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Riprap Stability in the Vicinity of a Bridge Pier Fitted with a Collar in the Rivers Bend

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Abstract: The use of riprap stones to deal with scour problems is very usual in civil engineering practice. Riprap particles are mostly failures with passing time by during floods and so regarding to increase riprap stability is a necessary issue and it has been considered as main object in this research. Several researches have been conducted during the past three decades in straight flumes. Experiments were conducted using a 180-degree laboratory flume bend for three various sizes of collars and four sizes of riprap. The cylindrical model pier was installed at 60-degree position with clear-water conditions. Analysis of the experimental results showed that the relative rock size significantly affected the stability number for cylindrical piers. Although the results show that riprap layer with collar widths of 3b.2b.1.5b (b, pier diameter) is, respectively, 8%, 15% and 22% more stable than that an unprotected pier.

Key words: Scour · Cylindrical Pier · Collar · Riprap · stability

INTRODUCTION

Bridges are among the most important and the most frequently applied river constructions that have been used from many years ago. Under natural conditions, meandering rivers are seldom straight through out but generally have frequent bends in the form of S on several reaches. Generally bridges are constructed at places where rivers are more stable. Because of limitations of road construction or straight river instability, it is possible to construct bridges in river bends. One of the most important causes of bridge failures is local scouring around their piers. When flowing water attacks the bridges pier, a downward flow on the face of the pier is developed because of the pressure gradient which hits the bed around the pier and causes bed erosion in front of the pier. The vortices occurred in the hole and horseshoe vortices, will help to acceleration the transport of sediments and growth of the hole to downstream. Contact and separation of the flow on the sides of the pier also creates the so-called arising vortices. These vortices vacant below the foundation which destroys the structure [1]. Protecting bridges against local scouring is one of necessary elements in designing structures on rivers. In recent years, using collars has been suggested as a type of countermeasure to control scouring around the piers. Collar acts as an obstacle for the down-flow and reduces the strength of the horse-shoe vortex. Zarrati *et al*. [2] investigated the efficiency of collar size on scouring around rectangular bridge piers with circular noses and tails in straight canals. Results showed that using a collar with the same width as the pier that lies at the same elevation of the sediments decreases scouring at by %74. Applying riprap around the bridge piers to increase the bed materials resistance is also one of the other common measures of controlling local scouring around the bridge piers. However, one of the problems of using riprap around the bridge piers is riprap failure throughout time. Researchers have considered different standards for destroying riprap. For example, Quazi and Peterson [3] considered the first movement of grains in front of the pier and Chiew [1] and Croad [4] considered complete removal of the riprap layer. Parola [5] believed that the removal of the middle riprap layer was the reason for riprap failure. Chiew [1] divides the failure of a riprap layer around a bridge pier into three causes: shear, winnowing and edge failure. Zarrati *et al*. [6] studied riprap behavior around cylindrical bridge piers with collars

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in a straight flume. Their results demonstrated that using a collar if $b/d_R \leq 7.5$(that b is pier diameter and d_R riprap particle size), increases the stability of the riprap layer and decreases riprap extension around the pier. A number of studies have been conducted to determine stable riprap median size, layer thickness and the extent around a pier (Neil [7]; Posey [8]; Breusers *et al*. [9]; Garde and Ranga Raju [10]; Worman [11]; Yoon *et al*. [12]; Chiew and Lim [13]; Lauchlan[14]; Zarrati *et al*. [15]; Mashahir *et al*. [16]). All the studies on stability of riprap around the bridge pier have been carried out in straight canals. Since the effect of secondary flow and spiral vortex on stability of the riprap layer around bridge piers in bends has not been considered in above researches, generalizing the obtained results to bends is with errors. The present research studies the effect of collar on the stability of the riprap layer around a cylindrical bridge pier at the 60-degree position in a 180-degree bend flume.

