Ain Shams Engineering Journal (2014) 5, 1059–1069

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
www.sciencedirect.com

CIVIL ENGINEERING

Minimizing downstream scour due to submerged hydraulic jump using corrugated aprons

Hossam Mohamed Ali [a,*], Mohamed Mohamed El Gendy [b], Ahmed Mohamed Hassan Mirdan [c], Abdel Azim Mohamed Ali [d], Fahmy Salah Fahmy Abdelhaleem [d]

[a] *Ministry of Water Recourses and Irrigation, Egypt*
[b] *Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt*
[c] *Faculty of Engineering, Port Said University, Port Said, Egypt*
[d] *Hydraulic Research Institute (HRI), National Water Research Center, Cairo, Egypt*

Received 1 December 2013; revised 2 July 2014; accepted 16 July 2014
Available online 10 August 2014

KEYWORDS

Local scour;
Hydraulic structures;
Corrugated aprons;
Submerged hydraulic jump;
Froude numbers

Abstract Local scour downstream of hydraulic structures due to hydraulic jump is considered one of the tedious and complicated problems facing their stability. Throughout this paper, an experimental study was conducted to study the effect of using different spaced corrugated aprons on the downstream local scour due to submerged jump. Sixty runs were carried out in a horizontal rectangular flume to determine the optimal corrugation wavelength which minimizing the scour. A case of flat apron included to estimate the influence of corrugated aprons on scour holes dimensions. Two types of non-cohesive soil were used. Experiments were performed for a range of Froude numbers between 1.68 and 9.29. The results showed that using spaced triangular corrugated aprons minimize the scour depth and length of fine sand by average percentage of 63.4% and 30.2%, respectively and for coarse sand by 44.2% and 20.6% in comparing with classical jump.

1. Introduction

Flow underneath gates has a tremendous amount of potential energy, which is converted into kinetic energy downstream the hydraulic structures. This energy should be dissipated to prevent the possibility of excessive scouring of the downstream river and to minimize erosion and the undermining of the 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. Studying the local scour process is a very complex problem given the numerous variables related to both

* Corresponding author. Tel.: +20 1006566037.
E-mail addresses: melgendy@elpla.com (M.M. El Gendy), a_mirdan@yahoo.com (A.M.H. Mirdan), azim1@hotmail.com (A.A.M. Ali), fahmyhri@gmail.com (F.S.F. Abdelhaleem).
Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2014.07.007

Notations

S	corrugation wavelength	L_S	maximum scour length of movable soil
t	the height of corrugated apron	F_r	Froude number at initial water depth
b	the base width of corrugated apron	g	the acceleration of gravity
d_{50}	mean particle diameter of movable soil	y_1	initial water depth of hydraulic jump
d_{10}	percentage of passed particles from 10 mm diameter	y_2	sequent water depth of hydraulic jump
d_{90}	percentage of passed particles from 90 mm diameter	μ	viscosity of fluid
d_{60}	percentage of passed particles from 60 mm diameter	ρ	density of the fluid
d_{84}	percentage of passed particles from 84 mm diameter	ρ_s	density of the movable soil
σ_g	geometric standard deviation	L_j	hydraulic jump length
C_u	uniformity coefficient deviation	L_r	roller hydraulic jump length
d_S	maximum scour depth of movable soil		

the heterogeneity of the eroded soil and the turbulent flow, which produces the erosive action. When jets due to submerged hydraulic structure impinge upon loose beds of granular material downstream of hydraulic structures such as weirs or sluice gates, they can lead to significant local scour and may cause stability problems of the structure which lead to failure. Constructing a rigid apron adjacent to the structure is a typical engineering solution to protect the structure. The safety of an apron downstream of a sluice gate is threatened by the erosive action of the submerged hydraulic jump due to scour downstream of an apron. Because flow conditions around a structure are complex, the design and planning of an apron are typically based on experimental results, modeling and measurements from similar projects. Prediction of local scour holes that develop downstream of hydraulic structures due to submerged jump plays an important role in their design.

Many studies have been conducted with non-cohesive apron materials in this area. But, most of these studies are related to formation of submerged jump upon flat aprons and few studies are carried out in the case of submerged jets on rough apron and the effect of roughness on local scour process. A jump formed in a horizontal, wide rectangular channel with a flat apron is often referred to as the classical hydraulic jump and has been studied extensively by Peterka [1], Rajaratnam, [2], McCorquodale [3] and Hager [4]. Also, there are many formulae for scour following hydraulic jump in a stilling basin such as developed by Schoklitsch [5], Eggenberger [6], Shalash [7], Novak [8], Catakli [9], Uymaz [10], Pillai [11], Rice and Kadavy [12], Baghdadi [13], Hoffmans [14], El-Abd [15], Dargahi [16], Aytac and Gunal [17], and Oliveto and Victor [18]. Different techniques to reduce local scour have been employed in previous studies by making use of splitter plates or collars. On the other hand, The first study on hydraulic jump over rough apron was carried out by Rajaratnam [19] and this study was showed that, the length of jump upon rough apron is smaller than the length of classical jump, and also Many different corrugated apron shapes have been proposed and studied by Ead and Rajaratnam [20], Izadjoo and Bejestan [21], Ead [22] and Fahmy et al. [23]. When a submerged jet passes over a corrugated apron, the characteristics of velocity and turbulence of flow are different from those of the corresponding jet over a flat apron Hamidifar et al. [24].

Breusers [25] studied the variation time of downstream scour by the flow over and under an estuary closure structure. Scour created downstream of the apron has been investigated by many researchers like Chatterjee and Ghosh [26], Farhoudi and Smith [27] [28], Hassan and Narayanan [29], and Chatterjee et al. [30] measured the velocity distributions of submerged jets issuing from a sluice opening over an apron followed by a scour holes in non-cohesive aprons; whereas Dey and Westrich [31] detected that the flow characteristics of submerged jets over the apron and in the equilibrium scour holes in cohesive soil.

Balachandar and Kells [32] [33], Balachandaret et al. [34], Kells et al. [35], Lim and Yu [36], Sarkar and Dey [37], Goel and Verma [38] and Dey and Sarkar [39] have studied development of scour holes downstream of an apron for a submerged jet. Downstream scour was studied by many investigators, and a comprehensive state-of-the-art review on the investigations done on scour due to jets was given by Sarkar and Dey [40].

Recently published results indicated that the scour holes develop rapidly in the early stages and progresses toward an asymptotic stage beyond which the scour profile does not change significantly with time and reaches an equilibrium state Alihosseini et al. [41], Oliveto et al. [42], Sarathi et al. [43], Omid et al. [44], and Hamidifar et al. [45,46]. Chen and Siow-Y [47] confirmed that the equilibrium scour state was never reached when jet-flipping occurred during the scouring processes as it consists of two intermittent and cyclical phases: a digging phase with an attached apron-jet scouring the apron to form a deep scour hole and a filling phase where the attached jet flips to become a surface-jet causing sediments to re-fill into the scour hole. Helal et al. [48] confirmed that the case of fully filled floor gave the smaller values of scour parameters. The experimental works were carried out by Blaisdell [49] 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 conclusion, the review of the previous published materials showed that the corrugated aprons can effectively decrease the required conjugate depth and length of the jump; it thus can reduce the cost of energy dissipating aprons. The present study is thus an attempt to extend the previous studies by investigating the effect of strip triangular corrugated apron shapes at downstream heading-up structures. The study reports an experimental investigation, whose findings are used to describe influences of various parameters on scour dimensions.

