Jul 5th, 12:00 AM - Jul 8th, 12:00 AM

Approach Flow Depth Influence on Nonlinear Weir Discharge Capacity

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Abstract: *The high hydraulic efficiency and the compactness of nonlinear weirs favor their use in several rehabilitation or new dams projects. Main types of nonlinear weirs are labyrinth and piano key weirs. The purpose of this paper is to provide indications on the influence of the approach flow depth on the discharge capacity of these nonlinear weirs. To do so, a series of experimental tests have been carried out in the laboratory of Engineering Hydraulics of the Liege University. A labyrinth and a piano key weir have been tested in channel configuration (upstream flow width equal to the weir width) considering various dimensionless dam heights. A large range of discharge has been tested for each case. The results show that the dimensionless dam height increase may decrease up to 8% of the labyrinth weir discharge capacity while it has only very limited but opposite effects for the piano key weir.*

Keywords: *Physical modelling, labyrinth weir, PK weir, head-discharge curve.*

1. INTRODUCTION

The weir is an essential element of dam spillways. It controls the upstream reservoir level rise by releasing excess water, in particular during floods. When placed across a natural or artificial watercourse, a weir can also be used for measuring discharge or controlling the water depth.Replacing a linear weir with a nonlinear weir can be an effective way to increase discharge efficiency (increase discharge released for a given upstream head) for a constant width on a dam crest or in a channel. Nonlinear weirs are linear weirs folded in plan to increase the crest length. Since the discharge capacity of a free surface weir is proportional to its crest length, nonlinear weirs exhibit higher discharge capacity than linear weirs for the same width (Tullis et al., 1995). Different geometric configurations for nonlinear weirs have been developed in order to increase this length while limiting the weir footprint area, such as labyrinth weirs (Hay and Taylor, 1970; Tullis et al., 1995; Crookston, 2010), skewed or oblique weirs (Kabiri-Samani, 2010; Noori and Chilmeran, 2005), duck-bill weirs (Khatsuria et al.,1988), piano key weirs (Leite Ribeiro et al., 2007; Laugier, 2007; Lempérière and Ouamane, 2003) and fuse gates (Falvey and Treille, 1995). In the present study, we are interested in two specific types of nonlinear weirs: the labyrinth weir and the piano key weir (PK weir).

1.1. Labyrinth weir

Labyrinth weirs are nonlinear weirs with vertical walls. The first study reported on the labyrinth weir was carried out by Gentilini (1941); although, the first prototype labyrinth weir documented in the literature was on the East Park Dam (1910) on Little Stony Creek, California, USA (Crookston et al., 2019). Depending on the geometry in plan view of the so called alveoli, there are several forms of labyrinth weir, i.e. trapezoidal, triangular or rectangular (Crookston, 2010). According to Falvey (2003), the symmetrical trapezoidal shape is the most used because of the ease of construction and its hydraulic performance. Alveoli may be aligned along a straight line or a curve (Crookston and Tullis, 2012 a).

Crookston (2010) defines the main parameters generally used to detail the geometry of a labyrinth weir with a linear arrangement (Figure 1). The alveoli geometry is defined by the length of side wall l_c, the width of a cycle w, the wall thickness t_w, the side walls angle α, the alveoli apex width A and the height of the vertical walls *P*. The total width of the weir *W*, the number of cycles *N* and the developed length *L* ($L=N(2l_c+2A)$) are parameters describing the full weir geometry.

