MINIMIZING OF SCOUR DOWNSTREAM THE OUTLETS OF THE BOX CULVERT

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ABSTRACT

Local scour downstream the box culverts outlet may cause to a complete failure of the culvert structure. New research is employed to reduce the max scour depth downstream the outlet of the box culvert under a different flow conditions based on an experimental investigation. A sharp edge sill is proposed on a rigid bed to dissipate the flow excess energy. Consequently, a great reduction of the scour hole dimensions is obtained by using the sharp edge sill. The experimental study was carried out using a different positions, heights and shapes of the sharp edge sill with different flow rates as well as tail water depths too. The results indicates that the sharp edge sill is a promising tool to reduce the scour dimensions. The reduction of the scour depths by using the sharp edge sill are 60%, while the reduction in the scour depths are 64%, that is because of using of rigid apron of length 7 times the height of culvert, compared to previous results without rigid bed.

KEY WORDS: Scour, culvert, culvert outlet, sill, submerged ratio, tailwater depth.


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1. INTRODUCTION

Culverts are covered man-made channel that conveys water below roads, railways, or any other structure. The flow mean velocity measured inside the culvert's barrel is higher than the velocity measured at the upstream due to the contraction of the flow section area in the barrel. Upon exiting of the culvert’s barrel, scour can occur if no suitable protection or energy dissipation structure is provided. Abt et al [1] studied the effecting of the culvert slope on scour depths at the outlets and they mention that the sloped culvert increased the scour depths up to 40% more than the scour dimensions for the horizontal culvert. Abt et al [2] studied the effecting of culvert shape on scour depth at the outlet of culvert and noticed that the dimensions of scour for the circular culverts significantly varies of other culvert shapes. Negm et al.[3], used a flow deflector to reduce scour dimensions at the pipe outlets under different flow
conditions. The results mentioned that the flow deflector was a promising tool to reduce the scour dimensions. The reduction of the scour depth by using the flow deflector was 68%, while the reduction in the scour depth was 80%, due to using a rigid apron of length 7 times the pipe diameter, compared to the previous results without rigid bed. Osman et al. [4], founded that the semi-circular apron gave less scour depth and width when compared to the linear front apron. The comparison of the outputs of the model and the field study was found of a good agreement. The model was recommended for engineering design of drainage structures located on streams of sandy bed. They developed an equation for prediction the scour depth at the outlet of the culvert. Liriano et al. [5], studied the effect of the turbulent flow on the culverts outlet scour and mentioned that the length of the scour depth for the fully developed scour hole coincide to the high values of turbulence intensities on the fixed bed. Hotchkiss et al. [6], studied the effecting of the hydraulic jump geometry and the effectiveness of the hydraulic jump on the outlet scour.. Hotchkiss and Larson [7], used two alternatives to dissipate the flow energy at the outlet of the culvert. Abida and Townsend [8], studied the effecting of the tailwater depth, the passing discharge and the cross-section area on the scour dimensions. Many developed empirical equations – see [3],[8], [9], [10], [11], [12], [13], [14], [15], [16], [17]– were depend on experimental studies to predict and calculate the scour depth under specified flow conditions. Equation (1) is one of the famous equations, which was founded by Ruff, et al., [18]

\[
\frac{d_{sc}}{R_c} = \frac{w_s}{R_c} \frac{d_{sl}}{R_c} \frac{V_s}{R_c} = C_s C_h \left( \frac{Q}{\sqrt{g R_c}^{2.5}} \right)^\alpha \left( \frac{t}{316} \right)^\beta
\]

In which, \( d_{sc} \) is the scour depth, \( w_s \) is the scour width, \( L_s \) is the scour length, \( V_s \) is the scour volume, \( R_c \) is the culvert end's hydraulic radius, \( Q \) the flow discharge, \( g \) is the gravitational acceleration, \( t \) is the duration of scour in minutes, \( \sigma = \sqrt{D_{84}/D_{10}}, C_s, C_h, \alpha, \beta, \theta \) are coefficients.

