

Article



Experimental and Numerical Studies on Local Scour around Closely Spaced Circular Piles under the Action of Steady Current

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Abstract: Scour at coastal structures is a serious problem that causes damage to structures. Focusing on scour around typical gravity-type breakwaters, previous studies have revealed that scour is mainly caused by standing waves in the front of structures. For breakwaters, which consist of closely spaced circular piles, scour caused by flow may occupy a dominant position. In the present work, the scour caused by a small velocity intensity flow was studied using both experimental and numerical models. The experiments revealed that the scour depth around closely spaced circular piles was significantly larger than that of a single pile with the same diameter. The numerical model was verified by theoretical values of flow field and experimental values of scour topography. More detailed flow field information is described using a numerical model that can improve the understanding of scour mechanics. Both experimental and numerical models demonstrate that scour first occurs on the side of piles owing to the shrinkage effect of streamlining and then extends forward and backward. In addition, the scour mechanics change with the increase of the pile spacing.

Keywords: closely spaced circular piles; local scour; experimental model; numerical models; scour depth

1. Introduction

Closely spaced circular piles are widely used as the foundation of breakwaters [1] and shore protection projects [2] in coastal engineering. Many previous studies focused on the hydrodynamic performance of such structures [1,3,4], but due to the blocking effect, they may be subjected to severe local scour.

Scour has been identified as a major threat in coastal engineering [5], which includes the scour around pipeline [6–8], pile foundation [9,10], and gravity-type breakwaters [11–14]. Many researchers have studied the scour around such structures. But studies on the scour around closely spaced circular piles are relatively less, and the scour mechanisms around closely spaced circular piles are very different from those previously studied.

Previous studies focusing on gravity-type breakwaters have revealed that scour is mainly caused by a standing wave in front of the breakwater [12,14–16]. This standing wave leads the generation of recirculating cells [17], which is the hydrodynamic reason for sediment transport. Due to the difference in sediment sizes, the sediment transport motion and seabed evolutions are different.

For a breakwater consisting of closely spaced circular piles, scour induced by regular waves has been studied using an experimental model [2]. It shows that the maximum scour depth around the closely spaced pile under the action of regular wave is approximately 1.5~2.0 times the pile diameter, which exceeds the maximum values observed for a single pile under the action of steady currents. It should be noted that in the experiment



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of Hayashi, et al. [2], the sediment particles were artificial particles rather than natural quartz sand.

A similar phenomenon was observed by Heikal, et al. [18]. Their studies showed that the maximum scour depth on the side of the pile is approximately 1.8 times the pile diameter. This scour depth is close to the maximum scour depth of a single pile under steady current in clear water critical conditions [19,20], where U/U_c is close to 1.0. Thus, scour on the side of the piles cannot be neglected.

Scour induced by solitary waves has been studied using several experimental models [21]. The results of studies indicated that scour occurs on both sides of the breakwater, and the maximum scour depth occurs in the gap between the two piles. This phenomenon is in accordance with the results observed by Heikal, et al. [18].

These phenomena mentioned above are very different from those observed around traditional breakwaters, where the scour is mainly in the seaward area. The major hydrodynamic difference between single piles (or pile groups) and breakwaters consisting of closely spaced circular piles is the blocking effect. The blocking effect is not taken into consideration in scour around a single pile or pile groups. For breakwaters consisting of closely spaced circular piles, the resulting blocking effect leads to strong jet flows which will enhance the scour depth and shorten the time required to reach equilibrium [21].

Ocean waves and currents are the important factors in the marine dynamic environment [22,23]. Many researchers considered steady flow as a wave with an infinitely large period [5], which means that the equilibrium scour depth for single piles in pure waves are smaller than those in steady currents with the same maximum velocity [21,24,25]. To determine the maximum scour depth around breakwaters consisting of closely spaced circular piles, steady currents are chosen as the hydrodynamic condition in present work.

