Experimental investigation on scour topography around high-rise structure foundations

Abstract

The current study aims to investigate the characteristics of scour topography around High-Rise Structure Foundations (HRSFs) via physical modeling tests. Clear-water scour tests with a uniform non-cohesive bed are modeled under the action of unidirectional steady flows. Time variations of the erosion and deposition topography are measured. The results show that deposition downstream of the first dune behind the HRSF is not located on the centerline of the wake. The deposition pattern indicates that a long steady wake region exists behind the permeable foundation. The scour depth around an HRSF is much less than that around a monopile because of the structural permeability, which gives rise to the bleed flow and a weakened downflow and horseshoe vortex. Additionally, the asymmetry of the HRSF affects the scour rate but not the final equilibrium scour depth. The average scour slope decreases along the direction of the flow. On the contrary, the scour radial distance increases along the direction of the flow, with the average value changing from $1.36D_e$ to $2.35D_e$ (where D_e is the equivalent diameter of the foundation). Furthermore, the scour hole around the HRSF is serrated rather than smooth owing to the presence of multiple piles. Empirical formulae are suggested for estimating the evolution of scour depth and volume. These laboratory experiments provide reference information for relevant numerical modeling studies and can be applied to guide engineering designs in an ocean area.

Keywords: High-rise structure foundation, Scour, Sediment transport, Pile groups.

1. Introduction

In recent years, the offshore wind industry has rapidly developed due to requirements for clean and renewable energy sources (Antonutti et al., 2014; Sumer, 2014). For Offshore Wind Turbines (OWTs), there are several typical types of foundations, namely monopiles, gravity-based structures, tripods, jackets, and pile groups (Dolores Esteban et al., 2015). As a new type of the pile-group OWT foundation, the High-Rise Structure Foundation (HRSF) is made of inclined piles and a platform, and has been gradually applied in many offshore wind farms (see Fig. 1).

It is a common phenomenon that scour occurs around OWT foundations, which may reduce the stability of the foundation, leading to its collapse, and, thus, significant economic loss (Kuo et al., 2012; Yuan et al., 2017). In recent decades, the local scour depths around monopiles, tripods, and bucket structures have been extensively studied (Cheng et al., 2016; Guan et al., 2019a; Melville & Chiew, 1999; Raudkivi & Ettema, 1983; Stahlmann, 2014; Tang et al., 2009; Wang et al., 2016; Whitehouse et al., 2011; Yu et al., 2016; Zhao et al., 2010). Nevertheless, there have been very limited studies that focus on the quantitative description of the scour topographic characteristics around an HRSF. This may be due to the complex geometry of the HRSF and the difficulties in measuring the global scour hole either in the laboratory or field.

When an HRSF is placed in an ocean environment, the flow fields and local scour around it may be very different from those around a monopile (Yang et al., 2020). Sumer et al. (2005) did scour tests concerning pile groups. They found that there clearly were two types of scour patterns. The first was the local scour around individual members, and the other was a global scour around the entire structure. As scour develops, the local scour holes around individual piles gradually merge and form a large

global scour hole. A schematic diagram of the local scour and the global scour around an HRSF is shown in Fig. 2. Their results showed that the global scour depth increased with the increase of the solid volume fraction before the global scour depth reached a limiting value. The solid volume fraction is defined as $\varphi = nd^2/D^2$, where D is the outer diameter of the entire foundation, d is the diameter of the individual piles, and n is the number of piles. Yagci et al. (2017) found that the scour pattern around pile groups with high solid volume fractions was similar to that around a monopile, while for pile groups with low solid volume fractions, local scour holes around individual piles do not interact with one another. Although their work has presented the equilibrium scour topography around the pile groups, the temporal evolution of the scour topography was not displayed. Previous studies (Graf & Istiarto, 2002; Sumer & Fredsøe, 2002) have proved that the formation of a horseshoe vortex was the leading cause of the scour around monopiles. As the current flow can penetrate through an HRSF, the flow through the foundation (so-called bleed flow) will reduce the strength of downflow upstream of the HRSF (Kitsikoudis et al., 2016; Yagci et al., 2017), thereby weakening the strength of horseshoe vortex. Therefore, the scour topography (scour pattern) around an HRSF could be substantially different from that around a monopile.

