Experimental Investigation of the Piers Shape Effect on the Scouring in Open Channels

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Abstract

Scour can be defined as the erosion of streambed around an obstruction in a flow field and the lowering of the level of the bed by water erosion, which leads to revealing the foundations of concrete structures. The scour and slitting process may occur naturally as part of the morphologic changes.
This paper presents an experimental study for local scour around different shapes of bridges piers columns using different shapes; namely circular, square, oblique square, a square with circular noses, and oblique rectangular. This experimental study was performed for constant discharge and direction of the flow of the water.

The obtained results showed that scour values for both length and width follow the same pattern as that of the vortices length and width formed for all the studied five pier columns. It was concluded that the lowest depth of scouring was achieved using the square pier column with circular noses, while the greatest depth of scouring was obtained using the square pier column.

The difference values for scour hole dimensions between the square pier column with circular noses and the other four shapes of pier columns were calculated. It was found that scour hole dimensions for the studied four shapes of pier columns were bigger than those of the square pier column with circular noses. From the obtained results, scouring length (and width) could be predicted by knowing vortex length (and width) for a specific shape of the pier column.

Keywords

Water structures – bridges – vortex – recirculating flume – piers

1. INTRODUCTION

Among the reasons affecting the safety of bridges are the scour and sedimentation processes around bridge structures, taking into account some parameters concerning flood flow, bed soil, and bridge geometry.
Generally, it is important to predict the maximum scour to minimize the risk of bridge failure and to minimize the cost of the bridge construction.
Many bridges collapse annually causing the loss of life and property for some people. Wardhana and Hadipriono (2003) presented a study of 503 failure bridges from 1989 to 2001 collecting the data from the New York State Department of Transportation (NYSDOT), wherein the USA there is about 60% of the total bridge failures. In 1993 during the flood event at Upper Mississippi, it was reported that 28 highway bridges failed including 22 because of scouring representing 80%.
Muzzammil and Gangadhariah (2003) investigated experimentally the primary horseshoe vortex formed in front of a cylindrical pier which is the prime agent responsible for scouring. A scour prediction equation was found to give better results compared to the results of well-known predictor models.
Barbhuiya and Dey (2004) studied the vortex size, vortex velocity, and vortex strength were determined in terms of the relevant hydraulic and geometric parameters and the temporal scour hole evolution. In contrast to most other studies, a generalized approach was selected to determine the velocity distribution.
Marsh et al. (2004) presented a comparison of four methods for predicting the incipient motion conditions of a uniform sand bed. The four methods were used to predict the incipient motion conditions for 97experimental runs. The simplified resolution of the rotational forces model and Shields method were most successful in predicting the incipient motion velocity. While the empirical method was the least successful at predicting the measured incipient motion conditions.

Dey and Barbhuiya (2005) presented a semi-empirical model to compute the time variation of scour depth in an evolving scour hole at short abutments, 45° wing wall, and semicircular.

Dey and Raikar (2005) studied experimentally the clear-water scour at circular and square piers embedded in a sand bed overlain by a thin armor layer of gravels. A comparison of the experimental data showed that the scour depth at a pier with an armor layer was greater than that without an armor layer for the same bed sediments.

Das and Mazumdar (2015) conducted an experimental study of the flow pattern and characteristics in a local equilibrium scour around a set of identical circular piers placed eccentrically. The eccentricity and longitudinal spacing were equal to three times of pier width and 0.5 times the scour-affected length in the equilibrium condition of a single pier. The maximum depth of the scour at the eccentric rear pier was about 44% greater than that in the single pier case.

Das et al. (2016) determined the equilibrium scour geometry around circular, square, and equilateral triangular piers, positioned in-line front and eccentric rear arrangement. The eccentricity was kept constant with the varying longitudinal spacing. The maximum depth of the scour hole upstream of the in-line front pier was about 35% more than at the single-pier case.

Jaman et al. (2017 a, b) investigated the hydrodynamic consequences of three-pier arrangement on scouring. Maximum equilibrium depth of all scour holes gauged for the inline front, eccentric-middle, and inline-rear piers were about 40, 61, and 15% larger than depth for one single-pier experiment.

Khaple et al. (2017) studied the effect of the kinds of pier arrangements. For two piers in tandem, the scour depth downstream the pier was always smaller than that upstream the pier.

