INFLUENCE OF MULTI-LINES OF FLOOR WATER JETS ON SCOUR HOLE BEHIND CONTROL STRUCTURES

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ABSTRACT

The accurate design of the hydraulic structures requires through prediction of scour hole dimensions. While, the economic design of the hydraulic structures requires shortening the length of the solid floor and reducing the scour hole dimensions. The objective of this research is to investigate the influence of using multi-lines of floor water jets on the expected scour hole downstream a control structure as energy dissipators. Thirty six runs were carried out using different flow discharges, jet discharges, and tailwater depths. Cases of floor without water jets were included to estimate the influence of using the suggested system. Obtained results were analyzed and graphically represented. The system of multi-lines of floor water jets reduced the maximum scour depth and scour hole length from 42 to 44% and from 41 to 45% respectively compared to the case of the floor without water jets.

Keywords: Local scour, Floor water jets, Hydraulic structure, Physical model

1. INTRODUCTION

Numerous of hydraulic structures were constructed in rivers and alluvial channels for controlling the flow of water but these structures usually exposed to scouring at downstream. Large number of hydraulic structures failed as a result of local scour undermined their foundations. Local scour downstream hydraulic structures can be defined as a phenomenon caused by turbulence and disturbances of the flow pattern due to the presence of the hydraulic structures. It is important to control local scour depth at downstream of hydraulic structures to ensure safety of these structures. The cost of protection works downstream of control structures can be reduced if suitable appurtenances are used to dissipate the excessive energy in an efficient manner. Floor water jets will help in deflecting the flow away from the canal bed.

Appurtenances such as sills, chute blocks, and baffle blocks are often installed to help in increasing the performance of a stilling basin, (Edward [1] and Peterka [2]). In addition, they are helpful in stabilizing the flow, increasing the turbulence, and distributing the velocities evenly through the basin. In some cases a reduction in the required tailwater depth and length of the basin may be possible by the addition of the appurtenances to the basin, (Edward [1]).

Sills stabilize the flow, deflect the current away from the river bottom, and may help in reducing the tailwater depth. Laboratory tests indicated that, the sill greatly increases the efficiency of the stilling basin, (Edward [1]). (Hitham, et al. [3]) studied experimentally the effect of semi-circular sill on the scour hole and hydraulic jump parameters downstream of a pipe culvert. They found that, the semi-circular sill decreased the scour hole dimensions and increased the hydraulic jump efficiency. (Negm, et al. [4]) studied experimentally multi-vents regulator laboratory model provided with curved deflector as an energy dissipation device. The curved deflector was carefully designed to be located at pre-specified positions in the basin. The scour dimensions downstream of the stilling basins were measured. Also, the velocity near to bed was measured. The curved deflector proved to be an effective tool for controlling local scour downstream of multi-vents regulators as the local scour downstream of the stilling basin which was reduced on the average by about 85% using this effective tool. (Mohammed, et al. [5]) studied experimentally the effect of downstream curvature of the spillway and its end sill angle on local scour at downstream. The spillway was modeled using hard teak wood while sand was used to simulate the erodible bed. The downstream curvature of spillway model with different end sill angle was tested. The effects of five different end sill angles on the local scour were tested. Data collected from the experiments conducted on the physical model showed a reduction of 15% in local scour depth at downstream when the end sill angle changed from 10^o to 60^o. (Saleh, et al. [6]) studied experimentally the effects of using end sills in the sudden expanding stilling basins. Stilling basins with different expansion ratios of 1.54, 2.0 and 2.5 were used to collect the scour information when a sill is installed at the end of the basin. Sills of different dimensions were tested under wide range of flow conditions. The optimal sill that reduced the extent of scour downstream of the most practical sudden expanding stilling basin was recommended.

Chute blocks are installed at the entrance of the stilling basin to increase the effective depth of the entering stream, break up the flow into a number of jets, help in creating the turbulence that are required for energy dissipation, (Edward [1] and Peterka [2]). The chute blocks also tend to lift the jet off the floor and result in a shorter basin length than would be possible without them. Baffle blocks are installed in stilling basins principally to stabilize the formation of the jump and increase the turbulence. Many different baffle block shapes have been studied by (Vischer and Hager [7], Bradly and Peterka [8], Peterka [2], El-Masry and Sarhan [9], El-Gamal [10], El-Masry [11 and 12], Helal [13] and Abdelhaleem, F. [14]) discussed the baffle blocks parameters and concluded the following recommendations:

- The optimum block front face is vertical and perpendicular to the approach flow with sharp corners.
- One row of block is used because the effect of the second row or staggered block row is small relative to the first one.
- Baffle blocks should not be used for approach velocity above 20 m/sec.
- The floor blocks should occupy between 40 and 55 percent of the floor width.

