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Clear Water Scour at Rectangular Bridge Pier with Collar

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ABSTRACT

Scour is the most significant threat to waterways because it leads to the failure of bridge piers and other structural components. When a collar is put in place around the pier to lessen the direct impact of the downflow on the streambed, the maximum scour depth and its velocity is reduced. Due to its simplicity of implementation around existing bridge piers and the protection of the body of bridge piers in navigational canals, the current paper aimed to test a new method of a flow-altering countermeasure by examining the effect of collars width and elevation on scour reduction around a rectangular pier. The results showed that the elevated collar piers have reduced the maximum scour depth by up to 45%, planner area, and volume of the scour hole upstream of the pier. Additionally, to calculate the maximum scour depth of upstream piers, an empirical formula was created. According to the study, higher collars can significantly lessen the depth of the scour as the Froude's number rises. The effect increases with collar width, and the collar's performance in decreasing scour increases with collar location.

Keywords: Scour depth; Bridge pier; Collar; Movable bed; Scour countermeasure.

1 INTRODUCTION

Local scour, which is a result of running water, causes the eradication of bed material around the piers and abutments [1]. Large amounts of bed materials can be abolished during high-flow occurrences from the area around and beneath the pier foundations. As a result, the piers' solidity is compromised, and as a result, the structural integrity of the bridge [2]. Many researchers have investigated the phenomenon of local scours. Some studies like [3-11] have distinguished between live bed and clear water scour as flows with upstream velocity that is greater than critical velocity or flows with upstream velocity that is less than critical velocity. Hence, a number of field and laboratory investigations have been carried out to analyse and model the scour around bridge piers. Only after an accurate estimate of the scour depth around the piers, a safe and cost-effective bridge pier design can be guaranteed. It is extremely difficult to estimate the normal local depth of scouring (ds) in situations when the direct application of these findings from single-pier experiments is significantly off.

The bridge pier scour was thought to be caused by the pier's creation of a three-dimensional flow separation. The semicircular vortex upstream of the pier, flow acceleration along its sides, and wake vortices downstream of the pier (based on the Reynolds number) are the three primary scour-causing processes that appear when the flow splits around the pier. When these elements are present, they combine to generate the scour holes seen around bridge piers [12-14]. [15, 16] conducted detailed examinations of the flow behavior around piers using experimental and numerical methods, respectively. As the scour hole surrounding the pier grows, these investigations determine the contribution of each mechanism of scour-causing mechanisms.

Bed-armoring and flow-altering countermeasures were divided into pier-scour countermeasures. Bed-armoring countermeasures involve carefully placing large and heavy armour stones that can withstand the horseshoe vortex and downflow while being unaffected by the flow. Bed attachments were also used to safeguard the moveable canal bed, such as riprap blocks, gabions, and collars e.g., [17-31]. To prevent scouring, macro components were placed on the bed near a circular pier by [32]. They demonstrated that their plan was effective in lowering the maximum scour depth. Flow-altering countermeasures are meant to reduce downflow and the horseshoe vortex. Moreover, four different flow water depths are present. [33] examined the effect of combining four ruggedness heights with three pier sizes. The results revealed that roughened piers were effective in reducing the maximum depth of scouring, slope angle upstream, planner area, and size of scour hole upstream of the pier.

The direct influence of the downflow on the streambed is mitigated when a collar is constructed around the pier, resulting in a reduction in the maximum scour depth and rate. Collars have been used to prevent scour around circular and rectangular piers; however, a full investigation of the effect of collar height and breadth on bridge piers with various span lengths upstream of the pier has yet to be conducted. To regulate scour around a cylindrical bridge pier, only at the bed level, [34] employed multiple circular collars of different sizes. [28] used a single type of collar to investigate the influence of collar elevation on scour mitigation around a rectangular pier.