2. Dimensional analysis

The maximum scour depth downstream of a rigid apron can be expressed as a function of the following independent variables:

$$d_S = f(g, \rho, \rho_S, y_1, y_2, v_1, S, t, b, d_{50}, L_j, \mu) \tag{1}$$

In which d_S is the maximum depth of scour, g is the acceleration due to gravity, ρ is the density of water, ρ_S is the density of movable soil, y_1 is the gate opening because lip gate was used to avoid the vena contract a i.e. water entered the flume under a sluice gate with a streamlined lip, thereby producing a uniform supercritical stream with a thickness of y_1, L_j is the length of submerged hydraulic jump, d_{50} is the mean particle diameter of soil, v_1 is the mean velocity under gate, y_2 is the sequent depth of jump, S is the corrugation wavelength between triangular strips corrugated apron, t and b are the height and width of triangular strips corrugated apron respectively, μ is the viscosity of water.

Moreover, in turbulent flow, μ has a negligible influence on scour and can be neglected. By applying the Buckingham π theorem with ρ, y_1 and v_1 as repeating variables, Eq. (1) can be written in dimensionless form as following;

$$\frac{d_S}{y_1} = \left(F_r, \frac{\rho_s}{\rho}, \frac{y_2}{y_1}, \frac{S}{y_1}, \frac{t}{y_1}, \frac{b}{y_1}, \frac{d_{50}}{y_1}, \frac{L_j}{y_1}\right) \tag{2}$$

In which $F_r = \frac{v_1}{\sqrt{g y_1}}$ is the Froude number under gate.

Because of ρ_s and ρ are constants so, can be ignored.

Height (t) and width (b) of triangle strip corrugated aprons are constant. Hence, Eq. (2) is reduced to Negm et al. [50].

$$\frac{d_S}{y_1} = f\left(F_r, \frac{y_2}{y_1}, \frac{L_j}{y_1}, \frac{S}{y_1}, \frac{d_{50}}{y_1}\right) \tag{3}$$

With the same concept, the maximum scour length L_S is dependent on the following independent variables

$$\frac{L_S}{y_1} = f\left(F_r, \frac{y_2}{y_1}, \frac{L_j}{y_1}, \frac{S}{y_1}, \frac{d_{50}}{y_1}\right) \tag{4}$$

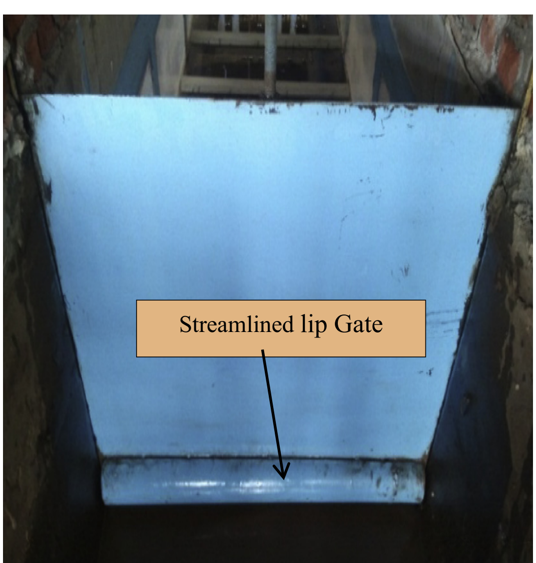

Figure 1 Streamlined lip gate in flume.

3. Experimental setup

In this paper, in order to reach the main purpose of this research, a model of a lip gate with horizontal basin has been constructed, to develop the required supercritical flow and initial depth of the jumps, as shown in Fig. 1. The model is investigated experimentally with flat apron to use its results as a comparison case to the other cases of corrugated aprons. To create the required roughness of the apron, aluminum triangular sheets were installed on the flume apron, and in order to diminish effect of cavitation, the crests of corrugation were set at the same level of upstream apron, as shown in Fig. 2. The corrugations acted as depressions in the apron, to create a system of turbulent eddies which might increase the apron shear stresses.

The dimensions of the corrugated sheet aprons are: triangular corrugated height, t = 40 mm and width b = 40 mm are kept constant and the sections have side slopes length equal to 44.7 mm with side angles 45°. The experiments have been conducted in the laboratory flume of the Hydraulics Research Institute (HRI), National Water Research Center (NWRC). The flume is constructed of bricks sealed with smooth cement mortar except part of Plexiglas sides with length = 2.25 m to facilitate the observation process, as shown in Fig. 3. The flume is 75 cm wide, 70 cm deep and 24.50 m long. A centrifugal pump is used to supply water to the head tank from the storage tank. The head tank has a gravel box which is used to provide an even flow distribution across the flume. The discharges were measured by Ultrasonic-Flow meter which is fixed in the supply lines.

To control the water flow rate, a gate valve is installed on the supply pipe line just before the head tank. The downstream bay is made of wooden with length 2.50 m overlaid on a 0.50 m layer of sand to prevent leakage, this bay is represented the flat apron also, prepared for the corrugated sheets fixation. Water depths and bed levels were measured by a point-gauge, Abdelaziz [51]. The gauge is mounted on carriage moving in the flow and the perpendicular directions. Downstream water depth is controlled by using a tail gate in order to form jumps over the rigid apron, and then, the water flowed to the by-pass channel. The length of floor and dimensions of corrugated sheets is kept constant for all runs. Spacing between corrugated sheets is changed from position to other to specify the optimum location. The rear reach of the channel is filled with a 30 cm layer of sand with d_{50} = 0.523 mm, d_{10} = 0.254 mm, d_{16} = 0.315 mm, d_{84} = 0.817, d_{60} = 0.596 and uniformity coefficient $C_u = d_{60}/d_{10}$ = 2.346 for the first sand sample whereas, d_{50} = 2.575 mm, d_{10} = 0.811 mm, d_{16} = 1.378 mm, d_{84} = 3.861, d_{60} = 2.92 and uniformity coefficient $C_u = d_{60}/d_{10}$ = 3.6 for the second sample in order to represent the movable apron. The grain size distribution curves for both samples are shown in Figs. 4 and 5.

Generally, bed fluctuations are an interesting feature of the transport of uniform or well sorted sediments, but are essential to the understanding of the transport of sediment mixtures. Sediment mixture grains start to move on the bed when the combined lift and drag forces produced by the fluid become large enough to counteract the gravity and frictional forces that hold the grains in place. An important assumption in most of the existing models is the uniformity of the sand, which means that the sediment mixture is characterized by a single sand size d_{50}.