To improve understanding of the characteristics of the scour hole around HRSFs, the current study investigates the temporal evolution of the scour topography around HRSFs with eight and ten inclined member piles and compares the results with that around a monopile foundation. Additionally, empirical formulae are suggested for estimating the evolution of scour depth and volume, which will benefit the design of scour countermeasures, for instance, the volume of the required riprap stones (Guan et al., 2019c). In the current study, the bed material is uniform and non-cohesive sand, and the flow is unidirectional and steady.

2. Experimental setup

The experiments were done in a glass-sided and steel-bottomed flume of 24 m long, 1.2 m wide, and 0.7 m deep. A schematic diagram of the experimental setup is shown in Fig. 3. To measure the global scour hole around the HRSF, detachable models were designed (as seen in Fig. 3b). A detachable model is composed of the upper part and the lower part. During the measurements, the flow was temporarily stopped, and the upper part of the structure was removed to facilitate measurement with Acoustic Doppler Velocimeter (ADV) probes. After the measurement was completed, the upper structure was reinstalled and the water flow and scour process was continued. The length of the test section was 6 m, and a sand layer with a thickness of 0.15 m was laid uniformly inside the flume recess, which was situated 9 m downstream of the flow entrance. Uniform quartz sand with a medium grain size, $d_{50} = 0.75$ mm, a natural repose angle of 34° , and a geometric standard deviation $\sigma_g = 1.18$ was used to describe the grainsize nonuniformity, where $\sigma_g = \sqrt{d_{84}/d_{16}}$, and d_{84} and d_{16} are the grain sizes for which 84% and 16% by weight of the sediment are finer, respectively.

The detail of the HRSF models is shown in Fig. 4, which are typical types of offshore wind foundations used in China. For comparison, a monopile also was tested in the experiments. As seen in Fig. 4, eight-pile and ten-pile HRSF models are octagonal and decagonal groups with a narrow top and a wide bottom, which are composed of inclined piles. The gaps among the piles of the HRSF are kept unchanged in the current study. The outer diameter (D) of the foundation at the bottom is 34 cm, and the diameter of individual piles (d) of the eight-pile and ten-pile models is 3.5 cm and 3 cm, respectively. Because of the size limitation of the flume, larger structures could not be tested to examine the scale effect. The inclined angle of the individual piles of the HRSF relative to the vertical

is 11° . The equivalent diameter of the foundation, D_e , was defined as the diameter of a solid monopile, which has an equal cross-sectional area with the HRSF (Yagci et al., 2017), i.e. $D_e = \sqrt{nd^2}$. For a monopile foundation, $D = D_e$. Since the HRSF is a permeable foundation composed of multiple piles, it is reasonable to non-dimensionalize the scour depth (d_s) with D_e . The equivalent diameter of the HRSF was less than 8.5% of the flume width in the current experiments, so the effect of the sidewall could be neglected (Diab, 2011; Lança et al., 2013; Yang et al., 2020). To ensure that the sidewall has no direct impact on the experimental results, the velocity profiles above the sand bed were measured using an ADV probe before the HRSF was installed at the locations ($x = 17$ cm, $y = 50$ cm) and ($x = 17$ cm, $y = 45$ cm), i.e. 10 cm and 15 cm away from the side wall, respectively. The results were compared with those after the HRSF was placed in the flume, as shown in Fig. 5. The comparison shows no significant differences between the two cases, indicating that the influence of the sidewall is negligible.

A total of 6 tests were done under clear-water scour conditions with a flow depth of $h = 15$ cm and a flow intensity $V/V_c = 0.9$, where V is the mean flow velocity ($V = 27.78$ cm/s) and V_c is the threshold velocity for sediment motion which is calculated using the equation of Schamovis (Tang et al., 2013). The parameters and key results of the different tests are listed in Table 1. Before starting an experiment, each foundation was placed in the center of the flume width direction and the bed surface was carefully levelled.

107 **Table 1.** Test conditions and results of experiments.

Test	Model type	D_e (cm)	V/V_c	θ (°)	d_{se} (cm)	d_{se}/D_e	V_{se} (m ³)
Run 1	Eight-pile	9.90	0.9	0	9.7	0.98	0.0259
Run 2	Eight-pile	9.90	0.9	15	9.8	0.99	0.0287
Run 3	Eight-pile	9.90	0.9	22.5	9.5	0.96	0.0248
Run 4	Ten-pile	9.49	0.9	0	9.4	0.99	0.0275
Run 5	Ten-pile	9.49	0.9	18	9.6	1.01	0.0268
Run 6	Monopile	8	0.9	—	12.5	1.56	0.0241*

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*note: θ is the alignment angle of the HRSF relative to the approaching flow as indicated in Fig. 4, d_{se} is the equilibrium scour depth, and V_{se} is the equilibrium scour volume.