Yilmaz et al. (2017) performed experiments and presented design charts giving the relation between dimensionless scour depth and time for practical use.

Zahraa F. Hassan et al. (2020) measured scour depths in the laboratory for both the upstream and the downstream pier using a rectangular-section flume. The scour depth measured at the upstream pier was greater than that measured at the downstream pier in all experiments. The maximum scour depth for the two in-line piers was 10% higher than the scour depth at the single pier.

Amir and Rasoul (2020) introduced three different physical models with different discharges to study the local scour downstream of the structure. The dimensions of scour pit decreased by increasing the steps height and tailwater depth. Increasing the discharge, the increased momentum of the flow promoted scouring. In addition, the results showed that scouring at the sidewalls was higher than in the middle of the cross-section.

Halah Kais Jalal and Waqed Hassan (2020) simulated the flow around a cylindrical pier using a Flow-3D numerical model. The results indicated that the scour depth reached a maximum value with the increase in pier width, and the rectangular piers had a maximum value of scour depth ratio of 1.7 at a maximum pier width ratio of 0.2. While other cases had a scour depth of about 1.01 at a pier width ratio of 0.2. Also, the results suggested that the lenticular shape could be considered as the optimum pier shape for reducing the maximum scour depth, producing a reduction of about 40% as compared with the rectangular shape in most cases.

Cardoso et al. (2021) studied the equilibrium scour depth at single vertical piers. The critical value of flow intensity at scouring was not constant but rather a function of the relative flow depth. The relative sediment size factor was not constant for values of D50 above 25 – 50, as it was frequently assumed, but it rather decreased in the range 100 < D50 < 500.

The main objective of this study is to get the best pier shape that minimizes the scouring effect and study the relation between vortices' geometric characteristics and scour hole dimensions.

2. MATERIALS AND METHODS

2.1. Experimental Methodology

To achieve the objectives of the research, practical experiments were carried out using recirculating flume as a model and different shapes of piers columns were employed at a constant speed and discharge during a specified period.

The depth of the scouring gap formed at each form of pier column was studied and calculated.

The experiments were conducted for 5 different forms of these piers and a comparison was made between the different results of these forms to find out the maximum and minimum depth of scouring and to know the best form that can be used to reduce the scour process affecting the piers columns in waterways.

2.2. Experimental Technique

The experiments were carried out in a recirculating flume with a max width of 60 cm and a total length of 2.6 m, and all its external parts and sides were made of metal, as shown in Figure 1. The channel was divided from the inside using transparent fibers so that all the changes and results formed within the flume could be studied. The width of the back part of the flume was 60 cm and remained in a regular width up to a length of 68 cm. Then a wire mesh was placed in a direction perpendicular to the direction of the water flow. Then, through a length of 60 cm, the flume narrowed gradually to a width of 24 cm. This width continues for a length of 1.22 m, which was the part dedicated to experimenting.

At the end of the flume, there was a circular weir to prevent the sand from leaking at the bottom of the flume into the pump again. The flume was provided with the main tank with a head of 1.5 m. There were also 2 glass secondary tanks equipped with thin hoses to inject water in different colors to clarify and study the impact of the different shapes of the piers columns on the vortices formed.

A laser device was used to measure the depth of the water inside the flume. Also, a high-quality camera was used, which was installed on the body of the flume, to photograph the different shapes of the vortices, to clarify the extent of their overlap, and to photograph the forms of the scour formed behind each of the models used. The velocity has been measured using a device Anemometer.

In this study, as shown in Figure 2, five different shapes of piers were considered:

1) A circular pier column with a diameter of 0.05 m.
2) A square pier column with a length of 0.05 m and a width of 0.05 m.
3) An oblique square pier column with a length of 0.05 m and a width of 0.05 m.
4) A square pier column with circular noses with a length of 0.05 m, a width of 0.05 m, and a nose radius of 0.025.
5) An oblique rectangular pier column with a length of 0.09 m and a width of 0.05 m.

The pier was first fixed in the flume at the desired location using a plate with a length of 0.60 m and a width of 0.20 m, as shown in Figure 3.

3. RESULTS AND ANALYSIS

3.1. Studying the Vortices formed for Different Shapes of Piers Columns

The experiments were done for five shapes of the piers columns, as shown in Figure 4. The depth of water in the flume was 0.20 m, the velocity of water was 0.35 m/s, the discharge was 0.0168 m^3/s, and the time of experimental for each pier was 5 sec. At the fifth second, the length and width of the vortices formed became constant.

