MINIMIZING SCOUR DOWNSTREAM OF SPILLWAYS USING CURVED VERTICAL SILL

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ABSTRACT

Large number of hydraulic structures failed because the progress of local scour undermined their foundations. So, it is important to minimize local scour depth at downstream of these structures. Through this paper, an experimental study was conducted to investigate the effect of using single curved vertical sill on the scour hole dimensions downstream of a spillway with different flow conditions. Various diameters of curved vertical sill were tested at different locations under different flow conditions. A case of flat floor without sill was also included in the test program. Results indicated that the suggested curved vertical sill gave from 20% to 43% reduction in maximum scour depth and from 45% to 66% reduction in scour length compared to the case of flat floor. Results showed that the best location of sill was found to be at the first one- third of the floor with relative diameter of 0.122 of spillway height. Simple formulae to evaluate the scour parameters were also provided.

Keywords: Experimental, Spillway, curved vertical sill, Hydraulic structures

1 INTRODUCTION

Scour downstream of hydraulic structures is an important problem and was studied by many researchers in order to identify the variables governing this phenomenon and also to find solutions to ensure safety of these structures. Protection works for preventing scour need to be designed to withstand the flow forces imposed on mobile bed at downstream of these structures in order to get successful solution to control scour. Chute blocks, baffle blocks and sills with different configurations are used in the stilling basin to dissipate large amount of water energy through formation of a hydraulic jump thereby increasing the performance of the stilling basin. Many researchers have studied scour downstream of hydraulic structures such as grade control structures, pipe outlets and stilling basins, typical examples were investigated by **Dargahi (2003)**, **Oliveto (2013)**, **Nasr** and **Nagy (1997)**, **Barlock (2013)**, **Helal (2014)**, **Othman (2008)**, **Hitham et al (2012)** and **Reza** and **Mehdi (2012)**.

More than 50 years, laboratory measurements of scour depths under various flow conditions and structure configurations were conducted by many researchers such as, **Schoklitsch (1932)**, **Eggenberger (1944), Altinbilek** and **Basmaci (1973)**, **Smith** and **Strang (1967), Martins (1975)** and **Rajaratnam (1981)**. **Negm et al. (2003)** investigated experimentally the effect of using central sill at different positions and different heights on the scour characteristics downstream of abruptly enlarged stilling basins. They concluded that, the scour pattern downstream of the sudden expanding stilling basin was asymmetric even when using central sill of limited height at a specific position.

The effect of sill arrangements in sudden expanding stilling basin on scour characteristics was studied by **Negm (2004)**. It was concluded that the use of sill inside the basin affects significantly the maximum scour depth downstream of the basin. **Negm (2007)** investigated experimentally the effect of the position of central symmetric sill on the maximum scour depth downstream of radial stilling basin. **Abdel-Aal et al. (2009)** studied experimentally the effect of the guide wall position on local scour downstream of stilling basins. They concluded that the guide wall deflector is an effective tool for minimizing the local scour downstream heading-up structures. **Tuna** and **Emiroglu (2011)** concluded experimentally that, step geometry downstream water levels and the sill types of the stilling basin are very important parameters for the geometry of the scour hole. **Mubeen (2014)** reveals that, there is a significant dissipation of energy and reduction in length of hydraulic jump due to the presence of vertical end sill. **Tiwari et al. (2014)** found that, scour process were reduced for a shaped of intermediate sill having height equal to the diameter of pipe outlet. **Tiwari et al. (2014)** concluded that, there is a significant effect of the shape of the end sill geometry on the reduction of scour depth downstream of end sill for the pipe outlet stilling basin. The optimum sill that reduces the extent of scour downstream of the most practical sudden expanding stilling basin was recommended by **Saleh et al. (2004)**.

Mohammed et al. **(2004)** employed a physical model to simulate the effect of downstream curvature of the spillway and its end sill angle on local scour at downstream. It showed a reduction of 15% in local scour depth at downstream when the end sill angle changed from 10^o to 60^o. Effects of tail water submergence, type of spillway flow and riprap apron length on scour results are interpreted in terms of the turbulent kinetic energy and velocity distributions near the bed by **Hong et al**. **(2015)**. Tests were carried by **Helal et al. (2013)** for minimizing of scour downstream hydraulic structures using sills. It was noticed that, the case of fully silled floor gave the smaller values of scour parameters. The depth of the scour hole developed along with its width and length was predicted using neural network models by **Azmathullah et al**. **(2005)**. **Edward (1959)** concluded experimentally that the sill greatly increases the efficiency of the stilling basin.

Abdallah (1990) found that the sill height had a great effect on scour hole dimensions than the sill shape. The proper location of floor sill which minimized the scour downstream of heading-up structure was studied experimentally by **Nashat (1995)**. **Abdel Razek** and **Baghdadi (1996)** investigated experimentally the influence of sills upon the scour characteristics. They concluded that, the maximum scour depth decreased with the increase in the distance between the sill and the gate opening until it reached its maximum reduction at distance from the gate equals to one third of the apron length. **Abdelhaleem (2013)** introduced an experimental study to minimize the scour downstream a fayoum type weir using a row of semi-circular baffle blocks. It produced reduction in scour depth ranged from 51.86% to 63.81%. **Abdelhaleem et al. (2012)** studied experimentally the effect of using corrugated beds on the flow characteristics and downstream local scour. It is found that, corrugated beds have significant effect on energy dissipation and corrugating the stilling bed can decrease the cost of stilling basin.

In conclusion, the review of the previous published researches showed that sills are used to increase the performance of the stilling basin and there is a significant effect of the sill shape, length and height on the scour hole dimensions. Herein, this research reports an experimental investigation of using single curved vertical sill of new shape to minimize the scour hole parameters downstream spillway. Various diameters and locations of the sill were studied under different flow conditions.