The characteristic variables used in the current study to quantify the scour topography are defined in Fig. 6. They are radial distance of the scour (R) at three different locations, namely R_u , R_s , and R_d , which are defined as the horizontal distances from the outer edges of the exposed piles (after scour) to the boundaries of the global scour hole in the upstream, cross-flume, and downstream directions. The slope angles of the scour hole at the three locations are defined as α , namely α_u , α_s , and α_d , respectively. An ADV probe manufactured by Nortek AS (5 cm down-looking type) with a sampling rate up to 50 Hz was used to measure the scour topography at selected times ($t = 0.5, 2, 12, 24, 48$ h). The spacing of the measurements was set at 2 cm and the measurement accuracy was verified to be $\pm 0.5\%$ of measured value ± 1 mm. The hourly increase rate of the scour depth in the current study was less than the median sediment size after 48 h, and the daily accumulated change of the scour depth at the end of the test was less than 10 mm. Therefore, it can be approximated that the scour achieved the quasi-equilibrium state at the end of the experiments (Guan et al., 2019b; Link et al., 2008; Melville & Chiew, 1999).

3. Results and discussion

3.1. Global topography

Figure 7 shows the variation of global scour topography with time around the eight-pile HRSF with different alignment angles, together with the monopile results as a reference. The scour radial distance upstream of the permeable multi-pile foundation (HRSF) was much shorter than that upstream of a monopile (e.g., for the eight-pile HRSF with $\theta = 0^\circ$, the scour radial distance upstream of it was 12 cm, while that upstream of the monopile was 16 cm). The result is in accordance with previous

research (Yagci et al., 2017). The bleed flow decreases the stagnation pressure and the strength of downflow upstream of the HRSF (Kitsikoudis et al., 2016; Yagci et al., 2017).

Once the scour process began around a monopile, a single dune was formed behind the pile (as seen in Fig. 7d), which slowly progressed downstream with time (Melville & Chiew, 1999). In contrast, several small dunes were formed behind the HRSF (Fig. 7a-c), as the result of the sediment washed out of downstream piles. While moving downstream, these dunes gradually merged into a single larger dune. When the flow passes through a permeable foundation (e.g., HRSF), an area with reduced flow velocity and turbulence intensity will be formed directly behind the foundation, which is called the steady wake region (Zong & Nepf, 2012). The presence of the region delays the emergence of the von Karman vortex street, resulting in a distinct wake structure that is different from that behind a solid monopile (Chen et al., 2012). As seen in Fig. 7d, the scour radial distance downstream of a monopile was visible, and the outline of the scour area was like an ellipse. At the equilibrium stage, a certain distance existed between the dune and the scour area because of the formation of the strong von Kármán vortex street behind the monopile (Zong & Nepf, 2012). The current result was in line with Dargahi (1990), Follett and Nepf (2012), and Yagci et al. (2017). Unlike the scour and deposition pattern downstream of a monopile, the dune was formed at a smaller distance downstream of the HRSF than that downstream of the monopile. Accordingly, the scour radial distance downstream of an HRSF was much smaller than that downstream of a monopile (e.g., for the eight-pile HRSF with $\theta = 0^\circ$, the scour radial distance downstream was 18 cm, while that downstream of the monopile was 32 cm). It can be explained that flow penetrating through the HRSF carries sediment to deposit directly behind the HRSF as the result of the decreased sediment transport capacity in the steady wake region (Yagci et al., 2017).

In this study, two obvious dunes existed behind the monopile on the centerline of the wake (Fig. 7d), which was consistent with previous research (Follett & Nepf, 2012). Follett and Nepf (2012) found that the von Kármán vortex street behind the monopile provided the lateral transport mechanism, leading to the sediment transport and deposition toward the centerline of the wake. Nevertheless, for the multi-pile foundation tested in the current study, only one obvious dune (the so-called first dune) existed behind the HRSF, and the deposition downstream of the first dune did not appear to always be located on the centerline of the wake (as seen in Fig. 7a–c), which was very different from that in the case of a monopile. This phenomenon resembled what was observed behind a loosely arranged permeable model patch (Follett & Nepf, 2012). These results indicate that behind a loosely arranged permeable foundation (e.g., an HRSF), there may exist a very long steady wake region, which leads to the formation of a relatively weak von Kármán vortex street beyond the area observed in the current study, thereby resulting in the shifting of the deposition (behind the first dune) from the centerline of the wake.

