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# Experimental Study on the Stability of Riprap at Bridge Piers in a 180 Degree Flume Bend

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**Abstract**

Every year, many bridges fail not for structural reasons but due to the scouring at their piers and abutments. One of the most important reasons for this destruction is local scour around the bridge pier in river bend. The use of riprap stones to deal with scour problems is very usual in civil engineering practice. In the present study application of riprap was examined experimentally for scour control around cylindrical bridge pier in a 180-degree laboratory flume bend. Experiments were conducted for four various sizes of riprap with flow discharge of 22, 25, 28 and $31 lit/\sec$.The cylindrical model pier was installed at the positions of 30, 60, 90 and 120-degree with clear-water conditions. The results show that the maximum of riprap stability occurs at 30-degree position, and at least stability occurs at the 60-degree position. As the riprap grain size decreases, the effect of bridge pier position in the river bends on the riprap layer instability declines. Furthermore, the riprap stability around the bridge pier at the river bend was less than the straight channels.

**Keywords**: Scour, Pier, river bend, Riprap, flow discharge

## Introduction

Bridge piers are an essential structural component of bridges; their failure may have significant consequences on an important infrastructural element. Bridge piers may be subjected to scour by severe hydraulic conditions, or when the bed sediment size is relatively small, resulting in a large scour hole exposing the entire bridge foundation. Bridge pier scouring occurs when rapid water flows wash away big amounts of soil materials adjacent to bridge piers and this can in turn result in the destruction of the structure. Researchers from all over the world have studied extensively the problem of local scouring from different points of view and under different conditions. It is well documented that the main cause of concern about the stability of bridge foundation is the occurrence of scour around the piers (Melville and Coleman 2000). Thomas (1967), Tanaka et al. (1967), Posey (1974), Odgaard and Wang (1987), Heidarpour (2002), Chiew(1992), Kumar and Ranga Raju (1999), Parola (1993), Jones et al. (1995), Melville and Hadfield (1999) and others, have introduced different methods of scour reduction. Protecting bridges against local scouring is one of necessary elements in designing structures on rivers. Applying riprap around the bridge piers to increase the bed materials resistance is one of the 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 (1973) considered the first movement of grains in front of the pier, and Chiew (1995) and Croad (1997) considered complete removal of the riprap layer. Parola (1993) believed that the removal of the middle riprap layer was the reason for riprap failure. Chiew (1995) divides the failure of a riprap layer around a bridge pier into three causes: shear, winnowing and edge failure. Zarrati et al. (2010) studied riprap behavior around cylindrical bridge piers with collars 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, 1973; Posey, 1974; Breusers et al., 1977; Garde and Ranga Raju, 1977; Worman, 1989; Yoon et al., 1995; Chiew and Lim, 2000; Lauchlan, 2001; Zarrati et al., 2006; Unger and Hager (2006); Mashahir et al., 2009). Chiew (1995, 1997) presented a thorough analysis of riprap failure mechanisms at bridge piers. His experiments were conducted with a pier of diameter 0.070 m inserted in an almost uniform sand of size 1 mm. The riprap sizes investigated were 2.6, 4, and 4.85 times larger than the sand. The extent of riprap was defined by the diameter and the riprap thickness. All tests involved an approach flow depth of 0.20 m for clear-water conditions. Three failure modes were identified:

1. Shear failure, where the riprap is unable to withstand the downflow and the horseshoe vortex associated with the pier scour mechanism;
2. Winnowing failure, where the underlying finer bed material escapes through

the voids of the riprap; and

3. Edge failure, where riprap material at the interface to the bed material slides into the scoured surface. Figure 1 illustrates the different parameters in riprap design around a cylindrical pier. 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 stability of the riprap layer around a cylindrical bridge pier in various position of river bend (in a 180 degree flume bend).