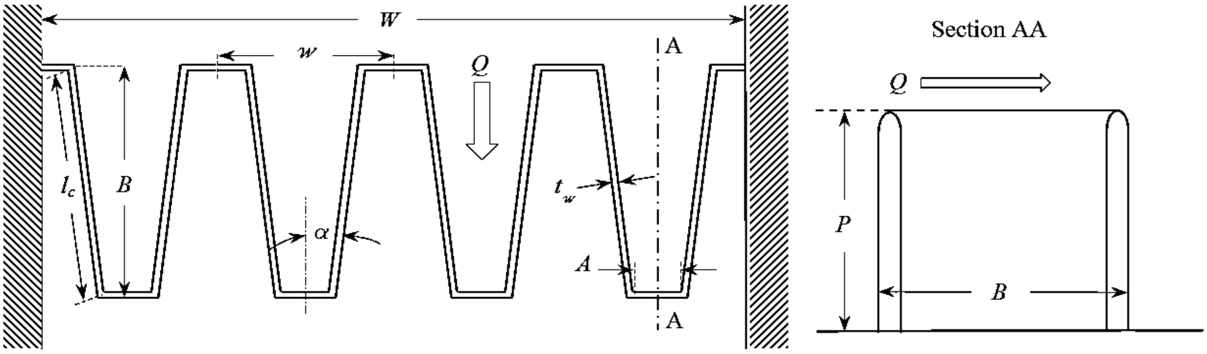

Figure 1 - Fundamental parameters of the labyrinth weir. Plan view (left) and typical cross-section (right).

1.2. Piano key weir

A PK weir is a rectangular labyrinth weir with ramped floor and cantilevered apexes. This arrangement enables a decrease in the basement length and then the area needed to ground the weir. It is then possible to place PK weirs on a very limited area, such as on the top of gravity dams. This specific geometry exhibits high discharge capacity, greater than a labyrinth weir with the same crest (Anderson and Tullis, 2012 and 2013). The PK weir was firstly described by Lempérière and Ouamane (2003). The use of the PK weir as a solution for the rehabilitation of spillways in operation started in 2006 at Goulours dam in France with a project by the EDF company (Laugier, 2007).

Similar to labyrinth weirs, the PK weir geometry (Figure 2) is characterized by (Pralong et al., 2011) the upstream and downstream heights P_o and P_i, denoted simply *P* when both values are equal, the width of the upstream and downstream alveoli W_i and W_o, the lengths of the upstream and downstream overhang B_i and B_o, the length of the base B_b, the length of the lateral wall *B* ($B = B_i + B_o + B_b$), the slopes of the upstream and downstream alveoli S_i and S_o and the wall thickness T_s. The total width of the weir W_t, the cycle width W_u, the number of cycles *N* and the developed length *L* ($L=N(2B+W_i+W_o+T_s)$) describe the global weir geometry.

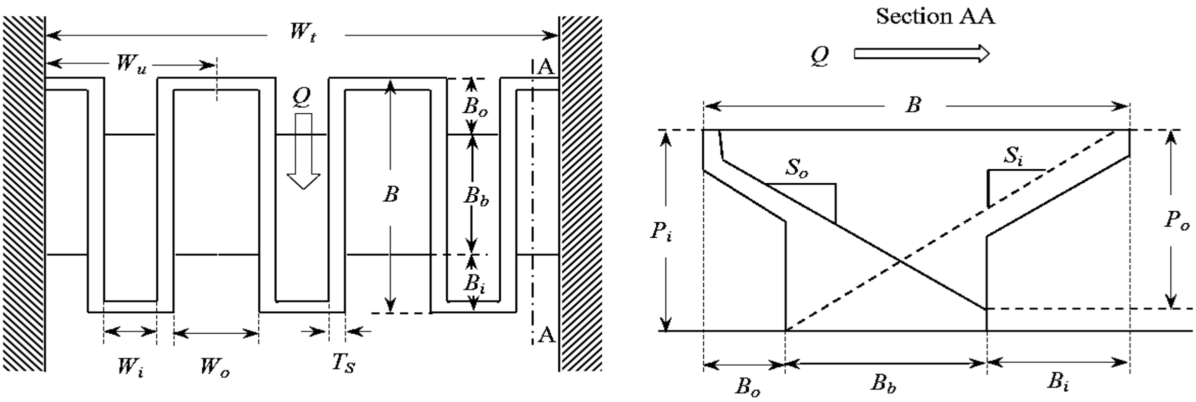

Figure 2 - Fundamental parameters of the PK Weir. Plan view (left) and typical cross-section (right).

1.3. Previous Studies

PK and labyrinth weirs have been extensively studied over the years using physical and numerical models. Both structures are free surface weirs. Their discharge capacity follows then an equation similar to (Tullis et al., 1995; Machiels et al., 2011a):

$$Q = C_d\, W\sqrt{2gH_T^3} \qquad (1)$$

with Q the discharge, C_d the dimensionless discharge coefficient, W the weir width, g is the gravity acceleration and H_T the total upstream head.