Herein, this study is concerned with the installation of multi-line of water jets to the floor of the structure under different flow conditions to minimize the scour hole parameters.

2. PROBLEM DEFINITION

To study the effect of multi-lines of floor water jets on scour hole parameters downstream of control structure, the flow over a plane solid floor and over a solid floor having multi-lines of floor water jets should be clarified as follow :-

2.1 Hydraulic Jump over a Plane Solid Floor

A hydraulic jump is formed over a plane solid floor as result of constructing a control structure across the channel. The solid floor length is usually designed to confine the entire length of the hydraulic jump. If the average velocity of the flow just downstream of the solid floor is greater than the critical velocity of the bed material, scour hole will be deformed just downstream of the solid floor. The eroded material will be transported in the downstream direction to a place where the sediment load is equal to the sediment transport capacity. The deposited material will form a mound just downstream of the scour hole. The depth and length of the scour hole will increase with time and the mound size will also increase consequently the water depth just downstream of the hydraulic jump will increase consequently the average velocity of the flow will decrease with time and sequentially the rate of the scour will decrease with time till the scour ceases. At that moment the scour hole reaches equilibrium, where no further erosion takes place,(Abedel Razek and Baghdadi [15]).

2.2 Hydraulic Jump over a Solid Floor Having Multi-Floor Water Jets

As mention in the previous section, the solid floor length is usually designed to confine the entire length of the hydraulic jump, because such a floor would be too expensive. Consequently, appurtenances should be added to the solid floor to control the jump. Floor water jets used here as an appurtenance. When the flow strikes the upward water jets from the floor, the flow is deflected upward. Eddy currents produced by the upward water jets from the floor and the deflected upward flow dissipate a considerable amount of energy. The floor water jets stabilize the hydraulic jump, deflect the current away from the movable bed and redistribute the flow velocities. So that maximum equilibrium scour depth and scour hole length will be decreased, Fig. (1).

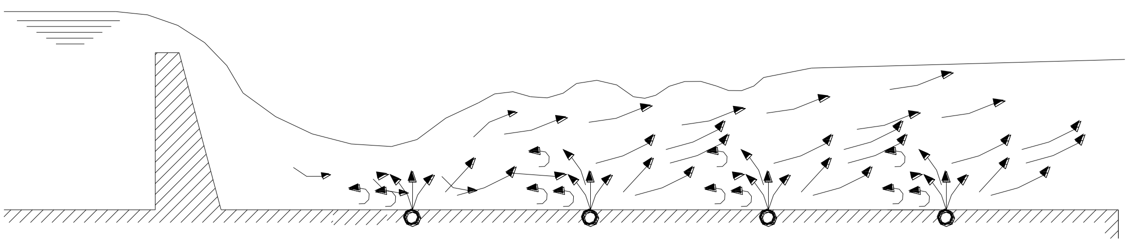

Fig. 1 Flow pattern of the suggested system

3. EXPERIMENTAL SETUP

The experimental investigations were carried out at the hydraulic laboratory of Civil Engineering Department menoufia University, Egypt. The recirculating flume was shown in Fig. (2), of 18 m long, 60 cm wide and 60 cm deep. The apparatus consists of head and tail tanks and the flume through which the flow was conveyed. Water was pumped to the head tank from ground sump. A bolder gravel box was fixed at the beginning of the flume downstream of the head tank to absorb any water eddies. Rectangular calibrated sharp crested weir was built up at the downstream end of the by-pass channel to measure the discharge passed through the channel. The weir is of 51 cm width and sharp edges manufactured from copper. The flow discharges measured by the sharp crested weir and checked by a flow meter. A tail gate was located downstream of the channel, it was used to control the downstream water depth. For measuring the water depths and bed levels at different reaches of the channel, an x-y carriage was constructed on two rails on the two sides of channel. The carriage can be moved along the whole length of the channel. While the point gauge was fitted on the carriage and used to measure both the water levels and bed levels in the longitudinal and the cross-section directions of the channel. The point gauge can measure the depths to an accuracy of 0.1 mm.