Bohan [19]as reported by Ruff, et al., [18]performed some scour experiments for flow for pipe culvert on sand material with \( d_{50}=0.22 \) mm and put the following equations.

\[
\frac{d_{sc}}{D} = t^{0.1}(1.3 + 1.4 \log F_o)
\]

(2)

\[
\frac{L_{sc}}{D} = 4t^{0.15}(1 + 5 \log F_o)
\]

(3)

in which: \( F_o \) is the Froude number. Fletcher and Grace [20]as reported by Ruff, et al., [18]extended bohan's works. Actually, some conclusions were presented including that; the parameter \( Q/D_{2.5} \) was a significant parameter. The following equation was developed.

\[
\frac{d_{sc}}{D} = 0.74(\frac{Q}{D^{2.5}})^{0.375} (t)^{0.15}
\]

(4)

Crookston et al [21] reviewed some empirical formulae for the prediction and calculation of the maximum scour depth at culvert outlet. Doehring and Abt [22] studied the effecting of the drop height on the localized scour at the culvert outlet. Abt et al. [11]and Chiew and Lim [23], developed two empirical equations to calculate the scour depth, see equations (1) and (2) respectively.

\[
\frac{d_{sc}}{D} = -3.67 (F_o^{0.57}D_{50}^{0.4} \sigma^{-0.4})
\]

(5)

\[
\frac{d_{sc}}{D} = 0.21F_o
\]

(6)
Chen et al. [24], studied the effecting of several energy dissipation structures for reducing the scour depth at the culvert outlets and founded that the combination of the low sill and a drop is the effective way for dissipating energy. Crookston and Tullis [25], studied the outlet scour for the culvert streambed stability using a 0.61m diameter arch culvert. The observations regarding the location and extent of scour events were discussed. Elfiky et al. [26], studied the effecting of the angled deflector on the local scour downstream of regulators. It was mentioned that locating the deflector within the first quarter of the stilling basin downstream of the piers' end gave the best performance. Helal et al. [27], reduced the max scour depth downstream the hydraulic structures using sills. Also, they noticed that for most considered values of sills height, the case of fully silled floor gave the smaller values of scour parameters. Omara et al. [28], they used a numerical model of FLOW-3D for predicting the scour depths around the pier. The model provided a good estimation of water levels, flow velocity and bed shear stress. They mentioned that a 3D hydro morphological model can be effectively used to predict and estimate the scour depth around piers. Fahmy [29] studied the scour depths at the pipe culvert tail escape outlet and developed and verified an empirical equations to be used to compute the scour depth and scour length downstream tail escape.

There are studies on the culvert blockage during flood. As an example, Rigby et al. [30] studied the blockage of culverts in the flood. They discussed causes and effects of culvert blockage. Rigby & Barthelmess [31] explored culvert blockage mechanisms and their impact on flood behavior. They noticed that one of the consequences of blockage culvert being the flow diversions caused by blockage of culvert. Sorourian et al. [32], studied the effecting of the blockage ratio and flow conditions on the scour depth at the outlet. It was mentioned that the maximum scour depth increased in partially blocked condition compared to the non-blocked condition. Tan and Sheau Maan [33], used a 3D full flowing horizontal jet scour to simulate and modelling the culvert scour in laboratory condition. They mentioned that the non-dimensionalized scour depth can be expressed as \( d = \frac{d_{se}}{R_h} = 1.22F_{o,84} \), where the \( d_{se} \) is the and \( R_h \) is The hydraulic radius, \( (F_{o,d84}) \) a modified densiometric Froude number, and \( d_{84} = d_{50} \sigma g \). Najafzadeh [34] used the neuro fuzzy-based group method of data handling to predict and estimate the scour depth at the conditions of equilibrium at the culvert outlets. Tjahyana and Lasmino [35], simulated the change of width and depth of the channel bed of box culvert on the same location and the same length in certain distance. There were three variations of channel bed. The first was the initial dimension of the box culvert, the second is the change of channel bed into twice wider than the initial width, and the third was the change of channel bed into twice deeper than the initial depth. They used The SSIIM 1 program to Simulation of Sedimentation Movement in Water Intakes. They found the second and the third variation show that the location of sedimentation changes in line with the changes of width or depth of the channel bed.

So, the aim of this experimental research is to reduce scour downstream the box culvert outlets. The present experimental investigation focuses on the reducing of the scour hole dimensions downstream of box culvert using a new approach based on a limited bed protection provided with Sharp Edge Sill.

