Maximum scour depth and length downstream of tail escape

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Abstract: Driven by the importance of designing tail escapes, this research was commenced with the impartial of investigating scour holes depth and length downstream them, experimentally. Flow parameters were varied; dimensional analysis was executed and statistical analysis was conducted in order to determine the optimum design of tail escape that could protect it against failure due to scour downstream. The diameters of the circular weir are 10.16cm, 12.5cm and 15.24cm with different heights of 29cm, 31.5cm, and 34cm. The pipe culvert diameter is 7.61cm and the pipe hole diameter is 2.6cm. The results analysis indicated that the maximum scour depth and length, downstream the pipe culvert, increases as the head of water above the weir crest increases. In addition, it was deduced that the weir diameter increase has a limited effect on the downstream scour and maximum scour length was found to be nine times as much as the maximum scour depth. Different empirical equations were developed and verified to be used to compute the maximum scour length and scour depth downstream tail escape.

Key words: Tail escape, pipe culvert, scour length, scour depth, circular weir.

1. INTRODUCTION

The main function of tail escapes is to protect the end of earthen canals from failure. Consequently, local scour downstream of such structures is considered one of the main reasons of their failure. This could be avoided by adjusting different parameters (i.e. water levels, flow discharge, pipe diameter and downstream fill soil characteristics). Literature in the field of scour downstream of water structures in movable bed and side slope materials was investigated. Moreover, the stability of such structures was studied from which, it was found that many researchers are involved in investigating.

Opie (1977) investigated a method for predicting the extent of scour in loose bed materials at culvert outlet. He designed general approach at outlet culvert to dissipate energy. Abida and Townsend (1991) designed laboratory model to investigate local scour downstream of the box culvert. The study included the different culvert model in case of steep slopes. They modified new phenomena used to determine maximum scour in a stone bed downstream the pipe culvert. Liriano and Day (2001) achieved a comparative study using different experimental data and different established equations to determine scour depth at culvert outlets using neural networks. They deduced that the neural networks provide accurate results relative to empirical equations. Hotchkiss and Larson (2005) investigated experimentally the energy dissipation realized at the outlet of a culvert with a new fixed weir at the nearest downstream of the culvert. They found out that the developed approach reduced outlet energy by 10-48% and momentum by 6-71%. Emami and Schleiss (2005) conducted a physical test to evaluate the erosion in mobile bed without protection. They developed a design chart and empirical formula to find the local scour depth and verified with other results. Musavi Jahromi and Helalat Nasserian (2010), studied the effect of tail water depth on the characteristics of local scour at downstream of filling jets. They proposed an empirical equation to predict characteristics of scour hole. Azamathulla and Ghani (2011) described the use of adaptive neurofuzzy influence system (ANFIS) to estimate accurate scour depth. They reported that further effort should be conducted to assemble field data to train genetic programs. Azamathulla and Haque (2012) developed Gene-expression programming to predict the scour depth at the culvert outlet. The
developed programming was validated against random data of previous studies. Nassralla and Abdelaziz (2013) conducted experimental work to minimize scour downstream hydraulic structures using sills. They noticed that the sill exists at the downstream floor gives the smaller of scour relative to the no sill case. Helal (2014) investigated experimentally the effect of water jet on minimizing scour downstream of Fayoum weir. Sorourian et al. (2014) predicted scour depth at the outlet due to partially blocked box culvert. They deduced the relationship between the maximum scour depth, blockage ratio of the culvert and flow characteristics. Aliead (1990), Ghoma (2011), McEnroe (2006) and Smith (1957) discussed problems of scour downstream culvert outlet and deduced different empirical formulae to predict scour hole depth.

