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Minimizing scour around bridge pile using holes

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KEYWORDS

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Abstract Driven by the importance of bridges, researchers are currently undergoing profound paradigm to implement piles to reduce the scour due to the erosive action of flowing water. This research aimed to investigate the minimization of the scour hole around a bridge pile, experimentally. Perforated piles with holes with different orientations were tested, a sacrificial pile and perforated sacrificial pile were placed at the upstream. Measurements were performed, analyzed and presented. Empirical equations were formulated to evaluate the scour parameters. The results indicated that about 89% reduction in scour depth was obtained due to using the combination of pile with hole angle of 45° and a perforated sacrificial pile with hole angle of 45° and hole diameter equals 0.43 of the pile diameter. The results of this study may be used in the field of application for the purpose of bridge pile protection design.

1. Introduction

The harmful effect of local scour around bridge piers and abutments can induce high maintenance costs or even bridge collapse resulting in the disturbance of traffic and possibly human losses. Literature was reviewed in the field of scour around piles of bridges. Many articles, papers and reports were collected, investigated and comprehended. Based on this review, it was apparent that many researchers investigated scour, as follows: Refs. [1,2] reported that investigated bridges' failure around the world is due to scouring. Therefore, there is an extensive research on bridge scour ranging from theoretical analyses, laboratory experiments, and numerical modeling. Deng and Cai [3] presented a comprehensive review of the up-to-date works on scour at bridge piers and abutments. Different techniques and instruments developed for bridge scour monitoring were presented. Various mitigation countermeasures developed for bridge scour were discussed. Mostafa [4] presented the results of an experimental study of scour around single pile and different configurations of pile groups exposed to waves and currents. It was documented that the scour depth for case of pile group is generally greater than that for the case of single pile depending on the group configuration and gap between piles. Akib et al. [5] tested the use of collars and geo-bags for reducing local scour around bridge piles. The results indicated that using a combination of a steel collar and a geo-bag yielded the most significant scour reduction for the front and rear piles, respectively. Akib et al. [6] presented an experimental study on the scouring mechanism at semi-integral bridge piers. The results specified that the scour development with respect to time was greater for higher flow

Abbreviations: GMDH, group method of data handling; NF-GMDH, neuro-fuzzy group method of data handling; S.P., sacrificial pile.
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Notations

B	clear flume width (L)	T	time at maximum scouring (T)
D	pile diameter (L)	x_p	sacrificial pile position (L)
d_1	hole diameter of bridge pile (L)	y_t	tail water depth (L)
d	sacrificial pile diameter (L)	θ	hole angle of pile (–)
d_2	hole diameter of sacrificial pile (L)	α	hole angle of the sacrificial pile (–)
d_s	maximum scour depth (L)	θ_r	hole angle of pile in radiant degree (–)
d_{smax}	maximum scour depth for no hole case (L)	α_r	hole angle of the sacrificial pile in radiant degree (–)
F_t	tail Froude number (–)		

depth and bigger flow discharge at semi-integral bridges. Refs. [7–10] investigated the equilibrium scour depth. They documented that it increased with the approach flow depth around piers at semi-integral bridges where scour around bridge piers was numerically simulated. Abouzeid et al. [11] investigated the flow and local scour variation around single pier and the interaction effect between bridge piers using 3D flow model. It was noticed that the maximum scour depth for circular pier is less than that for rectangular one for both single and double pier cases. Mohamed et al. [12] applied different methods of scour countermeasures to minimize local scour around multi-vents bridge supports experimentally. It was found that using collar around piers, current deflectors and sacrificial pile upstream piers reduced local scour depth by 90%. Elnikhely [13] studied the effect of using a protective pile installed upstream a bridge abutment for reducing the effects of local scour around it. It was found that using a pile upstream the abutment provided a reduction in the maximum scour depth by about 41%. Many researchers investigated the reduction of local scour around bridge pier by implementing a collar around the pier and riprap [14–17] and by using a slot through the pier [18–20]. Kurmar et al. [21] studied the efficiency of slots with different lengths and angles of attack. It was concluded that a slot can be effective in reducing scour, particularly if it extends into the bed, and that the slot is practically ineffective if the approach flow has a high obliquity with respect to the slot. Najafzadeh et al. [22] presented new application of group method of data handling (GMDH) to predict scour depth around a vertical pier in cohesive soils. It was found that, the GMDH has produced quite better scour depth prediction than those obtained using traditional equations. Najafzadeh et al. [23] used the GMDH to predict pile scour depth exposed to waves. It is noticed that, the GMDH produced the best realization of the inductive approach to predict the complexity of the scour process. Najafzadeh and Barani [24] investigated experimentally, the effect of current velocity, flow depth, initial moisture content, clay percentage and undrained shear strength on scour around a bridge pier. It was found that, saturated and unsaturated conditions are significant factors in predicting scour depth. Najafzadeh and Azamathulla [25] and Najafzadeh [26] utilized the neuro-fuzzy based group method of data handling (NF-GMDH) network to predict the scour process at pile groups. The NF-GMDH models indicated quite higher accuracy of scour prediction compared with the empirical equations.

