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Investigation of Local Scour and energy dissipation of Single Step Broad Crested Weirs by using hollow end sill with different height

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Abstract:

The most important problems for hydraulic structures are the local scour formed at the downstream of these structures. Scour control process considered as the main objective to ensure safety and economical design of hydraulic structures. The current study provides a new method to improve the performance of single step broad-crested weir, use in this study single step broad-crested weir with different hollow end sill. Four models were used named traditional single step broad crested weir (without end sill) (A) and the rest are (B, C and D) provided with different hollow end sill (24, 27 and30) cm respectively, with porosity (30%). Were tested under different discharges (15,20and25 l/s) for duration of 6 hours.

The result showed that, the model [B] of height (24) cm decreased local scour hole volume seven times in comparison with traditional single step broad crested weir and maximum depth of scour reduced five times as compared with traditional single step broad crested weir. The minimum distance of scour from weir was sufficient to prevent failure in the future. In this research, the single step broad crested weir was modified to achieve minimum local sour and the present method reduces costs because do not need to use countermeasures for scour depth by lining with rubbles and riprap to protect from failure.

Keywords— Broad Crested Weir, Scour Reduction, Local Scour, and Energy Dissipation Weir.

Introduction:

The weir is an obstruction constructed across a river or stream in order to increase and control water head at the upstream of the weir or for water flow measurement.

In order to prevent any erosion and scouring at the end of the weirs, the hydraulic energy must be dissipated. Therefore, several types were used such as lining by rubbles and ripraps or by constructing steps with concrete at the end of weirs but this more expensive. Local scour at the downstream of hydraulic structures may lead to damage or failure of this structure [1].

The authors [2] are studied the characteristics of square-edge and round-nosed, rectangular broad crested weir under free flow and submerged flow conditions and they found to be a function of the head of water at the upstream causing flow and the radius, of the upstream top corner.

The authors [3] are investigated experimentally the effect of upstream face slope of trapezoidal broad crested weir on discharge coefficient and water surface profile. They concluded that decreasing the upstream face slope prevent development of separation zone and the discharge coefficient increased up to 10% when the upstream face slope decreased to 21^0.

While others presented a method for predicting both subcritical and supercritical flow characteristics over drops and describe an empirical relation to roughly, calculate the relative energy loss [4].

The single step broad crested weirs are more efficient than traditional weir and the maximum energy dissipation ratio in single step broad crested weirs was approximately (10%) higher than traditional weirs [5].

Empirical formula was developed for estimating scour hole depth in terms of downstream flow conditions, Froude number, height of the weir, and number of openings, area of openings, diameters and heights of the openings [6].

Square edge broad crested weir can be improved and the discharge coefficient is increased by introducing an upstream face slope of 0.5H: 1V and this value of Slope are quite enough to give high values of discharge coefficient [7].

The local scour downstream of grade-control structure are estimated theoretically by the analogy between the local scour operation and jet diffusion in a plunge pool. Analysis of scour depth values showed that the length of jet diffusion can be calculate with reasonable accuracy, while calculates the jet angle with a mean prediction error of about ± 5 [8].

[9] They examined the effect of the approach angle on discharge efficiency of broad crested weir. The results indicated that the discharge coefficient is not only a function of crest length but also the approach angle. They also proposed empirical relation contained approach angle.

The installation of baffle blocks was a significant influence on the scour hole, which is smaller than the case with no baffles, for the baffled floor tests, the slope angles increase but the downstream slopes are steeper than the upstream slopes [10].
The investigation of [11] for single step broad crested weir, showed that the ratio of the length of D/S step to the length of the weir (L2/L1 = 0.5) gives a higher E% in similarity with other weir models. The experimental results of [12] showed that the single step broad crested weir increased the energy dissipation percent up to 46% and was better and gets higher values in comparison with traditional broad crested weirs.
The experimental results of [13] showed that, the model C reduces local scour hole volume was about 87.6%, 55.58% and 44.8% and the maximum depth of scour reduced 73.43%, 32.56% and 24.22% as compared with model D at each discharge.
Scour control process considered as the main objective to ensure safety and economical design of hydraulic structures to prevent any serious failure in the future.

Experimental setup:
The experiments were conducting in channel of 12 m long, 0.8m width and 0.9 m depth as shown in Figure.1.
The test section at the flume bed is 2 m long, 0.8 m wide and 0.21m depth. The model was prepared at a distance 3 m from the channel entrance to eliminate wave of water surface as shown in Figure 1.

