Ain Shams Engineering Journal (2013) 4, 675–684

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
www.sciencedirect.com

Effect of semi-circular baffle blocks on local scour downstream clear-overfall weirs

Fahmy Salah Fahmy Abdelhaleem *

Hydraulics Research Institute, National Water Research Centre, Delta Barrage, Egypt

Received 10 June 2012; revised 13 January 2013; accepted 23 March 2013
Available online 28 April 2013

KEYWORDS
Local scour;
Baffle blocks;
Scour equations;
Hydraulic structures;
Hydraulic jump;
Physical model

Abstract Local scour downstream hydraulic structures may result in damage or complete structural failure and loss of life and property. In this paper, an experimental study was conducted to predict the scour geometry downstream a Fayoum type weir and to minimize the scour using a row of semi-circular baffle blocks. The considered shape in this research is easy to be used as an extra element to existing water structures in order to minimize local scour downstream these structures. A hundred 53 runs were carried out considering various heights and positions of baffle blocks with different flow conditions. A case of flat floor without baffles was included in the test program to estimate the influence of using the baffle piers. Results were analyzed and graphically presented, and simple formulae were provided to evaluate the scour parameters.

1. Introduction

Flow over spillways or underneath gates have a tremendous amount of potential energy, which is converted into kinetic energy downstream control structures. This energy should be dissipated to prevent the possibility of excessive scouring of the downstream waterway bed, minimize erosion and undermining of structures, which endanger the structure safety. Local scour downstream of hydraulic structures such as low head and high head structures is an important research field due to its significant practical value. Different techniques to reduce local scour have been employed in previous studies by making use of splitter plates or collars. In the same context, baffle blocks installed on stilling basins have been also utilized to stabilize the formation of the jump and increase the turbulence, thereby assisting in the dissipation of energy. For low flow, baffle blocks help to compensate for a slight deficiency of tail water, and for high flow, they help to deflect the flow away from the river bed.

The employment of baffles may be helpful in reducing the tail water depth required and also in shortening the basin length. Baffle blocks should be used in the stilling basin even if they are not required to form a stable hydraulic jump, Edward [1]. Under initial operating conditions, however, the gates were opened much faster than the tail water could be build up, so that there was a deficiency of tail water for hours. Baffle blocks prevented excessive erosion of the exit area during this period. Also, they help to ensure good hydraulic jump action for unbalanced spillway gate operation or submerged conditions occurring at discharges greater than those for which the stilling basin was designed. There are many types and

* Tel.: +20 10 655 40 781.
E-mail address: fahmyhri@gmail.com.
Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

2090-4479 © 2013 Ain Shams University. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.asej.2013.03.003

Nomenclature

B	channel width (L)
b	basin width (L)
D_o	outer baffle's diameter (L)
D	inner baffle's diameter (L)
D_s	maximum Scour Depth (L)
D_{sw}	maximum scour depth without baffles (L)
D_{90}	sediment size (90% finer) (L)
D_{50}	sediment size (50% finer) (L)
D_{10}	sediment size (10% finer) (L)
F_{r1}	initial Froude Number (-)
g	gravitational acceleration (LT^{-2})
L_f	floor length (L)
L_s	maximum scour length (L)
L_{sw}	maximum scour length in case of no baffles (L)
L_b	distance between baffles line and the toe of the weir (L)
H_b	baffle's height (L)
Q	discharge (L^3T^{-1})
R_e	Reynolds number (-)
S	clear distance between baffles in the normal direction of flow (L)
S_o	bed slope of the channel (-)
t	thickness of baffle (L)
T	time at maximum scouring (T)
V_1	velocity of the supercritical flow of depth y_1 (LT^{-1})
Y	tail water depth (L)
y_1	initial water depth of a hydraulic jump (L)
y_2	sequent water depth of a hydraulic jump (L)
ρ	density of the fluid (ML^{-3})
ρ_s	density of bed material (ML^{-3})
u	dynamic viscosity of the water ($ML^{-1}\,T^{-1}$)

Acronyms

GIS	geographical information system
HRI	hydraulic research institute

shapes of baffles that have been used and served their intended purpose. Because of the many variables, no one solution may be applicable for all conditions. The various types of baffles employed in existing structures such as (Bonneville Dam; Pit River No.3 Dam; Gatun Dam; Texarkana Dam; Mississipi River Dam No.6; Khanki Weir, India; and Stevenson Dam) were illustrated in Edward [1].

As with various types of baffles, there are many arrangements that can be made with the floor blocks. It should be noted that sufficient water will not pass between the blocks if they occupy too much of the floor width. When the blocks occupy too much of the floor space, they tend to act like a sill more than individual blocks. Experimental work carried out by Blaisdell [2] indicated that, the floor blocks should occupy between 40% and 55% of the floor width and the most favorable conditions result when the baffles are placed perpendicular to the incoming flow. In addition to the features previously mentioned, the baffle piers should be easy to construct, maintain and if possible should be non-clogging and self-cleaning.

There are many formulae for scour following hydraulic jump in a stilling basin such as developed by Schoklitsch [3], Eggenberger [4], Shalash [5], Novak [6], Catakli et al. [7], Uymaz [8], Pillai et al. [9], Rice and Kadavy [10], Baghdadi [11], Hoffmans [12], El Abd [13], Bijan Dargahi [14], Aytac and Gunal [15], and Oliveto and Victor [16].

Many different baffle block shapes have been studied by Peterka [17], El-Masry and Sarhan [18], and El-Masry [19]. Vischer and Hager [20] discussed the baffle block parameters and summarized the following recommendations:

- The optimum block front face is perpendicular to the approach flow,
- One row of blocks is used because the effect of the second row is small relative to the first one, and
- Baffle blocks should not be used for approach velocity above 20 m/s.

Throughout the present paper with respect to the recommendations of Vischer and Hager [20] and Edward [1], the suggested baffle of a semi-circular shape is assumed to be perpendicular to the flow. The proposed element is easy to be used as a pre-cast unit to provide the floor of the existing structures in order to minimize the deformed scour parameters.

