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Threshold Submergence of Flow over PK Weirs

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***Abstract*—**In this study an extensive experimental research is carried out to develop a better understanding of the effects of Piano Key (PK) weir geometry on weir flow threshold submergence. Experiments were conducted in a 12 m long, 0.4 m wide and 0.7 m deep rectangular glass wall flume. The main objectives were to investigate the effect of the PK weir geometries including the weir length, weir height, inlet-outlet key widths, upstream and downstream apex overhangs, and slopped floors on threshold submergence and study the hydraulic flow characteristics. From the experimental results, a practical formula is proposed to evaluate the flow threshold submergence over PK weirs.

***Keywords*—**Model experimentation, flow characteristics, Piano Key weir, threshold submergence.

I. Introduction

WEIRS are one of the most common and simple hydraulic structures that have been used for centuries by hydraulic engineers. They can be used for different purposes such as; flow measurement and diversion, energy dissipation, water level management, and many others. Besides, many obstacles in a flood plain can perform as weirs. For example, the summer dike, the groyne, or the barrage. Although the explanation of many various kinds of weirs is clear, and their hydraulic behaviors have been investigated for long time, few studies have been conducted on Piano Key Weirs (PKWs). PK weir is an innovative shape of weirs that has been introduced recently. The PK weir has a simple rectangular crest layout with inclined inlet and outlet key floors. Variation of the shape in plan of the weir is possible; however, the most advantageous form corresponds to the rectangular symmetrical form in plan because it is easiest to be built. The PK weir was originally developed [4] to improve the performance of labyrinth-type weirs installed on smaller footprints. The main advantages of the PK weir regarding labyrinth weirs is its reduced footprint, which enable to place it on the top of gravity dams and the internal slopes in the alveoli, which reduce the forces acting on the lateral walls, and thus the structural costs. Some experiments were conducted [10] to introduce the specifications of flow over PK weirs. Their research showed that this kind of weir can improve the discharge capacity up to four times compared with a conventional frontal weir at constant head and crest length on the dam.

Since then, few researchers have studied the characteristics of flow over PK weir and geometric specifications of these types of weirs [6, 8, 7, 11, 3 13]. Although some interesting papers about PKWs have been published in the last 2 years, sufficient information on the flow characteristics of PK weirs is still not available. The main objective of this study is to investigate the flow characteristics over PK weirs and to determine the flow threshold submergence over the PK weirs.

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II. Dimensional Analysis

The threshold submergence (S_t) defines as H_{dt}/H_0, where H_{dt} is the threshold of downstream flow depth above the weir crest. Referring to figures 1 and 2, S_t can be written as a function of the weir height (P), crest longitudinal length (L), footprint or channel width (B), upstream or outlet key overhang length (c), downstream or inlet key overhang length (d), inlet key width (a), outlet key width (b), wall thickness (t), and number of keys or number of PK elements (n). Important hydraulic parameters are the total water head far enough upstream of the PK weir (H_0), the water head above the upstream apexes (H_1) and gravitational acceleration. The most important flow physical parameters are surface tension (σ) and viscosity (μ). Hence:

$$f(Q, H_o, H_1, H_{dt}, P, L, B, a, b, c, d, t, g, n, \sigma, \mu) = 0 \qquad (1)$$

While the effect of t is very small, it could be neglected. Moreover, the Reynolds number is usually large enough in open channel flow, so it is possible to neglect the effect of viscosity compared with the gravity effect (Henderson 1966). If the head of water above the weir crest is almost greater than 30 mm, the effect of surface tension is also negligible (Novak and Cabelka 1981). Accordingly, σ and μ could be omitted from Eq. (1). Using the Buckingham π theorem, dimensionless functional equation could be written as follows:

$$S_t = \phi\left(\frac{H_0}{P}, \frac{L}{B}, \frac{a}{B}, \frac{b}{B}, \frac{c}{L}, \frac{d}{L}\right) \qquad (2)$$

where ϕ is a functional symbol. The above functional relationship was worked out in this study.

