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Hydraulic Behavior Of Piano Key Weir Type B Under Free Flow Conditions

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Abstract: In this study, laboratory experiments were performed to evaluate the effects of the weir geometry of a Piano Key Weir (PKW) type B on the discharge coefficient under free flow conditions. Experiments were conducted in a 15m long, 0.3m wide and 0.45m deep rectangular glass-walled flume. The experimental work includes testing of fourteen PKW models which results 290 tests to cover the effects of weir length and height, up-and downstream key widths, upstream apex overhangs length, dam height and noses length on the weir flow discharge coefficient as well PKW with outlet stepped key were considered in the analysis. Considering the experimental data, the dimensional analysis allowed the development of relations between discharge coefficient and the shape of the PKW and gave a good agreement. Experimental results showed that the most influential parameters for the tested PKW models are the Relative length L/W, Key widths W_i/W_o, PKW Height B/P, and Overhangs length B_o/B. The effectiveness of Piano Key Weir at low heads ratio ($H/P = 0.25$) is up to 400% relative to Creager weir at the same head.

Keywords: Piano Key Weir, Physical modeling, Free Flow, Discharge coefficient, Type B.

1 Introduction

A piano key (PK) weir is a type of nonlinear (labyrinth-type) weir with relatively small spillway footprints which derives its name from its plan which looks like the keys of the piano, developed to increase the specific discharge of overflow spillways as compared with linear weirs. The PK weir is a modified rectangular labyrinth weir with cantilevered upstream and/or downstream apexes and ramped floors in the inlet and outlet cycles or keys forming a new set of variables, the PK weir's cantilevered apexes help to produce a longer weir crest length relative to a rectangular labyrinth weir with the same footprint which enables it to be placed on top of structures such as gravity dams and ramped floors in the keys reduces the forces acting on the lateral walls and hence the structural cost. Schleiss [1] and Lempérière et al. [2] gave historical summary on the development of piano key weir. The global cross section layout enables to distinguish several categories of PKW. Lempérière et al. [2] classified PK weirs according to the arrangement of the upstream and downstream overhangs. PKW with symmetrical upstream and downstream overhangs is classified as Type A, one with only upstream overhangs as Type B, one with only downstream overhangs as Type C, and one without overhangs as Type D as shown in figure 1. Lempérière and Ouamane [3] stated that Type-B is 10% hydraulically more efficient than a Type-A with identical n and P values. Thus, PKW Type B appears as the most hydraulic efficient solution especially for high discharges, however, floating debris may require special care [3]. Lempérière et al. [2] proposed a basic geometry for PKW type B, the proposed geometric parameters are: $L/W = 5$, $W_i/W_o = 1$, $B/P = 2.4$, and $B_o/B = 0.5$.

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The best solution for new dams is PK weir type B maybe and can be recommended for high discharges provided that because it is structurally stable during the periods when the level in reservoir is lower than the level of the sill [4].

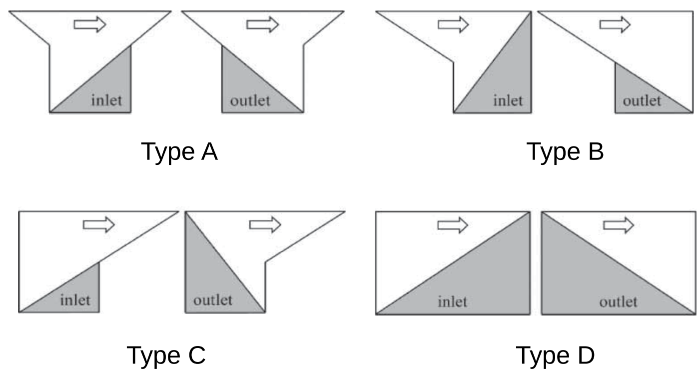


Figure 1 *Piano Key Weir types [5]*

Most of the previous studies on piano key weir have been on PKW type A with different geometries including the studies that predicted an empirical formula for estimating the coefficient of discharge. The goal of this study is to determine the effect of geometrical parameters on discharge coefficient and derive empirical formula for estimating the discharge coefficient of PKW type B for free flow conditions.

