ICSE6-219

Determination of Rectangular Collar Dimensions for Reducing Scour around Bridge Pier

Afshin JAHANGIRZADEH [1], Shatirah AKIB [2], Zubaidah ISMAIL [3], Babak KAMALI [4], Mahshid KAKOUEI[5], Arash BEHNIA[6]

[1]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
Afshin.jk@gmail.com
[2]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[3]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[4]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[5]Faculty of Arts and Social Sciences, University of Malaya, 50603 Kuala Lumpur, Malaysia
[6]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Researchers have utilized collars as a countermeasure to reduce scour because of their ability to bend the down flow affecting a pier. The shape and dimensions of a collar are important parameters to maximize the effect. The objective of this study is to determine the optimum dimensions of a rectangular collar in reducing scouring around a model bridge pier. Collars with different widths were positioned with different front and rear lengths in relation to the pier and the resulting scour development observed. Results showed intensity and scour hole depth were decreased by the rectangular collars. Regardless of the collar dimension, the optimum ratio of upstream length of collar to the diameter of pier and downstream length of collar to the diameter of pier were found to be 0.93 and 1.44, respectively. The optimum collar width was estimated to be 2.8 times bigger than the pier diameter. Applying these ratios, no scouring was observed during 72 hours running flume experiment.

Key words
Bridge pier; clear water; critical velocity; rectangular collar; scour

I INTRODUCTION

Bridges play an important role in transportation. An ever-increasing number of bridge failures are caused not only by structural defaults but also due to scouring at their piers and abutments [Zarrati et al., 2010]. Scour at bridge piers is a crucial issue which undermines bridge integrity.

Horseshoe and wake vortices contribute to scour holes around bridge piers [Breusers and Raudkivi, 1991; Deng and Cai, 2010]. The basic mechanism causing local scour at piers is the down flow at the upstream face of the pier and formation of the horseshoe vortex at the base of the pier. The horseshoe vortex thus developed due to the separation of flow at the edge of the scour hole upstream rolls to form a helical flow, which is similar to the ground roller downstream of a dune crest. The flow departure from the pier creates wake vortices behind the pier. Local scour is classified into two categories: clear-water and live-bed scour [Chabert and Engeldinger, 1956]. Clearwater scour is defined as the case where the bed sediment is not moved by the approach flow rather removal of sediment material from the scour hole that is not refilled by the approach flow [Melville, 1984]. Live-bed scour, on the other hand, occurs when there is general transportation of the bed material by the flow. Live-bed scour occurs when the scour hole is continually replenished with sediment by the approach flow [Dey, 1999]. For average flow velocity (V) larger than the average flow velocity of sediment grains (V_c) live-bed scour takes place. When the average flow velocity is in the range of $0.3\ V_c < V < V_c$, clear-water scour occurs [Melville and Chew,1999]. Flow characteristics, pier geometry, angle of attack of the approach flow to the pier and sediment characteristics are factors governing pier scour [Melville, 1997]. Akib et al. (2011) conducted an experimental investigation on scouring affected skewed integral bridge. Melville (1997) suggested the following equation for the bridge pier scour:

$$d_{se} = k_{yb}.k_i.k_d \quad (1)$$

[1] Corresponding author

In which d_{se}, k_{yb}, k_i and k_d are the depth of scour (in the balanced condition), coefficient of flow depth, coefficient of flow intensity, and coefficient of amount of sediment grains, respectively. Melville (1997) proposed the following equations to calculatek_{yb}:

$$k_{yb} = 2.4\,b \qquad \frac{b}{y} < 0.7 \tag{2}$$
$$k_{yb} = 2(yb)^{0.5} \qquad 0.7 < \frac{b}{y} < 5$$
$$k_{yb} = 4.5\,y \qquad \frac{b}{y} > 5$$

To calculate the flow intensity parameter the following equations were derived [Melville, 1997]:

$$K_i = \frac{V}{V_C} \qquad \frac{V}{V_C} < 1 \tag{3}$$
$$K_i = 1 \qquad \frac{V}{V_C} \geq 1$$

V is the average flow velocity and V_c stands for the average critical velocity (velocity in the threshold motion of the sediment grains).

