Reduction of local scour around a bridge pier by using different shapes of pier slots and collars

A. Bestawy, T. Eltahawy, A. Alsaluli IWA, A. Almaliki and M. Alqurashi

ABSTRACT

Local scour around bridge piers is one of the main causes of bridge failure all over the world. Experimental and hydraulic models were carried out to investigate two types of scour reduction methods around a single cylindrical pier, namely the pier's slots and collars. The efficiency of various types of pier slots and circular collars around the pier's base in reducing scour were studied. A new shape of a conical collar was developed by the authors and examined along with other shapes. The results revealed that collars, in general, have more influence in reducing scour depth than slots made in the front and rear of bridge piers. The sigma-slot acts better than other tested slots, with a reduction in the scour depths of 59.3% and 52.8% at the upstream and downstream of the pier, respectively. On the other hand, the conical collar appeared to be the most effective collar shape in reducing the scour around the bridge pier, with a 61.1% reduction in the scour depth downstream of the pier. A three-dimensional laser scanner was used to capture the bed topography at the end of each experiment and contour maps of the deformed bed were produced. A one-dimensional Hydrologic Engineering Center-River Analysis System model was developed with a single bridge pier to predict the scour depth around the pier in an attempt to introduce new values for the pier nose shape factor, K_1, which describes the tested piers.

Key words | bridge scour, collar, local scour, pier shape factor, pier slot

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INTRODUCTION

In many countries, bridges are built across waterways as traffic volume increases due to economic growth. Every year several bridges fail, not only because of structural reasons, but also because of pier and abutment scouring (Fayyadh *et al.* 2011). In the United States, hydraulic factors such as stream instability, local and general scour, long-term streambed aggradation/degradation, and lateral migration are responsible for 60% of all US highway bridge failures (Lagasse & Richardson 2001). The scour around bridge piers and foundations, as a result of flood flows, is also considered the main cause of bridge failure (Hoffmans & Verheij 1997).

The mechanism of scour around bridge piers has been extensively studied in the past (Dargahi 1990). Figure 1 shows the flow and scour pattern around a circular pier.

The pier nose shape, as well as the angle of attack of the approaching flow, significantly affects the scour pattern around the pier. It was shown that a downward flow is formed in front of the pier, which impinges on the stream bed and causes scour hole development in the front side of the pier, while a complex wake vortex system develops at the back of the pier. The vortex motion caused by the existence of the pier pulls bed sediments within the vicinity of the pier base (Lauchlan & Melville 2001). The vortex then spreads downstream along the sides of the pier. This vortex is often referred to as horseshoe vortex because of its similarity to a horseshoe (Breusers *et al.* 1977). The horseshoe vortex forms as a result of separation of flow at the upstream face of the scour hole excavated by the downflow. The horseshow vortex is involved in transporting the displaced particles

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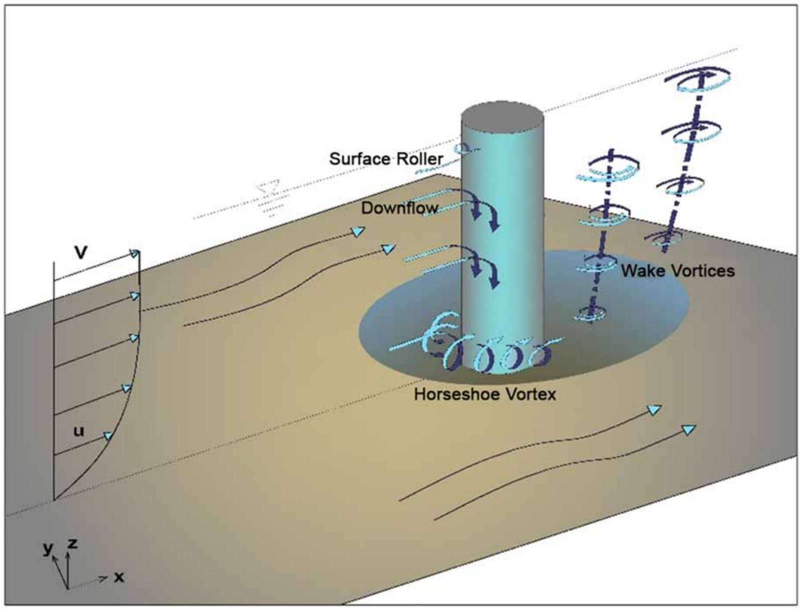

Figure 1 | Flow structure around a cylindrical bridge pier (Jahangirzadeh *et al.* 2014).

away fast the pier. The horseshoe vortex is formed as a result of the scour, but it is not the cause of it (Brice & Bloggett 1978). As the scour depth increases, the horseshoe vortex strength reduces, which automatically leads to a reduction in the sediment transport rate from the base of the pier.