2 Data Analysis

To compute the efficiency of a Piano Key Weir for free flow conditions, the general discharge equation for a rectangular sharp-crested weir is used [6-8], referring to the width of the weir W, writes with a discharge coefficient C_{dW}

$$Q_{act} = \frac{2}{3} C_{dW} W \sqrt{2g}\, H^{\frac{3}{2}} \quad (1)$$

However, some researchers [9] express discharge coefficient as C_{dL} referring to the developed crest length L

$$Q_{act} = \frac{2}{3} C_{dL}\, L \sqrt{2g}\, H^{\frac{3}{2}} \quad (2)$$

3 Dimensional Analysis

Discharge over weirs in general is a function of three groups of variables: Geometric characteristics of the model, Fluid properties (density ρ, dynamic viscosity μ, and surface tension σ), and Flow characteristics (the total head H, the gravitational acceleration g). According to Figure 2, the geometric parameters of the PKW include the weir height P, the total weir crest length L, the lateral weir crest length B, the channel or transverse width W, the upstream key cantilever (overhang) lengths Bo, and the up- and downstream key widths Wo and Wi. Notations of this study is in agreement with the naming convention of Pralong et al. [10]. In the present study, the effect of the nose length on the efficiency will be studied as the parameter (B_n/B_o), since the nose is located under the upstream overhang and its length extend with the length of the upstream overhang. The discharge over a PKW for free flow depends on:

$$Q_{act} = f\,(H, L, W, W_i, W_o, B, B_o, P, P_d, B_n, \rho, g, \mu, \sigma) \qquad (4)$$

where f is a functional symbol. Since the flow in nature is turbulent, and occurs at a relatively large head, it can be assumed that viscosity μ ,and surface tension σ are insignificant variables [11]. If for all tests H > 30 mm, the effects of surface tension on discharge are small [8]. Therefore, they can be dropped from equation (4). Applying dimensional analysis using the Buckingham's π-theorem, Eq. (4) is rewritten as :

$$C_d = f\left(\frac{H}{P}, \frac{L}{W}, \frac{W_i}{W_o}, \frac{B}{P}, \frac{B_o}{B}, \frac{P_d}{P}, \frac{B_n}{B_o}\right) \qquad (5)$$

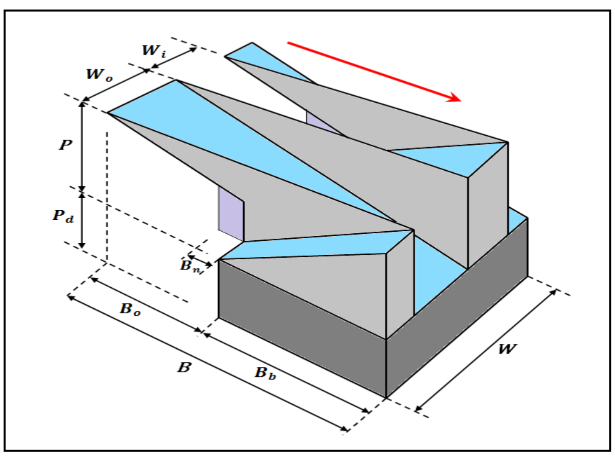


Figure 2 *Definition sketch of PKW model Type B 3D-view.*

4 Experimental Set-up

A series of runs at different discharge values were tested for each model, at each run upstream depth h and water depth at upstream apex were measured in a straight flume 15m long, 0.3m wide and 0.45m deep rectangular glass-walled to allow for visual observation of the flow patterns. Over the flume sidewalls, a rolling point gauge of ±0.3mm reading accuracy was mounted to measure the flow depth. All PKW models were fabricated from acrylic glass sheets of 2.5 mm thick (resulting in $Ts/P \approx 0.02$), the weir pieces were cut using a CNC (Computer Numerical Control) machine and then pasted together with all the edges were beveled to form flat top crest. Each weir was fixed to the flume bottom by two screws and sealed with silicon to prevent water leaks. To make sure that surface tension is negligible, the water depth over the weir was at least 30 mm. Flow depths were measured using a point gauge after the flow had been allowed to stabilize. The measurement of the upstream water level (h) was taken at distance equal to 3.5 times the height of Piano Key Weir model ($3.5P$) from the outlet key apex in the upstream direction. A minimum of seventeen different discharges allowed to pass per PKW model. In total, 290 model tests were conducted, with 14 different PKW geometries. According to the recommendation of Lempérière et al. [2] for configuration of PKW type-B has been selected and referred as model (B1) and then each parameter were changed twice as shown in table 1 . It should be noted the parameter (B_n / $B_o = 0$) means PKW without noses.