2 DIMENSIONAL ANALYSIS

A dimensional analysis was applied to correlate the different variables affecting scour depth downstream spillway. The variables considered were as following b = sill width, B = channel width, d_s = maximum scour depth, d_{so} = maximum scour depth in case of flat floor. D = Diameter of sill, d_{50} = mean size of bed material, g = gravitational acceleration, h = sill height, H = spillway height, L = distance between sill and the toe of the spillway, L_f = floor length, L_s= maximum scour length, L_{so}= maximum scour length in case of flat floor, S_o= bed slope of the channel, t = time at maximum scouring, y_1= initial water depth of the hydraulic jump, y_2 = sequent water depth of the hydraulic jump, y_t = tail water depth, and y_{up} = upstream water depth, $\rho =$ density of water, $\rho_s =$ density of bed material, and $\mu =$ dynamic viscosity of water.
The functional relationship for the maximum scour depth could be expressed as follows:

$$d_s = f(b, d_{s,} d_{so}, B, D, d_{50}, g, h, H, L, L_f, L_s, L_{so}, S_o, t, y_1, y_2, y_{t,} y_{up}\, \rho, \rho_s, \mu) \qquad (1)$$

Since b, B, d_{50}, g, H, L_f, S_o, ρ, $\rho_{s,}$ and the effect of viscosity μ can be neglected, the time of balance for the scour hole parameters was also fixed to be 5 hr for all experiments. The sill height was taken equal to the sill diameter (h=D); then, eq. (1) will be reduced as following:

$$d_{s=}\left(F_t,\frac{L_s}{y_t},\frac{y_2}{y_t},\frac{D}{H},\frac{L}{L_f}\right) \qquad (2)$$

Where, F_t = tail Froude number.

3 EXPERIMENTS

Experiments were conducted in a re-circulating laboratory flume of 0.30 m wide; 0.50 m deep and 15.6 m long with working section of 12 m which is used for the experimental stage. A centrifugal pump lifts the water from a ground tank to the flume inlet. The water runs through the flume working section then returns back to the ground tank. The discharge was measured by a pre-calibrated orifice meter installed in the feeding pipe line. Ninety runs had been conducted including 10 runs with flat apron which was taken as a comparison case. To adjust the tail water depth, the tail gate is screwed gradually until the considered depth is adjusted. A point gauge was used to measure both the water levels and the bed levels in the longitudinal and the cross sectional directional of the channel (of ± 0.1 mm accuracy). Each experiment was run for 5hr which there was no appreciable change in scour hole dimensions after this time. Scour hole profile was recorded with point gauge at different locations in the x-y directions. The flow rate and the tail water depth were also recorded. A spillway model made of timber was used. The spillway has 30 cm width, 24.5 cm height and its back was sloped by 30^o angle (Fig. 1). A solid floor of 1.1 m length and 0.3 m width was used. The movable bed was simulated by sand of mean particle d_{50} = 1.7 mm. For all runs, the grain size of the material forming the movable bed was kept the same. A curved vertical sill model was built from timber and was fixed at the mid width of the solid floor body (see photo1); the experimental tests were summarized as following:

1. The first set of experiments was carried out using flat floor (no sill).
2. Then, Four locations of sill were tested to investigate the effect of sill location on the scour downstream the solid floor, their locations were varied as (L = 0.3,0.4,0.6,0.8 L_f)
3. For each location of sill, four relative diameters of sill were used to estimate the most suitable diameter of sill, (D = 0.073, 0.122, 0.155, 0.184 H).

For each experimental run, five values of discharge were used with running time of 5hr. Experiments were carried out in the Hydraulic Laboratory of the Faculty of Engineering, Zagazig University, Egypt.