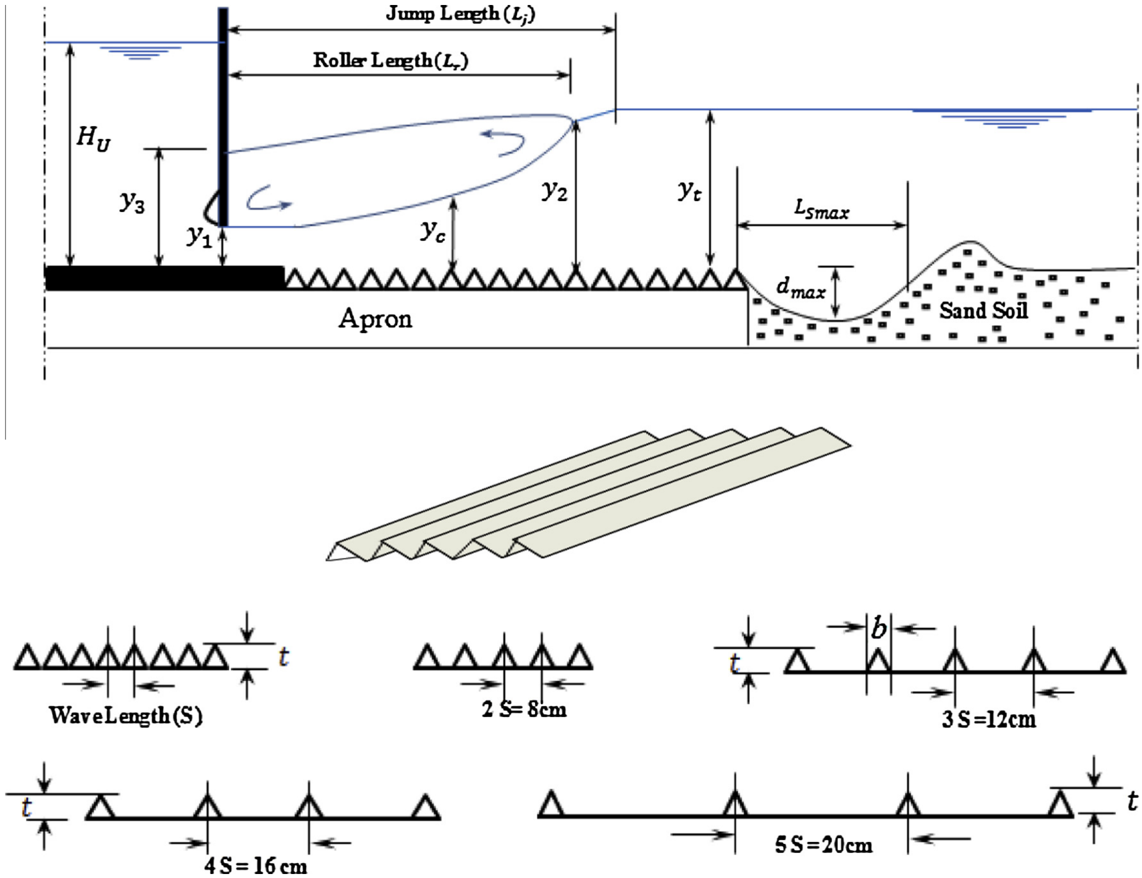

Figure 2 Schematic view of scour downstream of an apron due to submerged jump and spaced corrugated aprons.

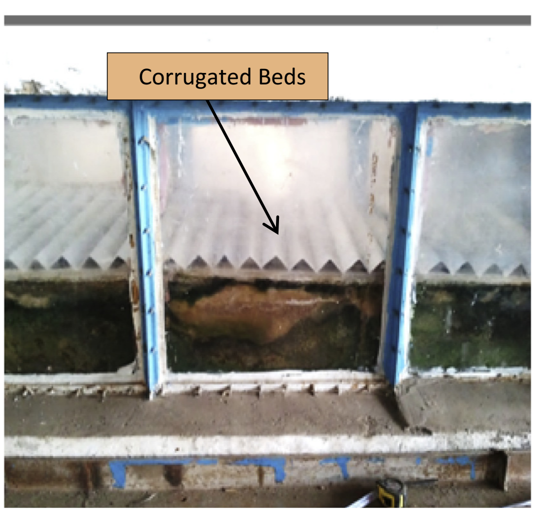

Figure 3 Plexiglas's wall section.

The gradation of the sediment mixture can be described by geometric standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5}$ thus, $\sigma_g = 1.63$ and 1.78 for first and second sample respectively.

4. Experimental procedure

To achieve the objective of this research, two discharges were considered ($Q = 30$ and 45 l/s). Initial water depth (y_1) equal

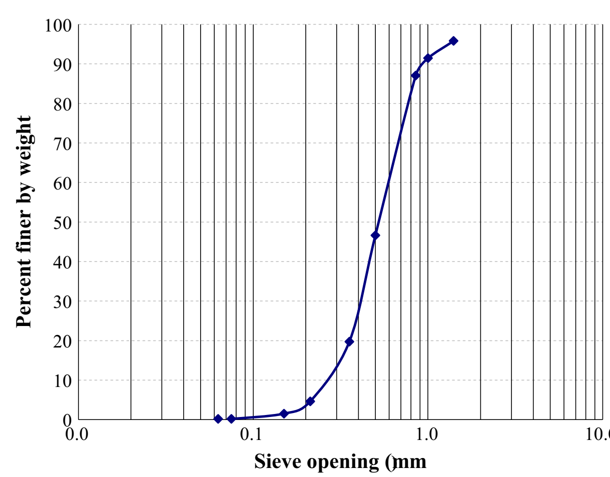

Figure 4 Grain size distribution curve for first sand sample.

to 3.86, 2.99 and 2.02 cm were used with discharge 30 l/s whereas, 2.15 and 1.62 cm were used with discharge 45 l/s. All types of submerged hydraulic jumps according to classification of Chow [52] were investigated. Sixty runs had been conducted including 10 runs with flat apron which was taken as a comparison case. For each run, the backwater feeding is started first until its depth reaches higher than the required downstream water depth, and then, the upstream feeding is pumped. To adjust the tail water depth, the tail gate is screwed gradually until the considered depth is adjusted.

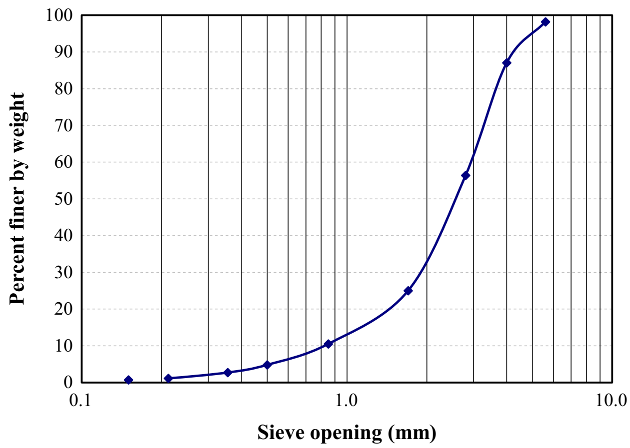

Figure 5 Grain size distribution curve for second sand sample.

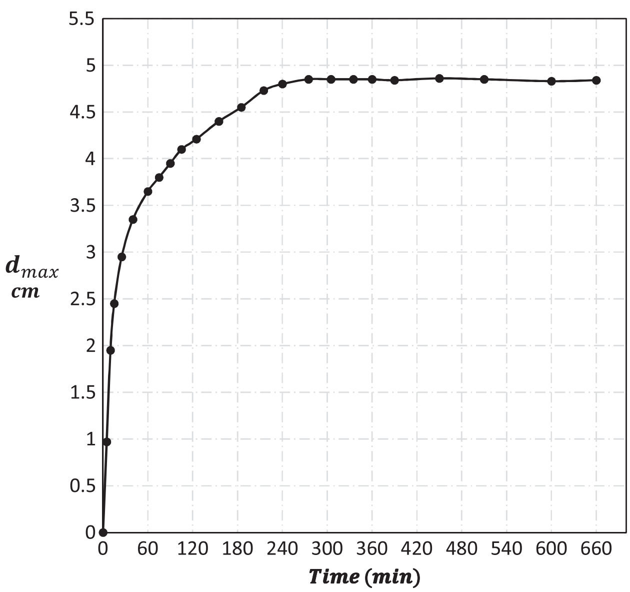

Figure 6 Relationship between maximum scour depths and time in case of flat apron.

