Scour holes or scour protection around offshore wind turbine foundations: Effect on Loads

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Abstract

The present study investigates the effect of scour hole/scour protection to the wave loads on wind turbine foundations. The investigations are carried out numerically partly using WAMIT and partly through fully non-linear 3D CFD computations with DHI’s ‘NS3’ code. WAMIT is a first order potential flow theory code and NS3 has a surface description based on the VOF technique (Volume of Fluid) that allows for describing breaking waves as well as slamming forces.

The influence of a scour hole/scour protection is investigated for regular waves. The influence of depth, wave height and wave period is addressed. One case with breaking waves is presented as well. Further, the kinematics inside a scour hole is examined. It is found that the horizontal force increases for a wind turbine foundation with a scour hole, and decreases for a case with scour protection. The effect on overturning moment is the opposite, i.e. smaller for a scour hole case, and larger in case of scour protection.

Introduction

Loads from wave and current motion are one of the key design parameters for offshore wind turbine foundations. It is well known that the presence of waves and currents creates scour holes around foundations that are placed on an erodible seabed. Scour holes deeper than one pile diameter are not unusual.

Scour protection, on the other hand, also influences the local topography. The protection is typically carried out by placing layers of gravel and stones on the seabed around the pile, leading to a local reduction of the water depth.

The kinematics around the pile is modified due to the change in bed topography so the scour hole or scour protection changes the loads on the turbine. In the case of a scour hole, the exposed length of the pile is increased. The change in depth associated with a scour hole or scour protection changes the diffraction pattern of the wave field.

Conventional design methods do not address these issues directly. Typically, the wave and current forces are calculated based on an undisturbed wave field without the structure. The description of the undisturbed water particle kinematics is often based on linearly superposed wave solutions or on a non-linear regular wave solution – both derived on flat seabed. It is not trivial how results obtained with such a design basis should be modified to take the effect of scour hole/scour protection into account. Alternatively, the wave and current loads may be determined either from physical model experiments or from CFD modelling. Experiments, however, are specific to the particular structure and local wave climate, and it is difficult to obtain information about the relative contribution to the wave loading from the scour hole/scour protection.

In the present study, the WAMIT code, cf. [8] has been used to study first order wave loads. WAMIT is a first order panel method to solve diffraction and radiation problems for offshore structures and to analyse floating body motions. The CFD code ‘NS3’ has been used to study the general case. Application of the ‘NS3’ code to wave loads and run-up on wind-turbine foundations has been reported already in e.g. Christensen et al. [2] and Bredmose et al. [1].

Potential Theory, Small Waves, without Current
For small waves, without presence of current, the flow and forces are well described by first order potential theory.

**Inertia Coefficient**

The force per unit length on a single two-dimensional (2D) structure placed in a uniform accelerating flow field, per unit length can be written as:

\[
f_x = C_M A \rho \frac{d(U_x)}{dt}
\]

in which \(A\) is the cross-section area

\[
\frac{d(U_x)}{dt}
\]

is the undisturbed fluid acceleration

\(C_M\) is the inertia coefficient

\(\rho\) is the fluid density

For a single 2D circular cylinder, one can show that the inertia coefficient is equal to \(C_M = 2\). For two cylinders placed close to each other, the acceleration fields are influenced by the presence of both cylinders, so when two identical cylinders are placed behind each other, the inertia coefficients are smaller than two, and when placed side by side, the inertia coefficients are larger than two. The presence of the free surface changes the flow and hereby also the inertial coefficient.

**Added Mass**

When a body accelerates with acceleration \(\frac{d^2X}{dt^2}\) in still water, the force has to accelerate its own mass, and a part of the water that is called added mass. The additional force required to accelerate the added mass force per unit length is normally written as:

\[
f_{\text{add}} = -\frac{dX}{dt} \rho C_a A,
\]

where \(C_a\) is the added mass coefficient, and \(A\) is the area of the cross-section of the structure. For a 2D cylinder accelerating in an infinite large volume of water, one can show that in this case the coefficient is equal to one, and further that:

\[
C_a = C_M - 1
\]

This equation is in general valid for all single bodies located far from other bodies.
boundaries and free surfaces. However, the equation is also used for flow cases where it definitively cannot be applied, as shown in Figure 3. The WAMIT program has been used to determine the added mass. Figure 3 (upper) shows the added mass coefficient for horizontal oscillation. (It shall be noted that the wave length in the figure corresponds to the period and the water depth).

