Reducing the Local Scour Depth at the Culvert Outlets
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Abstract:
Local scour downstream the box culverts outlet may cause 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 different flow conditions based on an experimental investigation. The experimental study was carried out using different flow rates and tail water depths and investigated the effect of the downstream wing wall angles on the scour depth at the culvert outlets. The results indicate that the downstream wing wall is a promising tool to reduce the scour dimensions. One empirical relationship is proposed to estimate the maximum scour depth by including the wing wall angles. The proposed relationship is further tested using extra experimental data, and a good agreement has been noted.

Keywords: Scour, culvert, culvert outlet, wing walls, submerged ratio, tailwater depth.

I. INTRODUCTION

Culverts are widely used in water management systems as a water-carrying structure under railway, highway, and embankments to carry storm-runoff. A poorly designed culvert could eventually result in structural collapses, which may cause significant damages to nearby infrastructures with high rebuild and repairs costs. It is reported that the cost to maintain and repair culverts are nearly 10 billion dollars each year in rural communities(Larry, 2017). It is important to protect the culvert by proper scour countermeasures. However, overdesign of scour countermeasures could significantly increase the project cost. Therefore, a proper estimation of scour at culvert outlets is critical to mitigating infrastructure failure. Local scour, which is defined as sediment movement locally around hydraulic structures, has received wide attention. Various studies have been conducted around many hydraulic structures under different conditions, such as bridge piers (Sheppard et al., 2013);(Wu et al., 2015), bridge abutments(Barbhuiya and Dey, 2004); (Dey and Barbhuiya, 2005), spur dikes (Kuhnle et al., 2002); (Zhang et al., 2009). Many empirical equations have been proposed to predict the equilibrium or maximum scour depth. However, none of these equations can be directly used to estimate scour depth at culverts. The prediction of scour dimensions at culvert outlets continues to be a concern for hydraulic engineers and researchers (Azamathulla and Haque, 2012). A few studies have been conducted on the scour depth prediction at the culvert outlets. As early efforts, (Schoklitisch, 1937) developed one equation to describe the local scour in an unprotected river bed below a free overfall (Schoklitisch, 1937). (Laursen, 1963) proposed an equation for long contraction scour. (Abt et al., 1985), 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., 1987), studied the effecting of culvert shape on scour depth at the outlet of the culvert and noticed that the dimensions of scour for the circular culverts significantly vary of other culvert shapes.(Abida and Townsend, 1991), studied the effecting of the tailwater depth, the passing discharge and the cross-section area on the scour dimensions. (Doehring and Abt, 1994) studied the effecting of the drop height on the localized scour at the culvert outlet. (Liriano et al., 2002), studied the effect of the turbulent flow on the culvert’s 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 and Larson, 2005), used two alternatives to dissipate the flow energy at the outlet of the culvert. (Crookston and Tullis, 2007), reviewed some empirical formulae for the prediction and calculation of the maximum scour depth at culvert outlet. (Crookston and Tullis, 2012), 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. (Negm et al., 2014), 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, and the reduction in the scour depth by using the flow deflector was 68%. (Najafzadeh, 2015) 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. (Fahmy, 2016), studied the scour depths at the pipe culvert tail escape outlet and developed and verified an empirical equation to be used to compute the scour depth and scour length downstream tail escape.(Osman and Adam, 2016), 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 predicting the scour depth at the outlet of the culvert. (Tjahyana and Lasmino, 2018), 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 the 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. There are studies on the culvert blockage during the flood. As an example, (Rigby et al., 2002) studied the blockage of culverts in the flood. They discussed the causes and effects of culvert blockage. (Rigby and Barthelmess, 2011) 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 the blockage of the culvert. (Sorourian et al., 2014), 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. 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 the effect of the wing wall angles downstream the outlet of the culvert and by the 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 applying 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:

\[
f (\rho, \mu, g, d_{sc}, H, W, v, y_{ds}, \Theta_{wall}) = 0\] .............................................................. (1)

Selecting \( \rho, H, v \) as repeating variables, the following dimensionless equation is obtained:

\[
\frac{d_{sc}}{H} = f (F_{culvert}, \frac{y_{ds}}{H}, \Theta_{wall}) \] .............................................................. (2)

In which: \( d_{sc}/H \) is the relative maximum scour depth; \( F_{culvert} \) is the Froude number, \( y_{ds}/H \) is the relative tail water depth; \( \Theta_{wall} \) is the downstream wing wall angle.

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

![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 has a dimensions of 34.65 cm width, 300 cm length, 11.55 cm height, slope of zero, the culvert was followed by wing wall (have an angle of 25 degrees) above a rigid bed with length 0.80 m, and, 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), experimental tests were categorized in two sets as follow.

1- The first set of the experiments was carried out with the downstream wing wall angle of 25 degrees.

2- The second set of the experiments was carried out using different angles of the wing wall downstream the culvert \( \Theta = 10,55 \) and 90 degrees.
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 the tail water depth on the scour parameters: The effect of tailwater depths on local scour characteristics was investigated experimentally on the box culvert has a dimension of (11.55 cm x 34.65 cm). The submerged ratio due to the tailwater depths is 2.16, 2.56 and 3.03 respectively. The relationship between maximum relative scour depth for \( \left( \frac{d_{s\text{max}}}{H} \right) \) and versus the culvert Froude number \( F_{\text{culvert}} \) at the submerged ratio of 2.16, 2.56 and 3.03 are shown in figure 3.