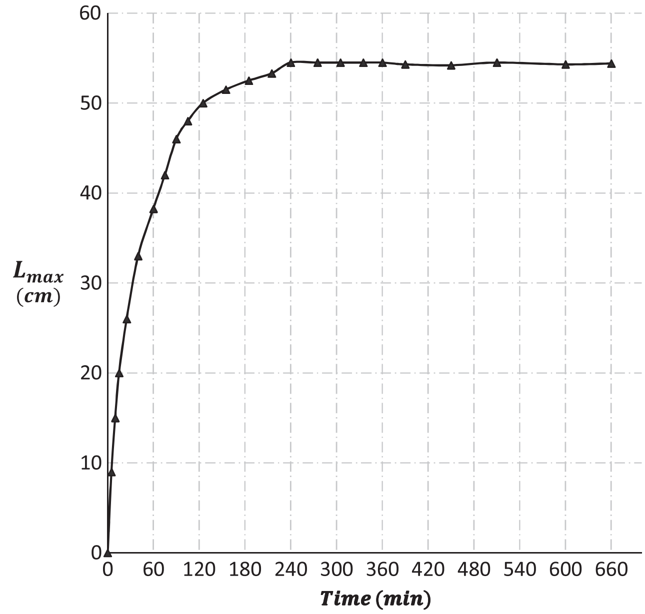

Figure 7 Relationship between maximum scour lengths and time in case of flat apron.

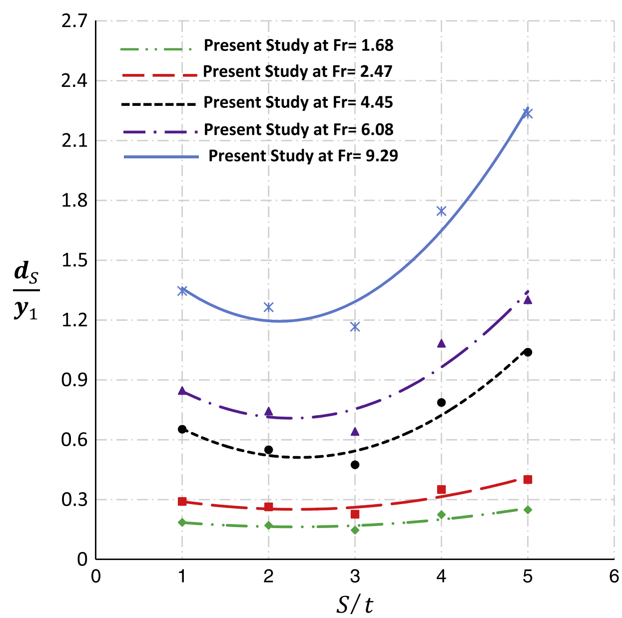

Figure 8 Relationship between d_s/y_1 and S/t for fine sand.

A precise point gauge was used to adjust the initial depth of jump, (gate opening) and another point gauge was used to measure the sequent depth. The length and the roller length of hydraulic jump were measured by a precise scale. Each test was run for 6 h, which were sufficient for most of the tests to reach a quasi-equilibrium state of scour, as shown in Figs. 6 and 7. The run was stopped and the flume was drained and the expecting scouring area was recorded by a precise point gauge to monitor the apron topography on a grid 2 cm × 2 cm.

5. Results and discussion

5.1. Effect of spaced corrugated aprons on scour depth for fine and coarse sand

Figs. 8 and 9 describe the relation between S/t, and d_s/y_1 for fine and coarse sand respectively with constant values of Froude number. One can see that, for the considered flow conditions, the minimum scour dimensions occurred at optimum spacing ratio $S/t = 3$. For $F_r = 1.68$, 2.47, 4.45, 6.08 and 9.29 the scour depth decreases by 63.21%, 62.23%, 61.09%, 60.55% and 59.23% respectively, in comparison with the scour depth of flat apron with considering the results presented in the following Section 5.3.

Based on the experimental data and using the statistical method, for different spaced corrugated aprons, several models were proposed and their regression coefficients were estimated. Out of all trials, the average best empirical equation predicting the relative scour depth can be put in the following form:

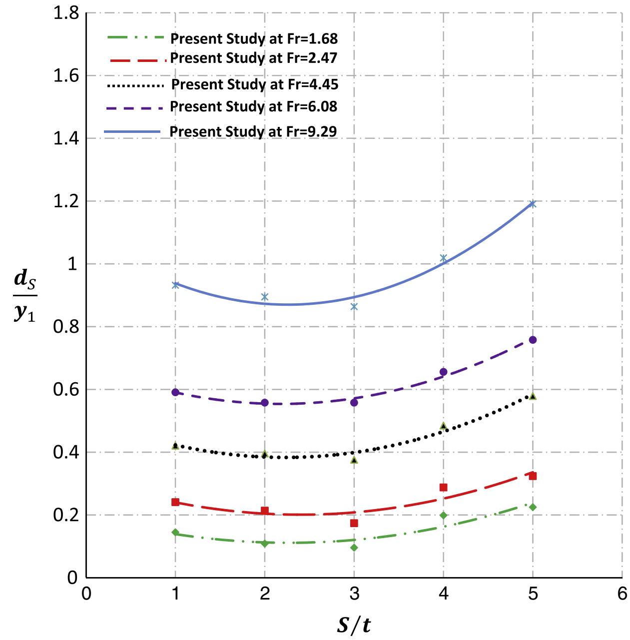

Figure 9 Relationship between d_s/y_1 and S/t for coarse sand.

$$\frac{d_s}{y_1} = 0.06\left[\frac{S}{t}\right]^2 - 0.29\left[\frac{S}{t}\right] + 0.89 \quad R^2 = 0.90 \tag{5}$$

5.2. Effect of spaced corrugated aprons on scour length for fine and coarse sand

Figs. 10 and 11 describe the relation between S/t, and L_s/y_1 for fine and coarse sand respectively with constant values of Froude number. One can see that, for the considered flow conditions, the minimum scour dimensions occurred at optimum spacing ratio $S/t = 3$. For $F_r = 1.68$, 2.47, 4.45, 6.08 and 9.29 the scour length decreases by 35.9%, 32.16%, 26.28%, 30.45% and 27.19% respectively, in comparison with the scour length of flat apron with considering the results presented in the following Section 5.3.

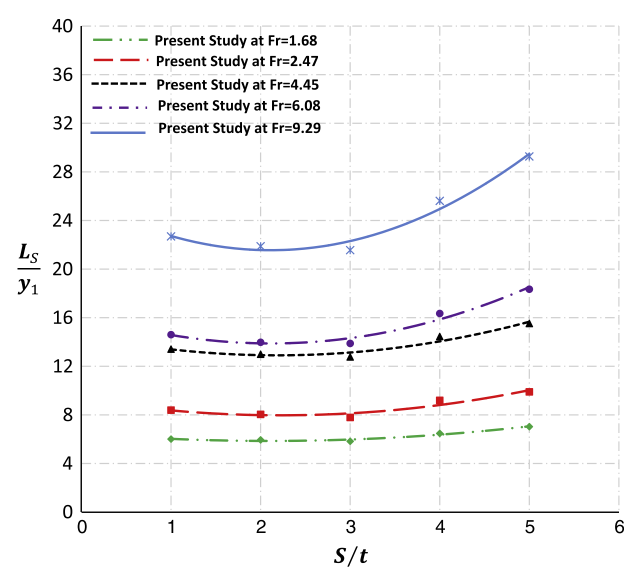

Figure 10 Relationship between L_s/y_1 and S/t for fine sand.

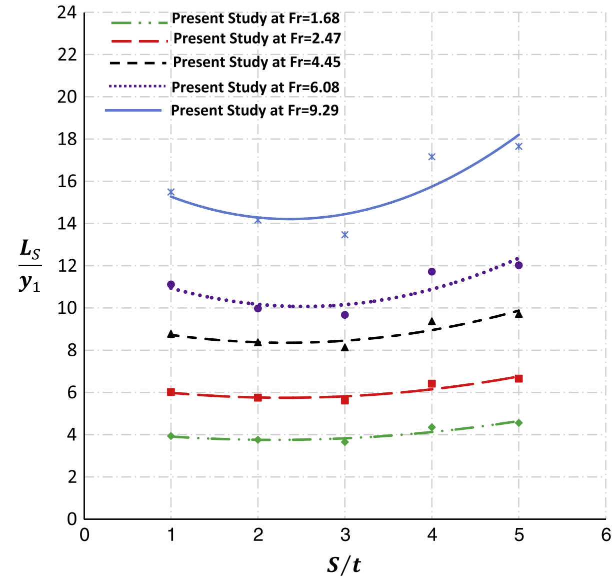

Figure 11 Relationship between L_s/y_1 and S/t for coarse sand.