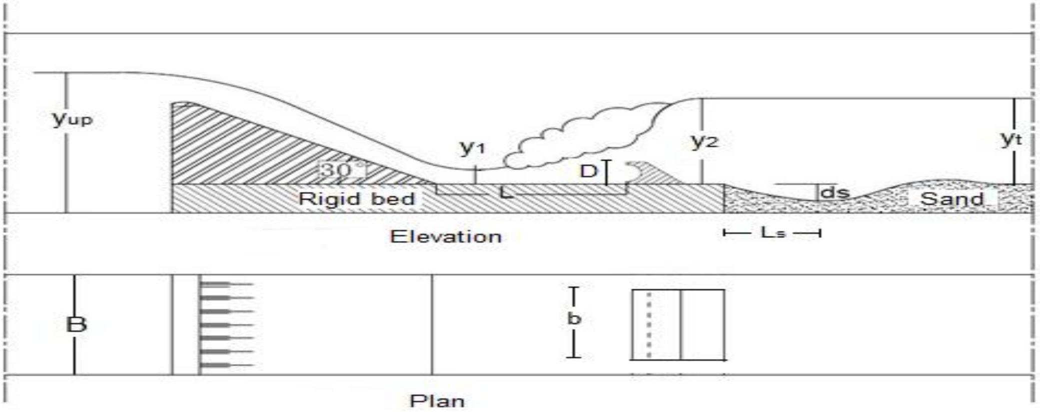

Figure 1. Layout of the experimental model

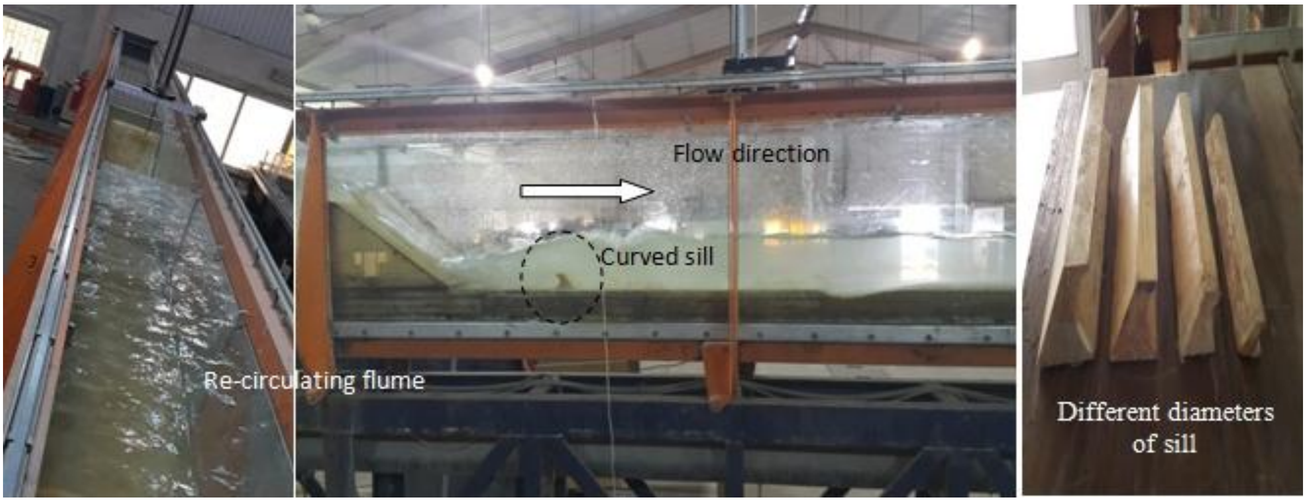

Photo 1. Selected photos

4 RESULTS AND DISCUSSION

A series of experiments were conducted to study the effect of curved vertical sill on both the maximum scour depth and scour length downstream of a spillway.

4.1 Effect Of Curved Single Sill On Scour Depth

The effect of different locations of curved sill on scour depth (L/L_f = 0.3, 0.4, 0.6 and 0.8) respectively was investigated. For each location, sill diameter is varied as (D/H = 0.073, 0.122, 0.155 and 0.184). Figs. 2-5 show the relationships between the tail Froude number F_t and the maximum relative scour depth d_s/d_{so}. It is obvious that, for the considered flow conditions, using curved single sill downstream of a spillway reduces the maximum scour depth compared to the maximum scour depth in case of flat floor (without sill), $d_s/d_{so} < 1.0$. It is apparent that for all different relative diameters of sill, the first location of sill (L/L_f = 0.3) gave the maximum reduction in relative scour depth d_s/d_{so} ranged from 20% to 43%. For the optimum location of sill (L/L_f = 0.3), the relationship between the tail Froude number and the relative maximum scour depth, d_s/d_{so} is illustrated in Fig. 6 for different relative diameters of curved sill. It can be noticed that, when the relative sill diameter increased to D/H = 0.184, the maximum scour depth was obtained. On the country, the relative scour depth reached to its minimum limits for D/H = 0.122.

On the other hand, Fig.7 shows the scour bed profile at the center line of the movable bed for the case of L/L_f 0.3 with different sill diameters. It is noticed that, The scour activities were clearly reduced in the case of locating the sill with in the first one-third of the basin. This zone can be considered as the effective zone to control the scour activities compared to the no-sill case.

4.2 Effect Of Curved Single Sill On Scour Length

Figs. 8-11 illustrate the relationships between L_s/L_{so} and F_t for different sill locations with considered relative diameters of sill D/H = 0.073, 0.122, 0.155 and 0.184. One can see that, For most flow conditions all different sill diameters and locations gave values of L_s/L_{so} smaller than that of the case of flat floor ($L_s/L_{so}<1$) except for the case of (L/L_f = 0.8 for D/H = 0.073 and 0.184). The most efficient location of curved sill is at L/L_f = 0.3, which produces maximum reduction in scour length ranged from 45% to 66%. After detecting the best location of sill L/L_f = 0.3, the effect of different sill diameters was illustrated in Fig. 12. It is obvious that, the sill diameter D = 0.122 H gave the maximum reduction in scour length with about 66%. Figs. 13-16 show also samples of the scour contour maps which, surveys downstream the fixed bed for the case of L/L_f = 0.3with different sill diameters at almost Q = 13.57 lit/sec.

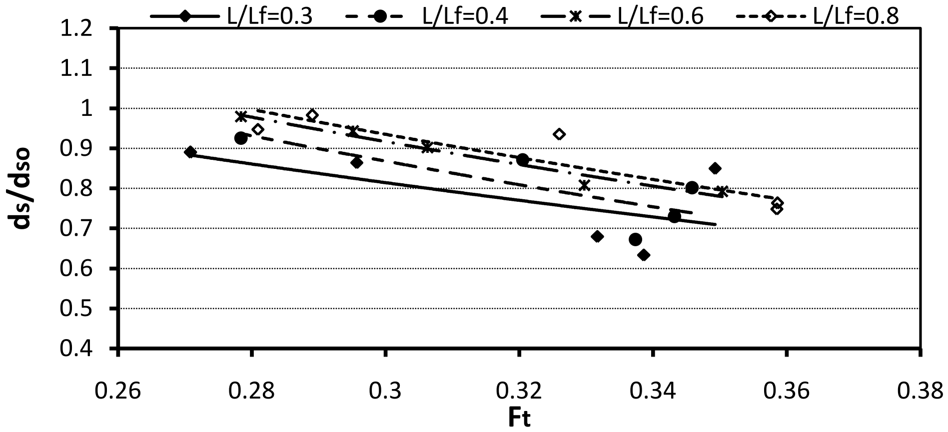

Figure 2. Relation between relative scour depth d_s/d_{so} and F_t (D= 0.184 H)

