INVESTIGATION OF HYDRAULIC PERFORMANCE OF PIANO SHAPED WEIRS USING THREE DIMENSIONAL NUMERICAL MODELING[*]

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Abstract– Throughout history dams have been important structures in water storage. To avoid overtopping, damage, and or failure of a dam, adequate spillway is needed to release excess water from upstream floods. Researchers found that spillways have to be made nonlinear in order to reach an economic structure with high performance. A piano key weir is one of the best solutions. Piano key weirs are the modified and developed labyrinth spillways which can discharge greater volume of water than the common spillways in limited width and can be used as economic structures with high efficiency. In this article, a calibrated Flow-3D modeling by laboratory results has been used to evaluate and analyze the discharge coefficient of piano key weirs as related to the variation in width at inlet and outlet keys. According to the researches, the geometrical and hydraulic parameters are the most important factors for evaluating the performance of piano shaped weirs. In this study, the analytical effects of these parameters on discharge coefficient, and also the capability of discharge in these models have been investigated. Moreover, the important hydraulic parameters including depth, velocity and pressure have been studied through 3D numerical simulation. From the numerical results, a practical formula is proposed to obtain the discharge coefficient for the release capacity of the piano key weirs.

Keywords– Piano key weirs, discharge coefficient, numerical simulation, hydraulic performance, flow-3D

1. INTRODUCTION

Throughout human history, dams have been important structures in water storage. Hydraulic engineers and water resources managers have the responsibility of paying attention to the construction and proper operation of dams. To avoid overtopping and damage or even destroying the dam, an adequate spillway is needed to release excess water from upstream floods. Therefore, the spillway serves a key role in dam safety and, therefore, evaluation of spillway is unavoidable.

Spillway should be a stable, safe and highly efficient structure, which requires the ability to operate all the time. Malfunction in the performance of spillway results in heavy damage to the dam or even its failure. Therefore, the design and construction of this part of the dam is of great importance. The cost of construction and maintenance of spillways comprise a considerable percentage of the overall cost of the dam. Researchers found that spillways have to be made nonlinear in order to reach an economic structure with high performance. A Piano Key (PK), weir is one of the best solutions. A PK weir is a multi-sided spillway that can be used for controlling the free flow on narrow spillways. In this type of spillway, various geometrical parameters affect the discharge coefficient and capability of excess water discharge. PK weirs are the modified multi-sided labyrinth spillways that, unlike the traditional ones, the keys are

inclined which leads to more structural stability. Besides, thanks to the small area of foundation, the way is prepared to lay out the spillway easily on the crest of dams. As expected, hydraulic behavior of PK weirs is different from the normal labyrinth spillways. In PK weirs, flow is classified in two types. The first type happens in inlet keys where the stream enters from upstream and the second one occurs in outlet keys where stream flows as a jet.

Up to now, few studies have been done on PK weirs. Lempérière and Ouamane (2003) presented a new economical, innovative solution for piano shaped spillways. In this study, PK weirs have been evaluated and compared with traditional spillways in terms of economic and safe solutions. The result of this study reveals that piano keys lead to increase in flow up to four times as the flow discharge reaches 100 m³/s/m. As such, the cost of construction will decrease in dams with these types of spillways. Also, PK spillways will control the flood flows more effectively even in existing dams [1].

Hien et al. (2006) and Barcoda et al. (2006) have shown that if the inlets are bigger than outlets in piano keys, the flow discharge will increase. Also, the studies conducted by Hien et al.(2006) showed that 7 keys and 5 to 6 keys for low and high heads, respectively, increase the discharge coefficient[2 & 3]. Erpicum et al. (2011) developed a first dimensional model of the flow over PK weir and compared the results with various experimental data. The comparison showed the ability of the numerical model to predict with reasonable accuracy the release capacity of a PK weir, whatever its geometry. They also suggested that improvements of the numerical model may lie in the evaluation of the discharge coefficient of the lateral crest [4]. Machiels et al. (2012) tested the use of parapet wall on hydraulic performance of piano key weirs and concluded that it enhanced the discharge capacity owing to increased spillway height. In addition, reducing the bottom slope relatively influenced the weir release capacity [5]. Ribeiro et al. (2012) reviewed the previous studies on the efficiency of planned and built PK weirs. They compared their results of an actual PK weir's discharge with that theoretically obtained for a sharp-crested spillway with crest length equal to the width of the PK-Weir for a given hydraulic head and finally established a preliminary design procedure [6]. Javahei and Kabiri-Samani (2012) carried out an extensive experimental research to understand the effects of PK weir geometries including the weir length, weir height, inlet-to-outlet key width, upstream and downstream apex overhangs, and sloped floors on weir flow threshold submergence. As a result, they proposed a practical formula to evaluate the flow threshold submergence over PK weirs [7].

In this research, in addition to verification of the built numerical model with available experimental data, the performance of PK weir is evaluated by changes in the width of the keys and spillway height. None of the researchers have investigated the effects of geometries of PK weirs on the discharge coefficient in a three dimensional numerical modeling. Lastly, a general equation is obtained for discharge coefficient based on the governing equation for sharp-crested weirs.

2. DIMENSIONAL ANALYSIS

Due to geometrical complications in PK weirs, discharge coefficient depends on many parameters. In Fig. 1 different parts of PK weirs are shown in detail.

Discharge coefficient of PK weirs can be derived from upstream water head (H_0), water thickness on the upstream crest(H_1),water depth on the downstream crest(H_2), water density (ρ), gravity acceleration (g),total developed crest length(L), spillway height(P),flow approach height (P'),canal width(W), inlet width(a), outlet width(b), length of upstream cantilever(c), length of downstream cantilever(d), Dynamic viscosity (μ), surface tension (σ), the trapezoidal labyrinth weir sidewall angle(α), inlet and outlet key slopes (S_{in} and S_{out}, respectively), side weir length (B), wall thickness (t), and the crest curvatureradius (R)which have been shown as below:

$$f\left(Q_{PKW}, H_0, H_1, H_2, \rho, L, P, P', W, B, a, b, c, d, t, S_{in}, S_{out}, \alpha, g, \sigma, \nu, R\right) = 0 \qquad (1)$$

Fig. 1. Geometrical details of PK weirs

The water depth on the upstream and downstream crests (H_1 and H_2) are functions of water depth in upstream of the spillway (H_0). As a consequence, these parameters have been omitted from Eq. (2). By using dimensional analysis, the discharge coefficient has been obtained as follow based on dimensionless parameterswhich play key roles in determination of discharge coefficient:

$$C_{PKW} = f\left(\frac{L}{W}, \frac{a}{b}, \frac{a}{B}, \frac{b}{B}, \frac{c}{L}, \frac{d}{L}\frac{P}{H_0}, \frac{P}{P'}, \frac{t}{P}, \frac{t}{R}, \frac{H_0}{a}, S_{in}, S_{out}, Fr, R_1, W_1\right)$$ (2)

In this equation, Fr, W_1, and R_1represent the Froude, Weber, and Reynolds numbers in the section of the upstream crest. The amount of Reynolds' number is sufficiently large in canals where the viscosity, e.g. R_1, can be eliminated [8]. In addition, Novakand Cabelka (1981) found that if water head on spillway exceeds 3 to 4 centimeters, the effects of surface tension, e.g. W_1, can be overlooked [9].In Fig. 2 the geometrical and hydraulic details of PK weirs are shown.

(a)	(b)

Fig. 2. Geometrical and hydraulic details of PK weirs, a) plan, b) cross-section

Studies show that owing to kinematic similitudeand prevailing subcritical flow in natural circumstances, gravity effects are simulated exactly in experiments. If the PK weirs are in rectangular shapes $\alpha = 0$, the effect of this parameter will not be considered in the analyses. According to the lab experiments, Eq. (3) is derived based on a, b, B, L and W parameters for the PK weirs with $\alpha = 0$ [10].

$$\frac{L}{W} = \frac{a+b+2B}{a+b}$$ (3)

Due to the three dimensional behavior of the flow and its complicated nature over the PK weirs, it is better to determine C_d from the laboratory data and/or simulate the flow with available software. In this study, the effects of the ratios of inlet-to-outlet key width and spillway height per upstream water head on the outlet discharge of the weir are investigated.

