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Experimental study of the hydraulic performance of piano key weir

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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 15 m long, 0.3 m wide and 0.45 m deep rectangular glass-walled flume. The experimental work includes testing of sixteen PKW models which results 172 tests to cover the effects of weir length and height, up-and downstream key widths, upstream apex overhangs length, dam height and height difference between up and downstream on the weir flow discharge coefficient. Experimental results showed that the most influential parameters for the tested PKW models are the relative length L/W and height difference between up and downstream Pi/Po, both increasing the discharge capacity by 42%. Also the energy dispassion was estimated from the parameter B/P by considering the effect of slope (B the base and P the height) on distance of hydraulic jump formation. Then, the PKW angle which makes it an energy dissipater itself has been selected. Experimental data were used to develop empirical formula based on dimensional analysis technique and the statistical software *SPSS*. This formula, having a coefficient of determination of (R^2=0.984), is used to find the discharge coefficient during free flow condition.

Keywords: Piano key weir; Free flow; Discharge coefficient; Energy dispassion; PKW Type-B.

1. Introduction

A Piano Key Weir (PKW) is a nonlinear weir which is a modified labyrinth weir with specific geometric characteristics such as the up- and downstream overhangs and inclined up- and downstream key floors, forming a new set of variables as in Figure 1. It is more efficient than ordinary ogee-crested weirs, in terms of discharge capacity (up to 3-4 times). This type was designed to satisfy the same requirements of standard labyrinth weirs (namely passing high discharges with low upstream heads relative to linear weirs). As compared with labyrinth weirs, the main advantages of the PKW are: Due to its reduced base area relative to the standard labyrinth weirs, Figure 1.a, it could be placed on new gravity or existing dam sections. Its cost can be less than labyrinth weirs as the structural behavior of sloped floors requires less quantity of reinforcement than vertical walls. Easy construction of PKW due to the rectangular layout enable of using precast units. Schleiss [1] and Lempérière et al [2] present historical reviews on the PKW development.
The overall cross section design of PKW enables to recognize several groups, a basic classification had been suggested by Lempérière et al [2] based on the array of the upstream and downstream overhangs. PKW is classified according to the position of overhangs into four types: type-A with symmetrical

overhang in upstream and downstream, Type B, with longer upstream overhangs. Type C, with longer downstream overhang and Type D without overhangs as illustrated in Figure 2. More hydraulic efficient from the four types of PKW is Type- B which can be considered the best suggestion for new dams and may be selected for high discharges produced.
In this study, all models from Type-B investigated under free conditions with different geometries parameters.16 models would be investigating the discharge coefficient of different PKW configurations and the discharge coefficient of each model must be evaluated. The main geometric parameter that dialed with are Relative Length (L/W), PKW height difference (P_i/P_o), crest width (W_i/W_o) and slope floor (B/P) and, (B_o/B) and (P_d/P). One model is used to satisfy the geometry of Lempérière et al [2] for type B in order to investigate there proposed optimum design. The effect of energy dispassion in piano key weir is also has been studied and select the best slope of outlet floor that make the PKW work as dispersed energy through forming distance of the hydraulic jump.