In terms of the importance of protecting bridges against failure, this research was started. It aims to consider the effects of piles with holes with different orientations (i.e. 0°, 90° and 45° in the flow direction) under clear-water conditions. The research also aims to investigate the effect of perforated pile with sacrificial pile at the upstream.

2. Dimensional analysis

A dimensional analysis was carried out. The analysis considered variables were as follows:

d_s = the maximum scour depth
d_{smax} = maximum scour depth for no hole case
D = the diameter of the pile
F_t = the tail Froude number
y_t = the tail water depth
d_1 = the diameter of the hole of the perforated pile
B = the width of flume
T = time at maximum scouring
θ = the oblique angle of the hole in the horizontal plan
d = the diameter of the sacrificial pile
d_2 = the diameter of the hole of the perforated sacrificial pile
α = the oblique angle of the hole of the perforated sacrificial pile in the horizontal plan, Fig. 1.

The functional relationship for the maximum relative scour depth $\frac{d_s}{D}$ was as follows:

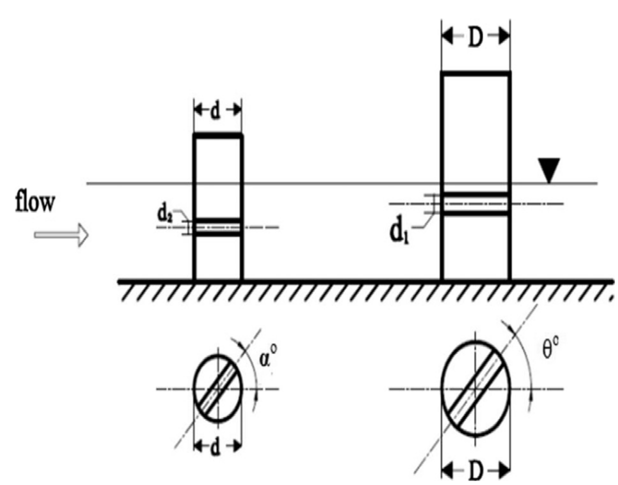

Figure 1 Schematic diagram of the experimental model.

$$\frac{d_s}{D} = f\left(F_{t,} \frac{y_t}{D}, \frac{d_2}{D}, \theta, \propto\right) \quad (1)$$

in which:

$\frac{d_s}{D}$ is the relative maximum scour depth
F_t is the tail Froude number
$\frac{y_t}{D}$ is the relative tail water depth
$\frac{d_2}{D}$ is the relative diameter of the hole of the sacrificial pile

Based on the experimental measurements, the functional relationship statistical tools were used to inspect many function forms to predict the different scour parameters. These parameters were obtained. They included ds/D, d_2/D, F_t, y_t/D, θ and α. The linear combination is presented by Eq. (2). It indicated the best performance.

$$\frac{d_s}{D} = 0.36F_t - 0.24\frac{d_2}{D} - 0.0024\theta_r - 0.0022\alpha_r - 0.198\frac{y_t}{D} + 0.181 \quad (2)$$

Table 2 provides the statistical indicators of the above equation.

3. Experimental work

The experiments were conducted in the Hydraulic and Water Engineering Laboratory Faculty of Engineering, Zagazig University, Egypt. In this section, the experimental installations are provided; the experimental program is displayed; the experimental procedure is presented; and the measurements are elaborated.