The coefficient of the sediment grains in the Melville's equation (1997) is calculated as follows:

$$K_d = 0.57\log\left(2.24\,\frac{b}{d_{50}}\right)\ , \qquad \frac{b}{d_{50}} < 25 \tag{4}$$
$$K_d = 1\ , \qquad \frac{b}{d_{50}} > 25$$

In the latter equations the quantity coefficient of the sediment grains is d_{50} and the width or diagonal is shown by 'b'. Shepherd and Miller (2006) have proposed the following equation to calculate the equilibrium depth of the scour hole in the clear-water scour condition:

$$\frac{d_{se}}{D} = 2.5 f_1\left(\frac{y}{D}\right).f_2\left(\frac{D}{d_{50}}\right).\left\{1 - 1.75\left[\ln\left(\frac{V}{V_C}\right)\right]^2\right\} \tag{5}$$

D is the pier diameter, f_1 and f_2 functions are to be calculated as follows:

$$f_1\left(\frac{y}{D}\right) = tanh\left[\left(\frac{y}{D}\right)^{0.4}\right] \tag{6}$$

$$f_2 = \left(\frac{D}{d_{50}}\right) = \frac{\frac{D}{d_{50}}}{0.4\left(\frac{D}{d_{50}}\right)^{1.2} + 10.6\left(\frac{D}{d_{50}}\right)^{-0.13}} \tag{7}$$

Bridges scour countermeasures include: riprap, sacrificial piles, slots, and collars. Laursen and Toch (1956) pioneered the use of collars. Several researchers have utilized this method [Dargahi 1987, Ettema 1980]. Combinations of methods have also been conducted [Chiew 1992]. The objectives of this study are to demonstrate the function of rectangular collars and optimize their dimensions.

II MATERIALS AND METHODS

The experimental canal was 12m long, 30cm wide, 50cm high, and with a slope of 0.002 and metal floor and glass walls. At the end of the canal there is a basin in which a triangular weir is devised in order to measure flow discharge with an accuracy of 0.1 L/s (Figure 1).

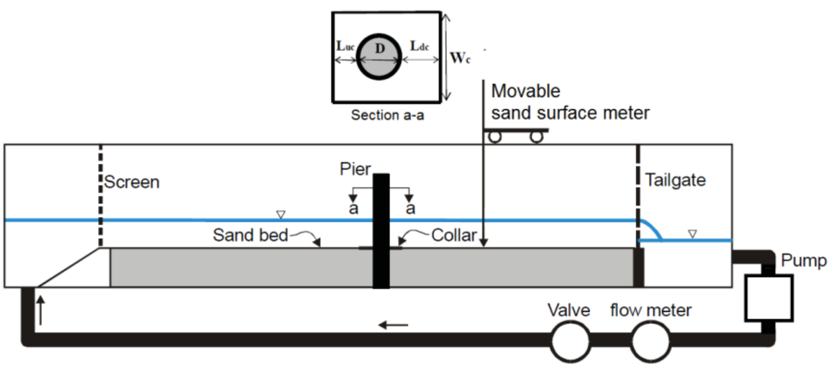

Figure 1: Plan and profile of the experimental canal.

Water was circulated using two pumps. An adjustable tail gate was set up in the downstream of the canal. The flow velocity and depth of scour measured and recorded respectively by 3 axis Electronic current velocity meter and Sand Surface Meter. The grain characteristics observe the following:
If $\sigma_g < 1.5$, bed materials are homogenous; and for $\sigma_g \geq 2$ they are not [Shafai-Bojestan, 1994]. Thus with $\sigma_g = 1.46$, the sediments leave no effect in terms of reducing the scour depth. The following points were considered to gain the maximum scour depth:

- Diameter of pier model and canal width (w). If $\frac{D}{W} < 0.1\,L$ then the scour depth is not affected by width [Arounaqi et al, 2006]. Diameter of 12mm was chosen.
- The average diameter of grains $\frac{D}{d_{50}} > 25$ (Melville, 1997).

$$D = 14\ mm\,, \qquad d_{50} = 0.35\ mm \quad \rightarrow \quad \frac{D}{d_{50}} = 42$$

- The water flow depth $\frac{D}{y} > 0.7$ is maintained not to affect the depth of scour hole [Melville, 1997].
- $\frac{V}{V_c} = 1$ Condition. Critical velocity was compared with equations of Neill (1973):

$$V_C = {\theta_c}^{1/2} K_u 31.08 y^{1/6} {d_{50}}^{1/3} \qquad (8)$$

In this equation V_c is the critical velocity (m/s), y stands for water depth (m), d_{50} for the average size of the sediment grains and K_u is a constant that is equal to 1 in the American system and 1.81 in the International system. Muller (1996) has developed an equation to calculate the critical Shields parameter(θ_c):

$$\theta_c = 0.0019 {d_{50}}^{-0.384}\,, \qquad d_{50} < 0.0009 \qquad (9)$$

The $\frac{V}{V_c} = 1$condition is difficult to maintain. $\frac{V}{V_c} = 0.9$ and $\frac{V}{V_c} = 0.95$ conditions were used.
The collars were made of rigid plastic 0.6mm thick. The collars were located on the bed while being symmetrical in relation to the sides of the experimental canal.

