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A Hydraulic Study of Sharp Crested Weir with Orifices

دراسة هيدروليكية للهدار الحاد المزود بفتحات

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خلاصة:

يدرس هذا البحث معمليا التدفق خلال هدار حاد مزود بفتحات. تم عمل 9 فتحات متناظرة فى هيكل الهدار قطر الواحدة 3 سم موزعة بالتساوى على 3صفوف و3 اعمدة لنقل كميات اكبرمن المياه في اتجاه المصب. أجريت 23 تجربة معملية باستخدام 9 نماذج من الهدارات. تهدف هذه الدراسة إلى تقييم تأثير التصرف، منسوب المياه عند بوابة الذيل، عدد وموقع الفتحات على معامل التصرف وطول القفزة الهيدروليكية. قد تم تحليل النتائج وعرضت بيانيا وتمت مقارنة نتائج التدفق على هدارمزود بفتحات مع هداراخر بدون فتحات واظهرت النتائج اختلافات جوهرية بين الحالتين. فى حالة الهدار المزود بفتحات وجد ان معامل التصرف اكبر من حالة الهدار بدون فتحات، إضافة إلي ان طول القفزة الهيدروليكية يتناسب عكسيا مع عدد الفتحات. طورت معادلات الانحدار المتعدد اعتمادا على معادلة الطاقة ونظرية التحليل العددى لحساب معامل التصرف وطول القفزة الهيدروليكية فوق هدار حاد بفتحات. تمت مقارنة المعادلتين المستنتجين لمعامل التصرف وطول القفزة إلى البيانات التجريبية وأكدت المقارنة درجة موثوقية جيدة ودقة عالية.

Abstract

This research investigates experimentally the flow over sharp crested weir and through rounded orifices. Nine symmetrical orifices of 3 cm diameter each were made in the weir to convey much water in the downstream direction. The orifices were distributed as 3 equals spaced rows by three equal spaced columns. Twenty three (23) experimental runs were conducted. Nine weir models were used. This study aimed to evaluate the effect of discharge, tail gate water level, orifices number, and locations on the discharge coefficient and length of hydraulic jump. Results were analyzed and graphically presented. The results of flow over the weir with orifices were compared with those of the weir without orifices. It was dedicated that there is a large difference between them. In case of weir with opening it was found that the discharge coefficient was higher than the weir without openings. The jump length was inversely proportional to the number of openings. Multiple regression equations based on energy principal and dimensional analysis theory were developed for computing the discharge coefficient and hydraulic jump length over sharp crested weir with orifices. The developed equations were compared to the experimental data. The comparison confirms a good reliability and high accuracy.

Keywords

Sharp crested weir; Orifices; Discharge coefficient; Hydraulic jump; Weir height, Water level.

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1. INTRODUCTION

Measurement of discharge in open channels is one of the main concerns in hydraulic engineering. Weirs have been widely used for the flow measurement, flow diversion and its control in the open channels (Kumar et al., 2011). Weirs are categorized in two main types: sharp-crested and broad-crested. Sharp crested weirs (also called thin-plate weirs or notches) are those of sharp upstream edges such that the water springs clear over the crest. They are used to measure discharge in open channels by using the principle of rapidly varied flow. They are extensively used in laboratories, industries, irrigation practice and also used as dam instrumentation device and thus accurate flow measurement is very important. As a result the capacity of the existing weirs built on those canals and the embankment height of the canals themselves upstream of the weirs became insufficient to pass this increase of high water demands. Therefore, the solution is to replace the old structures by new ones or to modify the existing ones. The first solution is costly prohibitive while the second requires a modification of the hydraulic characteristics of the weirs. The modifications may be the widening or lowering weir crest or making orifices to pass extra flow rates downstream.

2. LITERATURE REVIEW

In recent years, many researchers have carried out studies in order to measure discharge over the weirs exactly. Some of these studies were experimental whereas others were theoretical. These studies may be categorized upon the type of the weir and limitations of the research. Wide range of data was experimentally studied in the present study. Many studies were executed to determine the discharge coefficient of sharp crest weir and the various factors affecting it (i.e. height, width and length), (Granata et al., 2013; and Azimi, 2014). Weirs have various shapes such as rectangular, triangular, trapezoidal, circular and especial applications. Bos (1989), deduced a typical form of the governing equation of these weirs by as

$$Q = kH^z \quad (1)$$

where, k = coefficient depending on the size and shape of the weir and z = dimensionless number depending on the shape of the weir.

Rehbock (1929) made experiments on full width sharp crested weirs. He deduced a discharge coefficient equation which depends on water head above the weir crest (H) and weir height (p). The empirical equations of discharge and discharge coefficient are given in eqs. 2 and 3 respectively.

$$Q_{actw} = \frac{2}{3} c_{dw} B \sqrt{2g} H^{1.5} \quad (2)$$

$$c_{dw} = 0.611 + 0.08\frac{H}{p} + \frac{1}{1000} H \quad (3)$$

where, Q_{actw} = actual discharge passing over the weir, C_{dw} = weir discharge coefficient, H= static head over weir crest and P = weir height.