Previous studies have shown that the scour around closely spaced circular piles can be attributed to both the blocking effect and the horseshoe vortex. The low velocity intensity cannot lead to the generation of the horseshoe vortex [7], which is the main hydrodynamic mechanics feature for the scour in front of the pile [26]. Thus, a velocity intensity close to O(0.4), which is the lower limit of the local scour condition for a single pile, ensures that no horseshoe vortex occurs around a single pile. Additionally, it could eliminate the effect of the horseshoe vortex for single pile but cannot eliminate the blocking effect which may cause the horseshoe vortex. If a horseshoe vortex is found with small pile spacing, it would be caused by blocking effect.

In order to study the sophisticated flow field and vortex around the piles more accurately, a numerical model is a common and effective method. Five different categories of numerical models are often adopted in studies of local scour around marine structures. They are equilibrium scour models, depth-averaged models, sediment transport rate models, two-phase models, and CFD-DEM models [27]. Equilibrium scour models and depth-averaged models for faster calculation speed. Sediment transport rate models are one-phase models which cannot be used under high Reynolds number or strong turbulence conditions. This is different from sediment transport rate models and CFD-DEM models can be used under high Reynolds number or strong turbulence conditions. The main differences between two-phase models and CFD-DEM models and CFD-DEM models and the guantification of all sediment particles and require more computing resources. Here, two-phase models are adopted for the study of detailed flow-field information and the quantification of some variables that are difficult to measure, such as shear stress and vortex characteristics.

The aim of the paper is to study the effect of pile spacing on the hydrodynamic mechanics and scour depth of a breakwater under the action of steady current using both experimental and numerical simulations. The remainder of the paper is organized as follows: Section 2 introduces the physical experimental setup and the results. In Section 3, the numerical model and the verification of the model are given. The results and discussion of the numerical model are analyzed in Section 4. Finally, Section 5 contains the conclusion.

2. Experimental Model

2.1. Experimental Setup

The experiments were conducted in a rectangular glass-sided flume with a length, width, and depth of 60 m, 3 m, and 1.5 m, respectively. The flume is located at the Shandong Provincial Key Laboratory of Ocean Engineering, Ocean University of China. The detailed experimental settings can be found in the work of Lu, et al. [28]. The same cohesionless uniform sediment is used in present work, which means that the median particle size (D_{50}) is 0.66 mm, the geometric standard deviation of particles (σ_g) is 1.33, and the water depth is 0.30 m. Thus, the critical shear velocity (θ_c) is 0.029, and the critical flow velocity (U_c) is 0.32 m/s.

Flume was divided into two parts with glass partitions. Thus, two experiments can be conducted simultaneously (see Figure 1). There were 10 piles on one side and 12 piles on the other side. The diameters of all piles (made of aluminum alloy) were the same (0.1 m). The ratios of pile spacing (*S*) to the pile diameter D_p were set as 1.25 and 1.5. The experiment duration (*T*) was set to 5 h.



(b) Top view of sand recession

Figure 1. (a) Side view of flume and (b) Top view of sand recession, numbers $1, 2, \dots 10$, represent the marked number of piles in Experiment 2 and numbers $1, 2, \dots 12$, represent the marked number of piles in Experiment 1.

The mean velocity (*U*) in the present experiment was 0.14 m/s, and the velocity intensity (U/U_c) was 0.44, which was close to the lower limiting condition of the local scour for a single pile. This ensures that the local scour around a single pile with the same diameter is very small, or that there is no scour at all. The numerical model of this study proved that the maximum scour depth D_{st} can be treated as negligible compared D_p , because D_{st} was approaching $0.05D_p$. A three-dimensional handheld scanner (HSCAN) was used to scan the topography at the end of the experiment. The detailed experimental conditions and results are listed in Table 1.