## MATERIALS AND METHODS

In order to study the stability of riprap for reduce local scour around bridge pier in the rivers bend, a physical model was prepared. The experiments were conducted in the laboratory bended glass flume with central angle of 180 degree, central radius of R=2.8m and width of B=0.6m. Relative curvature of bend was R/B=4.7 which defines it as a mild bend. Straight entrance flume with the length of 9.1 m was connected to the 180 degree bend flume. This bended flume is connected to another straight flume with the length of 5.5m. At the end of this flume a controlling gate was designed to adjust the water surface height at the desired levels (Figure 1). The pier size was defined to meet the criteria defined by other investigators. According to Chiew and Melville (1987) recommendations, pier diameter should not be more than 10% of flume width to avoid wall effect on scouring. Raudkivi and Etema (1983) suggested that the ratio of flume width to pier diameter should be minimum 6.25. So a PVC cylinder of 60mm diameter was used as the pier physical model. It is recommended that the average particle diameter should be more than 0.7 mm to avoid forming ripples (Raudkivi and Etema, 1983). Furthermore, in order to eliminate the effect of sedimentations on scouring, ratio of pier diameter to average particles diameter should be kept more than 50 (Chiew and Melville, 1987). However Raudkivi and Etema, (1983) recommend a ratio of 25-30. To eliminate the effect of non uniform on the sediment scour, geometric standard deviation must be less than 1.3. According to these cases, a 150 mm-thick natural sand layer of river with a 1.5mm average diameter and standard diversion coefficient 1.13 was used. All the experiments of the study were conducted in clear water condition. According to Raudkivi and Ettema (1983), clear water scouring occurs under $U < 0.95U_C$ ($U$ average flow velocity $U_C$ threshold velocity for bed sediments) condition.

According to Chiew (1995), 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. Round-corner grains were used because these kinds of stones are usually available at river sites and their resistance to

scouring is also less than sharp-corner grains.
In all experiments riprap minimum thickness according to the criteria proposed by Richardson et al. (1991), Tripled the riprap median sizes was considered ($t = 3d_R$).In addition, a screen with a sieve size of 0.3 mm was used as a filter. Riprap layer Extension is one of the parameters affecting riprap stability around a pier. In order to find riprap layer extent, long duration tests were carried out on the 60 degree position of the bend. The scour affected was determined by longitudinal and transverse profiles drawings (figure 2 and 3). Riprap Layer extension tests were continued for 72 hours (Chiew, 1995). Long term experiments were continued to ensure that edge failure did not occur. Edge failure was defined as the formation of a scour hole in the vicinity of the riprap boundary with a depth equal to half of the riprap grain diameter. The purpose for the selection of 60 degree position was to obtain more powerful secondary flows and consequently maximum scour depth and extension (heidarnejad et al., 2010; Masjedi et al., 2010). Proper riprap layer extent around pier was achieved by trial and error. Finally, in order to prevent the creation of edge failure, extension of the riprap layer in accordance with the pattern suggested by Gales (1938), was chosen. The extension was considered for all riprap grain sizes and all experiments constant. For experimental set up, initially the cylindrical pier was placed in a suitable position, and then sediments spread uniformly in longitudinal and transversal direction over bed flume by movable cart. Then the riprap layer with certain characteristics (grain size, cover and thickness) was placed around the bridge pier and leveled with the stream bed. Before switching on the pump, the end gate was closed and then water conducted through flume gently. After rising up the water level and ensuring from soaking the sediments, after some hours pump switched on and by entrance pipe valve, water flowed gently through stilling basin with low flow rate; at the same time accurate adjusting downstream gate set flow discharge to desired one. Experiments in a specific discharge started with the higher flow depth and if after 15 minutes instability of riprap layer did not occur, flow depth was decreased about 5 mm and test continued for another 15 minutes. The experiment continued until instability (shear failure) was observed in the riprap layer. At this depth ($y$), flow velocity was recorded as the critical velocity of the riprap ($U_c$). The experiment was then repeated for a different discharge. This process was then repeated for each one of riprap grain sizes and different discharge in positions 30, 60, 90 and 120 degrees. Variables of these tests are shown in table 1.

