Local scour characteristics around offshore wind-turbine foundations under nonlinear waves and currents

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Abstract. In this study, we investigated the local scour around a large pile, termed the umbrella suction anchor foundation (USAF), under nonlinear waves and current. We developed a wave-foundation-seabed coupled model and analyzed the characteristics of the flow field, turbulence characteristics, and scour depth evolution, and the influence of wave height and anchor branches on local scour. The results indicate that the horseshoe vortex increases turbulence intensity around the offshore edge of USAF, amplifying the shear stress on the seabed, which causes local scour around the USAF upstream. The anchor branches protected the soil from scouring to some extent. The scour and accretion depths increased rapidly at the initial stage, and then, the scour rate decreased. After approximately 300 wave cycles, the scour and accretion depths gradually stabilized. The changing trend of the scour evolution with wave height converged, but higher wave heights resulted in larger scour and accretion depths simultaneously.

1. Introduction
Offshore wind energy is resourceful in the East China coastal area, and it has rapidly developed recently. So far, there are different foundation types for offshore wind turbines, such as monopile, gravity type foundation, and tripod, and suction anchor. Suction anchors include single, multiple, and skirt anchors, and they can be installed on the seabed by pumping water on the top of the anchor, which has the advantages of recyclability and cost-effectiveness [1-2]. Scour pits develop around foundations under wave and current, and they weaken the bearing capacity and stability of the foundations when their depths grow to some extent. As a result, Li et al. [3] proposed a new type of foundation for offshore wind turbines, termed the umbrella suction anchor foundation (USAF). USAF comprises (1) main buckets, (2) skirt, (3) anchor ring, (4) anchor branch, (5) supporting rod, and (6) telescopic hook (Figure 1). The anchor branches can protect the neighboring soil and improve the anti-scour and -overturning performance. Based on the relevant previous studies [4-6], hydrodynamic parameters, such as the wave height, water depth, flow velocity, and pile diameter, affect scour evolution and characteristics. Sumer et al. [7] reported that horseshoe vortex and wake vortices are responsible for scour at the up and lee sides of foundations, respectively, under waves. In addition, the KC number (Equation 1) impacts scour evolution under waves; the scour depth increases with an increase in KC [8-11]. Besides, current increases the intensity and lifetime of
horseshoe vortices in the wave cycle and reduces the time to the state of equilibrium of scour; hence, scour becomes more severe under the combination of wave and current than the condition of wave or current only.

\[ KC = \frac{U_m T}{D} \]  

(1)

where \( U_m \) is the maximum velocity of the water mass above the boundary layer of the bottom wave, \( T \) the wave period, and \( D \) the pile diameter.

So far, many relevant studies have focused on the scour characteristics for piles [12-14], whereas there are insufficient studies on suction anchors, especially for USAF. In this study, a coupled fluid-seabed-foundation numerical model was built to study the scour characteristics, evolution, and flow field around USAF under stoke waves and current.

2. Numerical method

The coupled seabed-foundation-fluid model was built using computational fluid dynamics software, Flow-3D. A 3D umbrella-suction-anchor geometric model was established using COMSOL software, and it was imported into Flow-3D as STL files. Flow-3D software employs the fluid volume method (VOF) to capture fluid-free surfaces and the fixed Euler grid method to capture scour morphology evolution. The 5th stoke wave theoretical model was employed to investigate the scour characteristic around USAF under different wave and current conditions.

