SLOPE EFFECT ON DISCHARGE EFFICIENCY IN RECTANGULAR BROAD CRESTED WEIR WITH SLOPED UPSTREAM FACE

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Abstract: *The rectangular broad crested weirs are widely used to measure the water discharge which is one of the most popular tools in the irrigation canals particularly, in developing countries.The present article is trying to demonstrate the results of an experimental work carried out on rectangular broad crested weir with sloped upstream face to investigate the effect of upstream slope on discharge efficiency. The upstream slope was varying from 90 to 23 degrees while incoming discharge was ranging from 14 to 75 lit/ sec. The experiments were conducted in a flume with a weir of fixed height under the normal downstream water depth .It is revealed that the slope of upstream face in rectangular broad crested weir would smoothen the flow profile having the critical depth on the weir crest adjacent and upstream of downstream edge of the weir . The results also lead to a novel achievement showing that the weir discharge efficiency is dependent on the slope of upstream face of the weir. As the slope of upstream face of the rectangular broad crested weir is decreasing from 90 to 23 the weir discharge efficiency is increasing and reaching to its maximum through a parabola function at slope angle of 25 degrees(i.e. 1:2.15). The investigation also showed that the depth of flow over the weir crest, the specific energy head of the approaching flow relative to chanel bed and the critical depth would be a pertinent similarity scales to asses the flow behavior over different sloped rectangular broad crested weirs between model and prototype. However, some broad investigation is recommended to endorse the achievements.*

Keywords: *Discharge efficiency, Rectangular weir, Upstream face slope, Critical depth.*

1. INTRODUCTION

The rectangular broad crested weirs are simple structures used to measure the water discharge in conveyance and distribution canals of irrigation systems. These structures are one of the most popular flow measuring tools in the regions of scares water resources.From the early days of hydraulics ,various flow measuring devices are developed and used in waterways. The flow measurement in these structures are hydraulically classified in two major categories as:

- Hydraulic head methods; in which the flow discharge is determined by measuring the hydraulic head difference through the flow reach.
- Velocity –area methods; in which the flow discharge is determined by measuring the local velocities along with effected area.

These methods are mostly ended to an empirical equation between discharge and flow head and sometimes give different values from the field measurements.

One of the most commonly used structures of these types are:

- Rectangular broad crested weir with sharp edged vertical upstream face;
- Rectangular broad crested weir with round edged vertical upstream face; and
- Triangular broad crested(Crump) weir.

Among these, the rectangular broad crested weir with sharp edged vertical upstream face has some advantages such as:

- Constant discharge coefficient in optimum flow condition;
- Less sensitivity to downstream submergence;
- Simple design and construction; and
- Low construction and utility costs.

which recommends its wide use in irrigation canals as well as small farm ditches.

Although the measurement accuracy of the weir may not be high enough but, one could justify its use by some modifications in its physical structure which would result in high discharge efficiency and accuracy.

Many researchers such as Fetely and Stearns (1883), Wood Burn (1932), Tracy (1957), Govinda Rao and Muralindhar (1963), Harrison (1964), Singer (1964), Crabbe (1974), Isaacs (1981) and Hager (1991 & 1994) conducted some broad research works to investigate the flow pattern and governing relationship in the hydraulics of rectangular broad and short crested weirs. Singer (1964) reported that the discharge coefficient of rectangular broad and short crested weirs (C_d) is dependent on weir height (P) as well as the crest length (L).He expressed the (C_d) as a function of h/P and h/(h+P) where h is the flow height over the weir crest. Based on total energy head (He) and crest length (Lw) Govinda Rao and Muralindhar (1963) classified the rectangular weirs to (a) rectangular long crested weirs; (b) rectangular broad crested weirs; (c) rectangular short crested weirs; and (d) rectangular sharp crested weirs. Hager (1991 & 1994) showed that the accuracy of broad crested weirs with sharp edge in vertical upstream face is higher than weirs with round edge in vertical upstream face. Except the work of E. S. Crump (1952) on triangular broad crested (Crump) weirs and study of USBR (1960) on Ogee spillways there is not enough reports to show the influence of upstream slope in rectangular broad crested weir on its behavior and discharge efficiency. The authors hope the present work would open a new era of work

to show the hydraulic properties of weir of this type.