The various research works carried out to date showed that discharge coefficient is higher for small upstream head and decreases with increasing upstream head. The weir geometry affects significantly its discharge capacity. For instance, for labyrinth weirs, Hay and Taylor, 1970; Lux and Hinchliff, 1985; Tullis et al., 1995; Crookston and Tullis, 2012 a, b, 2013 a, b., showed that the main parameters influencing hydraulic performance are the head water ratio H_T/P, the sidewall angle α, and the cycle width ratio w/P. With regards to the PK weir, since the proposal of a first design by Hydrocoop in collaboration with Biskra University (Algeria), the Hydraulic Laboratory of Electricité de France (France) and Roorkee University (India) (Lempérière and Ouamane, 2003), numerous works and publications have been carried out (Ouamane and Lempérière, 2006; Machiels et al., 2011 and 2014; Leite Ribeiro et al., 2012 a, b; Machiels, 2012; Anderson and Tullis, 2012, 2013) and showed that the main parameters influencing hydraulic performance of the PK Weir are the headwater ratio H_T/P, the developed crest length L/W ratio and the unit width ratio W_u/P.

The available literature indicates that all the studies conducted to date have never analyzed the effect of the dam height on the discharge capacity of a nonlinear weir. Since this might be an important parameter when considering the construction of a nonlinear weir on the top of a dam, the objective of the present study is to experimentally study this parameter considering a labyrinth weir and a PK weir.

2. EXPERIMENTAL SETUP

2.1. Test facility

Tests are carried out in a 1.2 m wide, 1.2 m high and 7.2 m long horizontal flume in the laboratory of Engineering Hydraulics of the Liege University. The flume is supplied through an upstream tank 1.8 m long, 1.2 m wide and 2.1 m deep and by two pipes connected to centrifugal pumps. A baffle wall is located at the connection between the tank and the flume. At the downstream extremity of the flume, the water freely falls down a 0.9 m high chute and goes back to a 400 m³ underground reservoir supplying the pumps (closed system).

The weirs were placed 3.6 m downstream of the baffle wall on a 0.76 m high support (Figure 4) with a vertical upstream face. A plywood plate has been used to modify the reservoir bottom level and then the dam height P_d (Figure 4) along the whole upstream section of the flume.

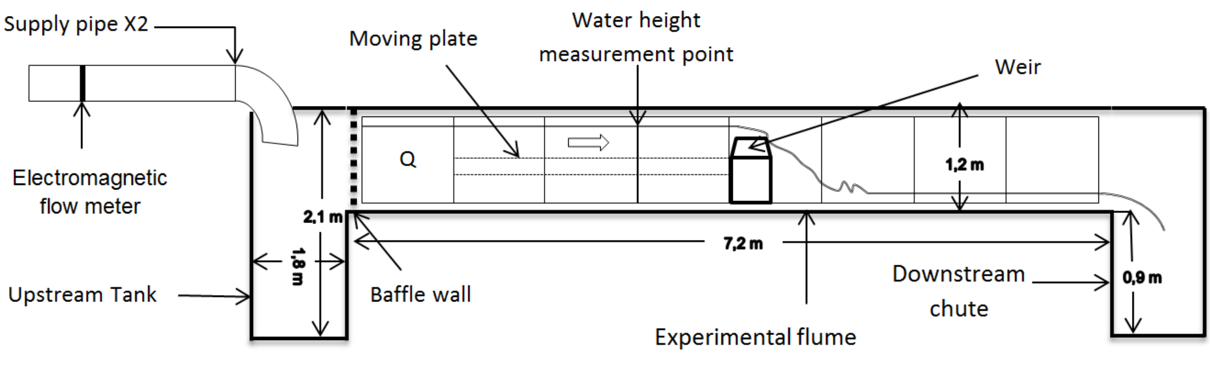

Figure 3 - Testing flume side view.

The discharge supplied to the flume was measured using an electromagnetic flow meter (accuracy of 0.5%) on upstream pipes. A point gauge with a vernier (accuracy of 0.1 mm on free surface at rest) and an ultrasonic sensor (accuracy of 1%) enabled the measurement of water levels upstream of the weirs. The ultrasonic sensor was calibrated on the model. The point gauge was used to check the ultrasonic sensor result. A drawing of the flume is shown in Figure 3 and hydraulic parameters are detailed in Figure 4.

