Ocean Engineering 136 (2017) 94–105

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical analysis of the long-term performance of offshore wind turbines supported by monopiles

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ARTICLE INFO

Keywords:
Wind turbine
Monopile
Cyclic loading
Long-term performance
Soil-structure interaction

ABSTRACT

Offshore wind turbines (OWT) are often supported on large-diameter monopiles and subjected to cyclic loading such as wind and wave actions. The cyclic loading can lead to an accumulated rotation of the monopile and a change in the foundation stiffness. This long-term effect is not yet well understood. This paper presents a three-dimensional finite element model for analyzing the long-term performance of offshore wind turbines on large-diameter monopiles in sand in a simple way. In this model the characteristics of pile-soil interaction under long-term cyclic lateral loading, observed from well-controlled laboratory model tests, are taken into account. A parametric study has been conducted for a full-scale wind turbine supported on a large-diameter monopile, with focus on the influence of several design parameters on the deformations of the monopile and the tower supporting the wind turbine. The study shows that under the serviceability limit state, the deflection and rotation at pile head in the case of considering the effect of long-term cyclic loading are notably greater than that computed in the case where this long-term effect is ignored. This significant difference suggests that the long-term cyclic loading effect cannot be overlooked in design and analysis.

1. Introduction

Offshore wind turbines have the potential to be a significant contributor to global energy production (Breton and Moe, 2009; Pérez-Collazo et al., 2015). Currently most offshore wind turbines have been installed in shallow water and founded on monopiles (Damgaad et al., 2014). During the operation a wind turbine and its foundation are exposed to several types of cyclic loads such as the wind and wave actions. It has been estimated that an offshore wind turbine needs to withstand about 10,000,000 cycles of loading in its life time (Schaumann et al., 2011). It is very likely that the foundation stiffness will change over this long period of time and this change may impose a notable impact on the natural frequency of the wind turbine-pile-soil system and consequently the system's response. In this regard, the performance of the wind turbine-pile-soil system under long-term cyclic loading is a major concern. If the long-term cyclic loading effect is not properly taken into account in design, the serviceability of the wind turbine may be seriously affected due to excessive deformations and, in the worst situation, the wind turbine may collapse. There is currently a lack of guidance in codes of practice on how to account for the long-term loading effect on wind turbines (Bhattacharya, 2014; Paul and Kenneth, 2011).

As far as monopiles are concerned, the standard design method for considering the effect of cyclic lateral loading is the use of API p-y curves (API, 2000). The p-y curve method was derived mainly from field tests on small-diameter piles subjected to a small number of loading cycles (typically less than 200 cycles) (Achums et al., 2009). The applicability of this method to offshore monopiles has been an issue under extensive discussion (Møller and Christiansen, 2011; Schmoor and Achmus, 2015; Bisoi and Haldar, 2015); this is because offshore monopiles usually have significantly large diameters (3–6 m) and are usually subjected to a much greater number of loading cycles. The DNV's guidance (DNV-OS-J101, 2014) also states that the p-y curves from API have not been calibrated for monopiles with large diameters and generally are not valid for such monopiles. Achmus et al. (2014) conducted a three-dimensional (3D) finite element (FE) analysis to predict the behavior of large-diameter monopiles for offshore wind turbines. The results indicated that the lateral deflection of monopiles predicted by the API p-y curves is significantly lower than that obtained from the 3D FE analysis. Pappusetty and Pando (2013) conducted a similar 3D FE analysis and also showed that the use of API p-y curves does not adequately predict the deflection of pile head. Wichtmann et al. (2008) carried out FE calculations of a monopile installed in sand in which a high-cycle sand model accounting for

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http://dx.doi.org/10.1016/j.oceaneng.2017.03.019
Received 17 October 2016; Received in revised form 17 January 2017; Accepted 12 March 2017
0029-8018/

Nomenclature

C_D	inertia coefficient;
C_M	drag coefficient;
D	diameter of the monopile;
E_0^d	Young's modulus of the densified soil around the pile;
E_0^c	Young's modulus of the soil without the densification effect;
h_s	subsidence depth at the pile-soil interface;
L	pile embedded length;
M_L	model for long-term cyclic loading;
M_S	model for short-term cyclic loading;
N	number of cycles;
t	pile wall thickness;
dF	horizontal wave load on a vertical element dz of the monopile at level z;
ρ	mass density of sea water;
ρ_0	initial density of the soil;
$\rho_{\max}$	maximum density of the soil;
$\Delta V_{Long-term}$	soil volume loss around the pile under long-term cyclic loading;
Δ_{M_L}	lateral deflection in the case of M_L;
Δ_{M_S}	lateral deflection in the case of M_S;
θ_{M_L}	rotation in the case of M_L;
θ_{M_S}	rotation in the case of M_S;
$\mu_{E_0^d}$	mean value of soil modulus;
ULS	ultimate limit state;
SLS	serviceability limit state;

deformation accumulation was adopted (Niemunis et al., 2005). The results showed that the lateral deflection of the monopile increases with increasing amplitude and with increasing average value of the cyclic loading.