3. MODEL CALIBRATION

In this research, based on the researches done by Anderson (2011), a non-viscous, incompressible fluid containing air with density of 1.2 kg/m³ and shear stress coefficient of 0.073 have been assumed in order to simulate flow over the PK weirs[11]. The laboratory model has been made with Plaxi Glass in which it has an average roughness height of 0.3 mm based on standard materials. As a result, an equivalent value of 0.01 has been considered for the manning coefficient (*n*) in the model. All the simulations and model calibrations have been done according to laboratory conditions. To obtain satisfactory results in a numerical or laboratory model, a stable condition must be reached. After executing several models, 10 seconds is finally assumed to reach the steady flow condition. The flow stability is shown in Fig. 3.
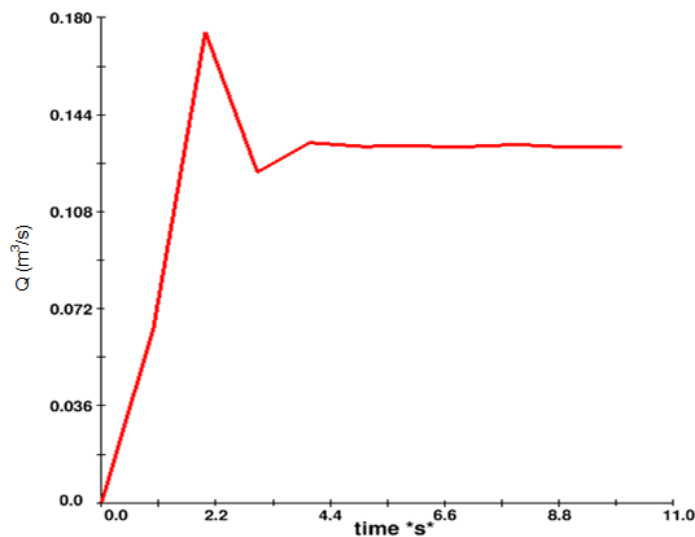
Fig. 3. Evaluating the discharge variation from outlet border with respect to time

One of the advantages of Flow3D models relative to other simulation models is to determine and estimate the best mesh based on geometry of the model. Thus, the suitable and optimal dimensions of cells in length and width are equal to 1 centimeter and depth is considered as 0.4 centimeter by examining different meshes with FAVOR program. The various dimensional conditions of calculation cells have been shown in Fig. 4.
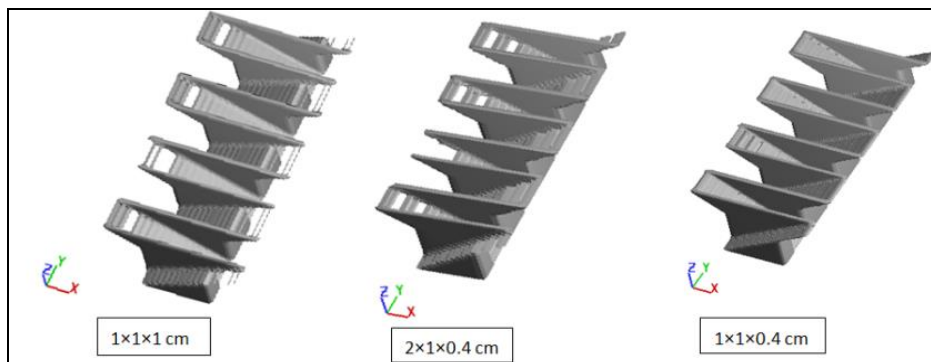

Fig. 4. Function of FAVOR with solid borders with different networks and network callibration of PK weirs

4. FLOW 3D

Computational fluid dynamics (CFD) models have become well developed as tools for simulation of free surface flow over a vast variety of structures. The commercially available CFD program Flow-3D developed by Flow Science Inc., Los Alamos, NM, was used herein. Flow-3D is a powerful modeling tool that gives engineers valuable insight into many physical flow processes. This software has been constructed for the treatment of time dependent flow problems in one, two, and three dimensions. Method for solution governing equation is finite volume.FLOW-3D solves numerically the following Navier-Stokes equations for the velocity components (u, v, w) and pressure as function of time (t) in the three dimensional Cartesian (x, y, z) or cylindrical (r, θ, z) coordinate system in both compressible and incompressible modes.

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + R\frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) + \xi \frac{\rho u A_x}{x} = RDIF + RSOR \tag{4}$$

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\{uA_x\frac{\partial u}{\partial x} + vA_yR\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\} - \xi\frac{A_y v^2}{xV_F} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x - b_x - \frac{RSOR}{\rho V_F}u$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}\{uA_x\frac{\partial v}{\partial x} + vA_yR\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z}\} + \xi\frac{A_y uv}{xV_F} = -\frac{1}{\rho}\left(R\frac{\partial p}{\partial y}\right) + G_y + f_y - b_y - \frac{RSOR}{\rho V_F}v \tag{5}$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}\{uA_x\frac{\partial w}{\partial x} + vA_yR\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z}\} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z - b_z - \frac{RSOR}{\rho V_F}w$$

where, p is the fluid pressure, G_x, G_y, G_z, the acceleration created by body fluids, f_x, f_y, f_z, viscosity acceleration in three dimensions and V_F is related to the volume of fluid, ρ is the fluid density, *RDIF* is a turbulent diffusion term, and *RSOR* is a mass source term, A_x, A_y, and A_z are the fractional areas open to flow in the *x*, *y*, and *z* directions, respectively. The coefficient *R* depends on the choice of coordinate system. Finally, b_x, b_y, and b_z are flow losses in porous media or across porous baffle plates.

Flow 3D offers 5 types of Turbulence models: Prandtl's mixing length, one-equation turbulence energy, two equation K-ε equation, renormalization-group (RNG) and large eddy simulation (LES). Turbulence models that have been proposed recently are based on Reynolds-averaged Navier–Stokes equations. These approaches involve statistical methods to extract an averaged equation related to the turbulence quantities [12-15].

5. NUMERICAL SIMULATION

It can be assumed that the discharge coefficient of piano key weirs can be derived from the global equation of spillways. Equation (6) is the global equation for sharp-crested weirs. In Fig. 5 various flow parameters are shown:

$$Q = \frac{2}{3}\sqrt{2g}C_d L H_0^{3/2} \tag{6}$$

The discharge coefficient has various expressions. Based on what was discussed above, the discharge coefficient (C_{PKW}) is expressed as Eq. (7) for PK weirs in which the factor of $2/3$ is merged in the discharge coefficient.

$$C_{PKW} = \frac{Q_{PKW}}{L H_0^{\frac{3}{2}}\sqrt{2g}} \tag{7}$$

where, C_{PKW} is discharge coefficient, g is gravity acceleration, L is crest length and H_0 is height of water above the weir crest. In this section, 25 simulations with different geometrical and hydraulic conditions on PK weirs have been done. Different simulations of geometrical conditions related to the variations in the inlet-to-outlet key width also have been presented as shown in Table 1. The geometrical characteristics of PK weirs have been illustrated in Fig. 6.

Table 1. Geometrical & hydrulic specifications in simulations by Flow 3D

Depth of incoming flow	Inlet/outlet keys' widths	height of spillway	width of spillway
H (cm)	Wi/Wo	P (cm)	W (m)
3	0.67	19.68	0.93
6	0.8	19.68	0.93
9	1	19.68	0.93
12	1.25	19.68	0.93
15	1.5	19.68	0.93
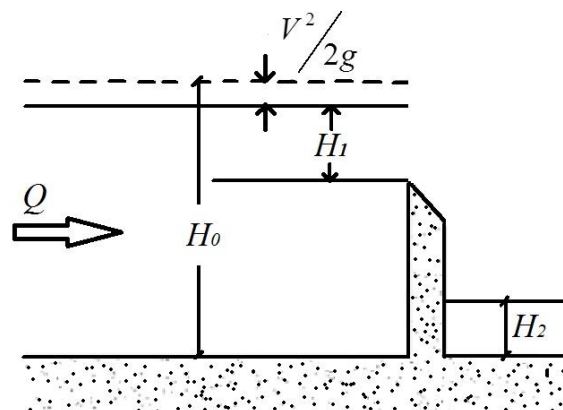
Fig. 5. Geometrical & hydraulic parameters of sharp-crested weirs
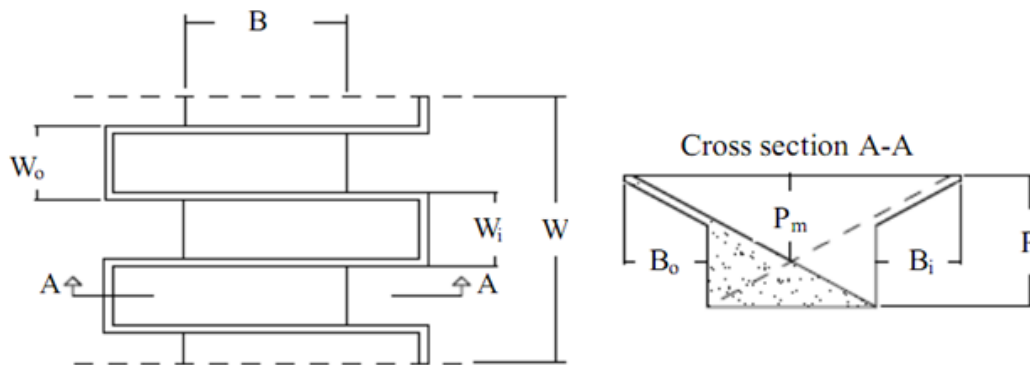
Fig. 6. Geometrical Specifications of PK weirs

By using the results of numerical simulations and experimental models, discharge (Q) has been determined based on piezometirc head (H) to evaluate the outlet discharge of PK weirs in different hydraulic and geometric conditions of flow. To compare numerical simulation with experimental results, values of errors have been shown in Tables 2 to 6 and Figs. 7 to 11.