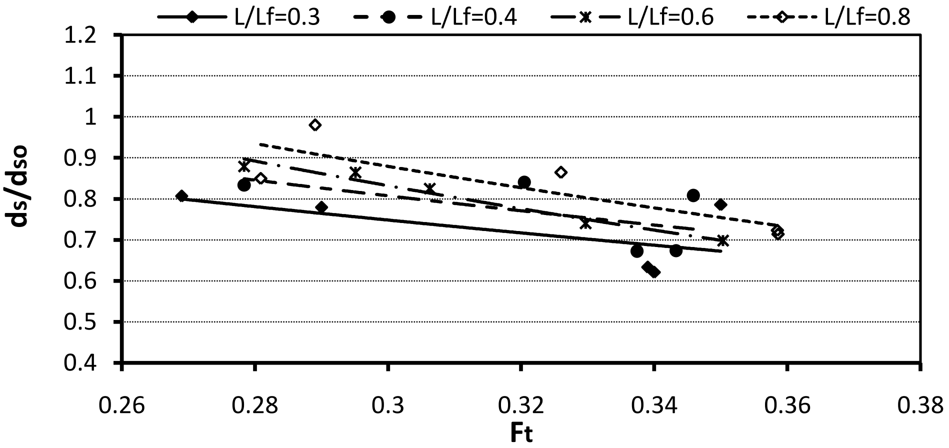

Figure 3. Relation between relative scour depth d_s/d_{so} and F_t (D = 0.155 H)

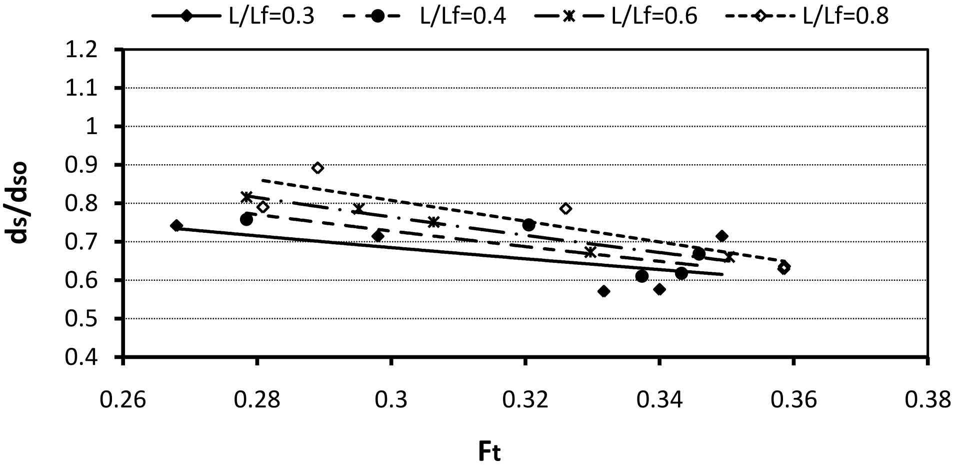

Figure 4. Relation between relative scour depth d_s/d_{so} and F_t (D = 0.122 H)

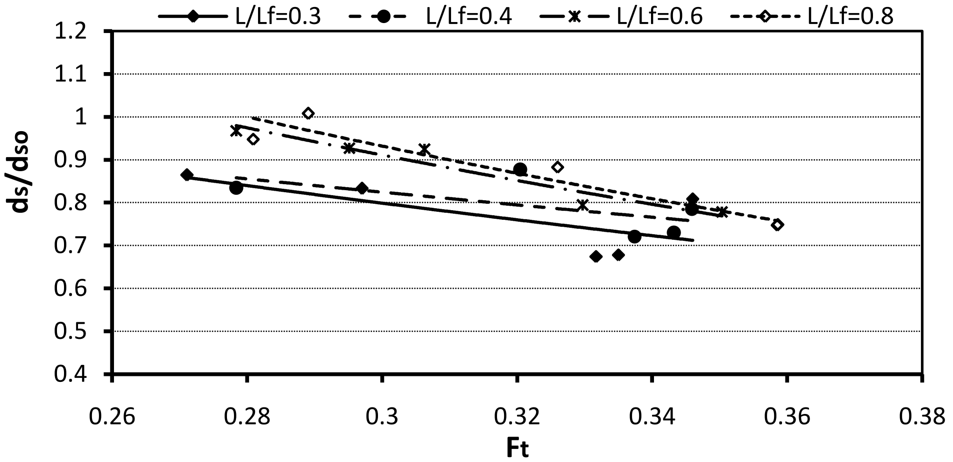

Figure 5. Relation between relative scour depth d_s/d_{so} and F_t (D = 0.073 H)

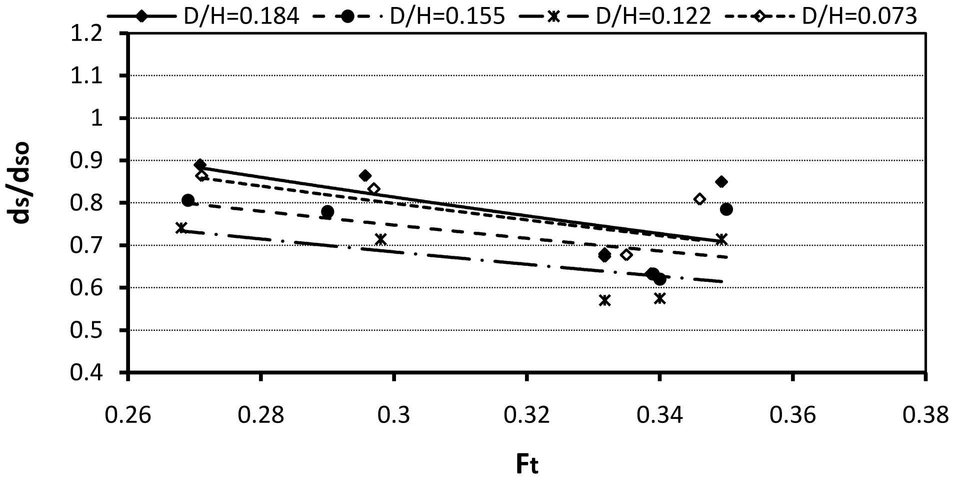

Figure 6. Relation between relative scour depth d_s/d_{so} and F_t (L/L_f = 0.3)