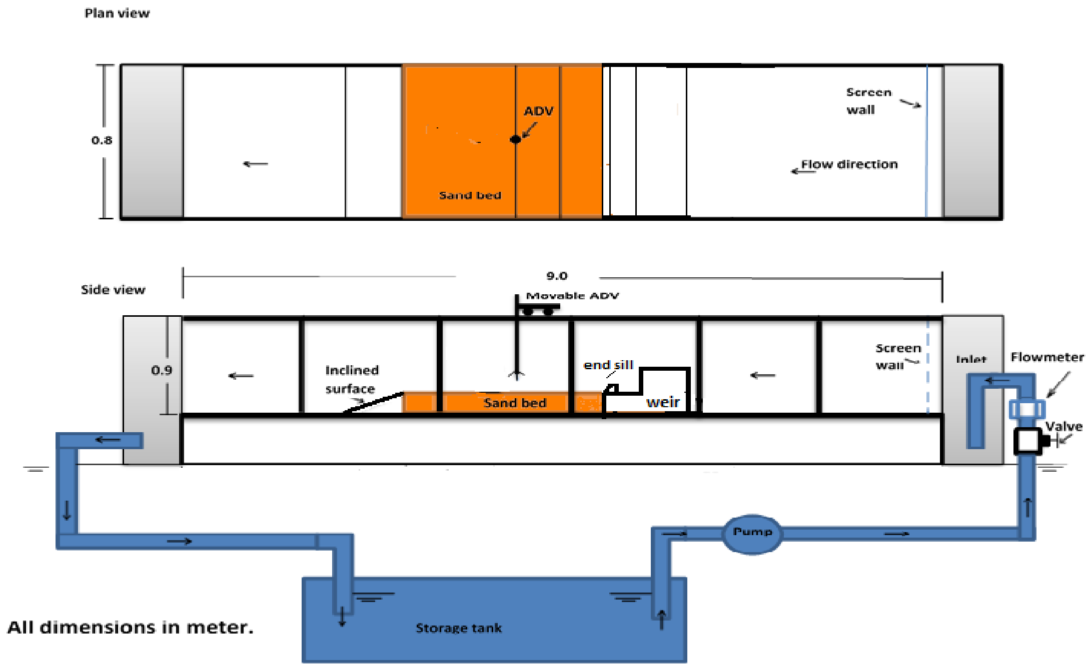

Figure (1): Illustration of the channel.

The test section was filled with sand of median particle size $d_{50} = 1.8$ mm and standard deviation, $\sigma g = 3.65$ with the specific gravity of 2.65, the sieve analysis of the sand is given in Figure (2).

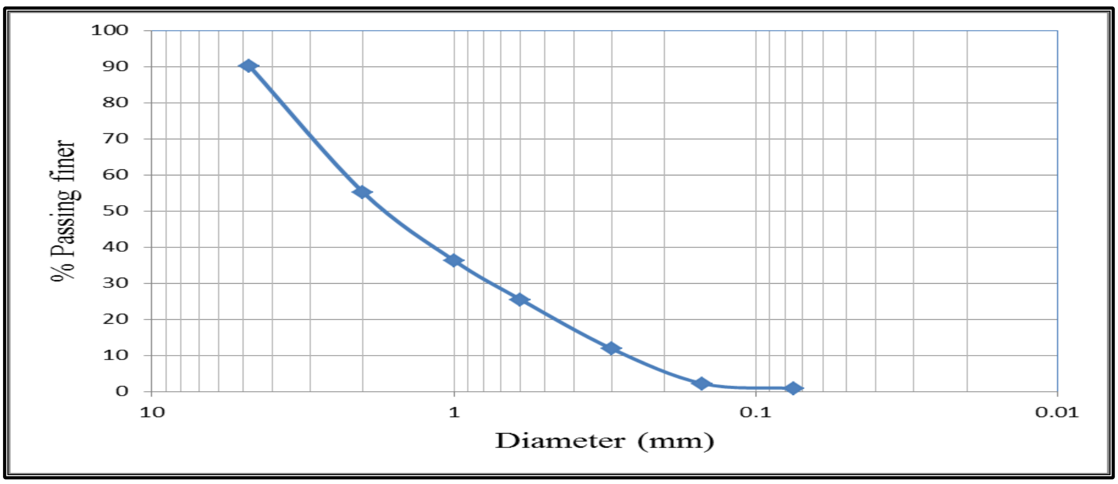

Figure (2): Grain size distribution of bed material.

The discharge was measured by a Magnetic Flow Meter installed in the pipe system at the entrance of channel. The depth of scour hole calculated by laser meter, the instrument put on rails at the top of the channel walls.

The regime of flow downstream traditional single step broad crested weir is supercritical flow and kinetic energy of water is still high and must be dissipated in order to prevent severe scouring of downstream riverbed and failure of downstream structures. The single step broad crested weir with continues hollow trapezoidal end sill and different heights used to disturb water and dissipate large amount of energy through formation of a hydraulic jump**.**

Therefore; four models were made from acrylic of 6mm thickness as shown in plate (3), with crest radius (R=2cm), width of the models (W=80cm) and upstream weir height (P_0=39cm), were used to Investigate Local Scour and energy dissipation downstream Single Step Broad Crested Weirs.

The experimental program of this study was divided in to two groups depending upon the profile of structure used to dissipated energy. Group (No.1); traditional single stepped broad crested weir without end sill type (A), downstream height (p_2=21cm), porosity (p_0=100%) and contain three discharges were used ($Q_{1,2\ \&3}$=15,20 &25)L/sec for 6hours duration .Group (No.2); traditional single stepped broad crested weir with hollow trapezoidal end sill and constant porosity 30%, divided in to three types based on the variation of downstream end sill heights, [(End sill type B were p_1=24cm), (End sill type C were p_1=27cm) and (End sill type D were p_1=30cm) ; also; Group (No.2) contain three discharges and duration the same as in Group (No.1) as shown in Figure (3).

After the bed of the channel is leveling by using laser meter. The discharge increased gradually until the required is obtained. Discharge and the temporal variation of scour were observed. The scour depth was recorded during the experiment. At the end of each run, the pump was stopped and the water was slowly drained, without disturbed scour topography. The test section was then allowed to dry and frozen by pouring glue material (varnish) after that the velocity of flow was calculated by using Acoustic Doppler Velocimetry.

The required porosity of hollow rectangular end sill was obtained by using uniform triangular distribution and circular holes. Depended on the previous study such as [14]. Only one optimum end sill holes with diameter (Φ =1.2cm), optimum porosity (p=40%) and thickness (t=0.6cm) used in previous study.

