Reduction of scour around circular piers using collars

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Abstract
River dynamics and sediment transport play an important role in river bed morphology. Building a bridge pier along the river alters the cross-section of the river and causes the change in flow processes. These changes are mainly responsible for pier scour. In this paper, the usage of collars to reduce scour around circular piers has been investigated. The collars with different diameters and depth positions have been studied using previous data and additional data collected in the present study to assess their effectiveness in reducing scour. Using a wide range of measured data, an empirical equation to compute the maximum scour depth around the circular piers in the presence of collars has been proposed. The proposed equation has been validated and proven to be applicable to a wide range of pier layouts. It has been found that the maximum efficiency can be achieved by fixing the collar at bed level and adopting a collar diameter 1.5–2.5 times of pier diameter.

KEYWORDS
bridge piers, clear-water scour, collars, scouring reduction, uniform sediment

1 INTRODUCTION

Rivers are changeable and unpredictable and can contain hidden dangers. Deposited and eroded sediment processes can be responsible for contributing to the change of flow directions (John et al., 2021). River flooding is becoming more frequent with climate change, causing damage to hydraulics structures and bridge elements (Dhali et al., 2020; Singh et al., 2019). The natural hazards posed by the river systems depend on river flow characteristics and sediment transport in the river system (Pagliara & Kurdistani, 2015; Pandey, Lam, et al., 2019). This capacity is affected by the erosion and deposition of sediment that is finally determined by the stream bed level, the lowest elevation to which a stream can flow. The scour around bridge elements is a major damage of bridge which appears during the flood hazard. A single bridge failure can have significant economic and political consequences, and accurate prediction of scour depth at bridge elements is very essential to estimate foundation level for a cost-effective design. Lin et al. (2014) studied 36 damaged bridges and stated that the possible damages and scour characteristics mainly depends on climatic and geological changes, which influences the erosion and deposition processes in the natural streams. Wang et al. (2017) reported that more than 500 bridges collapsed in the United States between 1989 and 2000. Published data showed that bridge element scour was responsible for 50% of the bridge failures. In 1993, around 20 bridges were failed due to bridge element scour resulting from flowing water and waves that caused damage of approximately $20 million in coastal regions.
(Jain et al., 2021; Singh et al., 2020). Pandey, Valyarakis, et al. (2021) reported that a bridge near Belgaon (Orissa), India, was washed by unpredictable scour around the pier. Recently, Hussain and Jan (2016) reported that the Chadoora bridge in Budgam district, India was collapsed due to excess scour around the piers. Around 60% of the pier scour hazards are caused by scour (Lagasse, 2007).

As proven, the local scour around the bridge pier is caused by the horseshoe vortices at the upstream as well as the wake vortices downstream caused by pier obstruction and separation to flow (Azamathulla, 2012; Chavan & Kumar, 2018; Liang et al., 2012; Oliveto, 2020; Pandey, Jamei, et al., 2021; Pandey, Valyarakis, et al., 2021; Pu & Lim, 2014; Qi et al., 2016). According to evidence provided by several studies (i.e., Radice et al., 2009; Liang et al., 2012; Deshpande & Kumar, 2016; Pandey et al., 2018; Panici et al., 2018; Choufu et al., 2019), the horseshoe vortex system is responsible for intensive scouring around the pier. It is a transport mechanism of the sediment suspended by the horseshoe vortex and downstream (Melville, 1997; Melville and Coleman, 2000; Pandey et al., 2020, 2020). The scour hole evolution around a structure with depth and time has also been studied by Li and Qi (2015), in which its enlargement process can affect the stability of the pier, abutment, or caisson foundation (Kumar et al. 1999). Such scour hole increases with the passage of flow—however, the rate of scouring decreases with time (Melville and Coleman, 2000).

In recent years, scour hazards throughout the world have attracted extensive attention (Heidarpour et al., 2010; Azamathulla et al., 2014). There are mainly two approaches for reducing the local scour around the pier, that is, (i) bed-armorung method (Lauchlan and Melville, 2001; Jueyi et al., 2010), and (ii) flow-altering method (Chiew, 1992; Kumar et al., 1999; Moncada-M et al., 2009; Heidarpour et al., 2010). In the first method, the scouring process is reduced using coarser material around the pier or by providing suitable riprap; whereas in the latter, the reduction in scour is achieved using different pier scour protection devices, that is, collars, slots, fins, and bed sills. Principally, these approaches reduce the scour rate by decreasing the impact of the horseshoe vortex (Moncada-M et al., 2009).

2 | LITERATURE REVIEW

Several studies have been carried out to calculate scour depths around the piers. Maza and Sánchez (1966) suggested an approach based on the sediment entrainment theory to protect the bridge piers against the scour problem. For protecting a pier against the local scour, it was suggested by Maza and Sánchez (1966) that the streambed material should be changed with a coarser material, which can be more resistant against the erosion for the same flow conditions. Chiew (1992) reviewed the pier scour protection approaches and suggested that slot and collar are useful methods for protecting the bridge piers against the scour problem. Kumar et al. (1999) conducted experiments using slots and collars and found that the slotting approach is ineffective when spread into the bed. However, they used only one slot width for this conclusion and mentioned that it should be further studied with different slot widths.