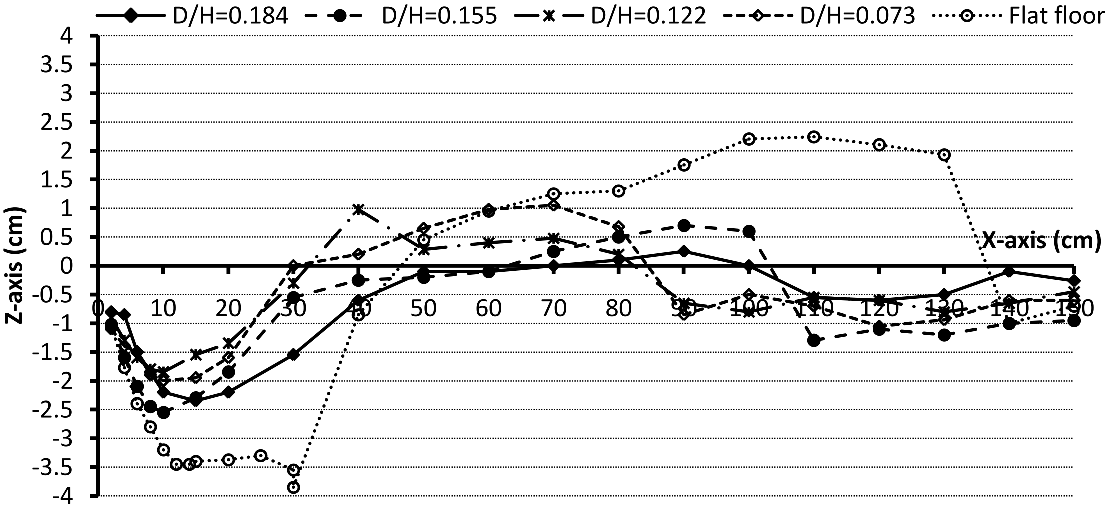

Figure 7. Bed profile at center line of movable bed (L/Lf = 0.3, Q = 13.57 lit/sec)

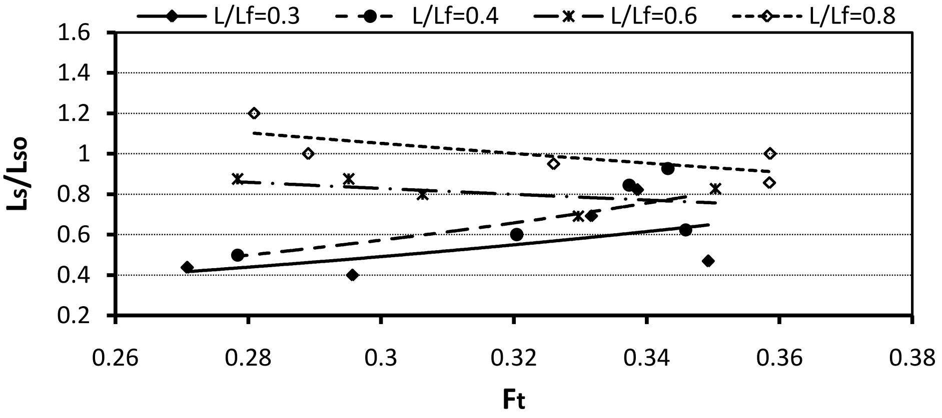

Figure 8. Relation between relative scour length L_s/L_{so} and F_t (D = 0.184 H)

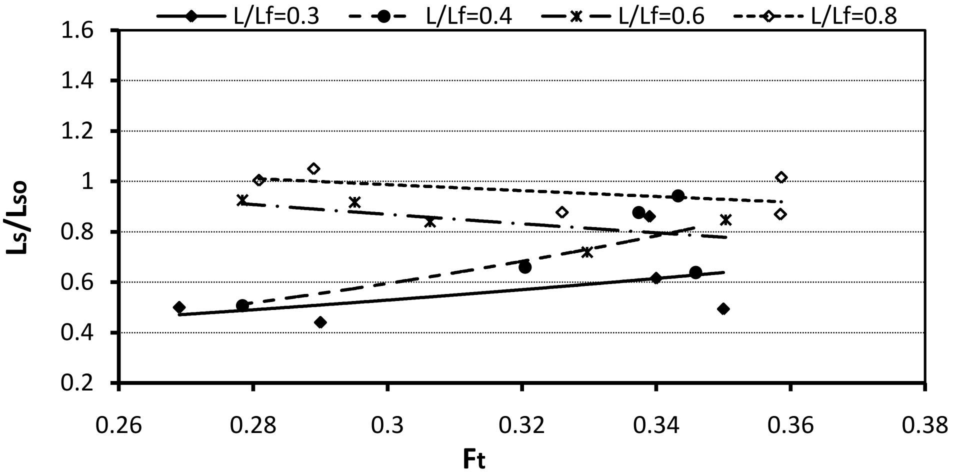

Figure 9. Relation between relative scour length L_s/L_{so} and F_t (D= 0.155 H)