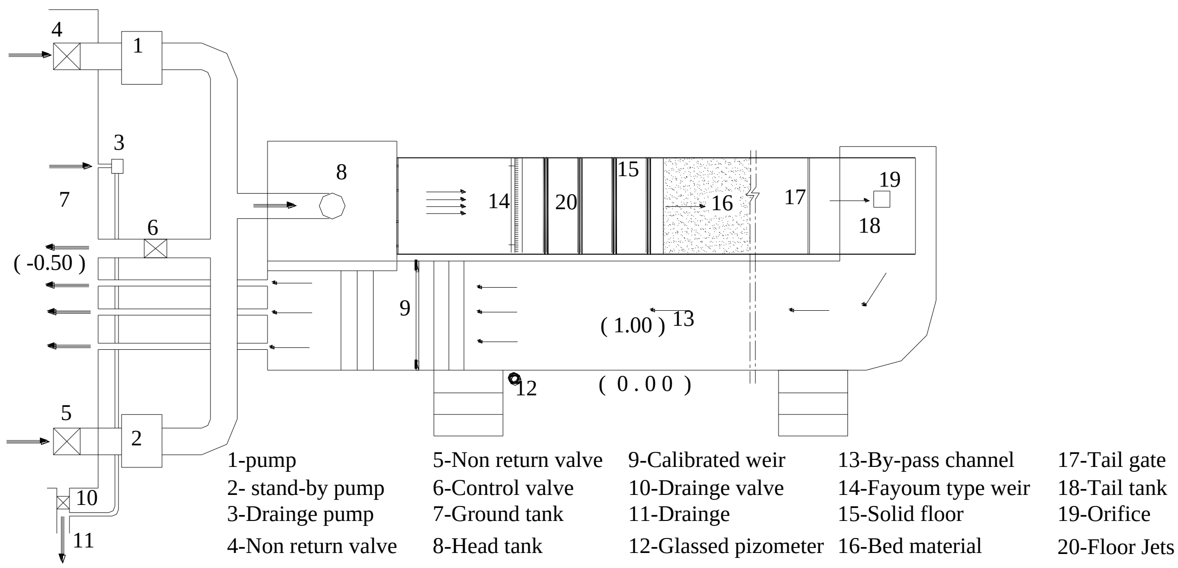

Fig. 2 Definition sketch of the testing flume.

The control structure was a weir made of timber with 5 cm crest width, 50 cm crest length, 19.7 cm height, slope of 1: 3, and two side contraction wing walls each of 5 cm width. These two side walls were used to fix a rubber punched pipeline used as aeration at the toe of the weir. A solid floor of length 1.0 m, and 0.60 m width was made of Perspex to avoid the deformations under the action of water. The floor was fixed on wooden frames every 20 cm. The solid floor was punched to fix rows of the water jets, Fig. 3. The movable bed was simulated by sand of mean particle size D_{50} = 0.7 mm and standard deviation σ =1.7. The grain size of the material forming the erodible bed and test run were kept the same for all the test runs to provide proper comparison under similar conditions. The water jets were pumped from pipes which were fixed embedded in the solid floor made of P.V.C of 2.5 cm diameter. The distances between water jets lines in the direction of flow were equal to one fifth of the floor length ($L_f/5$). The jet discharge was controlled using system of control valves and measured using flow meter. The jet discharge was pumped from the embedded pipes in the solid floor taking the upward direction striking the main flow.

4. EXPERIMENTAL APPROACH

In this study, thirty six runs were conducted and were categorized into two sets for each set of experimental work, three values of discharge were used (Q= 10.6, 13.94 and 17.57 L/S), Table 1. For each value of discharge, three values of downstream water depth were used. The first set of experimental runs was carried out on floor without water jets. This set included 9 runs and were considered as a reference in order to estimate the influence of using floor water jets. The second set of experimental runs, which was carried out using multi-floor water jets, three jets discharges were used (Q_j= 0.40, 0.80 and 1.60 L/S), Fig. 3, table 1. This set included 27 runs.

Table (1) Flow conditions for the tested model

Q (L/S)	Y_t (cm)	F_r (-)	Q_j (L/S)
10.6	8	0.2494	0.4
	10	0.1785	0.8
	12	0.1357	1.6
13.94	9	0.2748	0.4
	11	0.2033	0.8
	13	0.1583	1.6
17.57	10	0.2956	0.4
	12	0.2249	0.8
	14	0.1785	1.6

5. EXPERIMENTAL PROCEDURES

After the flume was filled with sand and accurately leveled, the tail gate was completely closed, downstream feeding was started first until its depth reached higher than the required downstream water depth, and then upstream feeding was started. The floor water jets discharge was controlled. Tailgate was tilted gradually until required downstream water depth was adjusted. After many trials, four hours were chosen as a constant time for all runs. After this time, there was no appreciable change in scour hole dimensions. After the running time, the run was stopped and the flume was evacuated. Scour hole profile along the center line of the flume was recorded with the point gauge.

