Evaluation of Diameter and Distance of Sacrificial Piles from the Bridge Pier in Reducing Local Scour

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***Abstract*— In this research, it was analyzed influence of variation of sacrificial piles diameter, as well as the distance between front pile and the face of the pier in reducing local scour depth. For this purpose, it was calibrated a physical test of an isolated cylindrical pier developed in a previous research. For calibration, numerical models were made with Manning's roughness coefficients of the sand of 0.023, 0.024 and 0.025 and the application of Froechlich and Colorado State University (CSU) equations to calculate the local scour depth. After that, 12 numerical models were made with the addition of sacrificial piles in a 30° triangular configuration to the calibrated model. The diameters of sacrificial piles were 5, 6, 7.5 and 10 mm and distances between front pile and the face pier were 75, 90 and 105 mm. According to the results, the highest percentage of local scour reduction was obtained when the sacrificial piles had a diameter of 10 mm and the distance between the front pile and the pier was equal to 105 mm. In this sense, when the distance between the front pile and the face pier was greater, the percentage of local scour reduction was higher. Also, based on the results, it is concluded that, Froechlich's equations and CSU lose precision when there are sacrificial piles.**

***Index Terms*— local scour, sacrificial piles, numerical modeling, Froechlich equation, CSU equation**

LIST OF SYMBOLS

V	Flow velocity
V_c	Critical velocity
D	Pier diameter
d	Pile diameter
X'	Separation between the front pile and the pier face
Sp	Separation between piles
y	Flow depth
d_{50}	Median sediment grain diameter
y_s	Local scour depth
g	Acceleration of gravity
ρ	Water density
D'	D (for piers aligned with the flow)
ϕ_F	Correction factor for the shape of the pier nose
Fr	Froude number
K_1	Correction factor for the shape of the pier nose
K_2	Correction factor for the angle of attack of the flow
K_3	Correction factor for bed condition
K_4	Correction factor for bed material size
n	Manning's roughness coefficient of the sand

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I. INTRODUCTION

Local scour is one of the main causes of bridge collapse around the world. For example, in the United States, until 1950, of a total of 823 bridges, 60% collapsed due to this phenomenon [1]. This type of scour removes the bed material around bridge piers and abutments because of the formation of horseshoe vortices, wake vortices and the downward flow in front of these structures [2]. Due to the need to guarantee the stability and functionality of bridges, several authors have investigated the efficiency of several countermeasures to reduce effects generated by local scour [3-11]. Some of them are the riprap, the use of disks in the piers, cables around the piers, the addition of sacrificial piles, among others. The use of sacrificial piles has been widely researched; they are located upstream of the bridge foundation and have the function of protecting the bridge pier from local scour [12]. Sacrificial piles generate a decrease in flow velocity and a weak region behind them, so there is a reduction of local scour around the bridge piers [12]. The effectiveness of the sacrificial piles is influenced by the angle of attack of the flow, since, if this angle is small, reductions of the depth of local scour can be obtained of up to 50% [13]. Also, sacrificial piles are recommended when the intensity of the flow is relatively small [14]. Melville and Hadfield [14] conducted tests under clear water conditions ($V/V_c < 1$) with different configurations of sacrificial piles. According to their results, the most efficient configuration to reduce local scour (figure 1) was a triangular one with 5 sacrificial piles, with 30° angle between piles, a front pile separation to the pier face of 2.5D (X') and a separation between piles equal to D (Sp).

According to Haque et al. [15], the transverse configuration formed by 3 sacrificial piles and a front pile separation to the face of the pier of 2D (X') (figure 2) was the most efficient in reducing local scour.

In this investigation, numerical modeling of hydrodynamics conditions was performed under clear water conditions to provide input data to Froechlich and CSU equations. Experiments include 5 sacrificial piles with a triangular configuration with a 30° angle and a

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separation equal to D between them. In these simulations diameter of sacrificial piles (d) and separation between the front pile and the pier (X') varied to determine the most efficient values of these parameters in reducing local scour.