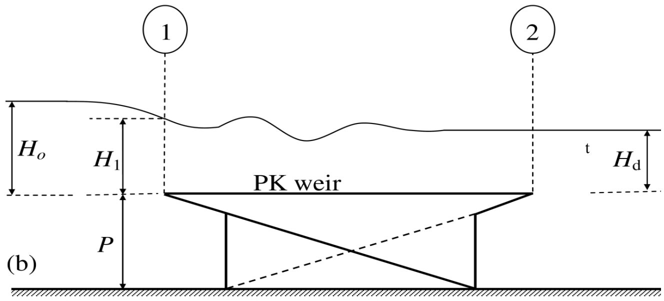

Fig. 1 Flow hydraulic aspects over PK weir (submerged flow)

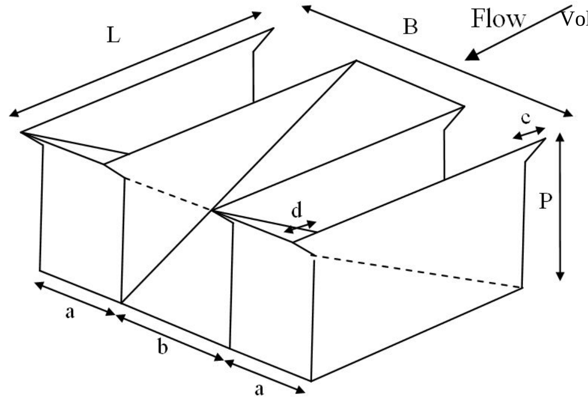

Fig. 2 3D view of PK weir and its elements

If the upstream flow conditions are affected by the downstream flow depth (H_d), then the weir is submerged (Fig. 1.b). For frontal weir flow, $S_t = H_{dt}/H$ is between 0.6 and 0.7, depending on the crest shape (Bos 1989, Tuyen 2007). Because of the complex and three-dimensional flow patterns of PK weir flow, it is simpler to determine threshold submergence based on model experimentation.

III. Model Experimentation

To determine the threshold submergence, models of PK weirs were made of 1mm thick galvanized iron. Weirs were inserted in a 0.4m wide, 0.7m deep and 12m long smooth horizontal rectangular flume. The flume sidewalls were made of glass sheets, with a metal bottom. A sluice gate was fitted at the end of the main channel to control downstream flow depth. The upstream head was measured with a point gage with precision of $\pm$0.1mm. Also, the discharge was measured using an electromagnetic flow meter with precision of $\pm$0.001 L/s. Water supplied to the channel, by a pump and supply pipe, from an underground reservoir and the flow was controlled by a gate valve. Experiments were conducted in sub-critical and stable flow conditions. A total of 200 test runs for threshold submergence measurements were performed in this study. Table I, shows the tested values (ranges) of the hydraulic and geometric parameters of flow over the PK weirs in the flow field.

TABLE I
Configuration of the PK Weir in the Flow Field

Variables (units)	Values (range)
Q (lit/s)	10-70
L (mm)	300, 500, 750
B (mm)	400
P (mm)	200, 250, 300
a (mm)	50, 100, 125, 200
b (mm)	75, 100, 150, 200
c (mm)	0, 50, 80
d (mm)	0, 50, 80
H_0 (mm)	30-140

IV. Experimental Observations and Results

A. Observations

The flow on the PK weir is complex compared with the flow over the traditional weirs. It is characterized by two discharging flow including a normal jet flow over upstream and downstream apexes and a spatially varied flow over the side walls of the keys. Two jets interacts each other and make a complicated flow structure during overflow. There is a separation zone over the side walls of the PK weir. The location of the separation zone relies on flow discharge and weir configuration. By increasing the flow discharge, the separation zone enlarges and moves toward the downstream end of the PK weir. Also, increasing in length of weir or width of outlet keys makes this separation zone bigger. The transition from a partially hanging nappe to a depressed nappe and then to a free nappe can be observed on the different parts of the PK weir crest. On the lateral crests, the depressed nappe remains in contact with the crest for $H_0/P \le 0.05$. For higher vertical aspect ($0.05 \le H_0/P \le 0.15$), the nappe becomes free and is detached from the crest on the most downstream crest length. This transition also occurs for downstream crest of the inlet. For $0.1 \le H_0/P \le 0.15$, depressed nappe changes to a free nappe. On the upstream crest, for the lowest H_0/P, the nappe is completely clinging to the walls. When the aspect of H_0/P becomes greater than 0.15, the nappe is directly fully aerated. For higher water depths the two discharging nappes become mutually dependent representing so a single nappe and consequently the hydraulic efficiency decrease.