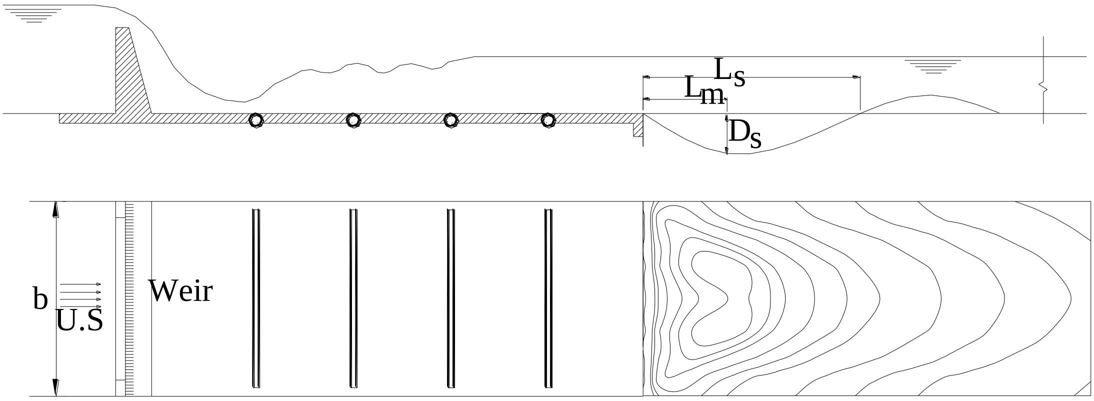

Fig. 3 Layout of the considered case of jets arrangements

6. DIMENSIONAL ANALYSIS

The local scour downstream of a weir with a horizontal floor depends on a large number of flow variables. The considered dimensional parameters were as follow, Fig. (3):-

- Tail water depth which was measured at the downstream of the flume away from the effect of control structure and tail gate, Y_t,
- Channel discharge, Q,
- Floor water jets discharge, Q_j,
- Maximum scour depth, D_s,
- Scour hole length, L_s,
- The distance between floor end and the location of maximum scour depth, L_m,
- Maximum scour depth in case of floor without water jets, D_{sw},
- Scour hole length in case of floor without water jets, L_{sw},
- The distance between floor end and the location of maximum scour depth in case of floor without water jets, L_{mw},.

From the dimensional analysis, the considered dimensionless relationships can be obtained as follows:-

$$D_s/Y_t = f\,(F_r^{-2}, Qj/Q) \quad (1)$$
$$D_s/D_{sw} = f\,(F_r^{-2}, Qj/Q) \quad (2)$$
$$L_s/Y_t = f\,(F_r^{-2}, Qj/Q) \quad (3)$$
$$L_s/L_{sw} = f\,(F_r^{-2}, Qj/Q) \quad (4)$$
$$L_m/Y_t = f\,(F_r^{-2}, Qj/Q) \quad (5)$$
$$L_m/L_{mw} = f\,(F_r^{-2}, Qj/Q) \quad (6)$$

In which F_r was the tail Froude number calculated at the location which tail water depth, Y_t, was measured.

7. EXPERIMENTAL RESULTS AND ANALYSIS

Experimental results were expressed in dimensionless forms and graphically represented to study the effects of the suggested system of multi-floor water jets on scour hole parameters.

7.1 Effect of Multi-Floor Water Jets on Maximum Scour Depth

To illustrate the effect of values F_r^{-2} on the values of D_s/D_{sw} for the case of multi-floor water jets, Fig (4) clarify the relationship between them for different relative jets discharge, Q_j/Q. From this figure it was obvious that, the suggested system of multi-floor water jets reduced the maximum scour depth under most of the flow conditions compared to the scour of the case without multi-floor water jets. It was clear that increasing the values of Q_j/Q decreases the values of $D_s/D_{sw.}$ It was also obvious that, the highest value of relative jets discharge, Q_j/Q=0.15, gave the minimum values of D_s/D_{sw}, meaning that, the highest values of relative jets discharge gave the maximum reduction of scour depth which ranged from 42 to 44%. For the the highest value of relative jets discharge, Q_j/Q=0.15, the effect of the values of Froude number on the values of D_s/D_{sw} was not significant than that of the other values of Q_j/Q. it was apparent that, increasing the relative jets discharge dissipates more energy and redistributes the velocities. It is concluded that, the suggested system of floor water jets gives a good energy dissipation means which presented by reducing the values of D_s/D_{sw}, this may be due to the effect of the upward current which deflect the flow away from the movable bed and increasing the turbulence which dissipate amount of energy

