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Minimizing scour downstream of hydraulic structures using single line of floor water jets

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Abstract Local scour downstream of control structures may result in damage or complete failure of the control structure. In this paper, one hundred and seventeen runs were carried out to study the effect of single line of floor water jets on the scour hole parameters downstream of a control structure (Fayoum type weir) with different jet discharges, locations, 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 suggested system is easy to be used as an extra element to the existing structures to increase the performance of stilling basin. Results indicated that the system of suggested floor water jets gave from 50% to 90% reduction in maximum scour depth and from 42% to 85% reduction in scour hole length compared to the case of the floor without water jets.

1. Introduction

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. Operating any hydraulic-energy dissipators depends largely on expending a part of the energy of the high-velocity flow by boundary shear stress. 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]. Abdallah [3] studied the influence of both the height and the shape of end sill on the scour hole dimensions downstream of solid apron. He found that the sill height had a great effect on scour hole dimensions than the sill shape. Nashat [4] studied experimentally the proper location of floor sill which minimized the scour downstream of heading-up structure. Abdel Razek and Baghdadi [5] studied experimentally the influence of sills upon the scour characteristics. They investigated the effect of gate opening, downstream

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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_j	distance from the weir toe to the location of the water jet
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
$\tan\alpha_s$	scour index ($\tan\alpha_s = 2D_s/L_m$)
$\tan\alpha_{sw}$	scour index in case of floor without jets ($\tan\alpha_s = 2D_{sw}/L_{mw}$)
σ	standard deviation of bed material

Froude number, relative length of the apron, height of the sill, and the distance between the gate and the sill on the formation of local scour downstream of the apron. They concluded that the maximum scour depth decreased with the increase in the distance between the sill and the gate until it reached its maximum reduction at a distance from the gate equals one third of the apron length. Saleh et al. [6] studied the effect of a symmetric side sill on the scour hole characteristics downstream of sudden expanding stilling basin. Determination of the optimum location of a symmetric side sill was the main objective of that study. Hitham et al. [7] studied experimentally the effect of semicircular sill on the scour hole and hydraulic jump parameters downstream of a pipe culvert. They found that the semicircular sill decreased the scour hole dimensions and increased the hydraulic jump efficiency.

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, and help in creating the turbulence that is 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. Baffle blocks are normally arranged in one or several rows that are oriented perpendicular to the direction of approach flow. Baffle blocks help to compensate slight deficiency of tailwater, and for high flow, they help to deflect the flow away from the river bed. Pillai [8,9] studied the effect of using wedge-shaped baffle blocks of vertex angle 120° cut back at right angle. Good results were obtained for Froude number ranged between 5 and 9. Vischer and Hager [10], Bradley and Peterka [11], Peterka [2], El-Masry and Sarhan [12], El-Gamal [13], El-Masry [14,15], and Helal [16] 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/s.
- The floor blocks should occupy between 40% and 55% of the floor width.

Abdelhaleem et al. [17] studied experimentally the effect of using three different shapes of corrugated beds on the characteristics of a hydraulic jump and downstream of local scour. The study confirmed the effectiveness of corrugated beds for energy dissipation downstream of hydraulic structures and corrugating the stilling bed can decrease the cost of stilling basin. Sobeih et al. [18] studied experimentally the openings fixed in the body of weirs. Three cases of opening arrangements were included: no opening, one opening, and three openings. Empirical formula was developed for estimating scour hole depth in terms of downstream of flow conditions, Froude number, height of the weir, number of openings, area of openings, and diameters and heights of the openings.

Herein, this study is concerned with the installation of a single row of water jets to the floor of the structures in various locations under different flow conditions to minimize the scour hole parameters.

2. Criteria for performance evaluation

There are two factors that should be taken into consideration in evaluating the performance of stilling basin: firstly, the safety of the structure against scour and secondly the cost of maintenance. The safety of the structure against scour and the cost of maintenance depend on both of maximum scour depth, D_s, scour hole length, L_s, and the distance of maximum scour depth from the toe of the solid floor, L_m Fig. 1. The safety of the structure against scour required smallest scour depth and its location should be farthest from the toe of the

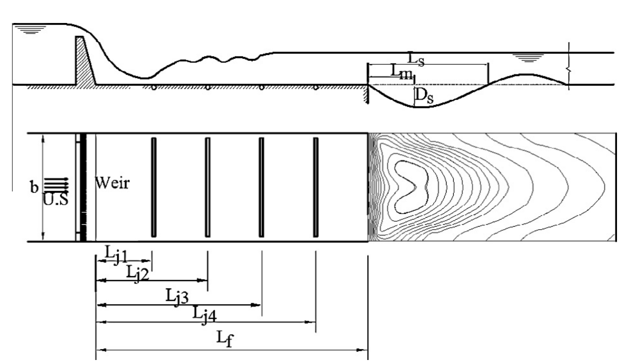

Figure 1 Layout of the considered case of jets arrangements.

solid floor, but the economic cost of maintenance required smallest scour depth and its location should be nearest to the toe of the solid floor, so that combining both these effects, a scour index ($\tan\alpha_s = 2D_s/L_m$) could be considered for the purpose of comparison of performances under similar conditions. If the scour pattern is assumed to be parabolic, the scour index $\tan\alpha$ is the slope of the tangent drawn to the base parabola of the scour hole at the toe of the solid floor, Verma and Goel [19].

3. Experimental setup

The experimental investigations were carried out in the hydraulic laboratory of Civil Engineering Department Menofia University, Egypt. The model was tested in a recirculating flume of 18 m long, 60 cm wide, and 60 cm deep Fig. 2. 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, and 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. The point gauge was fitted on the carriage and used to measure both the water levels and the bed levels in the longitudinal and the cross-sectional directions of the channel. The point gauge can measure the depths to an accuracy of 0.1 mm.