2. EXPERIMENTAL SETUP

An experimental work was achieved in order to determine the maximum scour length and depth. This was carried out in a flume of a large-scale size (i.e. 30 cm bed width). The implemented flume is rectangular and re-circulating with a closed operating system. Its overall length is 15.6 m, which is divided into three parts (i.e. inlet, outlet and working section). The length of the inlet, working section and outlet parts is 1.7m, 12.5m and 1.4 m, respectively. A general view to the flume is provided on Figure (1). The sump tanks consist of five tanks made of fiberglass. The first is 1.15 m long, 0.6 m wide and 0.85 m depth. The other tanks are 2.25m long, 0.7m wide and 0.6 m depth. The first tank is connected to the second by flexible rubber connection. The other tanks are connected to each other by 0.25 m P.V.C pipes through rubber connections. The first and last tanks have a drain valve at the lower part of their sides to drain the water of the sump tanks when required. The flow system is a closed circuit (i.e. re-circulating flume type). The flume takes its water from the sump tanks through 0.1m feeding pipe, which is connected to the pump. The tail gate consists of an aluminum plate, which is fixed at the end of the working section. Rubber sheets are provided, at its both sides, to prevent leakage at its connections with the outlet sides. The gate is pivoted at the bottom of the outlet tank by a watertight rubber connection. The submerged flow can be obtained by controlling the tail gate opening. The tail gate can be moved by using a hand driven gear system fixed at the top of the outlet tank.

Figure (2) shows the grain-size-distribution curve of movable riprap materials (i.e. $d_{10}=3\text{mm}$, $d_{50}=6.5\text{mm}$, $\rho_s=2.35\text{t/m}^3$ and $\sigma_g=1.6$) that was placed downstream the pipe culvert. The implemented models are circular weirs. They have different diameters (i.e. 10.16cm, 12.5cm and
15.24 cm) with different heights (i.e., 29 cm, 31.5 cm and 34 cm). The pipe culvert is fixed at a depth of 10 cm away from the channel bottom and its diameter is 7.61 cm. The pipe hole (i.e., with diameter is 2.6 cm) is fixed in the upstream weir at the bottom. All models are tested under different flow discharges with the riprap material at the downstream outlet of the pipe culvert.

3. DIMENSIONAL ANALYSIS

A dimensional analysis was conducted to relate the different parameters that affect local scour downstream tail escape (Figure 3). The obtained general function is:

$$d_{\text{max}} = f \left( \rho_s, \rho, g, \mu, v_o, P, D, H, L_s, L_{\text{max}}, b, L, h_c, h_{\text{d.s}}, d_c, d_{50}, \sigma_g \right)$$  \hspace{1cm} (1)

The parameters are channel bed width b (L), circular weir diameter D (L), circular weir heights P (L), head above weir H (L), Pipe culvert diameter d_c (L), head above culvert h_c (L), Riprap mean diameter d_{50} (L), maximum scour depth d_{\text{max}} (L), measured scour depth d_s (L), movable bed downstream stream L_s (L), measured scour length L_s (L), maximum scour length L_{\text{max}} (L), diameter of pipe hole at upstream weir d_o (L), head above pipe hole in upstream the weir h_o (L), v_o the mean velocity at the outlet (L.T^{-1}), \sigma_g the geometric standard deviation of sediment bed material and equals to \sqrt{d_{50}/d_{10}} , upstream water depth h_{u,s} (L) , downstream water depth h_{d,s} (L), the density of sediment bed material \rho_s (M/L^3), fluid density \rho (M/L^3), and dynamic viscosity \mu (F.L^{-2}.T).

Using the dimensional analysis Buckingham's \pi theory in which \rho, H, and g are selected as repeated variables representing fluid properties, geometry characteristics and the flow characteristics respectively, then:

$$\frac{d_{\text{max}}}{d_c} = f \left( F_o, \frac{h_c}{d_c}, \frac{H}{D}, \frac{h_o}{D}, \frac{P}{d_c}, \frac{L_s}{L}, \sigma_g \right)$$  \hspace{1cm} (2)

in which, \(d_{\text{max}}/d_c\) is the relative maximum scour depth, and F_o is the densimetric Froude number and equal \(F_o = \frac{v_o}{(S-1)^{\frac{\sigma_g}{d_{50}}}}\), S=\rho_s/\rho. Also:

$$\frac{L_{\text{max}}}{d_c} = f \left( F_o, \frac{h_c}{d_c}, \frac{H}{D}, \frac{h_o}{D}, \frac{P}{d_c}, \frac{L_s}{L}, \sigma_g \right)$$  \hspace{1cm} (3)

in which \(L_{\text{max}}/d_c\) is the relative scour length.
4. RESULTS ANALYSIS

