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Extent of riprap layer with different stone sizes around rectangular bridge piers with or without an attached collar

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Riprap sizing.

Abstract. In the present study, the extent of riprap layer with different sizes around bridge piers is investigated. Rectangular pier with or without an attached protective collar aligned with the flow and skewed at different angles are tested. The optimal configurations of riprap extent for each pier condition with different sizes are determined. Experiments showed that in case of aligned rectangular pier without a collar only 8% of the area around the pier is critical and the remaining 92% area can be protected with about 60% smaller riprap stones. As the skew angle of the pier increases up to 20°, the critical area increases up to 23% of the riprap extent. In case of protected pier with collar, the collar prevents the critical region around the pier in aligned and 5° skewed pier. However, by increasing the flow attack angle up to 20°, only a small area up to 30% in the riprap extent around the collar is critical and the remaining area can be placed with 40% smaller riprap size. Finally, the design algorithm for riprap extent with different sizes is presented.

1. Introduction

Local scouring around bridge piers occurs due to a complex flow field with large-scale turbulence structures generated by flow around the pier. As shown in Figure 1, notable structures are the horseshoe vortex, surface roller and wake vortices [1-3]. Experimental results show that different regions around a pier are exposed to different flow forces due to the action of horseshoe and wake vortices [4,5]. These forces include high shear stresses around the upstream face and sides of the pier which are under the action of down flow and horse shoe vortex and uplift forces in the wake of the pier under the action of wake vortices [6]. Obviously, strength of these forces reduces at further distances from the periphery of the pier.

Due to the danger of bridge failure when piers are undermined, many methods have been presented in the last two decades for preventing scouring. These methods include devices which change the flow pattern to reduce the flow force such as collars [7-11], sacrificial piles placed upstream of the pier [12], slots [8,13,14] and Iowa vanes [15], and methods with increasing the streambed resistance with using some materials such as riprap stones, cable-tied blocks, tetrapods, dolos, etc. [5,16-21]. Among devices used to change the flow pattern around piers, collars attached to the pier were investigated by more researchers. Collars prevent the direct impact of down flow and reduce the local scour depth due to decreasing the down flow strength and, therefore, the horseshoe vortex below the collar (Figure 2). The efficiency of a collar depends on its size and location on the pier with respect to the bed [4,5]. Though a collar prevents the action of horse shoe vortex, it cannot prevent scouring due to the action of wake vortices. Among different suggested

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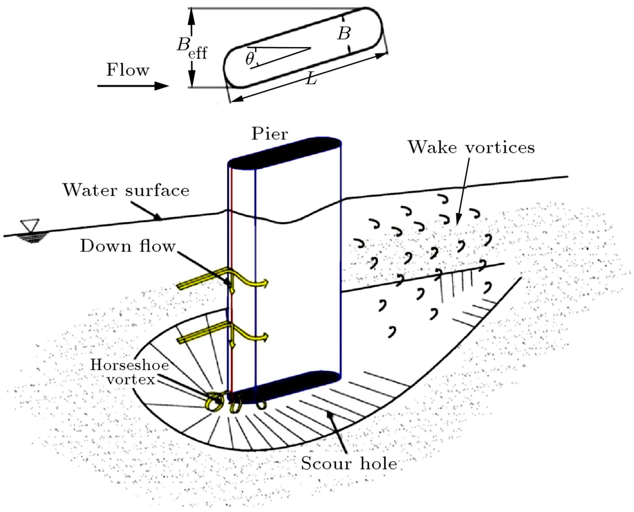

Figure 1. Schematic vortex structures around circular pier.