Figure 8 shows a comparison of the scour and deposition topography around the eight-pile HRSF with different alignment angles, θ . It can be seen that the scour topography changes with the alignment angle. In the case of $\theta = 15^\circ$, due to the asymmetry of the foundation, the scour radial distance of the global scour hole on the left side was obviously larger than that on the right side. This indicates that the asymmetric arrangement of the HRSF is likely to intensify the scour on one side. In the case of $\theta = 0^\circ$, the maximum height of the first dune behind the HRSF was 7.8 cm, which was much larger than those for the other two cases. The maximum elevations of the first dune in the cases of $\theta = 15^\circ$ and $\theta = 22.5^\circ$ are 6.5 and 6 cm, respectively. Additionally, the distance from the downstream global scour hole boundary to the first dune also was the smallest among the three cases. It can be speculated that

turbulence intensity behind the HRSF with $\theta = 0^\circ$ is the smallest among the three cases, which causes the deposition close to the HRSF.

3.2. Local scour pattern and depth

Within the HRSF, small dunes were generated at the initial stage of scour (from 0 to 2 h), which was due to the sediment washed away from the upstream piles, as seen in Fig. 7a-c and Fig. 9a-c. The elevation of the small dune inside the foundation gradually decreased with the development of scour. At the time of equilibrium, the dune inside the foundation has almost disappeared. The scour depth around the central area of the foundation, where the dune used to be, was less than those around individual piles (e.g., for the eight-pile HRSF with $\theta = 0^\circ$, the scour depth around the central area of the foundation was about 5.5 cm, while those around individual piles were larger than 7.5 cm). The eight-pile HRSF is an octagonal pile group without a center pile, so the central area of the foundation is only affected by the bleed flow and the flow diversion from the surrounding piles, resulting in a lower scour depth than those around individual piles.

Unlike the observed elliptical scour area around a monopile, the local scour holes around individual piles of the HRSF developed separately within the first 2 h of the scour process (as seen in Fig. 9), when there was no global scour. After 12 h, the local scour holes began to connect together, and the outline of the global scour hole appeared to approximately be a horseshoe shape until the scour process reached the equilibrium stage. Furthermore, the time history of the scour depth is illustrated in Fig. 10a, where d_s is the maximum scour depth around the foundations. For an HRSF, the maximum

scour depth occurs in a local scour hole, as seen in Fig. 9a-c. The scour approached equilibrium about 48 h into the experiments, and the scour depth around a monopile was much larger than that around an HRSF under the same flow conditions. This indicates that the flow through the permeable HRSF reduces the flow contraction around it, which causes a reduction in the bed shear stress and in the capacity for sediment transport (Yagci et al., 2017). Additionally, the bleed flow may decrease the strength of downflow, resulting in a reduction of the strength of the horseshoe vortex (Kitsikoudis et al., 2016). Chiew (1992) placed a slot through a monopile to investigate the slot's effect on the scour around the monopile. He found that the existence of the slot allowed the oncoming flow to pass through it as bleed flow (or a jet). The bleed flow deflected the downflow away from the bed, reducing the scour around the monopile. In the current study, the HRSF behaves in a similar way to a perforated structure or a solid structure with many vertical slots extending the entire water depth. The results of Chiew (1992) have proved that the bleed flow can greatly reduce the scour around the foundation, which is consistent with the findings in the current study.

For the eight-pile HRSF with $\theta = 15^\circ$, due to the asymmetry of the foundation, the maximum scour depth on one side was obviously larger than that on the other side (Fig. 9b). The asymmetry of the foundation increased the scour rate at the beginning of the scour process (Fig. 10a). Nevertheless, the alignment angle had little effect on the final equilibrium scour depth. Yagci et al. (2017) found that when the solid volume fraction, ϕ , of the pile groups was less than 0.14, the scour depths in different alignment angles were very similar among the seven pile-group foundations they considered. In the current study, the maximum solid volume fraction was less than 0.09. Therefore, the scour depths at different alignment angles were very close, consistent with the previous findings.