4.1 Effect of weir height and diameter on maximum scour depth at outlet tail escape

The effect of the weir height and diameter were determined and presented. Figures (4), (5) and (6) indicate their effect on the maximum scour depth. Figure (4) relates the relative maximum scour depth ($d_{smax}/d_c$) and densimetric Froude number $F_o$, from which, it is clear that minimum weir height induces the maximum scour depth and vice versa. In addition, it was clear that the maximum scour depth at minimum and maximum weir height is 44%, which corresponds to weir height increase by 14.7%.

Figure 4. Relationship between ratio of ($d_{smax}/d_c$) and $F_o$ with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure (5) presents the relationship between the relative maximum scour depth ($d_{smax}/d_c$) and the ratio of $(H/P)$ with different weir heights and diameters. From the figure, it is apparent that the maximum scour depth increases as the ratio of $(H/P)$ increases. In addition, the fitting of measurement data provided a regression equation of:

$$ (d_{smax}/d_c) = 0.485 (H/P)^{0.417}, R^2 = 92\% $$

(4)

Figure (6) presents the effect of the ratio $(H/D)$ on the relative maximum scour depth $(d_{smax}/d_c)$ at different weir heights and diameters. It indicated that the ratio $(d_{smax}/d_c)$ increases as the $(H/D)$ increases. The fitting of the plot data provided a regression equation of:

$$ (d_{smax}/d_c) = 0.599 (H/D)^{0.461}, R^2 = 93\% $$

(5)
4.2 Effect of weir height and diameter on maximum scour length at outlet tail escape

The effect of weir height and diameter on maximum scour length at outlet tail escape was determined. The maximum scour length \( L_{smax} \) was measured and plotted on Figures (7), (8) and (9), for all the tested models. Figure (7) indicated that the increase in densimetric Froude number \( F_o \) increases the relative maximum scour length. The comparison indicated that the fitting data produced parallel lines for the different weir heights and diameters. The percentage of increase in \( (L_{smax}/dc) \) is 52% when the weir height was decreased by 47%. Figures (8) and (9) indicated the increase in \( (H/P) \), and \( (H/D) \) increases in \( (L_{smax}/d_c) \). The fitting data of these figures provided a power regression line with \( R^2 = 90.2\% \) and 91.8\%, respectively.

Figure 5. Relationship between ratio of \( \text{d(max)/c} \) and ratio of \( (H/P) \) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure 6. Relationship between ratio of \( \text{d(max)/c} \) and ratio of \( (H/D) \) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure 7. Relationship between ratio of \( (L_{smax}/d_c) \) and \( F_o \) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)
Figure 8. Relationship between ratio of \((L_{\text{max}}/dc)\) and ratio of \((H/P)\) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure 9. Relationship between ratio of \((L_{\text{max}}/dc)\) and ratio of \((H/D)\) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

4.3 Effect of flow over weir on maximum scour depth and length with different weir heights and diameters at tail escape outlet

The effect of flow over weir on maximum scour depth and length with different weir heights and diameters at tail escape outlet was determined, from which, it was clear that the flow discharge through tail escape is the main item affecting scour at the outlet. Figure 10 provides the relationship between \(d_{\text{max}}\) and flow discharge over weir \(Q\). It indicated that the increase in maximum scour depth as the flow discharge increases. The percentage of increase in \(d_{\text{max}}\) is 83% while the percentage of discharge increase is 50%.