This figure explains that the maximum scours depth values at the low values of the culvert Froude number \( F_{\text{culvert}} \) are close to each other’s, but at the higher values of the culvert Froude number \( F_{\text{culvert}} \), the maximum scours depth values are separated to each other, and shows that the maximum relative scours depth increases as the culvert Froude number increases. The relationship between the relative energy loss \( \left( \frac{E_L}{E_1} \right) \) and the culvert Froude number \( F_{\text{culvert}} \) is plotted in figure 4 for different submerged ratio. It explains that increasing the culvert Froude number leads to increasing relative energy loss. The higher submerged ratio gives minimum energy losses so it gives low scour, but lower submerged ratio gives the maximum relative energy loss, so it exhibits high scour as shown in figure 4.
4.2. Effect Of the downstream wing wall angle 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 wing wall angles. The relationship between maximum relative scour depth for \( \frac{d_{\text{max}}}{H} \) and versus the culvert Froude number (\( F_{\text{culvert}} \)) at the different degrees of the downstream wing wall angles of 10, 25, 55 and 90 degrees are shown in figure 5. This figure explains that the maximum scour's depth values at the low values of the culvert Froude number (\( F_{\text{culvert}} \)) are close to each other's, but at the higher values of the culvert Froude number (\( F_{\text{culvert}} \)), the maximum scours' depth values are separated to each other, and shows that the maximum relative scours' depth increases as the culvert Froude number increases.

![Figure 5](http://ijesc.org/)

**Figure 5.** shows the relations between \( \frac{d_{\text{sc}}}{H} \) and \( F_{\text{culvert}} \) for different wing wall angles.

The relationship between the relative energy loss (\( E_L/E_1 \)) and culvert Froude number (\( F_{\text{culvert}} \)) is plotted in figure 6 for different angles of downstream wing wall (\( \Theta \)), which explains that, increasing the culvert Froude number leads to increasing relative energy loss for all cases and the slope angle of the wing wall = 90° gives minimum energy dissipation, this result can be obtained from figure 6.

![Figure 6](http://ijesc.org/)

**Figure 6.** shows the relationship between \( E_L/E_1 \) and \( F_{\text{culvert}} \) at a different angle of the wing walls (\( \Theta \)) at a submerged ratio of 2.16.

The scour contour map for bed morphology and velocity vectors downstream the outlet at rigid bed for \( F_{\text{culvert}} = 0.944 \) in case of presence of the wing wall angles on the basin is shown in figure 7 through figure 10. One can observe that, in all cases of slope angle of wing walls, maximum value of velocity was in the middle, so one maximum scour hole formed in centerline of the channel, but the case of slope angle of the wing wall (\( \Theta \)) = 90° gives the less value of velocity, so it gives less value of scour compared with the other cases.
Figure 7. Shows the Scour contour map for bed morphology for Θ=10° at F_{culvert}=0.944

Figure 8. Shows the Scour contour map for bed morphology for Θ=25° at F_{culvert}=0.944

Figure 9. Shows the Scour contour map for bed morphology for Θ=55° at F_{culvert}=0.944
5. STATISTICAL REGRESSION

The regression analysis was expanded by several trials using Microsoft Excel 2016 to find the best fitting of the experimental data. Suppose the general form of the empirical correlation is as the following Equation

$$d_{max} = f \left( H, F_{culvert}, \theta \right)$$

Where: $(d_{max})$ = the maximum scour depth, $(F_{culvert})$ = the culvert Froude number, $(\theta)$ = the wing wall angle downstream the outlet. The regression analysis is done using linear model equation and by the help of Microsoft Excel 2016 to achieve the highest value of $R^2$. Results of the experimental data can be expressed as shown in the following Equation.

$$\frac{d_{max}}{H} = f \left( F_{culvert}, \sin \theta \right)$$

Values of the best empirical correlation regression coefficients are listed in Table 1 to describe the maximum scour depth of the box culvert outlets.

<table>
<thead>
<tr>
<th>Table 1. regression coefficients value</th>
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<tbody>
<tr>
<td>Regression Variables</td>
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<tr>
<td>Constant</td>
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<tr>
<td>$F_{culvert}$</td>
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<td>$\sin \theta$</td>
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The final form of regression equation will be,

$$\frac{d_{max}}{H} = 1.35F_{culvert} - 0.044(\sin \theta) - 0.647$$

The Correlation Coefficient $R^2$ is 86.83%, means all values of the maximum relative scour depth of the box culvert outlets obtained from the empirical correlation are very close to the values were determined experimentally. The standard error of this equation is 0.077.

6. COMPARISON OF EXPERIMENTAL AND PREDICTED DATA:

Comparison with work by other authors is difficult due to the small data set available with information on scour depths at different tailwater depths. Figure 11, shows a comparison between the present experimental results and each of (Negm et al., 2014), (Ruff et al., 1982) and (Fletcher and Grace Jr, 1972). It shows the predicted values of $d_{sc}/y$ and $L_{sc}/y$.
The present experimental results are less than the other empirical equations by about 60% of (Ruff et al., 1982) and near to the results of (Negm et al., 2014). The main reason is that the outlet of the culvert used in the previous authors' equations is 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 economic benefit in engineering applications, as using a rigid bed with a length of 7times the height of culver to reduce the scour by about 60%.

7. 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 tailwater depth effect the relative scour depth at the culvert outlets and the higher values of the tailwater give minimum scour depth.
2. At the higher submerged ratio, the energy losses through the culvert are minimum.
3. The change of the downstream wing wall angles is effective in reducing the maximum relative scour depth at the outlets.
4. The wing wall angle of 90 degrees (sudden expansion) gives the minimum value of the scour depth.
5. 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 scouring by 60% compared with previous results without rigid bed;
6. The developed statistical equations compare well with the experimental measurements with a mean R² =90%.

8. REFERENCES