Dimensional Analysis: In this study, the parameters that influence the critical conditions for the displacement of riprap on the streambed surrounding a pier in steady, quasi-uniform flow can be arranged into a functional equation expressed as

$$f(d_R,d_{50},\mu,\rho,\rho_s,U,y,b,W,t,g,SH,\theta_p,c,B,H,S_0) = 0 \qquad (2)$$

where d_R = riprap size, d_{50} = median bed sediment size, μ = dynamic viscosity, ρ = fluid density, ρ_s = sediment density, U = approach flow velocity, y = approach flow depth, b = pier diameter, W = diameter of collar, t = thickness of riprap layer, g = gravitational acceleration, SH = pier shape and orientation factor, θ_p = 180-degree bend Position, c = riprap extension, B = channel width, H = location of collar in bed and S_0 = bed slope. In addition, the size and hydraulic conductivity of the underlying bed materials may be significant, considering possible removal of fine materials below rock protection and displacement of the rock protection due to settlement. The scope of this study was limited to evaluating the stability of large cohesionless bed materials placed on a fixed bed. Determination of the effects of displacement due to leaching of the fine materials, although is an important practical aspect, was beyond the scope of this investigation [8]. Applying the Buckingham theory and the dimensional analysis one can obtain the following equation:

$$N_c = f(R_e,\frac{d_R}{y},\frac{t}{c},\frac{d_R}{b},\frac{d_{50}}{c},\frac{W}{b},SH,\theta_p,\frac{B}{b},\frac{H}{b},S_0) \qquad (2)$$

N_c is defined herein as the stability number where:

$$N_c = \rho U^2/(\rho_s - \rho)gd_R \qquad (3)$$

The particle Reynolds number R_e is given by:

$$R_e = \rho U d_R/\mu \qquad (4)$$

In this study, the values $t/c, d_{50}/c, SH,$ θ_p = 60°, $B/b, H/b$ S_0 of all tests are assumed constant and they can be regardless. In the case of the highly turbulent flows that are required to dislodge rock protection, the influence of particle Reynolds number, R_e can be considered to be negligible. Applying these considerations, Eq (2) can be reduced to:

$$N_c = f(\frac{d_R}{y},\frac{d_R}{b},\frac{W}{b}) \qquad (5)$$

MATRRIALS AND METHODS

To reach the goals of this study experimental test were conducted in a rectangular cross section of a 180-degree flume bend of Plexiglas materials under clear water condition and using nonadhesive sediments. Figure 1 and Table 1 represent the model details including length, height, width, etc. In order to omit the effect of flume walls on local scouring, according to Chiew and Melville [17], the pier diameter must be less than%10 of the canal width; following Raudkivi and Ettema [18], the proportion of the flume width to the base width must be larger than 6.25. Considering the limitation of the flume width and diameter, a cylindrical pier with a 60 mm diameter and 180 mm height was utilized as the pier model. Bed sediments were selected so that they have the maximum scouring depth and bed situation would always be in clear water conditions. Scouring in non-cohesive sediments which have a diameter less than 0.7 mm a long with the movement of bed particles in upstream pier is similar to live bed situation. Movement begins in a situation that the ratio of shear velocity in bed exceeds the critical shear velocity of fine bed loads about 0.6. To eliminate the effect of sediment particle size on scouring depth, the proportion of b/d_{50} (pier diameter to mean diameter of bed materials) must be bigger than 25 [17]. In this study, a 150mm-thick sand layer with a 1.5mm average diameter was used. According to Raudkivi and Ettema [18], clear water scouring occurs under U<9.95U_C (U average flow velocity UC threshold velocity for bed sediments) condition. To calculate the critical velocity, in this study, Shafai [19]'s formula was employed:

Table 1: Details of the Physical hydraulic model

Discharge Be Use	Angle Bend Maximum	Depth Channel (m)	Radius of curvature to Channel Width (R_c/w_t)	Width Channel (m)	Length Bend Foreign	Length Bend Internal	Radius Curvature Central	Length Channel Output	Length Channel Input
31	180	0.45	4.67	0.6	9.74	7.85	2.8	5.5	9.1