Figure 1. The Flume

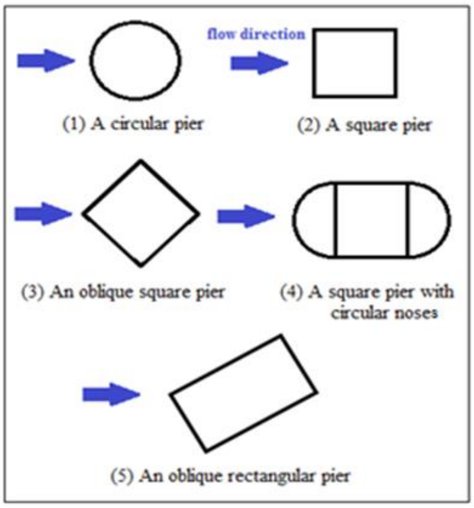
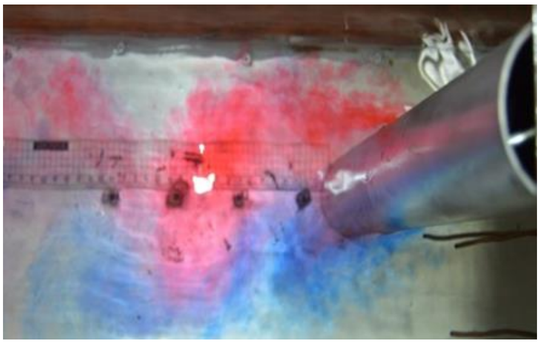
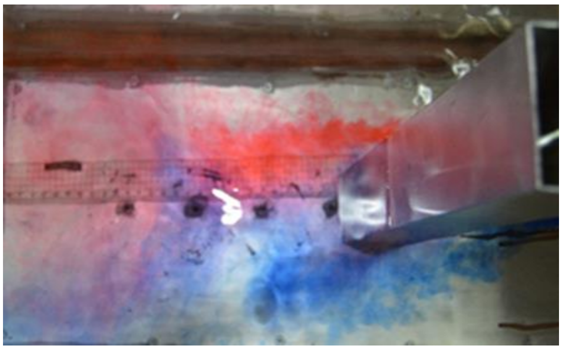


Figure 2. Different Shapes of Piers Columns

Figure 3. The Fixation Plate

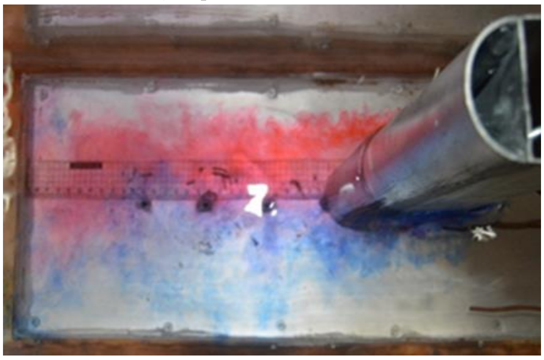


1) Circular Pier Column



2) Square Pier Column

3) Oblique Square Pier Column



4) Square Pier Column with Circular Noses

5) Oblique Rectangular Pier Column

Figure 4. Vortices for Different Piers Columns

It was noted that the square column had the most impact on the shape of the formed vortices, as it achieved the largest width and length of the vortices. While the square column with circular noses performed the least effect, as it achieved the least width and length of the vortices formed, as shown in Table 1 and Figure 5.

Table 1. Vortices Geometric Characteristics for Different Piers Columns

Pier Shape	b, cm	L_v, cm	W_v, cm	L_v /b	W_v/b
Circular	5.00	15	13.00	3.00	2.60
Square	5.00	24	20.00	4.80	4.00
Oblique square	7.00	22	19.00	3.14	2.71
Square with circular noses	10.00	14	12.50	1.40	1.25
Oblique rectangular	10.30	21	18.00	2.04	1.75

Where: b = pier length in the flow direction, Wv, Lv = width, and length of the vortex area behind the pier column.