Table 1. *The tested dimensions for PKW models:*

Model No.	L/W	W_i / W_o	B/P	B_o/B	P_d/P	B_n / B_o	Stepped Key
B1	**5**	**1**	**2.44**	**0. 5**	**0.6**	**0**	–
B2	3	1	2.44	0.5	0.6	0	–
B3	8	1	2.44	0.5	0.6	0	–
B4	5	0.4	2.44	0.5	0.6	0	–
B5	5	2.5	2.44	0.5	0.6	0	–
B6	5	1	1.63	0.5	0.6	0	–
B7	5	1	3.54	0.5	0.6	0	–
B8	5	1	2.44	0.3	0.6	0	–
B9	5	1	2.44	0.7	0.6	0	–
B10	5	1	2.44	0.5	0	0	–
B11	5	1	2.44	0.5	1.5	0	–
B12	5	1	2.44	0.5	0.6	0.5	–
B13	5	1	2.44	0.5	0.6	1	–
B14	5	1	2.44	0.5	0.6	0	Outlet

5 Results and Observations

5.1 Mode of Flow over PKW

The flow over a PKW is sum of three main parts: flow over the upstream crest which enters the outlet key, flow over the downstream crest which enters the inlet key, and the lateral flow over the side crest supplies from the inlet key entering the outlet key. All three parts of discharge interact resulting in a complicated three-dimensional flow as shown in figure 3. For higher heads, the spilled water from the side crest entering the outlet key is increased so the local submergence at the outlet key occurs decreasing the hydraulic efficiency till the two discharging nappes mutually interact forming a single nappe, making PKW tends to behave like a linear weir. When the water flows over the sidewall crest, two nappes were noticed. The first one, which is closer to the upstream side, is attached to the side crest with no aeration below it. While the second one is detached (or separated) from the side crest and aerated. Its location depends on the weir configuration and the discharge. If the discharge is increased, the separation zone enlarges and moves towards the downstream end of the PKW. The effected geometric parameters are the key width, as the outlet key width, W_o , increases (W_i/W_o decreases), the separation zone takes more length and vice versa as shown in figure 4. Also the relative length seems to reduce the length of separation zone as L/W ratio increases.

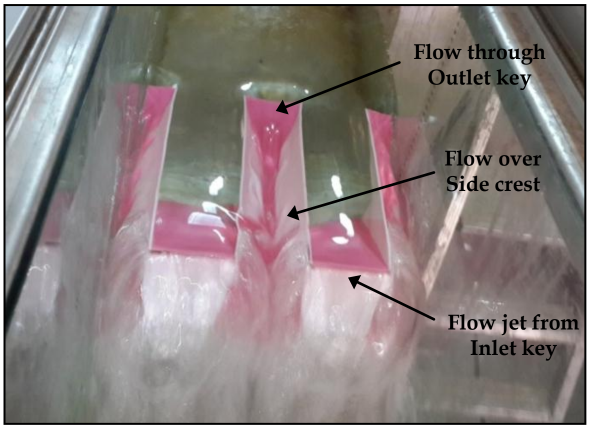
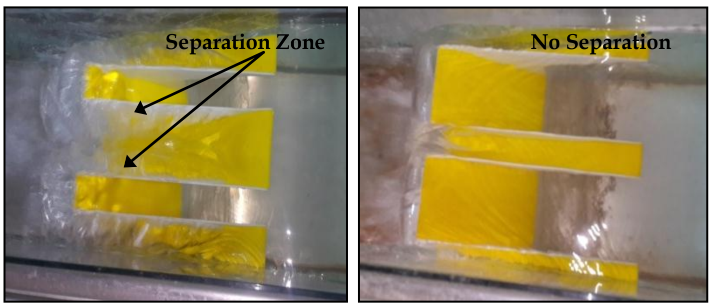


Figure 3 *Flow component over PKW type B.*



(a) (b)

Figure 4 *Effects of key width on separation zone at H/P=0.28 over PKW of (a) $W_i/W_o = 0.4$ (model B4), and (b) $W_i/W_o = 2.5$ (model B5).*

5.2 Comparison between Piano Key Weir and Creager weir

In order to see the enhancement in efficiency between linear and nonlinear weirs, a comparison must be made in rating curves between Creager weir (Linear weir) and PKW (Nonlinear weir). For Creager weir, the equation (6) was applied [2] :

$$q(m^3/S\ .m) = 2.15\,H^{1.5}\ \ (H\ in\ m) \qquad (6)$$

The test results revealed as presented in figure 5 that PKW models is more efficient than Creager weir about 225% to 115% for model with $L/W = 3$ at head ratios H/P=0.25 and 0.63 respectively. While model with $L/W = 5$ is more efficient about 350% at H/P=0.25 and 165% at H/P=0.55. Model with $L/W = 8$ is more efficient about 400% to 150% at H/P=0.25 and 0.6 respectively. Increasing L/W higher than 5 effects only on low heads due to local submergence at outlet key (regions where the flow depth in the outlet cycle exceeds the weir crest elevation). For more clarification, the data were represented as the percentage gain in discharge relative to Creager weir at the same head as shown in figure 6.