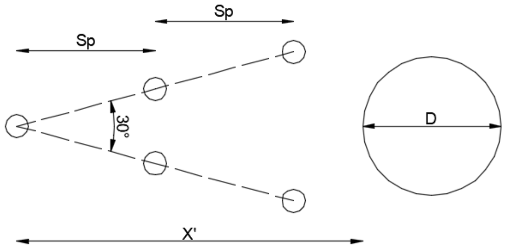


Figure 1. Sacrificial piles configuration [14].

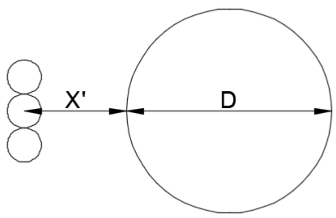


Figure 2. Transversal piles configuration [5].

II. EXPERIMENTATION

A. Method and Tools

In this research, the physical tests carried out by Vahdati et al. [3] under clear water conditions were taken as reference. Local scour under clear water conditions occurs when the average flow velocity is less than the critical speed required to transport the bed material ($V/V_c < 1$) which means that there is little or no movement of the bed material particles upstream of the pier [2], [14]. In the physical tests developed by Vahdati et al. [3], efficiency of sacrificial piles (figure 3) and cables around the pier in reducing local scour was evaluated.

The T1 test, performed by Vahdati et al. [3] (table I), was calibrated by means of hydrodynamic modeling in the Iber software [16] and the application of the Froechlich and Colorado State University (CSU) equations to calculate the local scour depth.

After calibrating the T1 test, new hydrodynamic numerical models were made by adding sacrificial piles to the calibrated model to evaluate their efficiency in reducing local scour. Additionally, it was carried out a dimensional analysis to know the most influential adimensional numbers in the reduction of local scour.

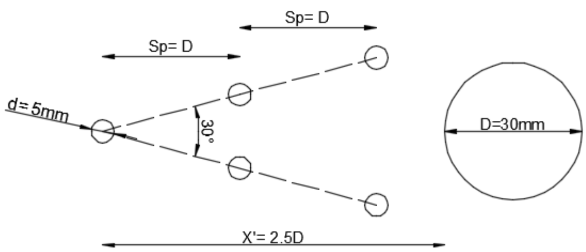


Figura 3. Configuration of sacrificial piles used in the physical tests developed by Vahdati et al. [3].

TABLE I. PHYSICAL TESTS DEVELOPED BY VAHDATI ET AL. [3]

Test	Type of piers	Cable	Sacrificial piles
T1	Single pier	Without	Without
T2	Single pier	Without	With
T3	Single pier	With	With
T4	Group of two piers	Without	Without
T5	Group of two piers	Without	With
T6	Group of two piers	With	With
T7	Group of three piers	Without	Without
T8	Group of three piers	Without	With
T9	Group of three piers	With	With

B. Identification of Flow, Channel, Sediment, Pier and Pile Characteristics

From the physical tests developed by Vahdati et al. [3], the main characteristics to be used in hydrodynamic numerical modeling were identified. The characteristics of flow, flume, sediments, pier and piles are shown in table II. The calculation of flow depth and mean flow velocity, shown in table II, was made based on equation (1) [2]:

$$V_c = 6.19 y^{1/6} d_{50}^{1/3} \qquad (1)$$

C. Dimensional Analysis

A dimensional analysis was carried out to identify the main non-dimensional numbers in the local scour. It was considered that the local scour depth is a function of the following variables:

$$y_s = f(y, D, V, g, X', d_{50}, Sp, \rho) \qquad (2)$$

After performing the dimensional analysis, it was obtained that the relative depth of local scour (y_s/D) is a function of the following non-dimensional numbers:

$$y_s / D = f(y/D, X'/D, Sp/D, Fr) \qquad (3)$$

TABLE II. CHARACTERISTICS OF THE TESTS CARRIED OUT BY VAHDATI ET AL. [3]

Characteristics of the flume	
Width (m)	0.40
Lenght (m)	10.00
High (m)	0.60
Flow characteristics	
Discharge (l/s)	18.00
V/V_c	0.88
Flow depth (m)	0.13
Mean flow velocity (m/s)	0.34
Sediment characteristics	
d_{50} (mm)	0.7
Geometric characteristics of the piles and piers	
Pier diameter (mm)	30
Sacrificial piles diameter (mm)	5