2. Dimensional analysis

The local scour downstream of a Fayoum type weir with a horizontal floor depends on a large number of flow and sediment variables as follows.

$$D_s = f(B, b, D_o, D_{50}, D_s, D_{sw}, g, H_b, L_b, L_f, L_s, L_{sw}, S, S_o, t, T, V_1, Y, y_1, \rho, \rho_s, u) \quad (1)$$

in which B = channel width, b = basin width, D_o = outer diameter of baffle, D_{50} = mean size of bed material, D_s = maximum scour depth, D_{sw} = maximum scour depth without baffles, g = gravitational acceleration, H_b = baffle's height, L_b = distance between baffles row and the toe of the weir, L_f = floor length, L_s = maximum scour length, L_{sw} = maximum scour length in case of no baffles, S = clear distance between baffles in the normal direction of the flow, S_o = bed slope of the channel, t = thickness of baffle, T = time at maximum scouring, V_1 = velocity of the supercritical flow of depth y_1, Y = tail water depth, y_1 = initial water depth of a hydraulic jump, ρ = density of the water, ρ_s = density of bed material, and μ = dynamic viscosity of water.

Since D_{50}, ρ, D_o, B, b, S, S_o, L_f, t and ρ_s were kept constant throughout the experimental program, they will be removed from Eq. (1). Also, the effect of viscosity is assumed of secondary importance in estimating the scour parameters as the flow is mainly gravitational, and therefore, the effect of Reynolds number, R_e, can be neglected. The time of balance for the scour depth and length was found to be 6 h for all runs; then, these variables can be grouped into the following non-dimensional parameters by use of dimensional analysis:

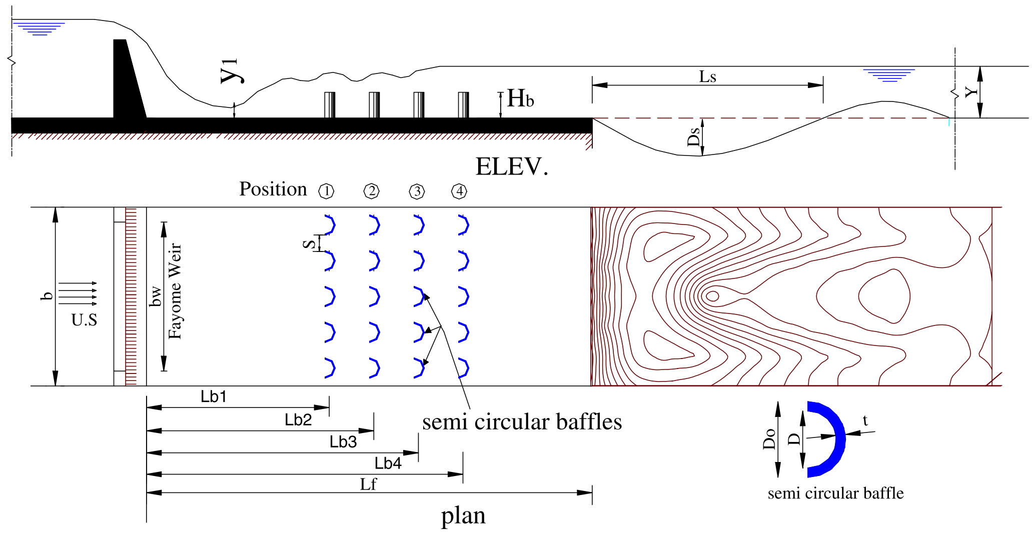

Figure 1 Layout of the single line of semi-circular baffles and their parameters.

$$\left(F_{r1}, \frac{Y}{y_1}, \frac{D_s}{y_1}, \frac{L_s}{y_1}, \frac{H_b}{y_1}, \frac{L_b}{y_1}\right) \quad (2)$$

where F_{r1} is the initial Froude number.

Referring to the model, the dimensions describing the baffles that are made of plastic material are the following:

- Semi-circular baffle outer diameter, $D_o = 0.10b$, is kept constant.
- Baffle thickness, t, is not changed and is taken as $t = 0.10D_o$.
- Spacing between baffle, S, is chosen to be $S = 0.8334D_o$, and
- Baffle height, H_b, is considered to be a variable to estimate the most suitable height (H_b = 0.334, 0.667, 1.0 and $1.33D_o$), Fig. 1.

To investigate the influence of baffle location on the scour downstream the solid floor, their position is varied as (L_b = 0.4, 0.5, 0.6, and $0.8L_f$). Adopted baffle is therefore of invariable shape but of variable height and position. It has a 50% open passageway across its vertical front, which places it midway between the well-known cases of 100% passageway for no baffles and 0% passageway for sill condition.

3. Experiments

Fig. 2 shows the apparatus used in the present study. The experiments were conducted in a 20-m-long, 0.60-m-wide, and 0.60-m-deep flume. The flume consists of head and tail tanks, main and by-pass channels. A centrifugal pump is used to supply water to the head tank from the ground sump. Water is controlled using a control valve installed on the pipe connected to the feeding pump. The head tank has a gravel box, which is used to provide an even flow distribution across the flume.

The main channel contains a Fayoum type weir model with 0.20-m-height, which is made of plastic material, the weir was calibrated using ultrasonic flow-meter. Water head over the calibrated weir is measured with a precise vertical scale. The downstream bay of 1.5 m is made of steel. This bay represents the solid floor and also prepared for the baffles fixation. The rear reach of the channel is filled with a 0.30-m-deep layer of a sand with D_{50} = 0.688 mm, D_{10} = 0.253 mm, D_{90} = 1.114 mm and uniformity coefficient = 3.468, in order to represent the movable bed. A precise point gauge is installed to measure the bed level and the water depth. The gauge is mounted on carriage moving in the flow and the perpendicular directions. Downstream water depth is controlled using a tail gate in order to form jumps over the rigid bed, and then, the water flowed to the by-pass channel. The length of floor and baffles is kept constant for all runs. Baffle positions are changed from one position to other to reach the most suitable location.

Three discharges are considered Q = 20, 25, and 32 L/s. Semi-circular baffles are arranged in four positions (L_b/L_f = 0.4, 0.5, 0.6, and 0.8). For each position, the baffle height is changed four times (H_b/D_o = 0.334, 0.667, 1.0, and 1.33) to reach the best height that leads to minimize the scour parameters. A hundred 53 runs were conducted including 9 runs without baffles. These nine flat floor runs were considered as a reference case. The experimental work was conducted under supercritical flow condition with initial Froude number, F_{r1} ranged from 2.58 to 5.07. Table 1 shows the considered flow conditions. It can be seen that a good agreement between calculated theoretical values of sequent depth and measured ones for classical jumps. Any discrepancy may be attributed to the turbulent water surface downstream the hydraulic jump.