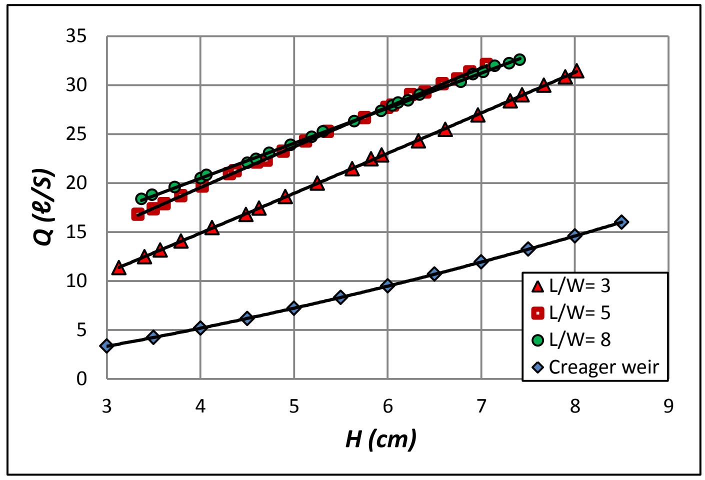


Figure 5 *Comparison in rating curves (Q-H) between Creager weir and PKW of different L/W ratio of ($W_i/W_o = 1$, $B/P = 2.44$, $B_o/B = 0.5$, and $P_d/P = 0.6$)*

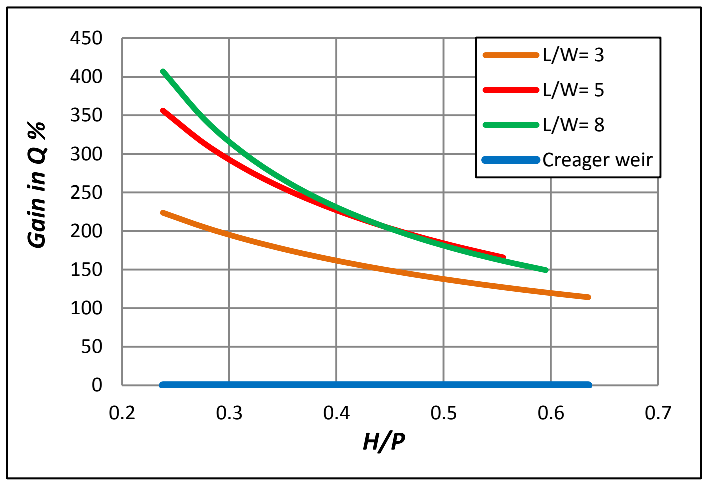


Figure 6 *Percentage gain in free overflow discharge versus $\boldsymbol{H/P}$ of PKW type B relative to Creager weir for the same head.*

5.3 Effect of the Relative Length (L/W)

Generally, the elongation of the crest, which results from the non-linear shape of PK-Weir, is expressed by L/W which is the ratio between the total length of the crest and the width of the weir. Experiments have appeared as shown in figure 7 that increasing L/W ratio from 3 to 5 increases the efficiency about 38% to 19% for low and high heads ratio respectively, and increasing it from 3 to 8 increases C_{dw} about 50% to 16% for low and high heads ratio ($H/P = 0.6$). Increasing L/W from 5 to 8 increases efficiency about 8.5% at H/P=0.25, but the increased C_{dw} values decreases with head increases and eventually becomes less than $L/W = 5$ at $H/P \geq 0.45$, about 2% at $H/P = 0.6$ due to local submergence.

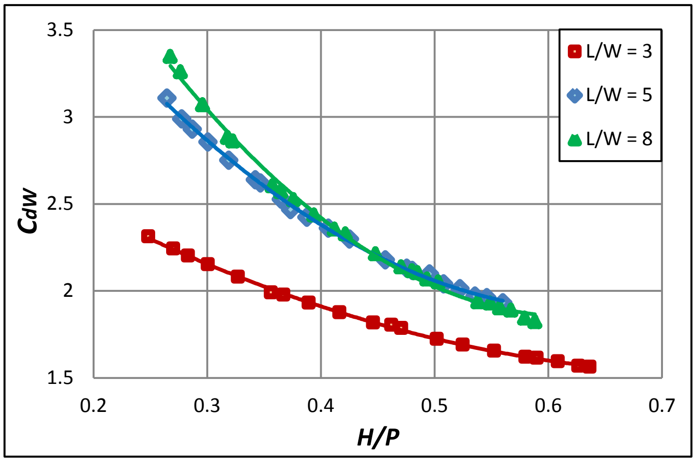


Figure 7 *Variation of free overflow discharge coefficient* $(\boldsymbol{C_{dw}})$ *versus* $\boldsymbol{H/P}$ *for various* $\boldsymbol{L/W}$.