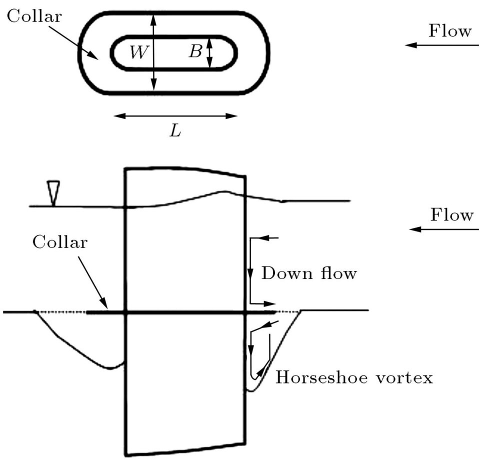

Figure 2. Scouring and flow pattern around a rectangular pier protected by a collar.

armoring methods, application of riprap layer around a pier is very common. Design of riprap layer involves finding stable size, optimum extent and thickness of riprap stones [16,22-24]. Numerous studies have been conducted to determine stable riprap size and extent around circular piers. Comparing with circular piers, design of riprap layer around rectangular piers involves two additional parameters, which are the pier aspect ratio and skew angle.

Most of the previous equations presented for riprap design around bridge pier can be rewritten in term of **riprap stability number** [5,15,17,25,26]. This parameter indicates the relationship between the flow condition and riprap stone characteristics and can be written as:

$$N_c = \frac{\rho.U^2}{g.(\rho_s - \rho).d_{50}}, \tag{1}$$

where N_c is riprap stability number; U is the undisturbed upstream depth-averaged flow velocity; d_{50} is the median size of stable riprap stones; g is the gravitational acceleration; ρ is the fluid density; and ρ_s is the riprap stone density. In addition, square root of N_c is called the Densimetric Particle Froude Number, which was also used by some researchers as an essential parameter affecting scour depth around hydraulic structures [27,28]. A list of different riprap design equations based on riprap stability number is presented in [5].

Mashahir et al. [19] studied the extent of riprap layer around rectangular piers unprotected and protected with a collar. Piers with different aspect ratios and skew angles were considered in this work. They found that application of a collar at the stream bed reduces the riprap extent by about 35 percent in piers aligned with the flow at all aspect ratios. However, with increasing the flow attack angle, the effect of collar on the area of stable riprap layer is reduced.

All previous studies considered a single riprap size in the stable riprap layer, whereas different regions of streambed around a pier are exposed to different flow forces. Therefore, smaller riprap sizes could be used in regions with lower flow forces to reduce the costs. This is especially important for rectangular piers where the extent of riprap layer around them is very large particularly at higher aspect ratios and skew angles. The present study is focused on designing the extent of riprap layer with different riprap sizes around rectangular pier with and without an attached collar and in different skew angles. For this purpose, a series of experiments were carried out which are explained in the following sections.

2. Experimental setup

Experiments were performed in a 10 m long, 0.74 m wide, and 0.6 m deep laboratory horizontal flume. The flume had a working section in the form of a recess below its bed, which was filled with sediment and was located 6 m downstream of the flume entrance. Median size of the sediment, d_{50}, was 0.95 mm with geometric standard deviation of sediment grading, σ_g, as defined below, less than 1.3.

$$\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{0.5}, \tag{2}$$

where d_a is the size of sediment for which a percent of material by weight is finer.

A rectangular pier model, with a circular nose and tail made from Perspex was used in these tests. Width (B) and length (L) of this pier were 50 mm, and 250 mm, respectively (Figure 2). Therefore, the aspect ratio (L/B) of this pier was 5. Flow depth was measured with a point gauge with 0.1 mm accuracy. Discharge was measured with a calibrated sharp crested weir installed at the downstream end of the flume.

Table 1. Properties of bed material and riprap stones.

Sediment description	Bed material	Riprap (***R*1**)	Riprap (***R*2**)	Riprap (***R*3**)	Riprap (***R*4**)
Median particle sizes (mm)	0.95	2.19	3.56	5.74	7.12
B/d_{50}	52.63	22.83	14.10	8.71	7.02
SG	2.65	2.65	2.65	2.65	2.65
σ	1.25	1.21	1.26	1.18	1.2
N_c	—	3.51	2.16	1.34	1.08

Note: SG is relative riprap stone density.