[35] suggested a new sort of collar called a hooked collar and discovered that maximal downflow is greatly reduced when compared to cases without the collar, with a commensurate decrease in horseshoe vortex intensity. The influence of pier shape on local scouring was also investigated by [36]. In comparison to various pier types, a plain octagonal shape was found to have better outcomes in decreasing the scour depth. The influence of collar external diameter, collar installation height, and collar protection range on scour depth was explored experimentally by [37]. Their results showed that the application of an anti-scour collar effectively reduced the scour at the pier. [38] examined how well various pier slot designs and circular collars around the pier's base reduced the scour depth. They designed the shape of a conical collar and tested it alongside other shapes. Collars, on average, have a stronger effect on reducing scour depth than slots that are drilled into the front and the back of bridge piers.

According to the previous review, few studies have tackled collars to reduce the scour upstream of rectangular bridge piers with various span lengths. The purpose of the current study is to test a proposed flow-altering countermeasure investigating the effect of collars width and elevation on scour reduction around a rectangular pier due to being easy to implement around the existing bridge piers and protecting the body of the bridge piers in navigational canals. In this regard, the application of elevated varied-sized collars on scouring around bridge piers with different span lengths is investigated in this study.

2. MATERIALS AND METHODS

All experiments were carried out in the irrigation and hydraulic laboratory, at Benha University, Egypt, the flume used in the study was 15 meters long, 0.4 meters wide, and 0.65 meters deep. A gravel box was employed at the flume entrance to produce an even flow distribution and to lessen turbulence and circulations. Furthermore, to control the depth of the tailwater, a convenient tailgate was installed at the end of the flume. Additionally, 6.0 m downstream from the flume entrance is a section of sand. To replicate the bed sediment, this sand section had dimensions of 3.00 m in length, the width of the flume, 0.25 m in depth, d_{50} = 0.71 mm, d_{90} = 1.8 mm, and geometric standard deviation (σ_g) = 2.176. To study the scour process' sensitivity to sediment size, the considered sand size has met the criterion of $D/d_{50} > 50$ to overcome the sediment size effect on the scour process according to [39]. In the middle of the sand portion, a wooden rectangle bridge pier was positioned and bolted to a massive steel plate beneath the sand. The breadth of the pier about the flume's width was selected to guarantee that flow would not be obstructed. A wooden pier in the shape of a rectangle to replicate the bridge pier, At 8.0 m downstream of the flume entry, sizes b/d 1, 1.5, and 2 were vertically built., where b is the width of the pier; it's parallel to the width of the flume, d is the length of the pier; it's parallel to the length of the channel i.e. parallel to the direction of flow. Figure 1 indicates that d; which in the streamwise direction is constant at 6 cm. Wooden collars with widths of 0.2 b and 0.4 b shown in Figure 2, were utilized at heights of 0.05 y, 0.1 y, 0.2 y, 0.4 y from the bed, where y; is the water depth above the sand layer equals 20 cm. The flow discharge was varied in all experiments to achieve Froude's numbers of 0.09, 0.14, 0.19, and 0.24, table 1 reports the experimental conditions. A magnetic flowmeter was used to determine the flow discharge. The water depth and geometric characteristics of the scour holes upstream of the pier were measured using a highly accurate point gauge.

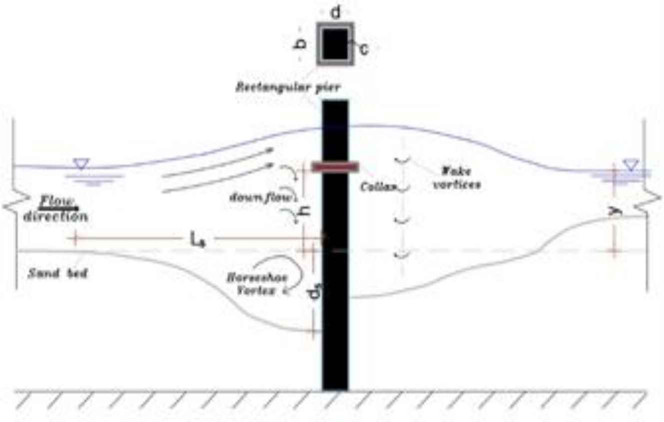

Figure 1: The rectangular bridge pier, the flow forms, and local scour definitions.

Figure 2: Rectangle bridge pier shape and collars width.

Table 1. Experimental conditions.