The problem of local scour of sediment around bridge piers has been studied extensively for several decades. The research has basically suggested two methods to diminish scour around the bridge pier. The first method is armoring the streambed around the pier to withstand shear stresses, which accompany with high flow events, by using riprap, gabions, tetrapods, dolos, or concrete aprons, etc. (Chiew & Lim 2000; Lim & Chiew 2001). The second method is altering the flow alignment to break up vortices and reduce velocities in the vicinity of the bridge pier by means of sacrificial piles and sills, collars, and slots to providing an array of piles in front of the pier (Melville & Hadfield 1999), a collar around the pier (Chiew 1992; Kumar *et al.* 1999; Zarrati *et al.* 2004), and a slot through the pier (Chiew 1992; Kumar *et al.* 1999).

When a collar is installed around the pier, the direct impact of the downflow on the streambed is prevented, which leads to a reduction in the maximum scour depth as well as its rate. The slots are used to divert the downflow away from the bed, or to reduce the downflow impinging on the bed. The width, length, and location of the slot are significant parameters.

Researchers have used different shapes of slots and collars around cylindrical and rectangular piers to control the scour; however, a comprehensive study to compare the effect of the collar shape in the vertical direction and the geometrical dimensions of the slot at the upstream and downstream of the pier has yet to be investigated. For example, Kumar *et al.* (1999) used a series of circular collars with different dimensions only at the bed level to control scour around a cylindrical bridge pier. Zarrati *et al.* (2004) examined the effect of collar elevation on the scour reduction around a rectangular pier just by using one shape of collar. Chiew (1992) and Kumar *et al.* (1999) proposed a vertical slot in a cylindrical pier for scour reduction.

Ghasemi *et al.* (2018) studied experimentally the effect of using nano-clay material with a concentration of 1% in the floor sediment to control scour depth around the bridge pier. Their results indicated a decrease in scour depth by 44.23% and 63% for steady and unsteady flow, respectively.

Shunyi *et al.* (2019) investigated experimentally the effect of collar installation height, collar external diameter, and collar protection range on the scour depth. Their results showed that the application of an anti-scour collar alleviates the local scour at the pier effectively.

Günal *et al.* (2017) investigated experimentally the performance of a group of bridge piers with different span lengths on the local scour around the bridge pier. They concluded that the scour depth increases with increasing span length between piers.

Najafzadeh & Barani (2014) evaluated the ultimate maximum scour depth d_{Smax} using a theoretical hyperbolic model. The model data were collected from short-duration tests conducted over a period of 4 h in three types of cohesive soils, each with a different clay content. They found that the ultimate scour depth increases with an increase in flow Froude number.

Mokhles *et al.* (2012) developed equations to predict the equilibrium scour around bridge abutments in cohesive soils based on experimental studies. They also developed an equation to predict the development of scour depth with time.

Wang *et al.* (2017) stated that the anti-scour collar external diameter and installation height proved to be the most important factors influencing its protection efficiency.

Chen *et al.* (2018) proposed a new type of collar, named a hooked-collar, and found that maximal downflow is highly reduced and there was a corresponding decrease in horseshoe vortex strength for the experiments with the hooked-collar compared to cases without the collar.

Farooq & Ghumman (2019) studied the influence of pier shape on local scouring. A plain octagonal shape was shown to have more satisfactory results in reducing scour compared to other pier shapes.

Study objectives

The aim of this study is to reduce the scouring around bridge piers by using slots through the pier or using collars around it. In this respect, this study investigates the application of slots with different shapes and dimensions, circular collars with wings, and frustum of a conical shape on the scouring around bridge pier. In addition to the experimental studies mentioned above, a Hydrologic Engineering Center-River Analysis System (HEC-RAS) hydraulic model was developed for a single bridge pier, with an attempt to calibrate the model and introduce new values for the pier nose shape factor, K_1, which describes the tested piers.

MATERIALS AND METHODS

The experiments were conducted in the hydraulics laboratory of the Civil Engineering Department at Taif University, Taif, Kingdom of Saudi Arabia. The experimental flume is 12 m long, 0.3 m wide, and 0.45 m high, as shown in Figure 2. The flume is provided with an adjustable slope ranging from +1:40 (1.432°) to −1:200 (−0.286°). The maximum discharge passes through the flume is 150 m^3/h (41.67 L/s). The flow rate is measured using an electromagnetic inductive flow meter and displayed on a digital readout. Water was circulated via a centrifugal pump. An adjustable tail gate was fixed downstream of the flume to control the water depth.