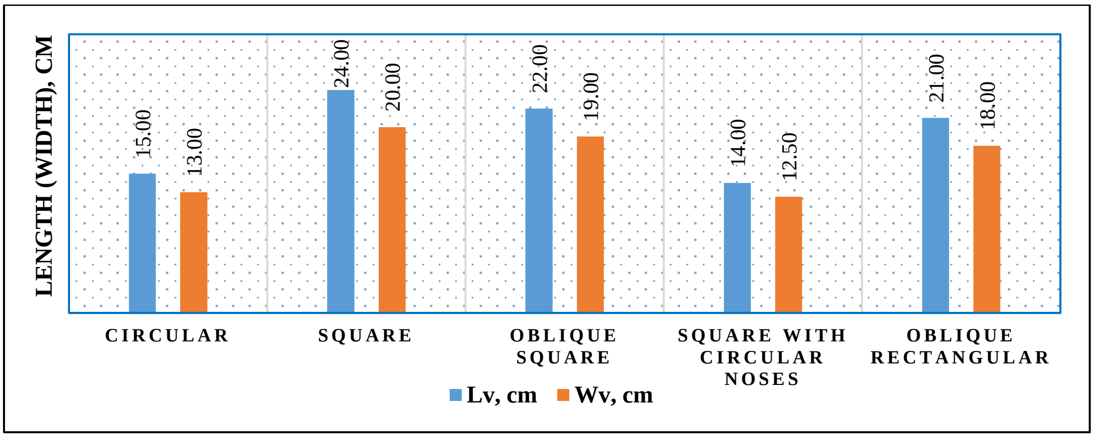
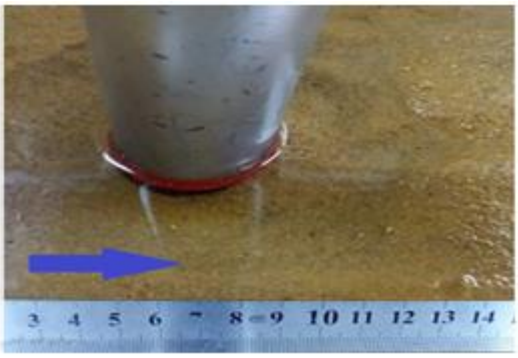


Figure 5. **Vortices Geometric Characteristics for Different Piers Columns**

3.2 Studying the Scour formed for Different Shapes of Piers Columns

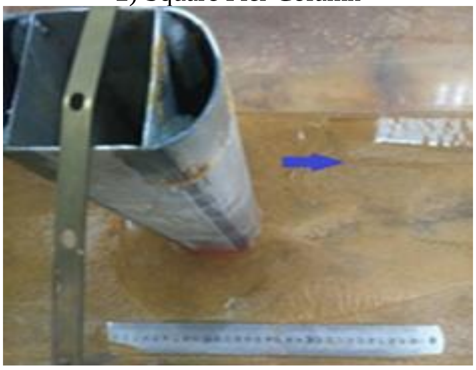
The experiments were conducted for each of the five shapes of piers columns, as shown in Figure 6. The depth of water in the flume was 0.20 m, the velocity of water was 0.35 m/s, the discharge was 0.0168 m^3/s, and the time of experimental for each pier was 20 minutes.



1) Circular Pier Column

2) Square Pier Column

3) Oblique Square Pier Column



4) Square Pier Column with Circular Noses

5) Oblique Rectangular Pier Column

Figure 6. Experiments of the Scour for Different Shapes of Piers Columns

The sand was spread well to a depth of 5 cm at the bottom of the flume in the part designed to experiment. A laser device was installed and used to measure the depth of the erosion with a movable trolley. A high-accuracy camera was also used to take pictures showing the shapes and places of the formed erosion and sedimentation for the soil employing the different shapes of the piers columns. Using the laser device, several readings were taken to clarify the depth of the erosion formed, behind and on both sides of the pier used. Employing the measuring rule, the distance of the erosion formed in all directions was calculated.

Using surfer program version 16, the scour-affected zones and contour lines of the scour holes for the five shapes of piers columns are shown in Figures 7 through 11. For each case, 3 longitudinal sections A-A, B-B, and C-C of the contour lines in the direction of the water flow were studied to clarify the locations of the formed scour and to measure the maximum depth, length, and width of the scour. Thus, the maximum scours depth, length, and width were determined in front of, at the rear of, and besides all studied shapes of piers columns. Also, the scour volumes were calculated.