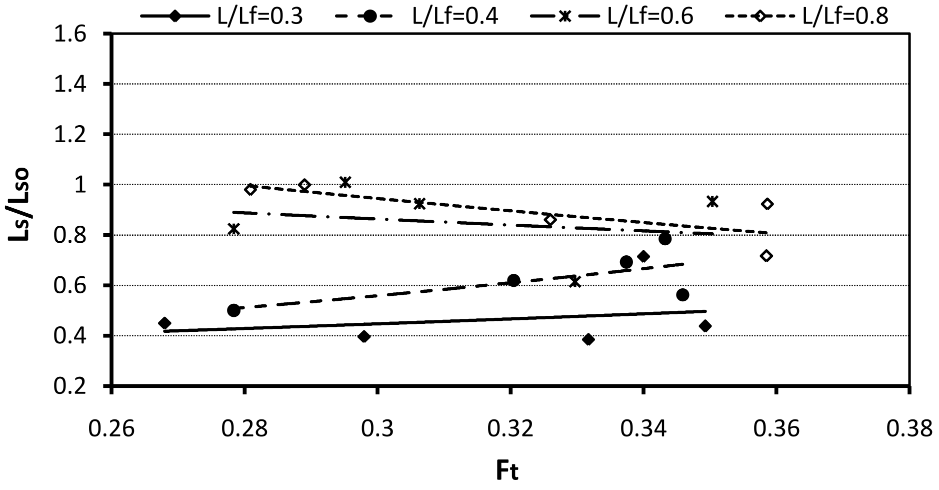

Figure 10. Relation between relative scour length L_s/L_{so} and F_t (D = 0.122 H)

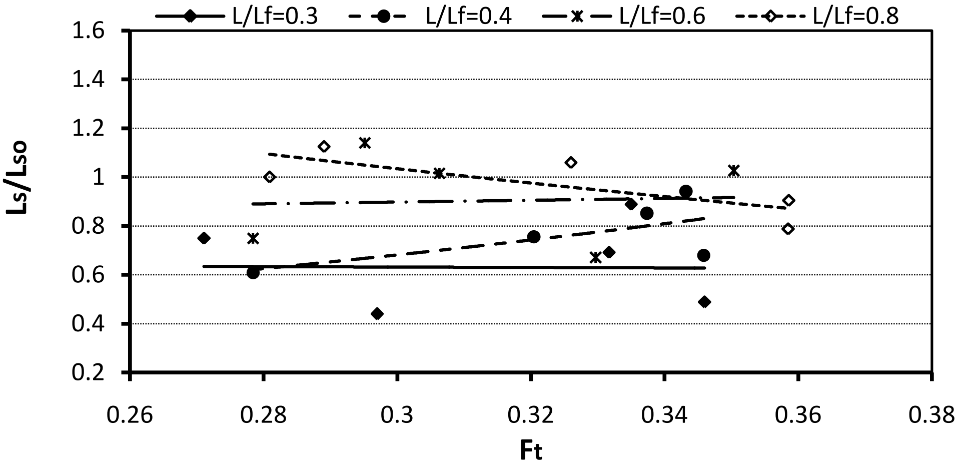

Figure 11. Relation between relative scour length L_s/L_{so} and F_t (D= 0.073 H)

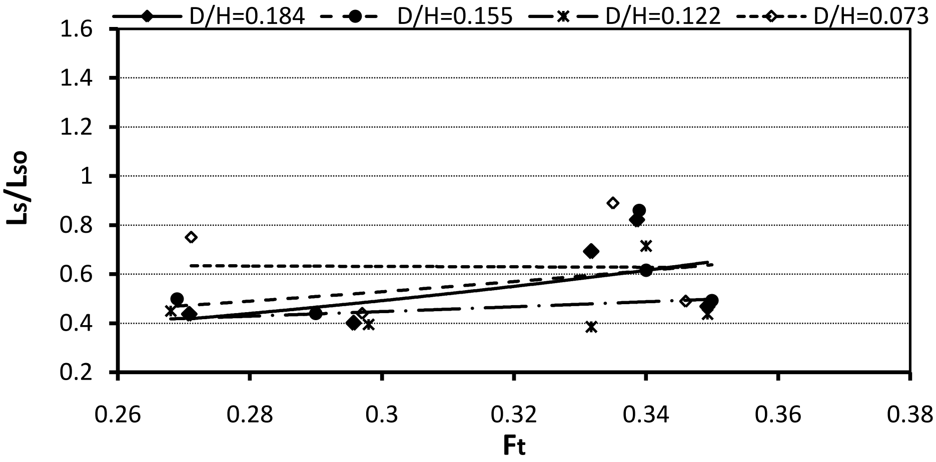

Figure 12. Relation between relative scour length L_s/L_{so} and F_t (L = 0.3 L_f)

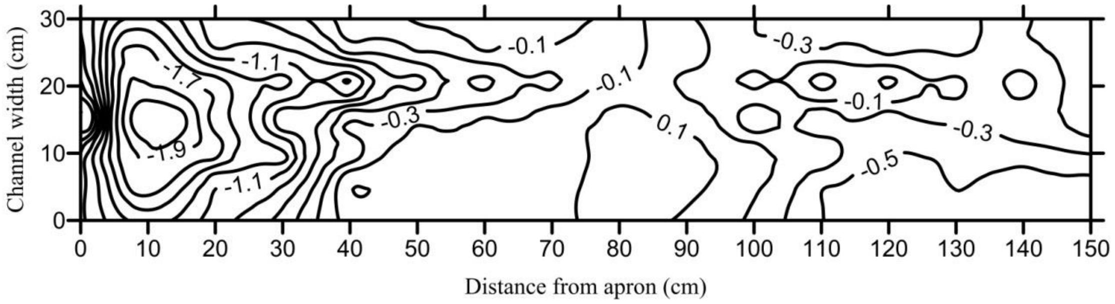

Figure 13. Scour contour map downstream apron (L/L_f = 0.3, D/H = 0.184, Q = 13.57 lit/sec)

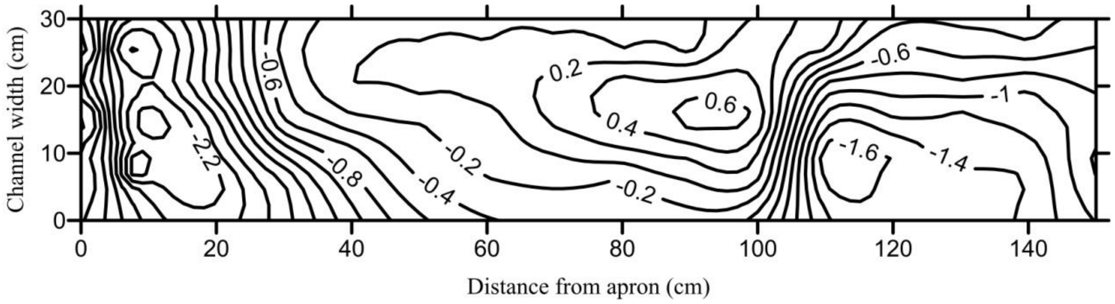

Figure 14. Scour contour map downstream apron (L/L$_f$ = 0.3, D/H = 0.155, Q = 13.57lit/sec)