Variables	Range
Flow depth, y	20 cm
Pier width, b	6, 9, and 12 cm
Pier length, d	6 cm
Flow velocity, v	(0.011 – 0.3375) m/s
Collar width, c	(0.2, and 0.4) b
Collar level, h	1, 2, 4, and 8 cm

To analyze the efficiency of the elevation of the collar on the characteristics of scour pits upstream of the pier, 84 experiments were carried out including 12 tests with unprotected piers, (b = d, b =1.5d, and b=2d without collars). The movable bed was leveled at the start of each run, Water was slowly fed into the flume using a hose at the end of the flume to avoid disturbing the sand bed. Once the desired water depth and discharge have been attained, for each run, the sand bed was horizontally leveled, and the test's running period began. The equilibrium period for scours depth was defined according to [40], the depth of scour remains unchanged by more than 5% of the pier diameter throughout this period. According to preliminary tests, 36 hours was sufficient to bring about this scenario. This time should apply for tests of smooth contraction. For comparison purposes, a duration of eight hours was maintained. [41, 42] believed that the percentage reduction of the scour is significant in the first phases of the tests, whereas it later decreases as the depth of scouring increases. Much of the previous research available in the literature measured the scour depth after time around 5 to 6 hours, this time should be used for rectangular pier tests. For comparative reasons between protected and unprotected piers, an eight-hour time frame was kept. The flume was progressively drained at the end of each test and the geometry of the scour hole was measured as well. The shape of scour and sedimentation is photographed for observation before the drainage process, which occurs slowly so as not to be affected by it. If the drainage process affects the experiment, it is repeated immediately. The maximum scour depth was measured using a 2.5 cm grid to study the bed topography. Using the SURFER and AutoCAD software, the planner area scour hole As and the volume of scour holes Vs were determined. Some experiments were repeated to evaluate uncertainty in terms of accuracy and reliability.

3. DIMENSION ANALYSIS

The next relationship for the relative maximum scour depth ds/d at a cuboid pier with an elevated collar was introduced using dimensional analysis:

$$f\left(\frac{ds}{d},\frac{b}{d},\frac{c}{b},Fr=\frac{v}{\sqrt{g*y}},\frac{y}{d},\frac{d_{50}}{d}\right)=0 \qquad (1)$$

Where: ds is the maximum depth of scour upstream of a pier, d is pier length, b is pier width, c is collar width, h is collar level from the bed, Fr is the Froude number, v is average flow rate velocity, y is The flow of water height, g is gravity acceleration, and d_{50} is sediment's average particle size. The dimensionless variables in Eq. (1) were utilized to create correlations to examine how these parameters affected the scouring properties.

4. RESULTS AND DISCUSSION

Piers with elevated collars were tested to see how the width and elevation of the collars affected the scour depth decrease. According to [43], the maximum scour depth for a rectangle pier without a collar or in the countermeasures is located upstream of a bridge pier. The highest scour depth occurred near the pier or just upstream of the pier.

The experimental measurements for the maximum relative scour depth were introduced in this section. For varying dimensions of bridge piers, the correlations between relative scour depth and Froude number are clear in this section.

4.1 The Impact of the Pier Length on Local Scour

According to Figure 3, decreasing the pier's length perpendicular to the flow direction results in the least amount of scour. This is since the three vortices thought to be the primary causes of local scour at bridge piers the wake vortex formed inside the scour pit, the horseshoe vortex formed in front of the rectangle bridge pier, and the downflow in front of the rectangle bridge pier all grow as the area corresponding to the flow does. It was evident that at the lowest Froude's number, the values of the scour at different b/d converge. In other words, the influence of b/d and the spacing between the values of the scour is stronger the higher the Froude's number.

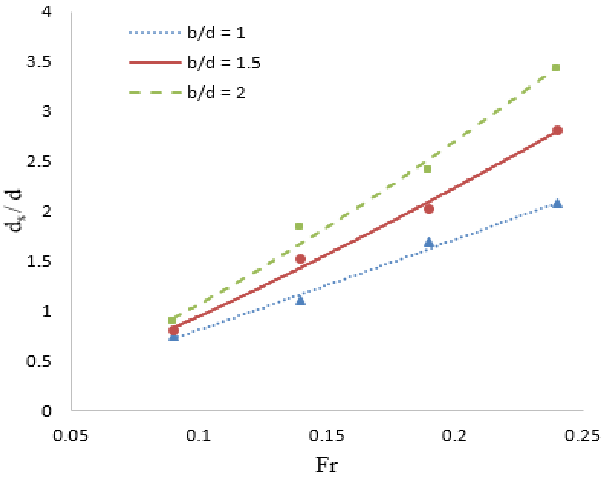

Figure 3: Relationship between the maximum relative scour depth and Froude number.