The maximum values for depth, length, and width of scouring for all studied shapes of piers columns are presented in Table 2. Figure 12 presents a comparison between the different shapes for piers columns in terms of scour depth, length, and width.

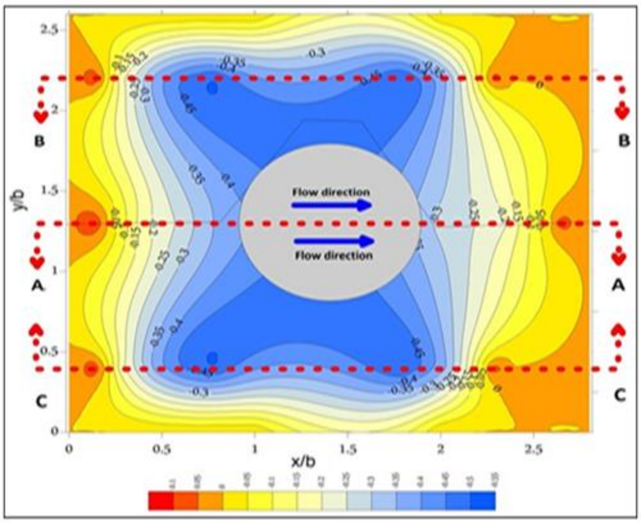


Figure 7. Contours of Scour-Affected Area for Circular Pier Column