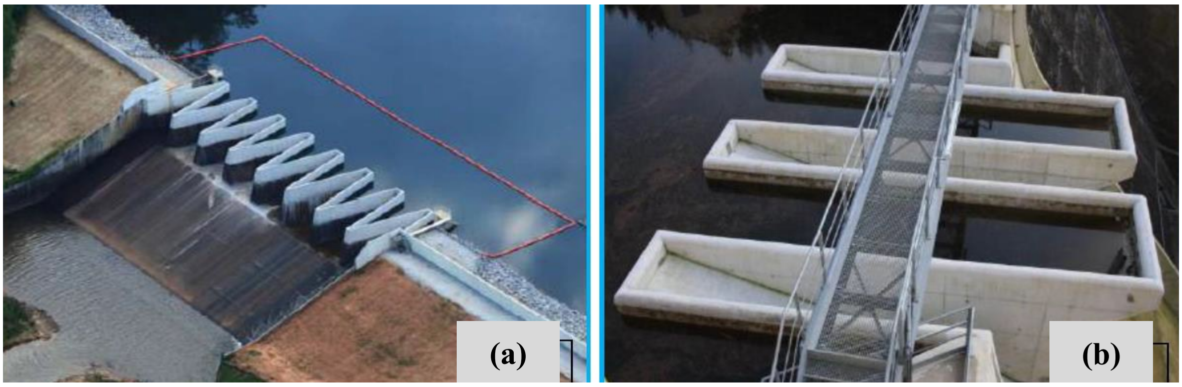

Figure 1. (a) Trapezoidal labyrinth weir, Robertson [3] and (b) Piano key weir Machiels [4].

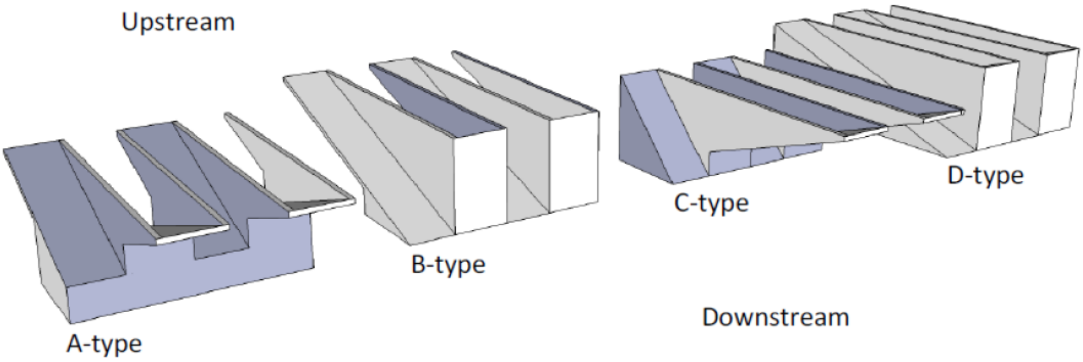

Figure 2. PKW Types (3D view), Erpicum [5].

2. 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 3, the geometric parameters of the PKW are 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 B_o, and the up- and downstream key widths W_o and W_i as shown in equation 1. Notations of this study are in agreement with the naming convention of Pralong et al. [6].

$$Q = f(H_o, L, W, W_i, W_o, B, B_o, P, P_i, P_o, P_d, \rho, g, \mu, \sigma) \quad (1)$$

Since the flow of the flume in the laboratory (open channel) is considered as turbulent flow and takes place at a relatively large head, the effect of the viscosity μ, and surface tension σ is not important Sitompul [7]. In all tests, to avoid the effect of surface tension, the measurements begin 3 cm above the crest of PKW

Novak et al [8]. In this study, thickness of all models (T_s) were 2.5 mm, so it has small influence on discharge capacity and is considered negligible Laugier et al. [9] so the equation 1 can be rewritten as:

$$Cd = f\left(\boldsymbol{H}o/\boldsymbol{P},\ \boldsymbol{L}/\boldsymbol{W},\ \boldsymbol{Wi}/\boldsymbol{Wo},\ \boldsymbol{P}/\boldsymbol{B},\ \boldsymbol{Pi}/\mathrm{P}\boldsymbol{o}\right) = 0 \quad (2)$$