These equations were verified by Kumar et al. (2011). Henderson (1966) modified eq.(3) by proving that the last term is ineffective, therefore the equation became:

$$c_{dw} = 0.611 + 0.08\frac{H}{p} \quad (4)$$

Kindsvater and Carter (1957) executed an extensive study about sharp crested rectangular weirs. They introduced a parameter of C_e which is free from the surface tension and viscosity effects due to contraction of water at the weir where:

$$Q_{actw} = \frac{2}{3} c_e B_e \sqrt{2g} H_e^{1.5} \quad (5)$$

$$c_e = 0.602 + 0.075\frac{H}{p} \quad (6)$$

$$B_e = B_c + k_b \quad (7)$$

$$h_e = H + k_h \quad (8)$$

where, H = static head over weir crest, h_e= effective head weir crest, p = weir height, B_c = weir width, B_e = effective weir width, K_b = quantity represents the effect of viscosity and surface tension and K_h = quantity represents the effect of viscosity and surface tension. Aydın et al. (2002) introduced the term (slit weir). This type of weir is a narrow rectangular sharp crested weir, efficient to measure small discharges accurately. They deduced an empirical equation, which depends on the Reynolds number as following:

$$c_{dw} = 0.562 + \frac{11.354}{\sqrt{R}} \quad (9)$$

$$R = \frac{Q}{h\upsilon} \quad (10)$$

where, R = Reynolds number and υ= kinematic viscosity of fluid.

Depending on the pipe condition and the water elevation on either side of the weir, flow is classified into three different flow categories (AbdelHalim et al. 1991; Samani and Mazaheri, 2009). More specifically those categories are; free orifice, submerged orifice with free weir and submerged orifice with submerged weir.

Wolters et al. (1987) made serious attempts to calculate the discharge for a system that consisted of a specific weir and a pipe. They made a distinction between flow over the weir, which can be calculated rather accurate, and the flow through the pipes, which is far less reliable. They presented rating curves for all studied weirs. Hassan et al. (2010) studied experimentally the flow over clear overfall weir with bottom circular orifice. The study demonstrated that there is a large difference between the flow over weir with a circular orifice and those of the weir without an orifice having the same dimensions. Also, they showed that the hydraulic jumps behind the weir with an orifice occur close to the weir toe. This may affect the scour characteristics downstream the weir. A combination between physical and numerical models was executed by Arvanaghi and oskuei (2013) to estimate the discharge coefficient for sharp-crested weir. They concluded that the discharge coefficient has a fixed value of 0.7. Haun et al. (2011) calculated water flow over a trapezoidal broad-crested weir by two different codes of flow, CFD 3D and SSIM 2. They verified the results with measurements of a physical model study using different discharges. They stated that the deviation between the computed and measured upstream water level was between 1.0 and 3.5%. Hoseini (2014) made laboratory measurements on triangular broad-crested weir with different geometry. He presented an accurate equation for the discharge coefficient of the triangular broad-crested weirs for overfall condition could be used with confidence. Afzalimehra and Bagherib (2009) developed an equation for estimating the discharge coefficient of rectangular sharp-crested weirs by the potential flow theory. Prabhata et al. (2011) developed an equation for the discharge coefficient of skew weirs as a function of weir head to weir height and the weir angle relative to the channel axis. Abdorreza et al. (2010) performed a comprehensive set of experiments on weirs placed obliquely in a rectangular open channel. Their results indicated that by increasing the oblique angle, the effective length of the oblique weir increases significantly. Saeid and Eghbal (2013) studied the hydraulic properties of the cylindrical and circular crested weirs. They indicated that in both the cylindrical and circular crested weirs by increasing the total partial head, the discharge coefficient increases and any changes in the upstream wall slope has no effect on the discharge coefficient. Abozeid et al. (2010) investigated experimentally the flow over weir with bottom orifice to obtain a relationship between the flow passing through the pipe and over the weir. Habib (2013) studied experimentally the characteristics of flow through weirs controlled by a gate with an orifice. He introduced equations to compute the combined discharge of the weir and the pipe. He also computed the discharge coefficient of the flow. Manoochehr et al. (2011) studied the forced hydraulic jump in stilling basin with a continuous tall sill downstream a sluice gate. Habib (2013) executed experimental study to investigate the effect of the relative pipe diameter on the characteristics of the free hydraulic jump occurred downstream a weir controlled by a sluice gate and with circular orifice. The study indicated that using weir with orifices has a great effect on the hydraulic jump characteristics.

This research was thus initiated in order to investigate the influence of discharge, tail gate water level, location and number of orifices on the changes of water level, discharge coefficient, and the associated hydraulic jump length, with the objectives of determining the effect of orifices on hydraulic performance for a sharp crested weir.

3. EXPERIMENTAL WORK

3.1 Model Set-up

All of the experiments were conducted in a flume located at the Hydraulics Research Institute experimental hall of the National Water Research Center, Egypt.

The flume channel has 21 m long, 0.6 m wide, 0.5 m deep, and the side walls along the entire length of the flume were made of brick. The flume is associated with a steel wooden gate with an orifice with a rectangular shape, also has movable downstream gate is located at the end of the flume. Centrifugal pump driven by induction motor to re-circulated the flow from an underground reservoir to the flume. The weir models were made of steel with a 2 mm thickness, 0.3 m height and 0.6 m width with different number of symmetrical, orifices 30 mm each were used in this study (Fig. 1). The used discharges were 10, 20, and 30 l/s, and the corresponding tail gate water depths were 10, 15, and 20 cm.

3.2 Measurement Techniques

The following procedure was used for each experimental run before the experiment starts the selected weir model is fitted in its place. The flume was then filled with water to obtain the desired depth. Next, the pump was started and the discharge adjusted (ultrasonic flow-meter with an accuracy of $\pm$ 1%). As soon as the flow rate in the channel was stable, the running time of the test is started. The experiments were all continued for at least 3hrs to assure constant flow rate over the weir and through the rounded orifices. After 2hrs, the water depth over the weir, upstream and downstream water depths, and the length of hydraulic jump were measured by a point gage and ordinary scale at least 4 times throughout the last 1 hr. The pump was switched off and the flume is gradually drained. On this basis, the effects of the far sidewall on the results of the experiments could be neglected. Ranges of experimental parameters are listed in Table 1.