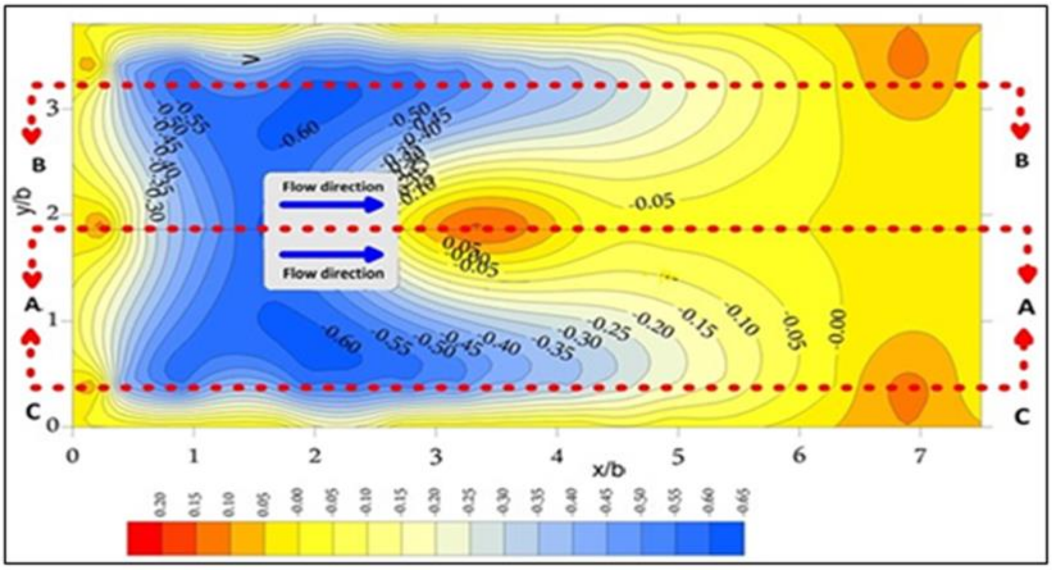


Figure 8. Contours of Scour-Affected Area for Square Pier Column

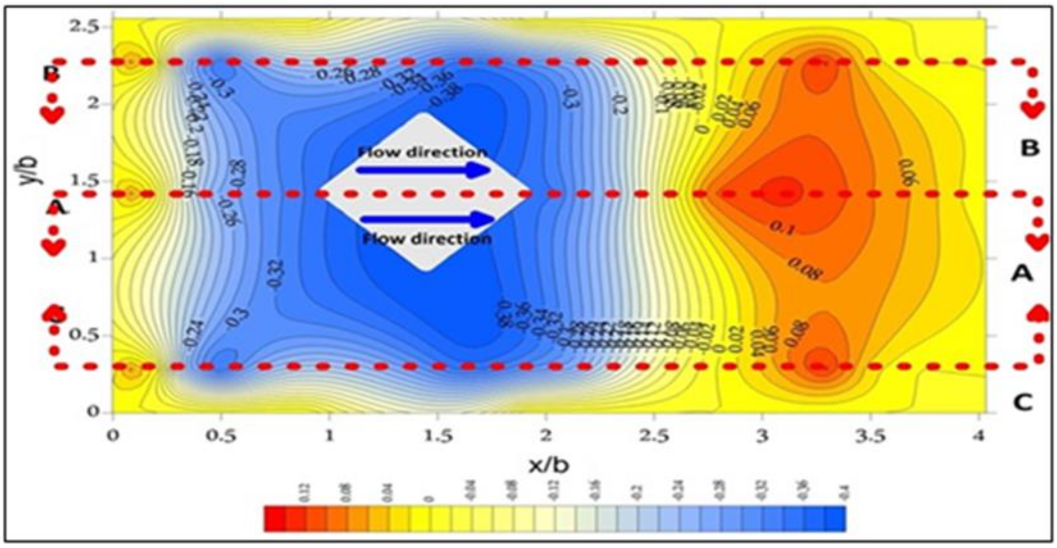


Figure 9. Contours of Scour-Affected Area for Oblique Square Pier Column

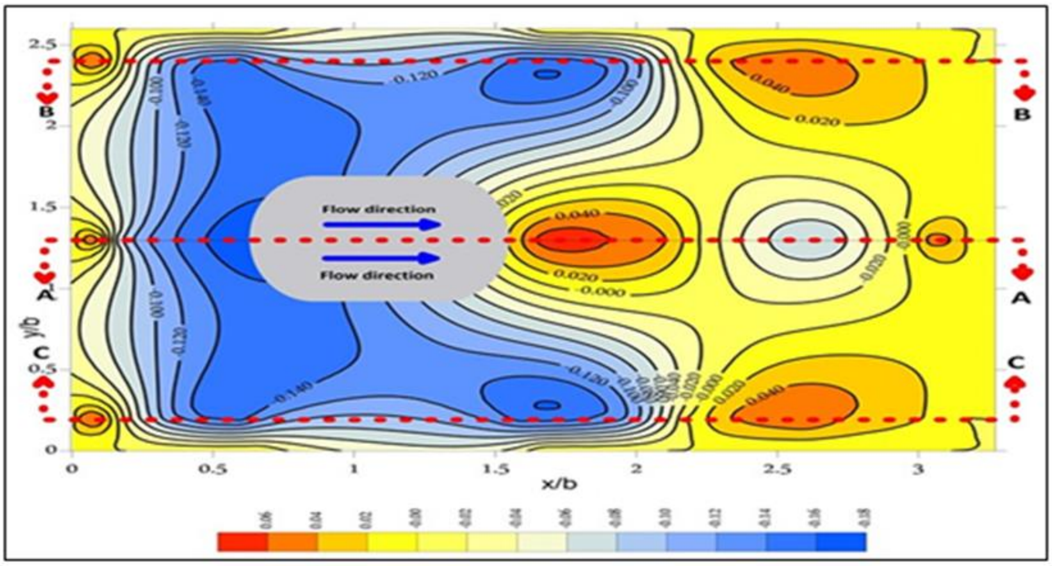


Figure 10. Contours of Scour-Affected Area for Square Pier Column with Circular Noses