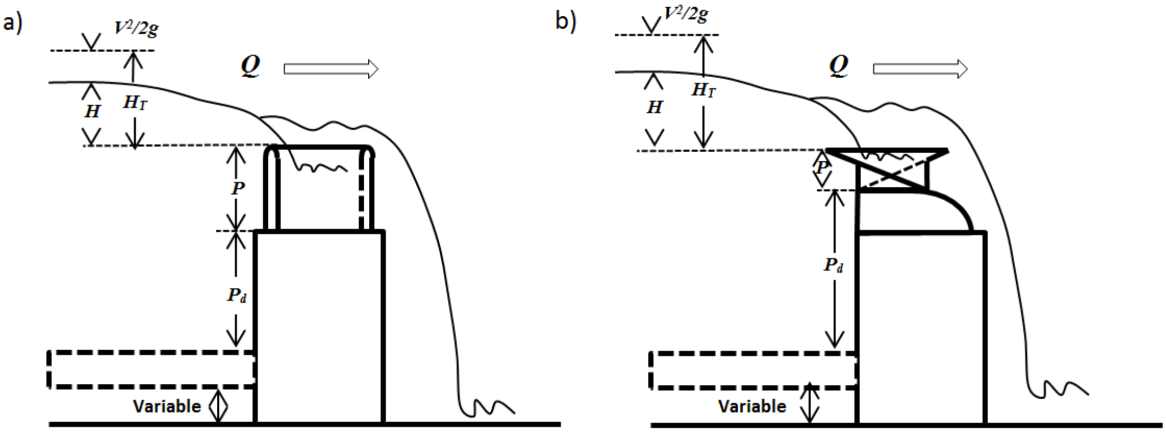

Figure 4 - Hydraulic parameters of flow over the labyrinth weir (a) and the PK weir (b).

2.2. Weirs characteristics

Both nonlinear weir models considered in this study (Figure 5) were fabricated with PVC by the laboratory staff. Their geometric characteristics are summarized in table 1 and table 2. The labyrinth weir had a half rounded crest. The PK weir had a flat topped crest. The labyrinth weir was placed 0.05 m downstream of the support vertical upstream face, while the PK weir was aligned with the support upstream face. The labyrinth weir width was equal to the flume width (1.2 m). Since the PK weir width was 0.8 m, vertical plywood plates were used to narrow the channel along the whole section upstream of the weir. Consequently, both weirs have been tested in channel configuration, i.e. with an upstream chanel width equal to the weir width.

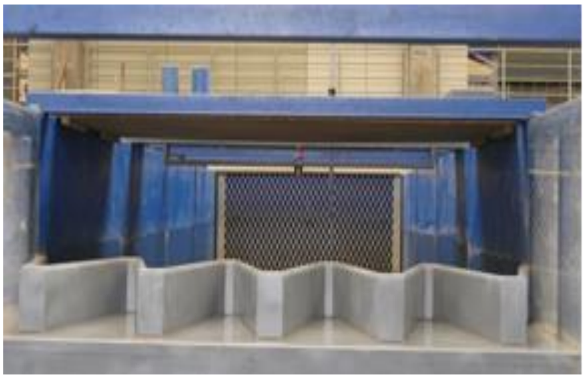 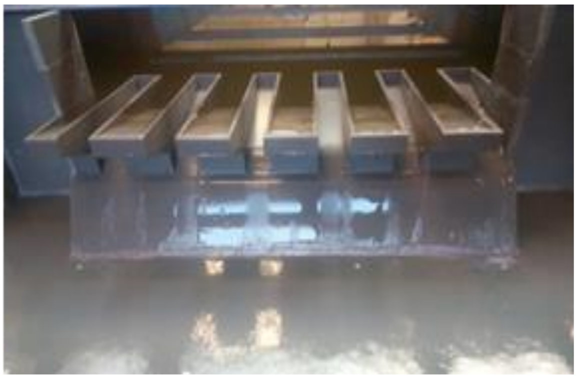

Figure 5 - Downstream view of labyrinth weir model (left) and PK weir model (right).

Table 1 - Geometric characteristics of the labyrinth weir.

Parameter	*P*	*B*	*L*	*w*	*α*	*A*	*D*	t_w	*N*	Crest type
Value (cm)	12.00	38.00	425.11	24.00	12.50°	2.50	5.30	2.00	5.00	Half rounded

Table 2 - Geometric characteristics of the PK weir.