2. THEORETICAL ASSESSMENTS

The theoretical relationships to asses the flow conditions on rectangular broad crested weirs are based on critical depth which is used in determination of discharge-depth relationship .In analyzing the flow conditions over the crest of rectangular broad crested weirs it is common procedure that the researches accept the following assumptions:

- The flow lines are parallel and hydrostatic pressure distribution over the crest prevails;
- The thickness of boundary layer is overlooked in comparison with the flow depth over the weir crest and the velocity distribution would follow a uniform pattern in outer layer.

Based on these resumptions and recall from the Bernoulli equation one could express the following relationship between weir discharge and flow head over the crest :

$$q=C[\sqrt{g}\ H^{3/2}] \qquad (1)$$

Denoting $Cd= C\sqrt{g}$ equation (1) could be written as:

$$q = Cd\ H^{3/2} \qquad (2)$$

Where:

q=flow discharge per unit width of weir(m^2/s),

g=gravitational acceleration (m/s^2),

H=flow depth over the crest measured upstream from the weir (m),

C=weir coefficient having a value of $(2/3)^{3/2}$, an

Cd=discharge coefficient of weir$(m/s^2)^{1/2}$.

The research reports indicate that the results determined by Eq. (2) are somehow different from the field measurements which would be attributed to the assumption made in achieving equation (1). It is apparent that this deviation will affect C in Eq. (1) and consequently Cd values in Eq. (2) which emphasizes the need for determination of the nearest accurate values for discharge

coefficient of the weir. The common practice to determine discharge coefficient in most discharge measuring structures is based on dimensional analysis. Considering the governing flow and geometric parameters one could end up with the following relationship:

$$F(Q, H, g, L, B, P, \sigma, \rho, \mu, \alpha)=0 \qquad (3)$$

Where:
Q =flow discharge,
L =length of crest
B =width of crest
P = height of crest
σ = surface tension of fluid
ρ = mass density of fluid
μ = dynamic viscosity of fluid
α = upstream slope of rectangular broad crested weir.

and the rest of parameters are defined in Eqs.(1) and (2). Regarding the used geometric conditions under the water flow with constant L, B, σ, ρ and μ one could come up within:

$$\Pi(Q, H, g, P, \alpha)=0 \qquad (4)$$

Recourse from Buckingham's Π theorem would result in:

$$(y_c/P)=\varphi[(H/P), \alpha, C_d] \qquad (5)$$

It is quite clear that in Eq. (5) H/P could be replaced by E/P where:
y_c = critical depth of flow=$(q^2/g)^{1/3}$,
E = specific energy of flow, and
Φ = function of.

3. EXPERIMENTAL LAYOUT

The experiments are planned in accordance with Equ.(5)and conducted in a plexy glass flume with a length ,width and height of 8, 0.6 and 0.7 meters respectively. A rectangular broad crested weir of 0.36 meters long, 0.155 meters high and 0.6 meters wide was prepared and secured across the whole width of the flume with 1.2 meters distance from the entrance of water tank. The upstream slope of the weir, ranging from 23 to 90 degrees, was modified by a separate sloping piece which could be replaced in each run. The upstream face of

the weir was water tightened using a water proof glue with special care. The flow was lead to the flume through upstream tank which was fed from the main reservoir. The flow was controlled by an adjustable valve and re-circulated to the main reservoir passing though the flume, over the weir crest, and downstream tank. The flow depth was controlled at downstream of the weir by means of a hinged gate and measured using a pre- calibrated sharp crested V-notch located at the end of downstream tank. The pressure head was measured taking the readings of 25 piezometers along the experimental reach as shown in Fig. 2.
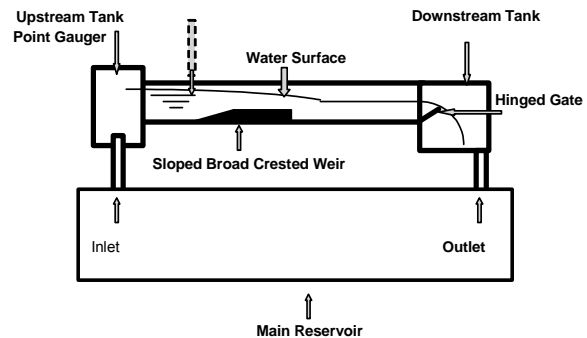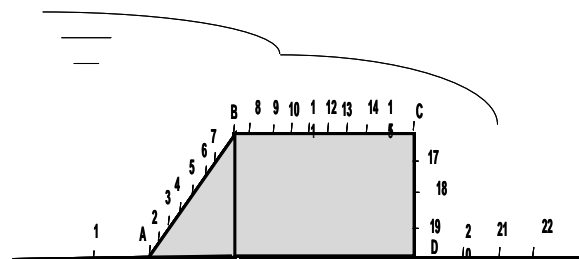