In recent decades, a lot of investigations have been done on the evolution of scour depth around piers or monopiles (Melville & Chiew, 1999; Sumer & Fredsøe, 2002). Nevertheless, the available investigations provide little guidance on the evolution of the scour depth around an HRSF. The current applied the most commonly-used exponential function to describe the evolution of scour depth around the HRSF. The exponential function can be written as:

$$d_s = d_{se} \left\{ 1 - \exp \left[-c_1 \left(\frac{t}{T} \right)^{c_2} \right] \right\} \quad (1)$$

where T is the time scale which can be calculated by $T = \int_0^{t_e} \frac{d_{se} - d_s}{d_{se}} dt$ (Larsen et al., 2017; Yang et al., 2020), where t_e is the equilibrium time in each case; and c_1 and c_2 are two empirical coefficients. The fitted curve and the original measured data are both shown in Fig. 10b, together with the $\pm 5\%$ error lines, the empirical coefficients c_1 , c_2 , and the coefficient of determination, R^2 . It can be seen that Eq. 1 gives a good fit of the experimental data, which indicates that the evolution rule of the maximum scour depth around a monopile and that around an HRSF are similar in the considered case.

3.3. Scour slope

Figure 11 shows the measured scour slopes on the upstream, side, and downstream parts of the HRSF and the monopile. For the eight-pile HRSF with $\theta = 15^\circ$, the left side of the scour slope, seemed to suffer more severe scour as shown in Fig. 11e. During the process of scour, the scour slopes of the upstream, side, and downstream areas remained nearly unchanged, with the exception being the scour slope downstream of the eight-pile HRSF with $\theta = 0^\circ$ and 15° (Fig. 11c and f). In these two cases, the downstream radial distance of scour firstly increased and then sharply decreased, before it finally

increased. Meanwhile, the downstream scour depth was found to continuously increase, resulting in the change of the scour slope. This indicates that the effect of the sediment washed out of the upstream region on the downstream scour depth is not at the same level as that on the downstream radial distance of the scour in the considered case. The downstream radial distance of scour is more easily affected by the sediment washed out of the upstream piles.

As seen in Fig. 12, the average slope consistently decreased from the upstream to the downstream, with the value changing from around 30° to around 18° . Additionally, in almost all the cases, the average scour slopes were always less than the repose angle of the sediment material, which was consistent with previous studies (Diab et al., 2010). This indicates that the vortices around the HRSF and monopile contribute to destabilize the scour slope. Nevertheless, there were three exceptions (Fig. 11a, j, and p), including the scour slope upstream of the monopile, the scour slope upstream of the eight-pile HRSF in the case of $\theta = 0^\circ$, and the scour slope upstream of the ten-pile HRSF in the case of $\theta = 0^\circ$. It can be speculated that the deep scour slopes were made stable by the flow-induced shear and seepage stresses in these three conditions. Diab (2011) believed that the weak anti-clockwise vortex at the bottom of the scour hole around the monopile was the main cause of the scour slope stabilization. Therefore, the effect of the anti-clockwise vortex is probably the reason why the scour slope is larger than the repose angle. Nonetheless, to clearly reveal the phenomena previously mentioned, the measurement of the turbulent flow fields around an HRSF will be needed in the future.

3.4. Scour radial distance

As for the HRSF, the scour radial distance of the global scour hole increased from the upstream part to the downstream part (Fig. 13), with the average value changing from $1.36D_e$ to $2.35D_e$. Although the scour hole around the monopile had a similar trend, the dimensionless scour radial distance (from an average of $2D_e$ to $4D_e$) was much larger than that in the case of the HRSF.

Figure 14 shows the variations of the radial distance of the scour with the scour depth in different directions, and the fit curves can be simply described as:

$$\frac{R}{D_e} = k \frac{d_s}{D_e} \quad (2)$$

where the constant k is 1.57, 1.87, and 2.99 for the upstream region, the side region, and the downstream region, respectively. The equation can be utilized to estimate the scour radial distance. Then the radial distances of the scour can be used to design the minimum area of the scour protection layer. In Fig. 14, the variation tendency of scour radial distance with scour depth was widely divergent in different directions. From the upstream direction to the downstream direction, the increase rate of the scour radial distance with scour depth gradually increased. This illustrates the differences of the flow structure in the different directions. According to Figs. 12, 13, and 14, it can be inferred that the downflow and the horseshoe vortex upstream of the foundation are likely to produce a narrow scour hole with a steep slope in the upstream region. In the side region, the horseshoe vortex and the flow contraction exist, resulting in a scour hole with a medium radial distance and slope. In the downstream region, the lee-wake vortices generate a wide scour hole with a gentle slope angle.