A Fayoum type weir made of timber was used as a heading-up structure. The weir has 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 1.0 m length 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. 1. 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 PVC of 2.5 cm diameter. The distances between water jets line 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, one hundred and seventeen runs were conducted and were categorized into two sets for each set of experimental work, and 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 was 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 single line of water jet, included four locations of floor jets where L_j/L_f = 0.2, 0.4, 0.6, and 0.8. For each location of water jet, three jet discharges were used (Q_j = 0.40, 0.80, and 1.60 L/S), Fig. 2, Table 1. This set included 108 runs.

5. Experimental procedures

After the flume was filled with bed material 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 water jet 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,

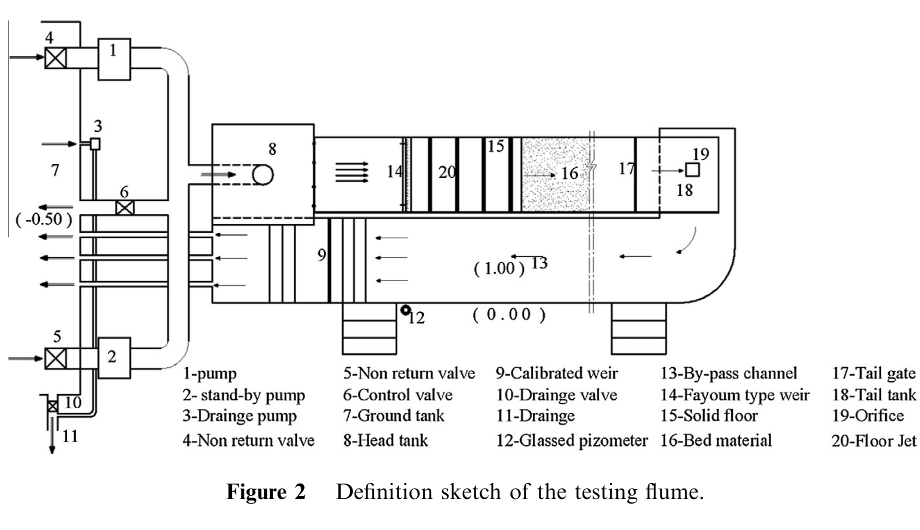

Figure 2 Definition sketch of the testing flume.

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

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.

6. Experimental results and analysis

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, Fig. 3. Apparently, the floor water jets are an important agent to damp out the excess of energy downstream of hydraulic structure and also provide better performance of stilling basin.

Data of 117 tests were reduced to dimensionless form and graphically presented to illustrate the effect of floor water jets on scour hole parameters downstream of the hydraulic structures. The considered dimensional parameters were tail water depth which was measured at the downstream of the flume away from the effect of control structure and tail gate, Y_t, flume discharge, Q, floor water jets discharge, Q_j, the location of water jet, L_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 jets, D_{sw}, scour hole length in case of floor without jets, L_{sw}, and the distance between floor end and the location of maximum scour depth in case of floor without jets, L_{mw}. From the dimensional analysis, the considered dimensionless parameters were D_s/D_{sw}, D_s/Y_t, L_s/L_{sw}, L_s/Y_t, L_m/L_{mw}, L_m/Y_t, L_j/L_f, F_r^{-2}, Q_j/Q, and $\tan\alpha_s/\tan\alpha_{sw}$, in which F_r was the tail Froude number calculated at the location which tail water depth, Y_t, was measured.

Relationships between the value of D_s/D_{sw} and F_r^{-2} for different values of L_j/L_f and Q_j/Q were illustrated as shown in Fig. 4. This figure showed that the suggested floor water jets system reduced the scour depth under most of the flow conditions compared to the scour of the case without water jets except for the last water jet location (L_j/L_f = 0.8) where the reduction in the scour depth was less than expected. It was also clear that the second location of water jet (L_j/L_f = 0.4) gave the minimum values of D_s/D_{sw}, meaning that the location of the second line of floor water jet gave the maximum reduction in scour depth which ranged from 50% to 90%. For the optimum location of water jet (L_j/L_f = 0.4), the effect of floor water jet discharges on D_s/D_{sw} was less significant than that of the other locations of floor water jet. For the optimum location of water jet (L_j/L_f = 0.4), increasing the values of jet discharge led to increase the values of D_s/D_{sw}. The last location (L_j/L_f = 0.8) gave the highest values of D_s/D_{sw}. It was apparent that the location of floor water jets near the initial depth of the hydraulic jump provided a better dissipation of the energy, which presented by the smallest values of D_s/D_{sw}, and this may due to the smallest water depth of the flow at that location, which needed small efforts to dissipate the excess energy, to damp the water sheet, and to distribute the velocities; however, when the water jets moved toward, the toe of the floor the values of D_s/D_{sw} increased, which may be due to the water jet additional eddies near the end of the solid floor. For the lower values of F_r^{-2}, the effect of water jet discharges on the values of D_s/D_{sw} was less significant than that of higher values of F_r^{-2}.

Fig. 5 illustrated the relationship between D_s/Y_t and F_r^{-2} for different water jet locations and discharges, and it was obvious that for most flow conditions, all the locations of the floor water jets gave values of D_s/Y_t smaller than that of the case of floor without water jets (Q_j/Q = 0) except for the last water jet location (L_j/L_f = 0.8). It was clear that increasing the values of F_r^{-2} decreases the values of D_s/Y_t. For the optimum location of water jet (L_j/L_f = 0.4), the effect of relative discharges on the values of D_s/Y_t was smaller than that of the other locations of water jets. For the higher values of F_r^{-2}, the effect of water jet discharges on the values of D_s/Y_t was less significant than that of lower values of F_r^{-2}.

