MINIMIZING SCOUR DOWNSTREAM OF SPILLWAYS USING CURVED VERTICAL SILL

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ABSTRACT

A 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 the 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 scouring length compared to the case of the flat floor. Results showed that the best location of sill was found to be at the first one-third of the floor with a relative diameter of 0.122 of spillway height (D/H). Simple formulae to evaluate the scour parameters were also provided.

Keywords: Experimental, Spillway, Curved vertical sill, Hydraulic structures.

Received 10 May 2016. Accepted 22, November 2016
Presented in IWTC 19th

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 the safety of these structures. Protection works for preventing scour need to be designed to withstand the flow forces imposed on the mobile bed at downstream of these structures in order to get a successful solution to control scour. Chute blocks, baffle blocks and sills with different configurations are used in the stilling basin to dissipate a large amount of water energy through the 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 Nasr and Nagy (1997), Dargahi (2003), Othman (2008), Hitham et al. (2012), Reza and Mehdi (2012), Oliveto (2013), Barlock (2013) and Helal (2014).

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), Edward (1959) concluded experimentally that the sill greatly increases the efficiency of the stilling basin. Smith and Strang (1967), Altinbilek and Basmaci(1973), 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.

Mohammed et al. (2004) employed a physical model to simulate the effect of the downstream curvature of the spillway and its end sill angle on local scour at downstream. They showed a reduction of 15% in local scour depth at downstream when the end sill angle changed from 10° to 60°. The effect of sill arrangements in the sudden expanding stilling basin on scour characteristics was studied by Negm (2004). He concluded that the use of sill inside the basin affects significantly the maximum scour depth downstream of the 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). The depth of the scour hole developed along with its width and length was predicted using neural network models by Azmathullah et al. (2005). Negm (2007) investigated experimentally the effect of the position of the central symmetric sill on the maximum scour depth downstream of the 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 a guide wall deflector is an effective tool for minimizing the local scour downstream heading-up structures. Tunca 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. 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. Mubeen (2014) reveals that, there is a significant dissipation of energy and reduction in length of the 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. 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).

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 (1997). 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 a distance from the gate equals to one third of the apron length. 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 a significant effect on energy dissipation and corrugating the stilling bed can decrease the cost of stilling basin. 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 a reduction in scour depth ranged from 51.86% to 63.81%.

In conclusion, the review of the previously 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 a 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

to correlate the different variables affecting scour depth downstream spillway. The variables considered Dimensional analysis was applied were classified into:

- **Boundary characteristics:** B = channel width; b = sill width; D = diameter of the sill; H = spillway height; h = sill height; L = distance between sill and toe of the spillway; Lₜ = floor length.
- **Scour characteristics:** dₛ = Maximum scour depth; dₜₒ = maximum scour depth in case of flat floor; Lₜₒ = maximum scour length; Lₜₒ = maximum scour length in case of flat floor; dₜₒ = mean size of bed material; t = time at maximum scouring; ρₜₒ = density of bed material.
- **Fluid characteristics:** ρ = density of water; μ = dynamic viscosity of water.
- **Flow characteristics:** y₁ = initial water depth of the hydraulic jump; y₂ = sequent water depth of the hydraulic jump; y₁ᵤₙ = tail water depth; y₁ᵤₙ = upstream water depth; q = discharge per unit width; g = acceleration due to gravity; Sₒ = bed slope.

The functional relationship for the maximum scour depth could be expressed as follows:

\[ dₛ = f (b, dₛ, dₜₒ, B, D, dₜₒ, g, h, H, Lₜ, Lₜₒ, Lₜₒ, q, Sₒ, t, y₁, y₂, y₁ᵤₙ, ρ, ρₜₒ, μ) \]  

(1)
Since \( b, B, d_{so}, S_o, \rho, \rho_s \), and the effect of viscosity \( \mu \) 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 follows:

\[
\frac{d_s}{d_{so}} = \left( F_t \frac{L_s}{y_t} \frac{y_2}{y_t} \frac{D}{H_t} \frac{L}{L_f} \right)
\]

Where, \( F_t = \text{tail Froude number} \).

3 EXPERIMENTAL WORK

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 a 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). 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 a 30° 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. Each experiment was run for 5hr which there was no appreciable change in scour hole dimensions after this time, Figure 2. 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 follows:

1. The first set of experiments were 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 the sill, four relative diameters of sill were used to estimate the most suitable diameter of the 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](image-url)
4 RESULTS AND DISCUSSION

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

4.1 Effect of curved vertical sill on scour depth

The effect of different locations of the curved vertical 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. 3 through 6 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 vertical single sill downstream of a spillway reduces the maximum scour depth compared to the maximum scour depth in case of the flat floor (without sill), \( d_s/d_{so} < 1.0 \). It is apparent that for all different relative diameters of the 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. 7 for different relative diameters of 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.8 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 vertical sill on scour length

Figs. 9 through 12 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 the 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 the curved vertical sill is at $L/L_f = 0.3$, which produces a 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. 13. It is obvious that, the sill diameter $D/H = 0.122$ gave the maximum reduction in scour length with about $66\%$. Figs. 14-17 show also samples of the scour contour maps which, surveys downstream the fixed bed for the case of $L/L_f = 0.3$ with different sill diameters at almost $Q = 13.57$ lit/sec.

