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Reduction of Local Scour at a Bridge Pier using Collar in a 180 Degree Flume Bend

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Abstract: In this study, the use of collars for reducing the effects of local scour at a bridge pier is presented together with the time aspect of the scour development. The adoption of a collar is based on the concept that its existence will sufficiently inhibit and/or deflect the local scour mechanisms so as to reduce the local scour immediately adjacent to the pier. The overall objective of the research is to study the temporal development of the scour for a pier fitted with a collar and a pier without a collar. The study was conducted using in a 180 degree laboratory flume bend with a relative radius of R/B = 4.67 operated under clear-water conditions. The median size and geometric standard deviation of bed material were equal to d50 = 2 mm and sg = 1.7, respectively. Tests were conducted using one pier with 60 mm diameter in positions of 60 degree under one flow conditions. In this study, the time development of the local scour around the abutment fitted with and without collar plates was studied. The effects of various sizes of collars fitted at different elevations on the temporal development of scour depth at the abutment were also studied. The time development of the scour hole around the model pier with and without a collar installed was compared with similar studies on bridge piers. The results of the model study indicated that the maximum depth of scour is highly dependent on the experimental duration. It was observed that, as the size of a collar plate increases, the scour decreases. The minimum depth of scour occurs for the collar at diameter of 3D placed at elevation of -0.1 D from the bed surface.

Key words: Scour depth, collar, circular pier, river bend, secondary flow

INTRODUCTION

Scour is defined as the erosion of streambed sediment around an obstruction in a flow field (Chang, 1988). The mechanism has the potential to threaten the structural integrity of bridges and hydraulic structures, ultimately causing failure when the foundation of the structures is undermined. A series of relatively recent bridge failures due to pier scour, as reported in the literature (Wardhana and Hadipriono, 2003), has rekindled interest in furthering the understanding of the pier scour process and for developing improved ways of protecting bridges against the ravages of scour. Lagasse and Richardson (2001) stated that, in the United States, general and local scour are the major cause of hydraulic factors such as stream instability, long-term streambed aggradations or degradation, general scour, local scour and lateral migration are blamed for 60% of all US highway bridge failures.

Chiew and Lim (2003) and Chiew (2004) reported the case of the August 2000 failure of Kaoping Bridge in Southern Taiwan. Dey and Barbhuiya (2004) made reference to the collapse of Bulls Bridge over the Rangitikei River, New Zealand. Farhadzadeh (1999) reported 9392 bridges have been damaged by scour (pier, abutment or contraction scour) in Iran.

It has long been established that the basic mechanism causing local scour at bridge piers is the down-flow at the upstream face of the pier and formation of vortices at the base (Muzzammil *et al*., 2004).

Numerous experimental and numerical studies have been carried out by researchers in an attempt to quantify the equilibrium depth of scour in various types of soil material. Some of the most common equilibrium scour depth predicting equations are shown in Table 1.

Local scour at a bridge pier principally results from the down-flow along the upstream face of the pier and the resulting horseshoe vortex which forms at the base of the pier (Kumar *et al*., 1999). One way of reducing pier scour is to combat the erosive action of the horseshoe vortex by armoring the riverbed using larger size materials such as stone riprap. Another approach is to weaken the down-flow and thus the formation of the horseshoe vortex using collar.

Melville and Coleman (2000) defined collars as devices attached to the pier at some level usually close to the bed. A collar is in the form of a thin protective disc. A collar extends around the outside edge of the pier with the

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Table 1: Some equilibrium scour depth prediction equations

Investigator(s)	Equation	Source
Breusers *et al.* (1977)	$y_{se} = 1.35 K_i b^{0.7} y_0^{0.3}$	Hoffmans and Verheij (1997)
(Based on Laursen and Toch (1956) data)	where y_{se} = Equilibrium scour depth, K_i = 1.0 for circular pier, b = Pier width, y_0 = Flow depth	
Neill (1973)	$y_{es} = K_s b$ where, K_s = 1.5 for circular pier	Melville and Coleman (2000)
Colorado State University (CSU)	$y_{se} = 2.0 K_i y_0 F_r^{0.43} \left(\frac{b}{y_0}\right)^{0.65}$	Hoffmans and Verheij (1997); HEC-18
	where K_i = 1.1 for a circular pier with clear-water scour, F_r = Froude number	
Raudkivi and Ettema (1983)	$y_{se} = 2.3\ bK_\sigma$ where $K = (\sigma_g) = 1$ for uniform sediment, σ_g = Geometric standard deviation of the grain size distribution	Dey (1997)
Shen and Schneider (1969)	$y_{se} = 0.000223\ R_b^{0.619}$ where R_b = pier Reynolds number	Dey (1997)