All tests were conducted at the threshold of bed material motion. The threshold of bed material motion was found by experiment when the pier was not installed. These tests showed that with 0.13 m flow depth and discharge of 0.034 m^3/s, bed material would be at incipient motion. In these experiments, the ratio of shear velocity calculated from flow depth and energy slope at the working section ($u*$) to the critical shear velocity calculated from Shields diagram ($u*_c$) was about $u*/u*_c = 0.92$.

Riprap materials with four different sizes ($R1$ to $R4$) were used in this study. The median particle sizes for these riprap materials, together with bed sediment, are given in Table 1. In addition to riprap characteristics, the riprap stability parameter (N_c) for each riprap size was also calculated based on the flow condition and is given in Table 1.

The extent of riprap layer around the pier in each experiment was considered based on what suggested by Mashahir et al. [20] and was found to be stable. However, the final configuration of riprap extent in cases of aligned unprotected and protected pier with collar was simplified by removing the downstream curve parts and substituting them with straight lines.

The top surface of the riprap layer was always leveled with the bed elevation. To prevent winnowing failure, the thickness of riprap layer in all tests was $2.5d_{50}$ where d_{50} is median size of riprap stones [17].

To ensure stability of riprap layer in the present work, experiments were conducted for 10 hours. After 10 hours if no riprap stone was removed and the scour hole around the riprap layer was less than one riprap size, that layer was considered as stable with no shear or edge failure.

In the present work, the first series of experiments were carried out with pier aligned or skewed with 5°, 10° and 20° angles corresponding to the flow direction. The necessary extent of riprap layer was then found by experiment. In addition, zones of lower flow forces which can be covered with finer sediment size were recognized.

In the next stage, a collar was attached to the pier, and the first series of tests were repeated to study the effect of collar on stable riprap size and extent. Due to its efficiency and acceptable size, a collar with $W/B = 3$ at the streambed level was used in all experiments where 'W' is the collar effective width (Figure 2) and 'B' is the pier width [8,9]. For both series of experiments, the critical region with highest flow forces was called Zone 1. Zones with lower flow forces which were stable with finer sediment size were, respectively, called Zone 2 and Zone 3.

3. Riprap design equation

Based on large amount of experimental data, Karimaee and Zarrati [5] presented the following equation for design of stable riprap around aligned and skewed round nose rectangular as well as circular piers:

$$N_c = 2.85 \times K_1 \times K_2 \times K_3. \tag{3}$$

In the above equation, $K_1 = \sqrt{d_{50}/B}$ is riprap size adjustment factor where B is the round nose rectangular pier width or circular pier diameter, and, $K_2 = (y/d_{50})^{0.25}$ is the flow depth adjustment factor $K_3 = (B/B_{\text{eff}})^{1.5}$ is the effective pier width adjustment factor where B_{eff} is equal to circular pier diameter or projected length of the rectangular pier perpendicular to the flow direction which is defined as $B_{\text{eff}} = L \times \text{Sin}\theta + B \times (1 - \text{Sin}\theta)$ where L is the rectangular pier length and θ is the pier skew angle. For circular as well as aligned rectangular pier, B_{eff} is equal to B.

Since a collar protects the regions close to a pier, which are exposed to higher stresses, lower riprap size is necessary to protect the area around the collar. Mashahir et al. [20] and Karimaee and Zarrati [5] showed that for skewed piers the regions at downstream and leeward side of the pier are also exposed to high flow forces. In the present work, it was decided to develop Eq. (3) for design of stable riprap around protected pier with a collar. Eq. (3) can therefore be written as:

$$N_c = 2.85 \times K_1 \times K_2 \times K_3 \times K_4, \tag{4}$$

where K_4 is collar adjustment factor which adjusts the calculated N_c in case the pier is protected with a collar. By analyzing the experimental data of Mashahir et

Table 2. Percentage of riprap area at different zones around the pier.