For each run, the backwater feeding is started first until its depth reaches higher than the expected downstream water depth, and then, the upstream feeding is pumped. To adjust the tail water depth so that the jumps were formed on the protective basin, the tail gate is screwed gradually and head over weir is also adjusted until the required upstream depth, y_1 is adjusted. For each run, when the required initial water depth, y_1 is adjusted and after reaching the equilibrium conditions, the movable bed was re-leveled horizontally with the solid bed and then the running time of the test was started. Each test was run for 6 h, which were sufficient for most of the tests to reach a quasi equilibrium state of scour. The measurements consisted of water surface and flow visualization were computerized. To visualize the flow field, a Potassium permanganate

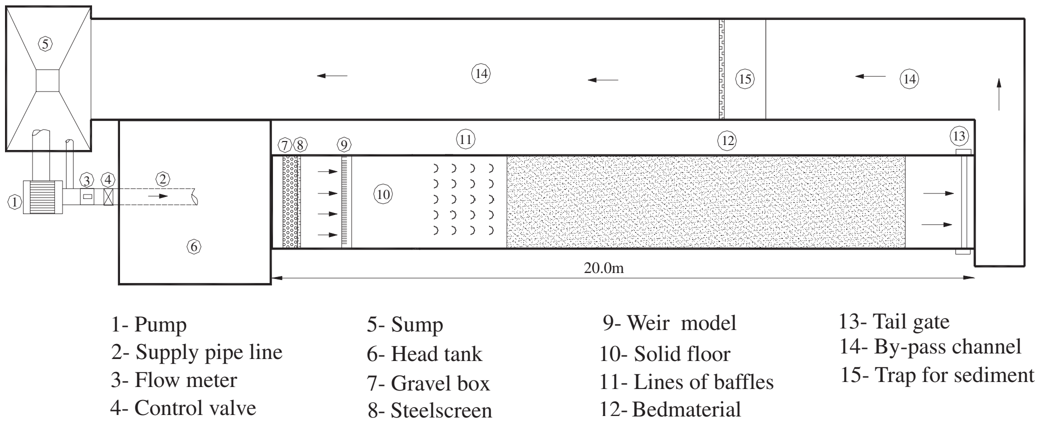

Figure 2 Flume Layout.

Table 1 Experimental flow conditions in case of smooth floor (reference case).

Discharge Q (L/s)	Initial water depth y_1 (cm)	Initial Froude number F_{r1} (–)	Type of Jump	Computed sequent depth $Y_{th} = y_2$ (cm)	Measured sequent depth Y_{meas} (cm)	Error (%) %
20	2.14	3.40	Oscillating	9.28	10.0	−7.81
	1.64	5.07	Steady	10.96	10.5	+4.27
	1.75	4.60	Steady	9.74	11.0	−4.36
25	2.88	2.72	Oscillating	11.21	10.0	−2.68
	2.33	3.74	Oscillating	12.20	11.5	−2.55
	2.04	4.57	Steady	11.20	12.5	−2.46
32	3.52	2.58	Oscillating	11.20	11.5	−2.77
	3.04	3.21	Oscillating	12.37	12.5	+1.05
	2.70	3.84	Oscillating	13.37	13.5	−1.00

solution was injected to the flow. A digital camera was used to record the visualizations in XY (horizontal) plane and XZ (vertical) plane. The video records were analyzed by images process system developed by GIS unit of HRI. After the running time, the run was stopped and the flume was drained, to estimate the maximum scour depth and length, a finer grid of 1.0 cm × 1.0 cm was used to monitor the bed topography using a precise point gauge.

4. Results and discussions

The effect of time on the scour depth is given in Fig. 3. It is noticed that the required time for settling the operation of scour was 6 h.

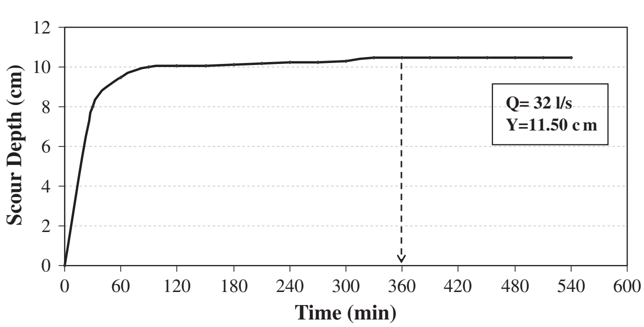

Figure 3 Relationship between scour depth and time in case of no baffles.

Based on the analysis of images during the experimental work, flow across the baffle row may be divided into three types of flow as shown in Fig. 4.

(1) Overtopping flow which flows over the baffles.
(2) Diverted flow which passes between the baffles.
(3) Curved eddy current, which forms vortices in front of the baffles.

The main flow feature was the rapid development of a hydraulic jump from the initial super-critical condition. The

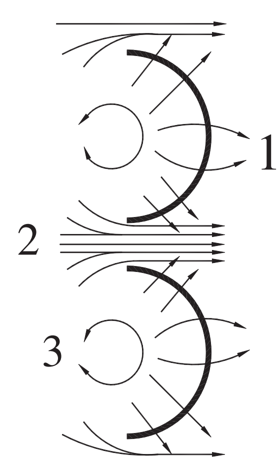

Figure 4 Observed types of flow across semi-circular baffles.

jump induces large secondary flows and clockwise vortices. The secondary flow system develops several scour holes. In the opinion of the author, the numbers of holes depended upon the used bed material and the considered discharge. The main transport agents are the hydraulic jump and the induced secondary flows. It should be mentioned that slightly higher scour depths were recorded at the center line of the channel compared to the channel sides. The bed profiles were

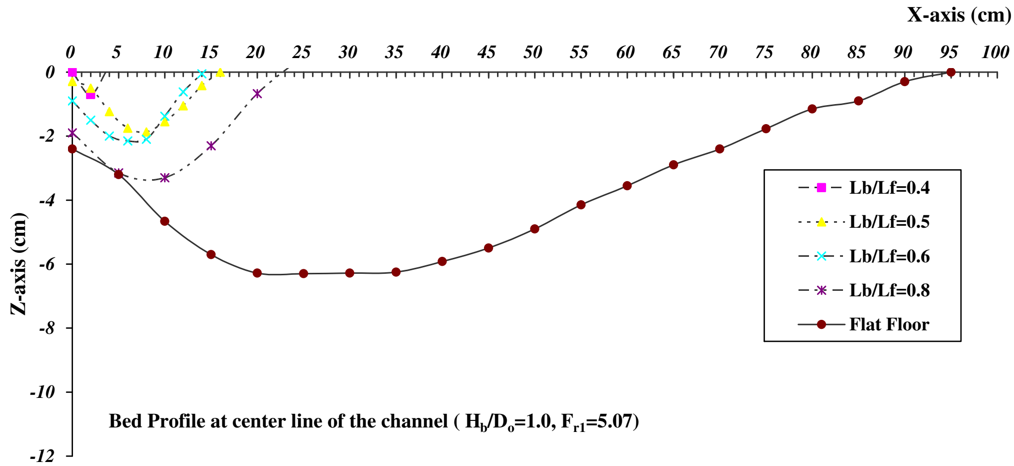

Figure 5 Bed profile at Y-axis = 0.30 m (H_b/D_o = 1.0, F_{r1} = 5.07).