The flume floor was raised 10 cm with Perspex platforms as shown in Figure 2. A section of a movable bed

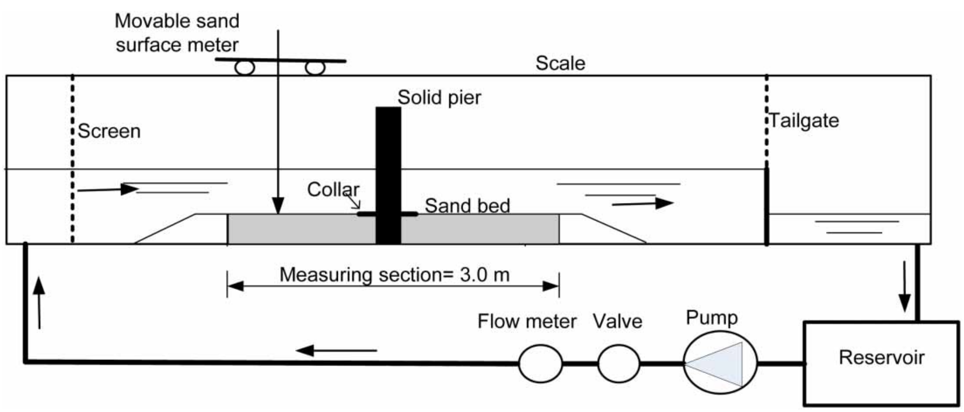

Figure 2 | Experimental flume set-up.

was prepared by filling the area between the platforms with sand to a length of 3 m and this section was situated at a distance of 3 m downstream from the entrance of the flume to ensure fully developed flows. A coarse sand with a geometric mean size of sand (d_{50}) equal to 0.7 mm was used. The bed sediment consisted of uniform sediment (uniformity coefficient, $C_u = d_{60}/d_{10} = 1.45 < 2.0$) and geometric standard deviation $\sigma_g = 1.24$.

All experiments were run for sufficient time to ensure equilibrium conditions were met. This time was determined by running the base experiment of a solid pier without a collar and plotting the scour development graph shown later in Figure 5. It was found that approximately 95% of bed scour occurs during the first 6 h of an experiment. Therefore, the 6 h running time was considered to be the equilibrium time, and was set to record the maximum scour hole for all experiments.

The size of the pier in this study was chosen to meet the criteria defined by Chiew & Melville (1987). They limited the pier diameter to 10% of the flume width to avoid wall effect on the scouring process. The pier model was cylindrical in shape with a 30 mm diameter, and 450 mm height and was made from cement mortar. Two different methods of reducing the scour around a bridge pier were investigated in this study, namely the slots and collars. All piers with slots were installed such that the invert of a slot coincides with the surface elevation of the sand bed. Following the recommendations of earlier researchers, collars with diameter of $3d_p$ (where d_p is the pier diameter) were installed around the pier at the bed level. Flat edged, and conical collars were used.

In this study, the experiments were performed under clear-water conditions at a constant flow intensity (U/U_c) of 0.95, where U is the approach flow velocity and U_c is the critical value for the inception of sediment motion. Table 1 presents the flow parameters used in the current study.

The critical shear velocity U_c^* for the sediment used in the experiments was determined from a Shields diagram. The critical velocity, U_c, was calculated using the logarithmic average velocity equation for a rough bed (Farooq & Ghumman 2019) as follows:

$$\frac{U_c}{U_c^*} = 5.75 \log\left(\frac{y}{k_e}\right) + 6 \qquad (1)$$

where y is the flow depth and $k_e = 2d_{50}$ is the equivalent roughness height.