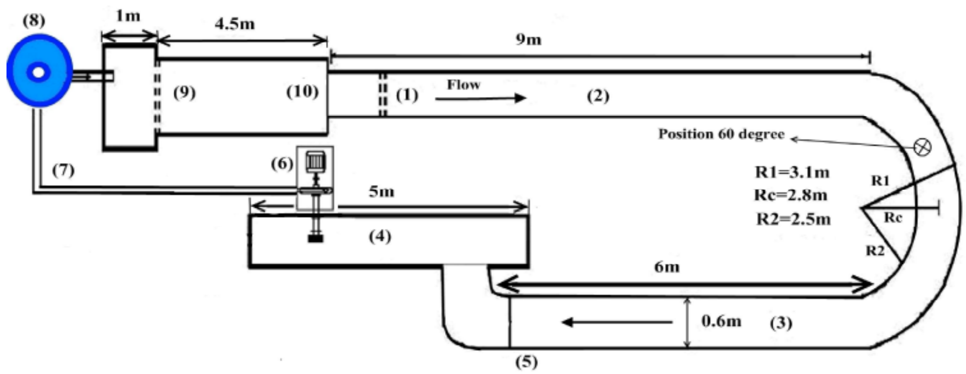

Fig. 1: Layout of the Physical hydraulic model

Table 2: Experimental variables

Colar size	$W = 0$	$W = 1.2b$	$W = 2b$	$W = 3b$
$Q(lit/s)$	22	25	28	31
d_R	2.58	3.68	4.38	5.53

$$U_c = 2.2\left[g(G_s - 1)d_{50}\right]^{0.5} \quad (7)$$

Regarding bed sediments specifications, the critical velocity was estimated from equation (7).

According to Chiew [1], if $b/d_R < 2.25$, then the existence of the pier in riprap instability is ineffective. With regard to the pier diameter in this study (60mm), the average diameter of the riprap particles must be less than 26.7mm. Four uniform riprap stones (involved fluvial material) with specific gravity of 2.65 and with different median sizes were selected. The riprap layer thickness in all experiments equaled $t = 3d_R$ to prevent winnowing failure [1]. To select a sufficient extent of riprap, three experiments with different discharges were conducted in the 60-degree position and the range of scouring was defined by longitudinal profiles. Finally, the riprap extension equaling c=5.5b for all riprap particles and in all tests was employed. In order to study the collar effect on riprap stability around the cylindrical pier, three different collar diameters of Plexiglas material were applied for all of the tests with a collar, the collar was located at surface of riprap layer. In this study, the bridge pier model in each experiment was first installed in an appropriate position on the flume. Prior to each experiment, to make the bed surface uniform, the sand bed surface was leveled using a wooden leveler as wide as the flume which moved on the roller next to the flume. Also, a point gauge was used to measure the scouring depth. In each test, the riprap was placed in three layers thick on the bed surrounding the pier. The experiments were performed in combination with the collar and the riprap; the collars were placed at the stream bed level. Having started the test, when the pump was started, the upstream valve was slowly opened until the flume was gradually filled with water. It is important to take a lot of time while filling the flume so that clear water conditions are arrived at. The flow was measured through a triangular weir installed on the front part of the flume. Experiments in a specific discharge started with the higher flow depth and if after 15 minutes the instability of riprap layer did not occur, the flow depth was decreased and the test continued for another 15 minutes. The experiment continued until instability (shear failure) was observed in the riprap layer. At this depth, the flow velocity was recorded as the critical velocity of the riprap (U_c).Table 2 shows the experimental variables.

RESULTS

Figure 2 illustrates the relative flow depth (*y/b*) at the point of threshold riprap versus relative grain size for different flow discharges. As it can be seen from Figure 2, as the relative riprap size becomes larger, the threshold condition is reached a lower flow depth. Practically, smaller riprap grain sizes (relative to the pier size) are displaced at lower velocities. Furthermore, in place of constant relative grain size, riprap stability decreased with increase in the flow rate so that the minimum stability occurred at *Q*=31*lit/s*. By analyzing the sequence of the changes in the flow depth instability, riprap grain size and flow rate, can be seen than in Figure 2, the distance of the points in threshold conditions approach together and finally with increasing velocity (getting increase grain size of riprap layer), the effect of flow rate on the riprap layer instability declines.