Pier skewed angle	Percentage of riprap area			Ratio of riprap extent area to pier section area
	Zone 1 (critical zone)	Zone 2	Zone 3	
Aligned pier	8	92	-	9.7
5°	9	91	-	12.4
10°	22	78	-	15.9
20°	23	12	65	17.5

al. [20] for a collar with $W/B = 3$ at the streambed level (see Figure 2) and in different pier aspect ratios, the following relationship was derived for K_4:

$$K_4 = \begin{cases} 1.6 & \text{for} \quad B_{\text{eff}}/B < 1.7 \\ 1.0 & \text{for} \quad B_{\text{eff}}/B \geq 1.7 \end{cases} \tag{5}$$

based on Eq. (4), for $B_{eff}/B < 1.7$ (low rectangular pier aspect ratio or skew angle or for circular pier) the parameter N_c increases by 60%. This is equivalent to decreasing stable riprap size d_{50} by about 30%. For $B_{eff}/B \geq 1.7$ collar has negligible effect on stable riprap size. Extent of riprap layer for piers with different aspect ratios with and without collar protection is also given in Mashahir et al. (2010).

4. Experimental results

4.1. Riprap extent with different stone sizes around a pier without a collar

Aligned rectangular pier. In the first stage of experiments, different riprap sizes were placed around the rectangular pier to check their stability. Experiments showed that riprap size with $B/d_{50} = 14.1$ (riprap $R2$ in Table 1) was stable all around the pier model. This riprap size confirms well with the predicted riprap size from Eq. (4). However, previous studies showed that, for aligned rectangular pier, the critical region with high flow forces is around the upstream nose of the pier under the action of down flow and concentration of shear stresses [5]. Therefore, new experiments were carried out to optimize the riprap extent configuration with finer stones in regions rather than the critical zone. Figure 3 shows the final extent of two size riprap layer around the aligned pier.

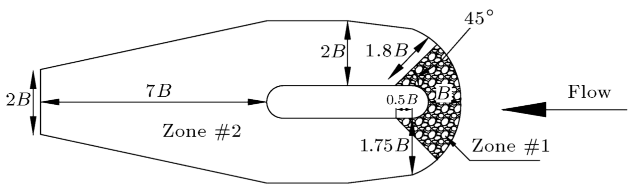

Figure 3. Extent of riprap layer and zones with different riprap sizes around aligned unprotected rectangular pier.

Table 2 shows the percentage of area with different riprap sizes around the pier. It can be seen that from the whole riprap extent which is about 10 times the pier area, only 8% is critical (Zone 1) and should be covered with the riprap size calculated from Eq. (4) and the remaining area (Zone 2) can be covered with about 38% finer material ($B/d_{50} = 22.83$).

Skewed rectangular pier. When pier was skewed corresponding to the flow direction, stronger action of the wake vortices with stronger suction effect was present downstream of the pier. Based on experimental observations it can be concluded that the combination of shear stresses and wake vortices at the separation zone are the main factor in moving the riprap stones in this region. This effect increases as the parameter B_{eff}/B increases (larger pier aspect ratio and pier skew angle).

In 5° skewed pier, the critical region is at the separation area downstream of the pier nose. Similar approaches to aligned pier were carried out to divide the riprap extent into two zones with different riprap size. Figure 4(a) shows the optimized layout. As shown in this figure, similar to the aligned pier, riprap $R2$ with $B/d_{50} = 14.1$ was stable in the critical region at the upstream periphery of the pier, and riprap $R1$ with $B/d_{50} = 22.83$ could be used in the remaining area. The critical region with designed riprap was only about 10% of riprap extent area and the remaining 90% could be covered with a finer riprap (Table 2).

For 10° skewed pier, the critical region was near the leeward side of the pier in the separation area [5]. In this case, based on experimental observations, riprap $R3$ in Table 1 with $d_{50} = 5.74$ mm or $B/d_{50} = 8.71$ was stable. This size also conforms to what was calculated from Eq. (4). Figure 4(b) shows the optimal riprap extent with two different sizes for 10° skewed pier. As can be seen in this figure and Table 2, about 22% of the riprap layer which is about 16 times the pier diameter area is critical and the remaining area can be protected with smaller riprap size R1 which is about 62% smaller than riprap $R3$.