Experimental procedures

The cylindrical pier was first fixed in the flume at the center of the measuring section. The measuring section is a 3-m long sand bed with a rectangular cross section. The bottom width is 0.3 m and the sand layer thickness is 0.10 m. Before each experiment, the sand bed was leveled throughout the measuring length of the flume and particularly in the vicinity of the pier using a wooden screed bar and hand-trowel. The initial bed elevations were checked at several locations using a point gage to ensure the flattening of the measuring section. To make sure the sand did not get disturbed during filling the channel with water at the beginning of the experiment, the tail gate was closed and the flume was slowly filled with water by means of a water hose to a depth greater than the calculated depth of the experiment, y. The pump was turned on and the water discharge was increased gradually until reaching the required value. Meanwhile, the tail gate was slowly raised to a predetermined mark set on the side walls of the flume to obtain the required water depth of the experiment. During the experiment, the scour depth around the pier, ds, was measured at different times using a point gage with a 1-mm accuracy. The frequency of the scour measurements varied throughout the experiment period. The

Table 1 | Flow parameters used in the experiments

Discharge, Q (L/s)	Flow depth, y (cm)	Approach flow velocity, U (m/s)	Critical velocity, U_c (m/s)	Critical shear velocity, U_c^* (m/s)	Flow intensity, U/U_c	Critical shields parameter, $\tau*$	Reynolds number, $R_e = U.y/\nu$	Froude number, F_r
5.147	6.45	0.266	0.28	0.018	0.95	0.034	117,157	0.33

measurements of the scour depth were taken every 5 min during the first hour or so of the test and less frequent thereafter because the required frequency of the scour depth measurements decreased with the decreasing of the scour rate.

After around 6 h, the equilibrium scour depth was nearly reached. The equilibrium condition is assumed to be reached when the scour depth did not change by more than 1 mm over a period of 3 h (Kumar *et al.* 1999). At the completion of each test, the tail gate was nearly closed and the pump was switched off to allow the flume to slowly drain without disturbing the scour topography. The deformed sand bed was then allowed to dry and the final scour depths around the pier were measured using both a point gage and a three-dimensional (3-D) laser scanner. These composite measuring techniques provided a high degree of confidence in the bed scour measurements.

Measurement of scour using 3-D laser scanner

The TOPCON GLS-1500 laser scanner was installed and used to capture the final equilibrium scour depth after each run. The digital laser scanner produced a high definition 3-D point cloud model of the deformed bed. Data were further processed to produce colored contour maps of the scour around the pier, as the one shown in Figure 3, where an elevation datum was set at 41 mm to represent the flat bed at the pier location at the beginning of each run.

Categories of experiments

The experiments were classified into two groups, as detailed below.

Piers with slots – no collars

A slot may deflect the downflow away from the bed and reduce its scour potential, thus breaking up the horseshoe vortex when the slot is placed near the bed. However, no one has studied the effect of slot shape on the scour pattern around a pier. Therefore, in this study, various shapes of slots, as shown in Figure 4, were used to investigate their effects on the scouring process. All piers with slots were installed so that the invert of a slot coincides with the surface elevation of the sand bed. The width of the slot (S) is $0.25d_p$.

Piers with collars – no slots

When a collar is used around the pier, the direct impact of the downflow on the bed is eliminated, which not only causes a reduction in the scour depth but the rate of scour is also reduced considerably. Reduction of the scour rate reduces the risk of pier failure when the duration of flood is short. Jahangirzadeh *et al.* (2014) suggested that a ratio of $D/d_p \approx 3$ to 3.5 is the most effective size in scour reduction for a circular collar with diameter (D). In this study, the diameter of the collar is equal to 3 d_p, where d_p is the pier diameter. The collar was made of a 3-mm thickness Perspex glass, and

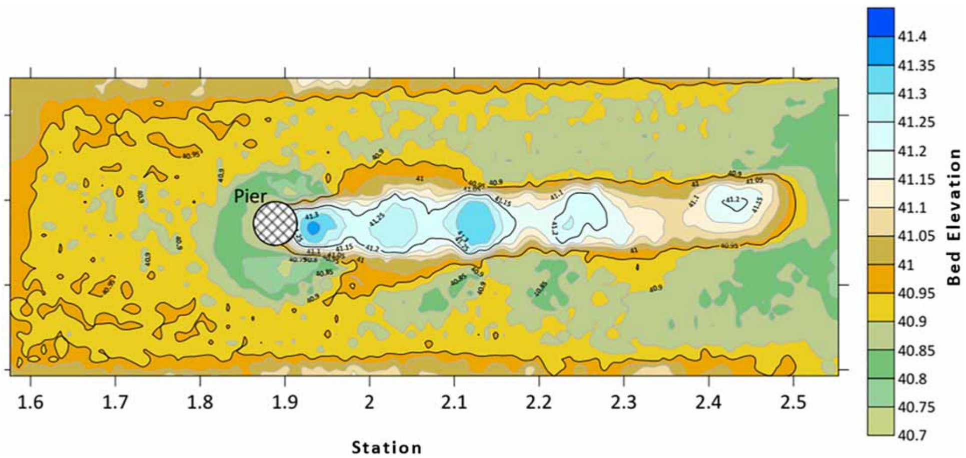

Figure 3 | Contour map for the bed deformation around the parallel slot pier experiment produced from laser scanner data.