Exp.	<i>d</i> (cm)	$\frac{U}{U_c}$	D _p (m)	$\frac{S}{D_p}$	T (h)	D _{s,end} (cm)
1	30	$\begin{array}{c} 0.44 \\ 0.44 \end{array}$	0.10	1.50	5.0	12.2
2	30		0.10	1.25	5.0	18.0

Table 1. Total experimental conditions and results.

2.2. Experimental Results and Discussion

The time factor (K_t) is key to extrapolating the experimental data to equilibrium scour depth, which is defined as:

$$K_t = \frac{D_{st}}{D_{se}} \tag{1}$$

where D_{se} is the equilibrium scour depth at time *t*. The experimental data includes a series of time (*t*) and the corresponding D_{st} ; full use was made of the observed data in order to make the prediction more accurate and reliable. The least-square method (LSM) was adopted to predict D_{se} using experimental data with Equation (2).

$$D_{se} = \frac{D_{st}}{K_t} \tag{2}$$

The method proposed by Briaud, et al. [29] [Equation (3)] was adopted to extrapolate the experimental data in this paper because of its good performance (square of correlation coefficient, $R^2 > 0.99$). The fitting curves obtained by Equation (3) and the experimental data are shown in Figure 2. This method has been widely adopted by researchers [30–33] as an extrapolation method for scouring around pile groups and submerged structures.

$$K_t = \frac{t}{t + T_0} \tag{3}$$

t is the experimental time; T_0 is the time which depend on the experimental condition. Both experiments had high values of R^2 ($R^2 > 0.99$). The D_{se} of the present experiments were 13.6 cm and 19.9 cm for Exp. 1 and Exp. 2, respectively, using the method described above.

The maximum scour depth occurred on the side of closely spaced circular piles, very different from the scouring around a single pile, which occurred in the front of the pile. This phenomenon was in accordance with the maximum shear stress in the numerical models, as discussed in the following section.

 D_{se} in all of our experiments were much larger than D_p . Photographs of the experiments are shown in Figure 3.







Figure 3. Photos of the experiments; (a) Exp. 1 and (b) Exp. 2.

3. Numerical Models

A numerical model from Flow3D was used to study the local scour around closely spaced circular piles with different spacings under the action of a steady current. The detailed information of this CFD software can refer to the user manual [34].

Two different types of models were established in present work. One is the hydrodynamic model, which was used to provide a steady flow field for further study. The other is the scour model, which was designed to model the sediment scour process under hydrodynamic conditions.

3.1. Model Setup

The Reynolds-Average Navier-Stokes equations (RANS), closed via the RNG $k - \varepsilon$ turbulence model, were adopted as the governing equations for the incompressible viscous flow around the breakwater consisted with closely spaced circular piles. The turbulence model is crucial in the sediment scour model, because it directly affects the calculation of shear stress, which is then used to calculate the rates of entrainment and bed-load erosion. The FAVOR (fractional area volume obstacle representation) method adopted by Flow3D can accurately describe the geometry with fewer mesh cells compared with the traditional finite difference method [34].

To simplify the simulation process and reduce the total grid number, symmetry boundaries were used. The pile was set at the center of the numerical flume, and the width of the flume was adjusted according to the pile spacing.

The sediment scour model was activated in the scour model in order to simulate the sediment scour process. The detailed sediment parameters are listed in Table 2.

Table 2. Sediment parameters.

D ₅₀ (mm)	$ ho_S$ (kg/m ³)	θ_{cr}	Entrainment Coefficient	Bed Load Coefficient	Angle of Response
0.66	2650	0.029	0.20	0.50	32°

Numerical size: The *x*-axis direction was consistent with the incoming flow direction. The direction of the *z*-axis was opposite to that of gravity. The *y*-axis was perpendicular to the XZ plane to form a right-hand coordinate system.

X-direction: -39 m-3 m, the specified velocity (0.14 m/s) was adopted as the inlet boundary, and the outflow boundary condition was adopted at the outlet; Y-direction: -0.375-0.375 m, the left and right sides used the symmetry boundary; Z-direction: -0.30-0.35 m, the top used the specified pressure, and the bottom was set as the wall. In the flow field calculation, the bed surface was set as a solid with the same rough length ($z_0 = D_{50}/12$) as the sediment surface.