Photo 1 The experimental model.

A re-circulating channel with 40 cm width, 20 cm depth and 4.0 m length was implemented. Stones of different sizes were used at the entrance to damp disturbance. The median sand size (D_{50}) is 1.5 mm and the geometric mean (D_{85}/D_{15}) is 1.41. The experimental work was conducted under the clear-water condition. Circular pile with 7.0 cm diameter was installed in the channel centerline. The tested models were provided with perforated sacrificial pile with different hole angles α = 0°, 90°, 45° and with different hole diameters of d_2 = 0.25, 0.43, 0.6 of its diameter.

Eighty "80" experimental runs were carried out. Different water depths were inspected. Different water depths and different pile characteristics were investigated.

Three different oblique angles of the hole θ = 0°, 90°, 45° were tested. The tested models, Photo 1, were provided with sacrificial pile with diameter 0.33 D and at position of 4 times the pile diameter (according to Mohamed et al. [12]). Different hole angles α = 0°, 90° and 45° with different hole diameters of d_2 = 0.25, 0.43 and 0.6 of the diameter of the perforated sacrificial pile were tested. The experimental program is summarized in Table 1. Each run lasted for 2 h during which 95% of maximum scour occurs. Fig. 2 shows the relationship between the time interval, T and the maximum scour depth, d_s/d_{smax}. The time of balance for the scour depth was found to be 120 min. In order to obtain a required water depth, a pump was used. It was turned on and its speed was increased slowly

Table 2 Basic statistical indicators of the developed equation.

Multiple R	R Square	Adj. R Square	Standard error
0.98	0.97	0.983	0.0086

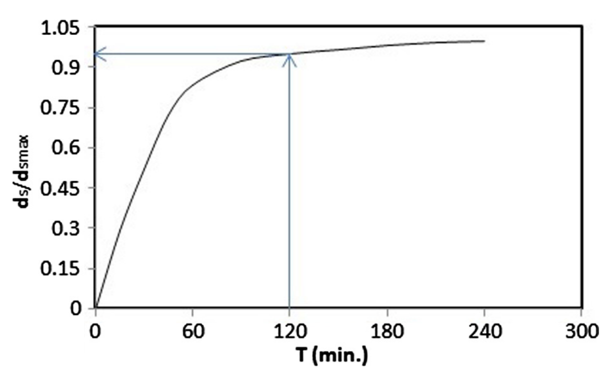

Figure 2 Relationship between d_s/d_{smax} and time in case of no hole.

Table 1 Experimental scheme.

Model stage	Description	Runs	Hole angle
I	No hole case	20	–
II	The effect of using a perforated pile	20	θ = (0°, 90°, 45°)
III	The effect of using sacrificial pile U.S. perforated bridge pile	20	θ = (0°, 90°, 45°)
IV	The effect of using a perforated sacrificial (d_2/d = 0.25, 0.43, 0.6) pile U.S. perforated bridge pile	20	θ = (45°), α = (0°, 90°, 45°)

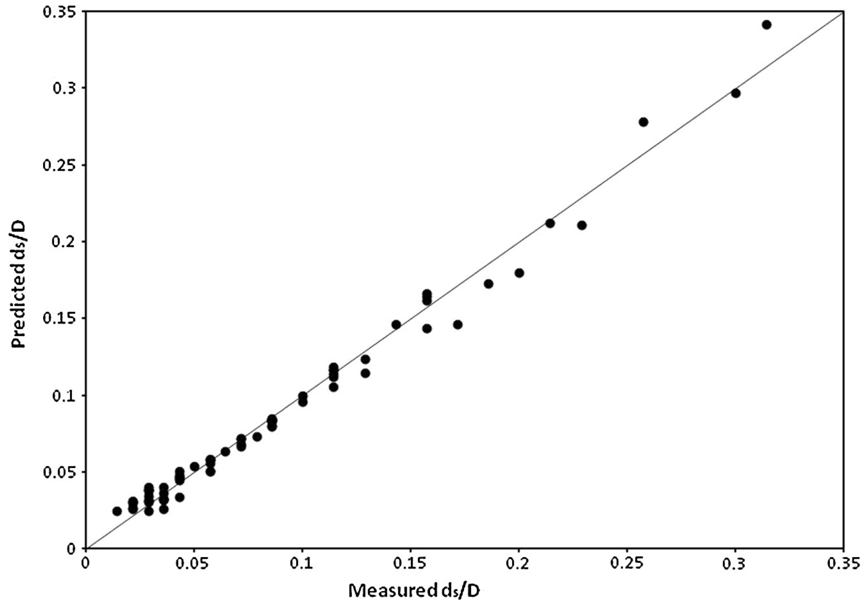

Figure 3 Comparison between experimental results and statistical equation.