2. DIMENSIONAL ANALYSIS

The local scouring at the box culvert outlet depends on a large number of flow and material variables as shown in figure (1). By applied the Buckingham' theorem to the variables affecting the scour hole dimensions downstream the box culvert. The following assumptions are adopted: the flow is steady and the temperature has a negligible effect on the results. Thus, the following functional relationship is formed:
$$f(\rho, \mu, g, d_{sc}, L_{sc}, d_d, L_d, d_{50}, b, y, v, y_t, L_{sill}, H_{sill}, \Theta_{sill}) = 0$$  \hspace{1cm} (7)

Selecting $\rho$, $y$, $v$ as repeating variables, the following dimensionless equation is obtained:

$$\frac{d_{sc}}{y}, \frac{L_{sc}}{y}, \frac{d_d}{y}, \frac{L_d}{y} = f(F_o, \frac{y_t}{y}, \frac{L_{sill}}{y}, \frac{H_{sill}}{y}, \Theta_{sill})$$  \hspace{1cm} (8)

In which: $d_{sc}/y$ is the relative maximum scour depth; $L_{sc}/y$ is the relative maximum scour length; $d_d/y$ is the relative maximum deposition depth; $L_d/y$ is the relative maximum deposition length; $F_o$ is the Froude number, $y_t/y$ is the relative tail water depth, $L_{sill}/y$ is the relative position of sharp edge sill in the flow direction, $H_{sill}/h$ is the relative height of sharp edge sill.

3. EXPERIMENTS

Experiments measurements were carried out in the laboratory of hydraulics at the Faculty of Engineering, Zagazig University, Egypt.

3.1. The flume

Experiments were carried out in a prismatic rectangular re-circulating flume. The flume has the dimensions of 66 cm width, 65.5 cm depth, and 16.2 m length. The flume is equipped with a tailgate to control the tail water depth at the culvert outlets. A rectangular calibrated weir fixed at the end of the flume to facilitate the measuring of the passed discharge during the experiment. The basin was made from a clear Perspex to enable visual inspection of the phenomenon being under investigation. see figure 1

![Figure 1. General view of the laboratory flume](image)

3.2. The experimental models

Box culvert made of clear Perspex was used as a crossing structure. The box culvert have a dimensions of 34.65 cm width, 300 cm length, 11.55 cm height, slope of zero, the culvert was followed by a solid floor of length 0.80 m, and 0.66 m width and made of marble, a movable sand bed of length 4.0 m and 20cm thickness was formed just downstream of stilling basin, which has a sieve analysis with $d_{50}$ equal 3.8 mm see Figure (1), the expansion ratio for experimental model (i.e. $e = B/b) =1.90$, where B is the flume width, the sills was fitted in the rigid apron, the experimental tests were categorized in fourth sets as follow. (see table 1)

1. The first set of the experiments was carried out without any sill
2. The second set of the experiments was carried out using one semicircular sill. It included three positions of sill where $L_{sill}/y = 0.86, 2.6, \text{ and } 4.3$. For each position of the height of the sill was constant,

3. The third set of the experiments was carried out using three segmental curved sill (i.e. 90 seg. curved sill, 120 seg. Curved sill and straight sill) with fixed height,

4. The fourth set of the experiments was carried out using the straight sill with different relative height (i.e $H_{sill}/y = 0.1, 0.2, 0.3, 0.35 \text{ and } 0.50$).

### 3.3. The experimental procedures

After the flume was filled with bed material (marble) and accurately leveled, the leveling accuracy was checked by means of a point gauge. The following steps were carried out for each model but the first step not done for case of without sill:

- **a)** The sill was fitted in the rigid apron with a certain height and position,
- **b)** The tail gate was closed and back water feeding was started first until its depth reached higher than the required tailwater depth at the flume,
- **c)** The control valve of the pump was opened gradually until the required discharge passing in the flume,
- **d)** The discharge was measured by using the sharp crested weir at the end of the flume,
- **e)** The tail gate was screwed gradually until the required downstream water depth was arrived using the point gauge,
- **f)** Start the time of the test,
- **g)** After 4 hours (there is no change in bed profile), the pump was turn off,
- **h)** The flume and the scour hole were drained from water slowly, the scour depths and lengths were measured using point gauge.

![Figure. 2. Definition sketch of the experimental model](image-url)
Table 1: Scheme of experimental work stages

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>L_{sill}/y</th>
<th>H_{sill}/y</th>
<th>Angle</th>
<th>Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>the case of floor without sill</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>the effect of the sill position</td>
<td>0.86</td>
<td>0.35</td>
<td>90 seg. sill</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>the effect of the shape in the plan</td>
<td>0.86</td>
<td>0.35</td>
<td>90 seg. sill</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120 seg. sill</td>
<td>(180 degree)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>straight sill</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>the effect of the height of the sill</td>
<td>0.86</td>
<td>0.1</td>
<td>straight sill</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4. RESULTS AND DISCUSSION

Experimental tests were carried out to study the max scour depth and the scour hole geometry downstream culvert outlet for different flow conditions.