Relationships between the value of L_s/L_{sw} and F_r^{-2} are illustrated in Fig. 6 considering the values of L_j/L_f and Q_j/Q. This figure showed that the suggested floor water jets system reduced the scour hole length under most of the flow conditions compared to the scour of the case without water jets except for the last water jet location (L_j/L_f = 0.8) where the reduction in the scour hole length was less than expected. It was also clear that the second location of water jet (L_j/L_f = 0.4) gave the minimum values of L_s/L_{sw}, meaning that the location of the second line of floor water jet gave the maximum reduction in scour hole length range from 42% to 85%. For the optimum location of water jet (L_j/L_f = 0.4), the effect of floor water jet discharges on L_s/L_{sw} was less significant than that of the other locations of floor water jet. For the optimum location of water jet (L_j/L_f = 0.4), increasing the values of jet discharge led to increase the values of L_s/L_{sw}. The last location (L_j/L_f = 0.8) gave the highest values of L_s/L_{sw}, and this may

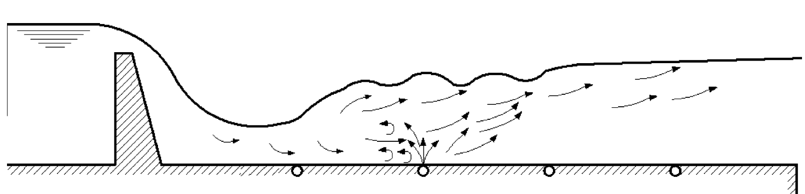

Figure 3 Flow pattern of the suggested system.

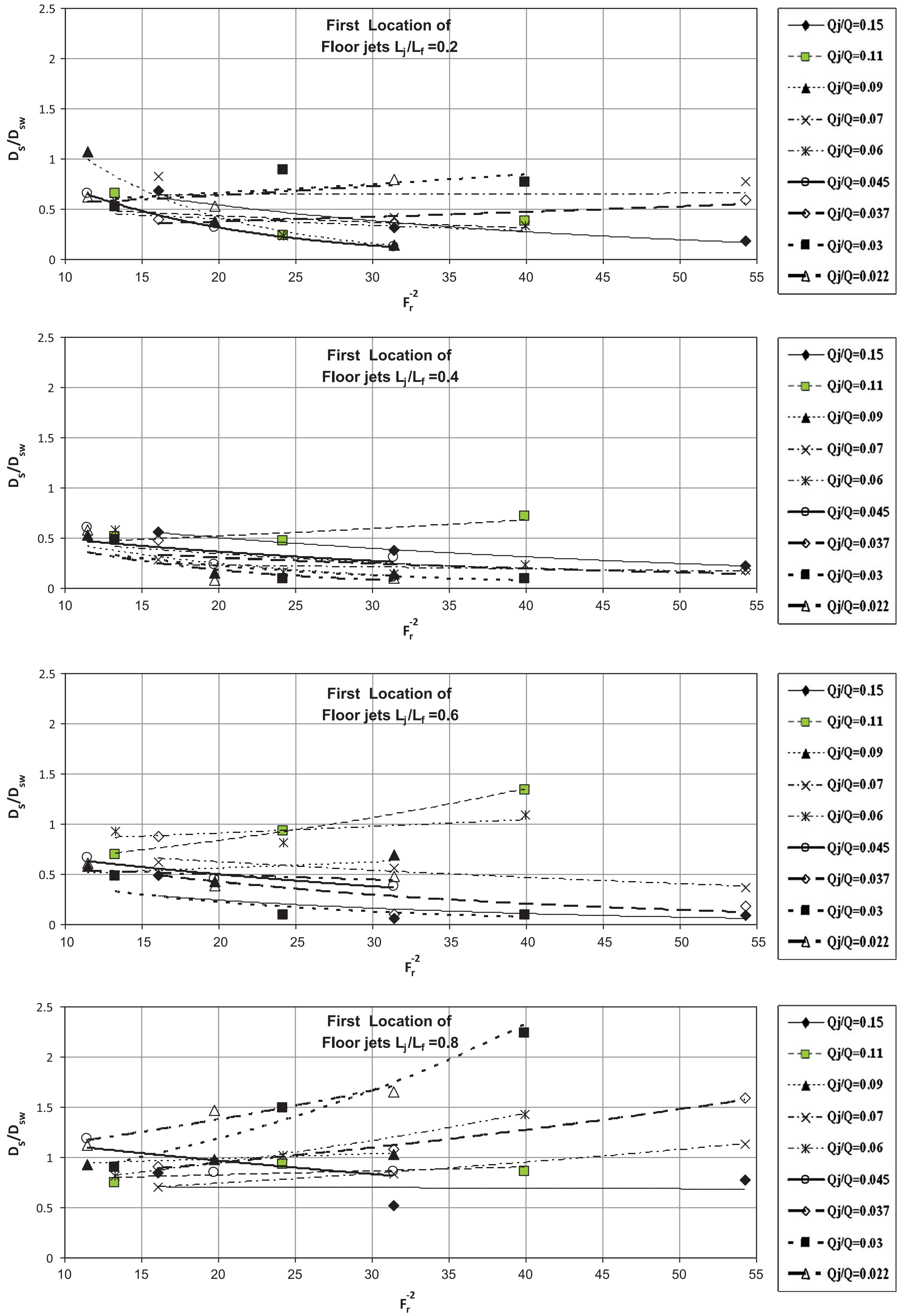

Figure 4 Relationship between D_s/D_{sw} and F_r^{-2} for different water jet locations and discharges.

be due to the water jet additional eddies near the end of the solid floor. For the lower values of F_r^{-2}, the effect of water jet discharges on the values of L_s/L_{sw} was less significant than that of higher values of F_r^{-2}.