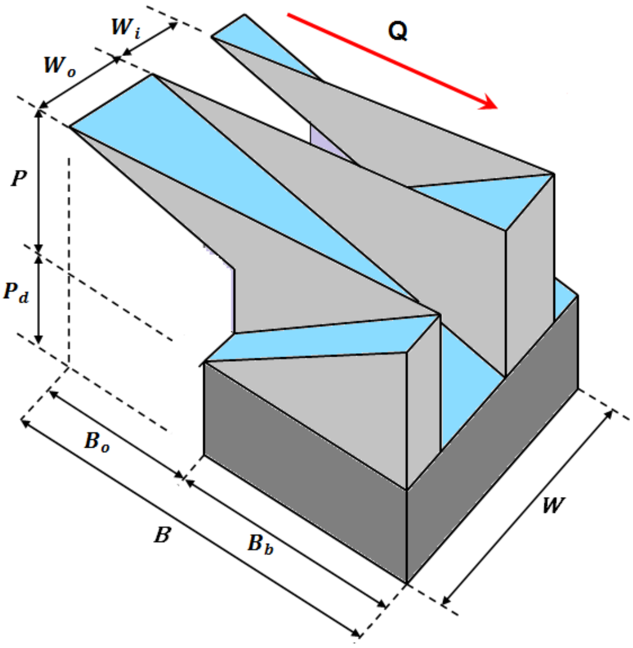

Figure 3. Clarification sketch of PKW model 3D-view type B.

3. 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 15 m long, 0.3 m wide and 0.45 m deep rectangular glass-walled to allow for visual observation of the flow patterns. Over the flume sidewalls, a rolling point gauge of ±0.1mm 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 beveled to form flat top crest. 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 was taken at distance equal to 3.5 times the height of PKW model (3.5P) from the outlet key apex in the upstream direction. As for the measuring of energy dispassion, the distance of hydraulic jump formation during the testing of the parameter *B/P*, which is considered the main indicator for energy dispassion, was also measured.

A minimum of seventeen different discharges were 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 (W1), see Table 1 in which all the ratios are stated.

It is worth mentioning that the other parameter (B_o/B and P_d/P) have a constant value which equal to 0.25 and 0.6 respectively in all models.

4. Results and discussion

4.1 separated nappe

Three main parts of the flow over a PKW are achieved: 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 4. 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 the

PKW tending to behave like a linear weir. When 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 influencing geometric parameter is 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 5.

Table 1. The tested dimensions for PKW models.

Model marking	L/W	W_i/W_o	B/P	P_i/P_o
W1	5	1	2.5	1
L3	3	1	2.5	1
L4	4	1	2.5	1
L7	7	1	2.5	1
W0.5	5	0.5	2.5	1
W0.8	5	0.8	2.5	1
W2	5	2	2.5	1
P1.5	5	1	1.5	1
P2	5	1	2	1
P3	5	1	3	1
P4	5	1	4	1
P5	5	1	5	1
0.7	5	1	2.5	0.7
1.2	5	1	2.5	1.2
1.5	5	1	2.5	1.5
2	5	1	2.5	2