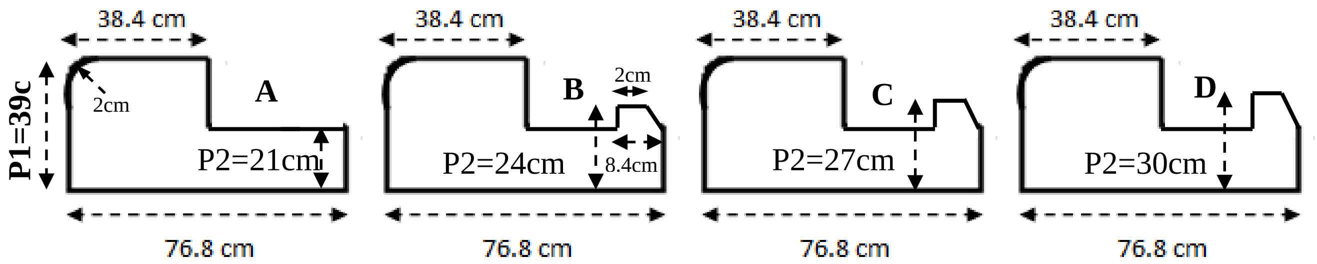

Figure (3): Views of testing models.

In this study different diameter of holes were taken for each models, (1.5) cm at model [B] of height (24) cm , (1.1)cm at model[C] of height (27) cm and (1)cm at model[D] of height (30) cm with the same distance for all models [B,C and D] between holes (1.5) cm and use one row of holes at model [B] and three rows of holes at model [C] and five rows of holes at model[D] ,therefore; same porosity was produced for all models [B, C and D]and it was [30%] because several of researchers refer of porosity about (20%-60%).The above porosity provides generally higher energy dissipation in comparison with other porosity.

<u>Acoustic Doppler Velocimeter Measurements:</u>

The velocity was periodically observed using an Acoustic Doppler Velocimeter (ADV). The velocity was calculated at the center of channel using the ADV. The probe of ADV was put above the scour hole and velocities were recorded every period of 60 seconds. The sample period of 60 seconds was chosen to consider flow changes.

<u>Local Scour Dimensions:</u>

Dimensions of the local scour for each test of experiments were measured and calculated. The total volume scour, maximum local scour (ds) and distance local scour from weir (X) were compared for each of the four models as shown in Table (1).

Table (1) Local scour dimensions for each model.

Model	dr (cm)	Q (l/s)	Volume of scour(VC)(cm^3)	Maximum depth of scour(ds)(cm)	Distance from weir (X) (cm)
A1	0	15	27993	11	40
A2	0	20	42537	12.8	52
A3	0	25	48583	12.4	68
B1	1.5	15	11160	6	16
B2	1.5	20	11347	6.5	18
B3	1.5	25	15686	7.5	26
C1	1.1	15	13772	9	12
C2	1.1	20	16715	10.5	16
C3	1.1	25	22328	11	16
D1	1	15	15311	11.5	10
D2	1	20	22218	13.5	15
D3	1	25	47904	17.3	20

As shown model [B] of height (24) gave the low scour depth and low local scour volume than another model for all discharges because the low height of end sill worked as obstruct led to decrease velocity and the water passed through the holes met with water drop at downstream of the weir led to decrease depth of scour and the minimum distance of scour from weir for each discharge has occurred at model [D] of height (30) cm because the water falling have velocity higher than water, which passed through the holes led to drop water at low distance from the weir.

The Reduction of the Local Scour and total volume for each run of experiments were measured and calculated as shown in Table (2).

Table (2) Reduction volume and depth of scour with respect of single step broad crested weir [A].

Q (l/s)	Model	dr (cm)	Redaction Volume of scour %	Model	dr (cm)	Redaction depth of scour %
15	**B1**	1.5	60.13	**A1**	0	45.45
20	**B2**	1.5	73.32	**A2**	0	49.22
25	**B3**	1.5	67.71	**A3**	0	39.51
15	**C1**	1.1	50.8	**B1**	1.5	47.83
20	**C2**	1.1	60.7	**B2**	1.5	51.85
25	**C3**	1.1	54	**B3**	1.5	56.65
15	**D1**	1	45.3	**C1**	1.1	21.74
20	**D2**	1	47.77	**C2**	1.1	22.22
25	**D3**	1	1.4	**C3**	1.1	36.42

Scour depth was reduced 45.45%, 49.22% and 39.51% for model [B] of height (24) cm. In addition, the model [B] reduces local scour hole volume about 60.13%, 73.32% and 67.71% comparing with single step broad crested weir [A] at each discharge. It is clear that the model [B] minimizes the scour depth because the height of hollow shape above (3) cm increase the velocity of water falling higher than the velocity which pass through the holes led to the water falling at downstream of the weir more effect from water pass through the holes, therefore; increase depth of scour and it is seen that the model [B] minimizes the volume of scour because the water which pass through the holes worked to reduce the effect of water falling on the contrary the step of weir [A] make to reduce depth of scour but effect on more distance led to increase volume of scour. The type of hydraulic jump for each model shown in Table (3).

Table (3) the height of water at upstream, downstream and average velocity for each model.

Model	U/S water depth (cm)	D/S water depth (cm)	Edge water depth (cm)	Velocity (Va) (m/s)	Fr
A1	5.5	10	1.2	1.563	4.554
A2	6.3	13	1.5	1.667	4.345
A3	7.3	14	1.8	1.736	4.131
B1	5.5	4.6	2.8	0.67	1.278
B2	6.3	5	3.9	0.641	1.036
B3	7.3	5.8	4.2	0.744	1.159
C1	5.5	4	2.9	0.647	1.212
C2	6.3	4.8	3.7	0.676	1.122
C3	7.3	5.5	4	0.781	1.247
D1	5.5	3.6	2.9	0.647	1.212
D2	6.3	4.5	3.4	0.735	1.273
D3	7.3	5	3.5	0.893	1.524

Range of Froude number for each model is between 1.03 and 4.55 because the effect of hollow shapes at downstream of the weir on velocity of water led to decrease Froude number. The water surface for each run of experiments were measured and calculated as shown in Figures (7, 8, and 9).