Fig. 1. Experimental layout.

Fig. 2. Position of piezometer taps.

Based on the recommendations made by Isaacs(1981),to avoid any influence caused by surface tension and viscosity of water the depth of flow over the crest kept higher than 5 cm. through whole experiments. To de-aerate the piezometers, the flume was filled with water prior to each run. During each experiment the readings of all piezometers were noted and the water profile was traced using a movable point gauge along the flow reach.

3. EXPERIMENTAL RESULTS ANALYSIS

According to Eq. (5) and experimental plan fifty runs (5 different upstream slopes with 10 varying discharges) were conducted and water depth over the crest level ,flow profile and piezometric heads were recorded to compute the required parameters such as Yc, E and Cd values. Despite the constant height of the weirs the parameter of P and H+P are selected to express the non-dimensional parameters in the study.

The flow profile over the weir with different upstream slopes of weir are depicted and plotted for some similar flow conditions, using the H/P and X/P, which are presented in Fig. (3) to Fig. (7). Assessing these figures show that the flow profile,in all weirs, dives in immediate section downstream the joint of the vertical and sloping faces. The position of such recession seems to be independent from the upstream slope. However, the H/P value slightly tends to increase as the upstream slope decreases. The flow profiles tend to show a smooth trend with decrease in upstream slope which would be a sign of developing flow and less energy loss along the flow. This indication may reflect the energy loss due to separation on the sharp edge of upstream face in vertical weir. The critical flow depth occurs on the weir crest adjacent to downstream edge of the weir with slight movement towards the upstream in sloping weirs.
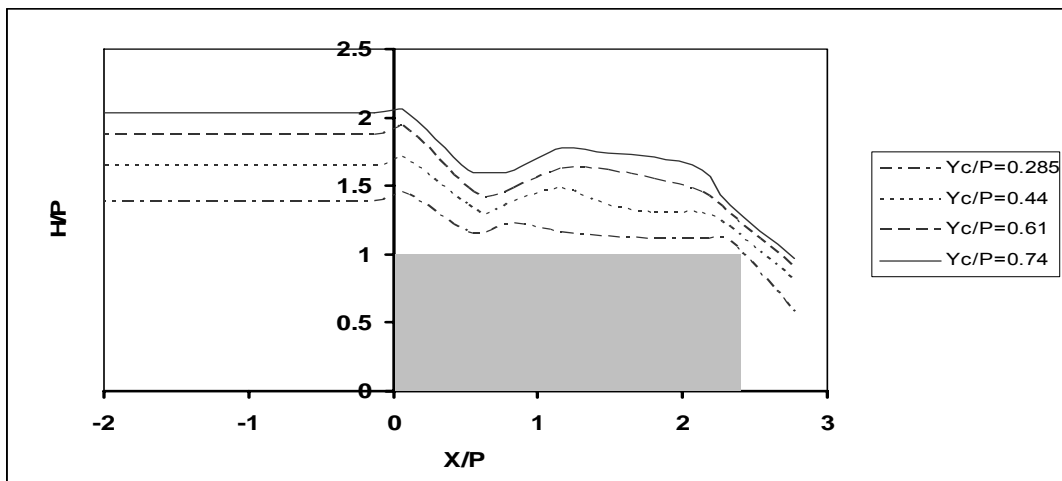