![Figure 3. Relationship between relative scour depth $d_s/d_{so}$ and $F_t$ ($D=0.184 H$)](image)

![Figure 4. Relationship between relative scour depth $d_s/d_{so}$ and $F_t$ ($D=0.155 H$)](image)

![Figure 5. Relationship between relative scour depth $d_s/d_{so}$ and $F_t$ ($D=0.122 H$)](image)
Figure 6. Relationship between relative scour depth \(d_s/d_{so}\) and \(F_t\) (\(D = 0.073\) \(H\)).

Figure 7. Relationship between relative scour depth \(d_s/d_{so}\) and \(F_t\) (\(L/L_f = 0.3\)).

Figure 8. Bed profile at center line of movable bed (\(L/L_f = 0.3, Q = 13.57\) lit/sec).
Figure 9. Relationship between relative scour length $L_s/L_{so}$ and $F_t$ ($D = 0.184 H$)

Figure 10. Relationship between relative scour length $L_s/L_{so}$ and $F_t$ ($D = 0.155 H$)

Figure 11. Relationship between relative scour length $L_s/L_{so}$ and $F_t$ ($D = 0.122 H$)
Figure 12. Relationship between relative scour length $L_s/L_{so}$ and $F_t$ ($D = 0.073 \ H$)

Figure 13. Relationship between relative scour length $L_s/L_{so}$ and $F_t$ ($L = 0.3 \ L_f$)

Figure 14. Scour contour map downstream apron ($L/L_f = 0.3$, $D/H = 0.184$, $Q = 13.57$lit/sec)

Figure 15. Scour contour map downstream apron ($L/L_f = 0.3$, $D/H = 0.155$, $Q = 13.57$lit/sec)
Figure 16. Scour contour map downstream apron (L/Lf =0.3, D/H =0.122, Q= 13.57lit/sec)

Figure 17. Scour contour map downstream apron (L/Lf =0.3, D/H =0.073, Q= 13.57lit/sec)

Figure 18. 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 Figs. (19a). Fig. (19b) shows a comparison between the measured relative scour length (L_s/L_so) and the predicted one using eq.(4). These equations are valid within the following ranges of the involved parameters: d_s/d_so [0.57-1.0], F_t [0.25-0.36],
D/H [0-0.184], L/L_{so} [0.39-1.0] and L/L_{f} [0.3-0.8]. The residuals of the statistical equations versus the predicted values of d_{s}/d_{so} and L_{s}/L_{so} are shown in Figs 20a and 20b, respectively.

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

(3)

\[
\frac{L_s}{L_{so}} = 0.66 + 0.44F_t + 1.95 \left( \frac{D}{H} \right)^{0.45} - 1.85 \left( \frac{L}{L_f} \right)^{0.15}
\]

(4)

6 CONCLUSIONS

Laboratory experiments investigated the effect of using a curved vertical 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 vertical sill of the suggested shape reduced the maximum scour depth as well as the scour 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 vertical 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 vertical sill (L/L_{f} = 0.3) decreased the relative maximum scour depth ranged from 20% to 43% and decreased the relative maximum scour length ranged from 45% to 66% for different relative diameters of the sill.
- The maximum reduction of the relative scour depth and scour length due to the curved vertical sill of the best dimensions (L/L_{f} = 0.3, D/H = 0.122) are about 43% and 66% respectively.
The suggested curved vertical sill is easy to be designed as an extra element to existing floors.

The proposed statistical equations were compared with the experimental measurements and an acceptable agreement was obtained with a mean $R^2 = 0.81\%$ and with RMSE = 0.0044.

NOTATION

The following symbols are used in this paper:

- $B$: channel width (L)
- $b$: sill width (L)
- $D$: sill diameter (L)
- $d_s$: maximum scour depth (L)
- $d_{so}$: maximum scour depth in case of the flat floor (L)
- $d_{50}$: mean size of bed material (50%)(L)
- $F_t$: the tail Froude number (-)
- $g$: gravitational acceleration (LT$^{-2}$)
- $H$: spillway height (L)
- $L$: 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)
- $R^2$: determination coefficient
- $S_o$: 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)
- $\mu$: dynamic viscosity of water (ML$^{-1}$T$^{-1}$)
- $\rho$: density of water (ML$^{-3}$)
- $\rho_s$: density of bed material (ML$^{-3}$)
- RMSE: root mean square error

REFERENCES