4.2 The Impact of the Width of Elevated Collar Piers on Local Scour

Figure 4 illustrates the effect of elevated collar width on the maximum relative scour at a constant pier length and Froude number. It is obvious that increasing the collar width leads to decreasing the local scour as the horseshoe vortex and downflow were attenuated and steered away from the canal bed. In addition, decreasing the collar heights results in decreasing the local scour at Froude number (Fr=0.19) and b/d = 1.5. The relative collar width c/b = 0.2, 0.4 decreases the maximum relative scour depth by an average percentage of 18.8%, and 27.72% respectively. While Figure 5 shows the effect of elevated collar width on a different length of the pier. The results indicate the effectiveness of increasing the width of an elevated collar on decreasing scour.

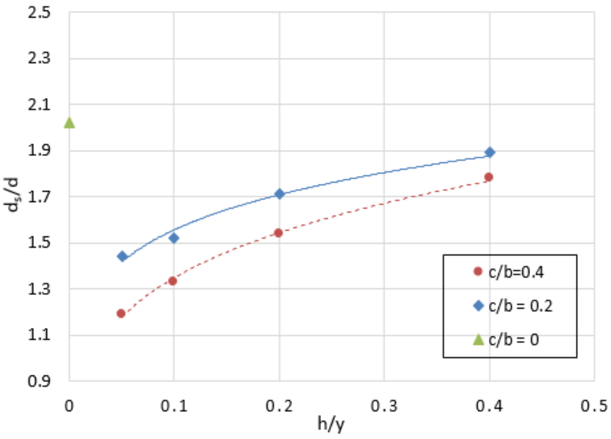

Figure 4: Relationship between the maximum relative scour depth and relative collar elevation at Fr = 0.19, b/d = 1.5

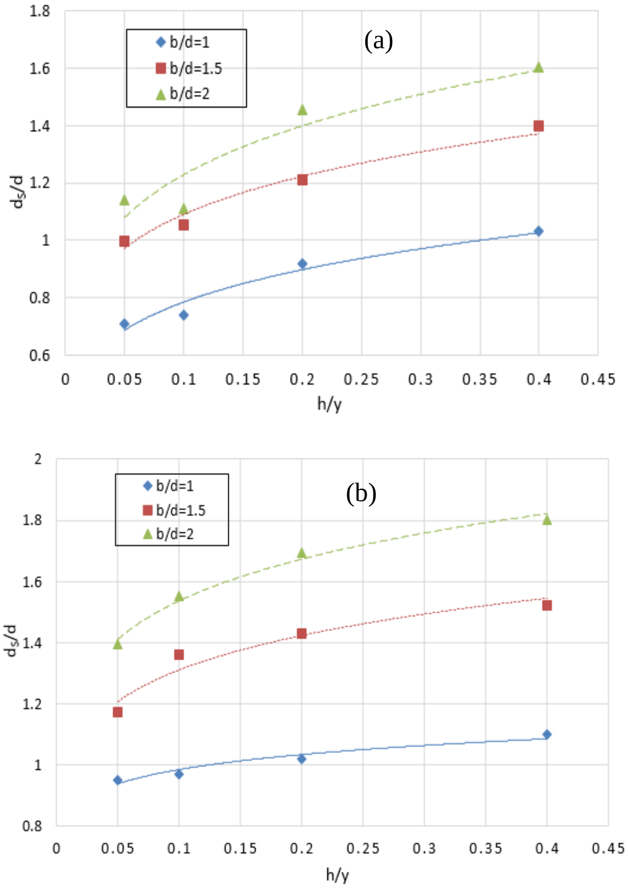

Figure 5: Relationship between the maximum relative scour depth and relative collar elevation at Fr = 0.14 a) c/b = 0.4, b) c/b = 0.2