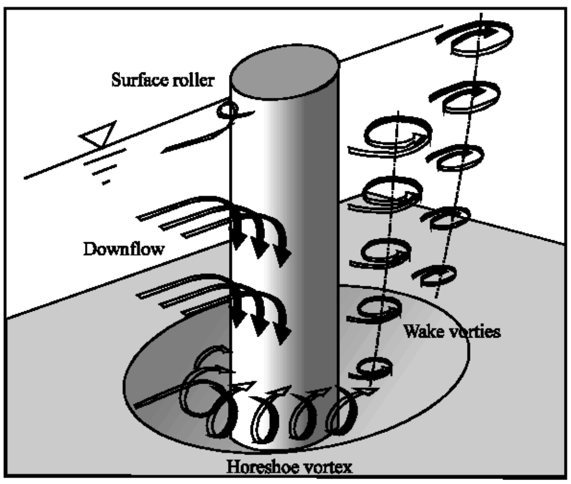

Fig. 1: Illustration of the flow and scour pattern at a circular pier (Melville and Coleman, 2000)

main objective of protecting the bed from the scouring effect of the down-flow at the pier and the associated vortex action around the base of the pier (Fig. 1). An example of a typical collar and its arrangement for both a rectangular and a circular pier are shown in Fig. 2.

The concept behind using collar is that it will sufficiently deflect the down flow vortex which results reduction of scour hole by reducing the strength of down flow and horseshoe vortices. The idea for using a collar for preventing scour at a pier was first studied by Laursen and Toch (1956). They concluded that such devices may be useful for scour mitigation. Use of a collar, a slot and combination of both were studied by Chiew (1992) for the purpose of determining a measure for scour mitigation at the vicinity of a pier. The collar alone was found to reduce the scour depth by as much as 20% while no scour occurred when a D/4 slot was used in conjunction with a collar. Similar results were obtained for the two collar diameters tested. Kumar *et al.* (1999) also experimentally

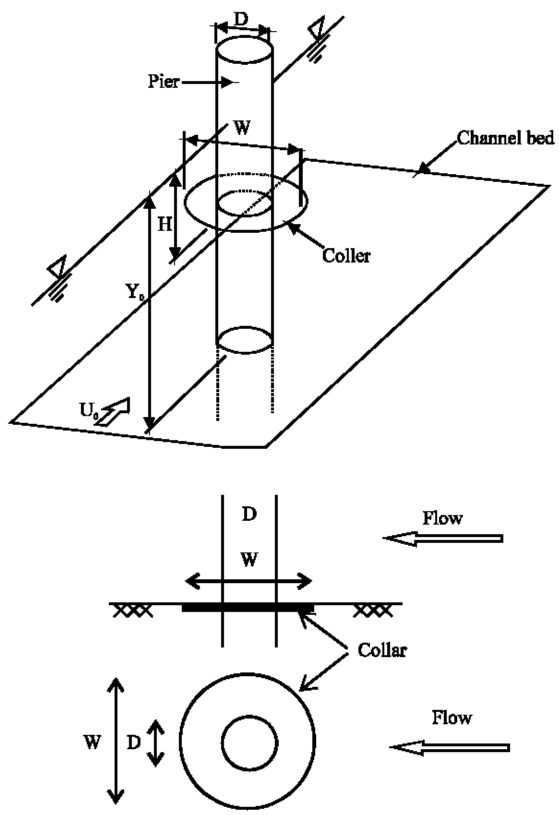

Fig. 2: Collars positioned around circular pier (Mashair *et al.*, 2004)