5.4 Effect of the Alveoli Width (W_i/W_o)

The geometry in plan of P.K. Weir is characterized by two keys of rectangular form, the first of width (W_o) oriented towards the upstream and the second of width (W_i) directed towards the downstream as shown in figure 2. Figure 8 shows that increasing W_i/W_o ratio from 0.4 to 1 led to increase the capacity by range 25% to 22%, and increasing W_i/W_o ratio from 1 to 2.5 reduces the capacity by range 10% to 13% due to the local submergence at outlet key.

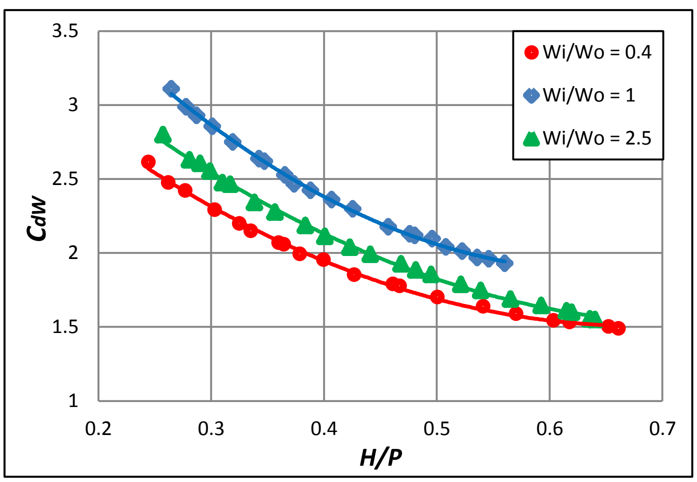


Figure 8 *Variation of free overflow discharge coefficient* $(\boldsymbol{C_{dw}})$ *versus* $\boldsymbol{H/P}$ *for various* $\boldsymbol{W_i/W_o}$.

5.5 Effect of the PKW Height

The height of weir is a significant factor influences the efficiency of a PKW. As can be seen in figure 9 that the experimental discharge coefficient for the PK weir decreased rapidly as the height increases (B/P ratio decreases). This increase observed only when the ratio changed from 1.63 to 2.44 but for values more than 2.44 , the discharge coefficient remains unchanged. The gain in capacity for low and medium heads from changing the B/P ratio from 1.63 to 2.44 is 28% and 25.5% respectively. Note that the models in figure 6 is unclear due to the data shift (the data are under different ranges of H/P because of different heights of models) due to flume limitations.

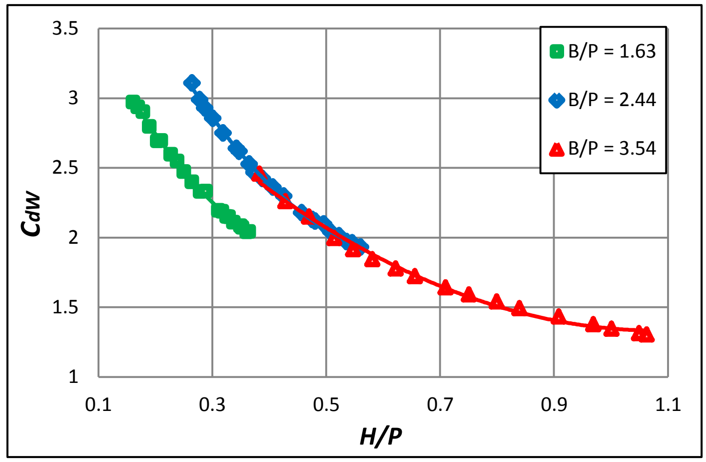


Figure 9 *Variation of free overflow discharge coefficient* $(\boldsymbol{C_{dw}})$ *versus* $\boldsymbol{H/P}$ *for various* $\boldsymbol{B/P}$.