D. Model Calibration

To calibrate the T1 test, a 1.8 x 0.4 m section of the flume was considered to perform the hydrodynamic numerical modeling in the Iber software with Manning's roughness coefficients of the sand of 0.023, 0.024 and 0.025 [17]. From the numerical modeling, the values of the flow depth and Froude number upstream of the pier were obtained. Then, these values were applied in the Froechlich (4) and CSU (5) equations [2]:

$$y_s = 0.32\phi_F(D')^{0.62}y^{0.47}Fr^{0.22}d_{50}^{-0.09} + D \quad (4)$$

$$y_s = 2.0K_1K_2K_3K_4D^{0.65}y^{0.35}Fr^{0.43} \quad (5)$$

In table III, results of flow depth and Froude number upstream of the pier are shown. These results were obtained in the numerical modeling and were applied in equations (4) and (5) in order to calculate the local scour depth (table IV and V).

From results shown in tables IV and V, the percentage of error with respect to local scour depth obtained in physical test T1 (47 mm) was calculated (table VI).

In Table VI, low error percentages are observed and there is no considerable variation between the results. Because of this, the following simulations were chosen with a Manning's roughness coefficient of sand of 0.024.

E. Numerical Modeling of Proposed Configurations

Twelve different configurations were proposed for the sacrificial piles (Table VII).

TABLE III. FLOW DEPTH AND FROUDE NUMBER OBTAINED IN NUMERICAL MODELING.

Manning's roughness coefficient of sand	y (mm)	Fr
n=0.023	95.521	0.219
n=0.024	96.948	0.221
n=0.025	97.258	0.222

TABLE IV. LOCAL SCOUR DEPTH OBTAINED WITH FROECHLICH EQUATION.

Test	φ_F	D' (mm)	y (mm)	Fr	d_{50} (mm)	D (mm)	y_s (mm) calculated
n=0.023	1	30	95.52	0.219	0.7	30	46.61
n=0.024	1	30	96.95	0.221	0.7	30	46.75
n=0.025	1	30	97.26	0.222	0.7	30	46.81

TABLE V. LOCAL SCOUR DEPTH OBTAINED WITH CSU EQUATION.

Test	K_1	K_2	K_3	K_4	D (mm)	y (mm)	Fr	y_s (mm) calculated
n=0.023	1.00	1.00	1.10	1.00	30.00	95.52	0.219	51.50
n=0.024	1.00	1.00	1.10	1.00	30.00	96.95	0.221	51.94
n=0.025	1.00	1.00	1.10	1.00	30.00	97.26	0.222	52.19

As shown in Fig. 4, all experiments use sacrificial piles with triangular configuration of 30°, the pier diameter was equal to 30 mm and the separation between piles was 30 mm. Diameter of sacrificial piles (d) and separation between the front pile and the face of the pier (X') varied in each test. In addition, in all hydrodynamic numerical modeling, a discharge of 18 l/s, a flow depth equal to 13 cm, and the same channel section used in the numerical modeling of calibration were considered (Fig. 5).

III. ANALYSIS OF RESULTS

A. Reduction of Local Scour in Proposed Configurations

After simulations of proposed configurations, values of flow depth and Froude number upstream of the pier were extracted to calculate local scour depth with Froechlich and CSU equations (table VIII and IX). In addition, Tables VIII and IX show the percentage reduction of local scour from that obtained in calibration test with n = 0.024. As shown in these tables, the highest percentage of reduction of local scour was obtained in test 9. Flow depth, flow velocity and Froude number around the pier of this test are shown in Figs. 6, 7 and 8, respectively.

It is important to note that test 4 of proposed configurations has the same arrangement of the physical test T2 developed by Vahdati et al. [3]. As it is observed in tables VIII and IX, in test 4 were obtained percentages of reduction of local scour of 6% and 26.75% with Froechlich’s and CSU's equation, respectively. However, these percentages differ from the reduction of local scour of 55% obtained between T1 and T2 physical tests developed by Vahdati et al. [3].