The scour hole around bridge elements typically occurs due to the primary vortex, which is caused by hydrodynamic lift and drag forces on sediments and carry them downstream of the structure (Choufu et al., 2019; Ghaderi and Abbasi, 2019; Hoffmans and Verhiej, 1997; Melville, 1997; Melville and Coleman, 2000; Pandey, Chen, et al., 2019; Pandey, Lam, et al., 2019). The scour mechanism, estimation, and prevention techniques at bridge elements have been widely studied by (Chiew, 1992; Choufu et al., 2019; Garg et al., 2005; Gaudio et al., 2012; Hoffmans and Verhiej, 1997; Kumar et al., 1999; Kothyari et al., 2002, 2007; Melville, 1997; Melville and Coleman, 2000; Pandey et al., 2018; Panici et al., 2018; Sheppard et al. 2014). The scour depth is high in front of the pier, with the main scour hole size develops along the pier (Kothyari & Rangaraju, 2001; Pandey et al., 2018). Melville and Coleman (2000) stated that the sediment transport near the pier generally occurs layer-by-layer and depends on flow properties and sediment characteristics.

When a collar fixes at a pier near the bed, it separates the maximum downstream discharge and reduces the impact of the developed vortex by restricting its evolution (Kumar et al., 1999). Chiew (1992) and Kumar et al. (1999) have found that scouring can be minimized by using slots in a pier; however, this method is highly location-sensitive based on where it is deployed. Further, a study from Moncada-M et al. (2009) confirmed that different maximum scour levels can be achieved with varying slot locations from free surface to pier foundation. Practically, slot in pier is usually obstructed by floating debris and could be inefficient for field usages. Moreover, a large collar diameter may be contracted the flow around the pier, which affects the stream banks. Figure 1 shows the sketch diagram of scour around the circular pier in the presence of a collar.

The collar is more efficient than a slot for reducing local scour as suggested by Kumar et al. (1999). In the present study, the laboratory measurements have been conducted by using various collar arrangements along the pier. The experiments have been carried out with collars of different diameters and their locations to study the influence of collars on maximum scour depth.
Gaudio et al. (2012) investigated five different pier scour reduction methods that is, a collar together with sacrificial piles; a bed sill together with a collar; a slot together with sacrificial piles; a collar together with a slot; and a bed sill together with submerged vanes. They found that a pier collar with a slot reduced scour most efficiently. Zarrati et al. (2004) further conducted a study on collar efficiency in rectangular piers. They conducted experiments for two angles of attacks that is, $5^\circ$ and $10^\circ$, and found that a wide collar near the bed is also effective for the case of a rectangular pier. They suggested the performance of the collar decreases with an increase in the angle of attacks. Garg et al. (2005) studied the influence of three different collars with a diameter of $1.5b$, $b$ is the pier diameter. For the same flow conditions, this approach reduced the maximum scour depth by approximately 80% as compared to a non-protected pier. Moncada-M et al. (2009) also investigated the effect of collar and slot on maximum equilibrium scour depth. They used one pier of 7.3 cm diameter and two different collars of 14.6 and 21.9 cm diameters. A 1.8 cm wide slot was also used together with collars. They had concluded that the collar shows the best scour reduction result when used at the bed level. For the slot case; they observed the most favorable results when the slot was placed near the bed. They also found that the maximum scour depth decreases with the increase of collar diameter and slot width.

Summarized from the aforementioned literature, the collar approach gives a reasonable reduction to pier scouring. However, in the discussed literature, there are limited collar arrangements and conditions tested thus far. In this study, a wide range of arrangements to collar-induced scouring at bridge pier have been used to quantify the efficiency of the collar approach to bridge pier scouring.

### 3 LOCAL SCOUR REDUCTION BY USING A COLLAR

A review of the literature reveals that the maximum scour depth ($d_{se}$) around a non-protected pier in uniform non-cohesive sediment depends on $F_r$, $F_{d50}$, $d_{50}$, $y$, $b$, $U$, $U_c$, and $B$; where, Froude number $F_r = U/\sqrt{gy}$; densimetric Froude number $F_{d50} = U/\sqrt{(S-1)gd_{50}}$, $g$ is gravitational acceleration; $y$ is the approach depth of flow; $S$ is the specific gravity of sediment; $d_{50}$ is the median diameter of bed particles; $b$ is the pier diameter; $U$ is the time-average flow velocity; $U_c$ is the critical velocity of bed particles; and $B$ is the width of channel/stream (Kumar et al., 1999; Kothyari and Rangaraju, 2001; Shepard et al., 2004, 2014; Pandey et al. 2018).

If $d_{sec}$ is the maximum scour depth in the presence of collar, and functional form can be written as (Kumar et al., 1999)

$$d_{sec} = f(b_c, b, y, h).$$

(1)

Here, $b_c$ is the collar diameter, $h$ is the depth from free surface, $h = y - z$, and $z$ is the collar elevation for stream-bed.