Figure 10. Relationship between maximum scour depth and discharge over weir with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure (11) indicates the relation between \(L_{\text{max}}\) and flow discharge \(Q\). The maximum scour length increases as the discharge over weir increases. The regression analysis equations for the
above cases are as follows:

\[ d_{\text{smax}} = 0.09 \times Q^{2.281}, \quad R^2 = 86.9\% \]  \hspace{1cm} (6)

\[ L_{\text{smax}} = 3.358 \times Q^{1.403}, \quad R^2 = 85.2\% \]  \hspace{1cm} (7)

where: \( d_{\text{smax}}, \ L_{\text{smax}} \) in cm and Q is in Lit/sec.

\[ L_{\text{smax}} = 3.358Q^{1.403} \quad R^2 = 0.852 \]

\section*{4.4 Effect of combined weir with upstream pipe hole in maximum scour hole downstream}

The effect of combined weir with upstream pipe hole in maximum scour hole downstream was determined. The effect of combining the vertical circular weir and upstream pipe hole (fixed at the bottom) on the maximum scour depth and length is provided on Figures (12) and (13). Figure (12) indicated that the combining the weir and pipe hole increases the maximum scour depth by 25\% when compared to the case of weir only. Figure (13) indicated that the average increase in maximum scour length in the case of combining the weir and pipe hole is 14.2\%, compared to weir only, which specified that at worst flow with high water level, protecting tail escape is required.

Figure 11. Relationship between maximum scour length and flow over weir Q (Lit/sec) with different weir heights and diameters (10.16cm, 12.5cm, and 15.25cm)

Figure 12. Relationship between \((d_{\text{smax}}/d)\) and \(F_o\) for combined weir and bottom pipe hole upstream weir

Figure 13. Relationship between \((L_{\text{smax}}/d)\) and \(F_o\) at combined weir with pipe hole upstream
4.5 Predict Scour Profile along Downstream Movable Floor

The scour profile along downstream movable floor was predicted. Figures 14, 15 and 16 indicate the predicted scour profile and deposit along movable bed downstream tail escape. The figures specified the scour length and depth increase as the head above the weir increases and vise versa. The effect of weir diameters on the scour depth and length is very limited.

![Figure 14. Scour profile along movable downstream bed at different weir height and D=10.16cm and Q=5.2 Lit/sec](image1)

![Figure 15. Scour profile along movable downstream bed at different weir height and D=12.5cm and Q=5.2 Lit/sec](image2)

![Figure 16. Scour profile along movable downstream bed with different weir heights, D=15.246cm and Q=5.2 Lit/sec](image3)

5. DEVELOPED EMPIRICAL EQUATIONS

Figure 17 plotted the regression analysis to develop an empirical equation used to determine the maximum scour depth. The relationship between \( \frac{d_{smax}}{d_c} \) and Xdata1 shows that the fitting curve of the observed data can be written as follows:

\[
\frac{d_{smax}}{d_c} = 1.137 \times Xdata1 - 0.05
\]

(8)

in which:
\[ Xdata_1 = -0.079 + 0.05 \cdot F_o + 0.281 \cdot \left( \frac{H}{P} \right)^{0.417} + 0.199 \cdot \left( \frac{H}{D} \right)^{0.461} \]

Then, the general form to develop equation can be written as follows:

\[ \frac{d_{\text{max}}}{d_c} = -0.018 + 0.062 \cdot F_o + 0.346 \cdot \left( \frac{H}{P} \right)^{0.417} + 0.247 \cdot \left( \frac{H}{D} \right)^{0.461}, \quad R^2=93.7\% \tag{9} \]

\[ \text{Figure 17. Plotted measurements and fitting developed equation to compute (}d_{\text{max}}/d_c\text{) with different weir heights and diameters} \]

The developed empirical equation to determine the maximum scour length is shown in Figure (18). The developed equation can be written as follows:

\[ \frac{L_{\text{max}}}{d_c} = 0.869 \cdot Xdata_2 + 0.542 \tag{10} \]

in which \( Xdata_2 = -1.056 + 0.534 \cdot F_o + 3.53 \cdot \left( \frac{H}{P} \right)^{0.528} + 2.34 \cdot \left( \frac{H}{D} \right)^{0.627} \)