Table 2. Comparison of results of discharge for simulated and experimental model (W_i/W_o=0.67)

Experimental results		The results of numerical simulations		Error percentage	
Q(m3/s)	H (m)	Q(m3/s)	H (m)	Q	H
0.0354	0.03	0.031	0.029	12.43	3.33
0.092	0.06	0.079	0.058	14.13	3.33
0.1344	0.09	0.113	0.0815	15.92	9.44
0.1769	0.12	0.1569	0.11	11.31	8.33
0.2193	0.15	0.1893	0.142	13.68	5.33

Table 3. Comparison of results of discharge for simulated and experimental model (W_i/W_o =0.8)

Experimental results		The results of numerical simulations		Error percentage	
Q(m3/s)	H (m)	Q(m3/s)	H (m)	Q	H
0.039	0.03	0.039	0.029	0.00	3.33
0.099	0.06	0.085	0.058	14.14	3.33
0.139	0.09	0.119	0.087	14.39	3.33
0.179	0.12	0.16	0.11	10.61	8.33
0.225	0.15	0.199	0.142	11.56	5.33

Table 4. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1)

Experimental results		The results of numerical simulations		Error percentage	
Q(m3/s)	H (m)	Q(m3/s)	H (m)	Q	H
0.03	0.04	0.029	0.037	3.33	7.50
0.06	0.09	0.058	0.081	3.33	10.00
0.09	0.145	0.087	0.125	3.33	13.79
0.12	0.185	0.11	0.161	8.33	12.97
0.15	0.24	0.142	0.22	5.33	8.33

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Table 5. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1.25)

Experimental results		The results of numerical simulations		Error percentage	
$Q(m3/s)$	$H (m)$	$Q(m3/s)$	$H (m)$	Q	H
0.04	0.03	0.035	0.029	12.50	3.33
0.1	0.06	0.109	0.056	-9.00	6.67
0.14	0.09	0.135	0.087	3.57	3.33
0.18	0.12	0.185	0.11	-2.78	8.33
0.256	0.15	0.25	0.142	2.34	5.33

Table 6. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1. 5)

Experimental results		The results of numerical simulations		Error percentage	
$Q(m3/s)$	$H (m)$	$Q(m3/s)$	$H (m)$	Q	H
0.04	0.03	0.045	0.029	-12.50	3.33
0.1	0.06	0.085	0.058	15.00	3.33
0.14	0.09	0.15	0.087	-7.14	3.33
0.185	0.12	0.19	0.11	-2.70	8.33
0.25	0.15	0.24	0.142	4.00	5.33

Table 7. the variations in discharge coefficent resulted in numerical simulation relative to H_0/P

H_0/P	W_i/W_o=0.67	W_i/W_o=0.8	W_i/W_o=1	W_i/W_o=1.25	W_i/W_o=1.5
0.15	0.49	0.47	0.49	0.53	0.51
0.3	0.36	0.34	0.356	0.36	0.372
0.45	0.295	0.265	0.2745	0.28	0.284
0.6	0.265	0.235	0.2535	0.261	0.272
0.75	0.235	0.202	0.221	0.25	0.24
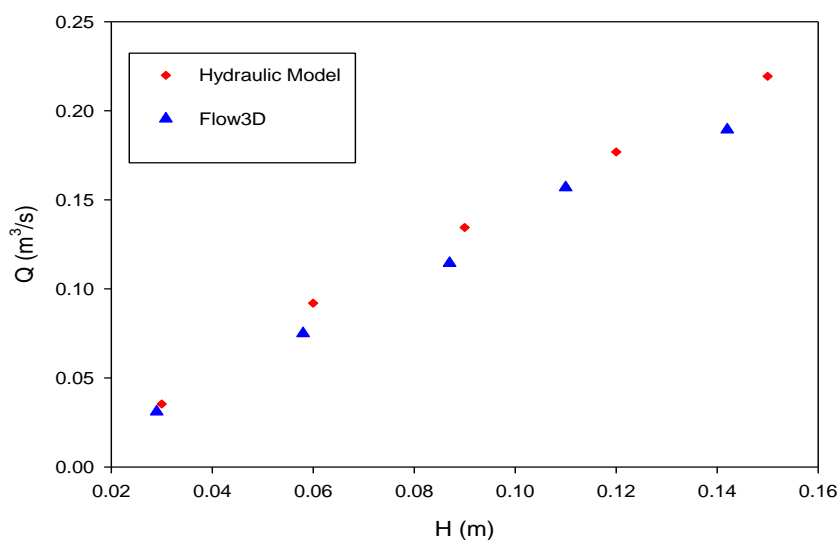
Fig. 7. Comparison of results of discharge for simulated and experimental model (W_i/W_o=0.67)
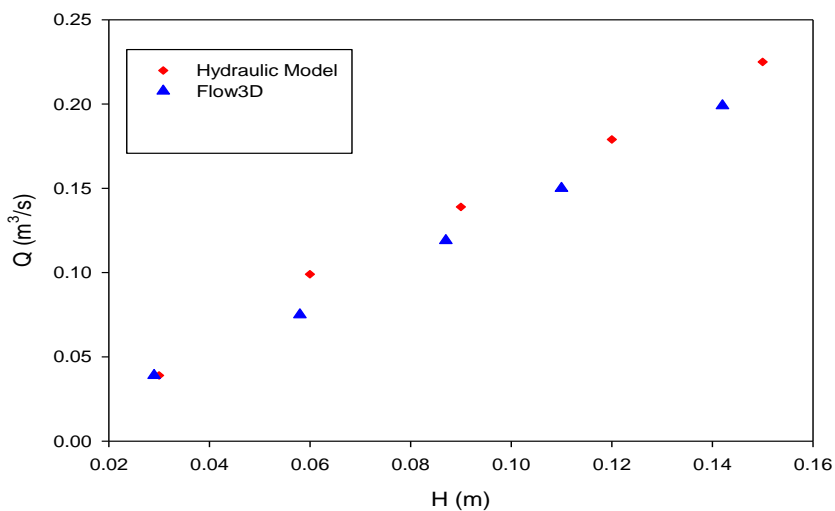
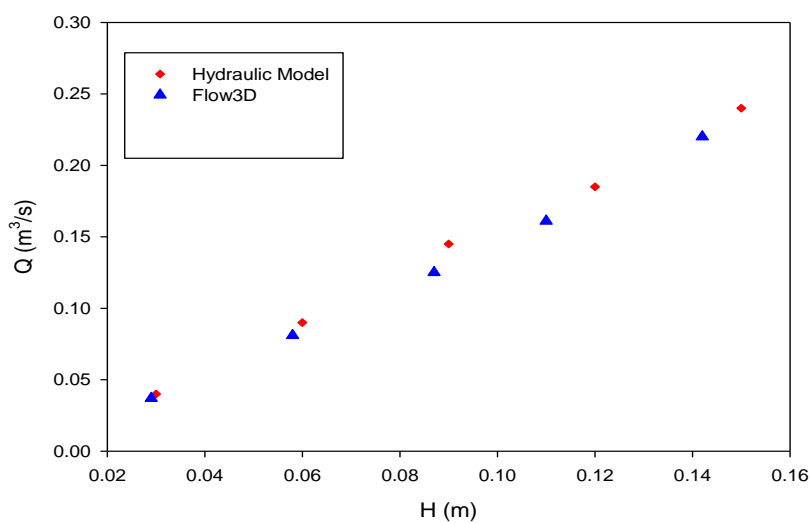Fig. 8. Comparison of results of discharge for simulated and experimental model (W_i/W_o =0.8)