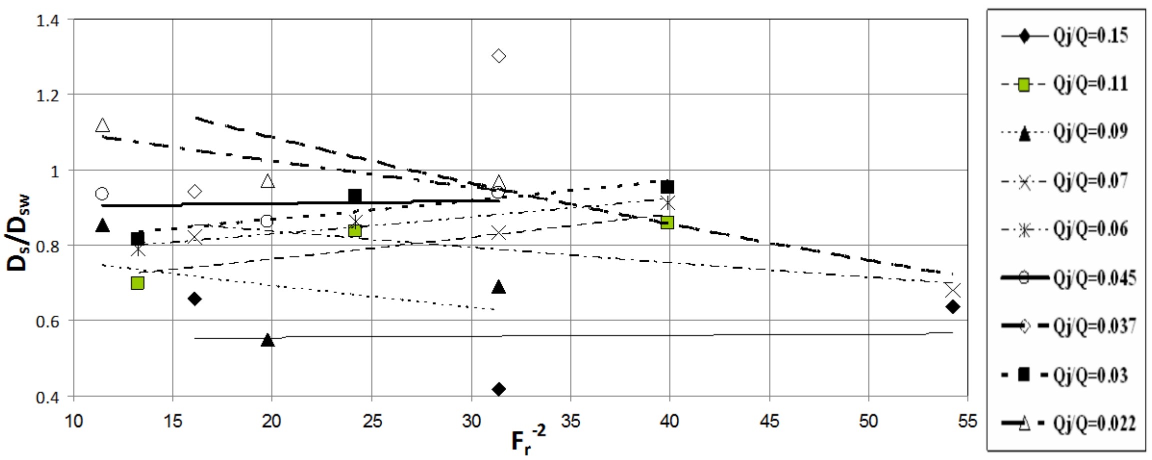

Fig. 4 Relationship between D_s/D_{sw} and F_r^{-2} for different water jets discharge

Relationships between the values of D_s/Y_t and F_r^{-2} were illustrated in Fig.5 considering the values of the water jets discharge. It was clear that, for all values of Q_j/Q increasing the values of F_r^{-2} decreases the values of D_s/Y_t. For the lower values of F_r^{-2} the effect of the values of Q_j/Q on the values of D_s/Y_t was more significant than that for the higher values.

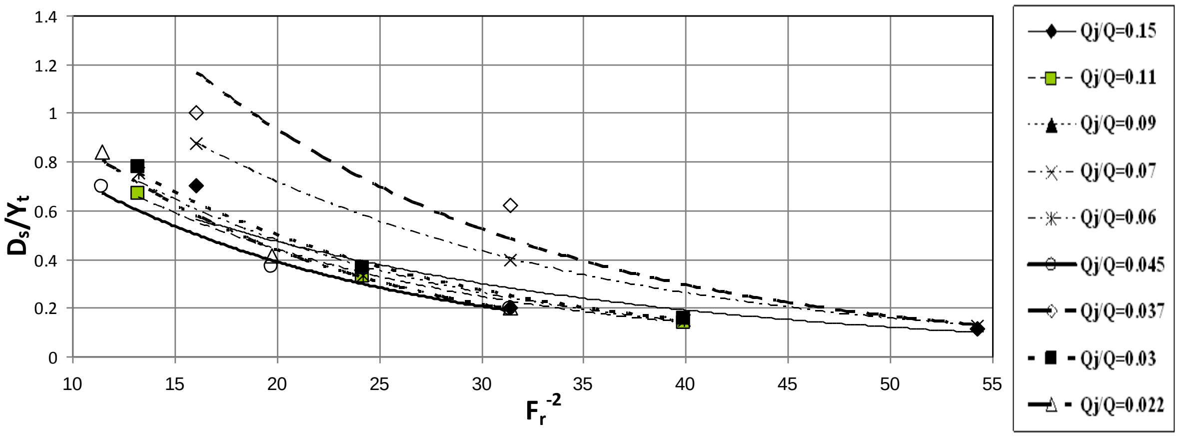

Fig 5. Relationship between D_s/Y_t and F_r^{-2} for different water jets discharge

7.2 Effect of Multi-Floor Water Jets on Scour Hole Length

Relationships between the value of L_s/L_{sw} and F_r^{-2} for different values Q_j/Q were illustrated as shown in Fig.6. This figure showed that the suggested system of multi-floor water jets reduced the scour hole length under most of the flow conditions compared to the scour hole length of the case without multi-floor water jets. It was obvious that, increasing the values of Q_j/Q decreases the values of $L_s/L_{sw.}$ It was also obvious that, the highest value of relative jets discharge, $Q_j/Q=0.15$, gave the minimum values of L_s/L_{sw}, meaning that, the highest value of relative jets discharge gave the maximum reduction of scour hole length which ranged from 41 to 45%. For the lower values of F_r^{-2}, it was clear that, the effect of the values of relative jets discharge, Q_j/Q on the values of L_s/L_{sw} was more significant than that of the higher values. It was obvious that, increasing that the values of F_r^{-2} decreases the values of L_s/L_{sw}.