B. Determining Threshold Submergence

The tailwater depth was slowly increased through experiment and the approach flow depth was recorded until it had increased up to 0.5 mm. This condition was taken as the threshold condition and the related H_d was considered as H_{dt} representing the threshold tailwater depth to determine $S_t = H_{dt}/H$. Figure 3 shows S_t versus H_0/P for various L/B. As is seen, by increasing H_0/P and decreasing L/B, the threshold submergence decreases. Figure 4 illustrate the variation of S_t versus H_0/P for different a/B. it could be included that by increasing a/B ratio, the threshold submergence decreases. Hence, by choosing smaller inlet key width, S_t increases. These figures show the effects of H_0/P, L/B, a/B and b/B on threshold submergence for PK weirs without overhangs. Sets of data were collected to determine the effects of upstream and downstream overhangs on threshold submergence. Experiments show that upstream overhang has no effect on S_t and downstream overhangs increase this ratio. As is seen in figure 5 for models with downstream overhangs, unlike models with no overhang, by increasing the ratio of H_0/P, S_t is increasing. Finally based on the above mention correlations, practical relationships were developed using the Statistical Package for the Social Sciences (SPSS). To check the correlations, the normalized root-mean-square error (NRMSE), the weighted quadratic deviation (WQD) and the coefficient of determination R^2 were considered. Contrary to R^2, both NRMSE and WQD must be small to have a good relation among parameters and the data. The best correlation for determining the threshold submergence could be written as:

$$S_t = 0.13(\frac{H_0}{P})^{0.03}(\frac{L}{B})^{0.21}(\frac{a}{B})^{-0.4}\exp(-2.27\frac{d}{L}) + 0.59(\frac{H_0}{P})^{\frac{d}{L}} - 0.38(\frac{H_0}{P})^{\frac{L}{B}} \quad (3)$$

with NRMSE=0.17, WQD=0.006 and R^2=0.92

Using the SPSS software showed that ratio of b/B has no consequential effect in evaluating of S_t. Therefore; it is omitted from Eq. (3). Figure 6 shows calculated (Eq. 3) versus observed threshold submergence. As is seen, there is a good agreement between the observed and calculated results of the present study.