In dimensionless form, Equation (1) can be obtained as

$$\frac{d_{se} - d_{sec}}{d_{se}} = f\left(\frac{b_c}{b}, \frac{h}{y}\right).$$

(2)
Kumar et al. (1999) proposed the relationship for computing the scour depth

\[
\frac{d_{se} - d_{sec}}{d_{se}} = 0.057 \left( \frac{b_c}{b} \right)^{1.612} \left( \frac{h}{y} \right)^{0.837}.
\]

This relationship is applicable for \( h \leq y \) or when the collar is fixed at bed-level or above the bed-level. Hence, this equation needs to be revised for \( h > y \) for more extensive applicability.

4 | DATA COLLECTION FROM PREVIOUS STUDIES

To evaluate the applicability and accuracy of Equation (3), 98 laboratory data sets of maximum scour depth around the pier with a collar have been collected from past studies (i.e., Chabert and Engeldinger, 1956; Chiew, 1992; Ettema, 1980; Kumar, 1996; Kumar et al., 1999; Moncada-M et al., 2009; Schneible, 1951). Additionally, 48 more data sets have been collected in the present study through experimentation for maximum scour around the pier with collar. Applicability and accuracy of Equation (3) have been validated using present and previous datasets (146 data), and Equation (3) is revised for broader applicability. Table 1 summarizes the ranges of data.

5 | ADDITIONAL EXPERIMENTS AND EXPERIMENTAL SETUP

Additional experiments were carried out in a rectangular flume of 20.0 m long and 1.0 m wide. The test section of the flume was 8.0 m long, 1.0 m wide, and 0.38 m deep, located at 7.0 m downstream from the flume entrance.

Test section of the flume was entirely filled with the two different sizes of uniform sands having 0.27 and 0.4 mm median diameter (\( d_{50} \)) and geometric standard deviation (\( \sigma = \sqrt{d_{84}/d_{16}} \)) of 1.23 and 1.2, respectively. \( d_{84} \) is the particle size at 84% finer and \( d_{16} \) is the particle size at 16% finer. For preparing sand-bed, a 2-D bed profiler was used to level the sand up-to-the flume bed-level.

Two cast-iron hollow pipes were used as circular pier models with 6.6 and 8.4 cm diameters (\( b \)). The discharge of the flume was regulated by an ultrasonic-flow meter fitted in the supply pipe. A point gauge was employed for measuring the maximum scour depth at the equilibrium scour condition. The approach velocity (\( U \)) and velocity components in \( X \), \( Y \), and \( Z \) directions (i.e., \( u \), \( v \), and \( w \)) were measured with an ADV at 150 Hz frequency from \( 0^\circ \) to 180° planes, as shown in Figure 2b. All experiments
were conducted for 24 h or when the equilibrium scour condition was reached.

Three different circular collars with diameters \( b_c \) of 1.5\( b \), 2.0\( b \), 2.3\( b \) were used. Under the non-contraction effect, Melville and Coleman (2000) stated that the maximum size of the effective pier diameter must be taken under 20% of the channel width. For neglecting the effect of contraction, the maximum size of the collar, that is, 19.3% of the channel width, was used. The collar was fixed at four different locations, that is, (i) at bed-level, (ii) \( y/3 \) above the bed-level, (iii) \( y/2 \) above the bed-level, (iv) \( 3y/4 \) above the bed level. Figure 2a shows a line sketch of the experimental setup.

The pier was placed normal to the flume bed at the center of the test section for each test. After the test section, the flume has an extra length of 5 m long. Hence, on the downstream side of the pier, the flume has a sufficient length that is, approximately 9 m long, which ensures no downstream boundary effects on the pier scour. The test section was perfectly leveled concerning the flume bed and covered with a transparent Perspex sheet. Once the fixed flow was established, the transparent sheet was removed delicately so that almost no scour was initiated.

All tests were conducted under clear-water conditions \((U/U_c<1)\). Here, \( U_c \) is the critical shear velocity of sand particles and computed using the following equation of Lauchlan and Melville (2001), given by equation below

\[
U/U_c = 5.75\log\left(\frac{y}{k_s}\right) + 6.0.
\]  

In Equation (4), \( U_c \) is critical shear velocity and calculated by shield’s approach, and \( k_s \) is the equivalent roughness height equal to \( 2d_{50} \) (refer to Pu et al., 2018).

This study conducted experiments for two cases; Case (I): experiments without any appurtenances around the pier, and the maximum equilibrium scour depth \((d_{sec})\) was taken; and Case (II): experiments in the presence of a circular collar, and the maximum equilibrium scour depth \((d_{sec})\) was analyzed with respect to the \( d_{sec} \) from Case (I). Tables 2 and 3 summarize the flow properties and scour depths for all the test cases.