Finally, for 20° skewed pier, all downstream of the pier was critical due to high suction effects in

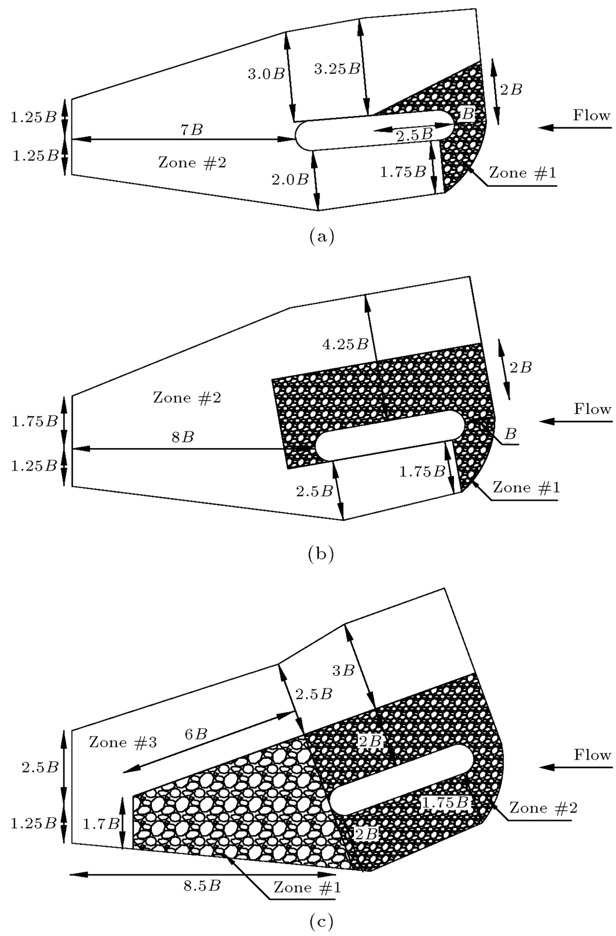

Figure 4. Extent of riprap layer with different sizes around skewed rectangular pier: a) 5° skewed pier; b) 10° skewed pier; and c) 20° skewed pier.

the separation area. In this case, experiments showed that riprap $R4$ in Table 1 with $d_{50} = 7.10$ mm or $B/d_{50} = 7.02$ was stable which confirms well to Eq. (4). Many tests were carried out to determine the optimal configuration of the riprap layer extent with different sizes. Figure 4(c) and Table 2 show the final results. About 23% of the riprap layer in the downstream of the pier was critical covered with $R4$ (Zone 1). The remaining area was divided into two different zones; Zone 2 with 12% and Zone 3 with 65% of the riprap extent area. Riprap $R3$ was stable in Zone 2 which is about 20% smaller than riprap $R4$; in Zone 3, riprap $R2$ which is about 50% smaller than riprap $R4$ could be used.

4.2. Riprap extent around the pier protected with a collar

In the second series of experiments, a collar with $W/B = 3$ was installed around the piers at the streambed level (Figure 2). Riprap with different sizes was then placed around the collar to determine the sufficient extent of riprap layer. Aligned pier as well as skewed at 5°, 10° and 20° were tested.

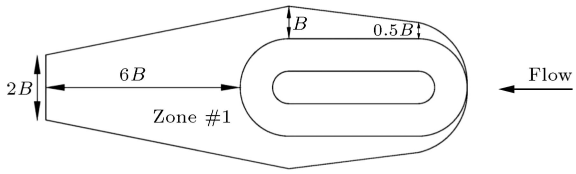

Figure 5. Extent of riprap layer around the protected aligned rectangular pier.