studied on the use of collars around a cylindrical pier to reduce the scour depth. Five different collar sizes of thickness 3 mm were used (i.e., W = 1.5D, 2D, 2.5D, 3D and 4D). It was found that depth and location of the maximum scour varies with collar width. They found that wider collar installed at lower elevation relative to the bed surface is more effective. From the study of Singh *et al.* (2001) it was concluded that the efficacy of a collar in preventing scour is a function of its width and its elevation relative to the bed surface. They found that collar of width of 1.5D, 2D and 2.5D placed on the bed reduced the scour depth by 50, 68 and 100%, respectively; collar of 2D wide placed at -0.1 D resulted a maximum reduction in scour depth. The use of collar as a countermeasure at bridge abutment was studied by Kayaturk *et al.* (2004). The effects of various sizes of collars placed at different elevations on the scour depth at the abutment. Their experimental results showed that not only did the presence of a collar reduce the scour depth; the rate of temporal development of the scour hole was also reduced. According to Kayaturk *et al.* (2004), a 67% reduction in the scour depth was achieved when the collar was positioned at an elevation of 50 mm below the bed. Zarrati *et al.* (2006) studied the use of independent and continuous pier collars in combination with riprap for reducing local scour around bridge pier groups. Their results showed that with two piers in line, a combination of continuous collars and riprap led to a scour reduction of about 50 and 60% for the front and rear piers, respectively. In another experiment with two piers in line, independent collars showed better efficiency than a continuous collar around both the pier. It was also observed that the efficiency of collars is more on a rectangular pier aligned to the flow than two piers in line. Mashair *et al.* (2009) studied the effectiveness of different countermeasures to control scour around bridge piers including application of riprap and installing a collar around piers. Piers aligned with the flow and skewed at 5°, 10° and 20° to the flow were tested. A 3D wide collar installed around the piers at the streambed level has been tested. The size and extent of stable riprap stones for prevention of scouring around the piers was found to decrease when using collar.

As it can be seen from the forgoing paragraphs, fast majority of researches on scour at bridge pier are conducted at a straight flume. In practice there are many examples where the bridges cross the river bends. In such a case the flow patterns which are mostly the cause of scour would not be the same as the case of straight canal and therefore it is the principal objective of this study is to carry out experimental tests on the effect of collar on scour development at pier in positions of 60 degree in a 180 degree river bend.

MATERIALS AND METHODS

Experimental apparatus: The experiment reported herein was conducted in a recirculation flume, with central angle of 180', central radius of R = 2.8 m and width of B = 0.6 m. 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' bend flume. This bended flume is connected to another straight flume with the length of 5.5m. The test area of the flume is made up of an aluminum bottom and plexiglas sidewalls along one side for most of its length to facilitate visual observations. At the end of this flume a controlling gate was designed to adjust the water surface height at the desired levels (Fig. 3). The study conducted at hydraulic laboratory of Islamic Azad university of Ahwaz during July 2008 to July 2009.

The size of pier in this study was defined to meet the criteria which have been defined by other investigators. From the study conducted by Chiew and Melville (1987) was found that to avoid wall effect on scouring, pier diameter should not be more than 10% of flume width. Therefore in this study a circular pier of diameter 60 mm fabricated from Polyvinyl Chloride (PVC) pipe was used. One were used for the study. In each case, the pier was placed on the centerline of the flume at the same longitudinal location. The 3 mm thick collar used in the experiments was made from a transparent plexi glass material. Four different collar diameters of 1.5D, 2D, 2.5D and 3D (in which D is the pier diameter) were used. Figure 4 shows a schematic illustration of a pier fitted with a collar. For all of the tests with a collar, the collar was positioned at the bed level, -0.1D,-0.5D and -1D in accordance with the recommendations of earlier researchers (Ettema, 1980; Kumar *et al.*, 1999; Singh *et al.*, 2001).

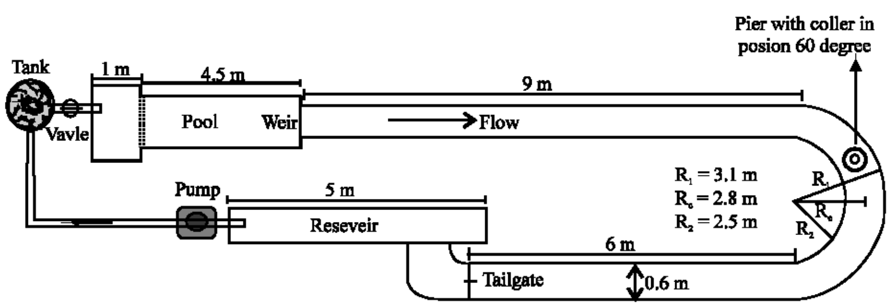

Fig. 3: Schematic illustration of the experimental setup (Plan)