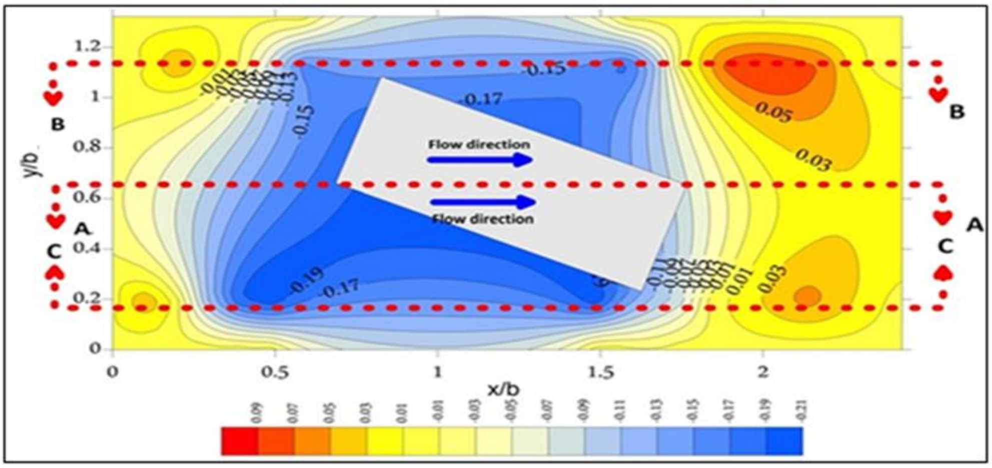


Figure 11. Contours of Scour-Affected Area for Oblique Rectangular Pier Column

Table 2. The Maximum Scour Hole Dimensions

Pier Shape	**b, cm**	**d_s, cm**	**l_s, cm**	**w_s, cm**	**$\forall_s$, cm^3**
Circular	5.00	2.50	10.40	11.50	230.47
Square	5.00	3.10	30.40	19.00	829.36
Oblique square	7.00	2.38	18.00	18.60	583.28
Square with circular noses	10.00	1.80	21.00	20.00	574.18
Oblique rectangular	10.30	2.10	23.50	22.00	611.77

<u>Where:</u> b = pier length in the flow direction, d_s, l_s, and w_s = max depth, length, and width

$\forall_s$ = scour volume

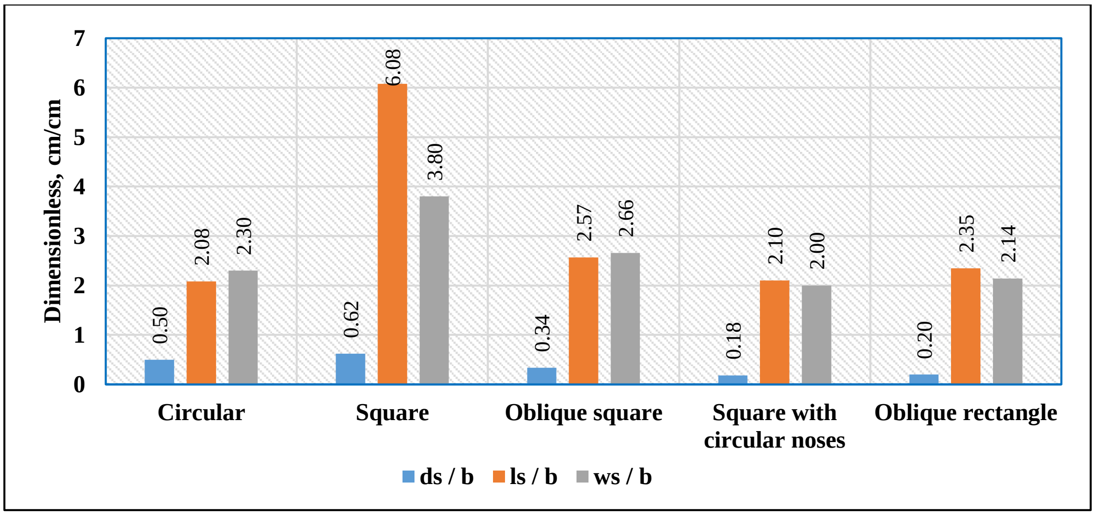


Figure 12. Comparison between the Different Shapes for Piers Columns in terms of Scour Hole Dimensions

From the obtained results, it was concluded that values of scour hole dimensions (l_s and w_s) followed the same pattern as that of the vortices geometric characteristics (L_v and W_v) formed for all the studied five pier columns, as shown in Figures 13 and 14.

It was concluded that the values of scouring length to vortex length for circular, square, oblique square, square with circular noses, and oblique rectangular piers were 0.69, 1.27, 0.82, 1.5, and 1.12, respectively. Also, the values of scouring width to vortex width for circular, square, oblique square, square with circular noses, and oblique rectangular piers were 0.88, 0.95, 0.98, 1.6, and 1.22, respectively. Thus, scouring length (and width) could be predicted by knowing vortex length (and width) for a specific shape of the pier column.