4.3 The Effect of an Elevated Collar on Different Froude’s Numbers

The difference between the scour of the smooth rectangle pier and the pier with the elevated collars is only marginal for experiments with a small Froude's number and constant water level. The collar's impact increases as Fr rises, causing a larger scour differential between the rectangle pier with and without a collar. However, under all test conditions, the broader collar generated significantly less scour upstream, close to the smooth rectangle pier. At the low collar, where the scour was at its lowest, an upstream and side depression could be seen running the length of the pier. According to Figure 6, the maximum relative scour depth decreases by an average of 19.21%, 19.45%, and 20.54% at Froude numbers of 0.09 and 0.4, respectively, and by an average of 23.3%, 27.72%, and 29.97% at Froude numbers of 0.19 and 0.19, respectively, for the relative collar lengths of 1.0, 1.5, and 2.0. The most suitable scenario to minimizing scour 45% at c/b = 0.4, h/y = 0.05, b/d = 2, for Fr = 0.19 as shown in Figure 7.

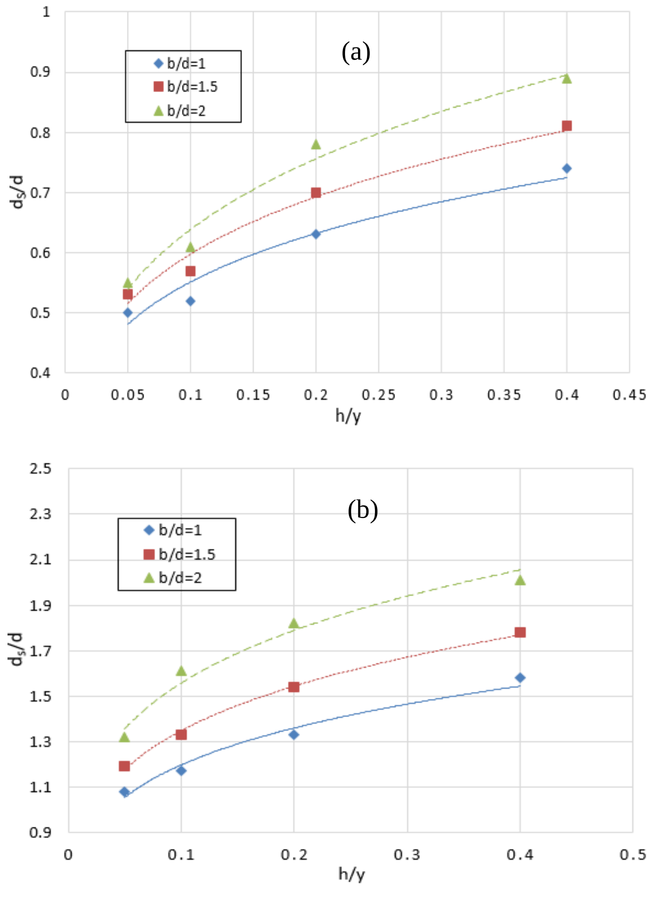

Figure 6: Relationship between the maximum relative scour depth and relative collar elevation at c/b = 0.4 a) Fr = 0.09, b) Fr = 0.19

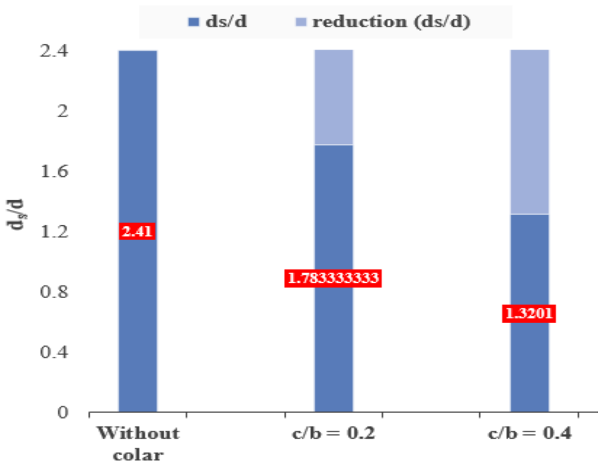

Figure 7: Comparison between maximum scour depth upstream bridge pier with and without collar at Fr = 0.19, b/d = 2, h/y = 0.05