Fig. 3. Flow profile over the rectangular broad crested weir with vertical upstream face.
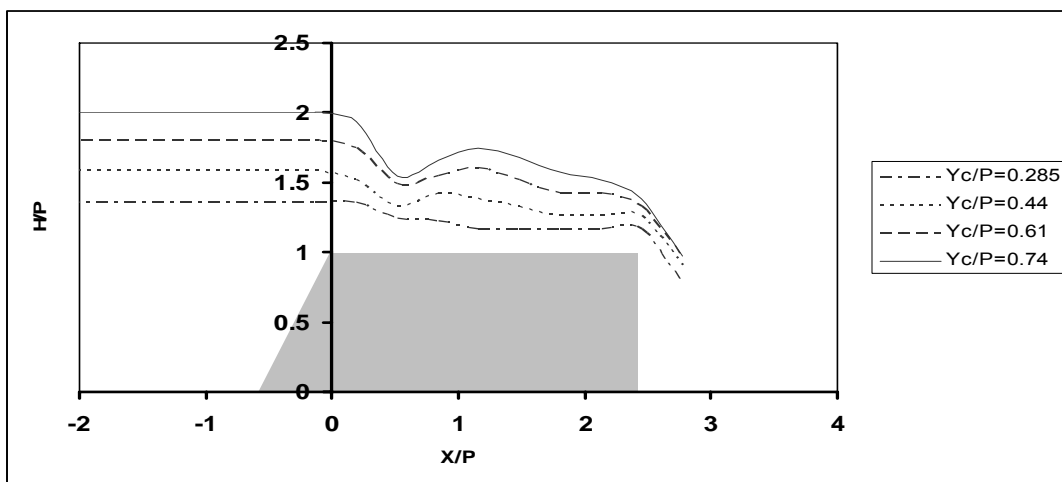

Fig. 4. Flow profile over the rectangular broad crested weir with upstream sloping face of (60) degrees.
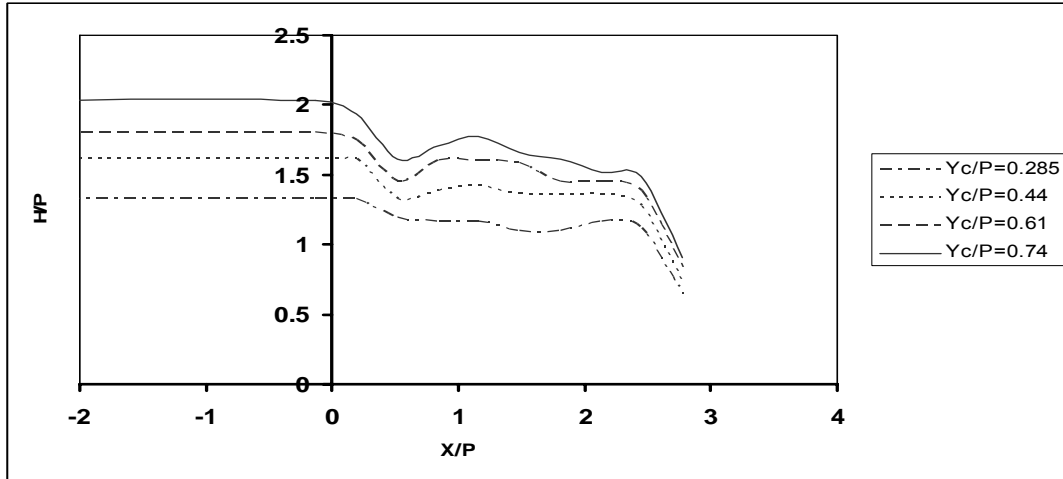
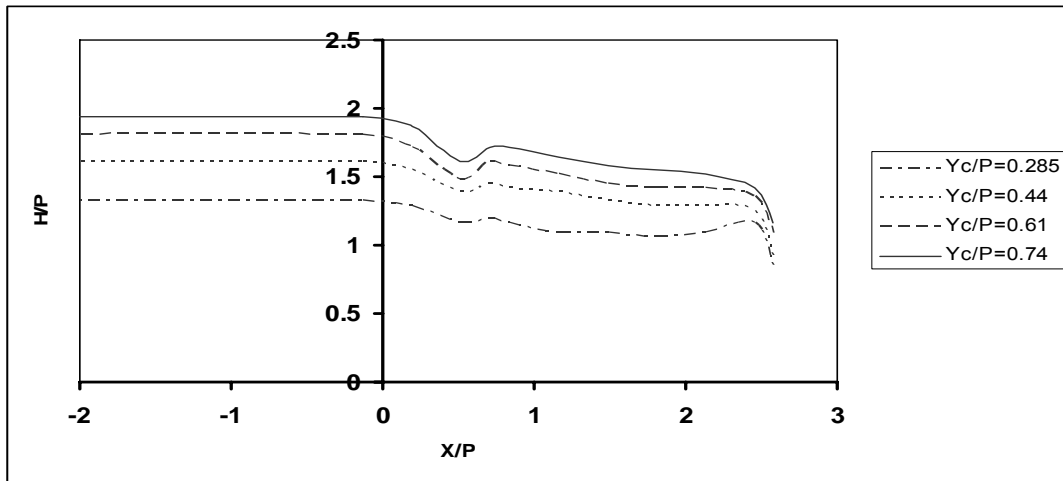**Fig. 5.** Flow profile over the rectangular broad crested weir with upstream sloping face of (45) degrees.