4. THEORETICAL APPROACHES

4.1 Discharge Equations

Flow over a rectangular weir without lateral contractions and a non-submerged hydraulic jump can be described by Aydin et al. (2002) and Habib (2013):

$$Q_{actw} = \frac{2}{3} c_{dw} B \sqrt{2g} H^{1.5} \qquad (2)$$

Also, the flow through the pipe is governed by the following equation for the orifice discharge (Habib, 2013):

$$Q_{acto} = \frac{\pi}{4} d^2 c_{do} \sqrt{2gH_p} \qquad (11)$$

Thus, any relation that controls the flow passing through the combined device of the weir and pipe must use these two equations to illustrate the interaction that happened in between. The following equation may be used in providing a relation between discharge over weir and discharge through orifice:

$$Q_{act} = Q_{actw} + Q_{acto} \qquad (12)$$

or

$$c_d Q_{th} = c_{dw} Q_{thw} + c_{do} Q_{tho} \qquad (13)$$

From Eq. (13), one can easily get the following form:

$$c_d = c_{dw} \frac{Q_{thw}}{Q_{th}} + c_{do} \frac{Q_{tho}}{Q_{th}} \qquad (14)$$

The values of c_d, c_{dw} and c_{do} may be experimentally estimated.

Table 1: Range of variables for laboratory experiments

Parameter	Symbol	Value	Range		Units
			From	To	
Discharge	Q	10,20,30	10	30	l/s
Tail gate water depth	y_{tail}	10,15,20	10	20	cm
Upstream water depth	y_1	Varied	31	38	cm
Upstream water depth	y_2	Varied	6.2	20.7	cm
Head over weir	H	Varied	0.95	7.9	cm
Length of hydraulic jump	L_j	Varied	13	85	cm
Number of orifices	n	3,6,9	3	9	------

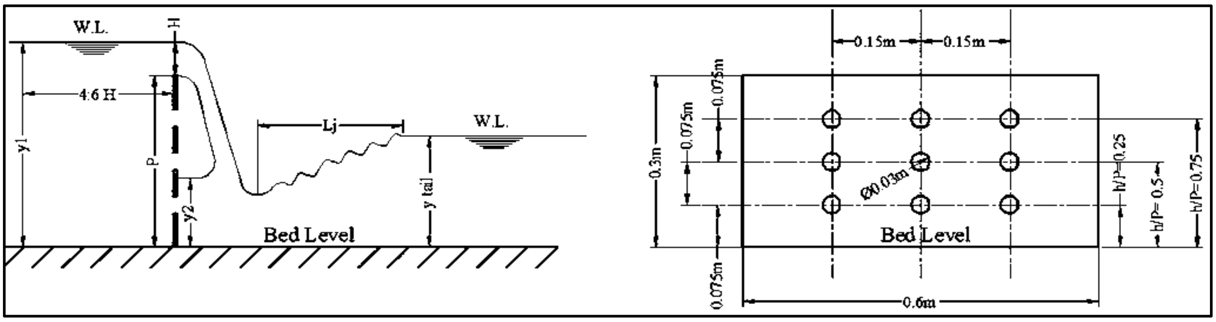


Figure 1: Definition sketch of the used models

4.2 Dimensional Analysis

A physically pertinent relation between the discharge and the other dependent parameters may be found by dimensional analysis. The non-dimensional relationship is also useful for checking the sensitivity of the different parameters which affect the phenomenon (Abozeid et al., 2010). The functional relationship of the discharge Q may be expressed by:

$$Q = \emptyset\,(B, p, h, y_1, y_2, y_{tail}, H, d, g, n, \rho, \mu) \quad (15)$$

Where B is the weir width, p is the weir height, h is the distance from bed level to the horizontal axis of orifices, y_1 is the upstream water depth, y_2 is the downstream water depth, y_{tail} is the tail gate water depth, H is the static head over weir crest, d is the orifice diameter, g is the gravity acceleration, Q is the discharge, n is the number of orifices, ρ is the fluid density, and μ is the dynamic viscosity of fluid.

Using π-theorem, it yields;

$$c_d = \phi\left(n\Sigma\frac{h}{p}, \frac{y_1}{y_2}, \frac{H}{p}, n\frac{d}{H}, \frac{H}{y_{tail}}, \frac{Q}{Bd^{1.5}\sqrt{2g}}, \frac{\rho Q}{d\mu}\right) \quad (16)$$

In which $\frac{\rho Q}{d\mu}$ = Reynold's number, in open channel flow, the Reynold's number effect may be neglected (Mohamed, 2010). The width of the weir is constant, so, Eq. (16) could be written as:

$$c_d = \phi\left(n\Sigma\frac{h}{p}, \frac{y_1}{y_2}, \frac{H}{p}, n\frac{d}{H}, \frac{H}{y_{tail}}, \frac{q}{d^{1.5}\sqrt{2g}}\right) \quad (17)$$

4.3 Model Runs

Twenty-three experimental runs with different weir models were reported. The experiments were designed to vary the independent variables of flow discharge, tail gate water depth, number and location of rounded orifices. Table 2 presents the relationship between the numbers and orifice locations with the ratio $\frac{h}{p}$. For example, in case of both bottom and middle rows were opened, the ratio $n\Sigma\frac{h}{p}$ = 6*(0.25+0.5) = 4.5 (Fig. 1)