3.2. Verification of the Hydrodynamic Model

Mesh independence:

The velocity distribution was adopted in order to verify the mesh independence, which can be calculated as,

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{4}$$

where $z_0 = k_s/30$ is the bed roughness length, $k_s = 2.5D_{50}$ is the Nicholas roughness, and κ is the Karman constant (0.4) according to Soulsby [35].

The unified grid size (dx) was used in all directions of the flume, and the numerical models were established with dx = 0.03 m, 0.02 m, 0.01 m, 0.0075 m, and 0.005 m. The deviation between the simulated velocity and theoretical velocity value [Equation (4)] gradually decreased with the decrease in the grid sizes. When the grid size reached 1 cm, the deviation did not decrease further but rather increased slightly (Figure 4). Thus, the following conclusions were drawn:





When the grid size is between 0.0075 m and 0.01 m, a further increase in grid accuracy cannot improve the calculation accuracy and will cause greater deviation. This it showed that the numerical model has grid independence.

The corresponding y^+ dimensionless distance from the first layer of the grid to the sediment surface; Equation (5) [34] is equal to 36, which meets the requirements of the manual, as in Equation (6) [34]. This ensured that the models could simulate the shear stress accurately.

$$y^{+} = \frac{\Delta y}{v} \sqrt{\frac{\tau_{w}}{\rho_{w}}} \tag{5}$$

$$O(11.5 \sim 30) < y^+ < O(100 \sim 500)$$
(6)

 Δy is the distance from the first layer of the grid to the sediment surface; v and ρ_w are the kinematic viscosity coefficient and density of water, respectively; τ_w is the shear stress of the water flow acting on the sediment surface.

Based on the analysis of the above results, the vertical velocity distribution at X = -20 to -15 m is in the best agreement with the theoretical values (Figure 5), and the flow field elements change slowly along the X direction within this range. Therefore, the piles should be placed in this range in subsequent simulations of sediment scour. The grid overlay (GO) boundary was placed at X = -25 m, and the pile center point was X = -15 m. Thus, the entire model was placed in the interval mentioned above.



Figure 5. Velocity distribution along the Z-direction at different X positions.

The GO boundary combined with the restart function can effectively reduce the number of grids, improve the calculation efficiency, and reduce the calculation time. The GO boundary uses the steady flow field obtained by the simulation as the input flow field of the subsequent scouring simulation.

3.3. Verification of the Sediment Scour Model

Based on the aforementioned settings, the hydrodynamic models were verified to simulate the flow field accurately. Subsequently, the sediment scour models were activated. It should be noted that the scour rate of the numerical models presented herein was much faster than that of the experimental models owing to the larger entrainment coefficient and bed-load coefficient (Table 2). These settings were chosen in order to reduce the simulation duration and save computing resources. The scour rate of the numerical models can be adjusted to the same rate as that of the experimental models by adjusting the coefficients mentioned above.

Exp. 2 was selected to verify the numerical model. The D_{st} of the numerical model is shown in Figure 6. D_{se} of the numerical model was 13.4 cm. The relative error of the numerical model was $\left|\frac{13.6-13.0}{13.6}\right| = 4.4\%$ in the scour depth. The equilibrium scour depth was underestimated slightly with the numerical model compared with the experimental models, which is consistent with the findings of Roulund, et al. [36] and Zhao, et al. [30]. It can be concluded that the proposed numerical models are effective in simulating D_{st} .



Figure 6. The temporal development of D_{st} in the numerical model.

The comparison of final scour topography in the numerical model and experimental model are plotted in Figure 7. The upper part of Figure 7 is the topography of the experimental models, and the lower part is the topography of the numerical models. The central circle is the pile.



Figure 7. The comparison of the final topography in the numerical models and experimental model.