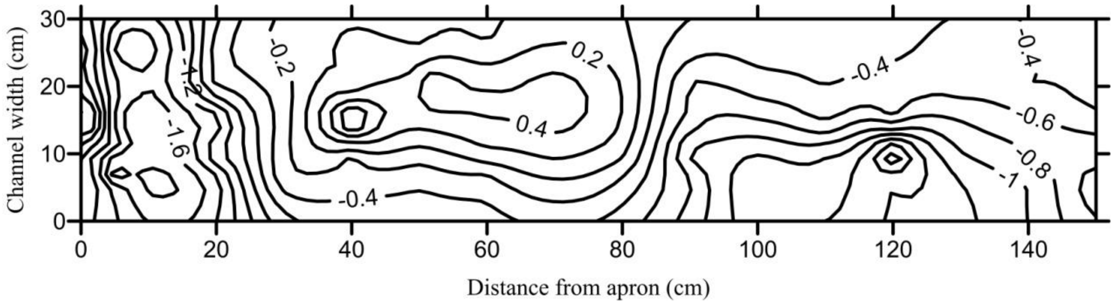

Figure 15. Scour contour map downstream apron (L/L$_f$ = 0.3, D/H = 0.122, Q = 13.57 lit/sec)

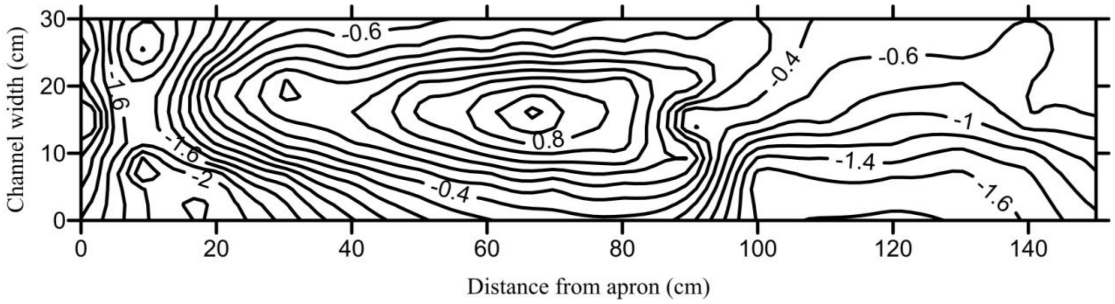

Figure 16. Scour contour map downstream apron (L/L$_f$ = 0.3, D/H = 0.073, Q = 13.57 lit/sec)

Figure 17, shows a comparison between the experimental results for the case of using a curved vertical sill of best dimensions (L/L$_f$ = 0.3, D/H 0.122) and scour equations for downstream of the hydraulic structures without any modifications for other researchers (Schoklitsh, Novak, and Wu). It is observed that, the relative scour depth for the case of using curved vertical sill of (L/L$_f$ = 0.3, D/H 0.122) are smaller than that of other cases for flat floor. It can be said that, the proposed curved vertical sill has a significant effect in reducing the scour depth downstream spillways.

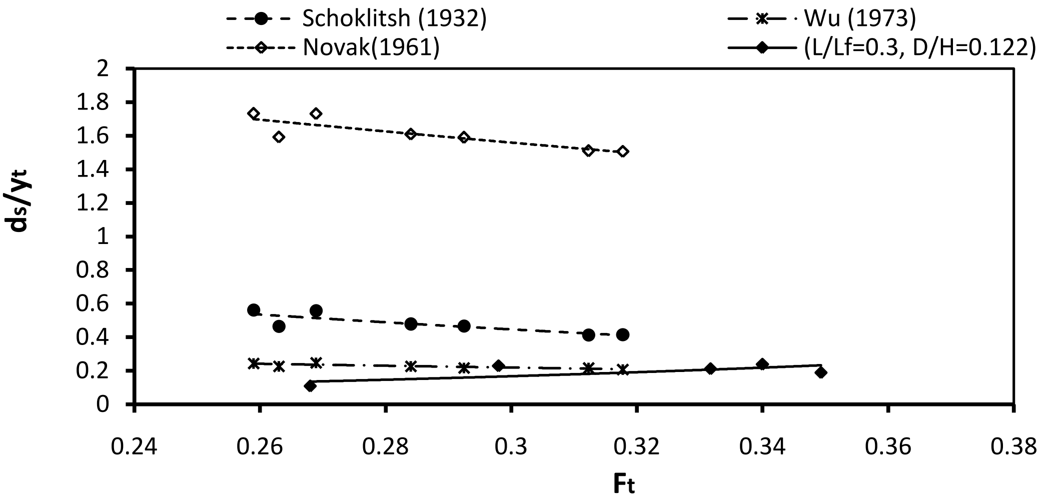

Figure 17. Comparison between values of d_s/y_t for curved vertical sill of (L/Lf = 0.3, D/H 0.122) and results for others

5 DEVELOPMENT OF STATISTICAL MODELS

The investigated scour characteristics have been modeled using multiple linear regression to predict the different scour parameters d_s/d_{so} and L_s/L_{so} downstream a spillway apron provided with a single curved sill. The following empirical formulas were obtained, eq. (3) and eq. (4) are valid for the considered flow conditions with correlation factors R^2 equal to 0.74 and 0.88, respectively. A comparison between the measured relative scour depth (d_s/d_{so}) and predicted one is shown in Fig. 18. Fig. 19 shows a comparison between the measured relative scour length (L_s/L_{so}) and the predicted one using eq. (4).