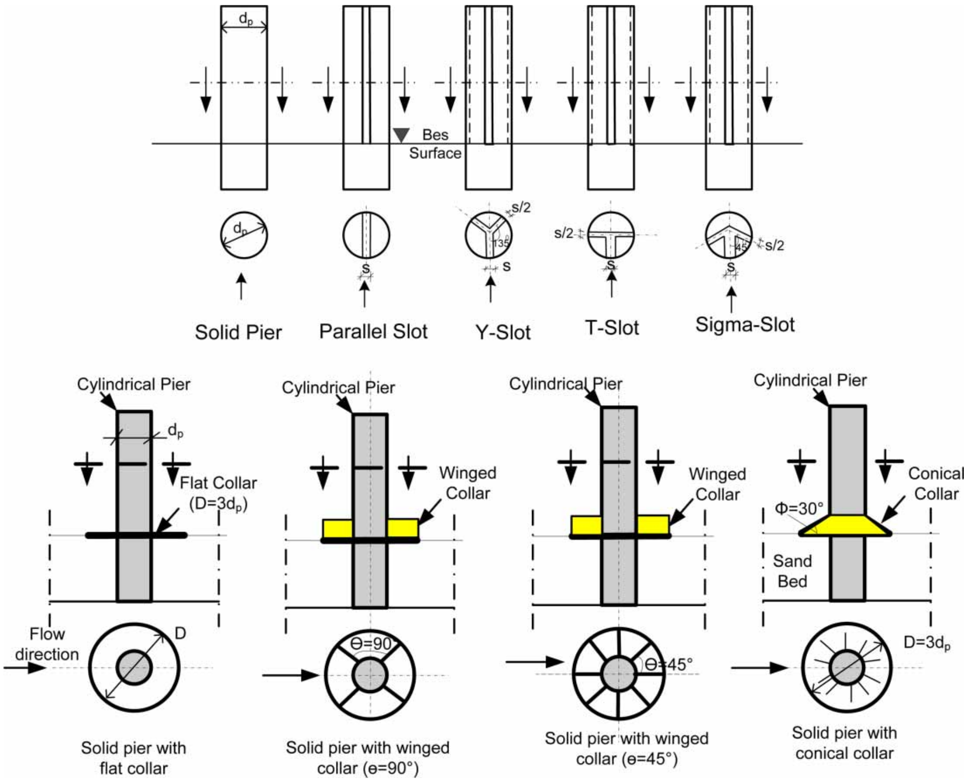

Figure 4 | A schematic of the various types of pier slots and collars used in this study.

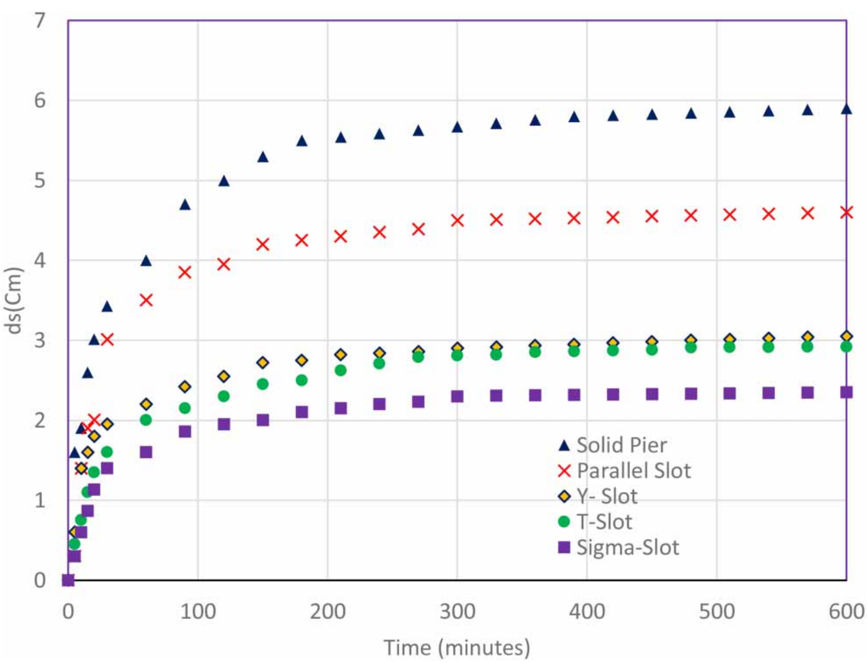

Figure 5 | Time development of scour for various shapes of slots upstream of the pier.

placed on the bed surface in accordance with recommendations of earlier researchers (Kumar *et al.* 1999). Figure 4 shows a schematic of the five collars shapes studied experimentally.