### 6 COMPARATIVE ANALYSIS USING COLLECTED DATA

A quantitative analysis has been performed using the difference between experimental and computed values of \( d_{sec} \) from Equation (3). The discrepancy ratio, \( D_R \), as given by White et al. (1973),

\[
D_R = \log \frac{d_{sec} \text{(computed)}}{d_{sec} \text{(experimental)}}
\]  

For \( D_R = 0 \), the computed values of \( d_{sec} \) are identical to the experimental values. For negative/positive values of \( D_R \), the computed values of \( d_{sec} \) are larger/smaller than the experimental finding. Accuracy of Equation (3) is defined as the data frequency for which \( D_R \) is within an appropriate range for all datasets (White et al., 1973). Calculated values of \( D_R \) for all the data are illustrated in Figure 3a. The data frequency within the \( D_R = \pm 0.25 \) is 79, \( D_R = \pm 0.50 \) is 106, \( D_R = \pm 1.0 \) is 133, and \( D_R = \pm 2.0 \) is 146, as can be observed in Figure 3a. More than 70% of datasets lie within \( D_R = \pm 0.50 \). For further analysis, \( D_R \) is plotted against the two main influencing parameters, that is, \( b_c/b \) and \( h/y \). Variation of \( D_R \) with \( b_c/b \) and \( h/y \) is illustrated in Figure 3b,c, which depict that Equation (3) underestimates \( D_R \) for \( 1.5b \leq b_c \leq 2.5b \) and \( 0.75 < h/y < 1.25 \) and overestimates for \( 0 < h/y < 0.75 \) and \( 1.25 < h/y < 3.0 \). Datasets are consistently spreading around \( D_R \approx 0 \) for the specific combination of \( b_c/b \) and \( h/y \), that is, \( 1.5b \leq b_c \leq 2.5b \) and \( 0.75 < h/y < 1.25 \). Hence, it can be concluded that Equation (3) shows good outcomes for a specific range, that is, collar location near the bed and with collar size \( 1.5b \leq b_c \leq 2.5b \).

The accuracy of Equation (3) has also been checked using the statistical parameters. If \( d_{sec} \) represents the experimental value of maximum scour depth and \( d_{sec}' \) is the respective computed value. These statistical indices are defined as (Pandey et al., 2020, 2021).

\[
CC = \frac{n\Sigma d_{sec}' - \Sigma d_{sec} \Sigma d_{sec}'}{\sqrt{n\Sigma d_{sec}'^2 - (\Sigma d_{sec})^2} \sqrt{n\Sigma d_{sec}^2 - (\Sigma d_{sec}')^2}}, \tag{6a}
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (d_{sec,i} - d_{sec,i}')^2}{n}}, \tag{6b}
\]

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |d_{sec,i} - d_{sec,i}'|, \tag{6c}
\]

\[
MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{d_{sec,i} - d_{sec,i}'}{d_{sec,i}} \right|, \tag{6d}
\]

\[
MSE = \frac{1}{n} \sum_{i=1}^{n} (d_{sec,i} - d_{sec,i}')^2. \tag{6e}
\]

In Equations (6a)–(6e), total number of datasets \((n) = 146\). Table 3 illustrates the values of all
statistical indices for tests with different collar locations and different collar diameters. In the equations, statistical indices $CC$ is coefficient of correlation, $RMSE$ is the root mean square error, $MAE$ is mean absolute error, $MAPE$ is mean absolute percentage error, and $MSE$ is mean square error. The values of $CC$ for collar location at the bed and collar diameter $1.5b \leq b_c \leq 2.5b$ are maximum among the other cases and indices. The good agreement of Equation (3) is due to the limited data range, that is, $1.5b \leq b_c \leq 2.5b$ and collar at bed or near the bed. For collar location below the bed-level, Equation (3) gives unsatisfactory, as shown in Tables 4 and 5. Kumar et al. (1999) had used datasets of $h/y \leq 1$ for proposing the equation. This analysis indicates that further revision is required in Equation (3) for its wide applicability, giving better results for $h/y > 1$.

TABLE 2 Hydraulic properties of reference tests (without collar)