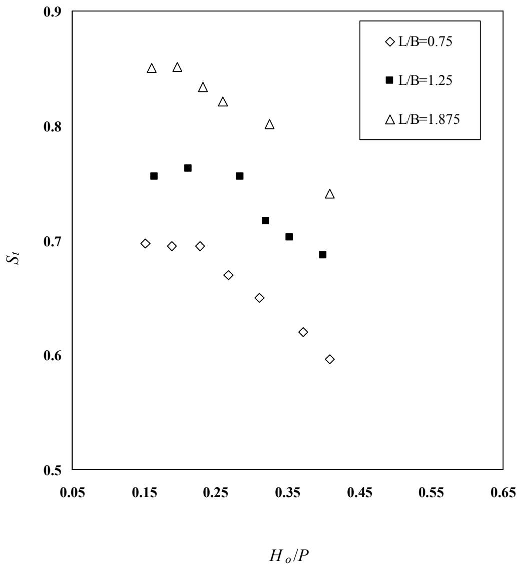

Fig. 3 Variation of S_t versus H_0/P for different L/B

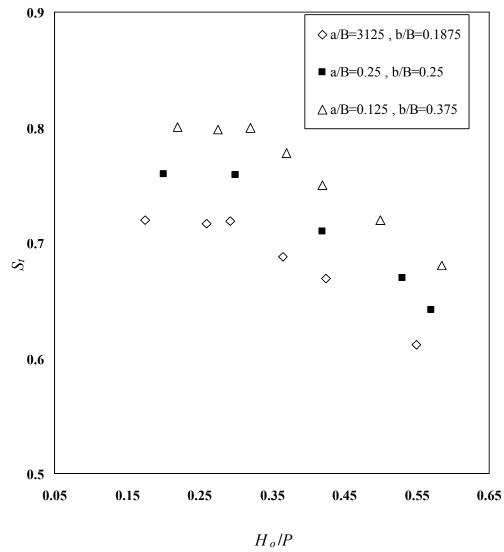

Fig. 4 Variation of S_t versus H_0/P for different a/B and b/B

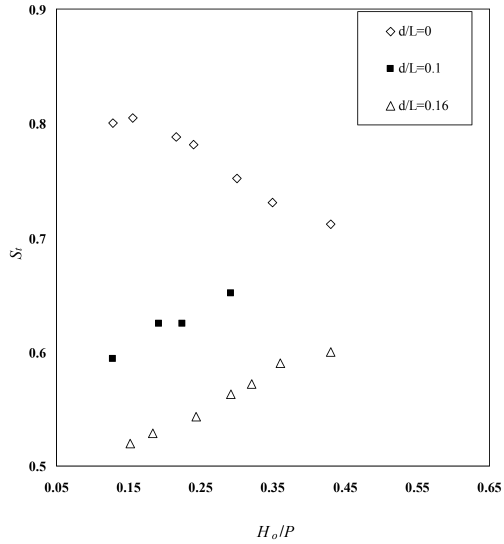

Fig. 5 Variation of S_t versus H_0/P for different d/L

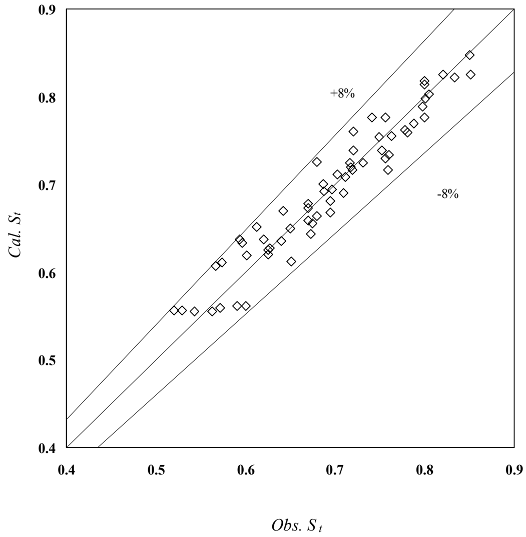

Fig. 6 Calculated (Eq. 3) versus observed threshold submergence

TABLE II
DEFINED PARAMETERS IN THIS STUDY

Symbol	Quantity
B	width of channel
H_o	upstream water head
H_1	water head above the upstream apex
H_2	water head above the downstream apex
H_d	downstream water head above the weir crest in submerged flow
H_{dt}	threshold tailwater head above weir crest
L	weir length
NRMSE	normalized root mean square error
P	weir height
Q	flow discharge
R^2	root mean square
a	width of the downstream apex
b	width of the upstream apex
c	length of the upstream overhangs
d	length of the downstream overhangs
f	function
g	gravitational acceleration
t	wall thickness
μ	surface tension
σ	viscosity
φ	function

V. Conclusion

In this study an experimental investigation was performed to determine the threshold submergence of flow over PK weirs. Results showed that the upstream apex width and length are the most influential parameters on weir flow threshold submergence. On the other hand by increasing the length of weir and upstream apex width (or decreasing downstream apex width), threshold submergence increases. Also it is seen that downstream overhangs have significant effect on threshold submergence. Unlike downstream overhangs, upstream overhangs have no meaningful effect on S_t. Based on a statistical investigation; Eq. (3) was deduced for estimating the threshold submergence of flow over a PK weir.

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