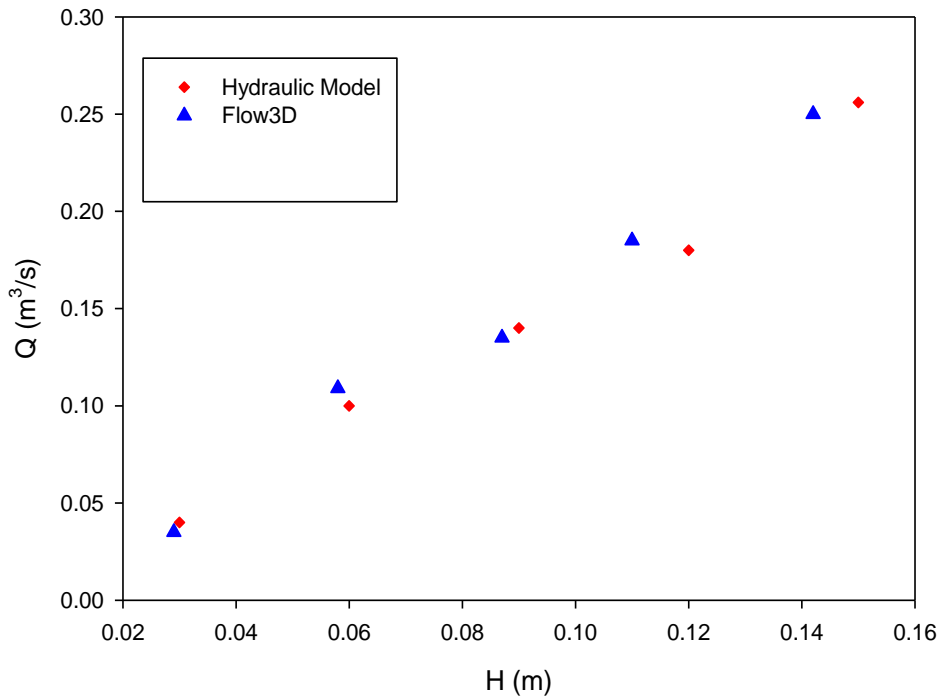Fig. 9. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1)

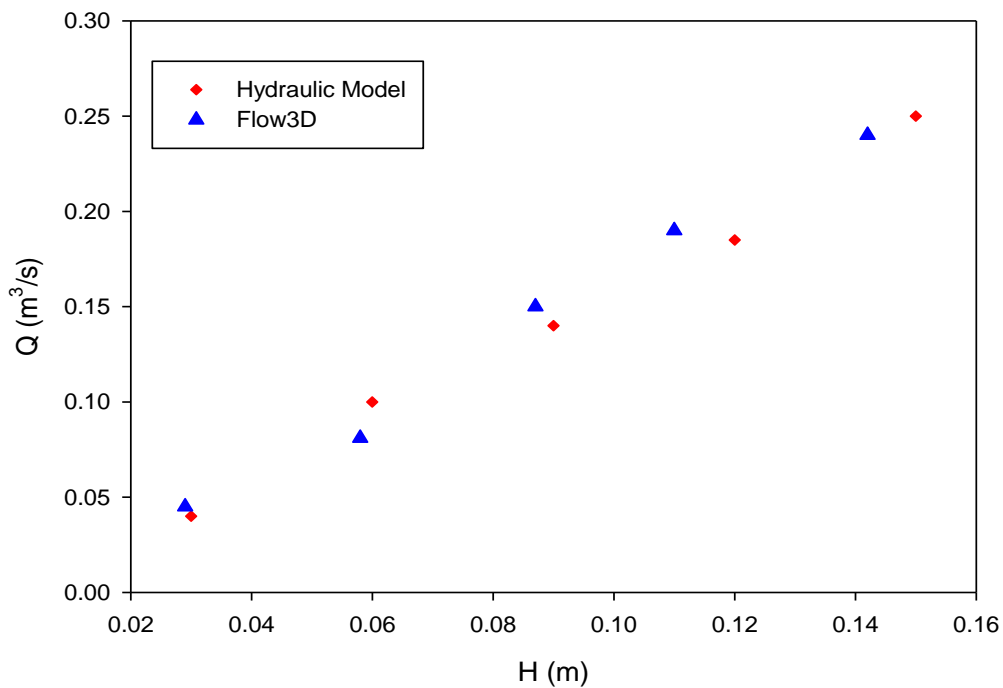Fig. 10. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1.25)

Fig. 11. Comparison of results of discharge for simulated and experimental model (W_i/W_o =1. 5)

As it can be seen from the figures, simulation of flow on PK weirs is extremely close to the result of the experimental model. In the above figures, for W_i/W_o=0.67, the discharge in terms of flow depth has a maximum 16% error. In the simulation process, the maximum error in discharge is less than 16% for different models. The important issue in this regard is that as W_i/W_o goes from 0.67 to 1.5, the discharge

error varies from negative to positive error. This means that for $W_i/W_o=0.67$, the discharge in numerical simulation is less than the discharge in experimental model. By increasing W_i/W_o to the value of 1.5, the discharge value is more than its experimental model.

In Figs. 12 and 13, the discharge coefficient values on PK Weirs for two models ($W_i/W_o=0.67$ & $W_i/W_o=1.5$) have been shown.
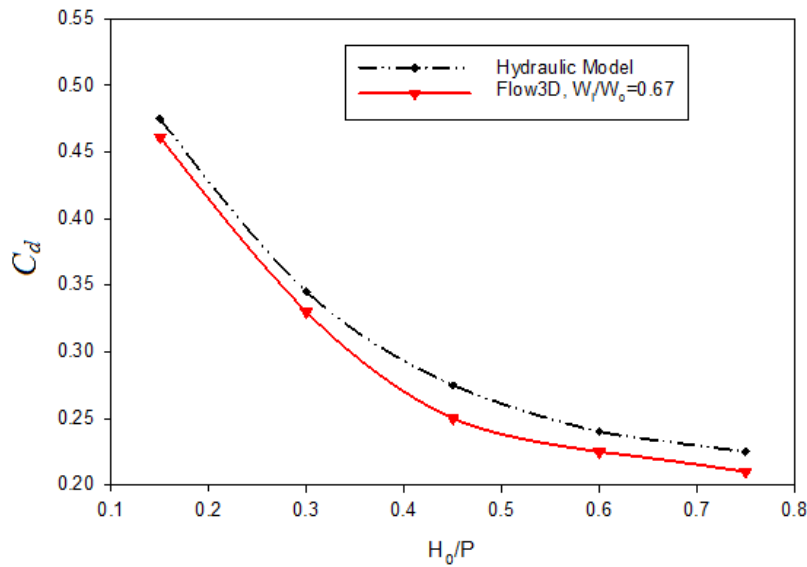
Fig. 12. Variation in discharge coefficient (C_d) versus the ratio of flow depth (H_o) to spillway height (P) for $W_i/W_o =0.67$
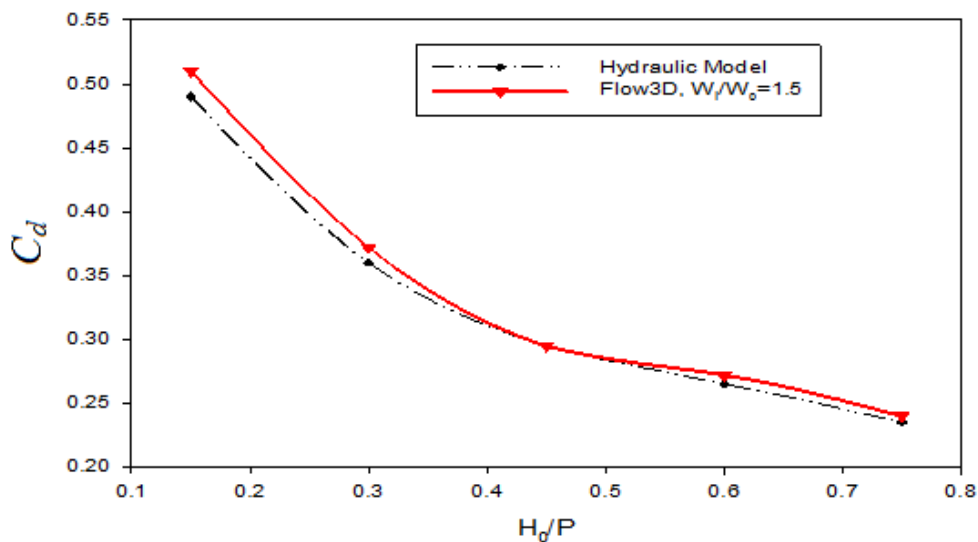
Fig. 13. Variation in discharge coefficient (C_d) versus the ratio of flow depth (H_o) to spillway height (P) for $W_i/W_o =1.5$