In general the added mass is a matrix quantity, which dimension equals the degrees of freedom for the system. The added mass for a ship is thus described by a six times six matrix, corresponding to its surge, sway, heave, roll, pitch, and yaw, movements. This added mass and the interaction of small surface waves with structures can be analysed by three-dimensional (3D) panel methods, for example the WAMIT program developed at MIT. In addition to the added mass forces which are in phase with the body acceleration, other force components are in phase with the body’s velocity, resulting in a first order damping force, in the offshore industry named wave damping.

For a non-floating wind turbine foundation modelled as an elastic continuum, the number of freedoms is in principle unlimited, however, only the turbine accelerations corresponding to the horizontal translation, and the first and second order deflections are of importance.

The lower part of Figure 3 presents the added mass for three different pile deflections shapes for a harmonic oscillation of the pile:

\[
X_{def}(z,t) = X_o \sin\left(\frac{2\pi}{T} t\right) \\
\text{Uniform deflection}
\]

\[
X_{def}(z,t) = \left(\frac{z - z_{bed}}{h}\right) X_o \sin\left(\frac{2\pi}{T} t\right) \\
\text{Linear deflection}
\]

\[
X_{def}(z,t) = \left(\frac{z - z_{bed}}{h^2}\right)^2 X_o \sin\left(\frac{2\pi}{T} t\right) \\
\text{Parabolic deflection}
\]

In which \(X_o\) is the amplitude of the oscillation at the surface, \(z\) is the vertical coordinate, \(T\) is the wave period, and \(h\) is the water depth. The added mass force is defined as:

\[
F(t) = 0.25\pi D^2 \rho C_a \bar{X}_{def}(z_{surface},t)^* h \\
\text{Linear deflection}
\]

\[
F(t) = 0.25\pi D^2 \rho C_a \bar{X}_{def}(z_{surface},t)^* \frac{h}{3} \\
\text{Parabolic deflection}
\]

Figure 3 (lower) clearly shows that for long waves \(D / L \approx 0\) the added mass coefficients are for all three deflections close to one. However, for short waves, the added mass coefficient is highly influenced by the mode of pile deflection.

Figure 3. Pile diameter equals to 0.4 the water depth. Upper part: the inertia and added mass coefficients (for uniform pile deflection) as function of ratio between the diameter and the wave length. Lower part: added mass coefficient for different flow conditions and structural deflection shapes

**Inertia Forces on Turbines placed on a Scour Protection**

The WAMIT program is used to determine the inertia forces on two bodies, this facility has been used to determine the added mass and inertia forces on a 4.2 diameter pile, at 10m of water depth as shown in Figure 4.
Figure 4. Pile with a diameter of 4.2 m placed on scour protection with a radius of scour protection 8m. Water depth is 10m, slope of scour protection 1:2.

The upper part of Figure 5 shows the added mass coefficient for uniform oscillations for three different scour heights, it can be seen that the scour protection only has a little influence of the added mass coefficients. (It shall be noted that the actual forces are determined by multiplying the added mass coefficient by the volume of the submerged pile above the scour protection, which decreases with increasing height of the scour protection).

Figure 5. Pile diameter 4.2 m, water depth 10m. The upper part shows the added mass coefficient for a pile oscillating above different scour protections shown in Figure 4. The lower part shows the amplitude of horizontal first order wave load as function of wave period, for wave height H=0.5m

Morison Equation

In many engineering programs the hydrodynamic forces on a unit length of a fixed structure are described by Morison equation, which consists of a drag term (proportional the squared velocity) and the inertia term. For a circular cylinder the forces are written as:

\[ f = C_D D \rho \frac{d(U_x)}{dt} + C_M \pi D^2 \rho \frac{d^2(U_x)}{dt^2} \] (3)

\( C_D \) is the drag coefficient

In cases where the structure is not fixed, the drag term in Morison equation is modified by using the relative velocity, and the additional added mass term due to the cylinder acceleration is included.

\[ f = C_D D \rho \left( U_x - \frac{d(X)}{dt} \right) \left( U_x - \frac{d(X)}{dt} \right) + C_M \pi D^2 \rho \frac{d^2(U_x)}{dt^2} \] (4)

This equation is often rewritten in the engineering program by assuming \( C_M = C_D - 1 \) to be valid.

\[ f = C_D D \rho \left( U_x - \frac{d(X)}{dt} \right) \left( U_x - \frac{d(X)}{dt} \right) + C_M \pi D^2 \rho \frac{d^2(X)}{dt^2} + \pi D^2 \rho \frac{d^2(U_x)}{dt^2} \] (5)

The upper part of Figure 3 clearly shows that the assumption \( C_M = C_D - 1 \) is valid only for slender piles or long waves. For typical offshore wind turbines with monopiles, the waves cannot be considered to be long with respect to the pile diameter, and the approximation is thus not valid.