| Ex. run | $b$ (m) | $d_{50}$ (m) | $U$ (mm) | $U/U_c$ | $d_{se}$ (m) |
|---------|---------|-------------|----------|--------|-------------|
| RF1     | 0.066   | 0.27        | 0.22     | 0.88   | 0.123       |
| RF2     | 0.066   | 0.27        | 0.19     | 0.76   | 0.112       |
| RF3     | 0.066   | 0.27        | 0.15     | 0.64   | 0.103       |
| RF4     | 0.084   | 0.27        | 0.22     | 0.88   | 0.14        |
| RF5     | 0.084   | 0.27        | 0.19     | 0.76   | 0.135       |
| RF6     | 0.084   | 0.27        | 0.15     | 0.64   | 0.126       |
| RF7     | 0.066   | 0.40        | 0.28     | 0.28   | 0.092       |
| RF8     | 0.066   | 0.40        | 0.24     | 0.24   | 0.071       |
| RF9     | 0.066   | 0.40        | 0.195    | 0.195  | 0.109       |
| RF10    | 0.084   | 0.40        | 0.22     | 0.88   | 0.098       |
| RF11    | 0.084   | 0.40        | 0.19     | 0.76   | 0.087       |
| RF12    | 0.084   | 0.40        | 0.15     | 0.64   | 0.109       |
| Ex. run | $b$ (m) | $b_c$ (m) | $z$ (m) | $d_{60}$ (m) | $U$ (mm) | $U/U_c$ | $d_{ave}$ (m) |
|---------|---------|-----------|---------|-------------|----------|---------|------------|
| R1      | 0.066   | 0.152     | 0       | 0.27        | 0.22     | 0.88    | 0.091      |
| R2      | 0.066   | 0.132     | 0       | 0.27        | 0.19     | 0.76    | 0.086      |
| R3      | 0.066   | 0.099     | 0.03    | 0.27        | 0.15     | 0.64    | 0.087      |
| R4      | 0.066   | 0.152     | 0.03    | 0.27        | 0.22     | 0.88    | 0.095      |
| R5      | 0.066   | 0.132     | 0.03    | 0.27        | 0.19     | 0.76    | 0.089      |
| R6      | 0.066   | 0.099     | 0.06    | 0.27        | 0.15     | 0.64    | 0.089      |
| R7      | 0.066   | 0.152     | 0.06    | 0.27        | 0.22     | 0.88    | 0.102      |
| R8      | 0.066   | 0.132     | 0.06    | 0.27        | 0.19     | 0.76    | 0.097      |
| R9      | 0.066   | 0.099     | 0.09    | 0.27        | 0.15     | 0.64    | 0.089      |
| R10     | 0.066   | 0.152     | 0.09    | 0.27        | 0.22     | 0.88    | 0.107      |
| R11     | 0.066   | 0.132     | 0.09    | 0.27        | 0.19     | 0.76    | 0.101      |
| R12     | 0.066   | 0.099     | 0       | 0.27        | 0.15     | 0.64    | 0.094      |
| R13     | 0.084   | 0.193     | 0       | 0.27        | 0.22     | 0.88    | 0.103      |
| R14     | 0.084   | 0.168     | 0       | 0.27        | 0.19     | 0.76    | 0.107      |
| R15     | 0.084   | 0.126     | 0.03    | 0.27        | 0.15     | 0.64    | 0.105      |
| R16     | 0.084   | 0.193     | 0.03    | 0.27        | 0.22     | 0.88    | 0.109      |
| R17     | 0.084   | 0.168     | 0.03    | 0.27        | 0.19     | 0.76    | 0.112      |
| R18     | 0.084   | 0.126     | 0.06    | 0.27        | 0.15     | 0.64    | 0.109      |
| R19     | 0.084   | 0.193     | 0.06    | 0.27        | 0.22     | 0.88    | 0.119      |
| R20     | 0.084   | 0.168     | 0.06    | 0.27        | 0.19     | 0.76    | 0.114      |
| R21     | 0.084   | 0.126     | 0.09    | 0.27        | 0.15     | 0.64    | 0.111      |
| R22     | 0.084   | 0.193     | 0.09    | 0.27        | 0.22     | 0.88    | 0.126      |
| R23     | 0.084   | 0.168     | 0.09    | 0.27        | 0.19     | 0.76    | 0.123      |
| R24     | 0.084   | 0.126     | 0       | 0.27        | 0.15     | 0.64    | 0.115      |
| R25     | 0.066   | 0.152     | 0       | 0.4         | 0.28     | 0.87    | 0.076      |
| R26     | 0.066   | 0.132     | 0       | 0.4         | 0.24     | 0.75    | 0.069      |
| R27     | 0.066   | 0.099     | 0.03    | 0.4         | 0.195    | 0.62    | 0.056      |
| R28     | 0.066   | 0.152     | 0.03    | 0.4         | 0.28     | 0.87    | 0.081      |
| R29     | 0.066   | 0.132     | 0.03    | 0.4         | 0.24     | 0.75    | 0.073      |
| R30     | 0.066   | 0.099     | 0.06    | 0.4         | 0.195    | 0.62    | 0.060      |
| R31     | 0.066   | 0.152     | 0.06    | 0.4         | 0.28     | 0.87    | 0.083      |
| R32     | 0.066   | 0.132     | 0.06    | 0.4         | 0.24     | 0.75    | 0.076      |
| R33     | 0.066   | 0.099     | 0.09    | 0.4         | 0.195    | 0.62    | 0.062      |
| R34     | 0.066   | 0.152     | 0.09    | 0.4         | 0.28     | 0.87    | 0.091      |
| R35     | 0.066   | 0.132     | 0.09    | 0.4         | 0.24     | 0.75    | 0.081      |
| R36     | 0.066   | 0.099     | 0       | 0.4         | 0.195    | 0.62    | 0.064      |
| R37     | 0.084   | 0.193     | 0       | 0.4         | 0.28     | 0.87    | 0.078      |
| R38     | 0.084   | 0.168     | 0       | 0.4         | 0.24     | 0.75    | 0.074      |
| R39     | 0.084   | 0.126     | 0.03    | 0.4         | 0.195    | 0.62    | 0.073      |
| R40     | 0.084   | 0.193     | 0.03    | 0.4         | 0.28     | 0.87    | 0.084      |
| R41     | 0.084   | 0.168     | 0.03    | 0.4         | 0.24     | 0.75    | 0.080      |
| R42     | 0.084   | 0.126     | 0.06    | 0.4         | 0.195    | 0.62    | 0.072      |
| R43     | 0.084   | 0.193     | 0.06    | 0.4         | 0.28     | 0.87    | 0.088      |