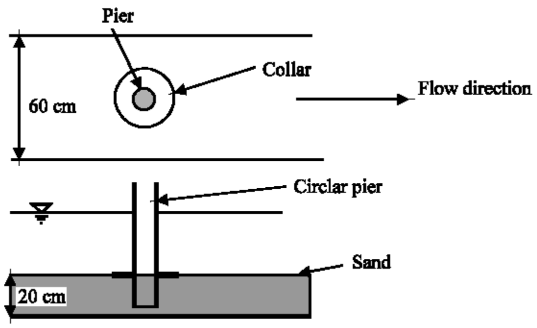

Fig. 4: Schematic illustration of a pier fitted with a collar

The effects of the grain size and the density of the sediment material are often expressed as a function of the critical flow velocity for the initiation of sediment motion. In this study to maintain the clear water condition without formation of ripple, sand of median diameter, d_{50} = 2 mm with geometric standard deviation of σg~1.7 were used. In this range of geometric standard deviation, the sediments are not uniform and the coarser grains armor the channel surface but are not large enough to armor the scour hole. In this study the experiments were performed under clear-water conditions at one flow intensities (u_*/u_{*c}) of 0.89, corresponding to a shear stress levels of 80% of the critical shear stress level based on critical Shields' parameter, respectively. The symbols u_* and u_{*c} are the shear velocity and the critical shear velocity, respectively. One Froude numbers of 0.41 were applied in order to investigate the effect of flow conditions on the scouring. All the experimental tests where conducted under the same flow depth and in positions of 60 degree of 180 degree river bend. A 60 degree triangular weir was used at the upstream section of the flume for flow measuring.

Duration of scour test: Equilibrium scour occurs when the scour depth does not change appreciably with time. Chabert and Engeldinger (1956) described the behavioral pattern of scour at a cylindrical pier with respect to the variation of scour depth with time. In clear-water scour, scour depth is approached asymptotically with time and may take an infinite amount of time for the equilibrium scour hole to develop, while in live-bed scour the scour develops rapidly and then fluctuates in response to the passage of bed forms.

In this study, a long time experiment was conducted at Froude number of 0.41 at the position of 60 degree for a pier without collar. The results are shown in Fig. 5. As it can be seen approximately 95% of scouring occurs during the first 6 h. Therefore in all remaining of our experimental tests, duration of 6 h was selected for each test.

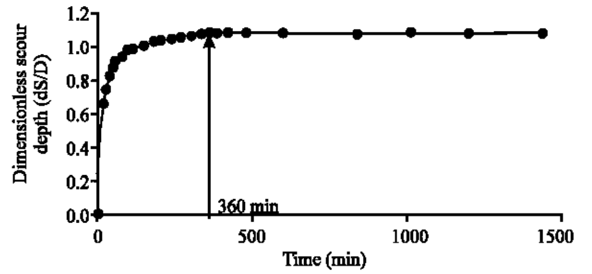

Fig. 5: Equilibrium time in the position of 60 degree for a pier without collar

Experimental procedures: The pier was first installed in the flume at the desired location. For the tests with the collar in place, the collar was also fitted to the pier at the required bed level. Before each test, care was taken to level the sand bed throughout the entire length of the flume and particularly in the vicinity of the pier using a wooden screed that is of the same width as the flume. The screed can be dragged along the flume rails to produce a sand bed having a smooth, uniform surface. Thereafter, any uneven bed surface was leveled using a hand-trowel. By employing the point gauge mounted on a carriage, initial bed elevations were taken randomly to check the leveling of the flume. To start the test, the flume was slowly filled with water to the desired flow depth. It should be noted that extra care is required when filling the flume, especially for tests of this nature where no sediment movement is allowed. Any deformity in the bed surface may trigger the development of ripples or dunes and general movement of the sand if the shear stress on the smooth bed is close to the critical shear stress. The pump was then started and the upstream gate slowly opened until the desired flow rate had been achieved. At the same time the tailgate gradually opened and was adjusted so as to maintain the desired flow depth in the flume.