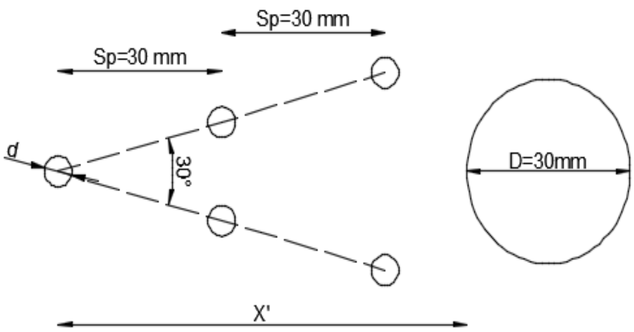


Figure 4. Sacrificial piles configuration.

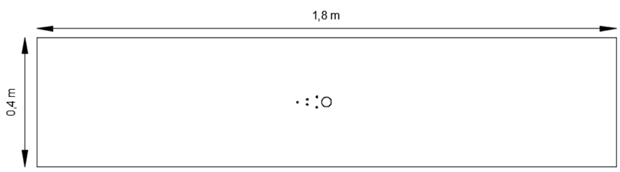


Figure 5. Channel section for testing.

TABLE VI. ERROR RA TE (%) OBTAINED WITH EQUATIONS OF FROECHLICH AND CSU.

Manning's roughness coefficient of sand	Error rate (%)	
	Froechlich	**CSU**
n=0.023	0.83	9.57
n=0.024	0.52	10.51
n=0.025	0.40	11.04

TABLE VII. PROPOSED CONFIGURATIONS.

Test	d (mm)	X' (mm)	Test	d (mm)	X' (mm)
1	10	75	7	6	75
2	7.5	90	8	5	90
3	6	105	9	10	105
4	5	75	10	7.5	75
5	10	90	11	6	90
6	7.5	105	12	5	105

B. Effect of Pile Diameter (d) in Reducing Local Scour

According to results shown in tables VIII and IX, the highest percentages of reduction were obtained in test 9 and 6, in which piles diameters were 10 mm (1/3D) and 7.5 mm (1/4D), respectively. However, most unfavorable results were obtained in test 7, 10 and 1, in which piles diameters were 6 mm (1/5D), 7.5 mm (1/4D) and 10 mm (1/3D). From these results, it is observed that, for the same value of diameter of sacrificial piles, high and low percentages of local scour reduction are obtained. Therefore, it is concluded that, diameter of sacrificial piles is not the main variable that influences reduction of local scour.

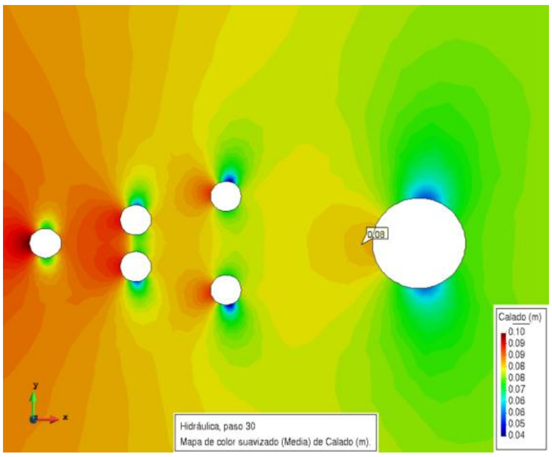


Figure 6. Flow depth around the pier.

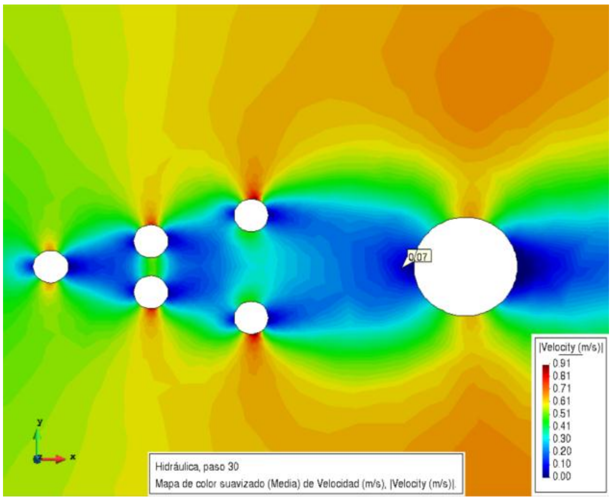


Figure 7. Flow velocity around the pier.