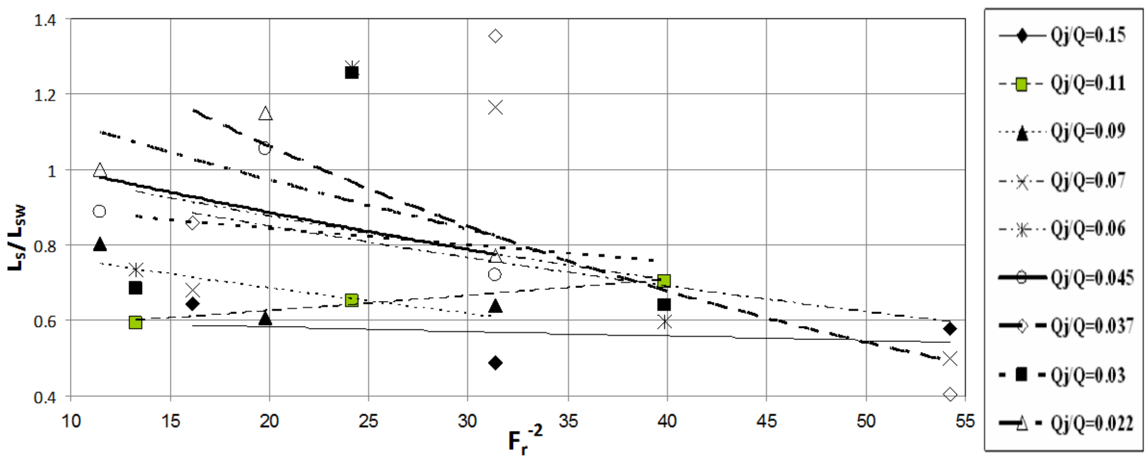

Fig. 6 Relationship between L_s/L_{sw} and F_r^{-2} for different water jets discharge

Relationships between the values of L_s/Y_t and F_r^{-2} were illustrated in Fig.7 considering the water jets discharge. From this figure it was obvious that, increasing the values of F_r^{-2} decreases the values of L_s/Y_t. For the higher values of F_r^{-2} the effect of water jets discharge on the values of L_s/Y_t was less significant than that of lower values of F_r^{-2}.

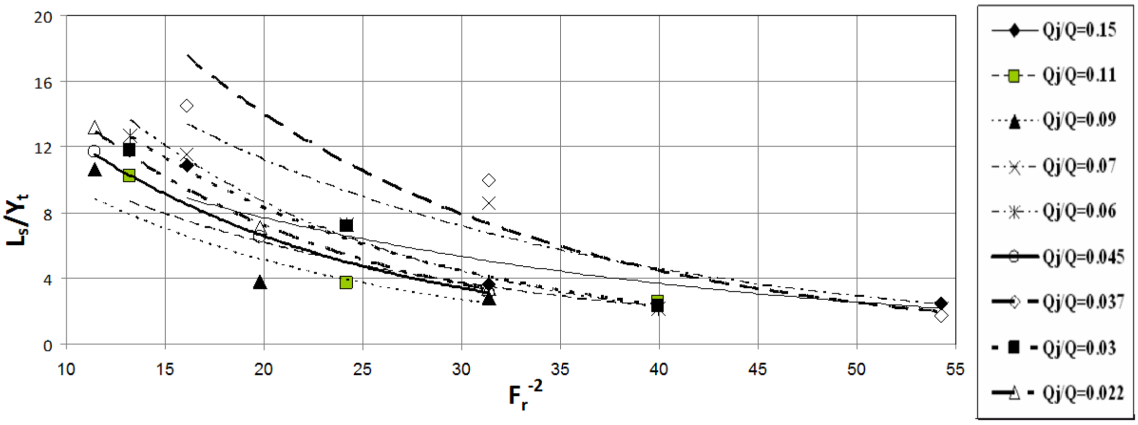

Fig. 7 Relationship between L_s/Y_t and F_r^{-2} for different water jets discharge

7.3 Effect of multi-floor water jets on the Distance between floor end and location of maximum scour depth

Fig. 8 showed that , the suggested floor water jets system reduced the distance from the maximum scour depth to the toe of the solid floor under most of the flow conditions compared to that of the case without water jets consequently decreases the cost of maintenance by shortening the distance which was required maintenance. It was clear that, for all values of relative jets discharge and F_r^{-2} there was not an obvious trend of the effect of the values of Q_j/Q and F_r^{-2} on the values of L_m/L_{mw}.