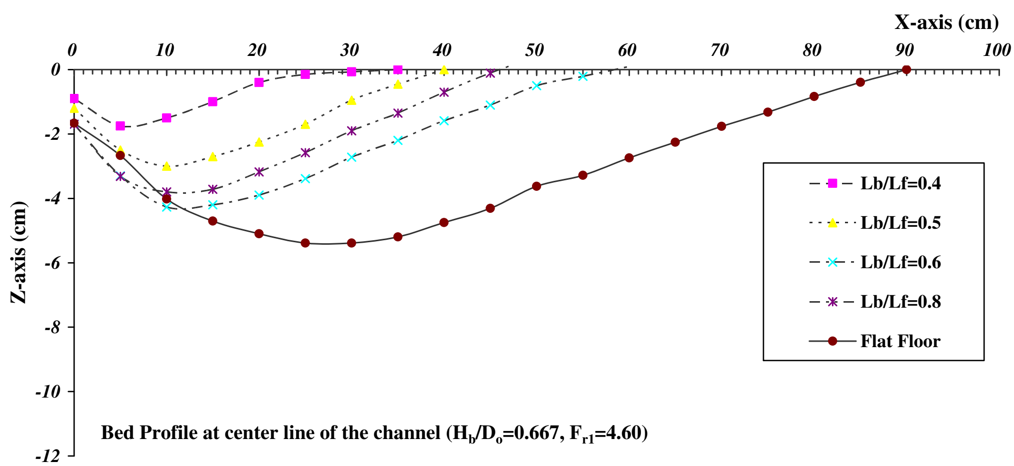

Figure 6 Bed profile at Y-axis = 0.30 m (H_b/D_o = 0.667, F_{r1} = 4.60).

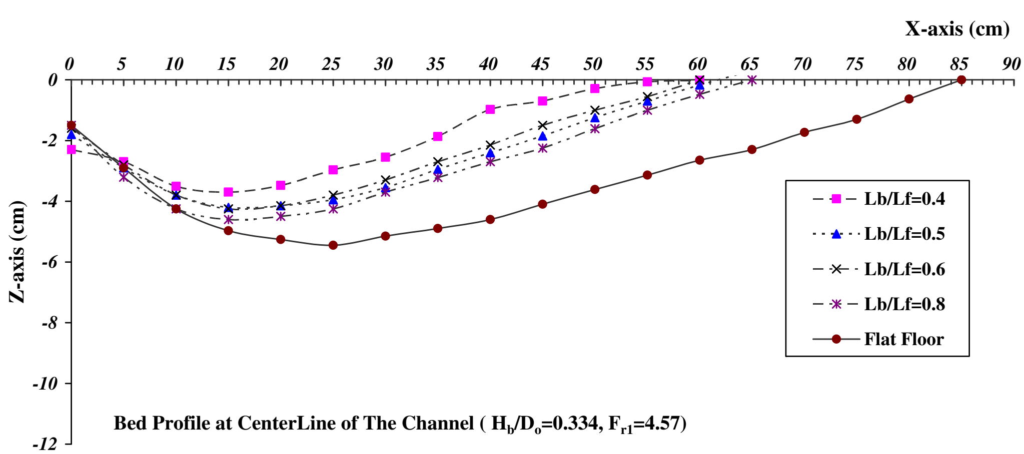

Figure 7 Bed profile at Y-axis = 0.30 m (H_b/D_o = 0.334, F_{r1} = 4.57).

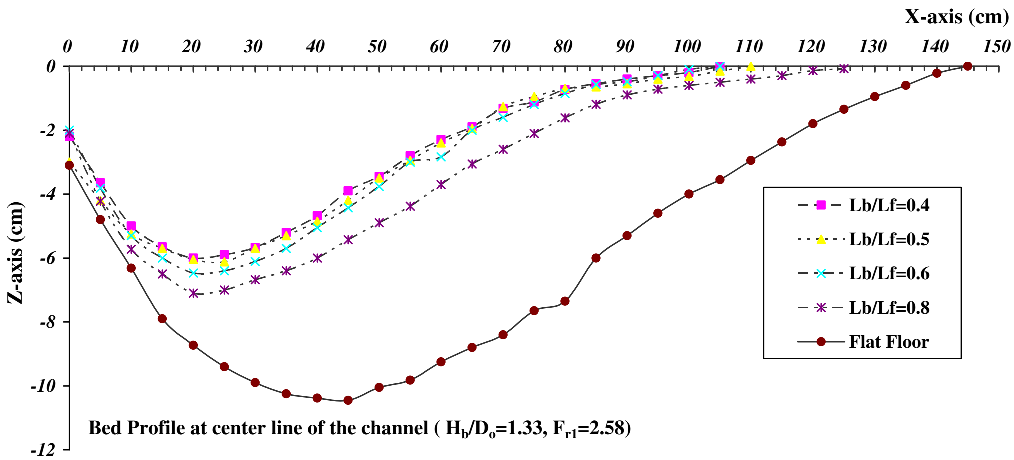

Figure 8 Bed profile at Y-axis = 0.30 m (H_b/D_o = 1.33, F_{r1} = 2.58).

characterized by upstream and downstream slopes. The upstream angles ranged from 12.86° to 61.38° while downstream angles ranged from 4.54° to 9.29°. The values of upstream and downstream slope angles decreased as the initial Froude number increased, although the upstream slope was steeper than the downstream slope, this result agrees with the positions of the secondary flow field in the upper region of the scour cavity, where secondary flow could maintain a steeper scour profile. The installation of the baffle blocks had a significant influence on the scour hole which is smaller than the case with no baffles. For the baffled floor tests, the slope angles increased but the downstream slopes were steeper than the upstream slopes. Figs. 5–8 show sample of scour profiles at the center line of the flume.

4.1. Effect of semi-circular baffle blocks on scour depth

Results were grouped into dimensionless terms and the relationships were drawn to study the effect of these parameters on the scouring dimensions, D_s and L_s.