III RESULTS AND DISCUSSION

III.1 Bridge Piers Scour in the Non-Collar Condition

Results with collarless piers for $\frac{V}{V_c}$: 0.9 and 0.95 showed scour starting from the front of the pier, moving to the sides of the pier and eventually reaching the downstream. The scour velocity was initially considerable and gradually decreased. Scour depth in the front of the pier and at 2mm from the pier was monitored. Figure 2 shows the development of the scour depth in the front of the pier with time. In the first two hours the scour velocity was 80% of scour depth created. In part 'b' the increase in scour depth was relatively small. In part 'c' the scour depth changes were negligible. The scour equilibrium depth could be calculated based on this part. Table 1 shows the summary of results where t_e is the scour depth equilibrium time and d_{se} represents equilibrium scour depth.

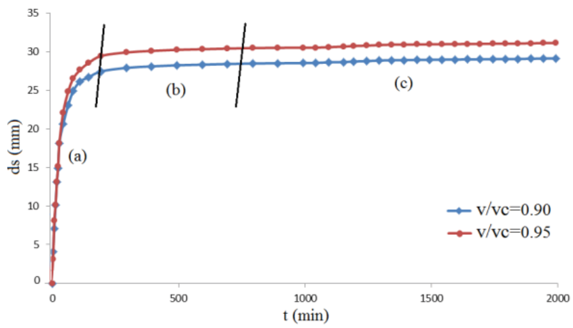

Figure 2: Scour depth time changes.

$\frac{V}{V_C}$	d_{se} (mm)	$\frac{d_{se}}{D}$	t_e (hr)
0.9	30.04	2.14	17.2
0.95	32.48	2.32	17.9

Table 1: Equilibrium time and depth of scour.

Non-dimensional depth of scour ($\frac{d_{se}}{D}$) was compared with equations proposed by Melville (1997) and Shepherd and Miller (2006). As shown in the Table 2, the experiment results of this study were close to the previous research (Table 2).

$\frac{d_{se}}{D}$ This research	$\frac{d_{se}}{D}$ Melville (1997)	$\frac{d_{se}}{D}$ Sheppard et al. (2006)
2.14	2.45	2.16
2.32	2.48	2.28

Table 2: Comparison of Non-dimensional depth of scour ($\frac{d_{se}}{D}$) with researchers.

III.2 Bridge pier model scour in the one-sided collar condition

One-sided collars were used to estimate the ideal upstream collar length (L_{uc}). Downstream collar length (L_{dc}) remained negligible while the upstream length gradually increased until no change in depth could be seen. The collar and flow characteristics were as follows:

$$L_{dc} = 2\,mm \;, \qquad L_{uc} = 2, 4, 6, 8, 10, 12, 14, 16, 18, 20\,mm$$

$$W_c = 30\,mm \;, \qquad e_c = 0.8\,mm \,, \qquad \frac{V}{V_c} = 0.90, 0.95$$

W_c is the collar width and e_c stands for its thickness. The scour mechanism in the one-sided collars was the same as collarless. The experiments usually took half an hour for the collar to clear the sediments, and from then on the experiment was to last until equilibrium scour depth was reached. Reduction of scour depth r_e and scour depth for piers fitted with collars d'_{se} was calculated using the equation:

$$r_e = \left[1 - \frac{d'_{se}}{d_{se}}\right] \times 100$$

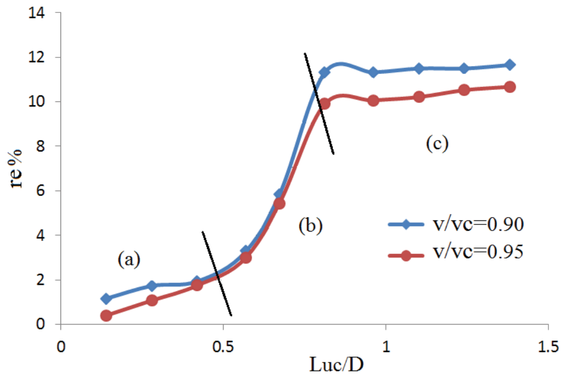

Figure 3: Reduction of scour depth with upstream non-dimensional length $\frac{L_{uc}}{D}$.