According to results from the shown figures and flow simulation results on PK weirs, it can be concluded that by increasing of W_i/W_o, the flow discharge over piano keys rises, and finally reaches its maximum value. The larger values of W_i/W_o for PK weirs will result in maximum flow if a constant width is assumed during the whole simulation process ($W_i+W_o=$ Const.). Also, as H_0/P rises, the flow discharge

decreases regardless of changes in inlet and outlet widths as the above figures depict. The reason is the submerging of the inlet and outlet keys in PK weirs. Increasing the water height on PK weirs leads to filling outlet keys and subsequently affects the performance of spillway. As observed in Fig. 14, if the ratio of H_0/P reaches 0.75, the spillway will have low performance in comparison with other ratios.
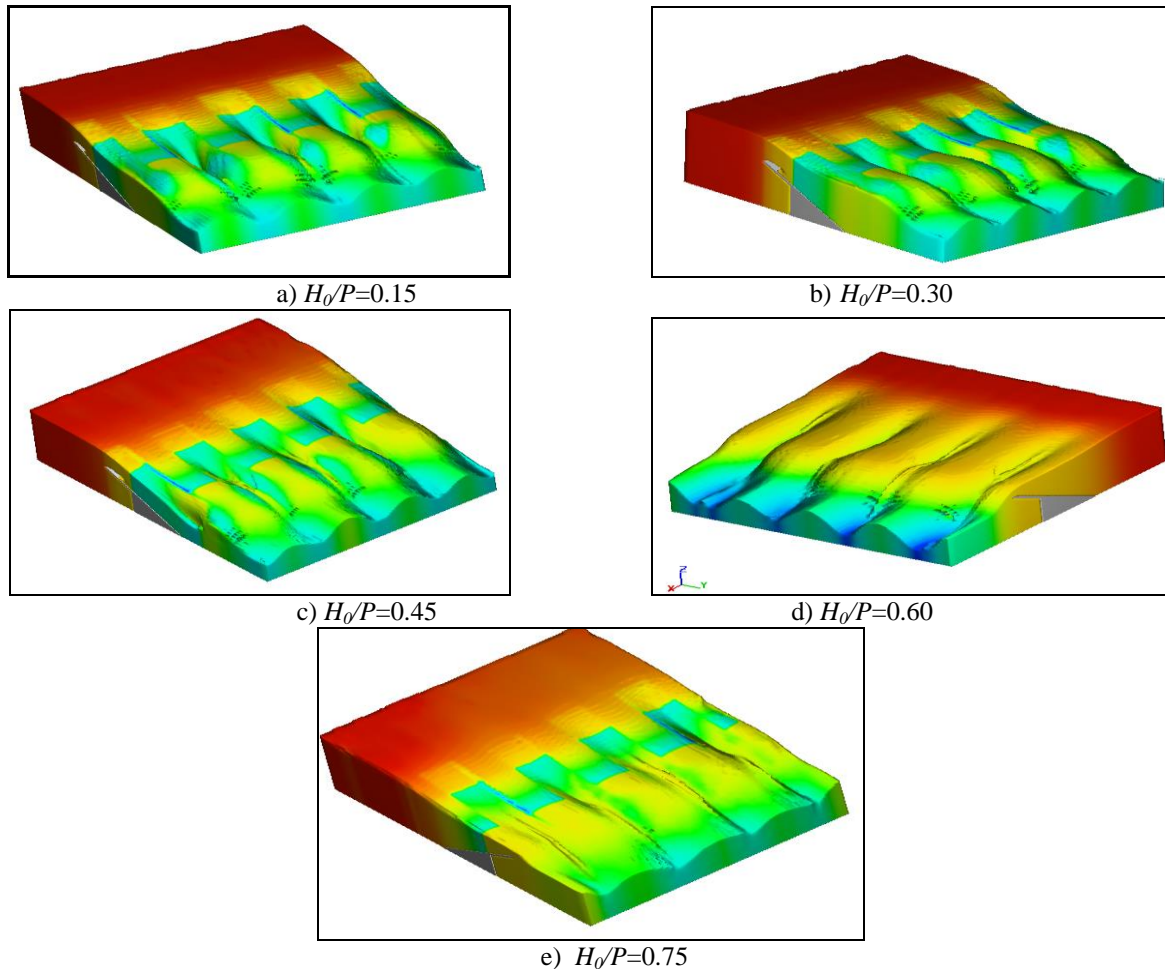

a) H_0/P=0.15

b) H_0/P=0.30

c) H_0/P=0.45

d) H_0/P=0.60

e) H_0/P=0.75

Fig. 14. Reducing the effective performance of PK weirs for maximum H_0/P

In order to evaluate the process of flow discharge variation over PK weirs, the discharge coefficient has been assumed to be derived from the sharp-crested weirs Eq. (Eq. (6)), but L is the canal width instead of crest length. Accordingly, for various inlet-to-outlet key width ratios, the discharge coefficient values have been obtained (Table 7) and its diagram has been drawn for different amounts of H_0/P as depicted in Fig. 15. It should be noted that the parameter P is the spillway height.

Equation (8) presents a relation for discharge coefficient based on the ratio of flow depth to spillway height which has been obtained from the curve fitting with the resulted numerical simulation data for PK weirs.

$$C_d = 0.19\left(\frac{H_0}{P}\right)^{-0.5} \qquad 0.67 \leq \frac{W_i}{W_o} \leq 1.5 \qquad 0.15 \leq \frac{H_0}{P} \leq 0.75 \qquad (8)$$

The correlation coefficient squared for the above equation is R^2=0.93. Discharge coefficient C_d is applicable for the ratios of piezometric head on the crest to spillway height between $0.15 \leq \dfrac{H_0}{P} \leq 0.75$, in situations where the value of W_i/W_o varies from 0.67 to 1.5.
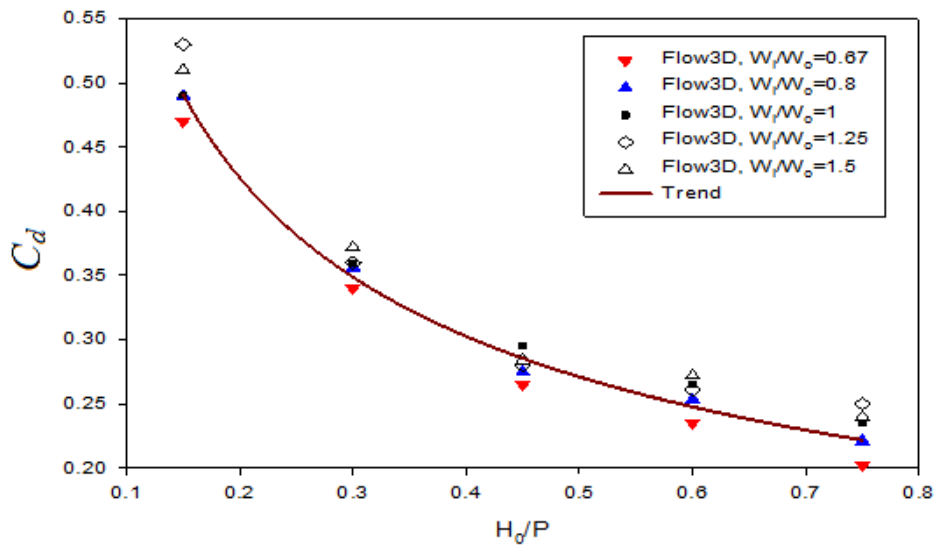
Fig. 15. Curve fitting on the resulted data from the numerical simulation for dimensionless relation of discharge coefficent based on the variations inthe inlet and outlet widths of keys

According to Javaheri's studies in 2012, Eq. (9) has been presented based on other parameters for determining the discharge coefficient. The parameters related to Eq. (8) have been shown in the Fig. 16.