Figure 3 illustrates that the value of riprap layer stability, N_c in the pier with collar increased compared to the pier without collar and the collar increases the riprap stability. In addition, it is observed that the stability value for the pier with a great collar size (*W*=3*b*) is more than the resulted quantity for medium (*W*=2*b*) and small collar sizes (*W*=1.5*b*). By analyzing the changing trend of the stability values and the relative riprap size, we can infer that the distance of data decreases by increasing the particles size and the effect of increasing the collar diameter on stability of the riprap decreases; nevertheless, the stability values for the pier with collar is more than the pier without collar.

In order to analyze the increasing stability due to using collar, the differences in the flow depths in critical conditions for the riprap around the piers with and without collar on the flow depth in critical conditions for riprap around pier without collar were divided and then expressed as percentage (Figure 4). Figure 4 illustrates that the percentages of the increase in the riprap stability layer in piers with collar compared to the non-collar pier were 22% for the collar size *W*=3*b*, 15% for the collar size *W*=2*b* and 8% for the collar size *W*=1.5*b*. When analyzing and interpreting these changes, it can be said that in the piers that were protected by collar, the riprap stability layer increased because the direction of the downward horizontal flow which is the main cause of the horseshoe vortex and one of the main factors of erosion around piers deviated from the pier.

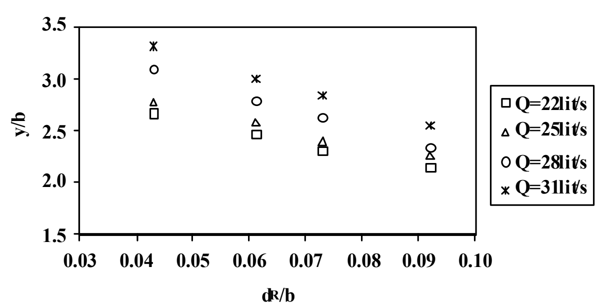

Fig. 2: Relative flow depth versus relative riprap size for various flow rates at the point of threshold conditions

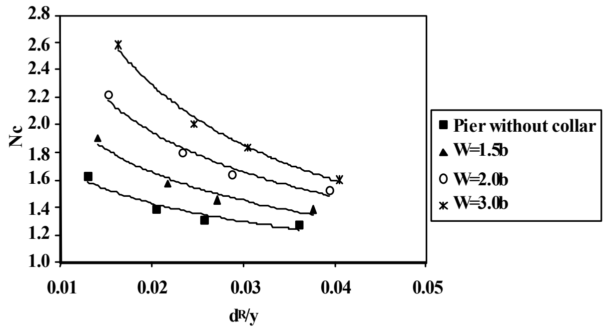

Fig. 3: Stability number versus relative riprap size for various collar sizes in riprap instability condition

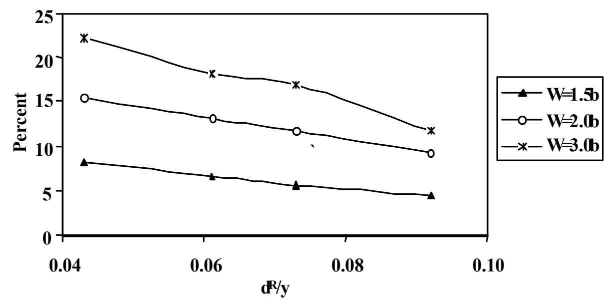

Fig. 4: The increase percentage of the riprap instability of the pier with collar to the pier without collar

CONCLUSION

The present study scrutinized the effect of collar on riprap stability and the reduction of local scouring in the vicinity of bridge piers in 180-degree river bends. Regarding the maximum scouring extent in the 60-degree position, the riprap extension was selected and assumed constant in all experiments. Results revealed that by increasing the average size of the riprap grains, the flow depth for starting instability of the riprap decreases. Also, by increasing the average size of the riprap grains, the effect of increasing the flow rate on the instability of the riprap layer decreased. The findings demonstrated that using collar in bridge piers increases the riprap stability and greater collars were more effective than smaller collars on increasing the stability.

Based on the experimental data, the riprap stability layers for the piers with W=1.5b, W=2b and W=3b collar were respectively, 8%, 15% and 22% more than that for the pier without collar; by using larger riprap grain sizes, the effect of collar on the riprap layer stability decreased. It can also be concluded that the effect of collar around the cylindrical pier on the riprap stability layer was less than the straight canal due to secondary flow and spiral vortex in the river bend.

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