3.5. Scour hole profiles

Since the HRSF was a multi-pile foundation, a single scour profile cannot fully reflect the scour shapes around individual member piles. Therefore, the concept of the equivalent profile is introduced. The schematic diagram of the equivalent profile is shown in Fig. 15. The equivalent longitudinal profile (x -axis direction) is the profile of the maximum scour depth obtained by the transverse projection (y -axis direction) of the scour hole. Similarly, the equivalent transverse profile can be obtained by the same method. Figure 16 shows the equivalent longitudinal scour profiles of bed. Figure 17 shows the equivalent longitudinal and transverse profiles of the scour holes around the HRSF and the monopile. The solid lines represent the outer boundary of the HRSF, and the vertical dashed lines show the outer boundary of the monopile.

The scour patterns around an HRSF were very different from that around a monopile due to the multi-pile design of the foundation (Fig. 16). The shape of the scour hole profiles around the HRSF shows a serrated shape instead of a smooth scour hole profile as observed around a monopile (Fig. 17). Further, the non-dimensional scour depth and scour radial distance of the scour hole around the monopile were much larger than that around the HRSF. The permeable multi-pile foundation (HRSF) causes a decrease in the strength of the downflow, thereby weakening the horseshoe vortex strength (Yagci et al., 2017) and ultimately reducing the amount of vertical and horizontal erosion.

In Fig. 17, the scour patterns were very similar among the various HRSF cases. The maximum scour depth of the longitudinal profile was concentrated around the region with $x = 1D_e$ to $2D_e$, while that of the transverse profile occurred around the region with $y = \pm 2D_e$, which corresponds to the locations of the middle piles of the HRSF. Figure 18 is used to explain the foregoing phenomenon.

When the flow approaches the upstream piles, horseshoe vortices can be generated, which are continuously convected downstream around the middle piles (Kitsikoudis et al., 2017). Furthermore, the bending and contraction of streamlines around the outer edge of the HRSF create a large amplification of the bed shear stress (Yang et al., 2020). The middle piles are exactly located on the side of the foundation. This may explain why the maximum scour depth occurs around the middle piles near the lateral edges of the HRSF.

3.6. Scour volume

Figure 19a shows the time variation of the scour volume in the development of the scour holes, where V_s is the scour volume. It can be noted that the scour volume reached over 40% of the equilibrium value in the initial stage. The initial increase rate of the scour volume around the monopile was less than that around the HRSF. Nonetheless, the values of scour volume around the two foundations were very close after 12 h. As previously mentioned, the scour depth around a monopile was much deeper than that around an HRSF (Fig. 10a). Moreover, the cross-sectional area, which represents the axial bearing capacity, of the monopile was smaller than that for an HRSF. Therefore, it can be concluded that as an offshore wind turbine foundation, a monopile may be less stable than an HRSF, as more intense erosion occurs around it.

The commonly-used exponential function also was used to predict the evolution of scour volume around the HRSF. The exponential function can be written as:

$$\frac{V_s}{V_{se}} = 1 - \exp \left(-c_1 \left(\frac{t}{T} \right)^{c_2} \right) \quad (3)$$

The fitted curve and the original measured data are both shown in Fig. 19b, together with $\pm 10\%$ error lines, the empirical coefficients c_1 , c_2 , and the coefficient of determination, R^2 . Generally good performance Eq. 3 was found.

4. Conclusions

The scour topographic evolution around the HRSFs were analyzed in a series of experiments, with the results around a monopile used as the reference. The following conclusions have been drawn based on the current study:

- Unlike the scour and deposition pattern downstream of a monopile, the dune is formed at a smaller distance downstream of an HRSF than that downstream of a monopile. Accordingly, the scour radial distance downstream of an HRSF is much smaller than that downstream of a monopile, which can be attributed to the decreased sediment transport capacity in the HRSF's steady wake region. Moreover, only one obvious dune exists behind the HRSF, and the deposition downstream of this dune does not appear on the centerline.
- Within the scope of testing conditions in the current study, local scour holes around individual member piles of the HRSFs develop separately in the first 2 h of testing, and then begin to merge after $t = 12$ h. The scour depth around the monopile is much larger than that around the HRSFs. This suggests that the presence of the bleed flow decreases the strength of downflow, resulting in a reduction of the strength of the horseshoe vortex. This type of permeable foundation of multiple piles (HRSF) provides a good option for OWT foundations.