Throughout the test period, the location and magnitude of the point of maximum scour depth was recorded, with the depth being acquired either using the point gauge or the 5 mm scale marked onto the side of the pier. The frequency of the measurements varied throughout the test period, with the maximum scour depth readings being taken every few minutes during the first hour of the test and every 30 min thereafter. It should be noted that since in the first few hours of each test the rate of scour depth versus time is very fast, accurate frequent readings it is very important. Because these data are required to be taken in order to properly define the equilibrium scour depth. The required frequency of scour depth measurements decreases as the rate of scouring decreases.

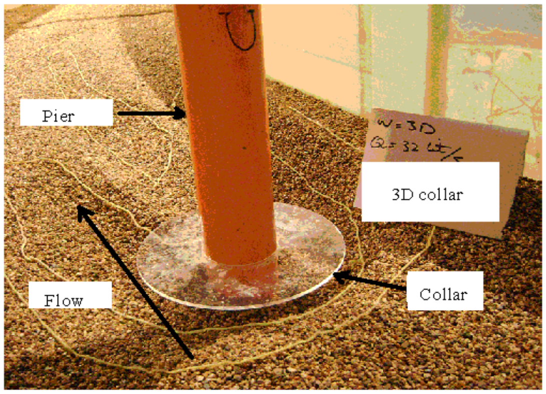

Fig. 6: Scour pattern at the end of a test

At the completion of each test, the pump was shut down to allow the flume to slowly drain without disturbing the scour topography. The flume bed was then allowed to dry, during which time photos of the scour topography around the pier were taken and the final maximum scour depth was recorded using the point gauge (Fig. 6).

RESULTS AND DISCUSSION

Effects of various sizes of collars fitted at time development of scour: Figure 7a-d show the time development of the local scour around the pier with and without collar. This figure shows the results obtained for four different diameters of collar which have been tested in this study. The collar diameter of 1.5D, 2D, 2.5D and 3D were placed at three bed level of -0.1D,-0.5D and -1D relative to the bed surface. From Fig. 7 it is obvious that, as the width of a collar increases, the scour decreases. Collar plates of size W = 3D resulted a maximum reduction in scour depth. Comparison of the results for rectangular piers aligned with the flow and the previous experiments on circular piers by Zarrati *et al*. (2004) and Mashahir *et al* (2009) showed that a collar of W/D = 3 is more effective at reducing the depth of the scour hole.

Effects of various elevations of collars fitted at time development of scour: Figure 8a-d show the time development of the local scour around the pier fitted with and without collar plates for four different elevations were used at the bed level, -0.1D, -0.5D and -1D with collar diameter of 1.5D, 2D, 2.5D and 3D. As it can be seen from Fig. 8, all collar of any diameter, installed at -0.1D results maximum reduction in scour depth. The main reason of such finding is that the strength of the downward vortex decreases when the collar placed at 01D below ground surface.