As for various Froude numbers, (b/d), (c/b), and (h/y), multiple models were developed, and their regression coefficients were computed based on the experimental data and the statistical method. The following formulation encapsulates the best empirical formulae for forecasting the maximum relative scour depth:

$$\frac{ds}{d} = 6.8Fr^{0.98}\left(\frac{b}{d}\right)^{0.52}\left(\frac{c}{b}\right)^{-0.23}\left(\frac{h}{y}\right)^{0.16} \qquad (2)$$

Previous studies did not conclude an equation to calculate the maximum scour depth around a rectangular bridge with an elevated collar, so Eq. (2) was suggested for the upstream of the rectangle pier with an elevated collar. Eq. (2) has a remarkable degree of predictive power (R^2 = 94.40%).

Table 2 compares the effectiveness of the suggested strategy to that of other countermeasures in reducing scour depth. Using elevated collars across the surface of the pier to limit scouring upstream of the bridge piers is the easiest and most economical solution. It is also simple to apply on existing piers. This is due to the limitations and difficulties most flow-altering countermeasures have, which were previously mentioned. To maximize its overall effectiveness, this strategy may be paired with other bed-armoring defenses. The results of this investigation demonstrated that the elevated collar around piers performs effectively in terms of the max depth, planning area, and volume of the scour hole reduction.

Table 2. The effectiveness of scour depth countermeasures reduces.

References	Pier-scour countermeasure	% Efficiency of scour reduction
[26]	Pier slot	35.00
[44]	Internal connecting tubes	39.00
[27]	Collars	27.00
[20]	Bed sills	26.00
[45]	Jet injection through the pier body	37.50
[21]	Rectangular collar with deflector	65.00
[33]	Roughened piers	29.60
Present study	Elevated Rectangular collar	45.00

4.4 The Effect of a Collar on Length, Planner Area and Volume of the Scour Hole

Following the completion of testing and the collection of scans of the ensuing bathymetry, three-dimensional models of the upstream bed were created. Elevation charts were constructed using these models to compare the variations in scour patterns across experiments. In Figure 8, it is extremely obvious how elevated collars affect scour depths. The length of the scour upstream of the pier is slightly lengthened by the elevated collar. This is due to the downflow being pushed further away from the pier by the higher collar's elevation. The scour hole shape was influenced by the collar's breadth, and certain holes that were made during the experiment more upstream of the pier and connected had a larger planner area than those provided by smooth piers. The elevated collar's width (c/b =0.4, 0.2) at h/y=0.1, Compared to those provided by smooth piers, the scour deeper for b/d = 1 decreased by up to 30%.