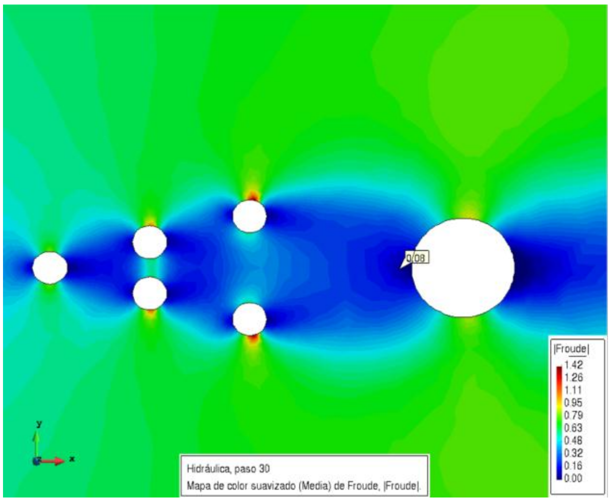


Figure 8. Froud number around the pier.

C. Effect of Separation Bettween the Front Pile and the Pier Face (X') in Reducing Local Scour

In tests 9 and 6 (the most efficient) separations between the front pile and the pier face were 105 mm (3.5D). In contrast, in tests 7, 10 and 1 (the least efficient), separation between the front pile and the pier face was 75 mm (1/4D) in all cases. Based on these results when separation is greater between the front pile and the face of the pier (X'), higher percentages of reduction of local scour are obtained.

D. Influence of Non-Dimensional Numbers on Local Scour

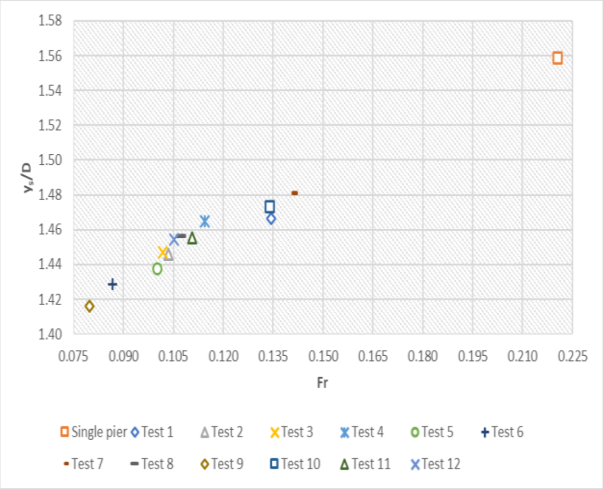
According to dimensional analysis, the most influential non-dimensional number in local scour is Froude number, since it significantly affects the results in Froechlich and CSU equations. As shown in Figs. 9, local scour reduction percentages were obtained in all tests. In addition, in these figures it is observed that the highest percentages of reduction of local scour were obtained for low Froude numbers (0.075-0.09).

TABLE VIII. RESULTS OF THE PROPOSED CONFIGURATIONS WITH THE FROECHLICH EQUATION.

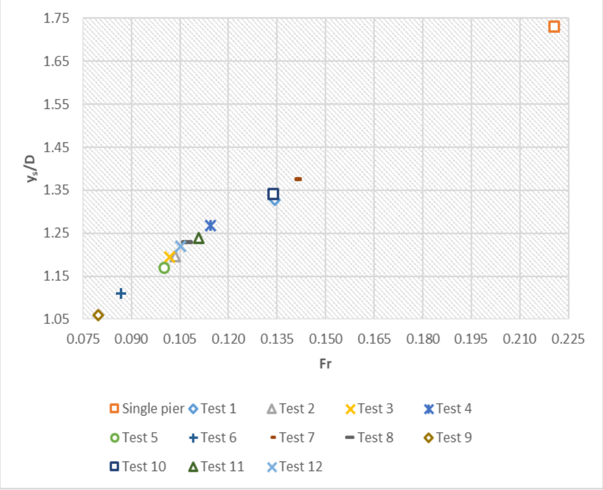
Test	φ_F	D' (mm)	y (mm)	Fr	d_{50} (mm)	D (mm)	y_s (mm) calculated	y_s (mm) of the single pier	% Reduction
1	1	30	83.34	0.13	0.7	30	43.99	46.75	5.90
2	1	30	85.49	0.10	0.7	30	43.37	46.75	7.24
3	1	30	86.65	0.10	0.7	30	43.41	46.75	7.16
4	1	30	89.29	0.11	0.7	30	43.95	46.75	6.00
5	1	30	83.42	0.10	0.7	30	43.13	46.75	7.76
6	1	30	85.48	0.09	0.7	30	42.86	46.75	8.33
7	1	30	87.06	0.14	0.7	30	44.43	46.75	4.97
8	1	30	88.41	0.11	0.7	30	43.69	46.75	6.55
9	1	30	83.37	0.08	0.7	30	42.48	46.75	9.15
10	1	30	86.15	0.13	0.7	30	44.20	46.75	5.46
11	1	30	86.75	0.11	0.7	30	43.66	46.75	6.61
12	1	30	88.26	0.11	0.7	30	43.62	46.75	6.70