From Figs. 9–12 illustrate the relation between D_s/D_{sw} and F_{r1} with respect to the considered values of baffle position, L_b/L_f = 0.4, 0.5, 0.6 and 0.8, respectively. For each location, baffle heights are changed as H_b = 0.334, 0.667, 1.0 and 1.33D_o.

For the considered flow conditions, using semi-circular baffle blocks reduce the depth of the scour hole compared to the depth in case of flat floor without baffles, $D_s/D_{sw} < 1$. For all

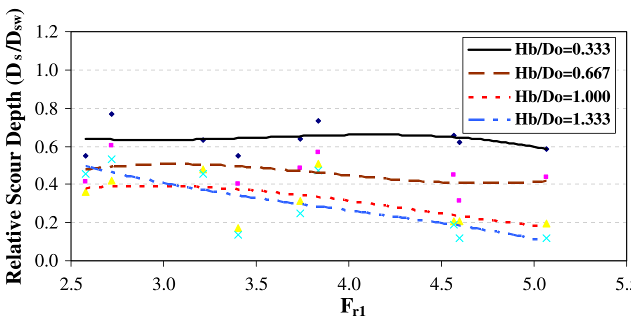

Figure 9 Relation between relative scour depth D_s/D_{sw} and F_{r1} (L_b = 0.4L_f).

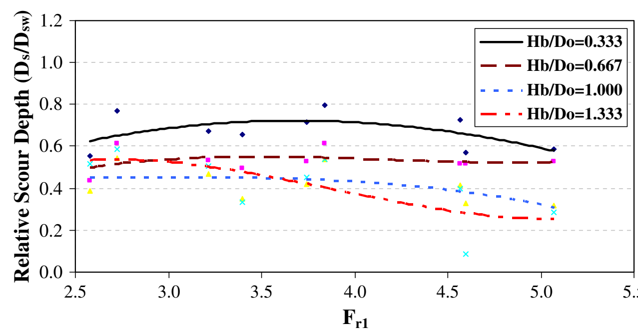

Figure 10 Relation between relative scour depth D_s/D_{sw} and F_{r1} (L_b = 0.5L_f).

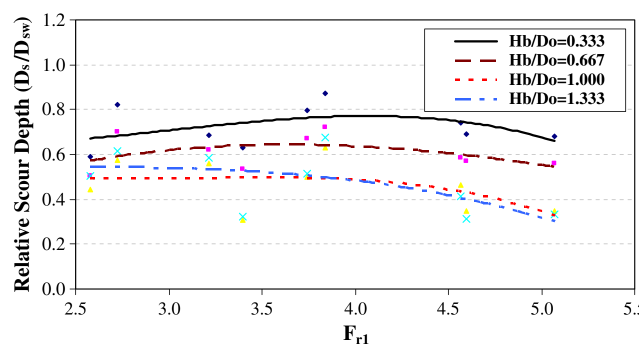

Figure 11 Relation between relative scour depth D_s/D_{sw} and F_{r1} (L_b = 0.6L_f).

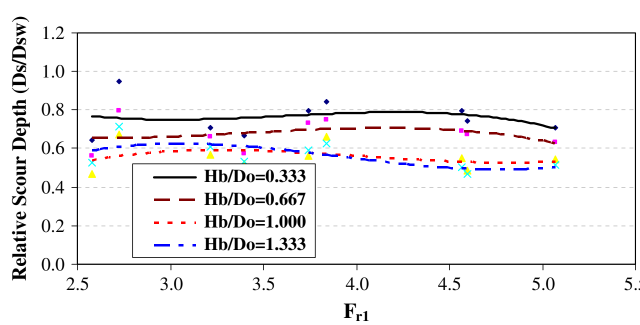

Figure 12 Relation between relative scour depth D_s/D_{sw} and F_{r1} (L_b = 0.8L_f).

considered arrangements of baffle blocks for relatively smaller value of F_{r1}, it is indicated that the value of H_b/D_o has less influence on the D_s/D_{sw} values than that for relatively higher values of F_{r1}. Clearly, for all considered arrangements of baffle blocks, using relatively smaller value of L_b/L_f ($L_b/L_f = 0.4$ and 0.5), the value of H_b/D_o has more significant effect on the value of D_s/D_{sw} than that of using relatively higher value of L_b/L_f ($L_b/L_f = 0.6$ and 0.8). For all considered arrangements of baffles with all tested values of F_{r1}, increasing of L_b/L_f leads to decrease the values of D_s/D_{sw}, whereas it is clear that the influence of L_b/L_f on D_s/D_{sw} is increased as H_b/D_o increases. This emphasizes that using smaller values of L_b/L_f give more reduction in the value of maximum scour depth. Generally, the effect of H_b/D_o on D_s/D_{sw} is more significant than that of the value of L_b/L_f. This means that more attention should be paid to the height of baffle blocks than their location.

The value of $H_b/D_o = 0.334$ gives the higher values of D_s/D_{sw}, and the value of $H_b/D_o = 1.33$ gives the lower values of D_s/D_{sw}. The case of baffled floor offers reduction of maximum scour depth for the most of the flow conditions, the most efficient case of baffle block arrangements for $F_{r1} < 3.5$ is using $H_b/D_o = 1.0$ and $L_b/L_f = 0.4$, which produces reduction in scour depth ranged from 51.86% to 63.81%. While for $F_{r1} > 3.5$, using $H_b/D_o = 1.33$ and $L_b/L_f = 0.4$ produces reduction in scour depth ranged from 52.50% to 87.91%.

4.2. Effect of semi-circular baffle blocks on scour Length

To show the effect of baffle positions on the length of scour hole, for the considered heights of semi-circular baffles, Figs. 13–16 present the relative maximum length of scour, L_s/L_{sw} versus initial Froude number, F_{r1}.