Møller and Christiansen (2011) investigated the effect of cyclic lateral loading on a model pile in both dry and saturated sand. The model pile was measured 0.052 m in diameter, 0.4 m in embedded length and 1.3 m in height above the mudline, and was laterally loaded with 12,000–24,000 cycles. These model tests indicated that both the stiffness and bearing capacity of the sand would increase after the completion of the cyclic loading.

Leblanc et al. (2010) tested the lateral response of a rigid model pile installed in unsaturated loose and medium dense sand. The slenderness ratio of the pile was 4.5. They concluded that cyclic loading increases pile stiffness and the increase is independent of relative density of the sand. Also, the accumulated rotation of the pile was found to be largely affected by the characteristics of the cyclic loading. They proposed a calculation model for estimating the displacement and stiffness of piles by taking into account the number of cycles and the magnitude of the cyclic loading.

In this paper, we present a 3D finite element model for investigating the performance of offshore wind turbines founded on monopiles in sand due to long-term cyclic lateral loading, with particular attention to the effects of long-term cyclic loading on the deflection and rotation of the support structure (including pile and tower) under the serviceability limit state (SLS) and the ultimate limit state (ULS). Using this numerical model, a parametric study has been conducted to examine the influence of several factors (e.g., wall thickness and diameter of the monopile; modulus of the sand surrounding the pile) on the long-term performance of the support structure and the selected results are discussed in this paper.

2. Pile-soil interaction under long-term lateral cyclic loading

Cuéllar (2011) conducted a series of model tests to investigate the performance of a tubular pile installed in saturated sand subjected to cyclic lateral loading. The prototype dimensions of the model pile were 7.5 m in diameter and 30 m in embedded length, which are typical of the monopiles supporting 5-MW wind turbines in the German Bight of the North Sea. As the model tests were performed under 1 g conditions, the kinematic and constitutive similarity between the prototype system and the model system were considered in designing the tests. The sand used was obtained from a quarry in the north of Berlin. A two-way harmonic lateral loading was applied on the top of the pile and several loading schemes with different amplitudes were applied. While a one-way cyclic loading may be common for offshore foundations, two-way loading is considered more severe than one-way loading and is possible in the situations of strong storms. The loading frequency was set 1 Hz and the number of cycles applied was as large as 5,000,000. One of the important observations from these model tests, as schematically shown

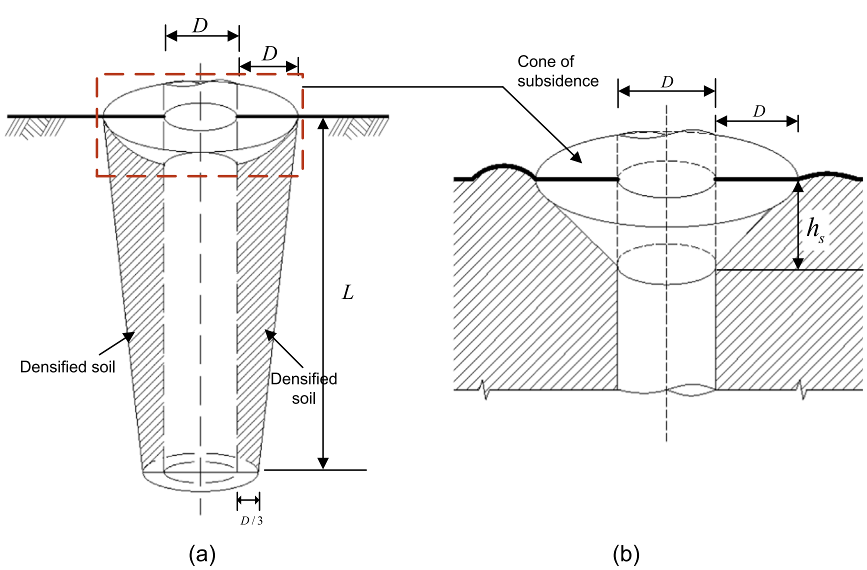

Fig. 1. Sketches of deformed soil around a pile due to long-term cyclic lateral loading: (a) a truncated cone-shaped zone of densification along pile shaft; and (b) a cone-shaped subsidence in the soil around the upper part of the pile.