Table 2: Orifice location and the corresponding $n\Sigma\frac{h}{p}$

Orifice Location	All closed	Bottom row	Middle row	Top row	Middle &bottom rows	Top &bottom rows	Top &middle rows	Right &left columns	All opened
n	0	3	3	3	6	6	6	6	9
$n\Sigma\frac{h}{p}$	0	0.75	1.5	2.25	4.5	6	7.5	9	13.5

5. RESULTS AND DISCUSSIONS

Water surface profiles for weir without orifice and with orifice at different locations are presented in Fig. 2.The figure shows that, the upstream water depth is higher for weir without orifice than that for weir with orifices. However, for constant orifice numbers, the orifice locations showed no valuable influence on water surface profile. So, increasing the number of orifices to pass discharge; increases the canal conveyance efficiency upstream of the weir. Also, it can be seen that the hydraulic jump downstream the weir with an orifice occurs nearer to the weir than that at weir without the orifice. This may affect the scour characteristics downstream the weir. The pre-mentioned remarks showed a good agreement with Hassan et al. (2010).

It should be mentioned that, during investigations of the discharge influence on different tested variables, the figures were plotted under fixed tail gate water depth (y_{tail}= 15cm). Also, investigating the effect of the tail gate water depth, the figures were plotted under constant discharge (Q= 20 l/s). However, the figures defining the effect of orifices were plotted under fixed discharge (Q= 20 l/s) and tail gate water depth (y_{tail}= 15cm)

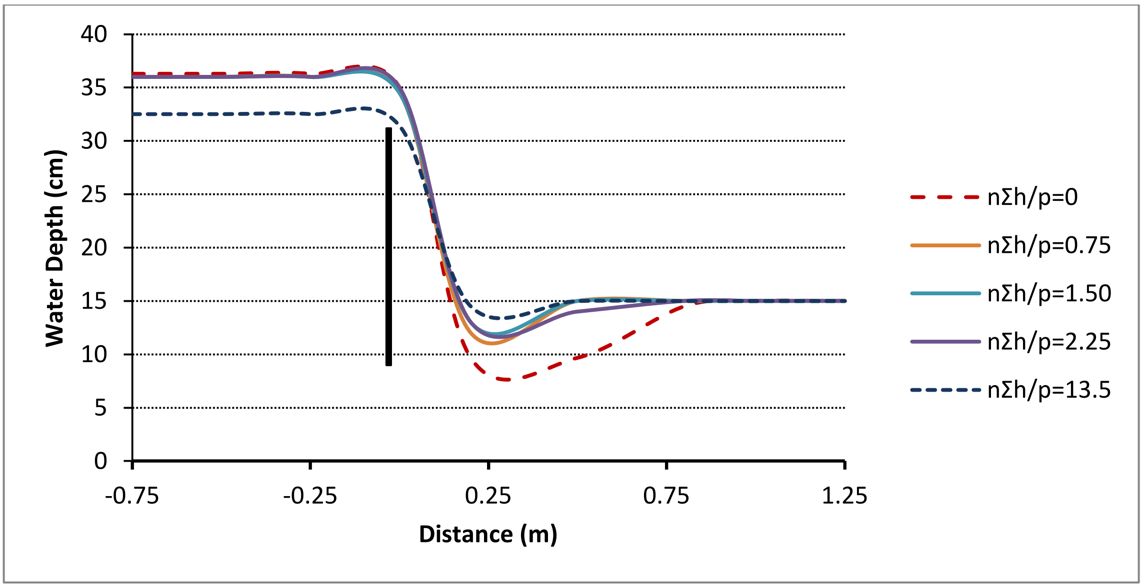


Figure 2: Water surface profile for weir with and without orifices

5.1 Variance of Water Depths

Figs. 3 to 5 define the relationship between the variance of water depths and discharge, tail gate water depth, location and number of orifices. Fig. 3 shows that both upstream and downstream water depths are directly proportional to the discharge. Also, in case of closed orifices, the upstream water depth increases and the downstream water depth decreases when compared to weir with orifices. Fig. 4 illustrated that, the tail gate water depth presented no noticeable influence on upstream water depth for both weirs with and without orifices. However, the downstream water depth increases directly with the tail gate water depth. Also, the influence of orifices is vanished at low tail gate water depth. Fig. 5 demonstrates that, both upstream water depth and head over weir are inversely proportional to the number of orifices. On the contrary, the downstream water depth is directly proportional to the number of orifices. This agrees with the findings given by Habib (2013).