Relationships between the values of L_s/Y_t and F_r^{-2} are illustrated in Fig. 7 considering the water jet locations and discharges. It was obvious that for most flow conditions, all the locations of the floor water jets gave values of L_s/Y_t smaller

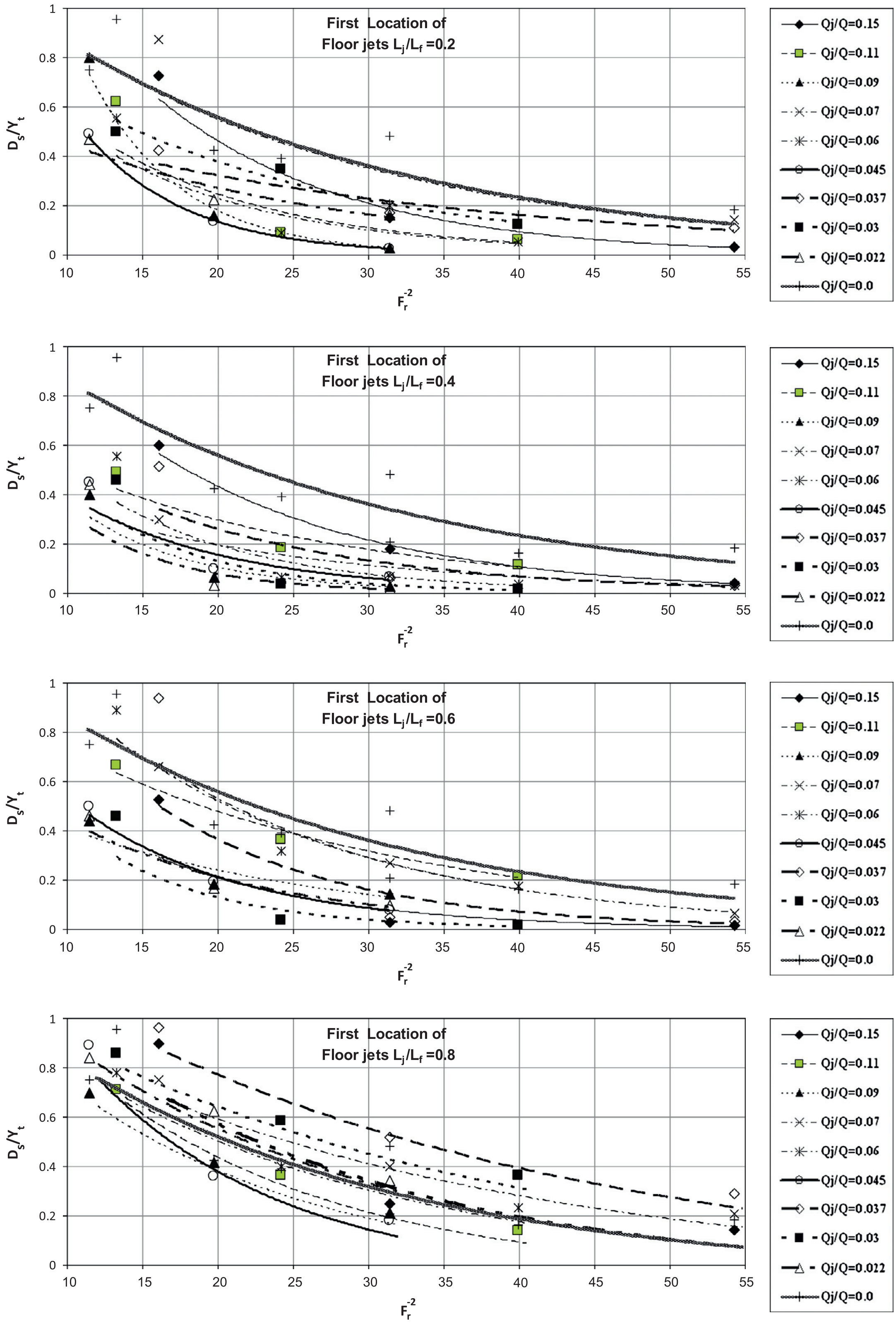

Figure 5 Relationship between D_s/Y_t and F_r^{-2} for different water jet locations and discharges.

than that of the case of floor without water jets ($Q_j/Q = 0$) except for the last water jet location ($L_j/L_f = 0.8$). From Fig. 7, it was obvious that increasing the values of F_r^{-2} decreases the values of L_s/Y_t. The effect of water jet discharges on the values of L_s/Y_t increased as the line of water jet moved toward the solid floor end. For the higher values of F_r^{-2}, the effect of water jet discharges on the values of L_s/Y_t was less significant than that of lower values of F_r^{-2}.

