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Assessment of foundation design for offshore monopiles unprotected against scour

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A R T I C L E I N F O

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A B S T R A C T

When designing offshore monopiles without scour protection, the stiffness of the foundation will vary with time due to the dependency of the scour depth on current and sea conditions. Currently, design regulations of organizations such as Det Norske Veritas (DNV) and the International Organization for Standardization (ISO) recommend the use of the most extreme local scour depth as the design scour depth. This is a conservative approach, because the scour depth depends on the sea conditions and because the equilibrium scour depth is low during moderate to extreme wave loading. In this paper the effect of using expected scour depths when designing for the ultimate limit state and the fatigue limit state is illustrated by means of a desk study.

1. Introduction

The monopile foundation concept is often employed as the foundation for offshore wind turbines. The monopile foundation concept consists of a steel cylinder driven or drilled open-ended into the seabed. Typical dimensions are pile diameters of $D=4-5$ m; pile wall thicknesses of wt $\approx 50-120$ mm; and embedded pile lengths of $L_p=15-30$ m. The monopile foundation concept has been mainly employed for offshore wind turbines in shallow waters with water depths ranging from approximately 10 to 25 m supporting 2–5 MW wind turbines.

Offshore wind turbine foundations are exposed to large lateral loads and overturning bending moments due to among others waves and wind. Ubilla et al. (2006) state that the design loading from hydrodynamics and wind on a 3.5 MW offshore wind turbine is approximately 6 MN in vertical loading, 4 MN in horizontal loading and 120 MNm in overturning moment. Of these the vertical loading is considered a static load originating from the self-weight of the wind turbine and the foundation, while the horizontal loads in contrast are cyclic. The wave frequency of extreme waves is typically 0.07–0.14 Hz while the energy rich wind turbulence typically has a frequency less than 0.1 Hz. Monopile foundations for offshore wind turbines are therefore designed such that the first natural frequency lies between the rotor frequency, 1P, and the blade passing frequency, 3P. Typically, 1P lies within 0.17–0.33 Hz, and 3P lies within 0.5–1.0 Hz. Therefore, the first natural frequency of offshore wind turbine is required to be within a narrow range. Hence, offshore wind turbines are heavily affected of changes in the first natural frequency. Offshore wind turbines are traditionally designed for a lifetime of 20 yr. During the lifetime of an offshore wind turbine approximately 100 cycles with a large load amplitude are expected and further 10^6–10^8 cycles with low or intermediate load amplitude are expected. Therefore, the wind turbines and the foundation of the wind turbines should be designed such that fatigue failure of the steel material is prevented.

Around offshore piles installed in sandy or silty soil erosion of soil material can occur leading to local scour holes. The scour depth relative to the pile diameter is in wave dominated conditions primarily dependent on the Keulegan–Carpenter number. However, Shield's parameter, Froude's number, the water depth, the bed shape and the sediment dimensions also influence the scour depth. Generally, the scour depth, S, is large when currents are dominating and small when waves are dominating. Several authors have investigated scour around piles (Breusers et al., 1977; Sumer et al., 1992a,b; Sumer et al., 1993; Whitehouse, 1998; Richardson and Davis, 2001; den Boon et al., 2004). To avoid the generation of scour holes, scour protection consisting of rock infill can be deployed around offshore monopile foundations. Deployment of scour protection is however costly. Furthermore, the deployment requires calm sea conditions. The economic feasibility of deployment of scour protection, therefore, depends on the site conditions.

When designing an offshore monopile foundation without scour protection, scour will occur and the depth of the scour hole will vary with time. Therefore, the stiffness and capacity of the foundation as well as the natural frequency of the offshore wind

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turbine will vary with time. DNV (2011a) suggests the use of the local extreme scour depth for all investigations of the wind turbine. This seems to be a conservative estimate for both the fatigue limit state (FLS) and the ultimate limit state (ULS), since the scour depth is generally small when waves are dominating and large when currents are dominating.

In this paper a review of the scour/backfilling phenomena is presented. Current knowledge regarding the equilibrium scour depth, the time scale of scour and backfilling, and the properties of backfilled soil material is assessed. An adaptive scour design approach is presented in which the time variation of scour depth is included in the FLS- and ULS-design. The potential savings are illustrated for a design example. The objective of the adaptive scour design approach is not to provide design methods for offshore monopiles unprotected against scour, but merely to illustrate potential savings by accounting for the variation of scour depth with the sea conditions in the design.

2. Review of scour/backfilling phenomena

Installing a vertical cylinder in the offshore environment causes significant changes to the waterflow resulting in one or more of the following phenomena: contraction of flow at the side edges of the pile; formation of a horse-shoe vortex at the base in front of the pile; formation of lee-wake vortices behind the pile; generation of turbulence; occurrence of wave breaking; occurrence of wave reflection; and occurrence of wave diffraction. These phenomena increase the capacity of the local sediment transport causing the formation of local scour holes. Scour occurs when the near bed shear stress exceeds the critical shear stress at which sediment starts to move.