**4.1. Effect of using fixed apron on scour parameters**

Figure 3 shows a comparison between the present experimental results and each of Negm et al[3]. Ruff, et al[18]; Fletcher and Grace [20]and Bohan [19]. It shows the predicted values of d_{sc}/y and L_{sc}/y using Eqs. (1), (2), (3) and (4) versus the present measured results.
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Figure 3 Agreement of Negm et al[3]; Ruff, et al[18]; Fletcher and Grace [20] and Bohan [19]. Equations with the experimental measurements (a)$d_{sc}/y$ (b)$L_{sc}/y$

The present experimental results are less than the other empirical equations by about 60% of Ruff [18] and near to the results of Negm [3]. The main reason is that, the outlet of the culvert used in the previous authors’ equations are directly rested on the movable bed. In contrast, the recent experimental results used a rigid bed downstream the culvert outlet. Its length is about 7-times the culvert height. A great portion of the flow energy is dissipated on the rigid apron and hence the erosive action of the water is greatly reduced. Consequently, the scour hole dimensions are significantly reduced. This would be of great importance with significant engineering and economics benefit in engineering applications, as using rigid bed with length of 7-times the height of culver to reduce the scour by about 60%.

4.2. Effect of Sharp edge sill on scour parameters
In order to reduce the scour dimensions at box culvert outlets, it is essential to realize the nature of the phenomenon and the interaction between the flow and the proposed sharp edge sill (flow deflector). The scour parameters $d_{sc}/y, L_{sc}/y, d_d/y$ and $L_d/y$ are assessed for the culvert Froude number ($F_n = V/\sqrt{gy}$); and three different characteristics of the sharp edge sill including the position, the angle of curvature of the sharp edge sill and the sill height.
4.2.1. The position of the sharp edge sill (Lsill/y)

Figure (4) shows the relations between culvert Froude number and the different parameters including \(d_{sc}/y, L_{sc}/y, d_{d}/y\) and \(L_{d}/y\) for the different values of sharp edge sill’s relative position of (i.e., \(L_{sill}/y = 0.86, 2.60\) and 4.30 as shown in figure 5). Generally, all scour and deposition parameters are grow up as \(F_n\) increases and this matched well with the previous results [Negm et al[3] and Ruff, et al.[18]]. In addition, the values of these parameters are reduced to their least values for \(L_{sill}/y = 0.86\). The case of \(L_{sill}/y = 0.86\) decreases \(d_{sc}/y, L_{sc}/y, d_{d}/y\) and \(L_{d}/y\) by 64%, 78%, 97% and 94% compared to the base case.

![Graph (a)](image1)

![Graph (b)](image2)
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Figure 4 Relations between $F_n$ and the different scour parameters for different sill positions ($L_{sill}/y$) (a) $d_{sc}/y$, (b) $L_{sc}/y$, (c) $d_{d}/y$ and (d) $L_{d}/y$

Figure 5 show the position of the sharp edge sill

4.2.2. The shape of the sharp edge sill in the plan view

Figure (6) shows the relations between culvert Froude number ($F_n$) and both of scour and deposition characteristics for the different shape of the sharp edge sill in the plan view (straight
sill, 120 segmental curved sill and 90 segmental curved sill) as shown in the figure (7). The case of straight sill compacted the different scour parameters \(d_{sc}/y\) and \(L_{sc}/y\) compared to the initial case by about by 79%, and 92%, respectively. Moreover, it decreased the deposition parameters \(d_{d}/y\) and \(L_{d}/y\) by 80% and 54%, respectively.

![Graph (a)](image-a.png)

![Graph (b)](image-b.png)

![Graph (c)](image-c.png)
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Figure 6 Relations between $F_n$ and the different scour parameters for different sill positions (angle of sill) (a) $d_s/y$, (b) $L_s/y$, (c) $d_d/y$, (d) $L_d/y$

Figure 7 shows the angle of the sharp edge sill in the plan view.