Parameter	*P*	*B*	*L*	W_i	W_0	S_i	S_0	T_s	*N*	Crest type
Value (cm)	13.30	37.80	537.10	6.90	4.90	2.08	3.73	0.60	6.00	Flat topped

2.3. Testing procedure

Each weir was tested separately with different dam heights P_d ranging from 0 to 0.76 m for the labyrinth (7 configurations) and equal to 0 or 0.897 m for the PK weir (2 configurations) and with discharges varying from 0.01 to 0.15 m³/s. For each weir configuration, two series of tests were conducted. The upstream water level was measured first with increasing discharges from the smallest value to the maximum value and then with decreasing discharges from the maximum value to the smallest value. Two water level measurements are then available for each discharge and each weir. The discharge variation step was 0.02 m³/s for the labyrinth and 0.01 m³/s for the PK weir. For each discharge, the water level was measured during 5 minutes at a 1 Hz frequency with the ultrasonic sensor and the mean value was computed.

The total upstream head H_T on the weir crest is calculated from water depth measurements as:

$$H_T = H + {V^2}/{2g} \tag{2}$$

The mean cross sectional flow velocity V is calculated as:

$$V = {Q}/{W(H + P + P_d)} \tag{3}$$

The discharge coefficient C_d is evaluated using equation 1.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 shows the variation of the total upstream head H_T with respect to the discharge for different values of the relative dam height P_d/P. The almost linear trends of head-discharge curves of the labyrinth weir and the PK weir are clearly visible and the difference between the tests with different dam heights P_d/P is limited.

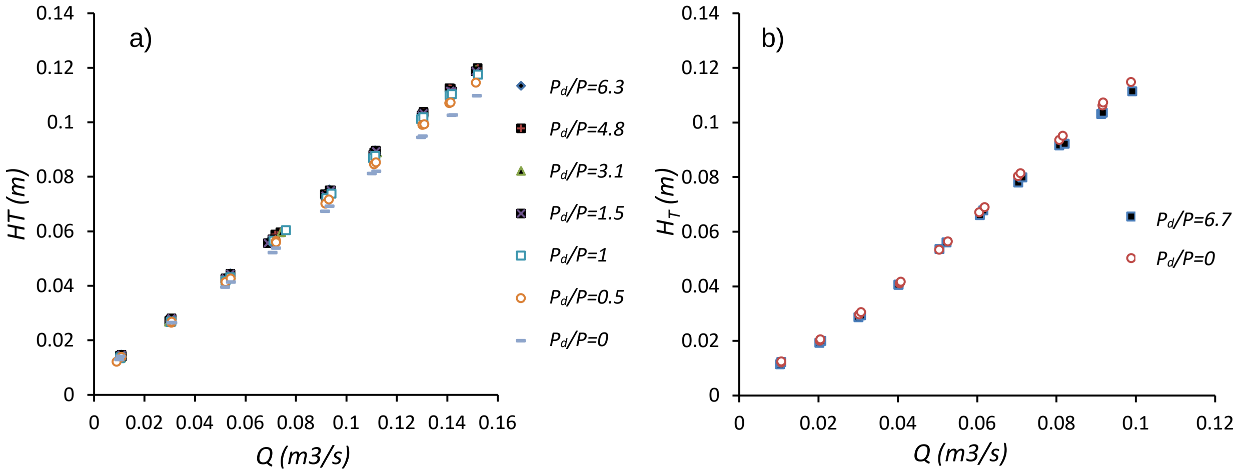

Figure 6 - Head-discharge curves of the labyrinth weir (a) and the PK weir (b).

Looking at the results in terms of discharge coefficient and dimensionless upstream head makes the differences more visible (Figure 7 and 8). On these figures, the dotted line represents the limit of experimental results affected by scale effects according to the 3 cm criterion on upstream water level proposed by Erpicum et al. (2016) for PK weirs. It can be seen that below this limit, results gained with the two series of tests with the same discharge are different.

For the PK weir, the discharge coefficient is slightly affected by the dam height while the labyrinth weir efficiency significantly decreases with increasing dam height.