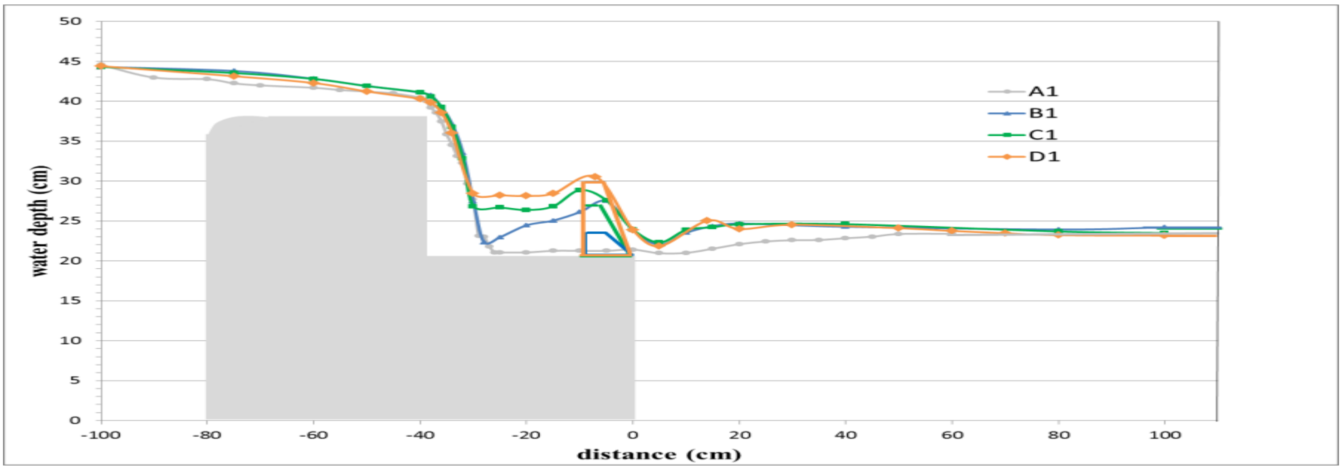

Figure (7): Longitudinal water surface and distances from the weir for each model and discharge (15 l/s)

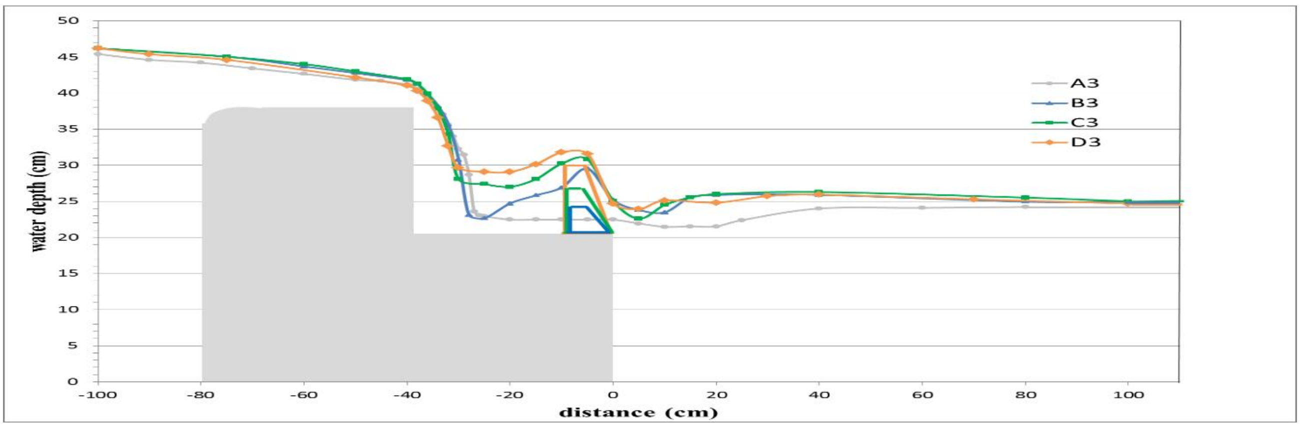

Figure 9 Longitudinal water surface and distances from the weir for each model and discharge (25 l/s)

It is seen from figures above that, the water surface at single step broad crested weir [A] is smooth and effect on more distance at downstream of the weir but the water surface at model [C] of height (27) cm and model [D]of height (30) cm are more turbulent because the effect of height hollow shapes on water falling at downstream of the weir, therefore; the horseshoe vortex is very strong for models, but the effect of horseshoe vortex is reduced at model [B] of height (24) cm due to large energy dissipation and effect the holes on water falling at downstream of the weir where it met with water which pass through the holes lead to decrease velocity of water . The energy dissipation for each model shown in Table (4).

Table (4) Energy dissipation for each model

Model	E_1(cm)	E_3(cm)	E_{1-3}%	FD	Vc (m/s)	Va / Vc	Type scour
A1	45.092	30.179	33.072	53.628	0.319	4.892	Live bed
A2	46.103	30.688	33.434	57.204	0.331	5.028	Live bed
A3	47.234	31.254	33.832	59.587	0.342	5.081	Live bed
B1	45.092	23.947	46.894	22.984	0.368	1.821	Live bed
B2	46.103	24.774	46.263	22	0.389	1.649	Live bed
B3	47.234	25.78	45.422	25.537	0.394	1.891	Live bed
C1	45.092	24.12	46.51	22.191	0.37	1.748	Live bed
C2	46.103	25.183	45.377	23.191	0.385	1.754	Live bed
C3	47.234	26.145	44.647	26.814	0.39	2	Live bed
D1	45.092	24.383	45.927	22.191	0.370	1.748	Live bed
D2	46.103	25.573	44.530	25.237	0.380	1.935	Live bed
D3	47.234	26.691	43.492	30.645	0.382	2.339	Live bed

It is clear from table above that, the type of scour for each run is live bed and high energy dissipation at model [B] of height (24) cm because the velocity for each model higher than critical velocity and model [B] of height (24) cm have optimum height where increase total energy with don't effect on velocity of water at downstream of the weir. The rate of scouring at each run of experiments is also reduced considerably as shown in Figures (10, 11, and 12).