RESULTS AND DISCUSSION

Experiments with slots

Comparing the scour development for different shapes of slots at the front and rear of the pier, it was seen that the parallel slot was nearly ineffective in decreasing scouring at the front of the pier, as shown in Figure 5, although it has a good performance at its rear. The T-slot reduces the scour in front of the pier more than its downstream, and the Y-slot has a considerable effect in reducing scour depth at both the front and rear of the pier. On the other hand, the sigma-slot had the best performance amongst the other tested slots in reducing scouring upstream and downstream of the pier. The parallel and T-slots had the worst performance in reducing scour depth at the front and rear of the pier, respectively.

Experiments with collars

Figure 6 shows the longitudinal profile of the bed level for equilibrium scour state around the pier with different types of collars. The center of the pier was set as the origin, i.e. X = 0. The figure shows that the length of the scour hole downstream of the pier is greater than upstream. The study shows that the collars are more efficient than slots in reducing scour depth at the front and rear of the pier. This is due to the fact that the collars cause the downflow to lose its strength, more than slots, on impingement on the bed. The flat and conical collar prevent scouring completely at the front of the pier. The angled collar with $\alpha = 90°$ was better than the collar with $\alpha = 45°$ in reducing scour depth at the front of the pier, while the collar with $\alpha = 45°$ had a better performance than the one with $\alpha = 90°$ at the rear of the pier. The flat and angled collar with $\alpha = 90°$ have nearly the same effect in reducing scour downstream of the pier, whilst the conical collar is the best one in reducing scour upstream and downstream of the pier.

Table 2 represents both of the equilibrium scour depths at upstream and downstream of the pier, and the reduction percentage of all the models used in this study to control scouring. Table 2 shows that the best model for controlling scouring around a bridge pier is the conical one proposed in this study. Moreover, the flat collar has the same efficiency as the conical one at the front of the pier.

The most effective two models for reducing the scour are compared in Figure 7. The figure shows the performance of the pier with sigma-slot and the one with conical collar at

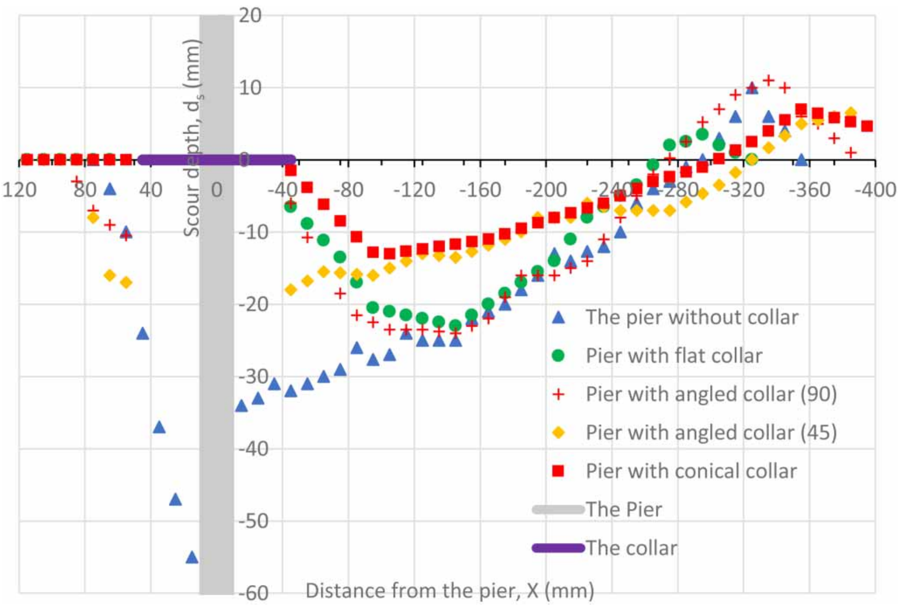

Figure 6 | Equilibrium longitudinal profile of the bed scour at the bridge pier with different shapes of collars.