(Continues)
Influence of Collar Size and Its Location on Maximum Scour Depth

To further inspect the collar diameters and location impact to scour, experiments for $1.5b \leq b_c \leq 2.3b$ and its location at the bed and above the bed were conducted in this study. Besides, the data collected from previous studies have also been employed for analysis. Scour profiles along the centerline of the channel and pier for different locations of the collar are shown in Figure 4. It can be observed from Figure 4 that the collar reduces the maximum scour depth and the volume of scour hole. Furthermore, it is also apparent that the collar gives the best results when placed at bed level or near the bed.

From the practical considerations also, it is easy and economical to provide a collar at the streambed. It was stated by Kumar et al. (1999) that in the case of $b_c = 4b$, along the centerline of the channel and pier for different locations of the collar are shown in Figure 4. It can be observed from Figure 4 that the collar reduces the maximum scour depth and the volume of scour hole. Furthermore, it is also apparent that the collar gives the best results when placed at bed level or near the bed.

From the practical considerations also, it is easy and economical to provide a collar at the streambed. It was stated by Kumar et al. (1999) that in the case of $b_c = 4b$,
Table 4: Statistical performances for different collar locations using Equation (3)

| Statistical indices | Collar at bed level | Collar above the bed level | Collar below the bed level |
|---------------------|---------------------|----------------------------|---------------------------|
| CC                  | 0.801               | 0.586                      | 0.542                     |
| Rank                | 1                   | 2                          | 3                         |
| MAE                 | 0.013               | 0.027                      | 0.108                     |
| Rank                | 1                   | 2                          | 3                         |
| MSE                 | 0.0004              | 0.0012                     | 0.0016                    |
| Rank                | 1                   | 2                          | 3                         |
| MRSE                | 0.019               | 0.035                      | 0.041                     |
| Rank                | 1                   | 2                          | 3                         |
| MAPE                | 0.421               | 2.272                      | 0.598                     |
| Rank                | 1                   | 3                          | 2                         |
| Average rank        | 1                   | 2.2 ≈ 2                    | 2.8 ≈ 3                   |

no significant scour at the upstream side of the pier. However, scour can be observed downstream and left and right sides of the pier. In that case, they found that the maximum scour occurred at the downstream side of the pier.

Figure 5a–e illustrates the comparison of reduction percentage for scour depth concerning the scour depth without a collar. To check the efficiency ($\epsilon$) of the collar, the following expression is used:

$$\epsilon(\%) = \left( \frac{d_{sc} - d_{sec}}{d_{sc}} \right) \times 100.$$  (7)

Figure 5a–e demonstrates the percentage reduction in maximum scour depth versus the collar’s location for its different collar diameters. For range of collar diameter $0.2b \leq b_{c} < 1.5b$, $\epsilon = 3\%–20\%$. When the collar is fixed below the bed at $z = -0.2$ m, the minimum reduction in scour is $\epsilon = 3\%–5\%$. For the collar near the bed (for $z = -0.03$ to $+0.03$ m), the scour reduction is $\epsilon = 10\%–20\%$. However, at bed-level, the maximum reduction in scour is $\epsilon = 10\%–25\%$, as in Figure 5a.

For collar diameter range $1.5b < b_{c} < 2.0b$, $\epsilon = 20\%–68\%$. At further location above the bed at $z = 0.1$ m, the minimum reduction in scour is $\epsilon = 20\%–30\%$. For the collar just above the bed, that is, $z = 0.01–0.03$ m, the reduction in scour is $\epsilon = 45\%–55\%$. At bed-level, the maximum scour reduction is $\epsilon = 60\%–68\%$, as presented in Figure 5b.

For collar diameter range $2.5b < b_{c} \leq 6.0b$, $\epsilon = 10\%–75\%$. When the collar is fixed at 0.05–0.15 m above the bed level, the minimum scour reduction can be observed as $\epsilon = 10\%–25\%$. Near, the bed, the reduction in scour is $\epsilon = 30\%–45\%$. And at the bed level, the maximum scour reduction is $\epsilon = 50\%–75\%$, as shown in Figure 5d,e.

The influence of the collar is great when it is provided at bed level. Besides, significant $\epsilon$ has also been found when the collar is near the bed ($-0.03$ to $+0.03$ m). Figure 5a–e clearly illustrates that the efficiency of the tested collars is low when it fixed at a distance relatively far from the bed. It is also worth noting that for the small collar diameter, that is, $0.2b \leq b_{c} < 1.5b$, the lowest reduction in scouring can be observed (results of Figure 5a).