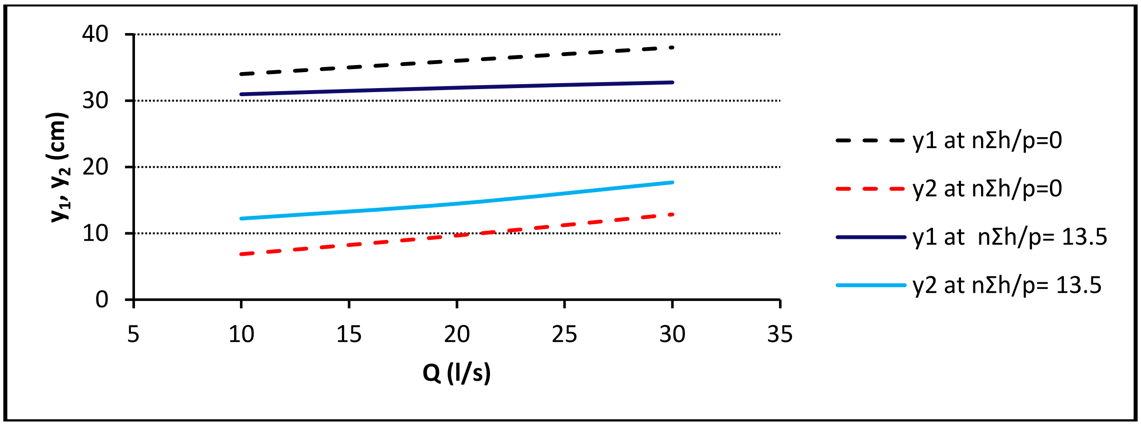


Figure 3: Influence of discharge on variance of water depths

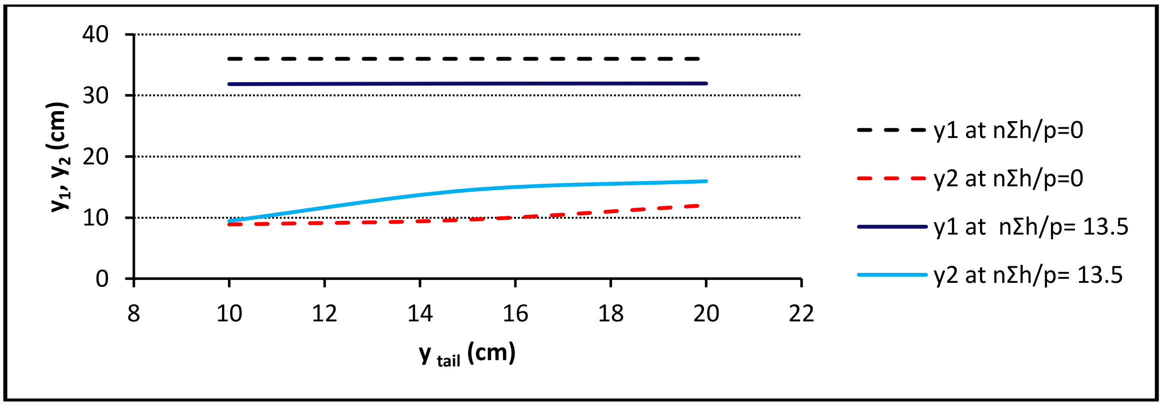


Figure 4: Influence of tail gate water depth on variance of water depths

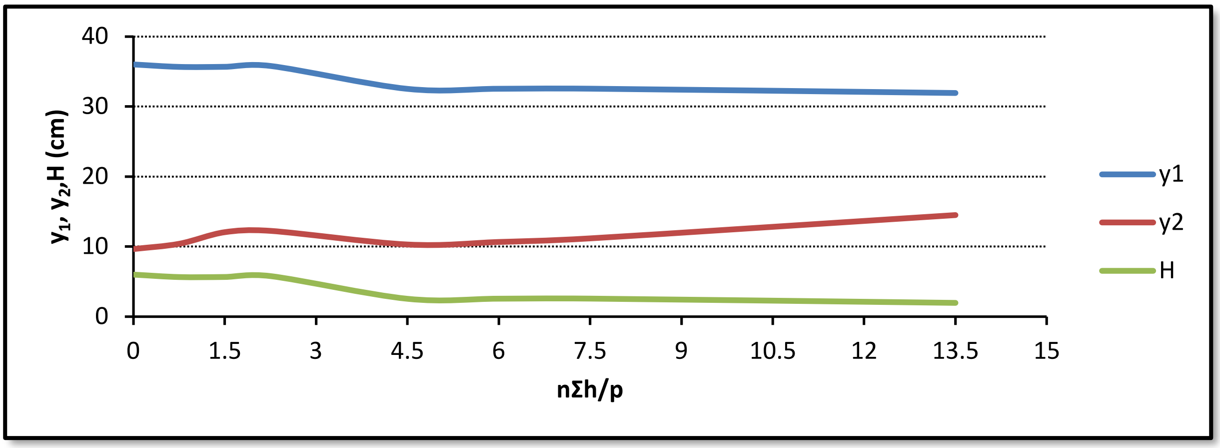


Figure 5: Influence of orifices on variance of water depths

5.2 Discharge Coefficient

Figs. 6 through 8 define the relationship between the discharge coefficient and discharge, tail gate water depth, and location and number of orifices. *The* current obtained results were compared to other studies such as given by Rehbock (1929), Henderson (1966), Kinsdvater (1957), and Aydın (2002) having the same flow conditions (Fig. 6). It's noticed that, the observed discharge coefficients gave higher values than the other studies by a constant average value of 0.136. Unless, the obtained discharge coefficients are close to the findings by Hadi (2013) and Habib (2013).

Combining Figs. 6 and 7, it is concluded that, in case of closed orifices, neither discharge nor tail gate water depth shows a noticeable effect on the discharge coefficient. On the contrary, the case of weir with orifices, both discharge and tail gate water depth are directly proportional to the discharge coefficient. Fig. 8 showed that, fixing the number of orifices, the location doesn't affect the discharge coefficient. Also, the discharge coefficient in case of weir with closed orifices was higher than in case of weir with single opened row regardless to its location.

