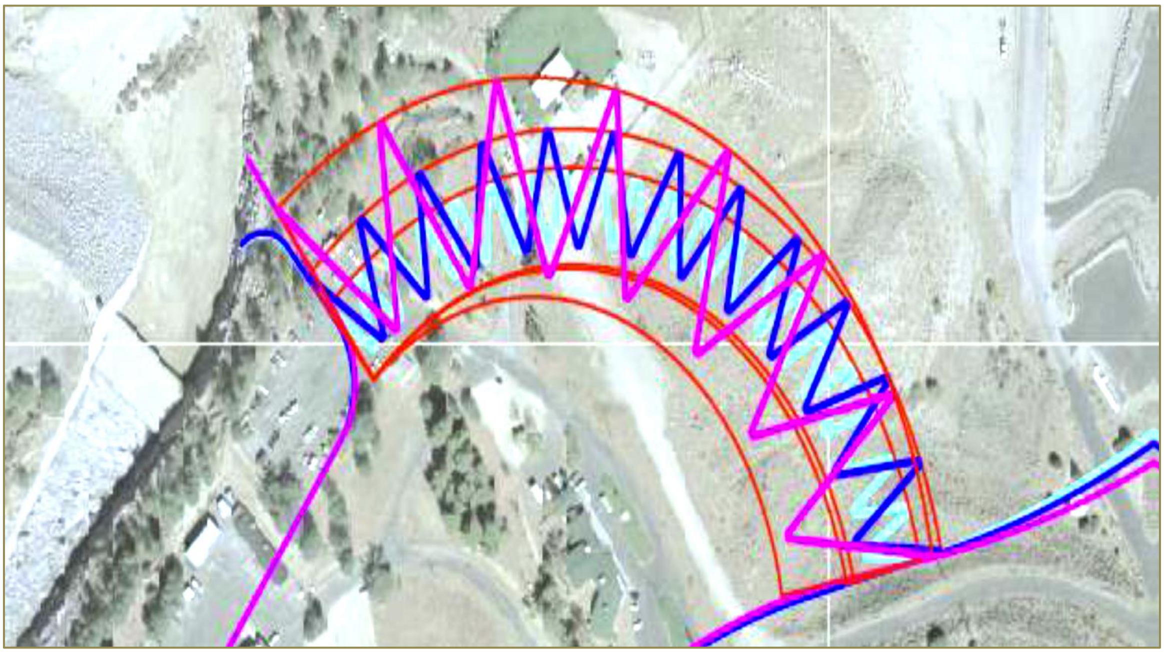

Figure 4. Different number of cycles of arced labyrinth weir

3.2. Cycle Arcing Effects

The capacity of an arced labyrinth weir is also affected by changes in the cycle arc angle (θ) and central arc angle (Θ). dictates how individual cycles are oriented in relation to the approaching flow. For a given cycle geometry α, increasing θ increases α', resulting in larger inlet cycle flow area. As grows, the curvature of the arc length R approaches a more semicircular shape. In a reservoir, arced labyrinth weirs are hydraulically more efficient than non-arced weirs, according to a popular hypothesis in the literature (Christensen *et al.*, 2012). The researchers show that arced weirs with smaller sidewall angles obtain 15% more discharge efficiency than those with wider sidewall angles (α=20°). This could be attributed to the upstream-downstream cycle flow area ratio (also known as the downstream cycles' free-flow capacity). This also means that arcing weirs with sidewall angles α=20° will have a lower discharge efficiency gain than arcing weirs with sidewall angles of less than (α<20°) (Christensen *et al.*, 2012).

Thompson *et al.*, 2016, designed a spillway for the Isabella Lake Reservoir located on the Kern River in Kern County, California. Amongst a 20-cycle weir, a 12-cycle weir and three 7-cycle weirs; The 12-loop weir was ultimately chosen by balancing hydraulic efficiency and cost needs (Figure 4) (Thompson *et al.*, 2016).

3.3. Nappe and Downstream Behavior

Submergence occurs when the tailwater height exceeds the weir crest elevation, either locally (known as local submergence) or over the full crest length (known as overall submergence) (Crookston & Tullis, 2012). The discharge efficiency of arced labyrinth weirs is likewise reduced by nappe interference and aeration (*Hydraul. Des. Labyrinth Weirs*, 2002). Changes in efficiency will occur as local submergence grows and flow patterns over the crest alter (as shown in arced labyrinth weirs). Local submergence increases when the upstream sidewall angle (α') increases (for a given head), and the cycle's free-flow capacity is maximized. Although the benefits in discharge efficiency for an arced labyrinth cycle arrangement are limited by weir submergence (Brian Mark Crookston *et al.*, 2010) and local submergence develops sooner for arced labyrinth weirs (compared to non-arced labyrinth weirs) (Christensen *et al.*, 2012).

Conclusion

H/P and tailwater level values affect arced labyrinth weir discharge capacity. In addition, it is seen that these parameters have a close relationship with cycle number (N), side wall angle (α) and cycle arc angle (θ) of arced labyrinth weir. This is because the direction of the velocity vectors and the sidewalls converge or diverge from the parallel position.

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