From Figure 5a–e, it can also be concluded that the scour reduction increases with a decrease in collar elevation. Figure 5 also indicates that the impact of the collar as a protection device reduces. The collar’s effect is more dominant as it becomes near the bed or at the bed.

In the present study, it has been found that a larger diameter collar ($b_{c} \geq 2.5$) reduces scour depth sufficiently when it is set at bed level, as described in Figure 5d,e. Results of the present study indicate that the best position for collar deployment is at bed-level with collar diameter $b_{c} = 1.5b–2.5b$.

The three-dimensional velocity data were measured using acoustic doppler velocimetry (ADV), and these velocity vectors have been used to determine the primary vortex size, which is mainly responsible for scouring (Kumar et al., 1999; Kothyari and Rangaraju, 2001; Pandey et al., 2018). Figure 6a,b further illustrates the comprehensive plot of the flow pattern around the pier with and without collar at bed level. These plots are drawn using measured flow velocity fields in the present experimental work. The flow vortices surrounded the pier inside the equilibrium scour-hole area at the pier’s upstream, which was defined as the primary vortex. However, the downward vortex was noted upstream near the pier. To the upstream of the pier, these vectors have shown their rotational path in the clockwise direction, while anti-clock rotation at the downstream. As presented in Figure 6a,b, the area of the primary vortex has
been lesser for the case with a collar than without a collar, which larger size of primary vortex is responsible for the larger scour depth and volume of scour hole.

### TABLE 5 Statistical performances for different diameters using equation (3)

| Statistical indices | $1.5b \leq b_c \leq 2.5b$ | $2.5b < b_c \leq 6.0b$ | $0.2b \leq b_c < 1.5b$ |
|---------------------|--------------------------|------------------------|------------------------|
| CC                  | 0.766                    | 0.416                  | 0.216                  |
| Rank                | 1                        | 2                      | 3                      |
| MAE                 | 0.026                    | 0.031                  | 0.037                  |
| Rank                | 1                        | 2                      | 3                      |
| MSE                 | 0.0011                   | 0.0017                 | 0.0019                 |
| Rank                | 1                        | 2                      | 3                      |
| MAPE                | 0.310                    | 3.032                  | 3.724                  |
| Rank                | 1                        | 2                      | 3                      |
| Average rank        | 1                        | 2                      | 3                      |

#### FIGURE 4 Longitudinal scour-hole profile at equilibrium condition

these rationales, a new equation using an extensive range of datasets has been derived by non-linear regression. Equation (8) has been proposed to compute the maximum scour depth around the pier in the presence of a collar.

$$\frac{d_{se} - d_{sec}}{d_{se}} = 0.20\left(\frac{h_c}{h}\right)^{0.17}\left(\frac{h}{y}\right)^{0.48}$$  \hspace{1cm} (8)

The scour depth computed by the proposed relationship at Equation (8) shows good agreements between observed and computed values, as can be seen in Figures 7b and 8. Figures 7 and 8 illustrate that most of the datasets are near to be the line of perfection, and around 75% of datasets have been found within ±25% errors when computed with Equation (8). For Equation (8), about 90% of datasets

| $d_{se}$ (cm) |
|---------------|
| 0             |
| 5             |
| 10            |

| $X$ (cm) |
|---------|
| -60     |
| -40     |
| -20     |
| 0       |
| 20      |
| 40      |
| 60      |
| 80      |
| 100     |
| 120     |

8 | **A NEW RELATIONSHIP FOR MAXIMUM SCOUR DEPTH**

The maximum depth of scour around pier in the presence of collar is a function of collar diameter and location and parameters affecting scour depth without a collar. Consequently, Equation (3) only showed good agreements for $1.5b \leq b_c \leq 2.5b$ and when the collar is fixed at and above the bed (refer to Figure 3 and Table 3). Most of the data points have shown more error, and only 35% of datasets have been found within ±25% errors when computed with Equation (3) as observed in Figures 7a and 8. For
FIGURE 5  (a)–(e) Reduction in maximum scour depth versus collar location
are located within ±50% errors, while comparatively only 50% of datasets are found within ±50% errors for Equation (3). Thus, it is concluded that the proposed equation gives more reasonable correspondence with observed data than Equation (3). The present equation also gives reasonable agreement of datasets below the bed-level, which has not been achieved by Equation (3).

Statistically, it can be found that the values of $CC$ for Equation (8) were at the greatest when the collar was at bed-level with collar diameter $1.5b \leq b_c \leq 2.5b$ (refer to Tables 6 and 7). These statistical results also indicate that Equation (8) gives good results for all the cases as compared to Equation (3). In other words, it can be concluded that Equation (8) has wide applicability.