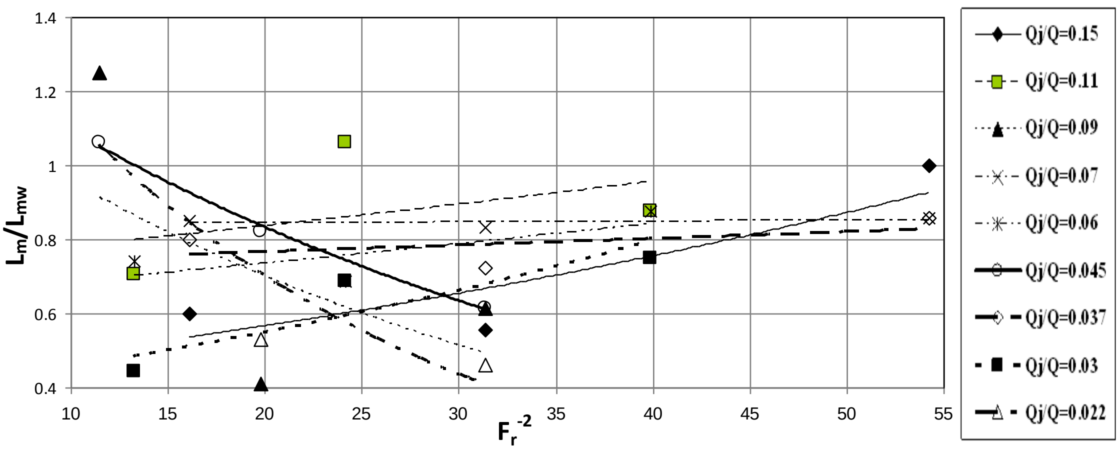

Fig. 8 Relationship between L_m/L_{mw} and F_r^{-2} for different water jets discharge

Fig. 9 illustrated the relationships between L_m/Y_t and F_r^{-2} for different water jets discharge. It was clear that, increasing the values of F_r^{-2} decreases the values of L_m/Y_t. It was obvious that, the effect of the values of Q_j/Q on the values of L_m/Y_t was almost the same for all values of F_r^{-2}.

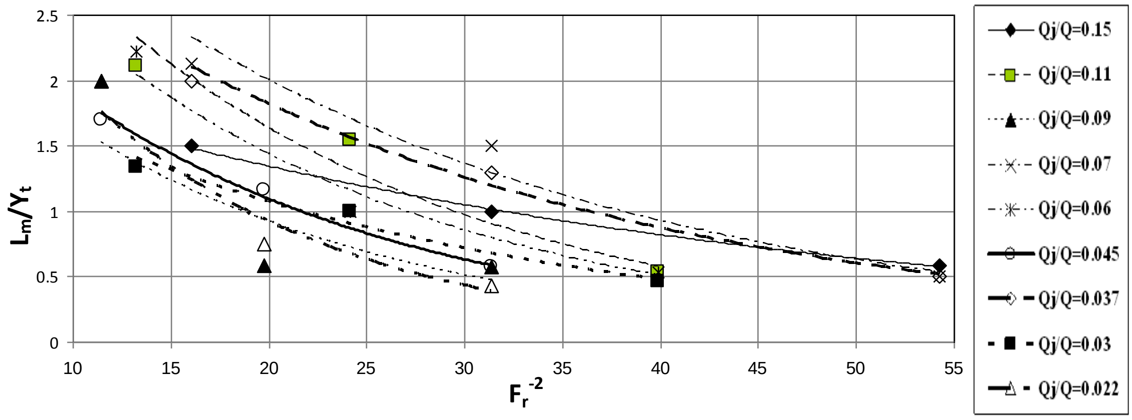

Fig. 9 Relationship between L_m/Y_t and F_r^{-2} for different water jets discharge.

8. EVALUATION OF SCOUR HOLE PARAMETERS

The maximum scour depth and the scour hole length are important design factors. Thus, experimental results were utilized for developing the following empirical formulas using the statistical methods (regression analysis), (using Data Fit software program):

$$\frac{D_S}{Y_t} = -41.5\ F_r^{\ 2} + 1247\ F_r^{\ 4} - 8615\ F_r^{\ 6}\ -1.04\left(\frac{Q_j}{Q}\right) + 0.623 \qquad \textbf{(1)}$$

$$\frac{L_S}{Y_t} = -550\,F_r^{\ 2} + 16691\ F_r^{\ 4} - 113453\ \ F_r^{\ 6} - 19.69\left(\frac{Q_j}{Q}\right) + 9.47 \qquad \textbf{(2)}$$

Eqs.1 and 2 are valid for the used flow conditions with correlation R^2 equal to 0.80 and 0.77, respectively.

9. CONCLUSIONS

Based on the results of experimental study the following conclusions have been drawn, which are valid for the range of the obtained experimental data:

- The suggested system:
  1. Reduced the maximum scour depth.
  2. Reduced the scour hole length.
  3. Moved the location of maximum scour depth closer to the floor.
  4. Consequently reduced the cost of maintenance by shortening the depth and the distance which are required maintenance.
- Increasing the relative multi-floor water jets discharge:
  1. Decreases maximum depth.