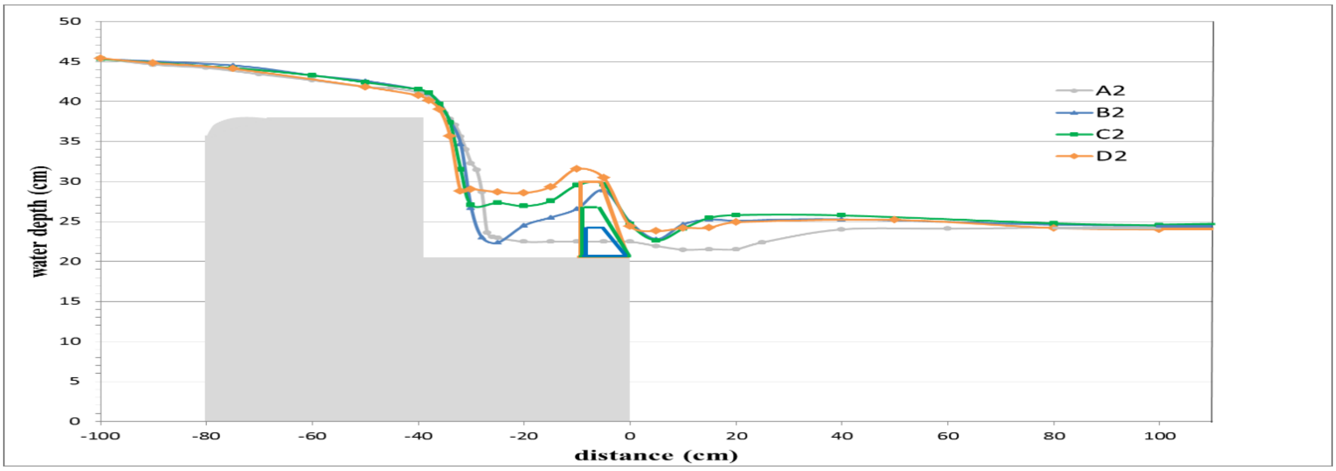

Figure (8): Longitudinal water surface and distances from the weir for each model and discharge (20 l/s)

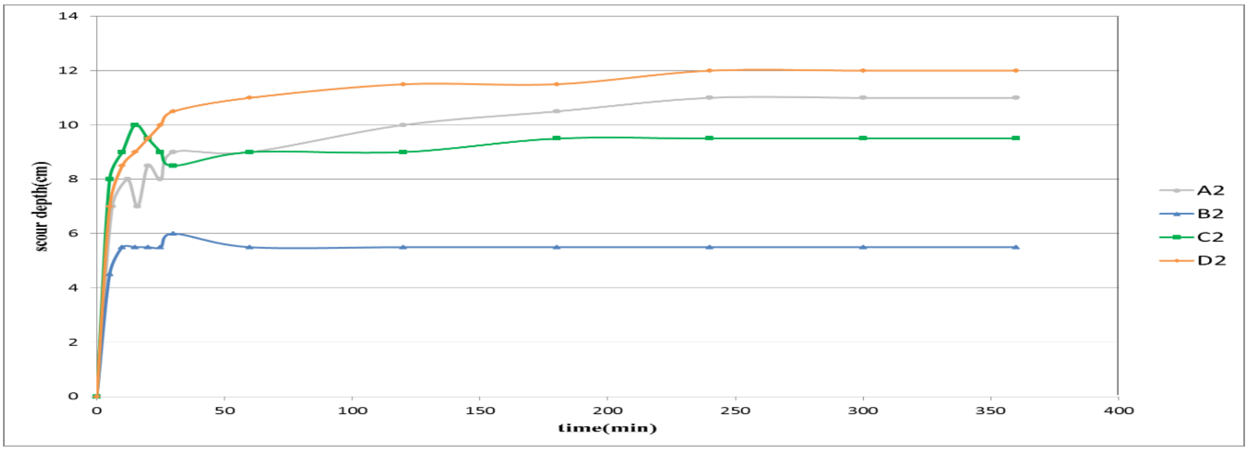

Figure (11): Relation between time and maximum scour depth for each model and discharge (20 l/s)

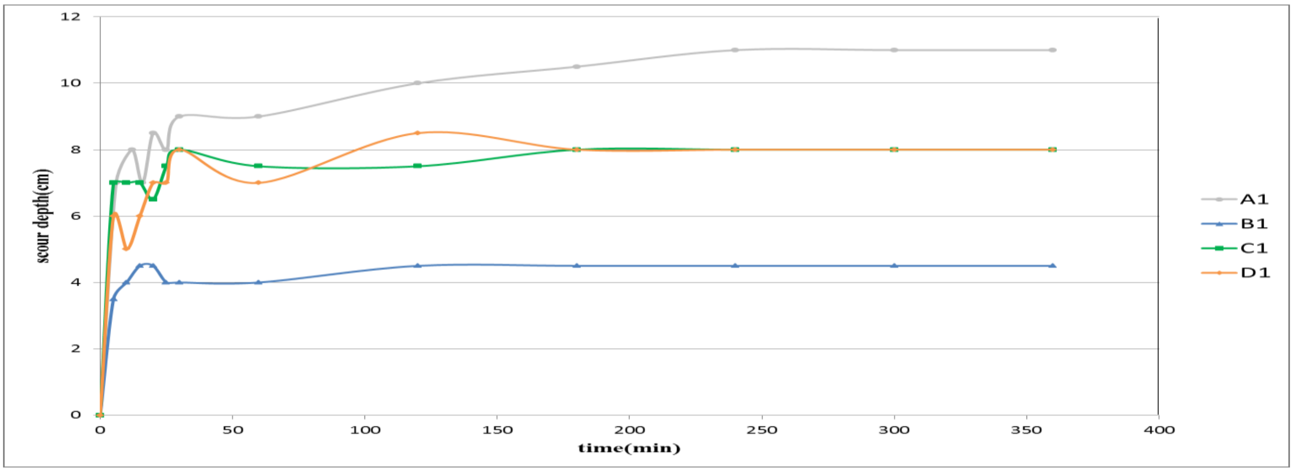

Figure (10):Relation between time and maximum scour depth for each model and discharge (15 l/s)