Then, the general form of the develop equation can be written as follows:

\[ \frac{L_{\text{max}}}{d_c} = -0.375 + 0.462 \cdot F_o + 3.067 \cdot \left( \frac{H}{P} \right)^{0.528} + 2.03 \cdot \left( \frac{H}{D} \right)^{0.627}, \quad R^2=90.7\% \tag{11} \]

\[ \text{Figure 18. Plotted measurements and fitting developed equation to compute (L_{\text{max}}/d_c) with different weir heights and diameters} \]

Figure (19) shows that the developed empirical equation to co-relate the relationship between (\(L_{\text{max}}/d_c\)) and (\(d_{\text{max}}/d_c\)). The developed equation can be written as follows:

\[ \frac{L_{\text{max}}}{d_c} = 9.060 \left( \frac{d_{\text{max}}}{d_c} \right) + 0.030, \quad R^2=92.60\% \tag{12} \]
If \((d_{\text{smax}}/d_c)=1.0, 2, 3\) then \((L_{\text{smax}}/d_c)=9.09, 18.15, \text{ and } 27.21\) respectively.

From Figure (19) and Equation (10) we can find that \(L_{\text{smax}}\) approximately equal nine times \(d_{\text{smax}}\).

**Figure 19. Developed empirical equation to co-relate between \((L_{\text{smax}}/d_c)\) and \((d_{\text{smax}}/d_c)\)**

### 6. VERIFYING EMPIRICAL EQUATIONS

The empirical equations were verified against measured data. Figure (20) presents the verification of Equation (9) which determines \((d_{\text{smax}}/d_c)\) depending on \(F_o\), \((H/P)\) and \((H/D)\). The measured \((d_{\text{smax}}/d_c)\) and computed values were as follows:

\[
\frac{d_{\text{smax}}}{d_c}\text{ computed} = 0.9921\times\frac{d_{\text{smax}}}{d_c}\text{ measured } + 0.031, \quad R^2=92.5\%
\] (13)

The percentage of error is 5.10% which is considered to be satisfactory results from the engineering point of view. Accordingly, this equation could be implemented to deduce the maximum scour depth.

Figure (21) presents the computed values of \((L_{\text{smax}}/d_c)\) using Equation (11) and the measured values that is written as follow:

\[
\frac{L_{\text{smax}}}{d_c}\text{ computed} = 1.034\times\frac{L_{\text{smax}}}{d_c}\text{ measured } + 0.066, \quad R^2=90.5\%
\] (14)

The percentage of error was determined to be 4.5% which is considered to be a satisfactory result from the engineering point of view.

**Figure 20. Plot of \((d_{\text{smax}}/d_c)\) measured and computed by developed equation**
Figure 21. Plot of \((\frac{L_{\text{max}}}{dc})\) measured and computed by developed equation

The verification of Equation (12) is plotted on Figure (22). It is used to determine the maximum scour length using the maximum scour depth. It is written as follows:

\[
(\frac{L_{\text{max}}}{dc})_{\text{computed}} = 0.882 \left(\frac{L_{\text{max}}}{dc}\right)_{\text{measured}} - 0.25, \quad R^2 = 94.5\%
\] (15)

The average percentage of error is estimated to be 16.8% which is considered to be a satisfactory result from the practical point of view.

Figure 22. Plotting fitting between measured and computed \((\frac{L_{\text{max}}}{dc})\)

7. CONCLUSIONS

Based on the obtained results from the conducted experimental work, the executed dimensional analysis and the established empirical equations, the following conclusions were extracted:

- The weir height has a big effect on the maximum scour length and depth downstream tail escape when compared to weir diameter that has limited effect.
- The increase in flow discharge in tail escape increases the maximum scour depth and length.
- The average increase in maximum scour length and depth is 80% when the percentage of increase in discharge is 50%.
- The established empirical equations are applicable to determine maximum scour depth and length downstream tail escape. They provided satisfactory results against measured data.
- The maximum scour length is nine times as much as the maximum scour depth.
- The average increase in maximum scour depth and length is 14.2% when weir and upstream pipe hole are implemented together.
REFERENCES