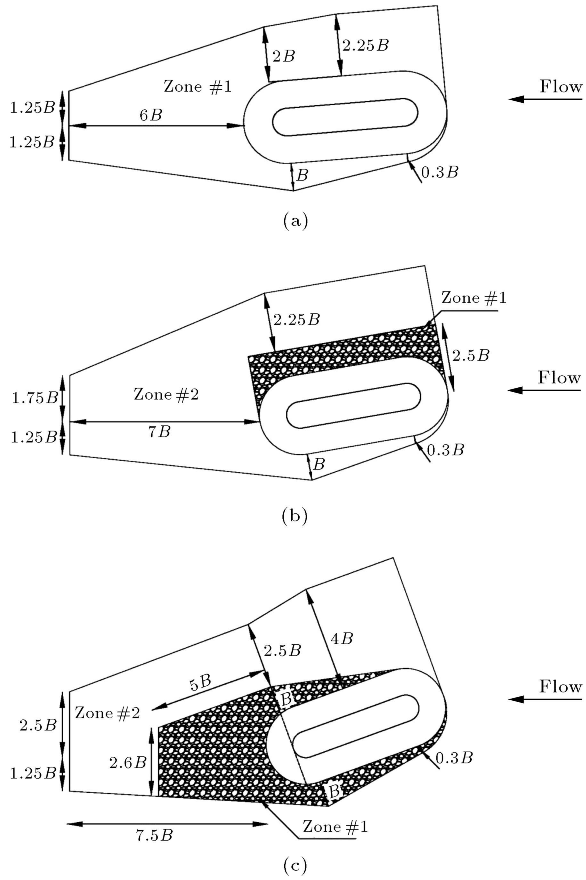

Figure 6. Extent of riprap layer with different sizes around the protected skewed rectangular pier: a) 5° skewed pier; b) 10° skewed pier; and c) 20° skewed pier.

Aligned rectangular pier. For aligned pier, due to existence of the collar, critical region close to the pier was well protected and therefore, only the areas around the collar were necessary to be covered by the finer riprap $R1$ which conforms well to what calculated from Eq. (4). Figure 5 illustrates the stable extent of riprap layer around the pier.

Skewed rectangular pier. For 5° skewed pier, similar to the aligned pier, the critical region is near the upstream periphery of the pier, which is protected by the collar. Based on Eq. (4) and observation, riprap R1 was stable all around the collar in the riprap extent (Figure 6(a)).

Figure 6(b) shows the final riprap extent with 2

Table 3. Percentage of riprap area at different zones around the protected pier with a collar.

Pier skewed angle	Percentage of riprap area		Ratio of total riprap extent area to the pier section
	Zone 1	Zone 2	
Aliened pier	1	—	7.2
5°	1	—	10.2
10°	12.3	87.7	13.7
20°	30	70	15.3

Table 4. Design factor for riprap stones at different zones.

Pier condition	Pier skewed angle	Design factor			Effective area
		Zone #1	Zone #2	Zone #3	
Unprotected pier	Aligned	1	0.38	—	9.74
	5°	1	0.38	—	11.41
	10°	1	0.62	—	14.73
	20°	1	0.81	0.50	17.46
Protected pier with a collar	Aligned	1	—	—	6.25
	5°	1	—	—	8.74
	10°	1	0.38	—	11.27
	20°	1	0.62	—	14.38

different riprap sizes for 10° skewed pier. In addition, Table 3 shows the percentage of riprap extent at different zones around the protected pier. About 12% of the riprap extent is critical and the remaining area could be covered by 38% smaller riprap. Finally, for 20° protected skewed pier, it was concluded that the critical region is mainly at the downstream tail of the pier. Figure 6(c) shows the final configuration of riprap layer with two different sizes (two different zones). The critical zone which was about 30% of the riprap layer extent (Zone 1) was stable with riprap $R3$ which agrees with the size calculated from Eq. (4), and the remaining area could be covered with smaller stones (Table 3).

5. Design method for riprap extent with different sizes

Eq. (4) predicts riprap stones to resist the maximum flow forces in the critical region around the pier. In order to calculate the riprap size in other regions, reduction factors for decreasing the designed riprap size are introduced in Table 4. The reduction factor for each zone was determined by dividing the stable riprap size in each zone to that in Zone 1 based on the present experimental results. The configuration of the riprap extent with different sizes are given in Figures 3 and 4 for unprotected and in Figures 5 and 6 for the protected pier with a collar. Further study is required to accurately determine the riprap zones boundary in different pier aspect ratios. However, since the necessary outer extent of riprap layer for different pier aspect ratios is given by Mashahir et al. (2010), the present work can be used as a guide to estimate the critical zone area in different pier aspect ratios too.