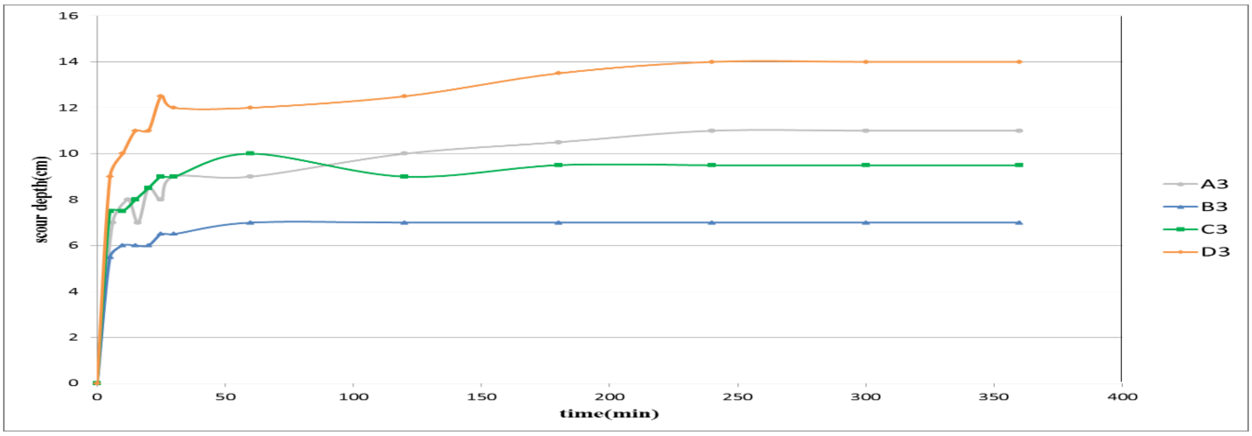

Figure 12 Relation between time and maximum scour depth for each model and discharge (25 l/s)

It is seen from figures above that, all model reach equilibrium case after 250 minute from start the run and model [B]

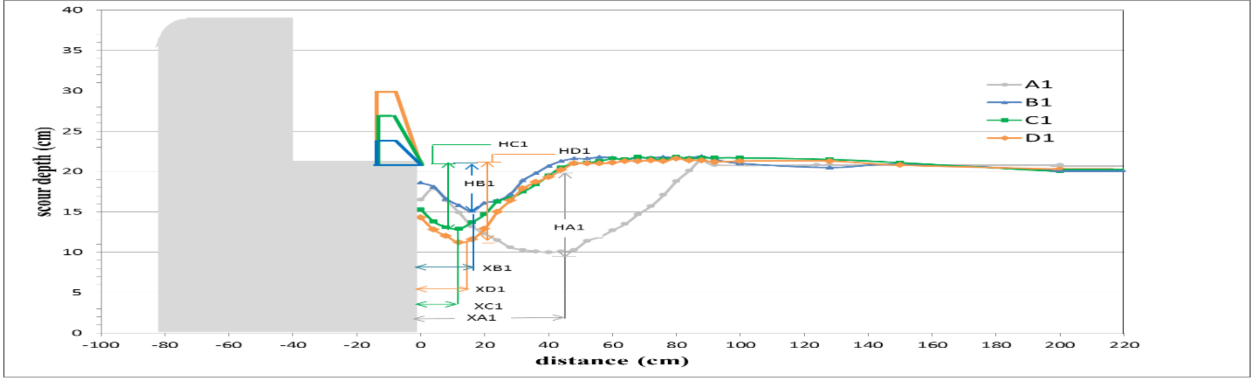

Figure (13):Longitudinal scour holes and distances from the weir for each model and discharge (15 l/s)

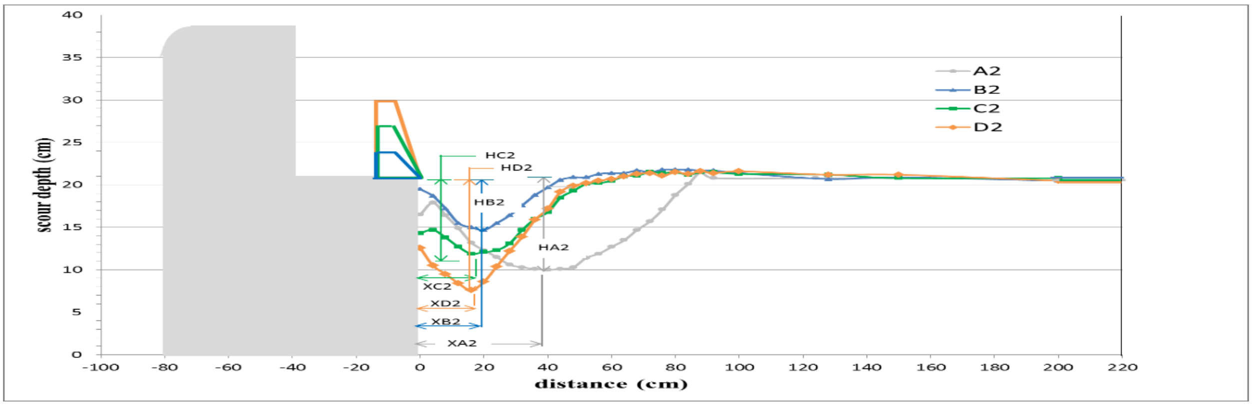

Figure (14): Longitudinal scour holes and distances from the weir for each model and discharge (20 l/s)

of height (24) cm more stable when compare with each model because the holes make to calm the water on the contrary the model [C] of height (27) cm and [D] of height (30) cm where more turbulence at start run. The minimum distance of scour from weir for each discharge and maximum depth of scour as illustrated in Figures (13, 14 and 15).