$$C_d = 0.62 \left(\frac{L}{B}\right)^{0.48} \left(\frac{a}{B}\right)^{0.18} \left(\frac{b}{B}\right)^{-0.44} \left(\frac{H_0}{P}\right)^{-0.51} \exp\left(\frac{c}{L}\right) \tag{9}$$
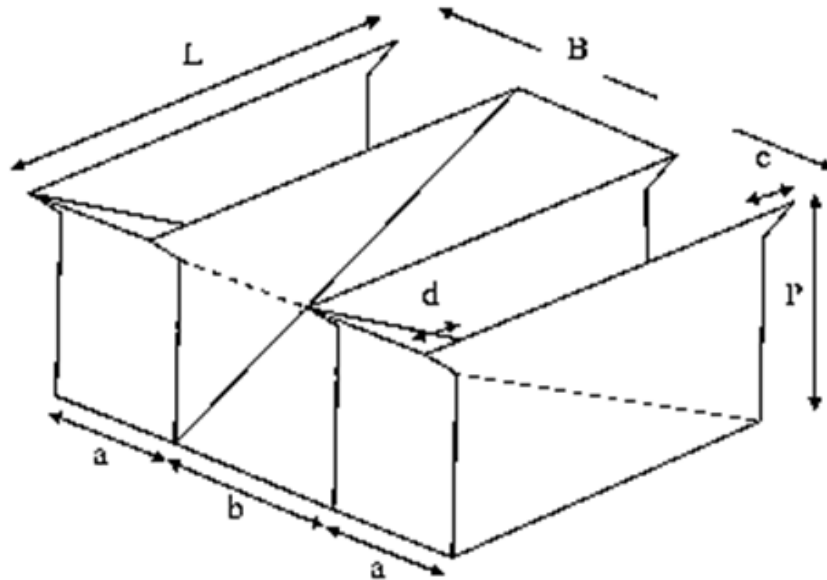

Fig. 16. Parameters related to Eq. (9)

The comparison of the obtained equation in this study with Eq. (9) reveals that the global form of the equation agrees with other researches. In this research, geometrical effects of spillway (Variations in the width of inlet and outlet keys) exactly have been studied and the constant coefficient, based on correlation coefficient value of 0.93, equaled 0.19 (Eq. (8)). Also, comparing the resulted C_d curve from Flow3D model, Fig. 18, with Olivier Michaels'(2011) curve, Fig. 17, confirms the derived equation.
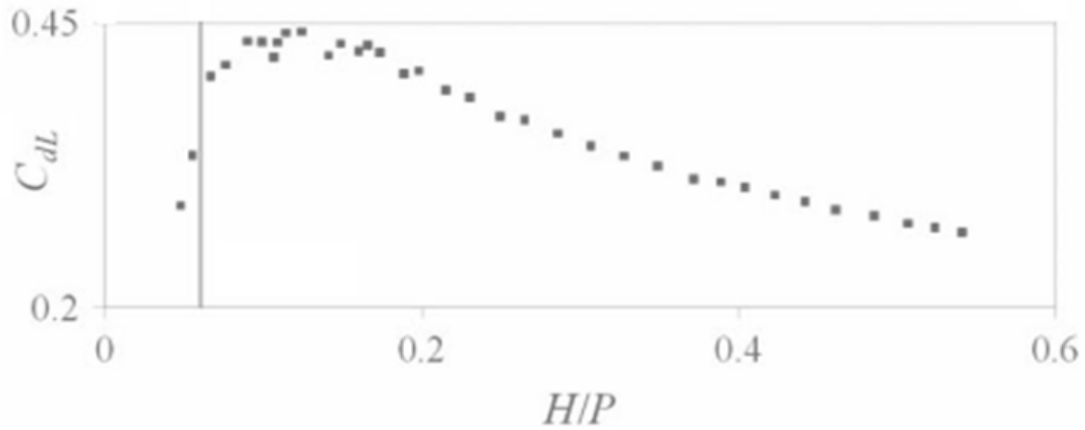
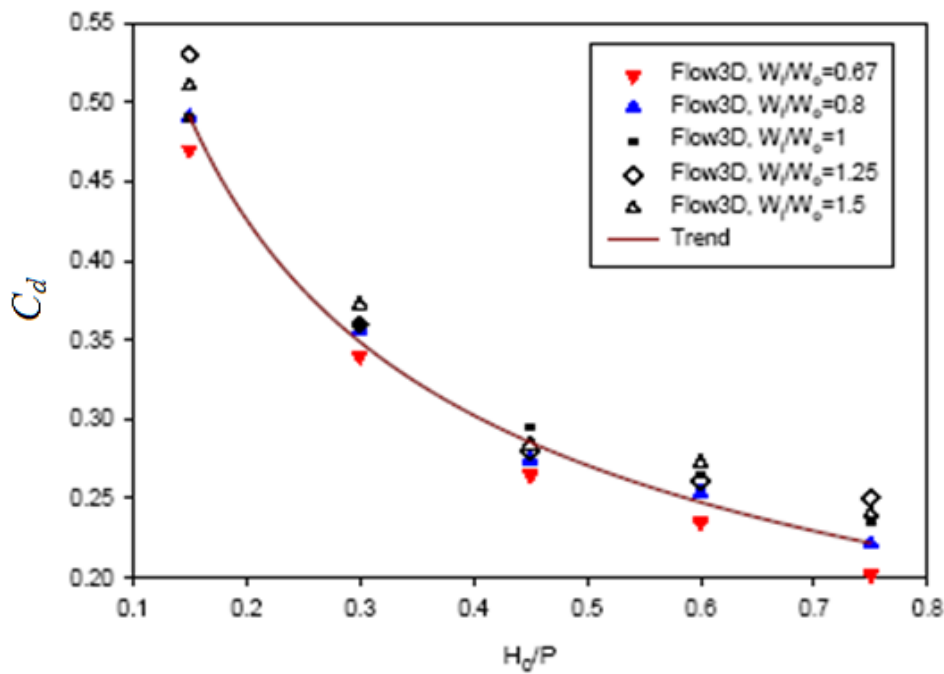Fig. 17. Discharge coefficent curve determined by Olivier Michaels (2011) for PK weirs

Fig. 18. Discharge coefficent curve determined by Flow 3D for PK weirs

As can be seen from Eq. (10), by substituting the defined equation for the discharge coefficient into Eq. (7), an equation that gives the discharge Q is resulted, which has a linear function of the head H_o.

$$Q_{PKW} = 0.19\left(\frac{H_0}{P}\right)^{-0.5} \cdot \sqrt{2g}LH_0^{1.5} = 0.19\sqrt{2gP}LH_0 \qquad (10)$$

This linear relationship can be found in the plots of Q versus H_o in Figs. 7 through 11. This linear relationship may not apply to full size PK weirs. This study only shows this is true for the small size models used in laboratory test, and the computer simulations. In this study, some other hydraulic parameters affecting the spillway performance have also been investigated. In the first step, the depths of flow on inlet and outlet keys have been studied and the results illustrated in Figs. 19 and 20.
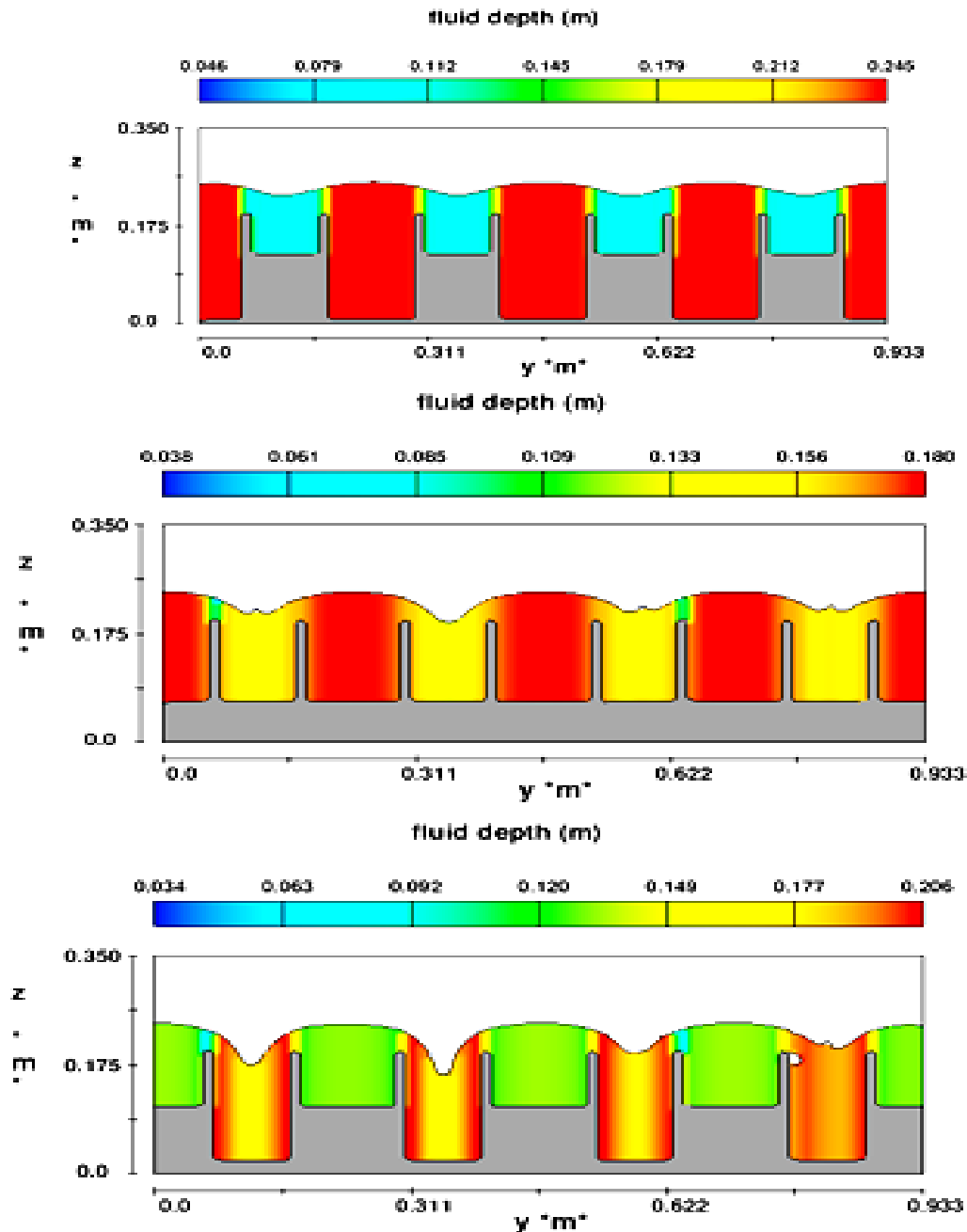
Fig. 19. Variations in flow depth in transverse direction in intlet, mid and outlet of PK weirs