Table 2 | Comparison of efficiency of different models used for reducing scour around cylindrical pier

		Equilibrium max. scour depth (d_{se}-mm)		Reduction in scour depth, R_p (%)	
Test no.	**Slots and collars**	**US pier**	**DS pier**	**US pier**	**DS pier**
1	Solid pier	59	36	—	—
2	Parallel slot	46	26	22.0	27.8
3	Y-slot	31	25	47.5	30.6
4	T-slot	29	24	50.8	33.3
5	Sigma-slot	24	17	59.3	52.8
6	Flat collar	0	24	100.0	33.3
7	Wing collar 90°	11	24	81.4	33.3
8	Wing collar 45°	17	18	71.2	50.0
9	Conical collar	0	14	100.0	61.1

US, upstream; DS, downstream.

the front and rear of the pier. From the figure it is clear that the conical collar, which was suggested in this study, is the most effective collar shape amongst all examined slots and collars in reducing the scour around the pier.

Figure 8 shows photographs of the experimental work results of the scour pattern around bridge pier with different collars. The photographs clearly present the effect of flat and conical collars in eliminating the scour depth in front of the pier. Moreover, the conical collar showed a good performance in reducing the scour at the back of the pier.

Hydraulic model using HEC-RAS

One of the mostly widely used computer programs for bridge scour analysis is HEC-RAS developed by the US Army Corps of Engineers HEC. The computation of bridge scour depth within HEC-RAS is based on the methods outlined in the Hydraulic Engineering Circular No. 18 (HEC 18) (FHWA 2001). In this study, a hydraulic model of a channel containing a bridge with a single solid pier and sufficient cross sections upstream and downstream of the bridge was developed. The HEC-RAS built-in Colorado State University (CSU) equation was used for the computation of pier scour. The flow distribution option was also selected to get more detailed estimates of depth and velocity within the cross section. The model was calibrated using the experimental results and the same maximum scour depth was obtained for the solid pier. The CSU scour equation does not apply to piers with slots or collars; it has a K_1 correction factor only for pier nose

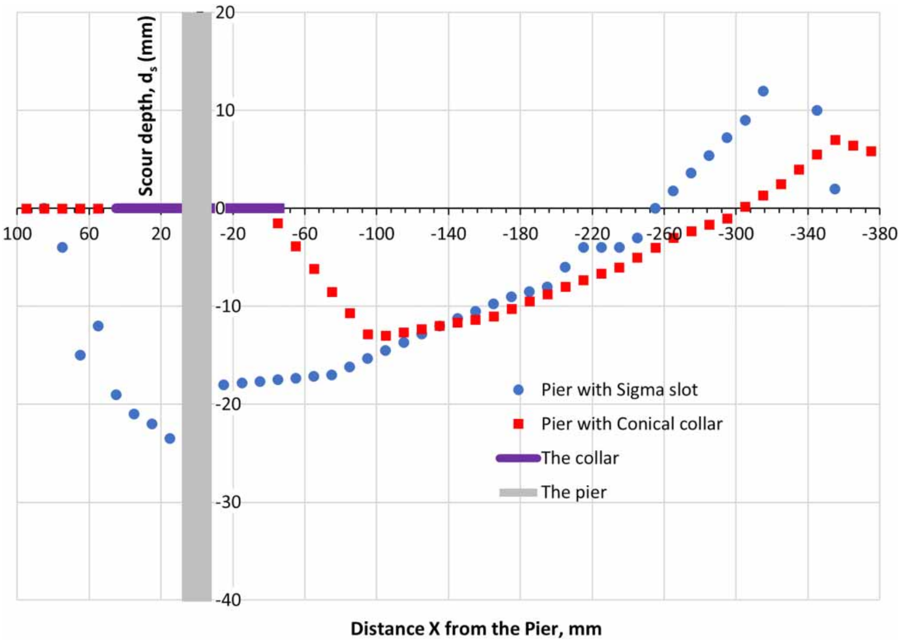

Figure 7 | Comparison between pier with sigma-slot and pier with conical collar in reducing the scour around the pier.