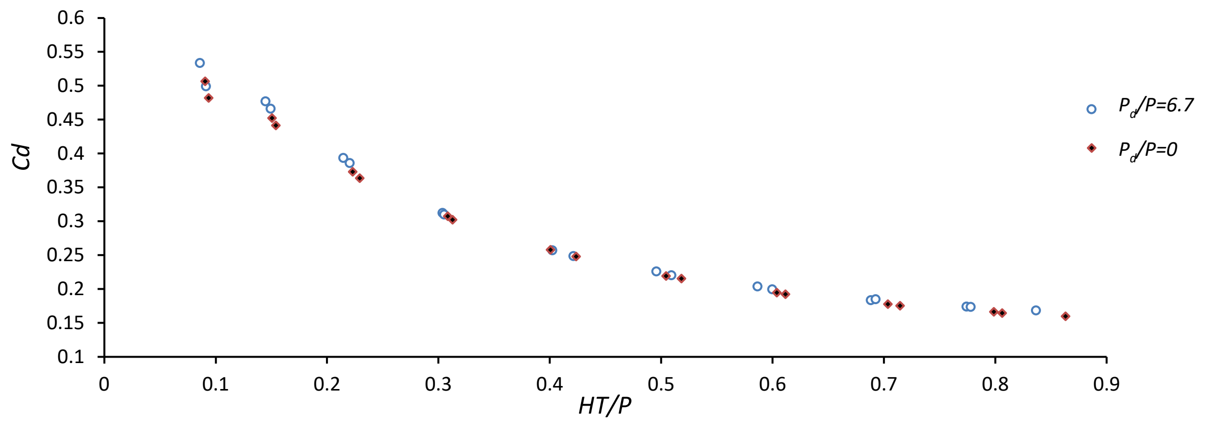

Figure 7 - Dimensionless discharge capacity the PK weir.

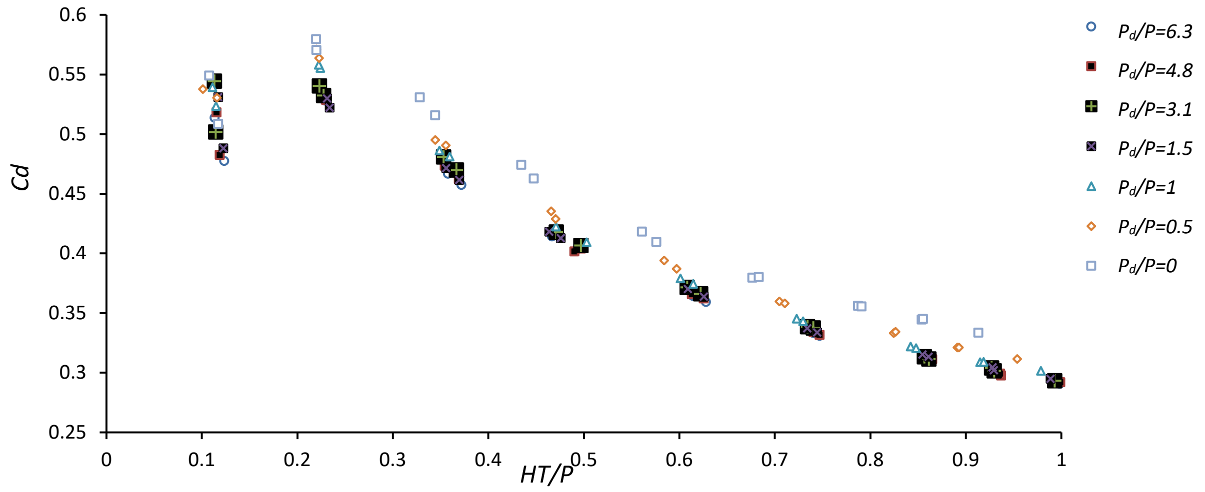

Figure 8 - Dimensionless discharge capacity of the labyrinth weir.

The labyrinth has a design similar to the one considered by Crookston et al. (2010) except where the wall thickness is larger in the present study (*P/6* compared to *P/8*). Interpolation of the analytical curves from Crookston et al. (2010) for α equal to 12.5° provides a reference for comparison when P_d/P=0 (figure 9). Both data sets merge well for H_T/P > 0.4. For smaller heads, the reference curve exhibits higher efficiency. This could be explained, at least partly, by the broader crest considered in this study.