Figure 3 shows the reduction of the scour depth with upstream non-dimensional collar length ($\frac{L_{uc}}{D}$). Part ‘a’ showed the upstream collar length did not decrease the scour rate. Part ‘b’ shows increase in the upstream collar length resulted in reduction of the scour depth with increasing trend. Part ‘c’ shows that the scour depth had stabilized. From the results and part ‘c’ the ideal upstream collar length was 13mm. The non-dimensional value was: $L_{uc}/D = 0.93$ mm

III.3 Bridge pier model scour in the two-sided collar condition

For two-sided collar, the upstream collar length was maintained at its ideal value and the downstream collar length (L_{dc}) gradually increased until equilibrium scour depth was reached. Collar and flow characteristics were as follows:

$$L_{uc} = 13\,mm \,, \quad L_{dc} = 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24\,mm$$

$$W_c = 30\,mm \;, \qquad e_c = 0.8\,mm \,, \qquad \frac{V}{V_c} = 0.90, 0.95$$

In the two-sided collars, the scour began behind the pier and around the collar borders and moved towards the front of the pier. The wake vortices started before the horseshoe vortices. Time to clear the sediments under the collar varied from half an hour to 10 hours.

Figure 4 shows the reduction of the scour depth with downstream non-dimensional collar length ($\frac{L_{dc}}{D}$). Part 'a' shows the downstream collar length did not decrease the scour depth. Part 'b' shows increase in the downstream collar length resulted in reduction of the scour depth with increasing trend. Part 'c' shows that the scour depth has stabilized. Using the results Part 'c' the ideal downstream collar length was 20mm:

$$L_{dc} = 20\ mm\ , \quad \frac{L_{dc}}{D} = 1.44\ mm$$

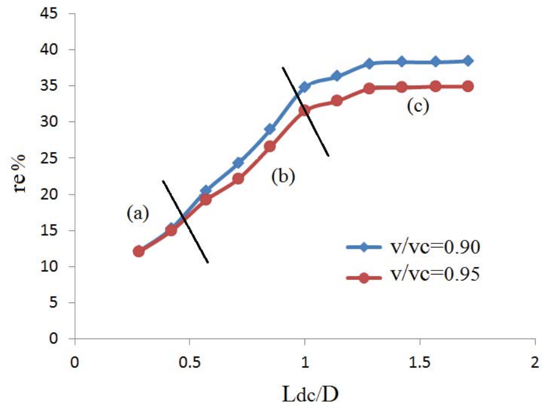

Figure 4: Reduction of scour depth with downstream non-dimensional length.

III.4 The effect of collar width in the bridge pier model scour

The ideal upstream and downstream collar lengths which achieved by last experiments were tested with the varied widths of collar. Increasing the collar width reduced significantly the scour depth that a width of 2.8 times the pier diameter produced no scour for 72 hours. The collar and flow characteristics were considered as bellow:

$$L_{uc} = 13\ mm\ , \qquad L_{dc} = 20\ mm\ , \qquad \frac{V}{V_c} = 0.90, 0.95$$

$$W_c = 18, 24, 30, 36, 42, 48\ mm\ , \quad e_c = 0.8\ mm$$

Figure 5 shows the reduction of scour depth with non-dimensional width collar ($\frac{W_c}{D}$). Increasing the collar width decreased the scour depth and with $W_c = 2.8D$ the scour remained small for 72 hours. The ideal collar width was 2.8 times the pier diameter:

$$W_c = 40\ mm\ , \quad \frac{W_c}{D} = 2.8$$

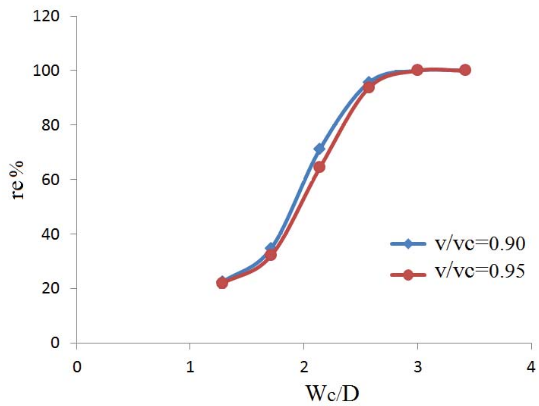

Figure 5: Reduction of scour depth in the two-sided collars with varying width.