Based on the experimental data and using the statistical method, for different spaced corrugated aprons, several models were proposed and their regression coefficients were estimated. Out of all trials, the average best empirical equation predicting the relative scour length can be put in the following form;

$$\frac{L_s}{y_1} = 0.45\left[\frac{S}{t}\right]^2 - 1.94\left[\frac{S}{t}\right] + 14.51 \quad R^2 = 0.92 \tag{6}$$

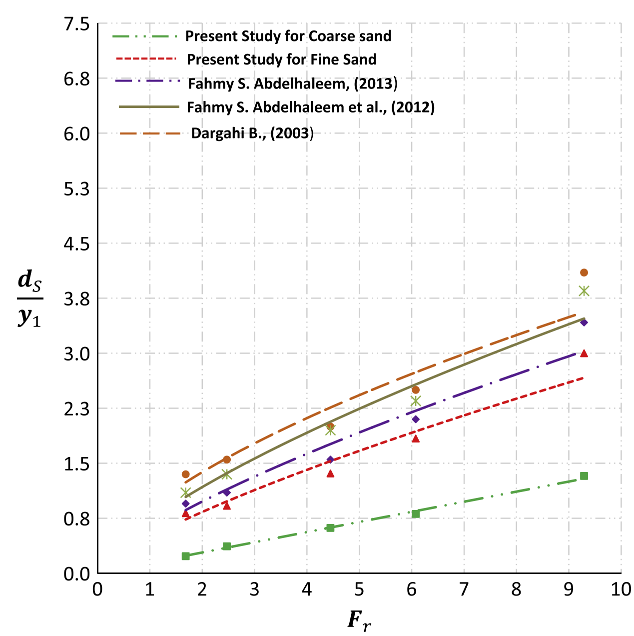

Figure 12 Comparison relationship between relative scour depth d_s/y_1 and F_r for flat apron.

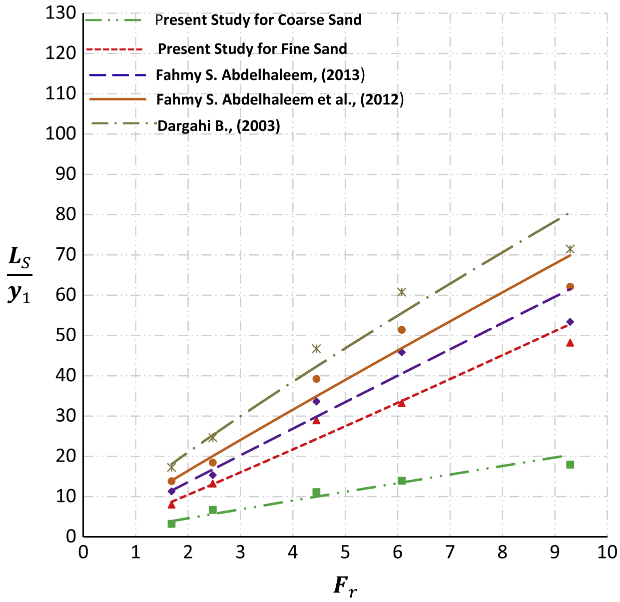

Figure 13 Comparison relationship between relative scour length L_s/y_1 and F_r for flat apron.

5.3. Effect of Froude number on the depth and length of scour for flat aprons

Figs. 12 and 13 illustrate the relation between d_s/y_1 and L_s/y_1 with F_r for present research and compare it with previous studies that were conducted by Fahmy et al. [23], Dargahi [16] and Fahmy [53] on flat apron respectively. One can see that, for the considered flow conditions, generally scour dimensions increase with increasing the Froude number. Figs. 12 and 13 show that, the developed equation of fine sand is approximately closer to Fahmy [53] than both Dargahi [16] and Fahmy et al., [23]. Knowing that, they studied the free jump.

By statistics analysis, average empirical equations predict the relative scour depth and length over smooth can be put as following formulas;

$$\frac{d_s}{y_1} = 0.31[F_r]^{0.8711} \quad R^2 = 0.96 \tag{7}$$

$$\frac{L_s}{y_1} = 3.70[F_r]^{0.1009} \quad R^2 = 0.92 \tag{8}$$

5.4. Effect of Froude number on the depth and length of scour for spaced corrugated aprons

Figs. 14 and 15 show the relation between d_s/y_1 and L_s/y_1 with F_r for fine sand in the present research respectively and compare it with previous study on corrugated aprons. Experimental study of Fahmy et al. [23] has been conducted by using three types of corrugated aprons, semicircular, trapezoidal and triangular shapes with no spacing. They concluded that, the triangular corrugated aprons gave the best minimizing of scour dimensions, thus, the results of this case are suitable to compare with the present study. Present study has been conducted on different corrugation wave length S = 4, 8, 12, 16 and 20 cm as mention previously in Fig. 2.

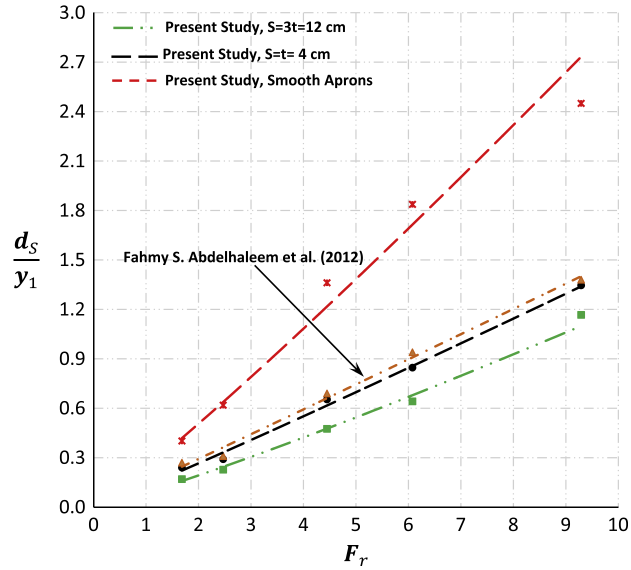

Figure 14 Comparison relationship between relative scour depth d_s/y_1 and F_r in case of spaced corrugated aprons for fine sand.

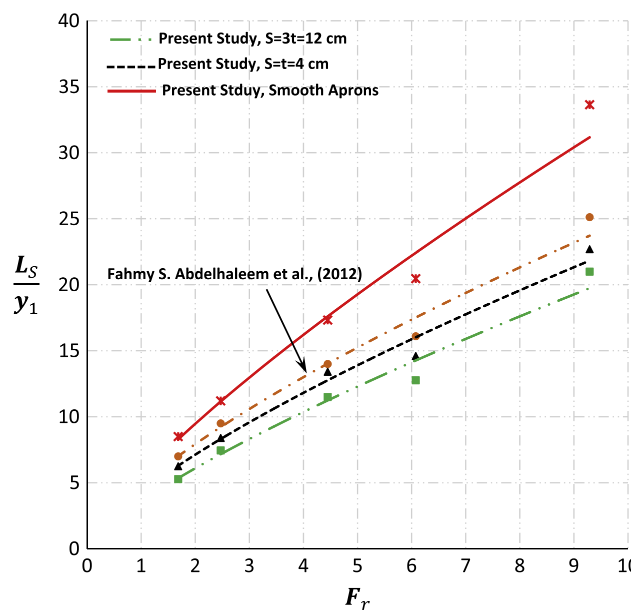

Figure 15 Comparison relationship between relative scour length L_s/y_1 and F_r in case of spaced corrugated aprons for fine sand.