## Results

Considering that in all the tests using uniform bed sediments ($d_{50} = 1.5mm$), the sediment critical velocity was constant and increase in relative velocity ($U / U_c$) is an indication of increased riprap stability. Figure 4 shows the critical velocity ratio $U / U_c$ plotted against, relative riprap diameter $d_R / y$ on different positions of the bend. Figure 4 illustrates that on all of the positions, as the riprap relative size become increases, the threshold conditions is reached at a higher critical velocity ratio (on the threshold of riprap failure); furthermore, by decreasing the riprap grain size the distance of the points representing critical velocity ratio approach together, and finally the effect of bridge pier position in the river bend on the riprap layer instability declines. For a constant grain size, maximum riprap stability (maximum of $U/U_c$) occurs at 30 degree position, while minimum riprap stability (minimum of $U/U_c$) can is seen to occur at 60 degree bend position. The maximum velocity distribution, created at 60-degree position was due to the effect of secondary flow forces. At this position in contrast to straight channels (maximum velocity occurs near the free surface), the maximum velocity occurs near the bed and consequently causes reduction in the stability of riprap layer. For the investigation of the effect of discharge values and cylindrical pier positions on riprap stability at the bend, variations of relative flow depth( $y/b$ ) versus cylindrical pier positions at the bend for various flow rates at the point of threshold conditions are presented in Figure 5. As shown in Figure 5 at all the bend positions, the value of $y/b$ ratio decreased (or riprap stability increased) with decreasing flow discharge, so that the minimum stability occurred at $Q = 31 lit/s$ and maximum at $Q = 22 lit/s$. It is also shown that the distances between points on the graph at 120-degree position are more compared to other positions and finally with changing flow discharge, the flow depth range on the riprap layer instability shows more sensitivity (see figure 5). Figure 6 shows comparison of present study in the bend with results of study of Parola (1993), Quazi and Peterson (1973), Yoon et al. (1995) and Lim and chiew (2001) in direct channels. As it can be seen from figure 6,that the results of this study and other investigators was the same for the relation between riprap diameter, $d_R / y$ and stability number of riprap layer, $N_c$ ( $N_c = \rho U^2 / (\rho_s - \rho) g d_R$). Maximum agreement between the results obtained by parola (1993) and our study occurred at 90 degree position (with $R^2 = 0.96$). As shown in figure 6 the highest stability of riprap was reported by Lim and Chiew (2001) and the minimum stability was obtained in this research at 60 degree position of bend. The riprap stability on various positions of the bend is more than straight channels. On the bend in addition to factors that affect to riprap instability (down flow and horseshoe vortex), secondary flows is another factor that will be exacerbate the riprap layer instability.

## Discussion

The present experimental study scrutinized the effects of different factors on stability of riprap layer around a cylindrical bridge pier in 180-degree river bend. According to the range of maximum scour in 60-degree bend, the extension of riprap selected and was fixed for all experiments. Results showed that changing the position of the bridge pier in the bend was affected on the riprap stability. So that maximum stability occurs at 30-degree position, and at least stability occurs at the 60-degree position (due to the increasing strength of secondary and spiral flows). Also by increase riprap grain size, the flow depth for the beginning of instability was decreased (flow velocity was increased). Comparison between present study on the bend with results other investigators on direct channel showed that process of riprap stability was accordance. Generally the riprap stability installed around the foundation cylindrical bridge pier at the river bend was less than the straight channels.

