Investigation of clear water scouring around wing-wall abutments

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An important challenge in river engineering is the local scour around the abutments due to the contraction of cross section and strong vortices. In this paper, the laboratory experiments were conducted around wing-wall abutments of 4, 6, 8 and 10 cm long to investigate the effect of protrusion on scouring. The tests were accomplished under clear water condition with \( \frac{V}{V_c} \) ratios of 0.8 and 0.9. The results indicated that the increase in abutment length associated with the application of higher flow rate (\( \frac{V}{V_c} = 0.9 \)) causes the expansion in size and the volume of scour hole. Meanwhile, the contraction of flow section causes the increase in dimensionless scour depth with almost a linear trend.

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1. **Introduction**

There are various methods to provide stability for bridges and river banks. In this regard, diversion of the flow direction and reduction of the velocity at the regions located close to the bank are typical methods that are commonly applied.

Abutment is one of the most important structures to achieve the bank stability but the drawback of its application is that it may cause scouring. Therefore, it is important to efficiently design the abutment size. It is obvious that there is always an uncertainty associated with the interaction of flow, sediment and hydraulic structures. Therefore in this paper, a series of laboratory experiments were conducted to assess the effect of protrusion length, herein called as abutment length, for wing-wall abutments.

1.1. **Background of the research**

Li et al. (2006) proposed that the maximum scouring depth will occur if the abutment length is less than 15 percent of the channel width. Many parameters affect the local scouring around the abutment including stream and sediment properties and also the scouring duration. Considering the mentioned parameters, many researches were accomplished to present an empirical relationship of local scouring around the abutment. Most of these researches concluded that the scouring depth increases with the increase in flow depth (\( y \)) but there is an extreme value of (\( \frac{y}{L} \)), where \( L \) is the abutment length, for which the maximum scouring depth will be independent from the flow depth (Melville, 1992; Dongol, 1994; Kandasamy and Melville, 1998).

Melville (1992) classified the abutments based on the shape to four groups including vertical, semi-circular, wing-wall and spill-through abutments. In fact, the contraction which is made across a river section by an abutment or bridge pier changes the flow pattern due to the vortex flow. He also
suggested that for $\frac{L}{d_{s0}} > 50$, equilibrium depth of scouring ($d_s$) is independent from the sediment size ($d_{s0}$). Dongol (1994) indicated that scouring around an abutment is to big extent similar to that of a bridge pier. According to his results, $\frac{d_s}{L}$ decreases when $\frac{L}{d_{s0}} \leq 40$. He also claimed that the sediment size has no effect on equilibrium depth of scouring for $\frac{L}{d_{s0}} > 40$. Ballio and Orsi (2001) presented an equation to determine the equilibrium time of scouring in flume with varying width. Fig. 1 shows that the down flow and primary vortex at upstream side and the secondary and wake vortices in the middle and downstream corner of the abutment lead to the scouring (Barbhuiya and Dey, 2004).

![Figure 1: Scouring mechanism around an abutment (Kayaturk, 2005)](image)

Considering the non-uniformity of the sediment materials, Dey and Barbhuiya (2004) concluded that the formation of a protective layer in scour hole significantly decreases the scouring depth. Researches continued during the last decade to present relationships for approximation of the scouring depth. Chaurasia and Lay (2002) obtained a relationship based on both their tests under clear water condition and also the previous reports.

1) $\frac{d_{se}}{y} = 2.657 \theta_c^{-0.16} F_0^{0.765} \left( \frac{L_a}{y} \right)^{0.245} \left( \frac{d_{s0}}{y} \right)^{0.265} - 1$

where $\theta_c$, $L_a$, $y$, $d_{se}$ and $F_0$ are Shields parameter, abutment length, flow depth, equilibrium depth of scouring and densimetric Froude number, respectively.

The densimetric Froude number is defined as follows (Eqs. 1, 2).

2) $F_0 = \frac{v}{\sqrt{gd_{s0}}}$

3) $\dot{g} = \left( \frac{\rho_s - \rho}{\rho} \right) g$

Where $g'$, $g$, $\rho_s$, $\rho$ and $V$ are relative gravitational acceleration, gravitational acceleration, density of sediment, density of fluid (water) and velocity of approaching flow, respectively. Dey and Barbhuiya (2004) studied the different types of abutments and suggested the following equation for the scouring depth of short abutments in clear water condition (Eq. 4).

4) $\frac{d_s}{L} = 5.16 k_s \left( \frac{V}{L} \right)^{0.18} \left( \frac{V_c}{\sqrt{(3-1)gL}} \right)^{0.26}$

Where $V_c$ is the critical velocity for the initiation of motion of bed particles (hereafter is called the critical velocity) and $k_s$ is the shape factor of the abutment which is 0.75 for Wing-Wall abutments. Coleman et al. (2003) introduced the parameter $T^\ast = teV/L$ where $T^\ast$ is the dimensionless equilibrium time. He also introduced the following relationships to approximate $T^\ast$ (Eqs. 5, 6).