5.6 Effect of the Overhangs Length

It can be seen from figure 10 that the longer the upstream overhang, the higher the discharge coefficient C_{dw} and the shortest the upstream overhang, the lower the C_{dw} due to the increase in the inlet flow area and the wetted perimeter, resulting in reduced inlet velocities, flow contraction and energy loss. The gain in efficiency when increasing B_o/B from 0.3 to 0.5 is about 10% to 12% and from 0.3 to 0.7 gives 21% to 26%, and increasing it from 0.5 to 0.7 gives 10% to 15% for low and high heads ratio respectively.

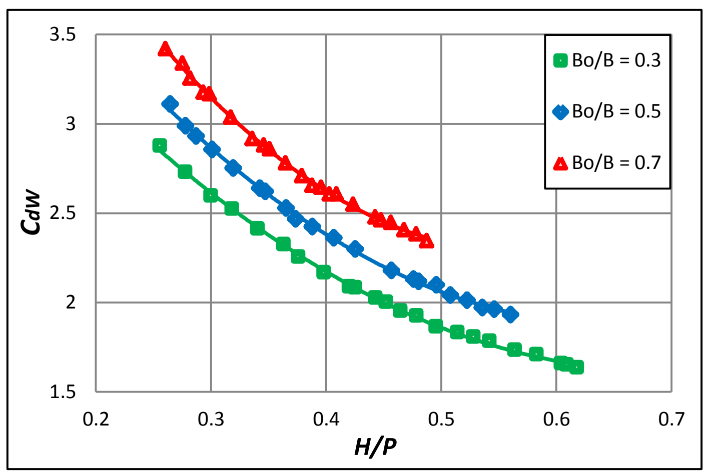


Figure 10 *Variation of free overflow discharge coefficient* (C_{dw}) *versus* H/P *for various* B_o/B.

5.7 Effect of the Dam Height (P_d/P)

As the PKW is mainly used on dam crest, the dam height under the weir has to be characterized. The height of the dam (P_d), can have a positive influence on the discharge capacity. This effect can be related to a head loss increase associated to the approach velocity in front of the outlet keys. As the dam height increases, the flow depth increases and inversely proportional the flow velocities along the inlet key decreases and the head loss decreases resulting in an increase in the PKW efficiency. The increased capacity is about 8% when changing P_d/P ratio from 0 to 0.6. Increasing P_d/P more than 0.6 dose not contribute any gain as shown in figure 11.

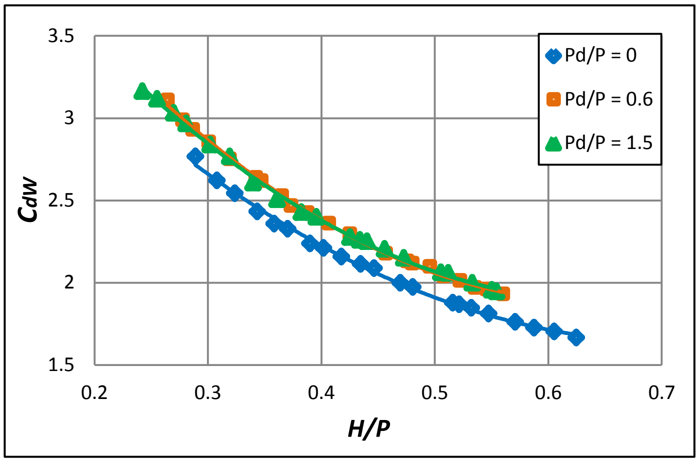


Figure 11 *Variation of free overflow discharge coefficient (C_{dw}) versus H/P for various P_d/P.*

5.8 Effect of the shape of entry under the upstream overhangs

The nose is a feature placed under the upstream overhang to enhance the flow pattern at inlet key entrance. Its shape can vary from triangular profile to rounded one. The geometry of the nose is mainly defined by its horizontal length (B_n), in addition to mentioning the nose shape. Using noses with length equal to half overhang length ($B_n/B_o = 0.5$) has an effect about 4.5% to 6.5% gain. But increasing the noses length further dose not introduce any gain as shown in figure 12.

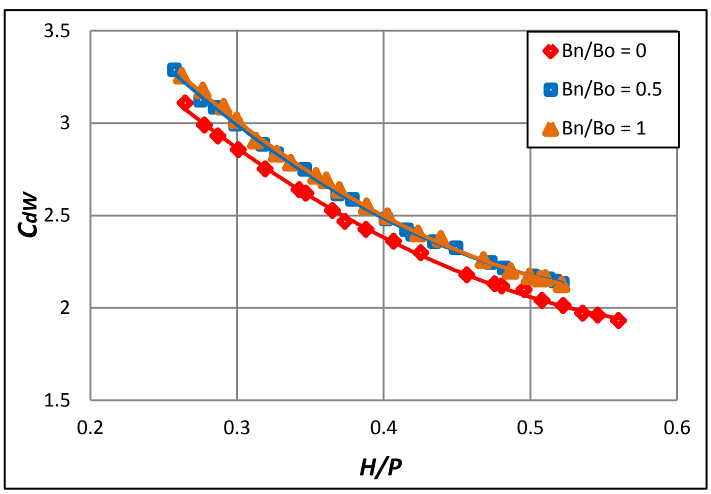


Figure 12 *Variation of free overflow discharge coefficient (C_{dw}) versus H/P for various B_n/B_o.*