As shown in Figure 7, in the area within the range of $-15.15 \sim -14.95$ m of the pile we focused on, the topography of the scour holes of the numerical models and experimental results are consistent. The numerical model proposed can simulate the scouring process around the pile.

Based on the verified sediment scour models, the following cases (listed in Table 3) were set to further study the effects of pile spacing. Case 6 is a basic test for a single pile, whose S/D_p can be treated as infinitely large.

Case	Model Type	S/D _p
1	Closely spaced circular piles	1.5
2	Closely spaced circular piles	1.8
3	Closely spaced circular piles	2.0
4	Closely spaced circular piles	3.0
5	Closely spaced circular piles	4.0
6	Single pile	∞

Table 3. Numerical simulations of the present work.

4. Numerical Results and Discussion

4.1. Hydrodynamic Characteristics

The increase of shear stress caused by streamline concentration is the main reason for the initial scour in the cases of single pile and closely spaced circular piles. τ_{max}/τ_0 the ratio of the maximum shear stress to the undisturbed shear stress; τ_{max} and τ_0 are the calculated values of 0.005 m (half of dx) above the sand bed is plotted in Figure 8. τ_{max}/τ_0 decreased rapidly with an increase in S/D_p . When S/D_p is equal to 4, τ_{max}/τ_0 can be treated as equal to that in Case 6. This means that $(S/D_p)_{cr}$ (the critical pile spacing with no pile group effect) is O(4).



Figure 8. τ_{max}/τ_0 changes with S/D_p of the present work; dashed line denotes τ_{max}/τ_0 in Case 6 (single pile).

Another characteristic of shear stress is its distribution.

The maximum excess shear stress, which is the shear stress minus the shear stress without piles in the same place, was 0.596 Pa, while the shear stress of the undisturbed flow (τ_0) was 0.041 Pa at the same location. Excess shear stress in Case 1 is plotted in Figure 9; the excess shear stress of Case 4 is plotted in Figure 10.



Figure 9. Excess shear stress distribution (0.05 m above the seabed) of Case 1.



Figure 10. Excess shear stress distribution (0.05 m above the seabed) of Case 4.

The maximum excess shear stress occurred in Case 1 on both sides of the pile, whereas the maximum excess in Case 4 occurred between the side and the upper flow side. The shear stress distribution of Case 4 is similar to that of the distribution of a single pile under a steady current [37].

The main reason for these differences is the blockage effect; in the case of closely spaced circular piles, streamline concentration occurs in all piles. Therefore, the most concentrated streamline was in the section where the adjacent piles had the shortest distance.

The horseshoe vortex is an important hydrodynamic characteristic. The horseshoe vortex of Case 1 at the end of time is plotted in Figure 10. The horseshoe is limited to the range of -0.13-0.08 m $(0.5D_p)$ in the Z-direction and -15.10-15.05 m $(0.5D_p)$ in the

X-direction. Based on the analysis of Sumer and Fredsøe [5], $Re_{D_p} \left(\frac{\delta}{D_p}\right)^{1/2}$ must follow Equation (7) then horseshoe vortex occurs.

$$Re_{D_p}\left(\frac{\delta}{D_p}\right)^{1/2} > 800\tag{7}$$

In this study, for the case of a single pile, $Re_{D_p} \left(\frac{\delta}{D_p}\right)^{1/2} \approx 600 < 800$. Thus, no horseshoe vortex occurs without blocking effect. In fact, no horseshoe vortex was observed in Case 6. However, a horseshoe vortex was observed in Cases 1–3, but the scale of the horseshoe vortex was quite different from that of the scour depth. This is significantly different from $1.1D_p$, the scour depth of a single pile [38]. With a single pile, the range of the horseshoe vortex is typically close to the scouring depth in front of the pile. However, in the scouring of pile row breakwaters, owing to the effect of the compressed horseshoe vortex [39], the size of the horseshoe vortex in front of the pile was much smaller than the scour depth. The scale of the horseshoe vortex for the other cases is presented in Table 4. The scale of the horseshoe vortex decreased with the pile spacing, as larger pile spacing results in a weaker blockage effect and a smaller reverse pressure gradient. The reverse pressure gradient was the directional reason for the horseshoe vortex. As shown in Table 4, when S/D_p is larger than 2, no horseshoe vortex occurs.