It can be noticed that, there is an acceptable agreement between results of corrugation wavelength (S = 4 cm) in the present study with that of Fahmy et al. [23].

One can see that, for the considered flow conditions, the present study confirmed that, the best minimizing of scour dimensions occurred at spacing ratio S/t = 3. Interpretation that refers to, at this spacing ratio more energy was dissipated between corrugated sheets in comparison with other spacing ratios. At spacing ratio S/t = 3 scour depth decreases by 63.15%, 56.43%, 49.85%, 41.78% and 33.85% and the scour length by 37.24%, 32.75%, 26.64%, 21.35% and 17.95% at

Froude number F_r = 1.86, 2.47, 4.45, 6.08 and 9.29, respectively in comparison with that over flat apron.

In the other hand, Figs. 16 and 17 illustrate the relation between d_s/y_1 and L_s/y_1 with F_r for coarse sand in the present research respectively and compare it with previous study that was conducted by Fahmy et al. [23] on corrugated aprons. For coarse sand at spacing ratio $S/t = 3$ the scour depth decreases by 42.43%, 36.15%, 29.56%, 25.32% and 21.23% and the scour length by 26.56%, 22.31%, 17.64%, 14.35% and 11.95% at Froude number F_r = 1.86, 2.47, 4.45, 6.08 and 9.29 respectively, in comparison with that over flat apron for coarse sand.

By statistics analysis, average best empirical equations predict the relative scour depth and length at spacing ratio $S/t = 3$ can be put as following formulas;

$$\frac{d_s}{y_1} = 0.07[F_r]^{1.3132} \quad R^2 = 0.99 \tag{9}$$

$$\frac{L_s}{y_1} = 3.01[F_r]^{0.7683} \quad R^2 = 0.98 \tag{10}$$

5.5. *Effect of the relative mean grain size on the scour holes dimensions*

Figs. 18 and 19 show the relation between d_s/y_1 and L_s/y_1 with d_{50}/y_1 for fine sand in the present research respectively and by comparing it with previous studies in flat apron case. Experimental study of Fahmy [53] has been conducted to analyze effect of semi-circular baffle blocks on local scour downstream clear-over fall weirs by changing the heights and positions of baffles with different flow conditions. As shown in the mentioned figures, there is a relative agreement between the results of present study with that were conducted by Fahmy [53] and Dargahi [16] on flat aprons with taking into consideration that, they studied performance of free hydraulic jump. The results of the present study on corrugated aprons confirm that, the best

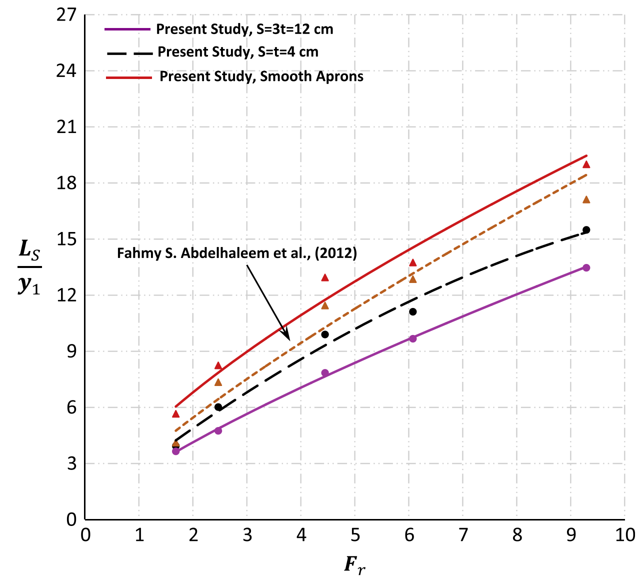

Figure 17 Comparison relationship between relative scour length L_s/y_1 and F_r in case of corrugated aprons for coarse sand.

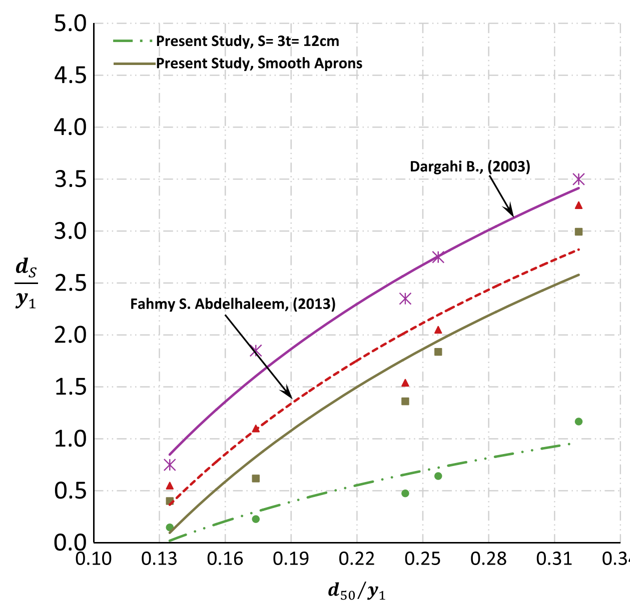

Figure 18 Comparison relation between relative scour depth d_s/y_1 and d_{50}/y_1 in case of smooth and corrugated aprons for fine sand.

minimizing of scour hole dimensions occurred at spacing ratio $S/t = 3$ for all types of jump. Out of all trials, the best empirical equation predicts the relative scour depth over corrugated apron which affected by d_{50} can be put in the following form;

$$\frac{d_s}{y_1} = 69.14\left[\frac{d_{50}}{y_1}\right]^2 - 33.97\left[\frac{d_{50}}{y_1}\right] + 4.66 \quad R^2 = 0.90 \tag{11}$$

On the other hand, the best empirical equation predicts the relative scour length over corrugated apron which affected by d_{50} can be put in the following form;

$$\frac{L_s}{y_1} = 459.98\left[\frac{d_{50}}{y_1}\right]^2 - 224.57\left[\frac{d_{50}}{y_1}\right] + 39.39 \quad R^2 = 0.90 \tag{12}$$

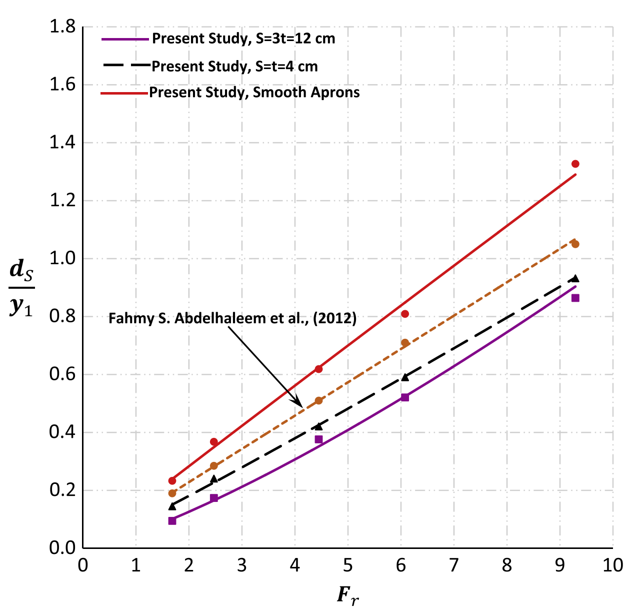

Figure 16 Comparison relationship between relative scour depth d_s/y_1 and F_r in case of corrugated aprons for coarse sand.