IV CONCLUSION

In the present work, subsequent non-collar results in conjunction with the time development of the scour hole showed maximum equilibrium scour depth which was 32.48 mm that accrued after 17.9 hours. Several dimensions of collar were applied to obtain the ideal collar dimensions which were calculated under different hydraulic parameters. Both the upstream and downstream collar lengths were measured in relation to the bridge pier body. The ideal values were determined to be 0.93 and 1.44 times bigger than the pier diameter respectively. The ideal collar width was found to be 2.8 times bigger than the bridge pier diameter. By using the aforementioned optimized collar dimension, equilibrium scour depth hit a minimum of 0.44 mm after 72 hours.

V ACKNOWLEDGEMENTS

The authors wish to thank Farhad Imanshoar from Faculty of Civil Engineering, University of Tabriz, Seyed Hadi Hosseini from Civil and Environmental Engineering Department, Amir Kabir University of Technology, Tehran, and Keyvan Kimiaei from Mahab Ghodss Consulting Engineering Company, Tehran for their valuable assistance in gathering data for this article.

VI REFERENCES

Akib S., Fayyadh M. M., and Othman I. (2011). –Structural Behaviour of a Skewed Integral Bridge Affected by Different Parameters, *Balt. J. Road. Bridge. Eng.,* 6(2), 107-114.

Breusers N.H.C., Raudkivi A.J. (1991). *–Scouring*. 2nd hydraulic structures design manual. Balkema, Rotterdam, Netherlands.

Chiew Y.M. (1992). –Scour protection at bridge piers. *J. Hyd. Eng.,* 118(11): 1260-1269.

Chabert J., and Engeldinger P. (1956). *–Etude des affouillements autour des piles de points (Study of scour at bridge piers)*. Bureau Central d'Etudes les Equipment d'Outre-Mer, Laboratoire National d'Hydraulique, France.

Dargahi B. (1987). *–Flow field and local scouring around a cylinder*. Bullten No.137. R. Inst. Tech. Hydr. Lab., Stockholm ,Sweden.

Deng L., Cai C.S. (2010). –Bridge Scour: Prediction, Modeling, Monitoring, and Countermeasures – Review, *Pract. Period. Struct. Des. Constr.,* 15(2): 125–134.

Dey S. (1999). *–Time variation of scour in the vicinity of circular piers*. Proceedings of the Institution of Civil Engineers, Thomas Telford Journals, London, 136(2), 67-75, Paper 11426, June.

Ettema R. (1980). *–Scour at bridge piers*. Report No.216, University of Auckland, New Zeland.

Laursen E.M., Toch A. (1956). *–Scour around bridge piers and abutments*. Iowa Highway Research Board, Bulletin 4, Bureau of Public Roads, Iowa.

Melville B.W., Chew Y.M. (1999). –Time scale for local scour at bridge piers. *J. Hyd. Eng.,* 125, 59-65.

Melville B.W. (1997). –Pier and abutment scour: Integrated approach. *J. Hyd. Eng.,* 132, 125-136.

Melville B.W. (1984). –Live bed scour at bridge piers. *J. Hyd. Eng.,* 110(9), 1234-1247.

Muller D.S. (1996). *–Local scour at bridge piers in non-uniform sediment under dynamic conditions*. Ph.D dissertation, Department of Civil Engineering, Colorado State University.

Neill C.R. (1973). *–Guide to bridge hydraulics*. University of Toronto press, Toronto, Canada.

Shafai-Bajestan M. (1994). *-Hydraulics of sediments*. Shahid-Chamran press office Pub., Ahvaz, Iran.

Shepherd D.M., Miller Jr. W. (2006). –Live-bed local scour experiments. *J Hyd. Eng.,* 132: 635-642. USA.

Zarrati A.R., Chamani M.R., Shafaei A., Latifi M. (2010). –Scour countermeasures for cylindrical piers using riprap and combination of collar and riprap. *Int. J. Sediment Res.*, 25, 313-322