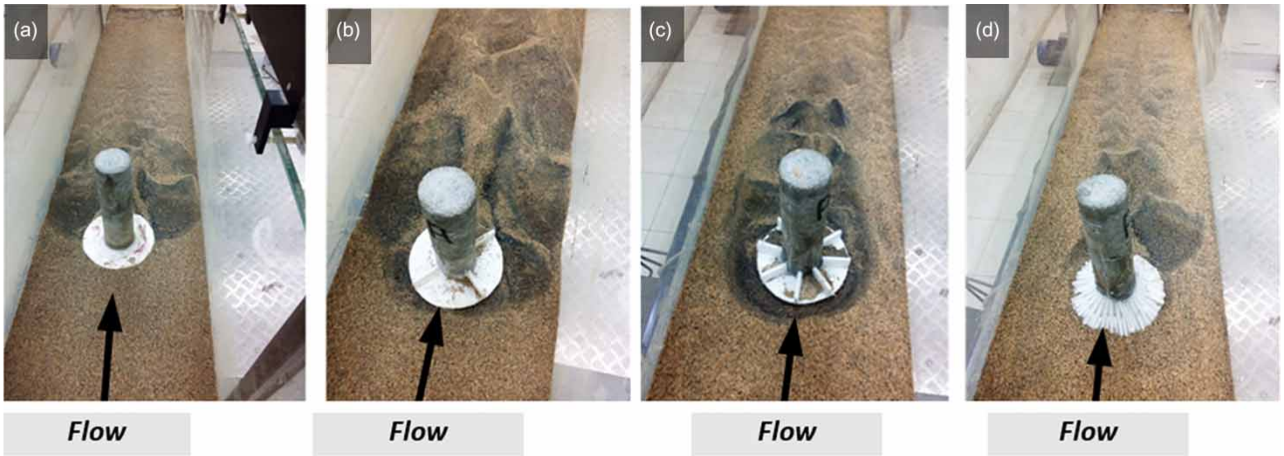

Figure 8 | Photographs of equilibrium scour depths resulting from flow around bridge piers with different types of collars: (a) flat collar; (b) wing collar 90°; (c) wing collar 45°; and (d) conical collar.

shape, as in Equation (2):

$$\frac{y_s}{b} = 2K_1K_2K_3K_4\left[\left(\frac{h}{b}\right)^{0.35} F_r^{0.43}\right] \quad (2)$$

where K_1 = correction for pier shape ($K_1 = 1$ for circular piers), K_2 = correction for attack angle of approach flow ($K_2 = 1$ for direct approach flow), K_3 = correction for bed form ($K_3 = 1.1$ for clear-water scour), K_4 = correction for armoring ($K_4 = 1$ for sand bed material), and F_r is the Froude number. An attempt to get an equivalent K_1 factor for the different piers with slots and collars was made. The results are shown in Table 3.

CONCLUSIONS

In this paper, experimental and hydraulic models were used to investigate the effect of using slots and circular collars with different shapes on reducing the scour around a cylindrical bridge pier. In general, the results revealed that using collars proved to be more effective in reducing scour around bridge piers than using of slots. The main conclusions drawn from this study are as follows:

- Around 85% of the total scour was obtained during the first 30% of the equilibrium time, while the maximum scour rate occurred during the first hour of an experiment. The scour rate was also shown to decrease with increasing the time of an experiment.
- The collars perform better than the slots in terms of controlling and weakening the downflow and reducing the scour depth upstream of the pier.
- The sigma-slot behaved better than the other tested slots in reducing the scour depth around the bridge pier. On the other hand, the conical collar showed the best performance amongst all slots and collars models examined in this study.
- A laser scanner was used to scan and record the sand bed elevations at the end of each experiment. The results obtained for the equilibrium maximum scour depths were in good agreement with the manually measured scour depths.
- A circular thin collar plate skirting around a cylindrical bridge pier at the bed level, which diverts the downflow and shields the streambed from flow direct impact, is considered a very effective means of protection against scour upstream of the pier.
- A hydraulic HEC-RAS model was developed to predict the maximum scour depth around the solid bridge pier

Table 3 | Equivalent K_1 pier shape factor presented in HEC-RAS model

Pier slots/collars	Solid pier	Parallel slot	Y-slot	T-slot	Sigma-slot	Flat collar	Wing collar 90°	Wing collar 45°	Conical collar
Equivalent K_1 pier shape factor	1.0	0.78	0.53	0.49	0.41	0.41	0.41	0.31	0.29

and showed very good agreement with experimental results. Equivalent K_1 pier shape factors have also been established for all examined piers with slots and collars.

- The flat collar and the frustum of the cone collar were the most effective shapes in reducing the scour depth upstream of the pier amongst all tested slots and collars, with $R_p = 100\%$, while the latter was the best one at the downstream side of the pier, with $R_p = 61.1\%$.

Recommendations for future work

It is highly recommended to develop a computational fluid dynamics model to predict the scour pattern around bridge piers with different slots and collars and to use the experimental data obtained in this study to calibrate and verify the computational fluid dynamics model and to perform sensitivity analysis of the scour parameters.

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