In addition to local scour natural instabilities can cause rise and fall of the seabed level, for instance, sand waves. Furthermore, scour can also occur over a large area. These ambient bed level change phenomena are typically denoted general scour. The present paper focuses on changes in the seabed level arising from local scour.

2.1. Equilibrium scour depth

The scour depth around offshore piles depends on the sea condition. Generally currents lead to large scour holes while waves lead to smaller scour holes. For a given sea state an equilibrium scour depth exists. The process in which the scour depth increases is denoted scouring, while the process in which the scour depth decreases is denoted backfilling.

Current induced scour has been studied extensively. Breusers et al. (1977) presented the following equation for the equilibrium scour depth, $S_{\infty,c}$, around a circular cylinder in steady currents:

$$\frac{S_{\infty,c}}{D} = \alpha \tanh\left(\frac{h}{D}\right) \quad (1)$$

where α is the depth independent equilibrium scour depth and h is the water depth. Høgedal and Hald (2005) suggest $\alpha = 1.75$ as a conservative design value of the current generated equilibrium scour depth. Based on physical experiments for the Q7 Offshore Wind Farm in The Netherlands, den Boon et al. (2004) adjusted Eq. (1):

$$\frac{S_{\infty,c}}{D} = \alpha K_1 \tanh\left(K_2 \frac{h}{D}\right) \quad (2)$$

where K_1 and K_2 are correction factors accounting for depth limitation and sediment grading.

Sumer et al. (1992b) determined the mean value and the standard deviation of the equilibrium scour depth from the experimental data from Breusers et al. (1977):

$$\frac{S_{\infty,c}}{D} = 1.3 \quad (3)$$

$$\sigma_{S_{\infty,c}/D} = 0.7 \quad (4)$$

Det Norske Veritas has in their design regulation DNV (2011a) adopted the mean value of the equilibrium scour depth, cf. Eq. (3). The International Organization for Standardization has adopted a scour depth of 1.5D in their recommendations, cf. ISO (2007).

Sumer et al. (1992b) investigated scour around piles under the presence of waves. They found that the existence and the extension of both the vortex shedding at the lee side of a pile and the horseshoe vortex at the upstream side of the pile are governed primarily by the Keulegan–Carpenter number. The Keulegan–Carpenter number is defined as

$$KC = \frac{U_m T}{D} \quad (5)$$

where U_m denotes the maximum value of the oscillatory flow velocity outside the wave boundary layer and T is the wave period. Sumer and Fredsøe (2001) indicate that the peak wave period, T_p, should be used for irregular waves.

The horseshoe vortex and the vortex shedding at the lee side of the pile increase the capacity of the local sediment transport. Hereby, these vortices lead to the formation of local scour holes, and the Keulegan–Carpenter number, KC, is governing for the equilibrium scour depth. Based on several small-scale tests, Sumer et al. (1992b) proposed the following dependency between the equilibrium scour depth around a pile in waves, $S_{\infty,w}$, and the Keulegan–Carpenter number:

$$\frac{S_{\infty,w}}{D} = \frac{S_{\infty,c}}{D}(1-\exp(-0.03(KC-6))), \quad KC \geq 6 \quad (6)$$

The equilibrium scour depth increases for increasing values of KC and approaches a constant value equal to the current generated scour depth for large values of KC.

Sumer and Fredsøe (2001) investigated scour around piles in combined waves and current through experimental modelling. From their study they introduced the dimensionless parameter U_{cw}:

$$U_{cw} = \frac{U_c}{U_c + U_m} \quad (7)$$

where U_c is the undisturbed current velocity at a distance $y = D/2$ from the bed. The dimensionless parameter U_{cw} describes whether currents or waves are dominating. For a current only condition, U_{cw} takes a value of 1, and for a waves only condition, U_{cw} takes a value of 0. Based on their tests, they proposed the following expression for the equilibrium scour depth in combined waves and current:

$$\frac{S_{\infty,cw}}{D} = \frac{S_{\infty,c}}{D}(1-\exp(-A(KC-B))), \quad KC \geq B \quad (8)$$

where $S_{\infty,c}$ is the equilibrium scour depth for a current dominated sea state and A and B are constants depending on U_{cw}:

$$A = 0.03 + \tfrac{3}{4} U_{cw}^{2.6} \quad (9)$$

$$B = \exp(-4.7 U_{cw}) \quad (10)$$

Høgedal and Hald (2005) compared data for the scour depth around existing unprotected monopiles for offshore wind turbines at the Scroby Sands Offshore Wind Farm with the expressions of Breusers et al. (1977), den Boon et al. (2004) and Sumer et al. (1992b), cf. Eqs. (1), (2), and (6). They found that the equilibrium scour depth proposed by Sumer et al. (1992b) overestimates the scour depth for shallower water ($h/D < 3$). Further, they concluded that the expressions for the equilibrium scour