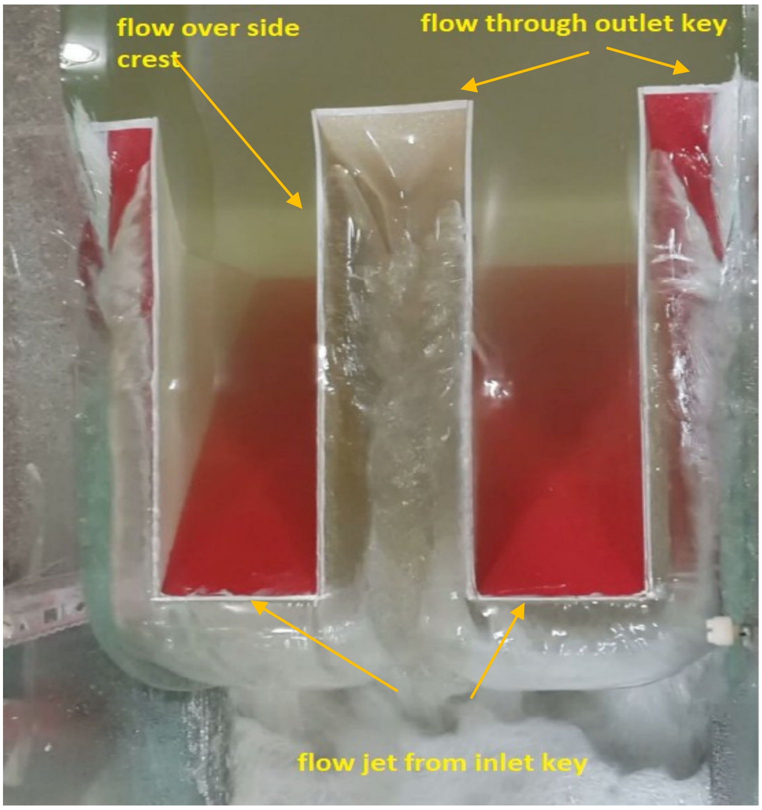

Figure 4. Flow components over PKW type B.

Figure 5. Effects of key width on separation zone at H/P=0.27 over PKW of (a) W_i/W_o = 0.5 (model W0.5), and (b) W_i/W_o = 2 (model W2).

4.2 Influence of the relative length (L/W)

Generally, the elongation of the crest, which results from the non-linear shape of PKW, is expressed by L/W which is the ratio between the total length of the crest and the width of the weir. Experiments have proved, as shown in Figure 6, that increasing L/W ratio from 3 to 4 increases the efficiency by about 36% to 19% for low and high heads ratio respectively, and increasing it from 5 to 7 increases C_{dw} by about 42% to 34% for low and high head ratios (H/P = 0.6). 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.

4.3 Influence of the alveoli width (W_i/W_o)

The geometry in plan-view of PKW 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 3. Figure 7 shows that increasing W_i/W_o ratio from 1 to 2 led to increase the capacity by range 3% to 1.5%, and decreasing W_i/W_o ratio from 1 to 0.5 reduces the capacity by range 11% to 8% due to the local submergence at outlet key.

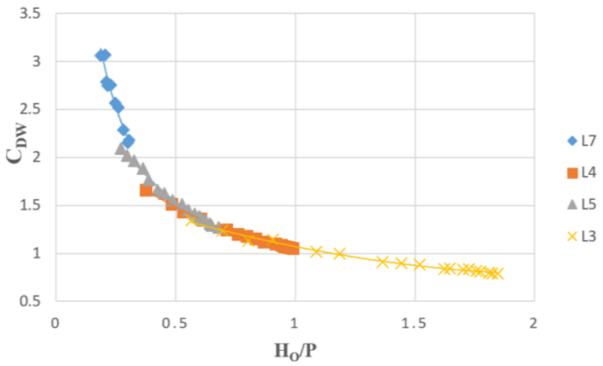

Figure 6. Change of C_{dW} vs. H_o/P for four ratios of L/W.

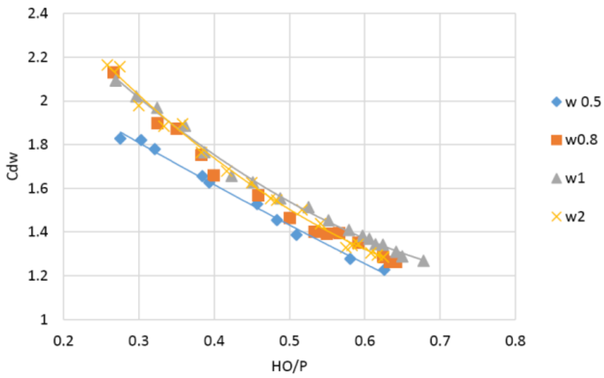

Figure 7. Change of C_{dW} vs. H_o/P for four ratios of W_i/W_o.

4.4 Influence of the PKW height

4.4.1 The discharge coefficient

The height of PKW is a significant factor influencing the efficiency. As seen in Figure 8, the experimental discharge coefficient for the PKW decreased rapidly as the height increased (B/P ratio decreases). The gain in capacity for low and high heads from changing the B/P ratio from 1.5 to 2.5 is 29% and 19% respectively while increasing this ratio from 2.5 to 3, 4, and 5 decreasing the capacity about 9%, 19% and 32% respectively.