to reach the desired flow, after which the tailgate was adjusted to obtain the desired depth. For each test of the experimental program, the sand was leveled along the length of flume using a wooden screen with the same width as the flume. The sand level was checked randomly at points with a point gauge. The flume was slowly filled with water to the required depth. The discharge was measured using a pre-calibrated orifice meter. At the end of the test the pump was turned off and the flume was drained slowly without disturbing the scour topography. The scour profile was recorded with a point gauge with 0.1 mm accuracy.

4. Verifying the empirical equations

Using all data sets used in this study, Fig. 3 is plotted. It presents the calculated values of the investigated parameters against the measured ones. From the figure, it is apparent that a small scatter between these variables is present.

Generally, it can be observed that, there is an acceptable agreement between the measured data and the predicted ones. The results indicated well agreement between the experimental and predicted values of d_s/D where, $R^2 = 0.97$ and R^2 between residuals and predicted value is $1.95E^{-15}$, see Fig. 4.

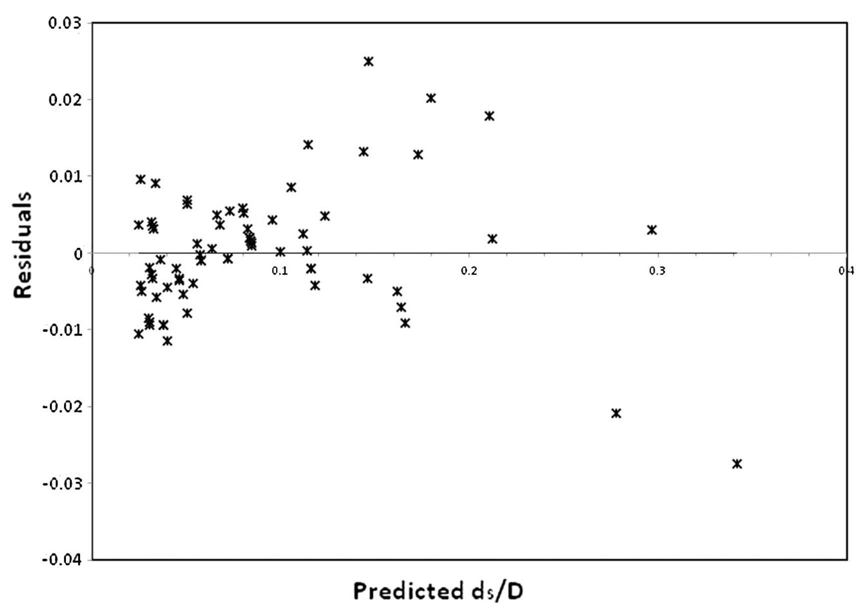

Figure 4 Variations of residuals for different data sets with predicted data.