9 | SUGGESTIONS FOR FUTURE WORK

Significant work on pier scour has been done in the past. Still, many things need to be done in the future. Computational power advancements, limitations of physical models, and their costs have pushed researchers to utilize numerical solutions and
computational fluid dynamics (CFD) modeling for their complex problems (Pourshahbaz et al., 2020; Pu et al., 2021). One of the primary steps for validating a numerical or CFD model is to compare numerical results with laboratory experiments and/or field data to understand if the model has been built correctly (Abbasi et al., 2021; Ghaderi et al., 2020; Pourshahbaz et al., 2017). This study provided 146 data sets of laboratory experiment results, including 98 sets of previous results and 48 new ones, which can be a precious source for numerical modeling. Future research can be done numerically as laboratory experiments have limitations, are time-consuming, and cost more than numerical simulations.

**FIGURE 7** Comparison of computed and observed scour depths; (a) using Kumar et al. (1999), and (b) using the present equation

**FIGURE 8** The variation between percentage error and data frequency

**TABLE 6** Statistical performances for different collar locations using Equation (8)

| Statistical indices | Collar at bed level | Collar above the bed level | Collar below the bed level |
|---------------------|---------------------|-----------------------------|----------------------------|
| $CC$                | 0.812               | 0.783                       | 0.759                      |
| Rank                | 1                   | 2                           | 3                          |
| $MAE$               | 0.018               | 0.031                       | 0.053                      |
| Rank                | 1                   | 2                           | 3                          |
| $MSE$               | 0.0004              | 0.0017                      | 0.0079                     |
| Rank                | 1                   | 2                           | 3                          |
| $MRSE$              | 0.013               | 0.042                       | 0.028                      |
| Rank                | 1                   | 2                           | 3                          |
| $MAPE$              | 0.31                | 1.341                       | 0.875                      |
| Rank                | 1                   | 3                           | 2                          |
| Average rank        | 1                   | $2.2 \approx 2$             | $2.8 \approx 3$            |
### 10 | CONCLUSIONS

An experimental study has been conducted to investigate the scour reduction around bridge piers using the collar. The accuracy of the equation proposed by Kumar et al. (1999) has been checked using previous data and data collected in the present study. Various statistical indices have also been used to estimate the performance of the equation of Kumar et al. (1999). It is concluded that Kumar et al.’s (1999) equation estimate the maximum scour depth with fair accuracy for $1.5b \leq b_c \leq 2.5b$ and collar placed near the bed.

A new equation for estimating maximum scour depth around the pier in the presence of collar has been proposed for the broader applicability. It is found that the proposed equation gives a better and more wide-range representative estimation of maximum scour depth around the pier with collar compared to Kumar et al. (1999) equation.

### NOTATIONS

| Notation | Description |
|----------|-------------|
| $B$      | channel width |
| $b$      | pier diameter |
| $b_c$    | collar diameter |
| $D_R$    | discrepancy ratio |
| $d_{s0}$ | median diameter of sediment |
| $d_{i16}$ | particle size at 16% finer |
| $d_{i84}$ | particle size at 84% finer |
| $d_{se}$ | maximum equilibrium scour depth around pier without collar |
| $d_{sec}$ | maximum equilibrium scour depth in the presence of collar |
| $d_{secx}$ | maximum equilibrium scour depth at longitudinal direction |
| $F_d = \frac{U}{\sqrt{(S-1)g\delta_s}}$ | densimetric Froude number |
| $F_r = \frac{U}{\sqrt{g}}$ | Froude number |
| $g$      | gravitational acceleration |
| $h = y - z$ | depth of collar from the water surface |
| $k_s = 2d_{s0}$ | equivalent roughness height |
| $n$      | total number of datasets |
| $S$      | relative density |
| $y$      | approach flow depth |
| $U$      | approach mean velocity |
| $U_c$    | critical velocity of particles |
| $U_{*c}$ | critical shear velocity |
| $z$      | collar elevation |
| $\sigma$ | standard deviation of particle size distribution |
| $\epsilon (%) = \left( \frac{d_{se} - d_{sec}}{d_{se}} \right) \times 100$ | efficiency of collar |

### TABLE 7

| Statistical indices | $1.5 \leq b_c \leq 2.5b$ | $2.5 < b_c \leq 6.0b$ | $0.2 \leq b_c < 1.5b$ |
|---------------------|---------------------------|------------------------|-------------------------|
| $CC$                | 0.793                     | 0.756                  | 0.731                   |
| Rank                | 1                         | 2                      | 3                       |
| $MAE$               | 0.021                     | 0.028                  | 0.032                   |
| Rank                | 1                         | 2                      | 3                       |
| $MSE$               | 0.001                     | 0.004                  | 0.002                   |
| Rank                | 1                         | 3                      | 2                       |
| $MRSE$              | 0.013                     | 0.021                  | 0.035                   |
| Rank                | 1                         | 2                      | 3                       |
| $MAPE$              | 0.250                     | 1.056                  | 1.378                   |
| Rank                | 1                         | 2                      | 3                       |
| Average rank        | 1                         | 2.2 ≈ 2                | 2.8 ≈ 3                |

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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