For all considered arrangements of baffle blocks with all tested values of H_b/D_o and F_{r1}, the values of $L_s/L_{sw} < 1.0$. This means that the suggested baffle arrangements reduce the scour length for all used flow conditions comparing to the case where no baffle was used. For all considered arrangements of baffle blocks with all tested values of H_b/D_o, the value of L_s/L_{sw} decreases as F_{r1} increases. For all considered arrangements of baffle blocks, the initial Froude number, F_{r1}, has small effect on the value of L_s/L_{sw}, except for the value of $L_b/L_f = 0.6$ and 0.8 and $H_b/D_o = 0.334$ and 0.667. For all considered arrangements of baffle blocks, the value of $H_b/D_o = 1.33$ gives the smaller values of L_s/L_{sw} and the value of $H_b/D_o = 0.334$ gives the higher values of L_s/L_{sw}, meaning that increasing the value of H_b/D_o decreases the value of L_s/L_{sw}. It is worth to mention that, for all considered arrangements of baffle blocks, the values of $H_b/D_o = 1.33$ and 1.0 have higher influence on the value of L_s/L_{sw} than that of $H_b/D_o = 0.667$ and 0.334. For all considered arrangements of baffle blocks with all tested values of F_{r1} and H_b/D_o, increasing L_b/L_f leads to increase L_s/L_{sw}. This means that using smaller values of L_b/L_f resulted in more reduction in scour length. For all considered arrangements of baffle blocks with all used values of F_{r1}, the influence of the H_b/D_o on the value of L_s/L_{sw} is more significant than that of the value L_b/L_f. Generally, for all considered arrangements of baffle blocks, using $L_b/L_f = 0.4$ and $H_b/D_o = 1.33$ gives the maximum reduction in the scour length which ranged from 77.06% to 93.66%.

Finally, Figs. 17 and 18 illustrate the relation between F_{r1} and both of D_s/D_{sw} and L_s/L_{sw} for one of the considered cases

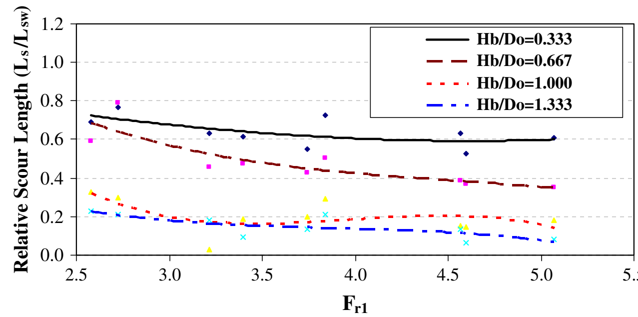

Figure 13 Relation between relative scour length L_s/L_{sw} and F_{r1} ($L_b = 0.4L_f$).

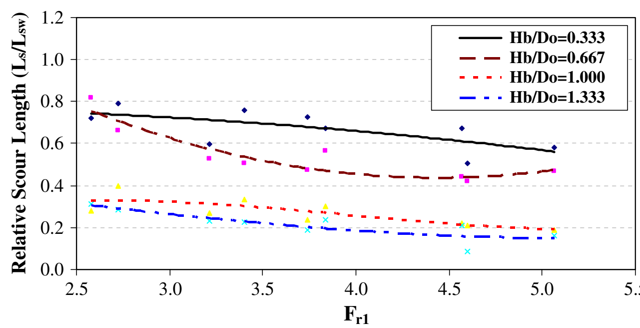

Figure 14 Relation between relative scour length L_s/L_{sw} and F_{r1} ($L_b = 0.5L_f$).

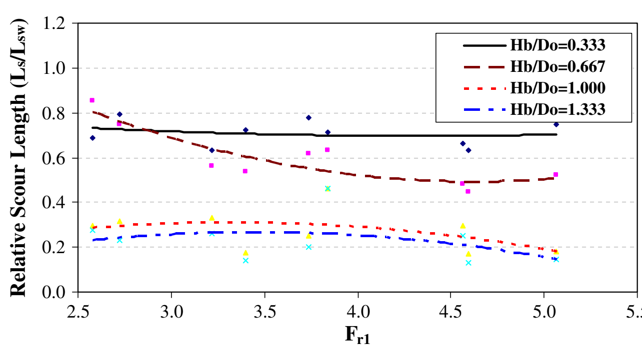

Figure 15 Relation between relative scour length L_s/L_{sw} and F_{r1} ($L_b = 0.6L_f$).

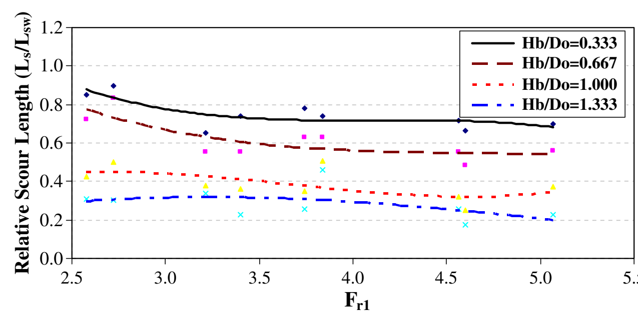

Figure 16 Relation between relative scour length L_s/L_{sw} and F_{r1} ($L_b = 0.8L_f$).

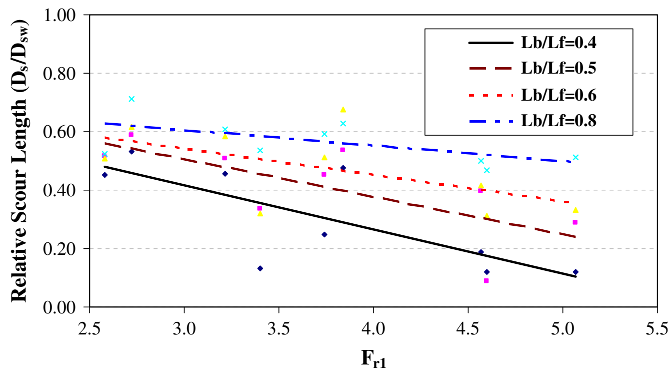

Figure 17 Relation between relative scour depth D_s/D_{sw} and F_{r1} (H_b/D_o = 1.33).

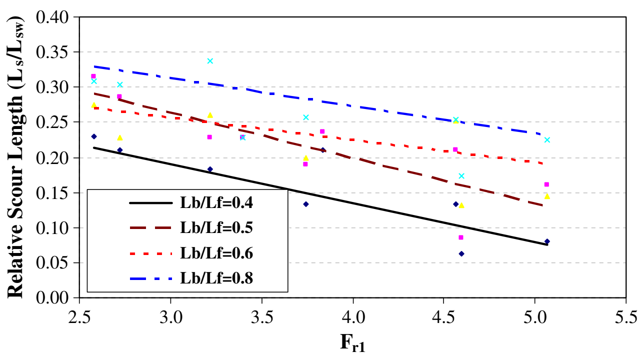

Figure 18 Relation between relative scour length L_s/L_{sw} and F_{r1} (H_b/D_o = 1.33).

(H_b/D_o = 1.33). From this figure, it can be concluded that the values of D_s/D_{sw} and L_s/L_{sw} increasing as the value of F_{r1} decreases. The most efficient case of baffle block positions is at $L_b = 0.4L_f$, which produces reduction in scour depth from 52.50% to 87.91% and gives reduction in the scour length from 77.06% to 93.66%.