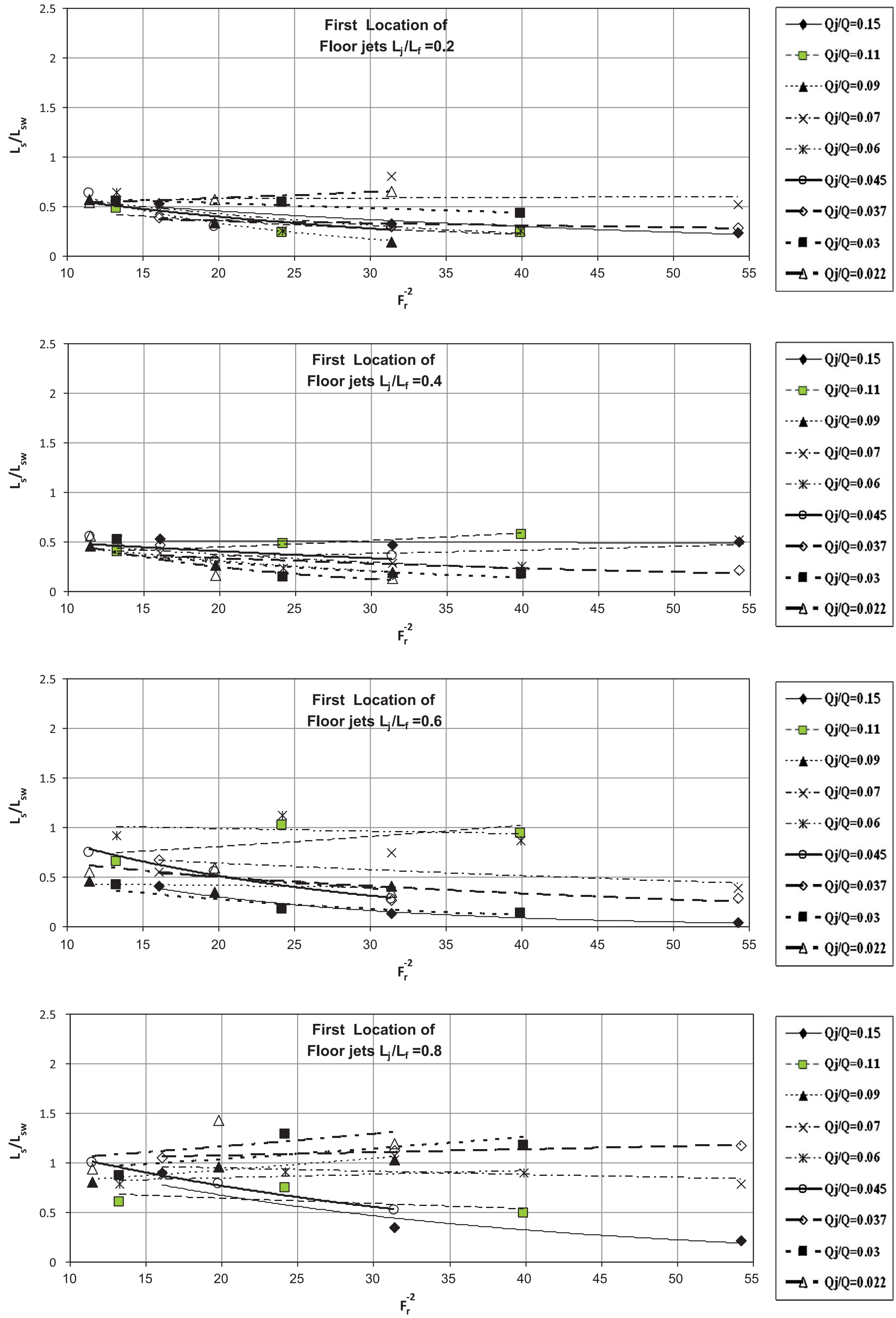

Figure 6 Relationship between L_s/L_{sw} and F_r^{-2} for different water jet locations and discharges.

Fig. 8 shows 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 required maintenance. For the last water jet location