4.4.2 Measuring the energy dispassion

Another effect for the ratio *B/P* can be considered by the estimation of energy dispassion. Regarding to PKW, models of different slopes have been made in order to select the slope that minimize the acceleration of the supercritical flow over PKW spillway and dissipate its energy. Five models were made with slope of (33.7, 26.6, 18.4, 14 and 11.3) degrees within the limitations of flume. The most important indicator for measuring the energy dissipation is the hydraulic jump distance measured from the toe of the PKW, Darweesh [10] and Khlif [11], see Figure 9, where *LP* = the hydraulic jump distance measured from the toe of PKW.

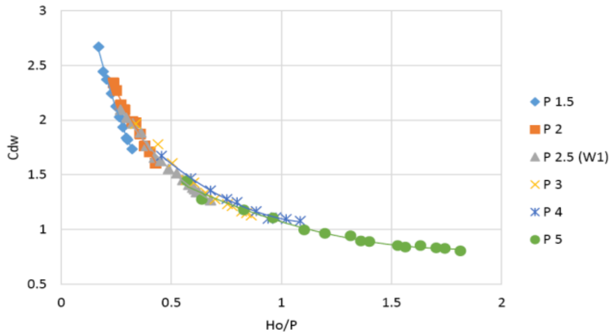

Figure 8. Variation of C_{dW} vs. H_o/P for five ratios of *B/P*.

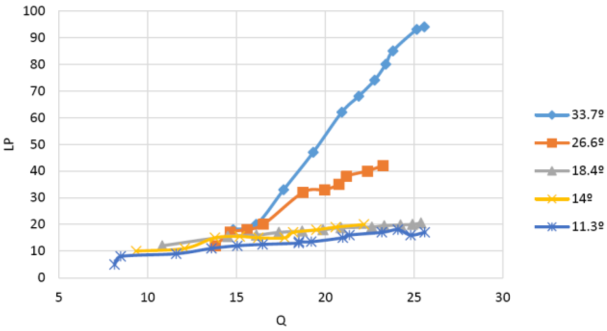

Figure 9. Variation of hydraulic jump toe distance with discharge.

It can be concluded that with large slopes, hydraulic jump is developed far away downstream the PKW. As the PKW slope becomes milder, values of hydraulic jump distances were reduced. The ranges of distance of the hydraulic jump for these five models were: LP (5.8-94) cm. A full reduction in the values of hydraulic jump distance was achieved in the low slopes (low height) of PKW because the acceleration of the flow passing along the PKW in all of the applied discharges was reduced and hence the distance of the hydraulic jump was reduced.

4.5 influence of parameter P_i/P_o

The parameter P_i/P_o has an important effect on the PKW discharge capacity. A group of five P_i/P_o ratios of (2, 1.5, 1.2, 1 and 0.7) was considered. The investigation began from ratio P_i/P_o=2, the models (2, 1.5 and 1.2) did not meet the PKW requirements, because the water level at highest discharge (according to laboratory conditions) was less than 3 cm which is under the influence of scale effects (surface tension and viscosity). Figure 10 shows the three models under maximum discharge; note that point gauge is fixed at 3 cm. For P_i/P_o >1 the dimensions do not suit requirements of PKW because it has been under scale effect but for P_i/P_o ≤1, there was an important effect on the PKW discharge capacity according to the discharge of mentioned flume. The ratio less than 0.7 could not be studied since its manufacturing was out of the limitation of piano key weir. As shown in Figure 11, 0.7 is the optimum value according to conditions of Fluid Mechanics Laboratory of Babylon University.

Figure 10. The models which non-conforming PKW requirements.