4.2.3. The height of the sharp edge sill ($H_{sill}/y$)

Figure (8) shows the relations between $F_n$ and both of scour and deposition characteristics for the different sharp edge sill's relative heights (0.10, 0.20, 0.30, 0.35 and 0.50). The case of $h_{sill}/y=0.35$ compacted the different scour parameters $d_s/y$ and $L_s/y$ compared to the initial case by about by 92%, and 92%, respectively. Moreover, it decreased the deposition parameters $d_d/y$ and $L_d/y$ by 97% and 94%, respectively.
5. STATISTICAL REGRESSION

Based on the experimental data, empirical correlation to predict the different scour parameters \(d_{sc}/y\) and \(L_{sc}/y\) at the outlet of the box culvert were developed using multiple regression techniques. Different scour parameters \(d_{sc}/y\) and \(L_{sc}/y\) could be estimated from the following equations. These equations are valid within the following ranges of the involved parameters: \(L_{sill}/y\) [0.86 - 4.3], \(H_{sill}/y\) [0.1 - .5], \(F_n\) [0.7 - 0.95] and \(y_t/y\) [1.3-2.6].

\[
\frac{d_{sc}}{y} = 1.48 + 0.73F_n + 0.03\sin\theta + 0.032\left(\frac{L_{sill}}{y}\right) - 4.86\left(\frac{H_{sill}}{y}\right) + 6.3\left(\frac{H_{sill}}{y}\right)^2 - 0.42\left(\frac{y_t}{y}\right) \tag{9}
\]

\[
\frac{L_{sc}}{y} = 4.63 + 3.3F_n + 0.1\sin\theta + 0.9\left(\frac{L_{sill}}{y}\right) - 18.17\left(\frac{H_{sill}}{y}\right) + 23.33\left(\frac{H_{sill}}{y}\right)^2 - 1.63\left(\frac{y_t}{y}\right) \tag{10}
\]

Table 2: provides the statistical measures of the above equations.

<table>
<thead>
<tr>
<th>equation</th>
<th>Multiple R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
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<td>9</td>
<td>0.944204</td>
<td>0.891521</td>
<td>0.870525</td>
<td>0.075445</td>
</tr>
<tr>
<td>10</td>
<td>0.950835</td>
<td>0.904088</td>
<td>0.885524</td>
<td>0.388242</td>
</tr>
</tbody>
</table>

Figure 9 shows a comparison between the measured and the predicted values of Eqs. (9 and 10). Using the data sets used in this study, Figure 9 shows the calculated values of the investigated parameters against the measured ones. Presence of a small scatter between these variables can be noted. Generally, it can be observed that, there is an acceptable agreement between the measured data and the predicted ones. The residuals of the statistical equations are plotted versus the predicted values as shown in Figure 10. The residuals show random distribution around the line of zero. These figures confirm that the developed equation is statistically correct.
Figure. 9 Comparison between experimental and predicted $d_{sc}/y$ and $L_{sc}/y$ for the proposed equations
(a) equation 9 , (b) equation 10
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Figure. 10 Residuals of $d_{sc}/y$ and $L_{sc}/y$ for the proposed equations (a) equation 9, (b) equation 10

6. CONCLUSIONS
In the present study, a new approach was suggested and tested experimentally to minimize the scour downstream box culvert outlet. Prediction equations were developed using the scour and flow parameters. Within the experimental range of the present research, the analysis of the collected experimental data and evidence revealed that:

1. The use of the rigid bed with a length of 7 times of culvert height reduced the average values of the relative depth and length of scour by 60% compared with previous results without rigid bed;
2. Fixing a sharp edge sill at 0.86 $y$ from the culvert outlet reduces the scour and deposition parameters $d_{sc}/y, L_{sc}/y, d_d/y$ and $L_d/y$ by 64%, 78%, 97% and 94%, respectively compared to the initial case;
3. The use of straight sill compacted the different scour parameters $d_{sc}/y$ and $L_{sc}/y$ compared to the initial case by about by 79%, and 92%, respectively.
4. The use of sharp edge sill height of $h_{sill}/y=0.35$ compacted the different scour parameters $d_{sc}/y$ and $L_{sc}/y$ compared to the initial case by about by 92%, and 92%, respectively. Moreover, it decreased the deposition parameters $d_d/y$ and $L_d/y$ by 97% and 94%, respectively.
5. The reduction of the scour parameters due to using the sharp edge sill is 60%.
6. The developed statistical equations compare well with the experimental measurements with a mean $R^2 = 90\%$.

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