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- The asymmetry of the HRSF has a certain effect on the scour rate, but the final equilibrium scour depth is not sensitive to the flow direction. In the current study, the scour depths at different alignment angles are very similar.
 - The average scour slope decreases in the direction of the flow, with the value changing from an around 30° in the upstream region to around 18° in the downstream region.
 - The scour radial distance around the HRSF increases in the flow direction, with the average value changing from $1.36D_e$ in the upstream region to $2.35D_e$ in the downstream region. The dimensionless scour radial distance increases linearly with the dimensionless scour depth. Equation 2 is useful for estimating the scour radial distance, and then the scoured area.
 - The current study is of great engineering significance because the OWT provides a good source of renewable energy and foundation scour remains a challenging issue for OWT devices. The current research outcomes can help validate numerical models for predicting scour depths around OWT foundations. The proposed empirical equations for estimating the evolution of scour depth and volume can contribute to the design of scour countermeasures.

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Fig. 1. An HRSF of Donghai Bridge wind farm, China (https://www.sohu.com/a/161910496_813219).

Fig. 2. Schematic diagram of the local scour and the global scour around an HRSF.

Fig. 3. Schematic diagram of experimental setup: (a) a complete HRSF, and (b) an HRSF with its upper part removed during ADV measurements.

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451 **Fig. 4.** Model details: profile view and plan view of the (a) eight-pile HRSF model, and (b) ten-pile

452 HRSF model.

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454 **Fig. 5.** Mean velocity profile in the vertical direction at the locations (a) $y = 50$ cm, and (b) $y = 45$ cm:

455 A – with the HRSF, B – without the HRSF.

460

461 **Fig. 7.** Scour and deposition topography around (a) eight-pile HRSF with $\theta = 0^\circ$, (b) eight-pile HRSF

462 with $\theta = 15^\circ$, (c) eight-pile HRSF with $\theta = 22.5^\circ$, and (d) monopile.

Fig. 7. Continued.

Fig. 8. The comparison of the scour and deposition topography around an eight-pile foundation at the equilibrium stage with (a) $\theta = 0^\circ$, (b) $\theta = 15^\circ$, and (c) $\theta = 22.5^\circ$.

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Fig. 9. Developing scour hole topography around the (a) eight-pile HRSF with $\theta = 0^\circ$, (b) eight-pile HRSF with $\theta = 15^\circ$, (c) eight-pile HRSF with $\theta = 22.5^\circ$, and (d) monopile.

Fig. 10. Time history of scour depth (d_s) around the monopile and the eight-pile and ten-pile HRSFs.

479

480 **Fig. 11.** Measured global scour slopes in the upstream, side, and downstream areas: (a) – (c) eight-pile
 481 with $\theta = 0^\circ$; (d) – (f) eight-pile with $\theta = 15^\circ$; (g) – (i) eight-pile with $\theta = 22.5^\circ$; (j) – (l) ten-pile with θ
 482 $= 0^\circ$; (m) – (o) ten-pile with $\theta = 18^\circ$, and (p) – (r) monopile.

Fig. 11. Continued.

Fig. 12. Equilibrium slope angles within the global scour holes.

Fig. 13. Equilibrium scour radial distance within the global scour holes.

Fig. 14. Variations of the scour radial distance with the scour depth in the upstream, side, and downstream areas around the HRSF and the monopile.

Fig. 15. The schematic diagram of the equivalent longitudinal and transverse profiles.

Fig. 16. The equivalent longitudinal scour profiles around the HRSF and the monopile during the equilibrium period. The solid lines represent the edge of the HRSFs, and the vertical dashed lines show the edge of the monopile.

Fig. 17. The equivalent (a) longitudinal and (b) transverse scour hole profiles in different cases during the equilibrium period. The solid lines represent the edge of the HRSF, and the vertical dashed lines show the edge of the monopile.

Fig. 18. Flow field features around an HRSF (ten-pile).

Fig. 19. Variation of scour hole volume with time around the HRSF and the monopile.