6. Conclusion

In the present study, extent of riprap layer with different sizes around rectangular bridge piers was investigated experimentally. Rectangular pier with or without an attached collar aligned with the flow and skewed at different angles were tested.

At the first stage of the studies, by analyzing the experimental data of Mashahir et al. [20], the riprap design equation presented by Karimaee and Zarrati [5] was developed for bridge piers protected by a collar. The analysis showed that in aligned piers the stable riprap size decreases about 30% in comparison to an unprotected pier.

As the strength of flow forces around a pier is different, smaller riprap sizes can be used in the areas with lower flow forces. Therefore, experiments were carried out to determine riprap extent with different sizes around an unprotected pier. These experiments showed that the riprap stones calculated by the riprap design equation are only needed in a small part of riprap extent (the critical zone), and smaller riprap sizes can be placed used in other parts. For example in case of aligned rectangular pier without collar only 8% of the riprap extent area was critical and the remaining 92% region could be covered with 60% smaller riprap size. As the pier skew angle increased, the critical region increased due to larger area of high flow forces in periphery and downstream of the bridge pier in wake zone. For example, in case of 20° skewed pier, the critical area increases to 23% of the riprap extent.

In the next stage of the studies, similar approach was carried out to determine riprap extent with different sizes for protected pier with a collar. For aligned and 5° skewed rectangular pier, experiments showed that the critical region around the pier was well protected with collar. However, by increasing the flow attack angle up to 20°, only a small area up to 30% in the riprap extent around the collar is critical and the remaining area can be placed with 40% smaller riprap size. Finally, based on the present investigation, the design step method for riprap extent with different sizes was presented.

Nomenclature

y	Undisturbed upstream flow depth
U	Undisturbed upstream depth-averaged flow velocity
d_{50}	Median size of stable riprap stones
σ_g	Geometric standard deviation of sediment grading
d_a	Size of sediment for which a percent of material by weight are finer
$u*$	Bed shear velocity
$u*_c$	Critical shear velocity for the bed material
SG	Relative riprap stone density
ρ	Fluid density
ρ_s	Sediment density
N_c	Riprap stability number
g	Gravitational acceleration
W	Collar effective width
B	Pier width
B_{eff}	Effective pier width
L	Pier length
θ	Flow attack angle
K_1	Riprap size adjustment factor
K_2	Flow depth adjustment factor
K_3	Effective pier width adjustment factor
K_4	Collar adjustment factor