5. Derivation of maximum scour parameters

It is important to predict the maximum scour depth and length for the different cases being under investigation because the maximum scour depth and its location downstream of hydraulic structure are important design factors. Based on the experimental data and using the statistical methods with the presence of the different flow conditions, several models were proposed and their coefficients were estimated. Scour depth equations for various types of weirs, jets, and stilling basins are available in the literature (Breusers and Raudkivi [21] and Bijan Dargahi [14]). For comparison purposes, some of these equations were used to calculate the maximum scour depths in the present experiments. These equations are the following:

Schoklitsch (1932), $$Z + Z_o = 4.75H^{0.2}q^{0.57}D_{90}^{-0.32} \quad (3)$$

Jaeger (1939), $$Z + Z_o = 6H^{0.25}q^{0.5}\left(\frac{H}{D_{90}}\right)^{0.33} \quad (4)$$

Eggenberger (1944), $$Z + Z_o = CH^{0.5}q^{0.6}D_{90}^{-0.4} \quad (5)$$

Shalash (1959), $$Z + Z_o = 9.65H^{0.5}q^{0.6}D_{90}^{-0.4}\left(\frac{1.5H}{L}\right)^{0.6} \quad (6)$$

Bijan Dargahi (2003):

$$\frac{Z_{mx}}{h_o} = 1.7\left(\frac{h_o}{D_{50}}\right)^{1/4.5} \quad (7)$$

$$\frac{X_{mx}}{h_o} = 5\left(\frac{h_o}{D_{50}}\right)^{3} \quad (8)$$

In which Z = scour depth, Z_o = downstream flow depth, H = difference between upstream and downstream water surfaces, q = flow discharge per unit width, D_{90} = sediment size (90% passing by weight), C = a constant that depends on the ratio of the underflow to the overflow discharges, being 22.8 when the underflow is zero, L = apron length, h_0 = operation head, Z_{mx} = maximum scour depth, X_{mx} = x-position of Z_{mx} and D_{50} = sediment size (50% finer).

Among these equations, the Bijan Dargahi [14] equation gave a good estimate of the measured scour depth in case of smooth floor, as shown in Table 2. Table 3 shows a good estimate of the measured scour length in case of no baffles of the present study with the Bijan Dargahi [14] equation.

Also, the best equations predicting the maximum scour depth and length in case of semi-circular baffled floor can be put in the following forms.

$$\frac{D_s}{y_1} = 1.62F_{r1}^{-0.14}\left(\frac{H_b}{D_o}\right)^{-0.65}\left(\frac{L_b}{L_f}\right)^{0.53}\left(\frac{H_b}{y_1}\right)^{0.28} \quad (9)$$

$$\frac{L_s}{y_1} = 22.459F_{r1}^{-0.22}\left(\frac{H_b}{D_o}\right)^{-0.88}\left(\frac{L_b}{L_f}\right)^{0.37}\left(\frac{H_b}{y_1}\right)^{0.16} \quad (10)$$

Fig. 19 shows a comparison between the measured relative scour depth (D_s/y_1) and the calculated one using Eq. (9). Fig. 20 compares the measured relative scour length (L_s/y_1) and the calculated one using Eq. (10). It can be noticed that the predicted data agree well with the measured one. The developed model of the equation has been validated through the tested condition. The regression statistics have been listed in Table 4.

Table 2 Comparison of maximum scour depths in case of smooth floor (no baffles).

Present study	Schoklitsch [3]	Jaeger [22]	Eggenberg [4]	Shalash [5]	Bijan Dargahi [14]
Calculated maximum sour depth using literature equations (cm)					
6.19	7.09	6.94	7.70	6.99	6.95
5.75	6.31	6.15	6.92	6.21	6.17
5.35	5.52	5.37	6.14	5.42	5.39
8.019	6.80	6.64	7.41	6.70	6.66
6.48	6.11	5.96	6.72	6.01	5.97
5.71	5.52	5.37	6.14	5.42	5.39
9.17	10.42	10.27	11.04	10.32	10.29
7.59	7.48	7.33	8.10	7.38	7.35
6.75	6.21	6.05	6.826	6.11	6.07

Table 3 Comparison of maximum scour lengths in case of smooth floor (no baffles).

Present study	Bijan Dargahi [14]
Calculated maximum sour length using literature equations (cm)	
102.61	108.00
98.54	102.60
94.80	97.20
128.26	116.64
114.21	108.00
106.57	92.88
154.16	156.60
136.41	145.80
127.97	122.04

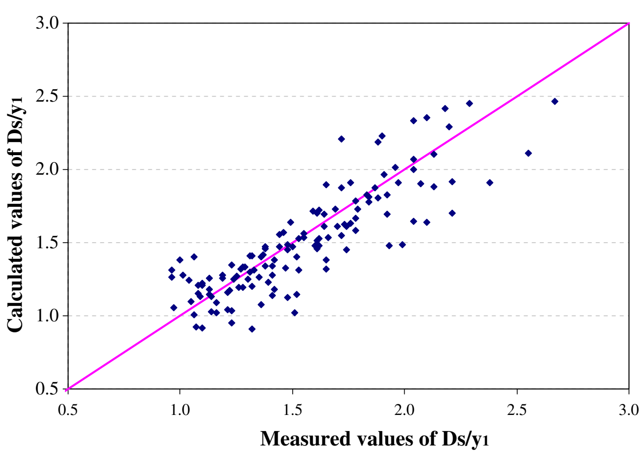

Figure 19 Comparison between calculated and measured values of D_s/y_1.

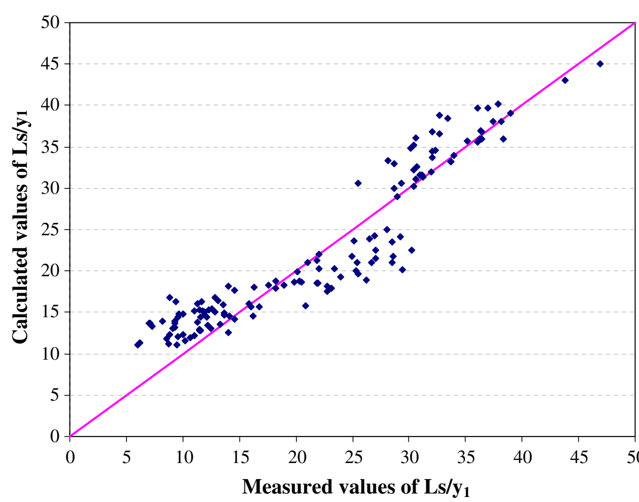

Figure 20 Comparison between calculated and measured values of L_s/y_1.