   2. Decreases the scour hole length.
- The suggested system of multi-floor water jets decreased:
   1. The maximum scour depth ranged from 42 to 44%.
   2. The scour hole length ranged from 41 to 45%.
- Decreasing Froude number led to:
   1. Decreasing the maximum scour depth.
   2. Decreasing the scour hole length.
   3. Moving the location of maximum scour depth towards of the floor end.

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NOMENCLATURE

B Channel width,
b Basin width,
D_s Maximum scour depth,
D_{sw} Maximum scour depth in the case of floor without water jets,
D_{50} Median size of bed material,
F_r Tail Froude number,
L_f Floor length,
L_m Distance between floor end and location of maximum scour depth,
L_{mw} Distance between floor end and location of maximum scour depth in case of floor without jets,
L_s Scour hole length in flow direction,
L_{sw} Scour hole length in case of floor without jets,
Q Channel discharge,
Q_j Jets discharge,
Y_t Tail water depth, and
σ Standard deviation of bed material.

REFERENCES

[1] Edward, A. E., "Hydraulic Energy Dissipators", Mc-Graw Hill Book Co., INC, New York, Toronto, London, 1959.

[2] Peterka, A.J., "Hydraulic Design of Stilling Basin and Energy Dissipators", U.S. Dept. of the Interior, Bureau of Reclamation, Washington, D.C., 1978.

[3] Hitham, A.S, Helal, E. Y, Ibrahim, S.A. and Sobeih M. F., "Minimizing of Scour Downstream Hydraulic Structures Using Semi-Circular Sill", Menoufia Eng.Jour. Vol. 35, No.2, April, 2012.

[4] Negm, A. M. Abdel-Aal, G. M., Elfiky, M. M. and Mohamed, Y. A. "Optimal Position Of Curved Deflector To Minimize Scour Downstream Multi-Vents Regulators" *Proceedings of the 12Th International Water Technology*

Conference, IWTC12 2008, Alexandria, Egypt.

[5] Mohammed, T.A., Megat Mohd Noor, M. J., Huat, B.K., Ghazali, A. H., Yunis, T.S. "Effect Of Curvature And End Sill Angle On Local Scouring At Downstream Of A Spillway" *International Journal of Engineering and Technology*, Vol. 1, No. 1, 2004, pp. 96 – 101

[6] Saleh, O. K., Negm, A. M., and Ahmad, N. G., "Effect of Asymmetric Side Sill on Scour Characteristics Downstream of Sudden Expanding Stilling Basin", *Proceedings of Al-Azhar Eng. 7th International Conf.*, Cairo, Egypt, April 2003.

[7] Vischer, D.L. and Hager, W.H. "Energy Dissipators", Hydraulic structures design manual, IAHR, 1995.

[8] Bradley, J. M., and Peterka, A. J., "The Hydraulic Design of Stilling Basin", *Journal of Hydraulic Division, ASCE*, Vol. 83, No.5, July 1957.

[9] El-Masry, A. A, and Sarhan, T.E., "Minimization of Scour Downstream Heading-Up Structure Using a Single Line of Angle Baffles", *Engineering Research Journal, Helwan Univ.*, Vol. 69, June 2000.

[10] El-Gamal, M. M., "Effect of Using Three-lines of Angle Baffles on Scour Downstream Heading-Up Structure", *Mansoura Engineering Journal*, Vol. 26, No. 2, June 2001.

[11] El-Masry, A.A., "Minimization of Scour Downstream Heading-Up Structures Using Double Line of Angle Baffles", *Proceedings of the* 6th *Int. Water Technology Conf. (IWTC),* Alexandria, Egypt, 2001.

[12] El-Masry, A.A, "Influence of a Fully Angle Baffled Floor on Scour Behind a Hydraulic Structure", *Mansoura Engineering Jour*nal, Vol. 26, No.4, December 2001.

[13] Helal, E. Y. "Minimizing of Scour Downstream Hydraulic Structures Using Semi-Circular Baffles", M.Sc. Thesis, Civil eng. Dept., EL Menoufia Univ., 2004.

[14] Fahmy S. Abdelhaleem. "Effect of semi-circular baffle blocks on local scour downstream clear-overfall weirs", *Ain Shams Eng. Journal.* Elsevier, available online on elsevier.com/locate/asej www.sciencedirect.com. April 2013.

[15] Abdel Razek, M. and Baghdadi, H.K., "Sill Effect on Local Scour Downstream Gates", *Alexandria Engineering Journal*, Vol. 35, No. 5, Sept. 1996.