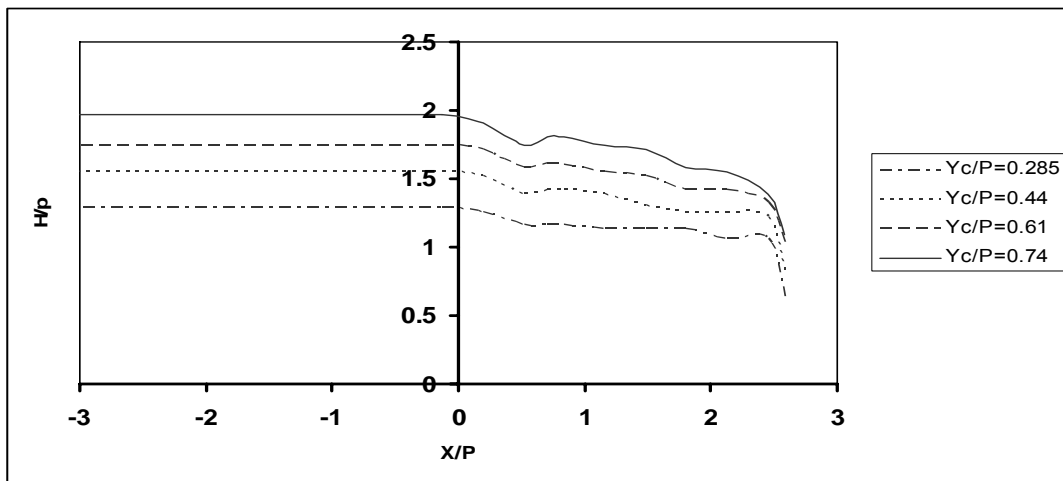**Fig. 6.** Flow profile over the rectangular broad crested weir with upstream sloping face of (30) degrees.

Fig. 7. Flow profile over the rectangular broad crested weir with upstream sloping face of (23) degrees.

The values of $Y_c=(q^2/g)^{1/3}$ and $E=H +(q^2/2gH^2)$ are determined to demonstrate the discharge relationship with effective head on the weir crest. The results are plotted in Fig. (8) to show the variation of Y_c/P with E/P for all experiments along with the

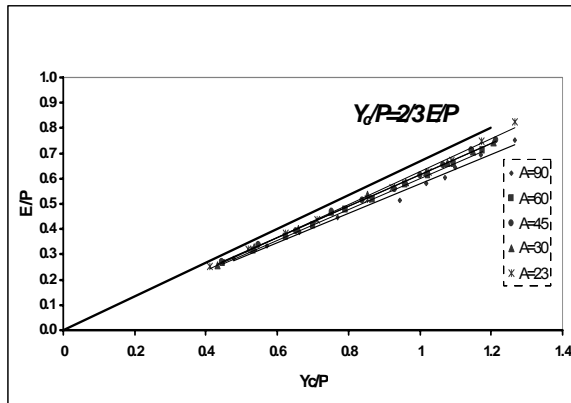critical depth line .In Fig. (8) parameter (A) indicates to the angle of upstream slope of the weirs.

Fig. 8. Variation of discharge over the weirs with incoming specific energy.