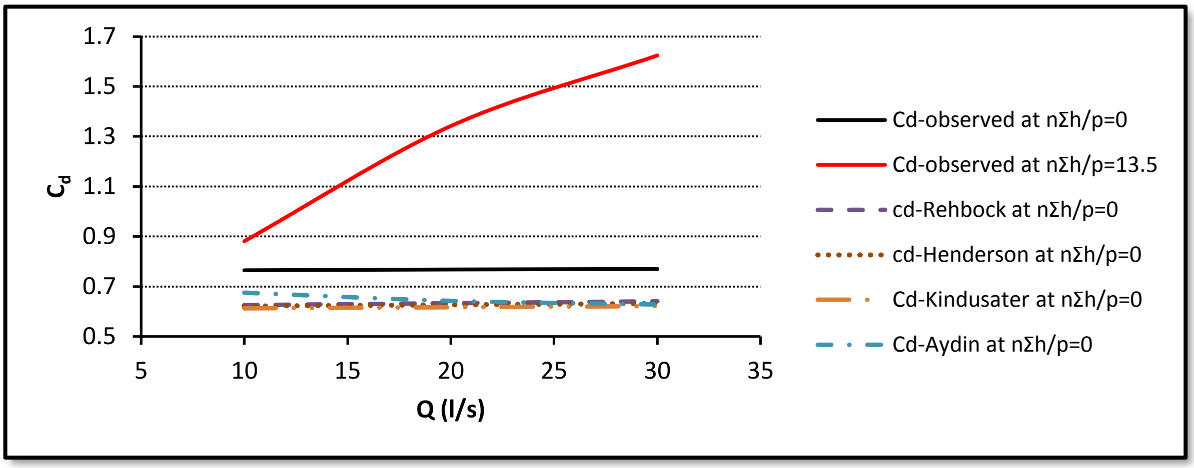


Figure 6: Influence of discharge on the discharge coefficient

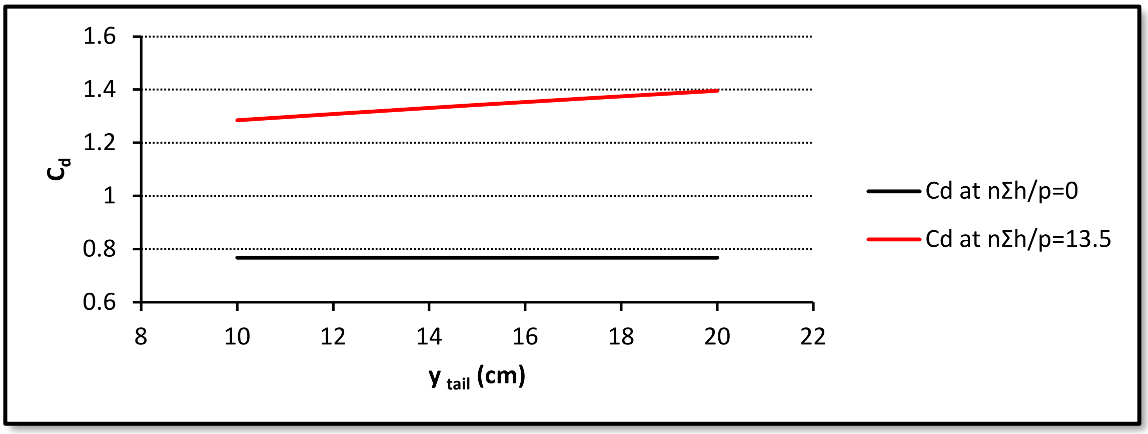


Figure 7: Influence of tail gate water depth on the discharge coefficient

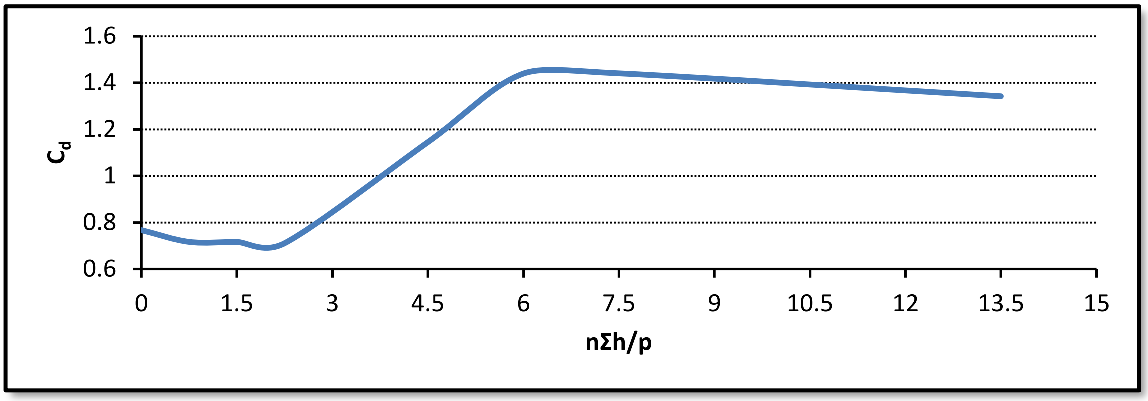


Figure 8: Influence of orifices on the discharge coefficient

5.3 Hydraulic Jump

The hydraulic jumps have been used for dissipating the kinetic energy in the stilling basins. They occur when the super-critical stream of high velocity meats a sub-critical stream of sufficient depth and lower velocity. The hydraulic jump downstream the weir with an orifice of different numbers and locations were analyzed in this part in comparison with the case of weir without orifices to obtain the effect of orifices on the length of the free hydraulic jump.

Figs. 9 through 11 define the relationship between the length of hydraulic jump and discharge, tail gate water depth, location and number of orifices. Fig. 9 illustrated that, the jump length was directly proportional the discharge. However, under fixed discharge, the weir of closed orifices showed longer jump length when compared to the weir with orifices. That agrees with the results obtained by Habib (2013). Investigating Fig. 10 it's noticed that, the length of hydraulic jump is inversely proportional to the tail gate water depth for both tested types of weirs. Discussing the effect of orifice location on the jump length Fig. 11 shows that, for fixed number of orifices, the jump length is directly proportional to the distance from bed level to the horizontal axis of orifices. (i.e. if the orifices in the top row only are opened, the jump length is longer than if the orifices in the middle row only or bottom row only are opened).