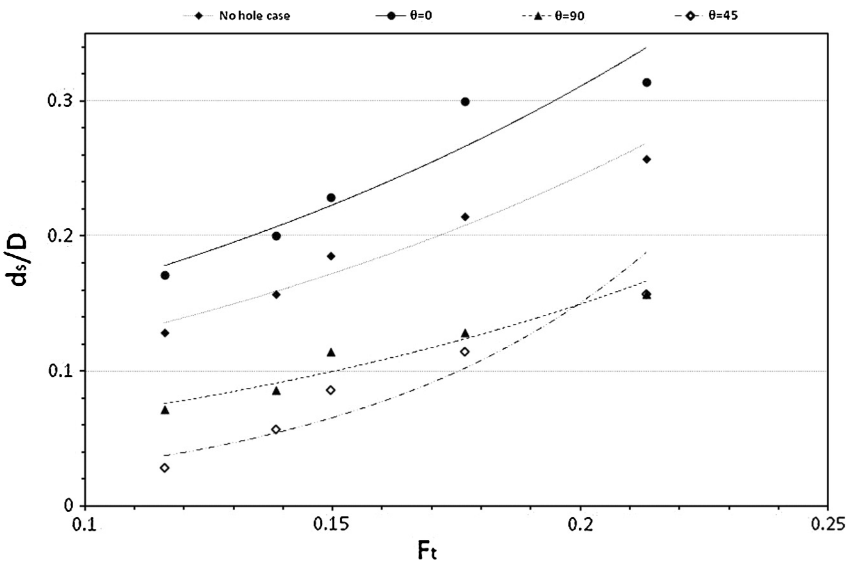

Figure 5 Relation between the relative scour depth d_s/D and Froude number F_t for different hole angles of the perforated pile.

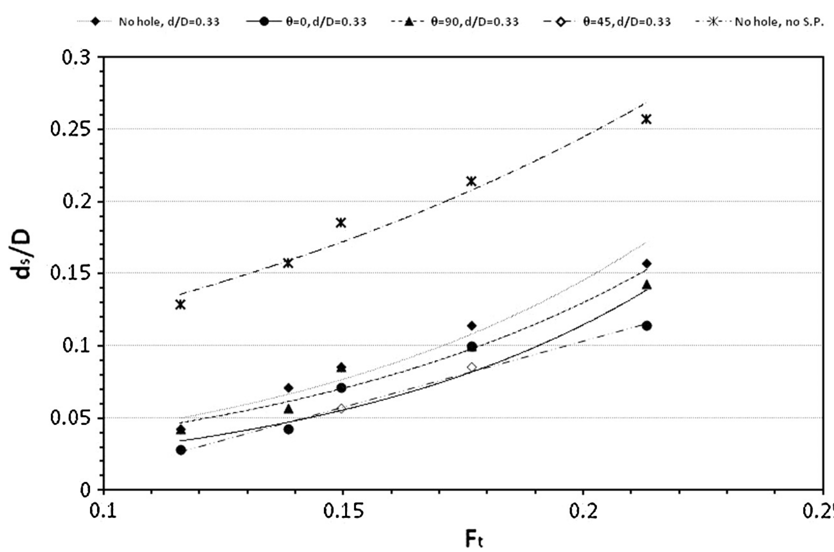

Figure 6 Relation between the relative scour depth d_s/D and Froude number F_t for using combined countermeasures.

5. Analysis and discussion

The effect of the different investigated parameters was analyzed and presented on graphs. They are discussed here, as follows.

5.1. Effect of hole angle of the perforated pile

In this section, the effect of using a perforated pile on local scour depth was investigated experimentally. Fig. 5 shows the relationship between the maximum relative scour depth d_s/D for the bridge's pile and tail Froude number F_t for unprotected pile and a perforated pile with different hole angles (0°, 90°, 45°). It was found that d_s/D increases as F_t increases and vice versa. The result of the test of an unprotected pile showed a continuous increase in the scour depth. This is attributed to the fact that the unprotected pile had a horseshoe vortex in front of the pile caused a deeper scour depth. It was found that, the scour depth formed around a perforated pile with hole angle of $\theta = 0°$ is higher than that created around the pile in cases of $\theta = 90°$, $\theta = 45°$ and unprotected pile (no hole case) under the same flow conditions. So the velocities created around the perforated pile increase when the hole is in the direction of flow $\theta = 0°$ and then larger scour depth will be created. The scour reduction was achieved for a perforated pile with hole angles of $\theta = 90°$ and $\theta = 45°$ with maximum reduction of about 47% and 80%, respectively. Therefore, a perforated pile seems to be effective for $\theta = 90°$, $\theta = 45°$ and it had a very significant effect on reducing the scour for $\theta = 45°$.