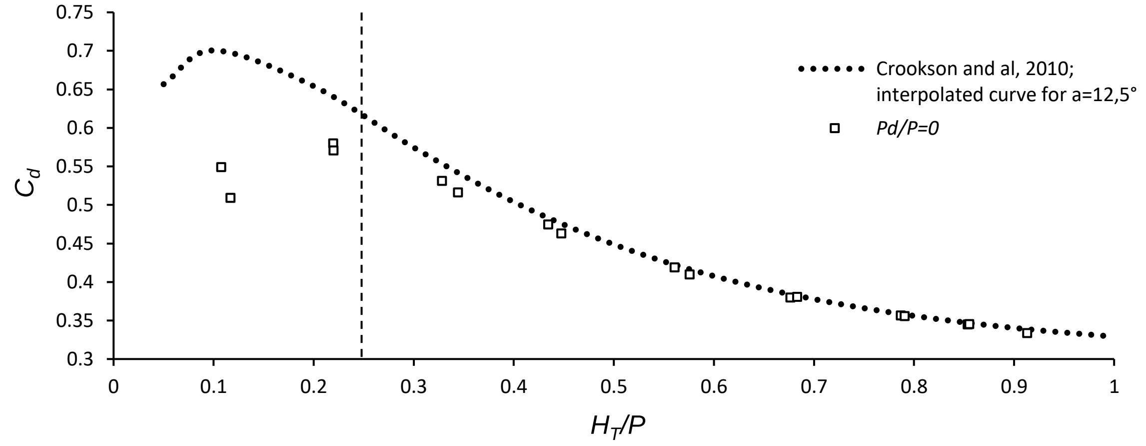

Figure 9 – Comparison of the experimental results with the interpolated relation from Crookston et al. (2010).

Figure 10 shows the ratio between the discharge coefficient with a non-zero relative dam height ratio (C_{di}) to the reference one (C_{d0}) gained with P_d/P = 0. To compare values at identical upstream head ratios, the data for each weir have been approximated with a polynomial of degree 6 where the polynomial equation has been used to calculated discharge coefficient value at various upstream heads. Table 3 and 4 present the averaged discharge coefficient ratio C_{di}/C_{d0} for the labyrinth weir and for the PK weir.

It appears that the efficiency of the labyrinth weir decreases fast with limited increase of dam height and then stabilizes at around a 8% decrease for a deep approach flow. In the case of the PK weir, the trend is of smaller amplitude and opposite: figure 11 shows that the efficiency increases slightly, around 2%, for the higher dam. Despite more investigation is needed to understand these different behaviors, the explanation might, at least partly, be linked to the direction of the flow velocity approaching the inlet key in relation to the inlet bottom slope. In the case of a labyrinth weir, the mainly horizontal incoming flow velocity is more affected by a deeper upstream water flow than in the case of a PK weir, where the ramped inlet key bottom induces incoming flow velocity with a stronger vertical component.