5.9 Effect of the Outlet Stepped Key

Using steps at the outlet key of PKWs instead of sloped floor has a minor gain in efficiency beside its interest in energy dissipation. The gain is approximately 4.6% and decreased to about 2% at low and high head ratio respectively as shown in figure 13.

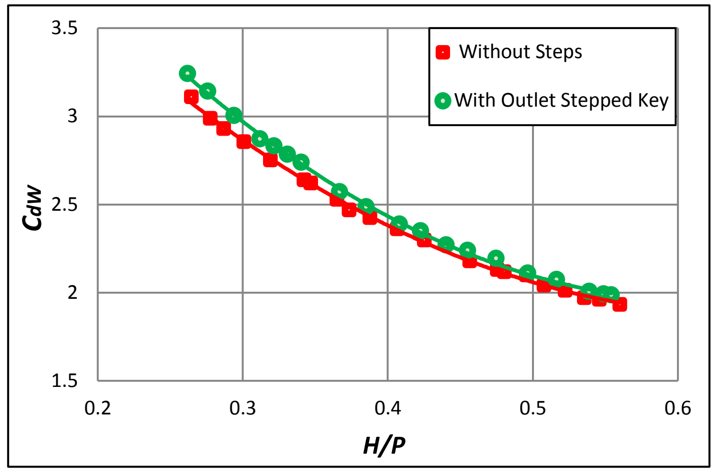


Figure 13 *Variation of free overflow discharge coefficient (C_{dw}) versus H/P for outlet stepped key.*

5.10 Practical discharge coefficient equations

Applying dimensional analysis, using a statistical software, relationships among the dimensionless parameters of Eqs. (7) and (8) were determined. The equation with the smallest error and the highest R^2 for free flow is (R^2 = 0.991)

$$C_{dw} = 0.138 \left(\frac{H}{P}\right)^{-0.450} \left(\frac{L}{W}\right)^{2.101} \left(\frac{W_i}{W_o}\right)^{0.845} \left(\frac{B}{P}\right)^{2.531} \left\{exp\left[-1.987\left(\frac{H}{P}\right) - 0.260\left(\frac{L}{W}\right) - 0.569\left(\frac{W_i}{W_o}\right) - 0.678\left(\frac{B}{P}\right) + 0.892\left(\frac{B_o}{B}\right) + 0.051\left(\frac{P_d}{P}\right) + 0.133\left(\frac{B_n}{B_o}\right)\right] - 0.002\right\} + 1.197 \quad (7)$$

Subjected to limitations that are resulted from modeling conditions :$0.25 \le H/P \le 0.6$, $3 \le L/W \le 8$, $1.64 \le B/P \le 3.54$, $0.4 \le W_i/W_o \le 2.5$, $0.3 \le B_o/B \le 0.7$, $0 \le P_d/P \le 1.5$, and $0 \le B_n/B_o \le 1$. Hence, Eq. (6) is a good tool to estimate the discharge coefficient under the all free overflow condition. Experiments further confirmed that the flow depth above upstream apex h1 is constant along the channel width, equal to

$$\frac{h_1}{P} = 0.9753 \left(\frac{h}{P}\right) \times \left(\frac{L}{W}\right)^{-0.0391} \left(\frac{W_i}{W_o}\right)^{0.0501} \times exp\left\{0.0552\left(\frac{B_o}{B}\right)\right\} \quad (8)$$

The limitations of Eq. (7) apply also for Eq. (8) and the coefficient of determination is (R^2= 0.994).

6 Conclusions And Recommendations

The important conclusions that can be drawn from the this study are:

1. Piano Key Weir type B is an innovative type of weirs that can increase the discharge capacity of spillways at low heads up to 400% relative to Creager weirs for a given head.
2. The total developed length to the PKW width (L/W) is the most influential parameter on the discharge coefficient. Increasing L/W from 5 to 8 effects only the low heads up to 8.5%, for higher heads ($H/P \ge 0.45$) the efficiency becomes less about 2%.
3. The ratio of inlet to outlet key widths (W_i/W_o) gives maximum PK weir performance when its value is 1, for

values higher or smaller than 1 the discharge capacity becomes low.