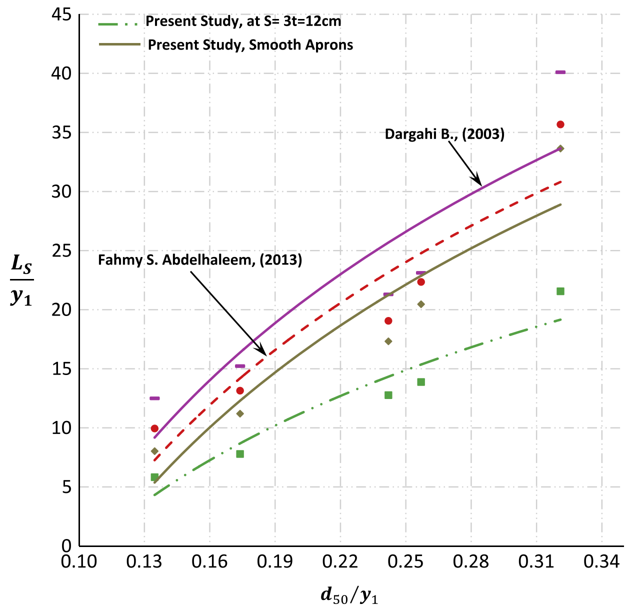

Figure 19 Comparison relation between relative scour length L_s/y_1 and d_{50}/y_1 in case of smooth and corrugated aprons for fine sand.

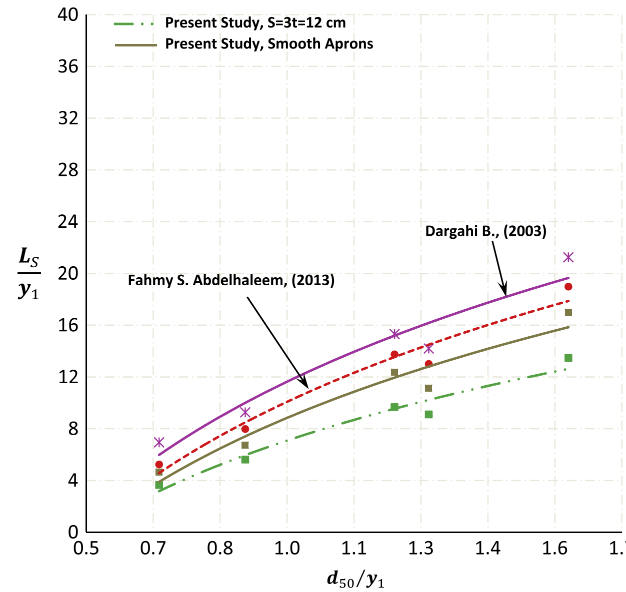

Figure 21 Comparison relation between relative scour length L_s/y_1 and d_{50}/y_1 in case of smooth and corrugated aprons for coarse sand.

Figs. 20 and 21 show the relation between d_s/y_1 and L_s/y_1 with d_{50}/y_1 for coarse sand in the present research respectively and compare it with previous studies that were conducted by Fahmy [53] and Dargahi [16] on flat aprons.

The results of the present study for corrugated aprons confirm that, the best minimizing of scour hole dimensions occurs at spacing ratio $S/t = 3$ for all types of jump. Out of all trials, the average best empirical equation predicts the relative scour depth over corrugated apron which affected by d_{50} can be put in the following form;

$$\frac{d_s}{y_1} = 0.89\left[\frac{d_{50}}{y_1}\right]^2 - 2.12\left[\frac{d_{50}}{y_1}\right] + 1.67 \quad R^2 = 0.95 \tag{13}$$

The average best empirical equation predicts the relative scour length over corrugated apron which affected by d_{50} can be put in the following form;

$$\frac{L_s}{y_1} = 8.85\left[\frac{d_{50}}{y_1}\right]^2 - 20.5\left[\frac{d_{50}}{y_1}\right] + 20.3 \quad R^2 = 0.98 \tag{14}$$

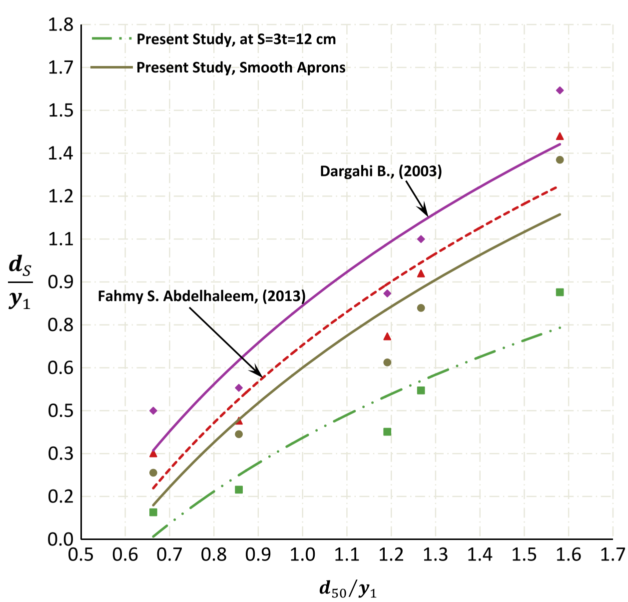

Figure 20 Comparison relation between relative scour depth d_s/y_1 and d_{50}/y_1 in case of smooth and corrugated aprons for coarse sand.

6. Conclusions

The results of the experimental and statistical study for the submerged hydraulic jump over smooth and different spaced corrugated aprons and downstream local scour have been presented; the discussion and analysis of the results highlighted the following conclusions:

- The dimensionless interrelationships between different parameters of local scour holes at downstream of a rigid apron are studied experimentally.
- Using corrugated aprons downstream of hydraulic structures is an effective engineering approach to minimize Scour holes dimensions.
- Some experimental equations were presented by using regression analysis.
- At optimal spacing ratio $S/t = 3$ the minimum dimensions scour occurred and large energy has been dissipated.
- The scour dimensions increase with Froude number increases.
- Scour depth and length are inversely proportional to the mean diameter of grain size particles.
- These proposed criteria can help hydraulic engineers to design structures more safely.

Acknowledgments

This paper is a part of the PhD thesis of the first author under the supervision of the other authors. I would also like to thank the Hydraulics Research Institute (HRI) of National Water Research Center (NCWR) for facilitating the achievement of this research.