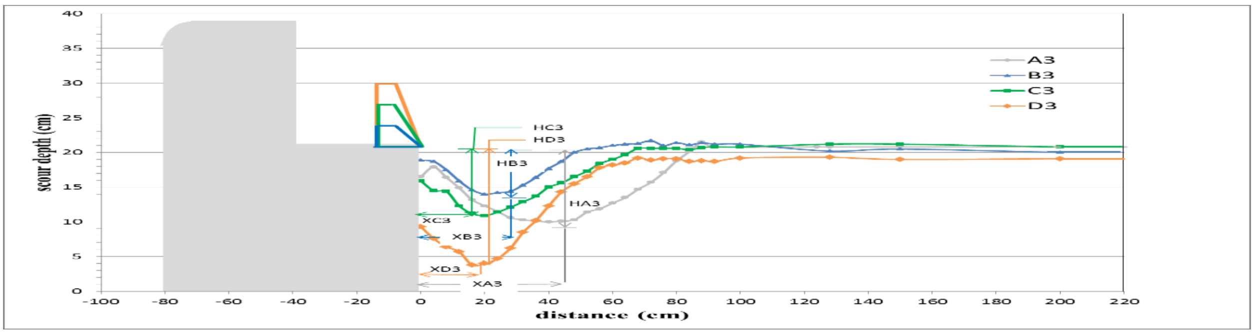

Figure (15): Longitudinal scour holes and distances from the weir for each model and discharge (25 l/s)

It is seen from Figures above that, the total volume of scour at single step broad crested weir [A] is higher than total volume for each model because effect of water falling at downstream of the weir on more distance until reach stable case, but the maximum scour depth was found after the model [D] height (30) cm because the height of hollow shape is enough to increase velocity of water falling and the size of holes decrease the total volume.

The minimum distance of scour from weir for each discharge has occurred at model [D] height (30) cm because the height of hollow shape increases the water falling and the water which pass through the holes is not enough to push water falling away from weir and lead to Exposure for failure in the future. Figures (16) show the scour pattern at each model after each run at Q=25 L/sec. The model [B] of height (24) cm minimizes the scour depth and drops the water away from the weir.

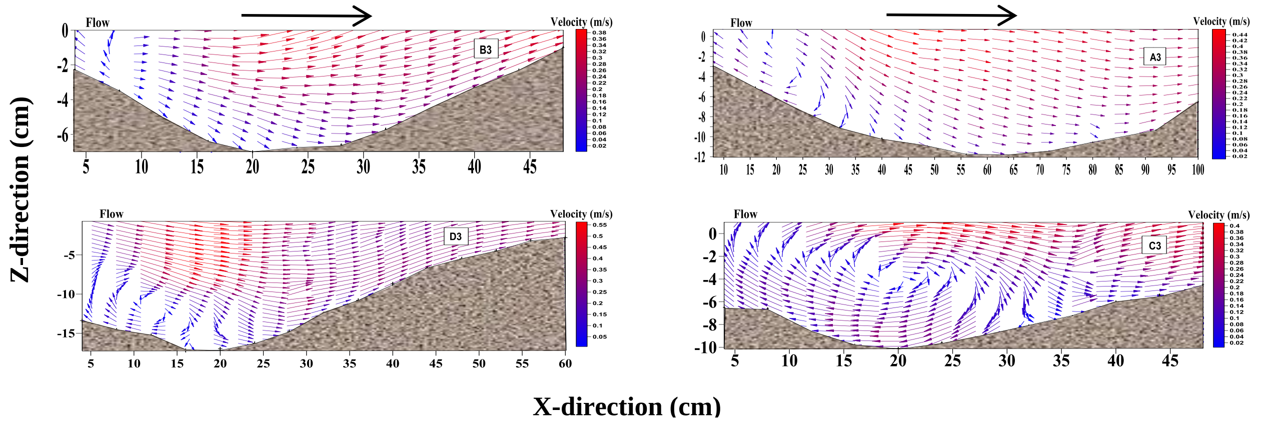

Figure (17): Longitudinal Velocity vectors for center models (A3) (B3) (C3) and (D3) at Q=25 l/sec

It is clear from Figures above that, the model [B] of height (24) cm minimizes the scour depth and the volume of local scour more than another models because the effect of horseshoe vortex is very strong at these models but the effect of horseshoe vortex is reduced for model [B] of height (24) cm due to large energy dissipation and the single step broad crested weir [A] maximize the volume of scour more than another models because the step of shape effect on the water jet at more distance led to more area effect from water jet therefore increase volume of scour, but another models have low effect of step of shape because height of shape is effect more than step of shape. The height of hollow shape at model [C] of height (27) cm and [D] of height (30) cm increase water velocity higher than the velocity, which pass through the holes led to the water falling at downstream of the weir more effect from water pass through the holes therefore increase the depth and volume of scour.

Prediction of Scour Depth:

Based on equation (1), Using step-wise regression (full cubic Method) analysis in **(**IBM SPSS Statistics 20**)** to correlate (d_s/y_1) with (y_3/y_1), (y_2/y_1), (F_r), (F_D), (P_2/P_1) and (d_r/p_1) in an empirical relation for traditional Single Step Broad Crested Weirs and Single Step Broad Crested Weirs with different continuous trapezoidal hollow end sill.