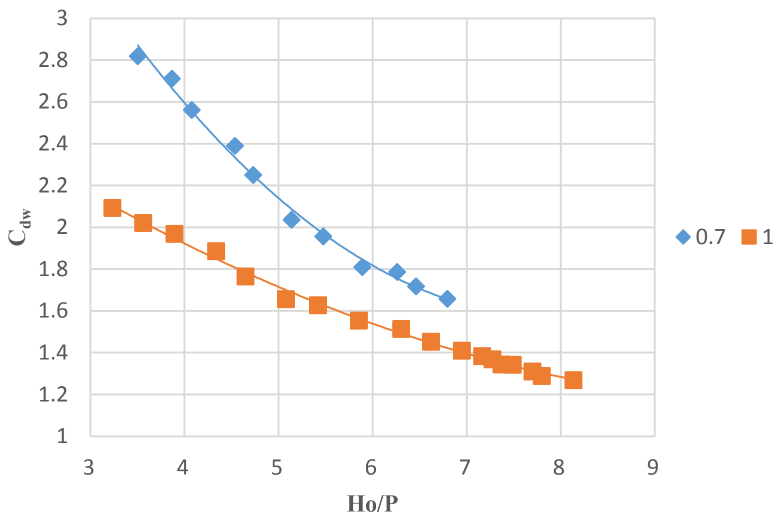

Figure 11. Variation of C_{dW} vs. Ho/P ratios of Pi/Po.

5. Proposed empirical formula

By dimensional analysis, using statistical software, a relationship had been derived relating the dimensionless parameters, as presented in equation 3 having R^2=0.984.

$$C_{dw} = 0.8816\left(\frac{H_o}{P}\right)^{-0.8539}\left(\frac{L}{W}\right)^{0.3619}\left(\frac{W_i}{W_o}\right)^{0.0802}\exp\left[0.0527\left(\frac{B}{P}\right) - 1.2182\left(\frac{P_i}{P_o}\right)\right] + 0.5346 \quad (3)$$

Equation 3 is subjected to limitations of laboratory modeling conditions. Values of each parameter should respect the tested range limits. The limitations are: $3 \le L/W \le 7$, $0.5 \le W_i/W_o \le 2$, $1.5 \le B/P \le 5$ and $0.7 \le P_i/P_o \le 2$. It is important to notice that values of B_o/B and P_d/P should always be 0.25 and 0.6 as these two parameters had not been changed during the test.

6. Conclusions

The most important conclusions that may be realized from this study are:

1. The Parameters P_i/P_o and L/W are the most influential parameters on the PKW discharge coefficient. Both have an effect of increasing C_{dW} by about +42% when decreasing P_i/P_o to 0.7 and L/W is increased by +1.0.
2. Inlet key to outlet key widths ratio (W_i/W_o) gives maximum PKW capacity when its value is around 1.0. Increasing W_i/W_o from 1.0 up to 2 provides no workable profit in discharge capacity. However, decreasing W_i/W_o under 1.0 has a negative effect on C_{dW}. W_i/W_o=0.5 gives 11.1% to 8.4% loss.
3. B/P ratio of length the upstream-downstream to the PKW height has an important effect on C_{dW}. Increasing B/P from 2.5 to 3.0, 4.0 and 5.0 can reduce the discharge coefficient by 3% ,18% and 32% respectively. Decreasing B/P from 2.5 to 2.0 and 1.5 increases C_{dW} by 13% and 27% respectively. All these percentages are checked with respect to the same head H_o.
4. The piano key weir is a good solution for dissipating the energy by adopting high ratio of parameter $B/P \ge 5$ (slopes $\le 11.3^o$) and the indicator of measuring the dissipated energy was the distance of hydraulic jump formation measured from the edge of downstream of the PKW which was zero for low slopes.
5. Equation (3) is an empirical formula which had been developed to estimate the PKW discharge coefficient represented as a function of H_o/P, L/W, W_i/W_o, B/P and P_i/P_o. The coefficient of determination was (0.984). It is limited by the test limitations: $3 \le L/W \le 7$, $0.5 \le W_i/W_o \le 2$, $1.5 \le B/P \le 5$, $0.7 \le P_i/P_o \le 2$, B_o/B=0.25 and P_d/P=0.6.

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