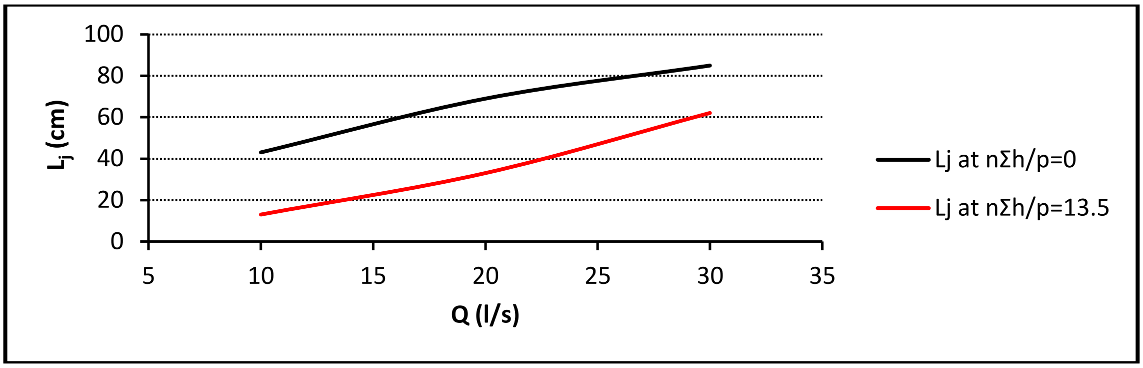


Figure 9: Influence of discharge on the length of hydraulic jump

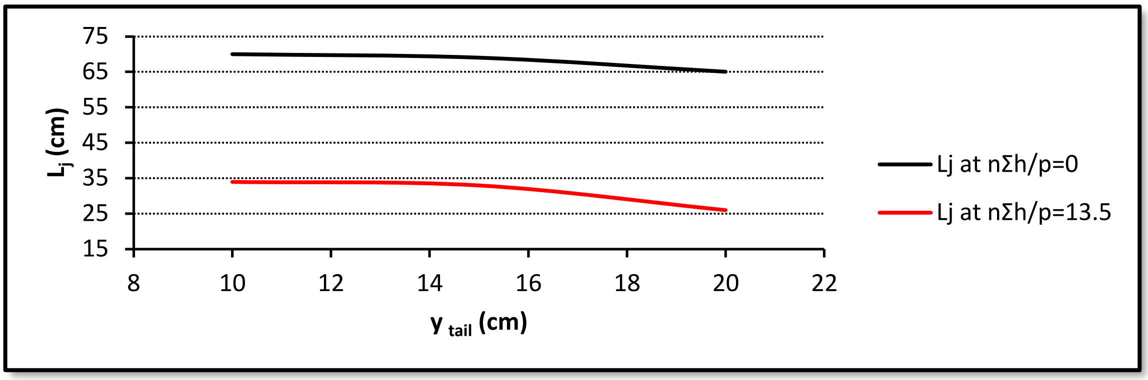


Figure 10: Influence of tail gate water depth on the length of hydraulic jump

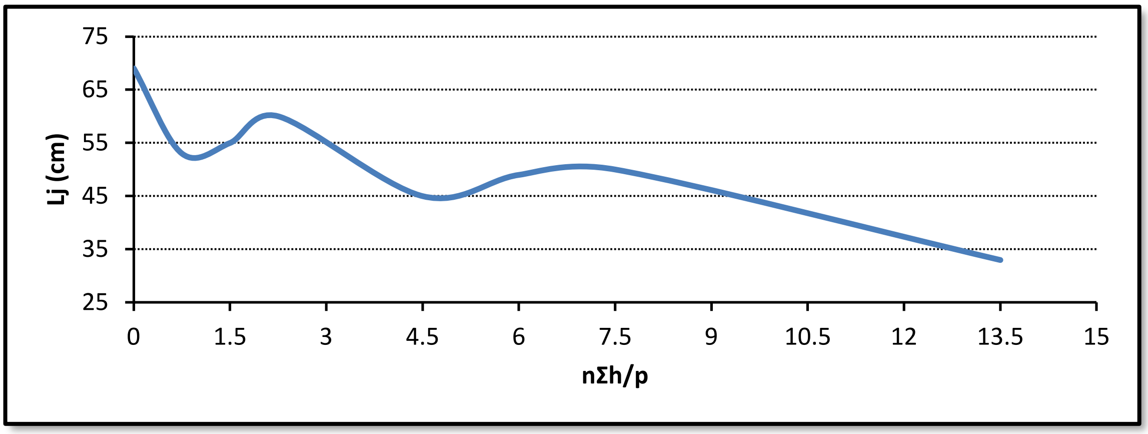


Figure 11: Influence of orifices on the length of hydraulic jump

The experimental results were used for correlating the different dimensionless variables to develop two empirical formulae for computing the discharge coefficient and the relative length of the hydraulic jump formed downstream weir with orifices.

The developed equations (eq. 18 and eq.19) could be applied only for the following conditions:

1- Discharge varies between 10 l/s and 30 l/s.

2- Tail gate water depth (y_{tail}) ranges from 10 cm to 20 cm.