Careful study on Fig. (8) shows that as the upstream slope decreases from 90° to 23° the discharge increases with specific energy head. This becomes too apparent as flow rate increases and weir behaves as a short crested rectangular weir. This is the consequence of lower slopes in increasing the specific energy through the increase of approach velocity to the weir crest. This leads to close study of the influence induced by the upstream slope on weir discharge efficiency which is the result of changes in discharge coefficient. Using the collected data the values of discharge coefficient (C_d) in various sloped weirs calculated for some flow rates (i.e. Q=50 l/s & Q=60 l/s) and the $C_{d(\alpha)}/ C_{d(90)}$ for each weir determined. The relative discharge coefficient (discharge efficiency) of the weirs defined and computed from:

$$C_r=[C_{d(\alpha)}/ C_{d(90)}-1]*100 \qquad (6)$$

Where C_r indicates to the increase in discharge efficiency of sloped weirs relative to vertical rectangular broad crested weir. The variation of (C_r) with (Sin α) is plotted and shown in Fig. (9) where α is the angle of the upstream face slope for weirs. Assessing Fig. (9) shows that the variation of (C_r) with (Sin α) follows a descending parabola function with R2=99% as:

$$C_r=K_1(Sin \alpha)^2+K^2(Sin \alpha)+K^3 \qquad (7)$$

where K_1, K_2 and K_3 are non-dimensional coefficients which would be determined by experiments. On the base of Eq. (7) the mean values of (C_r) for whole experiments with five weirs are computed and plotted in Fig. (10). The variation follows the trend of Eq. (7) with R2=98% as:

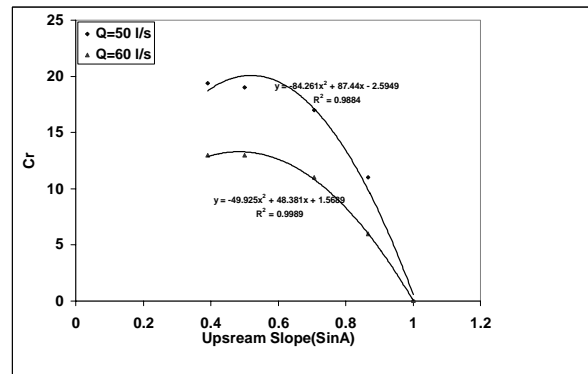$$C_r=(-55.83)(Sin \alpha)^2+(47.131)(Sin \alpha)+8.95 \qquad (8)$$

Fig. 9. Variation of discharge efficiency of broad crested weirs with angle of upstream face slope (for q=50 l/s & q=60 l/s).

Careful investigation in Eq. (8) reveals that the discharge efficiency of sloped weirs relative to vertical rectangular broad crested weir would reach to its maximum value of 19% with α=25° or upstream slope of (1:2.15) which is close to the value recommended to one of the triangular broad crested weirs by Crump (1952).This new finding emphasize on a broad study to determine the appropriate slope of the rectangular broad crested weir to reach the highest discharge efficiency.

To study the scale effects on the flow the parameters H and H+P are selected and the specific energy of the approaching flow relative to chanel bed determined by considering

$H_0=H+Q^2/[2g B^2(H+P)^2]$ and the variation of H_0/P with Y_c/P is plotted in Fig. (11).

The figure shows a linear relation ship between the selected parameters with R^2=99.7 % and could be defined as:

$$(Y_c/P)=K_4(H_0/P)+K_5 \qquad (9)$$

where K_4 and K_5 were found as 0.3888 and 0.117 respectively. From Fig. (11) it becomes apparent that all collected data
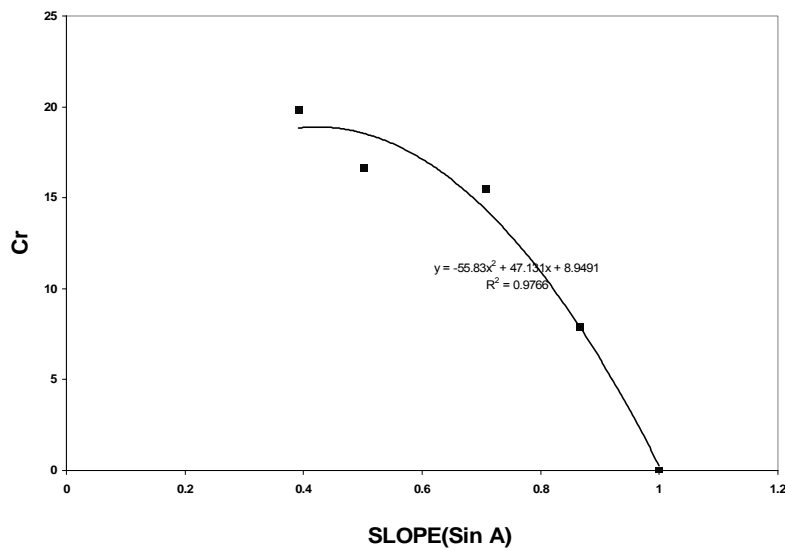
Fig. 10. Variation of mean discharge efficiency of broad crested weirs with angle of upstream face slope.
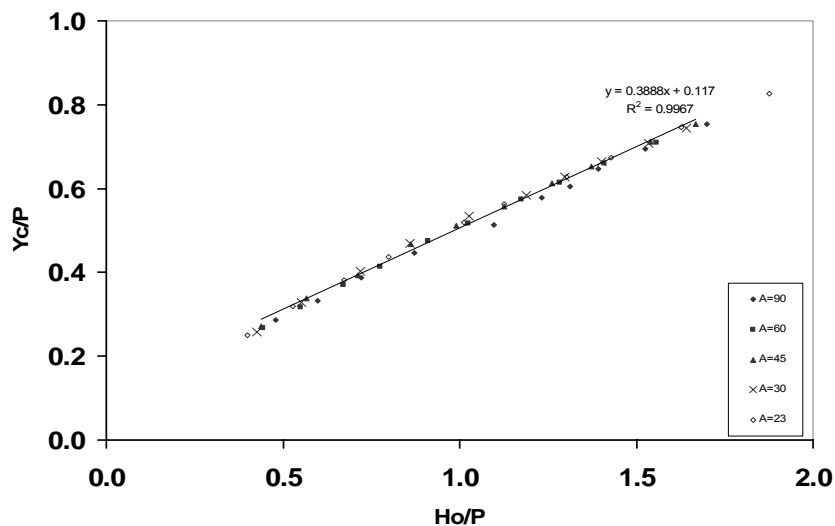

Fig. 11. Variation of discharge over the rectangular broad crested weirs with of the approaching flow specific energy.

would collapse in Eq. (9). In the other words the equation:

$$(Y_c/P)=K_4\{H+Q^2/[2g\ B^2(H+P)^2]\}/P+K_5 \qquad (10)$$

would be an appropriate similarity relationship to define the discharge with geometrical and flow length parameters .It means that selecting Y_c, H and H+P could lead the investigation on the rectangular broad crested weirs to a acceptable similarity between the model and prototype. It is noteworthy to mention that since in this research only one height for weirs is selected, it would be recommended to

proceed with some weir heights to ascertain the reliability of such conclusion.

NOTATIONS

A & α =Angle of upstream face slope (-)
B = Width of weir crest (L)
C = Weir coefficient (-)
C_d = Discharge coefficient ($L^{1/2}T^{-1}$)
$C_{d(\alpha)}$ = Discharge coefficient of sloped weir ($L^{1/2}T^{-1}$)
$C_{d(90)}$ = Discharge coefficient of vertical weir ($L^{1/2}T^{-1}$)

C_r = Discharge efficiency of sloped weirs relative to vertical rectangular broad crested weir (-)

E = Specific energy head (L)

G = Gravitational acceleration (LT^{-2})

H = Flow depth over the weir crest (L)

H_0 = Specific energy head of the approaching flow relative to bed (L)

L = Length of weir crest (L)

K_1, K_2, K_3, K_4 and K_5 = Non-dimensional coefficients (-)

P = Height of weir crest from channel bed (L)

Q = Flow discharge over the weir crest (L^3T^{-1})

Q = Flow discharge over unit width of the weir crest (L^2T^{-1})

Y_c = Critical depth (L)

Φ = Function of -

M = Dynamic viscosity of the flow ($ML^{-1}T^{-1}$)

σ = Surface tension of the flow (ML^{-2})

ρ = Mass density of flow (ML^{-3})

П = Buckingham's theorem (-)

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