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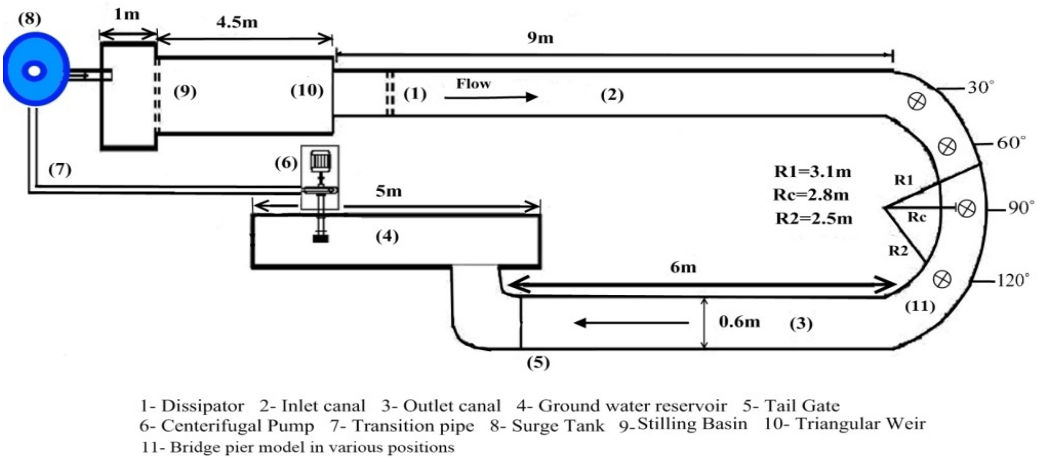