5) $T^\ast = 10^6 \left( \frac{V}{V_c} \right)^3 \left( \frac{V}{L} \right) \left\{ 3 - \left[ 1.2 \left( \frac{V}{L} \right) \right] \right\}$, $\frac{V}{L} < 1$, $\frac{L}{d_{s0}} > 60$

6) $T^\ast = 1.8 \times 10^6 \left( \frac{V}{V_c} \right)^3$, $\frac{V}{L} \geq 1$, $\frac{L}{d_{s0}} > 60$

Where $te$ is the equilibrium time. They also calculated the temporal variation of scouring depth around the abutments under the clear water condition and added the $K_c$ factor (Eq. 7) to the previous equation by Melville (1992).

7) $k_t = \frac{d_{st}}{d_s} = \exp[-0.07 \left( \frac{V}{V_c} \right) \ln \left( \frac{L}{T^\ast} \right)^{1.5}]$

Where, $V$ and $T$ are velocity of flow and equilibrium time of scouring, respectively.

Many other researches have been carried out to find appropriate alternatives to deal with the scour around the abutment (Kayaturk, 2005; Li et al., 2006; Melville et al., 2007).

In addition, Mazumdar and Barbhuiya (2014) investigated the live-bed scour around 45 degree wing-wall abutments. Mohammadpour et al. (2014) considered the local scouring around abutments using a three dimensional numerical model. They
concluded that the numerical method can be used to predict the temporal variation of scour in initial time of scouring as well as the depth of scour. Wu et al. (2015) experimentally studied the local scour around bridge abutments under ice covered condition. They plotted the contours of scour hole in ice covered condition and put forward an empirical relationship between maximum scour depth densimetric Froude number and sediment size. In this paper, the goal is to experimentally investigate the scour hole around the wing-wall abutments with different lengths and also to assess the temporal development and maximum depth of scour hole along with the topography and contours of the scour hole.

2. Materials and Methods

The experiments were conducted in a flume of 6 m long, 80 cm wide and 50 cm deep with rectangular cross section. There were a stilling basin at the end and an ultrasonic sensor to measure the discharge. In addition, a downstream gate was used to adjust the tail water depth. Some facilities including the false floor and moving bed were provided to make the sediment tests possible.

According to the previous studies by Dongol (1994), the maximum scouring depth occurs when L/d50 is greater than 40 and according to Dey and Barbhuiya (2005) the geometric standard deviation of sediment particles σg should be less than 1.4. Therefore, non-cohesive sandy soil was used with d50= 0.4 mm, specific gravity Sg=2.67. Using iron sheets, the wing-wall abutments were built in the laboratory setup with different lengths of 4, 6, 8 and 10 cm. Since the goal is to investigate the local scouring under clear water condition, the average velocity of flow (V) must be less than the critical velocity. Therefore, the tests were carried out for \( \frac{V}{V_c} \) equal to 0.8 and 0.9. The values of Reynolds and Froude numbers were controlled within the range of \( 6.8 \times 10^4 \) - \( 11.2 \times 10^4 \) and 0.14 - 0.2, respectively. Then, various parameters including the flow rate, flow depth, shear velocity and depth of scour hole were measured. According to Coleman et al. (2003), the values of \( y/L \) were kept greater than unity, i.e. 2.1 to 2.8, to make sure that the flow depth has no influence on the depth of scour hole. As a result, the range of flow rate was selected to be within 17-34 lit/s. The depths of scour hole and flow were measured using an ultrasonic sensor with the precision of ±0.1 mm. Fig. 3 demonstrates the scour hole around the abutment.

Table 1 shows the laboratory data obtained from the tests on abutments with four lengths of 4, 6, 8 and 10 cm. Meanwhile, the measured data were taken for abovementioned \( \frac{V}{V_c} \) values of 0.8 and 0.9.
Table 1: The laboratory data of scouring tests

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<th>L(cm)</th>
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<th></th>
<th>V/V_C=0.9</th>
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<td>Q(CMS)</td>
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<td>y(cm)</td>
<td>Q(CMS)</td>
</tr>
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<td>0.0282</td>
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</tr>
<tr>
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<td>20.55</td>
<td>0.0336</td>
<td>9.25</td>
<td>17.78</td>
<td>0.0322</td>
</tr>
</tbody>
</table>

3. Results and Discussion

It was observed during the experiments that the scour onsets in front of the abutment, region A, at an angle of about 117 degree (Fig. 4).

![Figure 4: The location of scouring onset.](image)

The sediments eroded from the front side of the abutment were carried to the downstream and formed the ripples. Formation of these ripples accelerated the sediment transport due to the wake vortices around and in front of the abutment. The deeper the scour hole became, the more it developed to the sides of the abutment. The observed result is in agreement with Oliveto and Hager (2002). The rate of deepening the scour hole was high at the beginning of the test but it gradually declined. In this regard, 70 percent of the maximum scouring depth took place earlier than one hour from the beginning of the test.