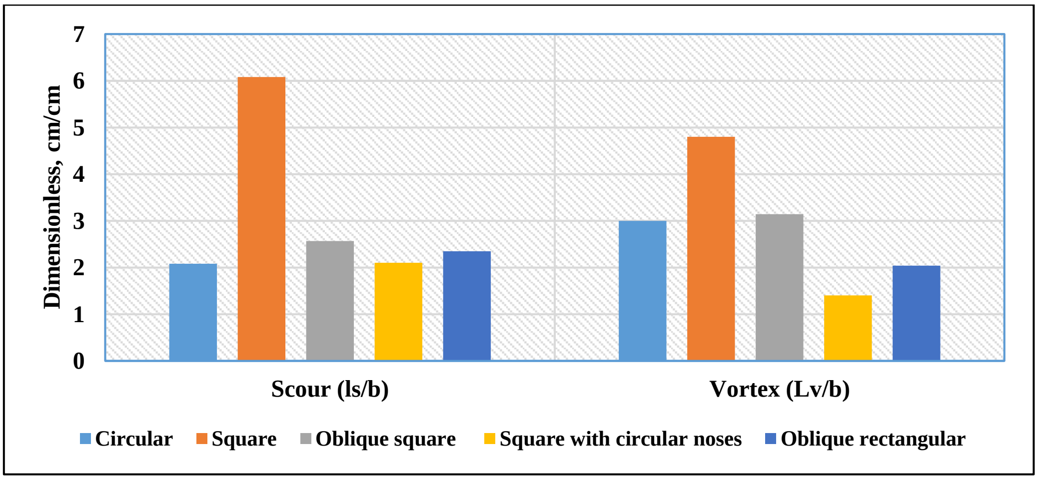


Figure 13. Dimensionless Length for Scour and Vortices for Piers Columns

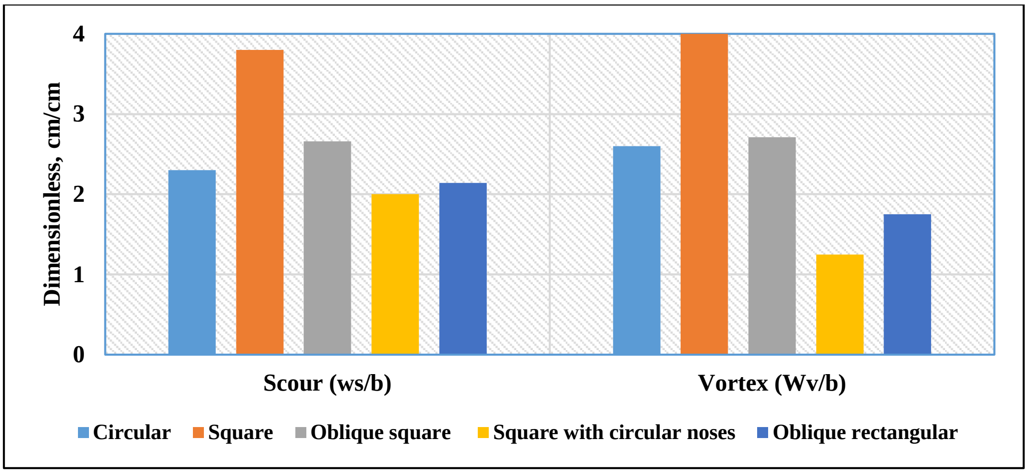


Figure 14. Dimensionless Width for Scour and Vortices for Piers Columns

4. CONCLUSION

From the obtained experimental results, it was found that values of scour hole dimensions followed the same pattern as that of the vortices geometric characteristics formed for all the studied five pier columns.
It was concluded that the best shape of the pier was the square with circular noses as it achieved the least local scour depth and the least length and width of the vortices formed behind it.
According to the values of the depth of the scour formed, the circular pier column was the second rank, followed by the oblique rectangular pier column, and the oblique square pier column takes the fourth rank.
The worst shape was the square pier column as it achieved the greatest scour depth and volume and the largest length and width of the vortices formed behind it.
The difference values for scour depth compared with that of the square pier column with circular noses were more by 11%, 89%, 178%, and 244% for the oblique rectangular, the oblique square, the circular, and the square piers, respectively.
The difference values for scouring length compared with that of the square pier column with circular noses and the circular were more by 13%, 24%, and 192% for the oblique rectangular, the oblique square, and the square piers, respectively.
The difference values for scouring width compared with that of the square pier column with circular noses were more by 7%, 15%, 90% for the oblique rectangular, the circular, and both the oblique square and the square piers, respectively.
From the obtained results, scouring length (and width) could be predicted by knowing vortex length (and width) for a specific shape of the pier column.

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