$$\frac{d_s}{d_{so}} = 1.61 - 2.22F_t - 1.62\left(\frac{D}{H}\right)^{0.33} - 0.04\left(\frac{L}{L_f}\right)^{0.5} \quad (3)$$

$$\frac{L_s}{L_{so}} = 1.04 - 0.09F_t - 6.58\left(\frac{D}{H}\right)^{0.45} - 0.12\left(\frac{L}{L_f}\right)^{0.15} \quad (4)$$

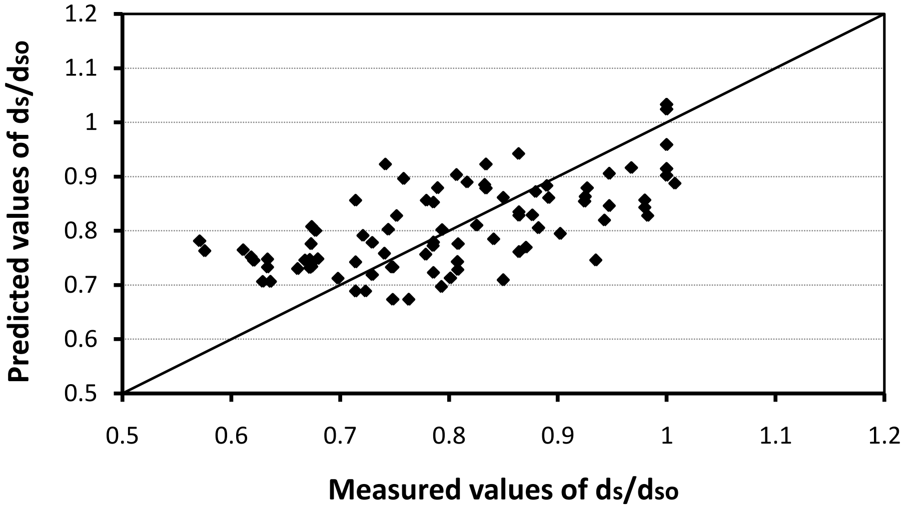

Figure 18. Comparison between predicted and measured values of d_s/d_{so}

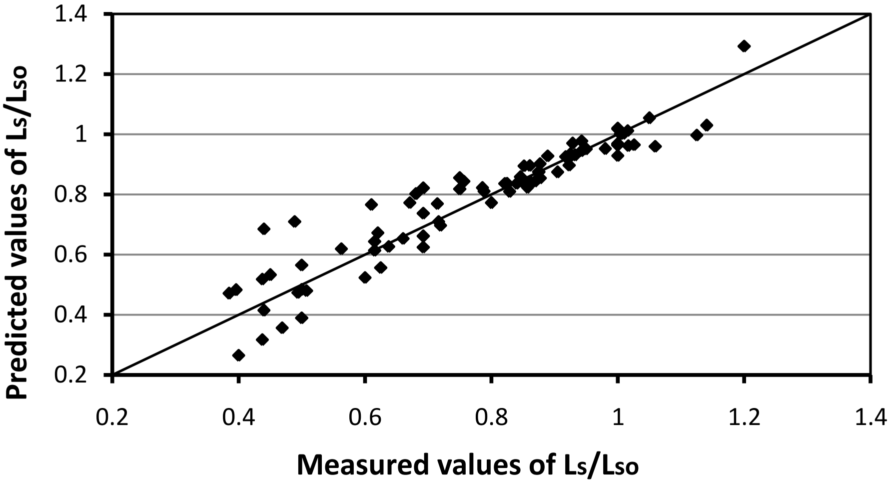

Figure 19. Comparison between predicted and measured values of L_s/L_{so}

6 CONCLUSIONS

Laboratory experiments investigated the effect of using a curved sill downstream a spillway on the maximum scour depth and the scour length. Analysis of the experimental results and statistical analysis led to the following conclusions:

- Using curved sill of the suggested shape reduced the maximum scour depth as well as the scour hole length compared to the no-sill case. (All values of d_s/d_{so} and L_s/L_{so} are less than 1.0).
- The best relative location of the curved sill was found to be at the first one-third of the floor ($L/L_f = 0.3$).
- The best relative location of the curved sill ($L/L_f = 0.3$) decreased the relative maximum scour depth ranged from 20% to 43% and decreased the relative maximum scour hole length ranged from 45% to 66% for different relative diameters of sill.
- The maximum reduction of the relative scour depth and scour hole length due to curved sill of the best dimensions ($L/L_f = 0.3$, D/H 0.122) are about 43% and 66% respectively.
- The suggested curved sill is easy to be designed as an extra element to existing floors.
- The proposed statistical equations are compared with the experimental measurements and acceptable agreement was obtained.

NOTATIONS

b	sill width (L)
B	channel width (L)
d_s	maximum scour depth (L)
d_{so}	maximum scour depth in case of flat floor (L)
D	sill diameter (L)
d_{50}	mean size of bed material (50%)(L)
F_t	the tail Froude number (-)
g	gravitational acceleration (LT^{-2})
L	distance between sill and the toe of the spillway (L)
L_f	Floor length (L)
L_s	maximum scour length (L)
L_{so}	maximum scour length in case of flat floor (L)
S_o	bed slope of channel (-)
t	time at maximum scouring (T)

y_1	initial water depth of the hydraulic jump (L)
y_2	sequent water depth of the hydraulic jump (L)
y_t	tail water depth (L)
y_{up}	upstream water depth (L)
ρ	density of water (ML^{-3})
ρ_s	density of bed material (ML^{-3})
μ	dynamic viscosity of water ($ML^{-1}T^{-1}$)

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