It shall further be noted that the so-called wave damping, which is not treated in this paper, gives a linear damping contribution, which may in many cases be far more important than the damping which is the result of using drag coefficient.
Combined Waves and Current and High Waves

If the foundations are placed in areas with a varying bathymetry and exposed to high waves and/or current, the forces cannot be determined from potential theory. The flow and forces are determined using the DHI program, NS3, where the Navier-Stokes equations in three dimensions are solved using a finite-volume approach on a multi-block grid.

NS3 has been used and validated in Mayer et al. [3] and Nielsen and Mayer [6]. The model has previously been used for offshore wind turbines, see Bredmose et al. [1] or Christensen et al. [2]. The model has been set up for a 4.2m diameter turbine at 10m of water depth, and three different seabed conditions have been investigated, see Figure 7: (upper) the plane bed situations, (mid) a 2m high scour protection radius 8m, and (lower) a 4m deep scour hole.

The simulations are carried out in the numerical domain shown in Figure 6. The width of the domain is 40m. The waves enter into the domain 50m upstream from the centre of the pile and propagate 250m downstream from the pile centre.

Figure 6. Numerical domain

Figure 8 shows the calculated horizontal forces for water depth h=10m, wave period T=8s, wave height H=0.5m. The model predicts forces that vary from wave to wave, this is caused by non-linear phenomena, reflections etc, which are exactly the phenomena that occur in physical wave flumes. The horizontal forces in the scour case are almost equal to plane bed case. It is further seen that the presence of a scour protection reduces the horizontal forces by 25 percent.

The force situations calculated by first order potential theory are shown in the lower part of Figure 8. This theory also predicts a force reduction due to the scour protection. In case of a small wave height the numerical model predicts approximately ten percent higher peak forces than the first order potential theory. This difference is expected to be caused by reflection and other phenomena covered by the potential theory.

Figure 7. Numerical domain. Upper part: plane bed. Mid part: scour protection. Lower part: without scour protection
In Figure 9, the wave heights have been increased from 0.5 m to 5m by a factor 10. Compared with Figure 8, the forces are increased approximately by 10. However, the peak forces under the wave crest are almost identical, while the return force under the through is largest for the scour case. In Figure 10, the wave height have been increased to 6m, also in this case the positive peak forces are almost identical, and return force under the through is largest for the scour case.

In Figure 11, a current has been added for the wave height equal to 5m, also in this case the positive peak forces are higher for the scour case than for the two other cases. Also here, the return force under the through is largest for the scour case. It should be noted comparing Figure 11 with Figure 9 that the wave period is the same seen from the turbine, so the wave lengths are not the same in the two situations.

The overturning moment \( M_y \) increases with a scour protection in place compared to the plane case, and decreases for the scour hole case. This is actual the opposite of the behaviour for the horizontal force.

Figure 8. Calculated horizontal forces and overturning moment. Water depth \( h=10\text{m} \), wave period \( T=8\text{s} \), wave height \( H=0.5\text{m} \)

Figure 9. Calculated horizontal forces and overturning moment for water depth \( h=10\text{m} \), wave period \( T=8\text{s} \) and wave height \( H=5.0\text{m} \),

Figure 10. Calculated horizontal forces and overturning moment for water depth \( h=10\text{m} \), wave period \( T=8\text{s} \) and wave height \( H=6.0\text{m} \),
Figure 10. Calculated horizontal forces and overturning moment for water depth $h=10\text{m}$, wave period $T=8\text{s}$ and wave height $H=6.0\text{m}$

Figure 11. Calculated horizontal forces and overturning moment for water depth $h=10\text{m}$, wave period $T=8\text{s}$, wave height $H=5.0\text{m}$ and current velocity $V=1\text{m/s}$
Conclusion

Based on the calculation presented, it can be concluded that for offshore wind turbines the added mass $C_a$ is not related to $C_M$ by the equation $C_a = C_M - 1$. The horizontal forces are affected by the presence of a scour hole or a scour protection. All cases presented in the present paper showed that for non-breaking waves, the presence of a scour protection will reduce the horizontal forces and enhance the overturning moment. A scour hole will increase the horizontal forces but reduce the overturning moment compared to the plane bed situation.

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