2.1 Governing equations

2.1.1 Momentum equation

The momentum equations describe the fluid velocity (\( u \), \( v \), and \( w \)) in \( x \), \( y \), and \( z \) directions as follows:

\[
\frac{\partial u}{\partial t} + \frac{1}{V_F}(u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z}) = -\frac{1}{\rho_1} \frac{\partial p}{\partial x} + G_x + f_x
\]  

(2)

\[
\frac{\partial v}{\partial t} + \frac{1}{V_F}(u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z}) = -\frac{1}{\rho_1} \frac{\partial p}{\partial y} + G_y + f_y
\]  

(3)

\[
\frac{\partial w}{\partial t} + \frac{1}{V_F}(u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z}) = -\frac{1}{\rho_1} \frac{\partial p}{\partial z} + G_z + f_z
\]  

(4)

where \( u \), \( v \), and \( w \) are the fluid velocities in the \( x \), \( y \), and \( z \) directions in Cartesian coordinates, respectively; \( A_i \) is the flow area fraction; \( G_i \) is the gravity acceleration; \( f_i \) (\( i = x, y, z \)) is the viscous acceleration; \( \rho \) is the fluid density; \( V_F \) is the volume fraction.

2.1.2 Turbulent model

Considering computational precision and investment, the renormalization group (RNG) \( k-\varepsilon \) turbulent model can efficiently reflect the flow field characteristics around foundations under waves. Hence, the
RNG k-ε turbulent model was employed to study the local scour around the foundation under wave and current.

\[
\frac{\partial k_T}{\partial t} + \frac{1}{V_f} (u_A \frac{\partial k_T}{\partial x} + v_A \frac{\partial k_T}{\partial y} + w_A \frac{\partial k_T}{\partial z}) = P_T + G_T + \text{Diff}_{k_T} - \varepsilon_{k_T}
\]  
(5)

\[
\frac{\partial \varepsilon_T}{\partial t} + \frac{1}{V_f} (u_A \frac{\partial \varepsilon_T}{\partial x} + v_A \frac{\partial \varepsilon_T}{\partial y} + w_A \frac{\partial \varepsilon_T}{\partial z}) = \text{CDIS} \frac{\varepsilon_T}{k_T} \left( P_T + \text{CDIS} 3 G_T \right) + \text{Diff}_{\varepsilon_T} - \text{Diff}_{\varepsilon_T} \frac{\varepsilon_T}{k_T}
\]  
(6)

where \( G_T \) is the turbulent energy; \( \varepsilon_T \) is the turbulent energy dissipation rate; \( P_T \) is turbulent flow production; \( k_T \) is the turbulent kinetic energy; \( \text{Diff}_{k_T} \) and \( \text{Diff}_{\varepsilon_T} \) are diffusion terms; \( \text{CDIS} 1, \text{CDIS} 2, \) and \( \text{CDIS} 3 \) are dimensionless parameters.

### 2.1.3 Sediment transport model

The sediment transport process comprises the suspended load and bedload transport under wave and current. It occurs when the entrainment force induced by wave and current is larger than the combination of sediment gravity and friction force. The entrainment lift velocity of sediments is calculated by the following equation:

\[
\mathbf{u}_{\text{lift},i} = \alpha_i \mathbf{n}_i \frac{d_i^{0.3}}{\rho_f} \left( \theta - \theta_{cr} \right)^{1.5} \sqrt{g \left( \rho_i - \rho_f \right)}
\]  
(7)

Where \( \alpha_i \) is the entrainment parameter, \( d_i \) the dimensionless diameter of the sediment, calculated by Equation (8), \( \mathbf{n}_i \) the outward point perpendicular to the seabed interface, \( \theta_{cr} \) the critical Shields parameter, \( \theta \) the Shields parameter, \( d_i \) the sediment diameter, \( \rho_f \) the fluid density, \( \rho_i \) the sediment density, and \( g \) the acceleration due to gravity.

\[
d_i = d_i \left( \frac{g \rho_f (\rho_i - \rho_f)}{\mu_f^2} \right)^{1/3}
\]  
(8)

Where \( \mu_f \) is the dynamic viscosity of the fluid.

Suspended sediments begin to settle when the entrainment force is less than the combination of sediment gravity, and the settling velocity can be calculated using the following equation:

\[
\mathbf{u}_{\text{settling},i} = \frac{\rho_f}{\rho_i} \left[ (10.36^2 + 1.049 d_i^{0.5})^{0.5} - 10.36 \right]
\]  
(9)

Where \( \nu_f \) is the kinematic viscosity.