5.2. Effect of using a sacrificial pile

Fig. 6 presents the results for no countermeasure and for the combined countermeasures of a sacrificial pile upstream a bridge pile with hole of $\theta = 0°, 90°, 45°$. A sacrificial pile is placed upstream the perforated pile for the purpose of protecting it from local scour. The pile, which itself may be subjected to substantial scour, protects the bridge pile from scour by deflecting the high velocity flow and creating a wake region behind it [27]. Effect of sacrificial pile of $d_2/D = 0.33$ was fixed upstream the perforated pile at $x_p = 4D$ to control and minimize the formed scour holes. There is a great difference between no countermeasure and the combination of making a hole in the bridge pile and using a sacrificial pile upstream it. It was investigated that, the sacrificial protective pile located upstream of the perforated bridge's pile at $x_p = 4D$, produces minimum relative scour depth around the perforated bridges pile compared to no-hole, no sacrificial pile case. The scour reduction using the combination of a hole in the bridge pile of $\theta = 45°$ and sacrificial pile upstream it was about 76%.

5.3. Effect of using a perforated sacrificial pile

Fig. 7 provides the effect of using a perforated sacrificial pile with a hole angles of $\alpha = 0°$ (in the flow direction), 90° and 45° located upstream a bridge pile provided with a perforation of hole angle of $\theta = 45°$. It is obvious that, the perforated sacrificial pile is considered a good tool to minimize the local scour depth for the case of $\alpha = 45°$. It reduced the relative scour depth by at least 84%.

5.4. Effect of relative hole diameter of sacrificial pile

Fig. 8 shows the variation of d_s/D with various diameters of the hole for sacrificial pile $d_2/d = 0.26, 0.43, 0.6$. It could be seen that, under the condition of same flow and bed material, the relative scour depth of the scour hole around the perforated pile increases as F_t increases. In addition, the relative scour depth reached its minimum value in case of $d_2/d = 0.43$, and it reduces the relative scour depth d_s/D, by about 89% compared to the no-hole no sacrificial pile, which can be considered as the optimum diameter of the hole in the sacrificial pile.

5.5. Comparison of percentages of scour reduction

Fig. 9 shows a comparison between maximum percentages of scour reduction for different scour countermeasures used by

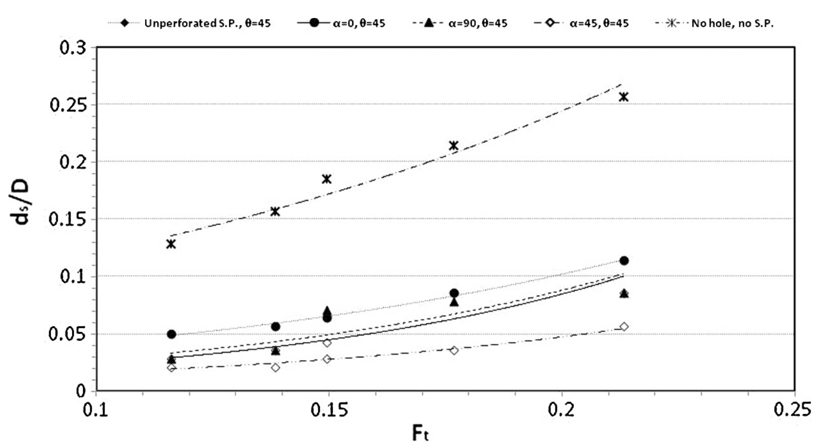

Figure 7 Relation between the relative scour depth d_s/D and Froude number F_t for using a perforated S.P.

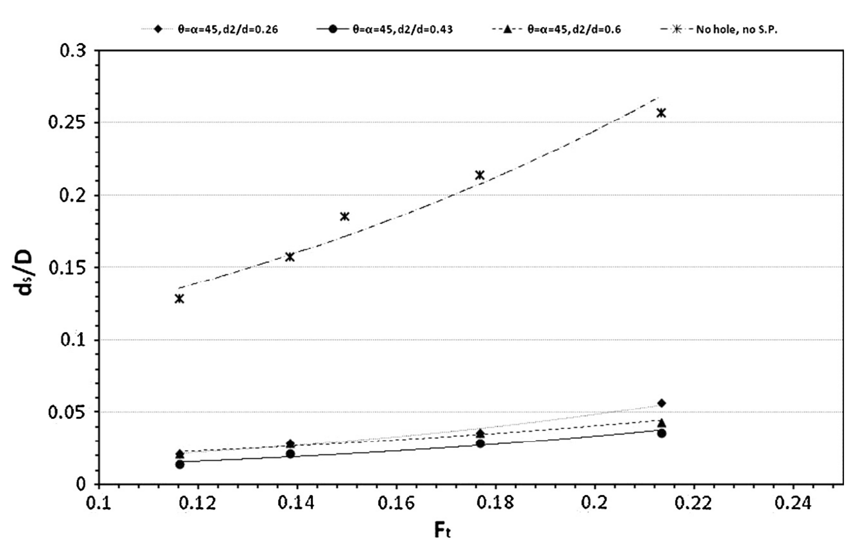

Figure 8 Relation between the relative scour depth d_s/D and Froude number F_t for different relative perforation diameters of the S.P.