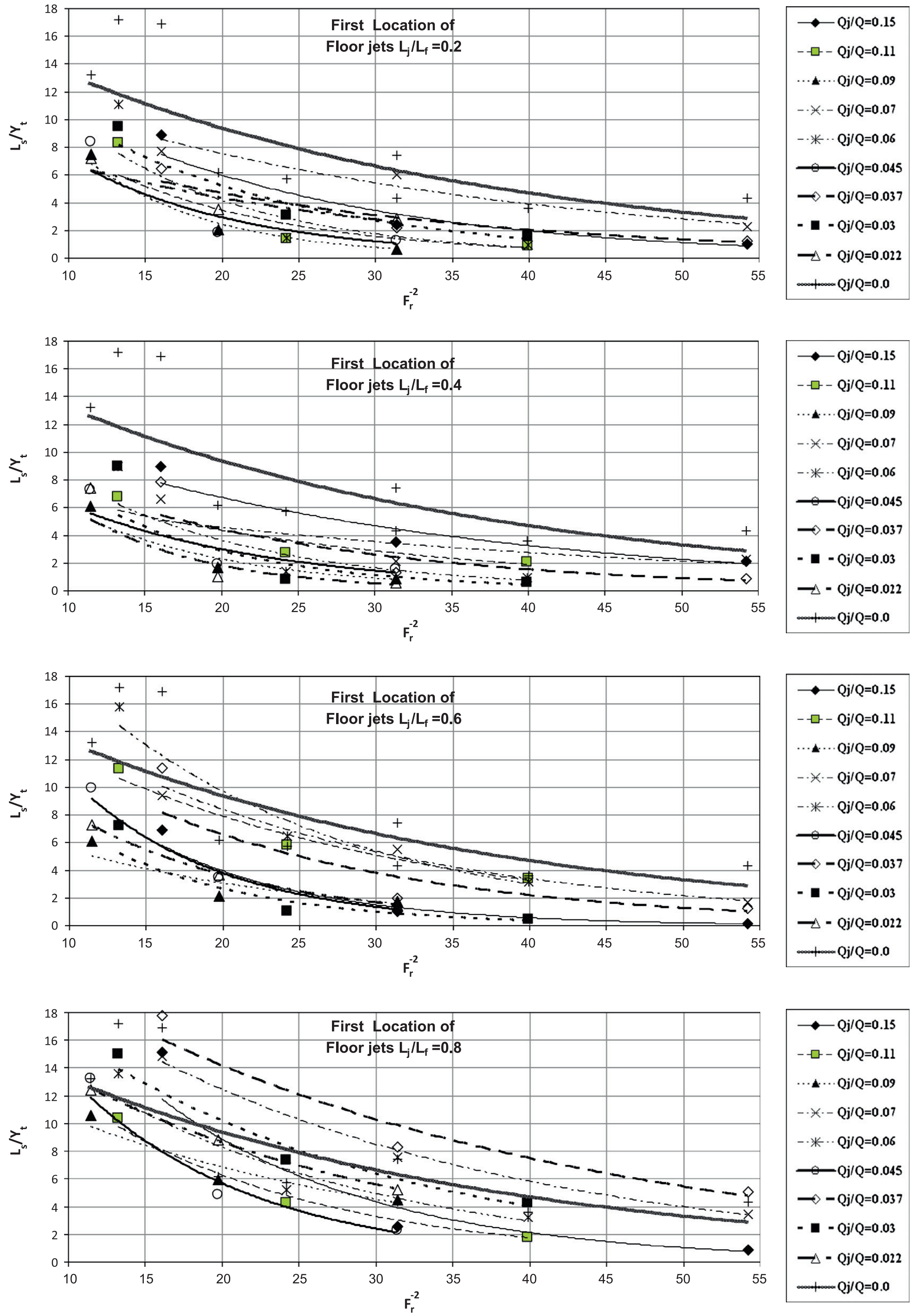

Figure 7 Relationship between L_s/Y_t and F_r^{-2} for different water jet locations and discharges.

(L_j/L_f = 0.8), the reduction in L_m with respect to L_{mw} was less than expected. Further, the figure shows that the effect of water jet discharges on the values of L_m/L_{mw} increased as the line of water jet moved toward the solid floor end.

Fig. 9 illustrated the relationships between L_m/Y_t and F_r^{-2} for different water jet locations and discharges. It was obvious that for most flow conditions, all the locations of the floor water jets gave values of L_m/Y_t smaller than that of

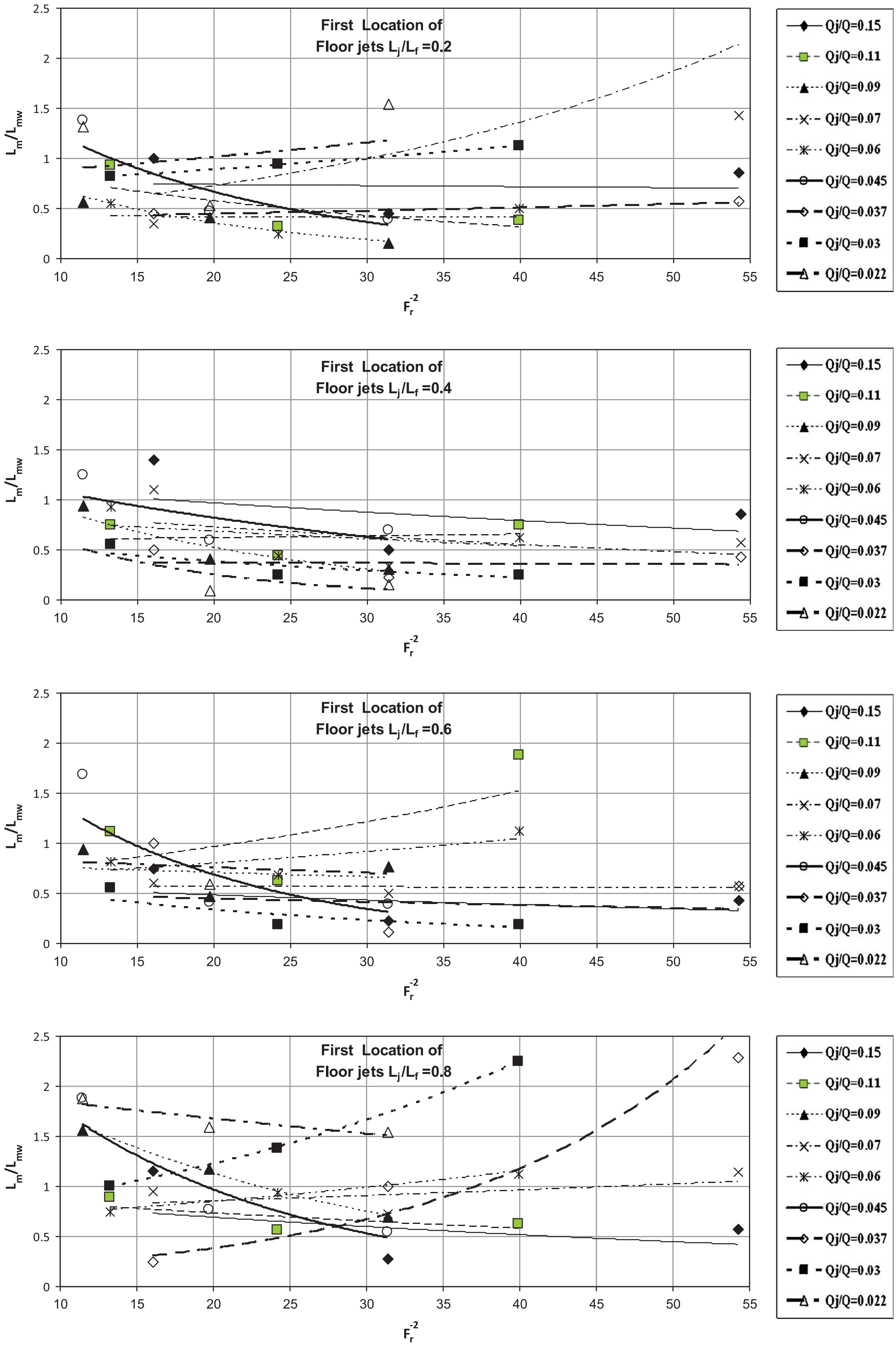

Figure 8 Relationship between L_m/L_{mw} and F_r^{-2} for different water jet locations and discharges.

the case of floor without water jets ($Q_j/Q = 0$), except for the last water jet location ($L_j/L_f = 0.8$). It was clear that increasing the values of F_r^{-2} decreases the values of L_m/Y_t.