The dimensionless bedload transport rate \( \phi_b \) can be calculated using the formula proposed by Meyer et al. [15]:

\[
\phi_b = \beta_i \left( \theta - \theta_{cr} \right)^{1.5} \mathbf{C}_{b,s}
\]  
(10)

where \( \mathbf{C}_{b,s} \) is the sediment volume fraction.

The bedload transport volume rate \( q_{b,s} \) is calculated using the following equation:

\[
q_{b,s} = \phi_b \left( \frac{g (\rho_i - \rho_w)}{\rho_w} d_i^{3} \right)^{0.5}
\]  
(11)

The critical shields parameter \( \theta_{cr} \) can be obtained from the empirical formula developed by Soulsby [16]:

\[
\theta_{cr} = \frac{0.3}{1 + 1.2 d_i} + 0.055 \left[ 1 - \exp(-0.02 d_i) \right]
\]  
(12)
\[
\theta = \frac{\tau}{gd(\rho_s - \rho_w)}
\]  
(13)

where \(\tau\) is the shear stress on sediments induced by wave and current.

2.2 Seabed-foundation-fluid model
The coupled seabed-foundation-fluid model comprises the sandy seabed, USAF model, computational fluid area, and waveband elimination. The specified parameters of USAF and sandy seabed are shown in Table 1. To improve calculation efficiency and ensure preciseness, global and nested mesh grids are included in the numerical model. The global mesh is a \(6 \times 6 \times 6\) m cubic box, and the nested mesh size is \(0.3 \times 0.3 \times 0.3\) m cubic box near the foundation. The initial fluid area is the same as the seabed. As shown in Figure 2, the wave and outflow boundaries were set on the up and lee sides end of the foundation, respectively. The symmetry boundary was chosen at the top side and two sides of the model. At the bottom of the model, the wall boundary was used, meaning the velocity in all directions was zero. The no-slip condition was satisfied at the interface between the foundation and fluid.

| Item                | Dimension/m | Item                      | Parameter  |
|---------------------|-------------|---------------------------|------------|
| Main tube height    | 11.2        | Seabed thickness/m        | 12         |
| Main tube diameter  | 4           | Sand particles size/mm    | 0.257      |
| Main tube wall thickness | 0.02   | Sand density / (kg/m\(^3\)) | 1903   |
| Tube skirt height   | 2           | Critical Shields parameter | 0.05      |
| Tube skirt diameter | 8           | Turbine diameter/m        | 4          |
| Tube skirt wall thickness | 0.02   | Model dimension (length/width/height)/m | 200/30/30 |
| Anchor branch length| 4           | Global mesh size /m       | 0.6        |
| Anchor branch thickness | 0.048  | Nested mesh size/m        | 0.3        |

![Figure 2. Coupled seabed-foundation-fluid numerical model](image)

2.3 Numerical plan
Based on the wave and hydrodynamics data of the Yellow River Delta, nine cases were simulated using the numerical model to investigate the scour characteristics around USAF under wave and current (see Table 2).

| Case | Wave height/m | Flow depth/m | Current velocity/m/s | Wave period/s | KC | \(U_{cw}\) |
|------|---------------|--------------|-----------------------|---------------|----|-----------|
| 1    | 3             | 10           | 1                     | 8.6           | 5.342 | 0.402 |
| 2    | 3.5           | 10           | 1                     | 8.6           | 5.874 | 0.366 |
| 3    | 4             | 10           | 1                     | 8.6           | 6.407 | 0.336 |
| 4    | 4.5           | 10           | 1                     | 8.6           | 6.939 | 0.310 |

Table 1. Parameters of present numerical model
Table 2. Test simulation conditions
### 3. Model validation

To verify the reliability and preciseness of the developed model, the laboratory flume experiments reported by Roulund et al. [17] were simulated using the numerical model. The scour evolution curve obtained using the model and that of Roulund et al. [17] flume experiments are shown in Figure 3. The scour evolution curve obtained using the developed model is consistent with that obtained from the flume experiments, indicating that this model can reflect local scour around foundations. The wave heights in five wave cycles of case 1 were compared with the theoretical results calculated using the 5th stoke wave theory. As shown in Figure 4, the simulation and theoretical results converge, indicating that the wave generated by the model is favorable.