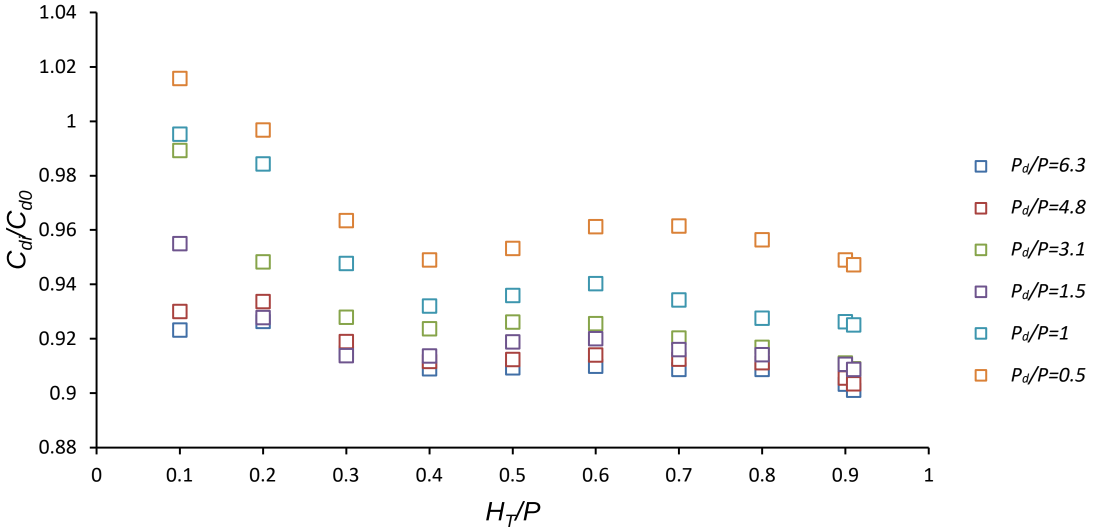

Figure 10 - Theoretical C_{di}/C_{d0} ratio as a function of H_T/P for the labyrinth weir.

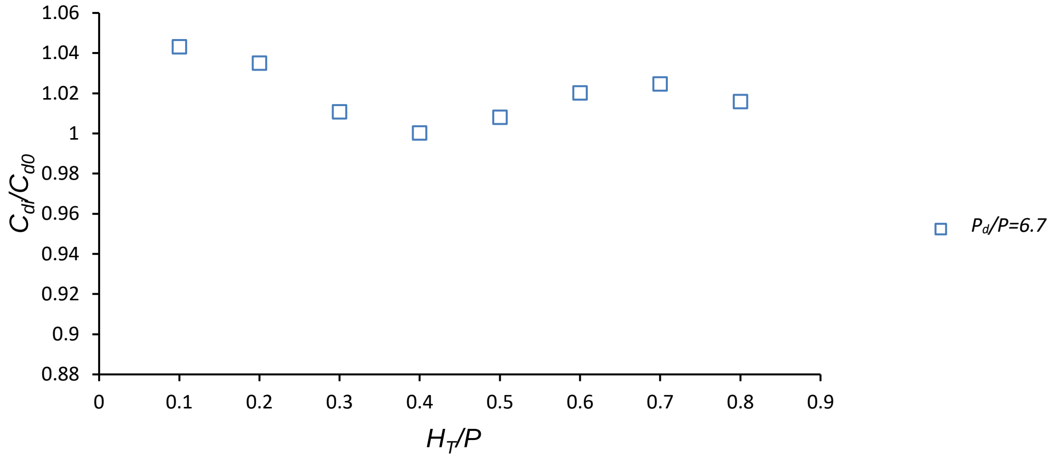

Figure 11 - Theoretical C_{di}/C_{d0} ratio as a function of H_T/P for the PK weir.

Table 3 - Averaged C_{di}/C_{d0} for the labyrinth weir

P_d/P	6.3	4.8	3.1	1.5	1	0.5
C_{di}/C_{d0}	0.91	0.92	0.93	0.92	0.94	0.97

Table 4 - Average C_{di}/C_{d0} for the PK weir

P_d/P	6.7
C_{di}/C_{d0}	1.02

4. CONCLUSION

In an effort to provide indications on the influence of the approach flow depth on the discharge capacity of nonlinear weirs, a series of experimental tests have been carried out considering a labyrinth and a PK weir scale model operated in channel configuration in a flume with a movable upstream bed level.

The results show that a dimensionless dam height in the range 0 to 1.5 significantly affects the labyrinth weir discharge capacity. In particular, the reference discharge capacity observed with an upstream bed elevation equal to the labyrinth weir bottom elevation (P_d/P=0) is reduced by 8% in average when P_d/P is equal to or higher than 1.5.

On the contrary, for the PK weir, the influence of dam height was found to be negligible despite showing opposing results: discharge capacity increases slightly, around 2%, with increasing dam height compared to the reference situation where the upstream channel bed elevation is equal to the elevation of the PK weir inlet entrance.

As shown in this study, the dam height might be an essential parameter to take into consideration when designing nonlinear weirs placed on the top of dams. Additional research is required to confirm the findings of this paper, considering other labyrinth and PK weir geometries in addition to providing a better understanding of the reason for the varied effects observed between different weir types.

5. ACKNOWLEDGMENTS

The Authors acknowledge the help of the technicians of the Engineering Hydraulics laboratory of the Liege University in building and operating the models. They also acknowledge ISL Ingénierie and Groupement GBN-CCN for their permission to use the labyrinth weir model in the framework of this research.

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