As regards the results of flow depth over the PK weirs along the transverse direction of flow, it was concluded that the approaching flow is divided into the number of inlet keys due to the intermediate walls of inlet and outlet keys (3 full inlet keys and 2 half inlet keys). Therefore, dividing flow in canal takes place at the inlet of spillway. In addition, the flow depth in the middle section of spillway in inlet and outlet keys is similar. What is more, by reaching the flow to the end of spillway, the flow divides into two parts at inlet and outlet keys. In this condition, outlet keys have more variations in flow depth than inlet keys due to the slope variations in the outlet keys.

Another major hydraulic parameter of the flow over PK weirs is to determine velocity over the spillway. Therefore, the velocity component in the longitudinal direction of flow for the inlet and outlet keys and flow velocity vectors obtained by Flow3D model are given in Fig. 21.
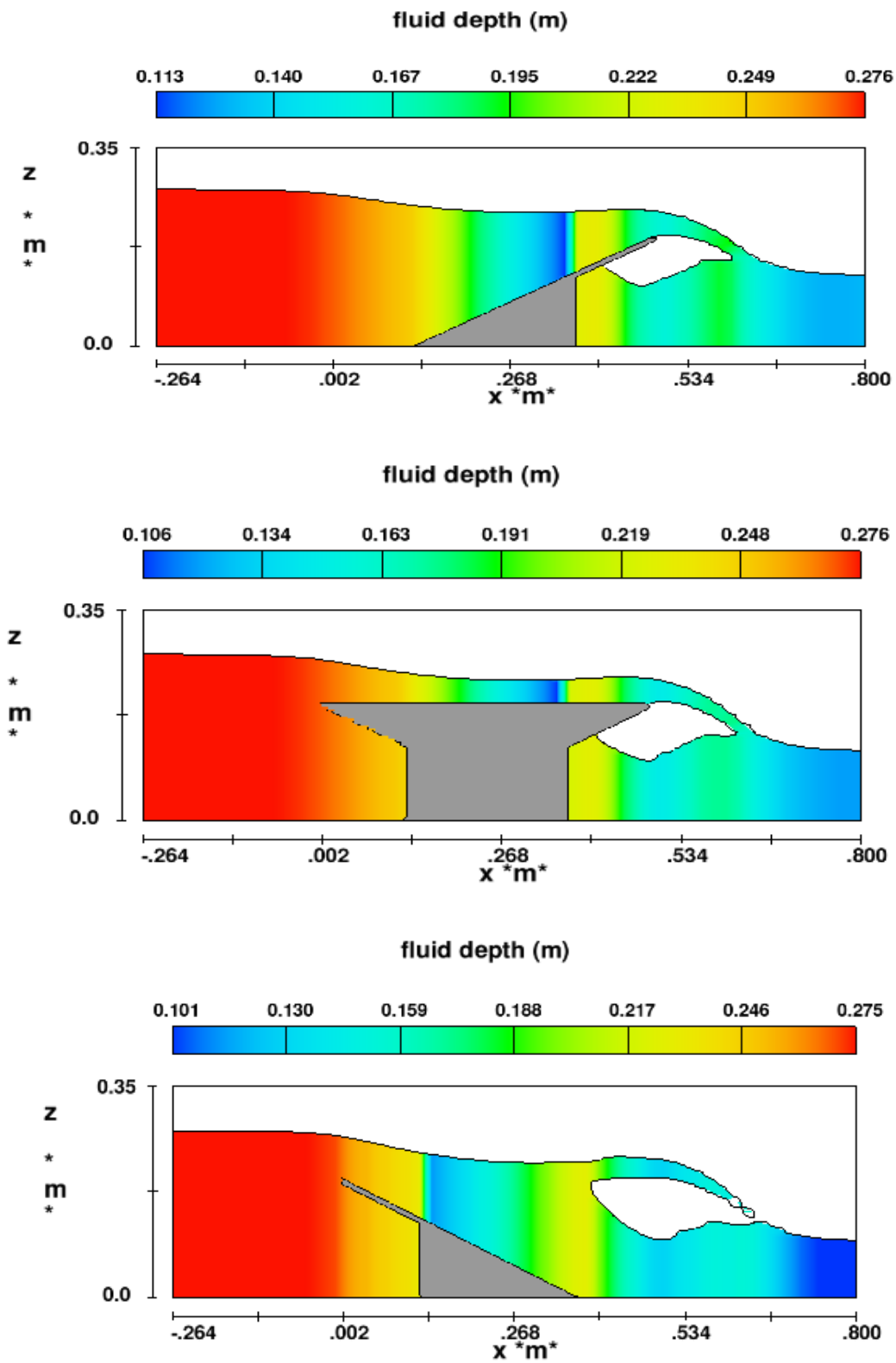
fluid depth (m)

0.113   0.140   0.167   0.195   0.222   0.249   0.276

fluid depth (m)

0.106   0.134   0.163   0.191   0.219   0.248   0.276

fluid depth (m)

0.101   0.130   0.159   0.188   0.217   0.246   0.275

Fig. 20. Variation in flow depth on inlet & outlet & midspan keys of PK weirs

x-velocity (m/s)

-0.21	0.12	0.46	0.79	1.13	1.46	1.79

x-velocity (m/s)