TABLE IX. RESULTS OF THE PROPOSED CONFIGURATIONS WITH THE CSU EQUATION.

Test	K_1	K_2	K_3	K_4	D (mm)	y (mm)	Fr	y_s (mm) calculated	y_s (mm) of the single pier	% Reduction
1	1	1	1.1	1	30	83.34	0.134	39.81	51.94	23.35
2	1	1	1.1	1	30	85.49	0.103	35.90	51.94	30.89
3	1	1	1.1	1	30	86.65	0.102	35.81	51.94	31.05
4	1	1	1.1	1	30	89.29	0.114	38.05	51.94	26.75
5	1	1	1.1	1	30	83.42	0.100	35.11	51.94	32.41
6	1	1	1.1	1	30	85.48	0.087	33.28	51.94	35.94
7	1	1	1.1	1	30	87.06	0.141	41.26	51.94	20.57
8	1	1	1.1	1	30	88.41	0.107	36.88	51.94	28.99
9	1	1	1.1	1	30	83.37	0.080	31.80	51.94	38.77
10	1	1	1.1	1	30	86.15	0.134	40.22	51.94	22.58
11	1	1	1.1	1	30	86.75	0.111	37.15	51.94	28.48
12	1	1	1.1	1	30	88.26	0.105	36.56	51.94	29.61



(a)



(b)

Figure 9. y_s/a as a function of Froud number (Fr) from the application of (a) Froechlich equation, (b) CSU equation.

IV. Conclusions

In this article, hydrodynamic numerical models of a cylindrical pier with sacrificial piles in triangular configuration were made to evaluate the influence of piles diameter (d) and separation between the front pile and the face of the pier (X') in local scour. The conclusions obtained from this study are presented below:

- Highest percentage of reduction of local scour was obtained in test 9. In this test, distance between the front pile and the pier face was 3.5D and diameter of sacrificial piles was 1/3D. Froechlich's equation and CSU's equation gave local scour reduction percentages of 9.15% and 38.77%, respectively.
- According to results of all tests, with Froechlich equation, lower percentages of local scour reduction are obtained compared to the percentages of reduction obtained with CSU equation. This variation is because Froechlich equation is sensitive to pier width (parameter that was constant in all tests) and CSU equation is sensitive to flow depth and Froude number (parameters that varied in all tests).
- The reduction of local scour is influenced by diameter of sacrificial piles and mainly by separation between the front pile and the face of the pier (X').
- When separation between the front pile and the face of the pier (X') was 3.5D, higher percentages of local scour reduction were obtained.
- The most influential dimensionless number in local scour is the Froude number.
- According to results of T2 test, Froechlich and CSU equations lose precision with the presence of sacrificial piles.
- It is necessary to carry out physical tests to validate the results obtained in this research.
- For future research it is recommended to perform CFD models to obtain more accurate results. Furthermore, it is recommended to perform tests with different diameters of sacrificial piles and different distances between the front pile and the pier face.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jorge Gamboa and Valeria Quintanilla carried out the tests, analyzed the results and wrote this research. Emanuel Guzmán and Sissi Santos reviewed the final version this research. All authors had approved the final version of this investigation.

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