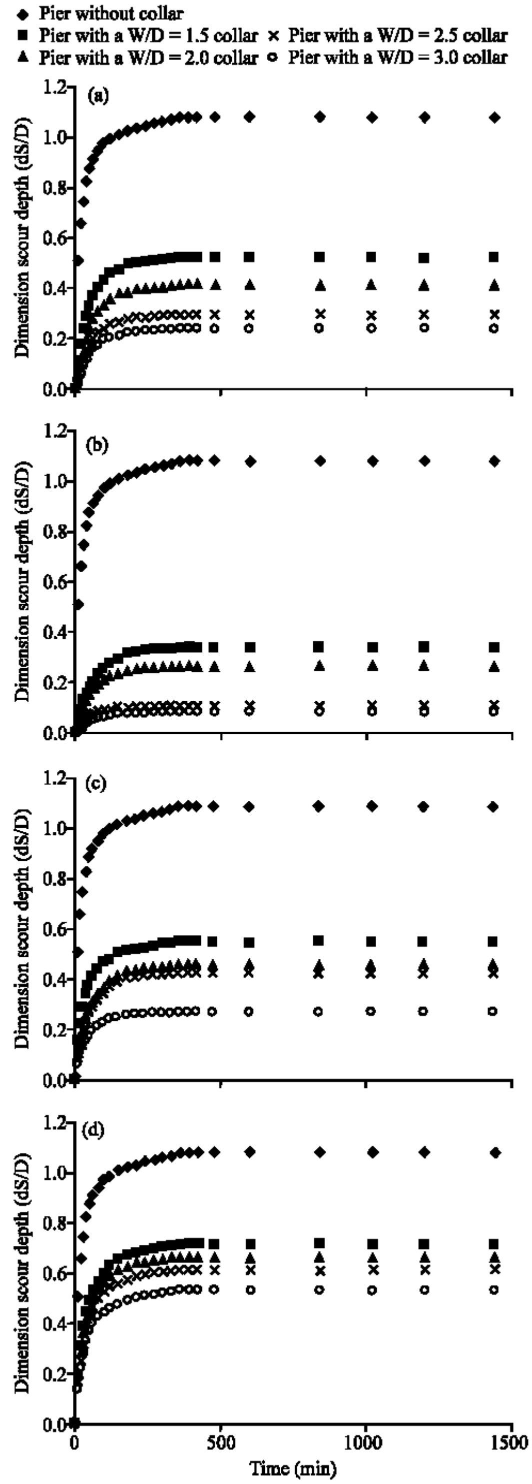

Fig. 7: Time development of scour for different collar sizes (dS = scour depth), (a) time development of scour at bed level, (b) time development of score at -0.1D, (c) time development of scour at -0.5D and time development of scour at -1D

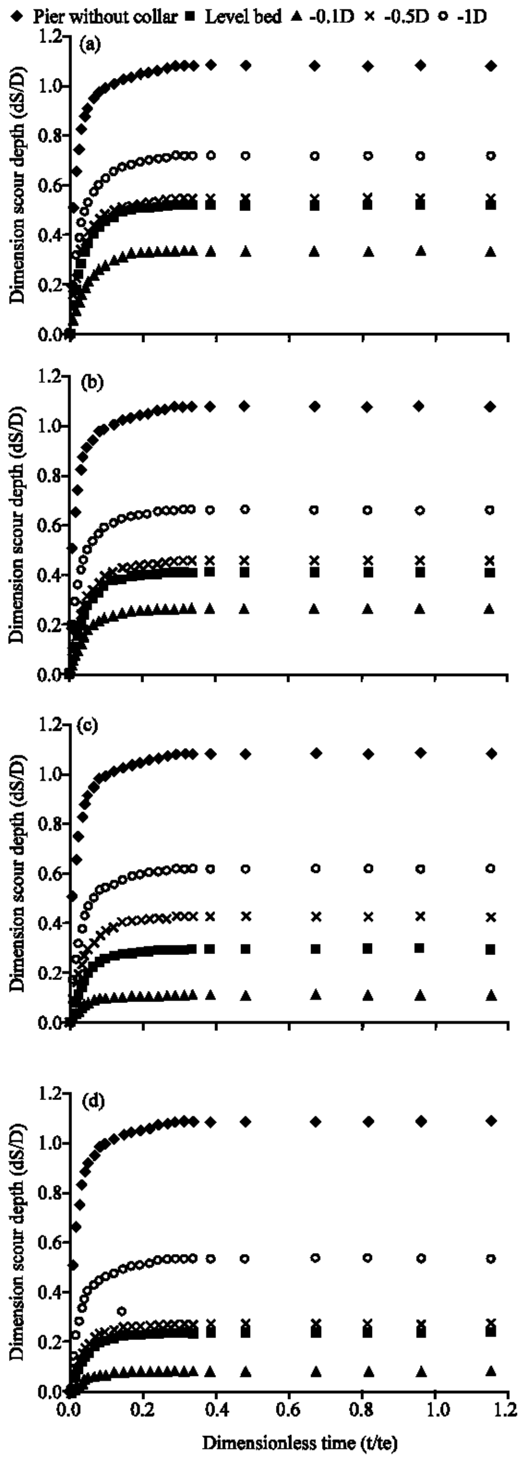

Fig. 8: Time development of scour for different elevations, (a) time development of scour with a W/D = 1.5 collar (b) time development of scour with a W/D = 2.0 collar (c) time development of scour with a W/D = 2.5 collar and (d) time development of scour with a W/D = 3.0 collar