3.1. Temporal development of scouring

Fig. 5 shows the temporal development of scouring around 8 and 10 cm long abutments for $\frac{V}{V_c}$ ratios of 0.8 and 0.9.

![Figure 5: Temporal development of scouring around 8 and 10 cm long abutments.](image)

With increase in $\frac{V}{V_c}$ ratio for both of the abutment lengths, it is observed in Fig. 5 that there are increases in values of the dimensionless scouring depth $\left(\frac{d_s}{L}\right)$ and the rate of scouring development. Therefore, the greater is $\frac{V}{V_c}$, the stronger is the stream power around the abutment which leads to the increase in down flow. As $\frac{V}{V_c}$ increases from 0.8 to 0.9, $\frac{d_s}{L}$ value for 10, 8 cm long abutments varies after ten hours from 0.925 to 1.185 and 1.031 to 1.231, respectively.

3.2. Temporal development of scouring and comparison with previous reports

In Fig. 6, the temporal development of the scour depth for abutments with different lengths is compared with the results presented by Ballio and Orsi (2001) and Coleman et al. (2003).
Figure 6: Temporal development of scour depth in comparison with previous reports

It is demonstrated that the temporal development of scouring around the abutment is in agreement with the results of Coleman et al. (2003) but Ballio and Orsi (2001) obtained underestimated results comparing with the current study. This conclusion stems from the same conditions of the current research and that of Coleman et al. (2003). Generally, the relationship by Coleman et al. (2003) offers more acceptable results than that proposed by Ballio and Orsi (2001).

3.3. Comparison of scour depth with previous reports

In Fig. 7, the maximum scouring depth obtained from the current research for \( \frac{V}{V_c} = 0.9 \) is compared with the previous reports. Fig. 7 indicates that the values of scouring depth obtained by Chaurasia and Lai (2002) are closer to those of the current study. The cause of better approximation by Chaurasia and Lai (2002) is that they took into account more parameters affecting the scour depth.

Figure 7: Relationship between \( \frac{d_s}{d_{50}} \) and \( \frac{V}{V_c} \) in comparison with previous reports.

According to Melville (1992), for \( \frac{y}{L} > 1 \), the flow depth has no influence on the scour depth and consequently \( \frac{d_s}{y} \) will have a constant value.

Fig. 8 demonstrates the variation of dimensionless scouring depth with \( \frac{L}{B} \) for two applied \( \frac{V}{V_c} \) values.

Figure 8: Variation of \( \frac{d_s}{d_{50}} \) with \( \frac{L}{B} \) for different \( \frac{V}{V_c} \) values.

It is observed that the dimensionless scouring \( \left( \frac{d_s}{d_{50}} \right) \) has an ascending trend with increase in \( \frac{L}{B} \) ratio. Additionally, value of \( \frac{d_s}{d_{50}} \) increases as greater \( \frac{V}{V_c} \) is applied. The increase in \( \frac{L}{B} \) ratio, that shows the contraction of flow section, causes larger dimensionless scouring depth with almost a linear ascending trend. Meanwhile, Fig. 8 shows the comparison of results with those obtained from Barbhuiya and Dey (2004). It is obvious that the variations of dimensionless scouring depth follow the same trend as the results from Barbhuiya and Dey (2004). But there is an apparent distance between the curves that may origin from the difference in both standard deviation (σg) and sediment size (\( d_{50} \)).

3.4. Topography and contours of scour depth around the abutment

Figures 9-10 show the topography and contours of scour depth around the abutment. According to the figures, the prevailing erosive flow is observed inside the hole toward the central axis of flume. The increase in abutment length associated with the application of \( \frac{V}{V_c} = 0.9 \) causes the larger size and volume of the scour hole. The maximum scour depth was observed in front of the abutment. Moreover, the bed level at the upstream of abutment was left smooth and without change.
4. Conclusion

During the tests, it was observed that the scouring process started at the intersection of upstream face and front part of the abutment. Meanwhile, other conclusions can be summarized as follows:

- Scouring rate was higher at the beginning of the tests but it gradually declined as the scour holes developed. Nearly, 70 percent of scouring occurred during the first hour since the start of the tests.

- Dimensionless scour depth $\left(\frac{d_s}{d_{50}}\right)$ was almost constant for $\frac{V}{V_c} > 1$ that is in agreement with Melville (1992) and Babhuiya et al. (2004).

- The value of $\frac{d_s}{d_{50}}$ increases as higher $\frac{V}{V_c}$ is applied.

- Application of greater $\frac{L}{B}$ values, which indicates the contraction of flow section, causes the increase in dimensionless scour depth with almost a linear trend.

The increase in abutment length associated with the application of higher flow rate ($\frac{V}{V_c} = 0.9$) causes the expansion in size and the volume of scour hole.

References