References

1. Melville, B.W. and Raudkivi, A.J. "Flow characteristics in local scour at bridge piers", *J. Hydraul. Res.*, **15**(4), pp. 373-380 (1977).
2. Ettema, R. "Scour at bridge piers", Rep. No. 216, School of Engineering, Univ. of Auckland, Auckland, New Zealand (1980).
3. Dargahi, B. "Controlling mechanism of local scouring", *J. Hydraul. Eng.*, **116**(10), pp. 1197-1214 (1990).
4. Zarrati, A.R., Gholami, H. and Mashahir, M.B. "Application of collar to control scouring around rectangular bridge piers", *J. Hydraul. Res.*, **42**(1), pp. 97-103 (2004).
5. Karimaee, T.M. and Zarrati, A.R. "Design of stable stone size to prevent scouring around rectangular bridge piers", *J. Hydraul. Eng.*, **139**(8), pp. 911-916 (2013).
6. Raudkivi, A.J. *Loose Boundary Hydraulics*, Balkema, Rotterdam, The Netherlands (1998).
7. Tanaka, S. and Yano, M. "Local scour around a circular cylinder", *Proc., 12th Congress of IAHR*, Fort Collins, Colo., **3**, pp. 193-200 (1967).
8. Kumar, V., Ranga Raju, K.G. and Vittal, N. "Reduction of local scour around bridge piers using slot and collar", *J. Hydraul. Eng.*, **125**(12), pp. 1302-1305 (1999).
9. Zarrati, A.R., Nazariha, M. and Mashahir, M.B. "Reduction of local scour in the vicinity of bridge pier groups using collars and riprap", *J. Hydraul. Eng.*, **132**(2), pp. 154-162 (2006).
10. Karimaee, M. and Zarrati, A.R. "Effect of collar on time development and extent of scour hole around cylindrical bridge piers", *Int. J. Eng., Transactions C*, **25**(1), pp. 11-16 (2011).
11. Tafarojnoruz, A., Gaudio, R. and Calomino, F. "Bridge pier scour mitigation under steady and unsteady flow conditions", *Acta Geophysica*, **60**(4), pp. 1076-1097 (2012).
12. Melville, B.W. and Hadfield, A.C. "Use of sacrificial piles as pier scour countermeasures", *J. Hydraul. Eng.*, **125**(11), pp. 1221-1224 (1999).
13. Grimaldi, C., Gaudio, R., Calomino, F. and Cardoso, A.H. "Countermeasures against local scouring at bridge piers: Slot and combined system of slot and bed sill", *J. Hydraul. Eng.*, **135**(5), pp. 425-431 (2009).
14. Chiew, Y.M. "Scour protection at bridge piers", *J. Hydraul. Eng.*, **118**(9), pp. 1260-1269 (1992).
15. Odgaard, A.J. and Wang, Y. "Scour prevention at bridge piers", *Proc., Nat. Conf. Hydraul. Eng., ASCE*, Williamsburg, Va., pp. 5253-5257 (1987).
16. Parola, A.C. "Stability of riprap at bridge piers", *J. Hydraul. Eng.*, **119**(10), pp. 1080-1093 (1993).
17. Chiew, Y.M. "Mechanics of riprap failure at bridge pier", *J. Hydraul. Eng.*, **121**(9), pp. 635-643 (1995).
18. Richardson, E.V. and Davis, S.R. "Evaluating scour at bridges", *Hydraul. Eng. Circular*, No. 18 (HEC-18 Fourth Edition), FHWA NHI 01-001, Federal Highway Administration, Washington D.C. (2001).
19. Lagasse, P.F., Clopper, P.E., Zevenbergen, L.W. and Girard, L.G. "Countermeasures to protect bridge piers

from scour", NCHRP Report 593, TRB, NAS, Washington D.C., p. 272 (2007).

20. Mashahir, M.B., Zarrati, A.R. and Mokallaf, E. "Application of riprap and collar to prevent scouring around piers rectangular bridge", *J. Hydraul. Eng.*, **136**(3), pp. 183-187 (2009).

21. Froehlich, D.C. "Protecting bridge piers with loose rock riprap", *J. Applied Water Eng. and Res.*, **1**(1), pp. 39-57 (2013).

22. Chiew, Y.M. and Lim, F.H. "Failure behavior of riprap layer at bridge piers under live-bed condition", *J. Hydraul. Eng.*, **126**(1), pp. 43-55 (2000).

23. Lauchlan, C.S. and Melville, B.W. "Riprap protection at bridge piers", *J. Hydraul. Eng.*, **127**(5), pp. 412-418 (2001).

24. Zarrati, A.R., Chamani, M.R., Shafaei, A. and Latifi, M. "Scour countermeasures for cylindrical bridge piers using riprap and combination of collar and riprap", *I. J. Sed. Res.*, **25**(3), pp. 313-321 (2010).

25. Quazi, M.E. and Peterson, A.W. "A method for bridge pier riprap design", *Proc., 1st Can. Hydraul. Conf.*, pp. 96-106 (1974).

26. Croad, R.N. "Protection from scour of bridge piers using riprap", Transit New Zealand Res. Rep. No. PR3-0071, Works Consultancy Services Ltd., Central Laboratories, Lower Hutt, New Zealand (1997).

27. Rajaratnam, N. and Nwachukwu, B.A. "Erosion near groynelike structures", *J. Hydraul. Res.*, **21**(4), pp. 277-287 (1983).

28. Oliveto, G. and Hager, W.H. "Temporal evolution of clear-water pier and abutment scour", *J. Hydraul. Eng.*, **128**(9), pp. 811-820 (2002).

Biographies

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