Fig. 1 Layout of Physical hydraulic model

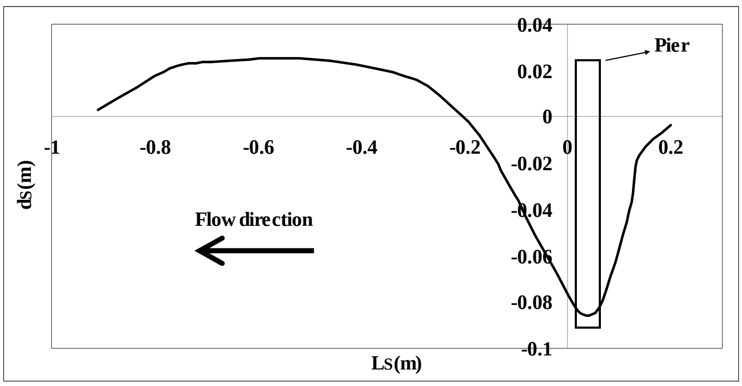


Figure 2. Longitudinal scour profile in position 60 degree

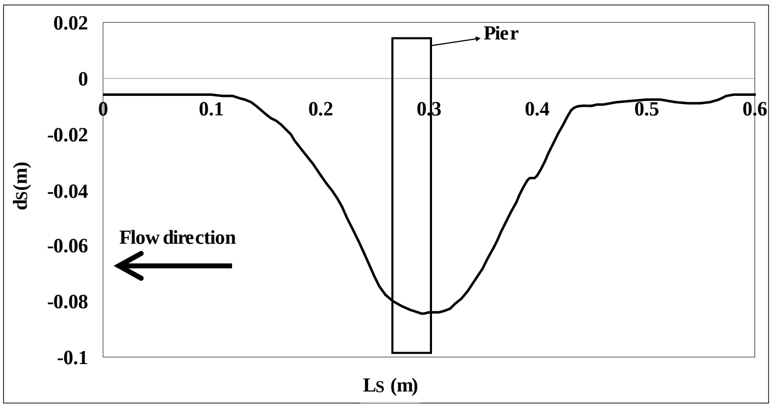


Figure 3. Transverse scour profile in position 60 degree

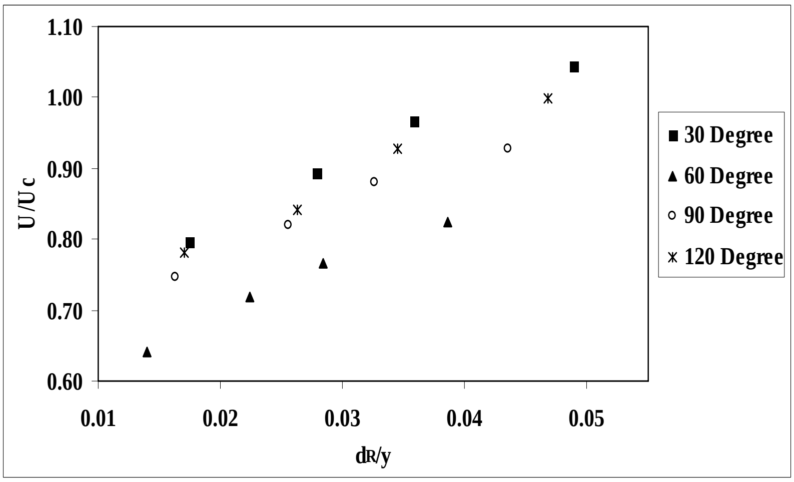


Figure 4. Critical velocity ratio against relative riprap diameter on different positions

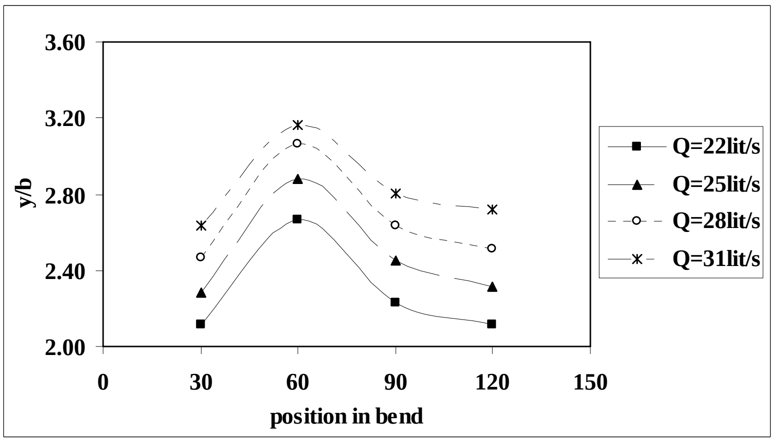


Figure 5. Relative flow depth versus cylindrical pier positions at the bend for various flow rates at the point of threshold conditions

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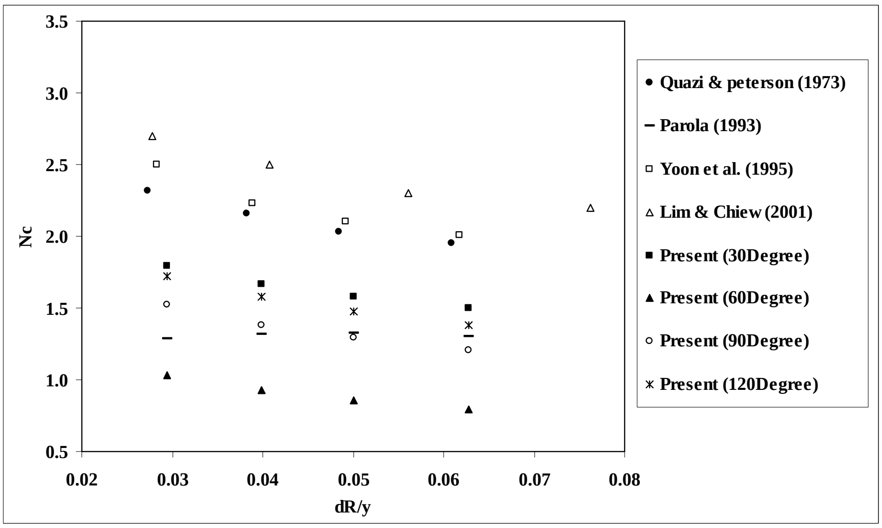


Figure 6. Comparison of riprap failure proposals in direct channels with present result

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