4. The ratio of upstream-downstream length to the PKW height (B/P) has an important influence on discharge efficiency in to a certain value, increasing B/P (decreasing the PKW height) led to increase C_{dW}. In other words, increasing B/P ratio more than 2.44 has no effect.
5. The effect of the upstream overhangs length (B_o/B) on the PKW efficiency is significant. The longer the upstream overhang, the higher the discharge coefficient C_{dW}.
6. The dam height (P_d/P) has a small influence on discharge coefficient (C_{dW}). The increased capacity is about 8% when changing P_d/P ratio from 0 to 0.6. Increasing P_d/P more than 0.6 dose not contribute any gain.
7. Installing triangular noses under the upstream overhangs improves the efficiency of PKW.
8. Using steps at the outlet key of PKWs instead of sloped floor has a minor gain in efficiency beside its interest in energy dissipation.
9. The water depth above the upstream apex (h_1) is constant along the weir width and it is always less than the upstream piezometric head h by (12% to 4%). Its effected by relative length (L/W), alveoli width (W_i/W_o) and upstream overhang B_o/B while the other geometric parameters have insignificant influence.

NOTATION

B = lateral weir crest length
B_o = upstream overhang lengths
C_{dW} = discharge coefficient
g = gravity acceleration
H = total upstream water head
h = upstream flow depth
h1 = flow depth above upstream apex
L = total weir crest length
P = weir height
Q = free weir flow discharge
Ts = side wall thickness
W = channel width or transverse width
W_i, W_o = widths of down- and upstream apexes
μ = viscosity
σ = surface tension

REFERENCES

[1] Schleiss, A. J. (2011). From Labyrinth to Piano Key Weirs – A historical review. Proceedings of the International Conference (Labyrinth and Piano Key Weirs – PKW 2011), Liège, Belgium, CRC Press, London, pp. (3-15).

[2] Lempérière, F., Vigny, J.-P. and Ouamane, A. , (2011), "General comments on Labyrinths and Piano Key Weirs: The past and present", Proceedings of the International Conference Labyrinth and Piano Key Weirs 2011, Liège Belgium, CRC Press, London, pp.(17–24).

[3] Lempérière, F. and Ouamane, A. (2003), "The Piano Keys weir: a new cost-effective solution for spillways", www.vncold.vn.

[4] Ouamane, A., (2011), "Nine years of study of the Piano Key Weir in the university laboratory of Biskra "lessons and reflections" ", Proceedings of the International Conference Labyrinth and Piano Key Weirs 2011, Liège, Belgium, CRC Press, London, pp. (51–58).

[5] Leite Ribeiro, M. , Pfister, M. , Schleiss, A. J. and Boillat, J. , (2012), "Hydraulic design of A-type Piano Key Weirs", Journal of Hydraulic Research Vol. 50, No. 4, pp. (400–408).

[6] Ouamane, A. and Lempérière, F. , (2006), "Design of a new economic shape of weir", in proc. of International Symposium on Dams in the Societies of the 21st Century, Barcelona, Spain, pp. (463-470).

[7] Noui, A. and Ouamane, A. , (2011), "Study of optimization of the Piano Key Weir", Proceedings of the International Conference Labyrinth and Piano Key Weirs 2011, Liège, Belgium, CRC Press, London, pp. (175–182).

[8] Kabiri-Samani , A. and Javaheri, A. , (2012), "Discharge coefficients for free and submerged flow over Piano Key weirs", Journal of Hydraulic Research, Vol. 50, No. 1, pp. (114–120).

[9] Anderson, R. M., (2011), "Piano Key Weir Head Discharge Relationships" , M.Sc thesis, Utah State University, Department of Civil and Environmental Engineering, Logan, Utah, USA.

[10] Pralong, J., Vermeulen, J., Blancher, B., Laugier, F., Erpicum, S., Machiels, O., Pirotton, M., Boillat, J.L., Leite Ribeiro, M., and Schleiss, A.J. (2011), "A naming convention for the Piano Key Weirs geometrical parameters", Proceedings of the International Conference Labyrinth and Piano Key Weirs 2011, Liège, Belgium, CRC Press, London, pp. (271–278).

[11] Sitompul, A. T., (1993), "Hydraulic Modelling of a Sharp Crested Labyrinth Weir", Master theses, Memorial University of Newfoundland, Faculty of Engineering and Applied Science, Newfoundland, Canada.