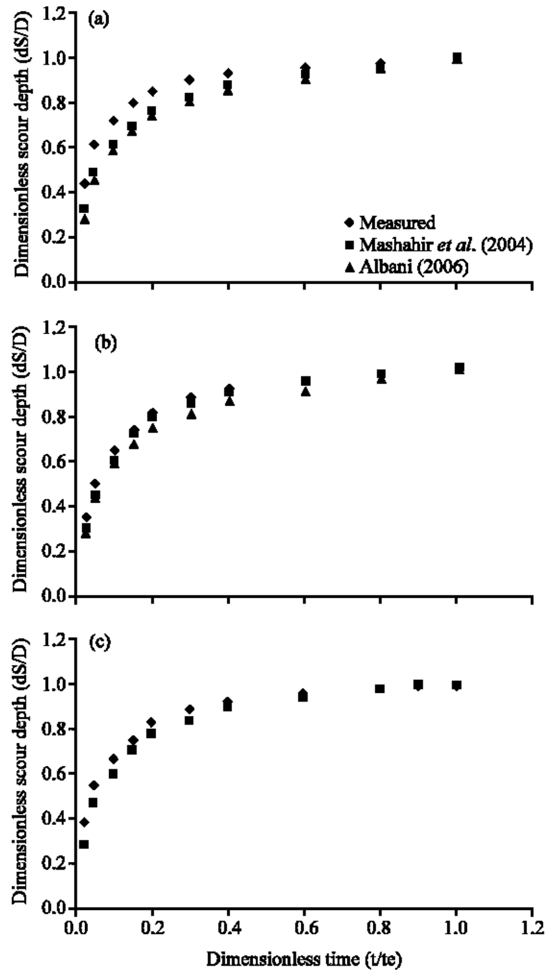

Fig. 9: Comparison of scour depth with time (t = Time development of scour and te = Maximum of Time development of scour), (a) time development of scour without coller, (b) time development of scour with a W/D = 2 coller and (c) time development of scour with a W/D = 2.5 coller

Comparison of measured scour depth with existing predicted formula: The comparison of the present study data with others study data is given in Fig. 9a-c. In this study the ratio of scour depth to the collar diameter has been plotted versus dimensionless time parameter. This parameter is defined as the ratio of duration of test to the maximum duration of equilibrium scour depth. As it can be seen from Fig. 9, a good agreement can be found between the results of this study with work of Mashair *et al.* (2004), with the study of Alabi (2006), with the studies of Ettema (1980), Alabi (2006) and Melville and Raudkivi (1996) using collar of 2D diameter.

Resulting curves using the general form of the Ettema (1980)'s equation displayed a good correlation with the

Table 2: Percent reduction in the scour depth (%)

Elevation of size of collars	Bed level	0.1D	0.5D	D
1.5D	52	69	50	34
2.0D	62	76	58	39
2.5D	73	90	61	43
3.0D	78	95	75	51

present experimental data as shown in Fig. 9, respectively. From the Fig. 9, the Ettema (1980)'s equation fits well to the data of the present study.

Table 2 shows the reduction in the scour depth around the pier fitted with collar plates for four different elevations were used at the bed level, -0.1D, -0.5D and -1D with collar diameter of 1.5D, 2D, 2.5D and 3D. Table 2 shows collar plates of size W = 3D when placed at 0.1 D below the bed surface gives a maximum reduction in scour depth equal to 95% of the scour depth without collar. Comparison of these finding with previous studies such as Singh *et al*. (2001) shows that for the same reduction in scour depth, the size of collar diameter in river bend must be taken higher. Singh *et al*. (2001) found that for maximum reduction in scour depth, collar of 2D diameter should placed at 0.1D below river bed level. The results of this study, however, shows that maximum reduction of scour depth can reach if collar of 3D diameter placed at 0.1D below ground surface.

CONCLUSIONS

The results of the experimental study indicated that the depth of scour is highly dependent on time. The depth of the scour increases as the time increases. The extent of scour observed downstream of the pier also increases as time increases. It was found that the temporal development of the scour hole at a pier is dependent on the size of collar as well as the level at which the collar has been installed below the bed surface. Other conclusions from this study are:

- Based on the testing done as part of this study and some of the results reported in the literature, it appears that collar installed at a pier can reduce the maximum scour depth
- Collar efficiency increases with increasing collar diameter
- A 3D wide collar is very effective at reducing both the scour depth and the scour rate when compared with a 1.5D, 2D and 2.5D collar
- All collars of any diameter, at -0.1D resulted in maximum reduction in scour depth
- Minimum depth of scour occurs for the 3D wide collar placed at -0.1D below bed surface. The percent of reduction by 95% compare to without collar
- The comparison of the present study data with existing formula shows good agreement with the Ettema (1980)'s equation

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