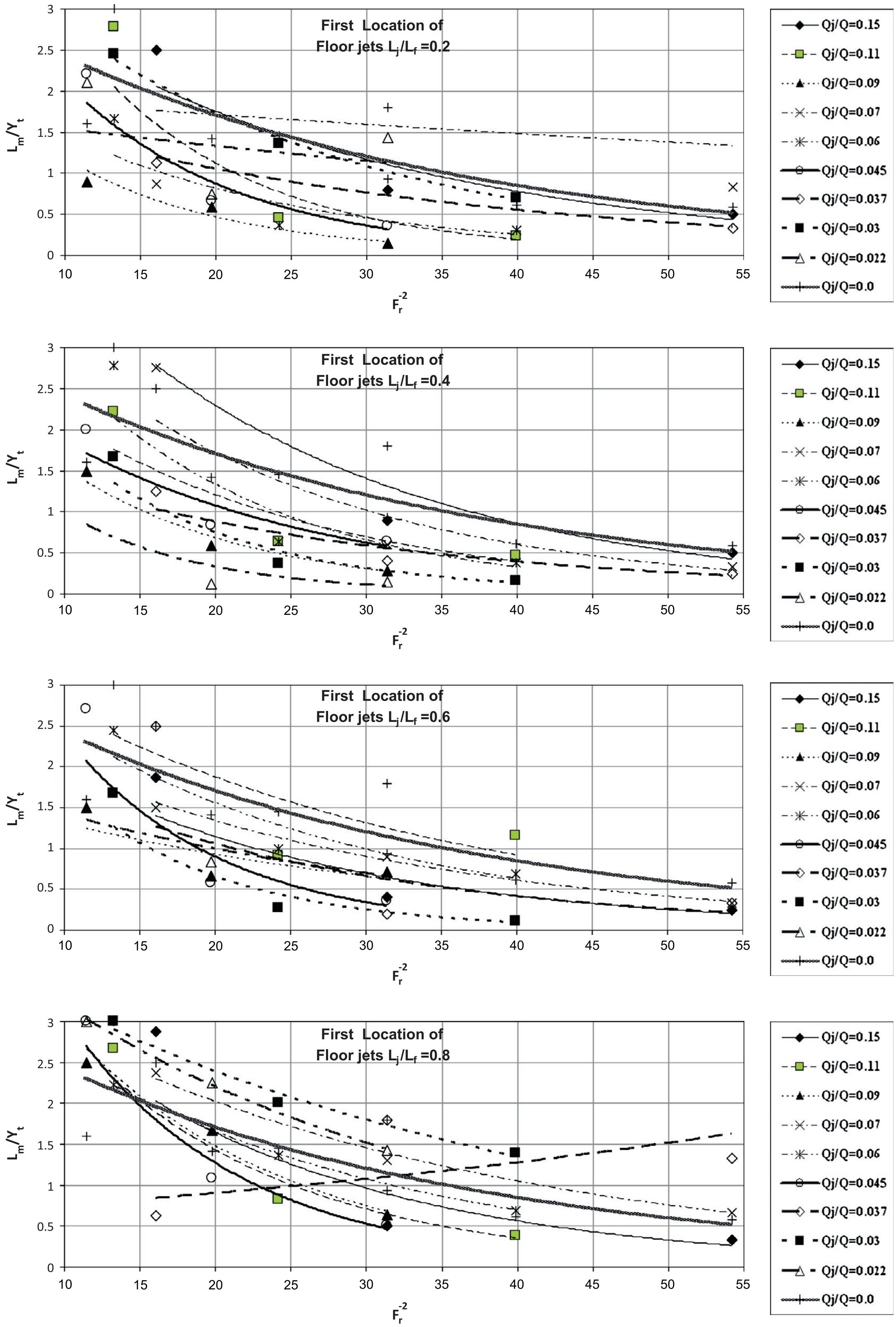

Figure 9 Relationship between L_m/Y_t and F_r^{-2} for different water jet locations and discharges.

Fig. 10 shows that the suggested floor water jets system reduced the scour index under most of the flow conditions compared to the scour index of the case without water jets, except for the last water jet location (L_j/L_f = 0.8) where the reduction in the scour index was less than expected. It was also clear that the second location of water jet (L_j/L_f = 0.4) gave the