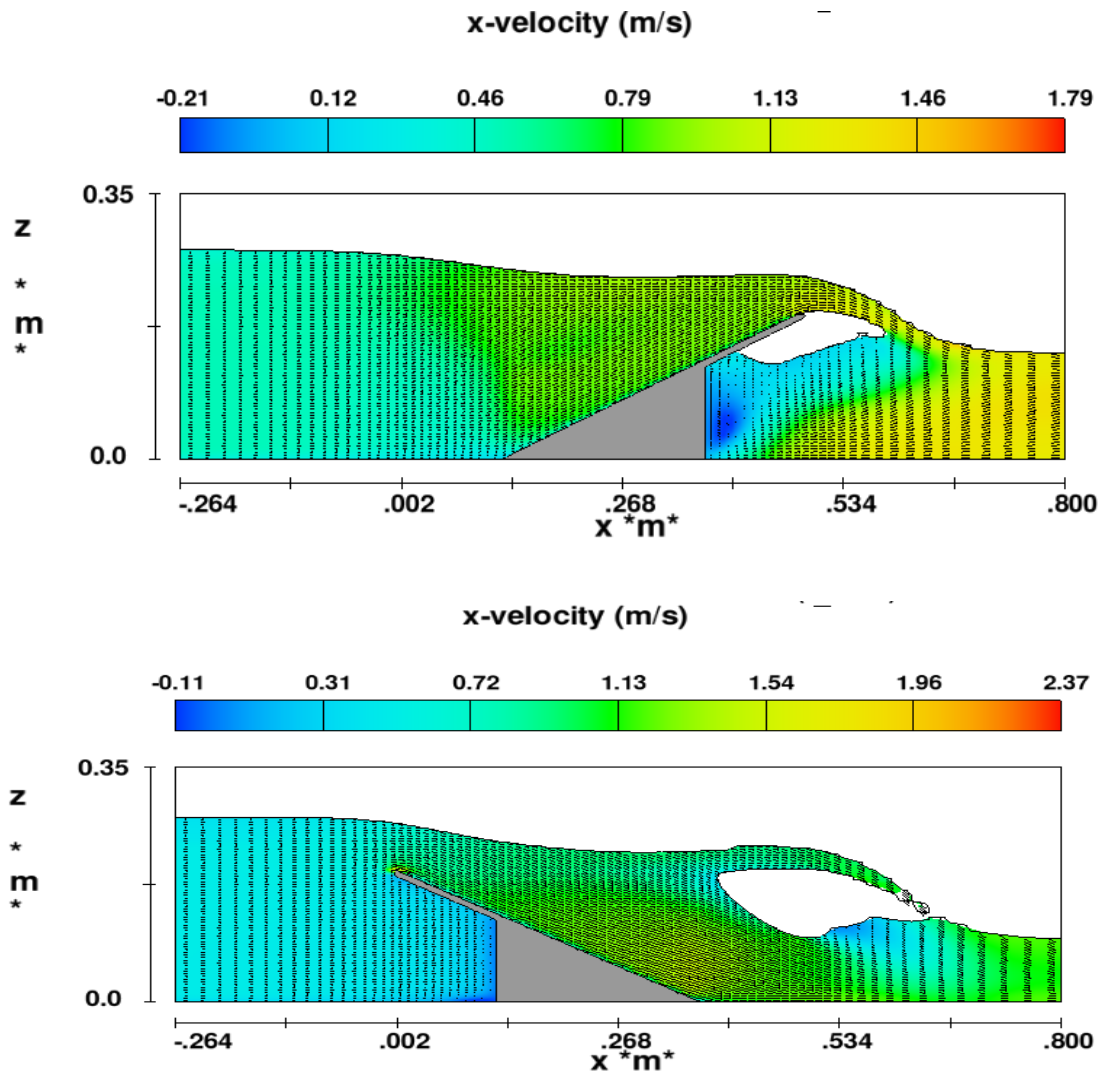| -0.11	0.31	0.72	1.13	1.54	1.96	2.37

Fig. 21. Flow Velocity values and their vectors over the 1) inlet keys, 2) outlet keys

As it is observed from flow velocity variations' figures, the maximum velocities occur in the middle depth of outlet keys. While the flow is passing over spillway, the velocity increases from 0.79 m/s to 1.45 m/s in inlet keys. After spilling the flow from the inlet keys, a vortex occurred under the inlet keys which is shown in the figures with blue color. The Vortex velocity is about -0.2 m/s. Moreover, by passing the flow over the outlet keys, due to slope favoring the flow direction, the velocity increases over the keys. As a result, the velocity varies from 0.3 to 1.5 m/s. The major point in velocity contours is the presence of vortex with the magnitude of -0.1 m/s near the bed, as the flow approaches to the outlet keys. This should be considered in the designing of these types of spillways.

The other hydraulic parameter, which is mostly is used in designing the PK weirs, is how the pressure changes on crest and inlet and outlet keys. Hence, by using numerical simulation in this study, the pressure distribution values have been studied along the flow over the PK weirs. In Fig. 22, the pressure variations on PK weirs are shown for different longitudinal sections.
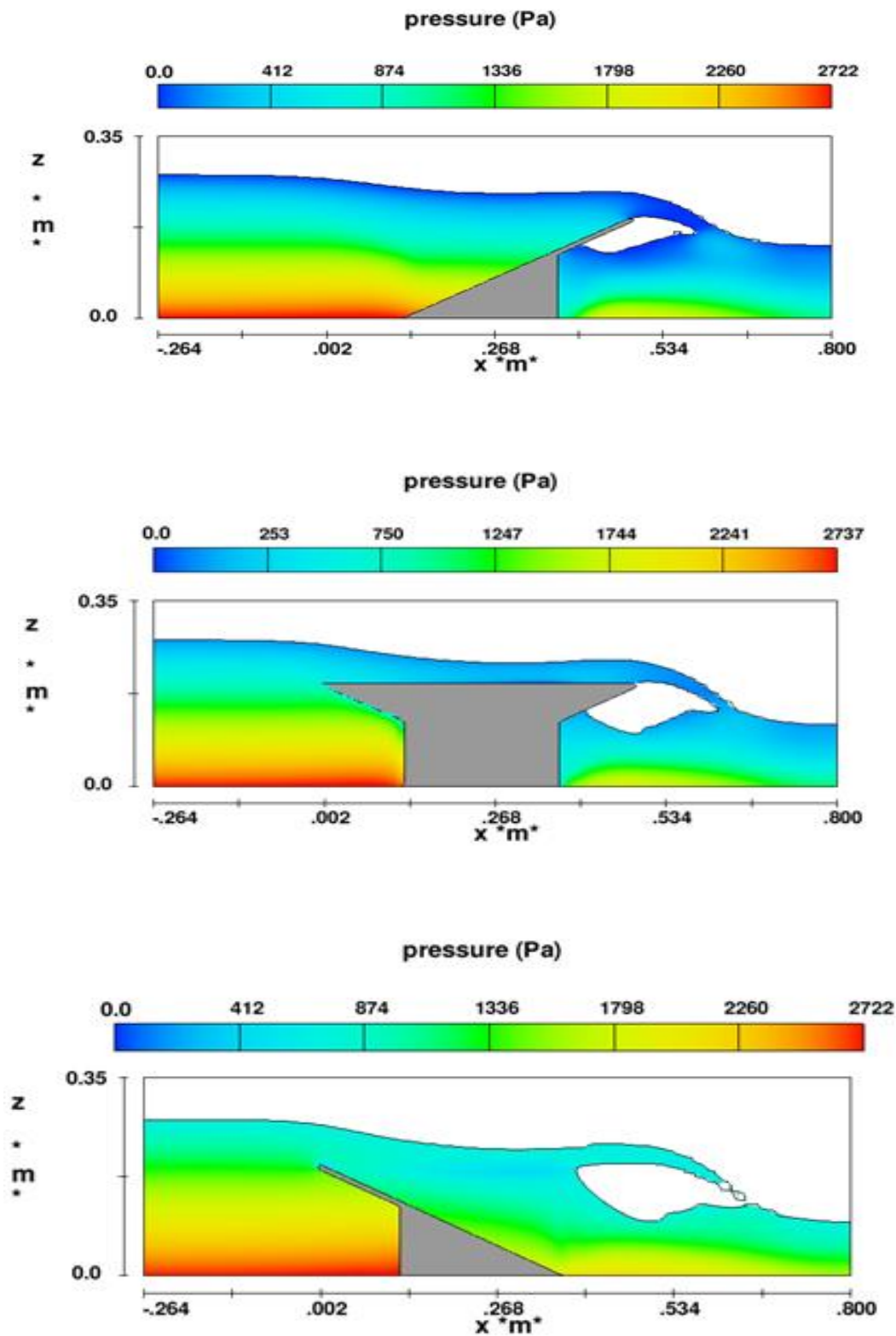
Fig. 22. Pressure variations over the inlet keys, middle wall, outlet keys and crest of PK weirs

As regards the figures associated with pressure distributions over the inlet and outlet keys, the pressure distribution has direct relation with fluid height in canal and spill way. Therefore, the maximum pressure values first occur at the canal bed with maximum depth and then over the inlet keys. While the flow passes over the spillway, due to decrease in flow depth at the inlet keys, the maximum pressure does

not occur and this process is valid for outlet keys too. Consequently, for designing the inlet and outlet keys in PK weirs the concrete slabs do not have great thicknesses. In the above figures, due to natural aeration over the surface of water, the value of pressure is zero.

6. CONCLUSION

To recapitulate, piano key weirs can discharge a greater volume of water than the common spillways in limited width and be used as economic structures with high efficiency. In this research, patterns of three dimensional flow were modeled numerically over the piano key weir.In order to reach a stable condition in the simulation process, at least 10 seconds were needed as the minimum time.The model was verified by available experimental data and was then utilized to derive a formula for calculating the discharge coeficient.Significant factors including the keys' widths, spillway height, and hydraulic parameters significantly affected the achieved results and was investigated thoroughly. By incresing the amount ofinlet-to-outlet key width ratio(W_i/W_o),the discharge increases and the errors in discharge rate change from negative to positive values. Conversely, by a rise in the H_0/P ratio, the discharge coefficient value decreased regardless of the variation inthe inlet-to-outlet key width ratio. Finally, an equation has been derived for discharge coeficient based upon the ratio of flow depth to spillway height (H_0/P) in order to calculate the flow rate over PK weirs. It is worthwhile to mention that the proposed equation is applicable for the specified ranges of W_i/W_o and H_0/P.The findings of the research cannot be appliedfor full size PK weirs and it needsto be verified by the data obtained in a real condition.The paper only shows this is true for the small size models used in laboratory test, and the computer simulations.

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