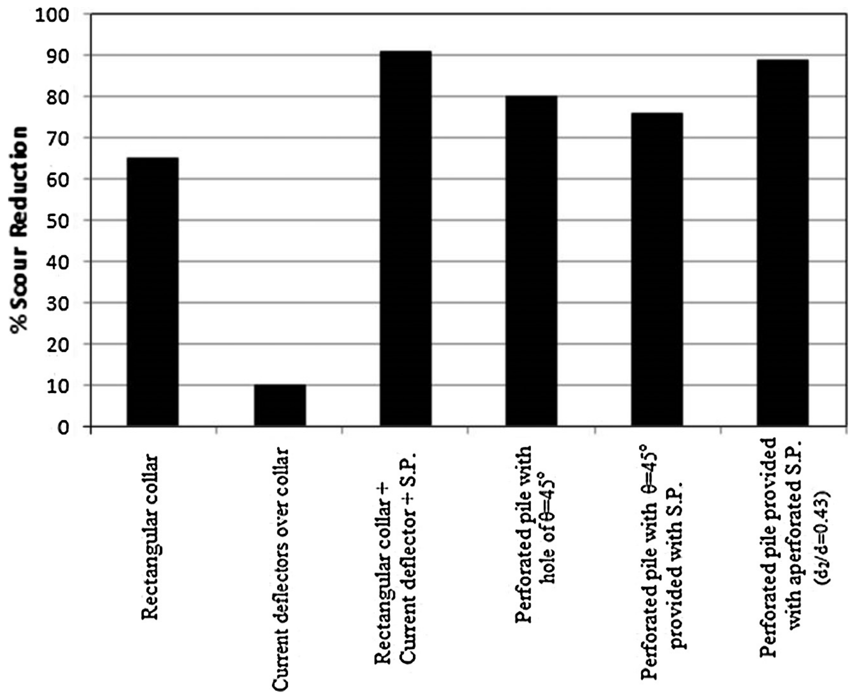

Figure 9 Percentage of maximum scour reduction versus different scour countermeasures.

Mohamed et al. [12] and those obtained in this study. It is obvious that using a pile with hole of $\theta = 45°$ is considered good tool to minimize the local scour depth. In addition, using the combination of pile with hole of $\theta = 45°$ and a perforated sacrificial pile of $\alpha = 45°$, $d_2/D = 0.43$ has a very significant effect for controlling and minimizing the formed scour holes.

6. Conclusions

In the present work, the scour around bridges' piles through multi-vents bridge was studied, experimentally. The following conclusions were deduced:

- The use of a perforated pile leads to reduce the local scour depth by 80% for $\theta = 45°$.
- The scour depth formed around a perforated pile with $\theta = 0°$ is higher than that created around the pile in cases of $\theta = 90°$, $\theta = 45°$ and unprotected pile (no hole case) under the same flow conditions.
- The scour reduction achieved for a perforated pile with $\theta = 90°$ is about 47%.
- The protective imperforated sacrificial pile upstream of bridge perforated pile reduces the local scour depth at bridge pile by 76% compared to the unprotected bridge pile, for $\theta = 45°$.
- Implementing a hole in the sacrificial pile has the ability to minimize and control the scour depth around the bridge pile by about 84% for the case of $\alpha = 45°$ and $\theta = 45°$.
- The overall reduction of the scour depth occurring due to perforated sacrificial pile of $d_2/d = 0.43$ is 89%.
- The application of this work can be utilized in real world by making perforation using wooden or steel frames with the same design diameter during implementation of pile.
- The developed statistical equation agrees well with the experimental measurements with a mean $R^2 = 97\%$.

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