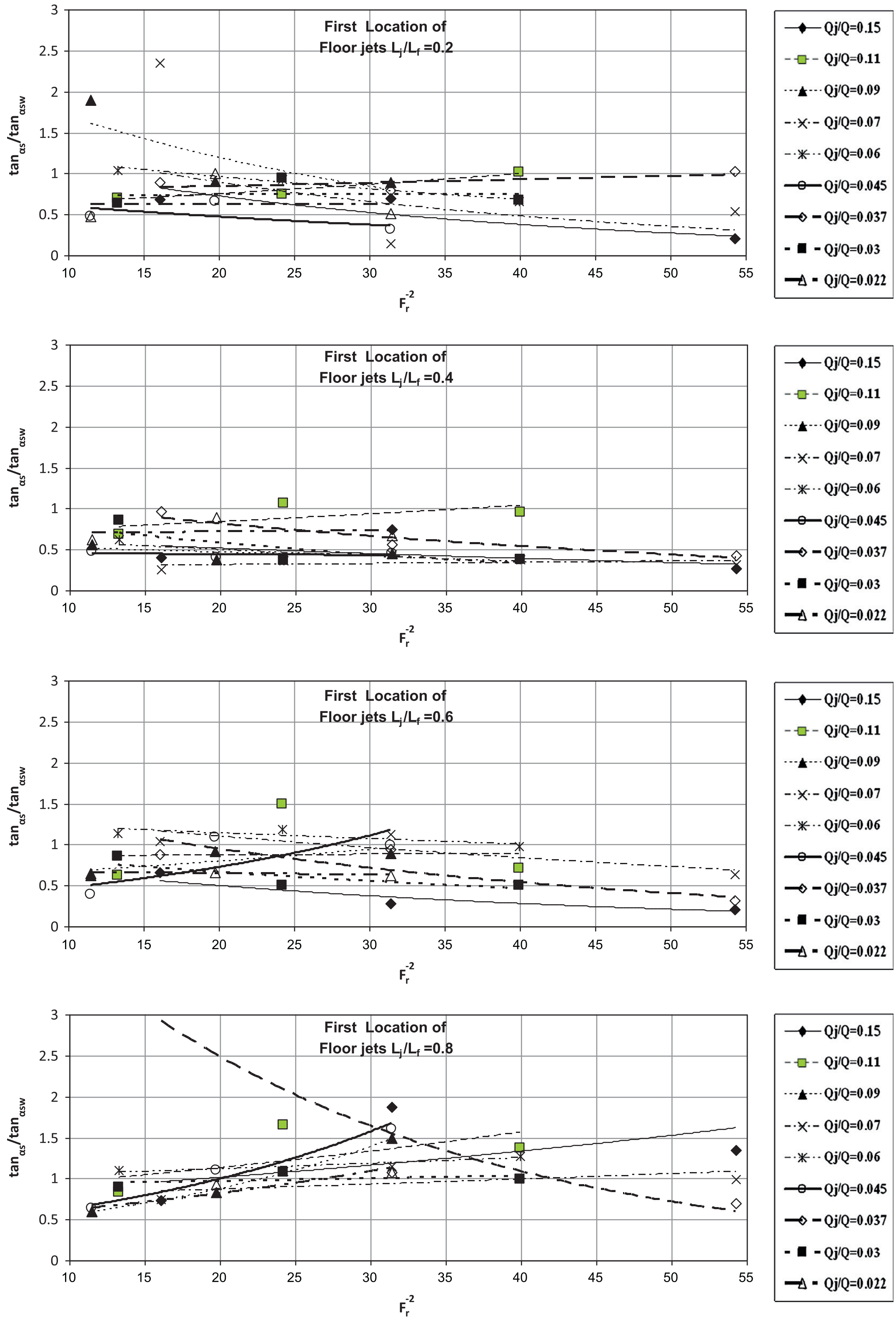

Figure 10 Relationship between $\tan\alpha_s/\tan\alpha_{sw}$ and F_r^{-2} for different water jet locations and discharges.

minimum values of $\tan\alpha_s/\tan\alpha_{sw}$, meaning that the location of the second line of floor water jet gave the maximum reduction in scour index range from 20% to 60%. The last location ($L_j/L_f = 0.8$) gave the highest values of $\tan\alpha_s/\tan\alpha_{sw}$, and this may be due to the water jet additional eddies near the end of the solid floor. For the lower values of F_r^{-2}, the effect of water jet discharges on the values of $\tan\alpha_s/\tan\alpha_{sw}$ were less significant than that of higher values of F_r^{-2}. For the optimum location of water jet ($L_j/L_f = 0.4$), the effect of water jet discharges on the values of $\tan\alpha_s/\tan\alpha_{sw}$ were less significant than that of the other locations of floor water jets.

7. 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):

$$\frac{D_S}{Y_t} = exp\left(-16.17(F_r) - 1.55\left(\frac{L_j}{L_f}\right) + 0.5\left(\frac{Q_j}{Q}\right) + 3.736\right) \quad (1)$$

$$\frac{L_S}{Y_t} = exp\left(-16.17(F_r) - 1.55\left(\frac{L_j}{L_f}\right) + 0.55\left(\frac{Q_j}{Q}\right) + 6.29\right) \quad (2)$$

Eqs. (1) and (2) are valid for the used flow conditions with correlation R^2 equal to 0.75 and 0.75, respectively.

8. Conclusions

To improve the safety of heading-up structures, a system of single line of floor water jets is suggested and provided to reduce the scour problem downstream of new designed or existing structures. The suggested system is easy to be used as appurtenances. Based on the results of experimental studies, the following conclusions have been drawn, which are valid for the range of the obtained experimental data:

- The suggested system reduced the maximum scour depth as well as the scour hole length and moved the location of maximum scour depth closer to the floor.
- The optimum location of floor water jets was found to be at $L_j/L_f = 0.4$
- The optimum location of floor water jets ($L_j/L_f = 0.4$) decreased the maximum scour depth ranged from 50% to 90%.
- The optimum location of floor water jets ($L_j/L_f = 0.4$) decreased the scour hole length ranged from 42% to 85%.
- The optimum location of floor water jets ($L_j/L_f = 0.4$) decreased the scour index ranged from 20% to 60%.
- Decreasing Froude number led to:
  1. Decreasing the maximum scour depth.
  2. Decreasing the scour hole length.
  3. Decreasing the scour index.
  4. Moving the location of maximum scour depth toward of the floor end.
- For the optimum location of water jet ($L_j/L_f = 0.4$) the effect of floor water jet discharges on the scour hole parameters was less significant than that of the other locations of floor water jet.
- For the optimum location of floor water jets increasing the values of jet discharge led to:
  1. Increasing the maximum scour depth.
  2. Increasing the scour hole length.
  3. Moving the location of maximum scour depth away from of the floor end.

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