![Figure 3](image1.png)
**Figure 3.** Scour evolution reported by Roulund et al. and that obtained using the developed model

![Figure 4](image2.png)
**Figure 4.** Comparison of wave height between the developed model and theoretical calculations

### 4. Results

#### 4.1 Flow field characteristics around foundations

Figure 5 depicts the fluid velocity distribution in the x–y and x–z cross-sections around USAF. The flow mainly transfers downflow at the offshore edge of the foundation, and the flow velocity increases simultaneously, which is helpful to the formation of horseshoe vortices (Figure 5a). The horseshoe vortex increases turbulence intensity around the offshore edge of USAF, amplifying the shear stress on the seabed, which causes local scour around the USAF upstream. Besides, the flow velocity increases at the two sides of the foundation due to streamline compression. The horseshoe vortex trips to the lee side of the foundation with the wave passage, and the wake vortex is shed off from the downstream. Figures 5 and 6 show that the flow velocity is amplified at the wake vortex zone, causing high turbulence energy, which contributes to the local scour at the lee side of the foundation.
4.2 Scour evolution

The scour evolution curves are similar in all cases in this study. For case 3, the scour and accretion depth evolution curves are shown in Figure 7. The scour and accretion depths increased rapidly at the initial stage, and then, the scouring rate decreased. After about 300 wave cycles, the scour and accretion depth was gradually stabilized. The maximum scour and accretion depths were −1.877 and 0.544 m, respectively, after 420 wave cycles, i.e., the wave action time $t = 3600$ s. Figure 8 depicts the scour and accretion depth contours at different times. At the upside of the foundation, scour mainly occurred between neighboring anchor branches where the horseshoe vortex formed, indicating that the anchor branches protect the soil from scouring to some extent. The maximum scour depth was recorded at the lee side of the foundation where the wake vortex was shed off.
4.3 Parametric study

4.3.1 Effects of wave height
Figure 9 shows the scour and accretion depth evolution curves with wave height. The changing trend of the scour evolution with wave height converged, but higher wave heights resulted in larger scour and accretion depths simultaneously, which can be attributed to the higher energy associated with higher wave heights. This results in high turbulence flow energy around the foundation, contributing more violent horseshoe and wake vortices. The time required for scour to stabilize was the same under different wave heights, indicating that the timescale has a weak correlation with the wave height.

(a) Relative scour depths  
(b) Relative accretion depths

**Figure 9.** Time history of relative scour and accretion depths around USAF

4.3.2 Effects of anchor branches
To investigate the anti-scour properties of the anchor branches, the skirt anchor foundation (SAF) was simulated under wave and current. The parameters were the same as in case 3 for USAF. Figure 10 depicts the scour depth contours of USAF and SAF. The scour morphology for both USAF and SAF is similar. However, the extent of the scour zone for SAF was larger than that for USAF. In addition, there were evident scour pits surrounding SAF, and these scour pits were interconnected. However, only some scour pits were observed at the lee side of USAF, indicating favorable anti-scour properties of anchor branches.
5. Conclusions

(1) A coupled seabed-foundation-fluid model was developed herein, and it could generate the satisfied waveform and well reflect local scour around foundations.

(2) Horseshoe vortices increase turbulence intensity around the offshore edge of USAF, amplifying the shear stress on the seabed, which causes local scour around the USAF upstream. The anchor branches protect the soil from scouring to some extent.

(3) The scour and accretion depths increased rapidly at the initial stage, and then, the scouring rate decreased. After about 300 wave cycles, the scour and accretion depths gradually stabilized.

(4) The changing trend of scour evolution with wave height converged, but higher wave heights resulted in larger scour and accretion depths simultaneously.

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