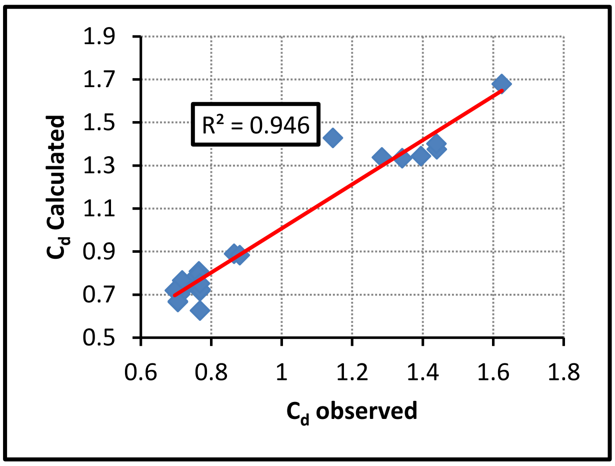
$$c_d = A_1 n\frac{h}{p} + A_2\,\frac{y_1}{y_2} + A_3\,\frac{H}{p} + A_4\,n\frac{d}{H} + A_5\,\frac{H}{y_{tail}} + A_6\,\frac{q}{d^{1.5}\sqrt{2g}} + A_7 \tag{18}$$

$$\frac{L_j}{p} = A_1 n\frac{h}{p} + A_2\,\frac{y_1}{y_2} + A_3\,\frac{H}{p} + A_4\,n\frac{d}{H} + A_5\,\frac{H}{y_{tail}} + A_6\,\frac{q}{d^{1.5}\sqrt{2g}} + A_7 \tag{19}$$

Table 3: Coefficient values

Variable / Eq. No.	A_1	A_2	A_3	A_4	A_5	A_6	A_7	R^2	SEE
18	-0.0143	0.0161	-6.762	-0.0149	-0.477	0.685	1.21	0.985	0.044
19	-0.053	-0.0635	-1.418	-0.0158	0.717	0.792	1.12	0.923	0.192

The predicted values were plotted against the experimental values as shown in Fig. 12. The model results show a good agreement between the experimental and predicted values.



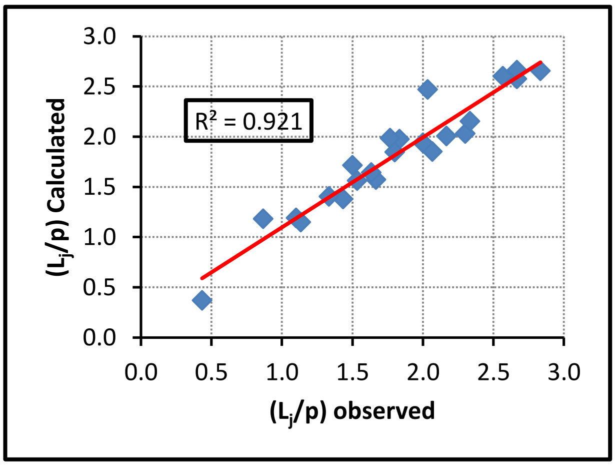


Figure 12: Comparison between observed and calculated values

CONCLUSIONS

The experimental study of the influence of discharge, tail gate water depth, location and number of orifices on the variance of water depth, the discharge coefficient, and the hydraulic jump, led to the following conclusions:

- The influence of tail gate water depth on the upstream water depth was extremely minimized for all cases under study.
- The downstream water depth was increased directly with the tail gate water depth.
- The number of orifices was inversely proportional to the upstream water depth and the head over weir, while it was directly proportional to the downstream water depth.
- The effect of discharge and tail gate water depth vanished on the discharge
- coefficient in case of weir with closed orifices.
- The discharge coefficient was directly proportional to the discharge and the tail gate water depth in case of weir with orifices.
- In case of weir with orifices, the discharge coefficient doesn't affected by orifices location under fixed orifice number.
- The jump length was directly proportional to the discharge and inversely proportional to tail gate water depth and number of orifices
- The jump length was directly proportional to the distance from bed level to the horizontal axis of the orifices.

For a further evaluation of possible combined weir with orifices designs and their influence on flow pattern, more aspects should be considered like orifice diameters, weir width, slope, and weir layout.

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NOTATION

The following symbols are used in this paper:

B = Weir width [m];
B_e = Effective weir width [m];
C_d = Discharge coefficient of the combined device;
C_{do} = Orifice discharge coefficient;
C_{dw} = Weir discharge coefficient;
C_e = Effective weir discharge coefficient
d = Orifice diameter [m];
g = Gravity acceleration [m/s^2];
H = Static head over weir crest [m];
H_p = Difference of head over the pipe centerline [m];
h = Distance from bed level to the horizontal axis of orifices [m];
k = Coefficient depending on the size and shape of the weir
K_b = Quantity represents the effect of viscosity and surface tension [m];
K_h = Quantity represents the effect of viscosity and surface tension [m];
n = Number of opened orifices
p = Weir height [m];
Q_{act} = Actual discharge of the combined device [m^3/s];
Q_{actw} = Actual discharge passing over the weir [m^3/s];
Q_{acto} = Actual discharge passing through orifice [m^3/s];
Q_{th} = Theoretical discharge [m^3/s];
Q_{tho} = Theoretical discharge passing through orifice [m^3/s];
Q_{thw} = Theoretical discharge passing over the weir [m^3/s];
q = Discharge per unit width [m^3/s/m\];
R = Reynolds Number;
y_1 = Upstream water depth [m];
y_2 = Downstream water depth [m];
y_{tail} = Tail gate water depth [m]; and
z = Dimensionless number depending on the shape of the weir.

Greek Symbols

μ= Dynamic viscosity of fluid [kg/m.s];
υ= Kinematic viscosity of fluid [m^2/s]; and
ρ = Fluid density [kg/m^3].

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