Table 4. Numerical simulation results.

Case	S/D _p	Scale in the X-Direction	Scale in the Z-Direction	D_{se} (cm)
1	1.5	$0.5D_p$	$0.5D_p$	13.4
2	1.8	$0.5D_p$	$0.4D_{p}$	9.0
3	2	$0.3D_p$	$0.3D_p$	4.7
4	3	0	0	1.1
5	4	0	0	0.96
6	∞	0	0	0.9

4.2. Scour Features

The most important scour characteristic is the maximum scour depth; the results of the present study are listed in Table 4. D_{se} decreased with an increase in pile spacing, and it is obvious that larger pile spacing results in a weaker blockage effect and weaker shear stress, as described in the previous section. When the S/D_p was larger than 3, D_{se} was approximately $0.01D_p$ and was very close to the D_{se} of a single pile under the action of a steady current with the same velocity intensity. D_{se} can be treated as negligible compared to D_p . This means that the pile group effect can be neglected when S/D_p is larger than 3 in the present work, as is the case for scour depth. This critical value is very different herein from that obtained in the work of Sumer and Fredsøe [5] in which the critical value was O(11). The main reason for this discrepancy is that the velocity intensity in the present work was very low, while that in the work of Sumer and Fredsøe [5] was close to U_c . The interaction between velocity intensity and pile spacing has been experimentally studied [9,40].

There was a relatively flat area in front of the pile (upper part of the pile) in the present study; this flat area was also observed in the experiments (Figure 11). The scale of this flat area was close to that of the horseshoe vortex. This phenomenon is significantly different from that of single piles or pile groups, which can be explained as follows.



Figure 11. Streamline and scour topography of Case 1 at the end of the simulation.

Owing to the small velocity intensity and compressed horseshoe vortex effect, the scale of the horseshoe vortex behind the pile was limited to $O(0.5D_p)$ both in the X- and Z-directions, but the streamline shrinkage effect caused the scour depth around both sides of the pile to be much larger than $0.5D_p$. In fact, D_{st} was approximately $2.7D_p$ in Case 1.

Another flat area was observed behind the pile. The scale of this area was $O(1.0D_p)$, and it was located in the shedding area. The length of this area in the X-direction was close to the scale of the shedding vortex. The shedding vortex had an upward action on the sand behind the pile. This action resulted in a relatively flat sand bed rather than a sloping bed.

Both the flatbeds in front of and behind the pile were observed in the experimental studies; their scales were smaller than those in the numerical model.

5. Conclusions

This paper focused on the effect of pile spacing on the scour around closely spaced circular piles. The experiments were conducted in a wide flume with uniform and cohesionless sand as the bed material under the action of steady current. Numerical models were established and verified based on the experiments conducted. Both were used to study the features of the hydrodynamic and scour characteristics of closely spaced circular piles under steady current with a small velocity intensity.

Based on the experiments and computations, the following conclusions can be drawn:

- 1. The scour depth around the closing spacing pile was much larger than the scour depth around a single pile with the same diameter under the same flow intensity.
- 2. The shear stress increased rapidly with a decrease in the pile spacing. When S/D_p was larger than O(3), the shear stress distribution of closely spaced piles could be treated as a single pile.
- 3. The scour depth increased rapidly with a decrease in pile spacing. When S/D_p was larger than O(4), the scour depth could be treated as a single pile.
- 4. There were flat areas both in front of and behind the pile; the main hydrodynamic mechanics for those areas were the compressed horseshoe vortex and shedding vortex.

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