The functional relationship for (d_s/y_1) with the main flow parameters may be expressed in dimensionless form as follows:

$$\frac{d_s}{y_1} = f_1\left\{\frac{y_3}{y_1}, \frac{y_2}{y_1}, \frac{p_2}{p_1}, \frac{d_r}{p_1}, F_D, F_D,\right\} \text{--} (1)$$

Where

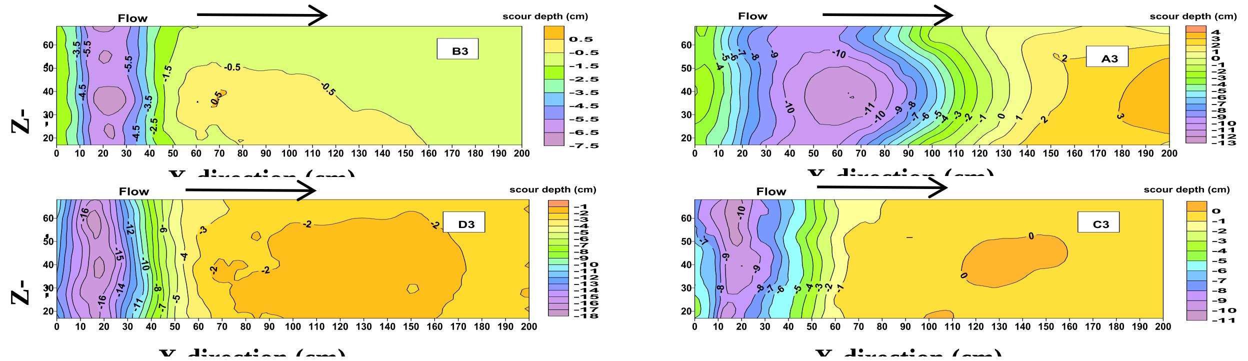

Figure (16): The scour pattern in front of models (A3) (B3) (C3) and (D3) at Q=25l/sec.

F_D = Dens metric Froude number.

$$F_D = \frac{Va}{\sqrt{((ss-1)D50g)}} \quad \text{--} (2)$$

We get equations as below.

$$\frac{d_s}{y_1} = \left\{4.2904 * \left[\frac{p_2}{p_1}\right] * \left[\frac{y_2}{y_1}\right] + 0.7592 * \left[\frac{y_3}{y_1}\right] * F_{r-1.1033}\right\} \text{--------------------------} (3)$$

The correlation coefficient (R^2) for equation (3)is 97%.

A comparison between predicted values by each equation and monitored values experimentally is shown in Figures (18).

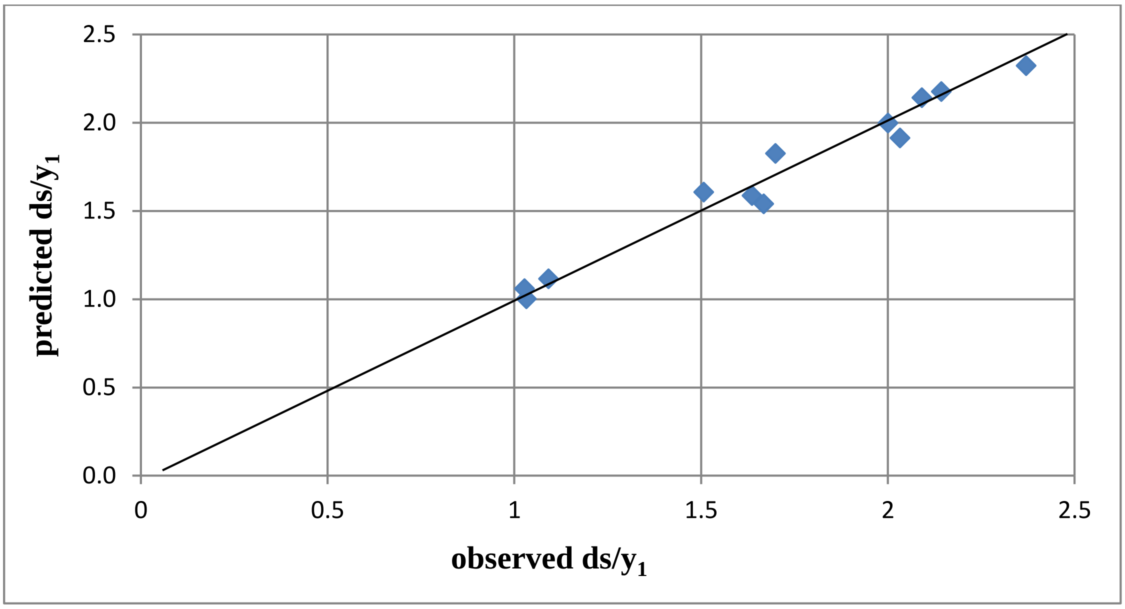

Figure (18): Variation of predicted values of ds/y_1 with observed ds/y_1 for all models.

Figure(18) indicates that all equations represented the measured data very well and it be used safely to predict the relative maximum depth of scour.

Conclusion:

This research is an experimental study examined the application of a new shape of single step broad crested weirs by using end sill with different height and diameter to reduce local scour on downstream of the weir. Changing the height of the shape and diameter at downstream of the weir was achieved minimum local scour than single step broad crested weir which depend it most of irrigation projects. Results showed that the model [B] of height (24) cm reduced the maximum depth of scour 45.45%, 49.22% and 39.51%. In addition, the scour hole volume reduced to 60.13%, 73.32% and 67.71% when compared with single step broad crested weir at each discharge. The present experimental study does not need to countermeasure the scour depth by lining with rubbles and riprap to protect from failure because the distance of scour from weir was significant to prevent that, the new idea only to put end sill at downstream of the weir.

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