References

[1] Peterka AJ. Hydraulic design of stilling basins and energy dissipators, Engineering Monograph No. 25, U.S. Bureau of Reclamation, Denver; 1958.
[2] Rajaratnam N. Hydraulic jumps. Adv Hydrosci 1967;4:197–280.
[3] McCorquodal JA. Hydraulic jumps and internal flows. In: Cheremisinoff NP, editor. Encyclopedia of fluid mechanics, vol. 2. Houston: Gulf Publishing; 1986. p. 120–73.
[4] Hager WH. Energy dissipators and hydraulic jump. Dordrecht: Kluwer Academic; 1992.
[5] Schoklitsch A. Kolkbildung unter U berfallstrahlen. Die-Wasser-wirtschaft; 1932, p. 341 [in Germany].
[6] Eggenberger W. Die Kolkbildung bein einen Ü berströmen und beider Kombination Ü berströ men- Unterströ men. Disseration. ETH Zü rich; 1944. [in Germany].
[7] Shalash MSE. Die Kolkbildung beim Ausfluss unter Schutzen. Diss. von der Fakultat fur Bauwesen der Techn. Hochschule Munchen, Germany; 1959.
[8] Novak PJ. Influence of bed load passage on scour and turbulence downstream of stilling basin. In: 9th Congress, IAHR, Dubrovnik, Croatia; 1961.
[9] Catakli O. 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.
[10] 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.
[11] Pillai NN. Hydraulic jump type stilling basin for low Froude numbers. J Hydraulic Eng – ASCE 1989;115(7):989–94.
[12] Rice CE, Kadavy KC. Protection against scour at SAF stilling basins. J Hydraulic Eng – ASCE 1993;119(1):133–9.
[13] Baghdadi KH. Local scour downstream drop structure. Alexandria Eng J 1997;36(2).
[14] Hoffmans GJ. Jet scour in equilibrium phase. J Hydraulic Eng – ASCE 1998;124(4):430–7.
[15] 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.
[16] Dargahi B. Scour development downstream of a spillway. J Hydraulic Res 2003;41(4):417–26.
[17] Aytac S, Gunal M. Prediction of scour downstream of grad control structures using neural networks. J Hydraulic Eng – ASCE 2008;10:0733–9429.
[18] Oliveto G, Victor C. Local scour downstream of positive-step stilling basins. J Hydraulic Eng – ASCE 2009;135(10):846–51.
[19] Rajaratnam N. Hydraulic jumps on rough bed. Trans Eng Inst Canada 1968;11(1):1–8.
[20] Ead SA, Rajaratnam N. Hydraulic jumps on corrugated bed. J Hydraulic Eng – ASCE 2002;128:656–63.
[21] Izadjoo F, Bejestan MS. Effects of trapezoidal shape corrugated bed on the characteristics of hydraulic jump. In: 17th Canadian hydrotechnical conference, Alberta, Canada; 2005, August 17–19.
[22] Ead SA. Effect of bed corrugations on the characteristics of a hydraulic Jump. King Saud University, Final Research Report, No. 14/1427H; 2007.
[23] Abdelhaleem Fahmy S, Amin AM, Helal YE. Effect of corrugated bed shapes on hydraulic jump and downstream local scour. J Am Sci 2012;8(5):1–11.
[24] Hamidifar H, Omid MH, Nasrabadi M. ''Scour downstream of a rough rigid apron'' College of Agricultural Eng. and Technology, University of Tehran, Karaj, Iran. World Appl Sci J 2011;14(8):1169–78, ISSN 1818-4952.
[25] Breusers HNC. Conformity and time scale in two-dimensional local scour. Publication 40, Delft Hydraulics Laboratory, Delft, Netherlands; 1965.
[26] Chatterjee SS, Ghosh SN. Submerged horizontal jet over erodible bed. J Hydraulic Div 1980;106(HY11):53–90.
[27] Farhoudi J, Smith KVH. Time scale for scour downstream of hydraulic jump. J Hydraul Div – ASCE 1982;108(10):1147–62.
[28] Farhoudi J, Smith KVH. Local scour profiles downstream of hydraulic jump. J Hydraulic Res 1985;23(4):343–58.
[29] Hassan NMK, Narayanan R. Local scour downstream of an apron. J Hydraul Eng – ASCE 1985;111(11):1371–85.
[30] Chatterjee S, Ghosh S, Chatterje M. Local scour due to submerged horizontal jet. J Hyd Eng – ASCE 1994;120(8):973–92.
[31] Dey S, Westrich B. Hydraulics of submerged jet subject to change in cohesive bed geometry. J Hyd Eng – ASCE 2003;129(1):44–53.
[32] Balachandar R, Kells JA. Local channel scour in uniformly graded sediments: the time-scale problem. Can J Civil Eng 1997;24(5):799–807.
[33] Balachandar R, Kells JA. Instantaneous water surface and bed scour profiles using video image analysis. Can J Civil Eng 1998;25(4):662–7.
[34] Balachandar R, Kells JA, Thiessen RJ. The effect of tail-water depth on the dynamics of local scour. Can J Civil Eng 2000;27(1):138–50.
[35] Kells JA, Balachandar R, Hagel KP. Effect of grain size on local channel scour below a sluice gate. Can J Civ Eng 2001;28:440–51.
[36] Lim S, Yu G. Scouring downstream of sluice gate. First international conference on scour of foundation. College Station, Texas (USA): Texas Transportation Institute, Texas A & M University; 2002, Nov. 17–20.
[37] Sarkar A, Dey S. Scour hole downstream of aprons caused by sluices. Proc Inst Civil Eng, Water Manage J: London, UK 2005;158(June):55–64.
[38] Goel A, Verma DVS. Scour downstream of a sluice gate. ISH J Hydraulic Eng 2005;11(3):57–65.
[39] Dey S, Sarkar A. Response of velocity and turbulence in submerged wall jets to abrupt changes from smooth to rough beds and its application to scour downstream of an apron. J Fluid Mech 2006;556:387–419.
[40] Sarkar A, Dey S. Review on local scour due to jets. Int J Sediment Res 2004;19(3):210–38.
[41] Alihosseini P, Ebrahimi K, Sanei M, Mashaal M. Experimental investigation of temporal variation of scour profile downstream of submerged hydraulic jumps. In: Proceedings of the 7th Iranian conference on hydraulic. Tehran. Iran: Sh. Abbaspour University; 2008, Nov. 11–13 in Farsi.
[42] Oliveto G, Comuniello V, Onorati B. Temporal development of local scour downstream of positive-step stilling basins. Proceedings of River Flows. Izmir. Turkey; 2008, p. 1673–8, Sep. 3–5.
[43] Sarathi P, Faruque MAA, Balachandar R. Influence of tailwater depth, sediment size and densimetric froude number on scour by submerged square wall jets. J Hydra Res 2008;46(2):158–75.
[44] Omid MH, Hamidifar H, Reisi A. Effect of tailwater depth on local scour downstream of an apron. In: Proceedings of 8th international congress on Civil Engineering. Shiraz, Iran; 2009, May 11–13.
[45] Hamidifar H, Omid MH, Nasrabadi M. Bed scour downstream of sluice gates. J Water Soil 2010;24(4):728–36.
[46] Hamidifar H, Omid MH, Nasrabadi M. Scour downstream of a rough rigid apron. World Appl Sci J 2011. Accepted.
[47] Chen XIE, Siow-Y. Effect of jet-flipping on scour development downstream of a sluice gate. DHI-NTU Water & environment research centre school of civil and environmental engineering nanyang technological university, 639798 Singapore; 2012.

[48] Helal EY, Nassralla TH, Abdelaziz AA. Minimizing of scour downstream hydraulic structures using sills. Int J Civil Struct Eng 2013;3(3).

[49] Blaisdell FW. Development and hydraulic design of St. Anthony falls stilling basin. Proc J Hydraulic Eng – ASCE 1947.

[50] Negm AM, Saleh OK, Abdel-Aal GM, Sauida MF. Investigation scour characteristics downstream of abruptly enlarged basins. In: Bousmar D, Zech Y, editors, River Flow Proceedings of the International Conference on Fluvial Hydraulic, Swets & Zeitlinger, Lisse, The Netherlands; 2002, ISBN 90 5809 509 6.

[51] Abdelaziz AA. Scour depth downstream weir with opening. Int J Civil Struct Eng 2012;3(1):259–70.

[52] Chow VT. Open-channel hydraulics. New York: Mc-Graw Hill Book Co.; 1959.

[53] Fahmy Abdelhaleem Fahmy S. Effect of semi-circular baffle blocks on local scour downstream clear-overfall weirs. Ain Shams Eng J 2013;4:675–84.

Eng. Hossam has an wide experience in hydraulic applications in the field, covering the different aspects of hydraulic engineering; his good experience in planning and design an irrigation and drainage system, topographic survey, river and hydraulic structures studies, executing pump station, different hydraulic structures such as (bridges, culvert, barrage, etc.), flow in pipes, Holds an international diploma in river basins Sciences.