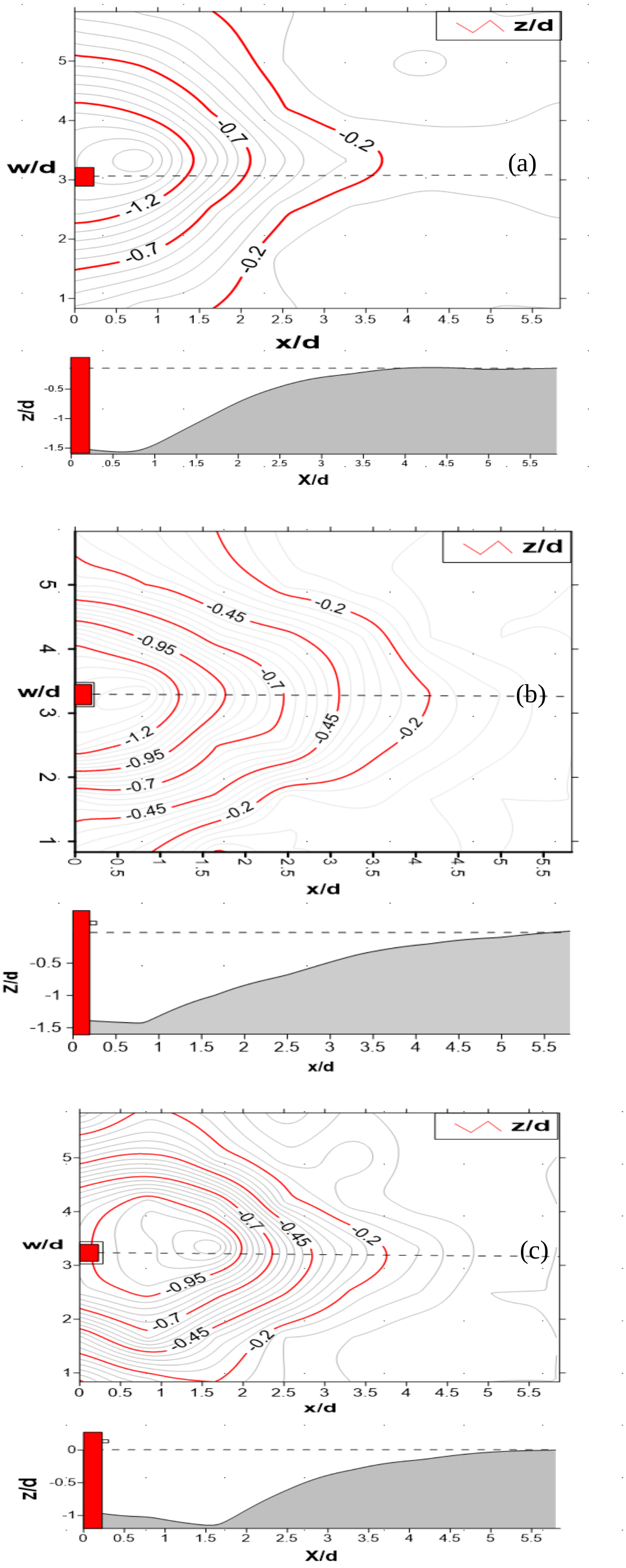

Figure 8: Scour hole relative contour lines for Fr = 0.19, b/d =1 (a) without collar (b) h/y = 0.1, c/b = 0.2 (c) h/y = 0.1, c/b = 0.4

5. CONCLUSIONS

Experiments were conducted in the current work to assess the impact of a raised collar on the scour features upstream of a rectangular pier. Elevated collar piers are preferred from a practical standpoint since they are straightforward and affordable countermeasures. In addition, they are simple to construct for existing bridges. Benchmarking some of the regional scouring procedures for bridge piers was done using laboratory data on piers. The study shows that elevated collars are highly effective in reducing the depth of the scour as the Froude's number increases, at Froude number (Fr=0.19) and b/d = 1.5. The relative collar width c/b = 0.2, 0.4 decreases the maximum relative scour depth by an average percentage of 18.8%, and 27.72% respectively. The wider the collar is, the higher the effect is; the maximum relative scour depth decreases by an average of 19.21%, 19.45%, and 20.54% at Froude numbers of 0.09 and 0.4, respectively, and by an average of 23.3%, 27.72%, and 29.97% at Froude numbers of 0.19 and 0.19, respectively, for the relative collar lengths of 1.0, 1.5, and 2.0. The most suitable scenario to minimize scour 45% at c/b = 0.4, h/y = 0.05, b/d = 2, for Fr = 0.19. This technique as a scour countermeasure needs additional testing in the lab to ascertain its efficacy under scour conditions and skewed flow before being applied in the field. Additionally, the impact of various new shapes of elevated collars with other pier shapes on bed level upstream of the pier in use needs to be determined.

Declaration of competing Interest

The author declare that, he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit Authorship Contribution Statement

Amir Sabry Ibrahim: Methodology, original draft, review, editing and supervision.

6.NOTATION

As	the planner area scour hole;
B	channel width;
b	pier width;
c	collar width;
d	Pier length;
d_{50}	median size of the sediment particles;
d_{90}	sediment size which 90% of sediment is finer;
ds	maximum scour depth;
Fr	Froude number;
g	acceleration due to gravity;
h	collar level;
v	flow velocity;
w	the transverse distance;
x	the longitudinal distance from pier to upstream;
y	flow depth;
z	scour depth;
σg	geometric standard deviation.

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