Table 4 Regression statistics of derived equations.

Regression statistics	Eq. (9)	Eq. (10)
Coefficient of multiple determination (R^2)	0.80	0.83
Adjusted coefficient of multiple (Ra^2)	0.79	0.82
Standard error	0.25	2.96
No. of observation	112	112

6. Conclusions

The experimental and statistical study of local scour downstream of a Fayoum type weir with a horizontal apron with and without baffle blocks led to the following conclusions:

- The main flow characteristic is the development of a hydraulic jump from the initial super-critical conditions. The jump induces large secondary flows and clockwise vortices.
- The secondary flow system develops several scour holes. The number of holes depended upon the bed material and the discharge.
- Most locations of the hydraulic jump are controlled upstream the baffle blocks.
- The bed profiles showed upstream and downstream slope angles ranged from 12.86° to 61.38° and from 4.54° to 9.29°, respectively.
- The values of upstream and downstream slope angles decrease as the initial Froude number increases.
- The installation of baffle blocks had 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.

- The considered shape is easy to be used as an extra element to existing heading-up structures to minimize the scour downstream these structures.
- All suggested baffle block arrangements reduce the maximum scour depth as well as the maximum scour length and move the position of the maximum scour depth closer to the floor, this may endanger the whole structure if the bed downstream the solid apron is not protected against scour.
- All values of D_s/D_{sw} and L_s/L_{sw} are less than 1.0.
- The effect of H_b/D_o on the scouring characteristic is more significant than that of L_b/L_f.
- The case of baffled floor offers reduction of maximum scour depth for the most of the flow conditions, the most efficient case of baffle block arrangements for $F_{r1} < 3.5$ when, using $H_b/D_o = 1.0$ and $L_b/L_f = 0.4$, which produces reduction in scour depth ranged from 51.86% to 63.81%. While for $F_{r1} > 3.5$, using $H_b/D_o = 1.33$ and $L_b/L_f = 0.4$ produces reduction in scour depth ranged from 52.50% to 87.91%.
- For all considered arrangements of baffle blocks, using $L_b/L_f = 0.4$ and $H_b/D_o = 1.33$ gives the maximum reduction in the scour length which ranged from 77.06% to 93.66%.
- The results of the proposed statistical equations are compared to those of the experimental measurements. and available previous equations and acceptable agreement have been found.

Acknowledgements

This work was carried out at the Hydraulics Research Institute (HRI), National Water Research Center (NWRC), Egypt. The author gratefully acknowledges the collaboration done by all staff members of the Institute during the experimental work.

References

[1] Edward AE. Hydraulic energy dissipators. New York, Toronto, London: Mc-Graw Hill Book Co., INC.; 1959.
[2] Blaisdell FW. Development and hydraulic design of St. Anthony Falls Stilling Basin. Proc J Hydraulic Eng, ASCE; 1947.
[3] Schoklitsch A. Kolkbildung unter Überfallstrahlen. Die-Wasserwirtschaft; 1932. p. 341 [in Germany].
[4] Eggenberger W. Die Kolkbildung bein einen Überströmen und beider Kombination Überströmen- Unterströmen. Disseration, ETH Zürich; 1944 [in Germany].
[5] Shalash MSE. Die Kolkbilung beim Ausfluss unter Schützen. In: Diss. T.H. Müchen, editos; 1959 [in Germany].
[6] Novak PJ. Influence of bed load passage on scour and turbulence downstream of stilling basin. In: 9th Congress, IAHR, Dubrovnik, Croatia; 1961.
[7] Catakli O. et al. A study of scour at the end of stilling basin and use of horizontal beams as energy dissipators. In: 11th Congres of large dams; Madrid. 1973.
[8] Uymaz A. The Investigation of the scours originating when water passes simultaneously over and under vertical gates. J Hydraulic Eng ASCE 1988;114(HY 7):811–6.
[9] Pillai NN et al. Hydraulic jump type stilling basin for low froude numbers. J Hydraulic Eng ASCE 1989;115(7):989–94.
[10] Rice CE, Kadavy KC. Protection against scour at SAF stilling basins. J Hydraulic Eng ASCE 1993;119(1):133–9.
[11] Baghdadi KH. Local scour downstream drop structure. Alexandria Eng J 1997;36(2).
[12] Hoffmans GJCM. Jet scour in equilibrium phase. J Hydraulic Eng ASCE 1998;124(4):430–7.
[13] El Abd SM. Effect of using stilling basins on local scour downstream irrigation structures. MSc. thesis, Irrigation and Hydraulic Dept. El-Mansoura University, Egypt; 2002.
[14] Dargahi Bijan. Scour development downstream of a spillway. J Hydraulic Res 2003;41(4):417–26.
[15] Aytac S, Gunal M. Prediction of scour downstream of grad-control structures using neural networks. J Hydraulic Eng ASCE 2008;10:0733–9429.
[16] Oliveto G, Victor C. Local scour downstream of positive-step stilling basins. J Hydraulic Eng ASCE 2009;135(10):846–51.
[17] Peterka AJ. Hydraulic design of stilling basin and energy dissipators. U.S. Dept. of the Interior. Denever, Colorado: Bureau of Reclamation; 1978.
[18] El-Masry AA, Sarhan TE. Minimization of scour downstream heading-up structure using a single line of angle baffles. Eng Res J Helwan Univ 2000:69.
[19] El-Masry AA. Minimization of scour downstream heading-up structures using double line of angle baffles. In: Proc of sixth international water technology conference (IWTC). Alexandria, Egypt; 2001.
[20] Vischer DL, Hager WH. Energy dissipators. Zurich, Switzerland: Swiss Federal Institute of Technology, ETH; 1995.
[21] Breusers HNC, Raudkivi AJ. Scouring, Hydraulic structures design manual. Rotterdam: A. A. Balkema; 1991.
[22] Jaeger Ch. Über die Ähnlichkeit bei flussbaulichen Modellversuchen. Wasserwirtschaft und Wassertecknik 1939;34(32/27):269 [in Germany].

Dr. Fahmy Salah Fahmy Abdelhaleem Dr. Fahmy has a broad experience, covering the different aspects of hydraulic engineering; his professional experience in the sphere of hydrographic, topographic and bathymetric survey, producing surveys maps, river and hydraulic structures studies, executing power plants, barrages studies, teaching national scientific courses in Egypt and Africa, published researches in the field of specialization, supervising master of science and doctoral researchers and technical report writing in both English and Arabic languages.