Soil Dynamics and Earthquake Engineering 80 (2016) 192–209

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Hybrid foundation for offshore wind turbines: Environmental and seismic loading

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ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form
9 August 2015
Accepted 23 October 2015
Available online 21 November 2015

Keywords:
Offshore geotechnics
Wind farms
Monopile
Shallow foundation
Seismic shaking

ABSTRACT

A hybrid foundation for offshore wind turbines (OWT) is studied, combining a monopile of diameter *d* and length *L* with a lightweight circular footing of diameter *D*. The footing is composed of steel plates and stiffeners forming compartments, backfilled to increase the vertical load. A special pile–footing connection is outlined, allowing transfer of lateral loads and moments, but not of vertical loads. The efficiency of the hybrid foundation is explored through 3D finite element modelling. Hybrid foundations of $L=15$ m are comparatively assessed to an $L=30$ m reference monopile. A detailed comparison is performed focusing on a 3.5 MW OWT. While the moment capacity of the monopile is larger, the hybrid foundation exhibits stiffer response, outperforming the monopile in the operational loading range. Under cyclic loading, the hybrid foundation experiences less stiffness degradation and rotation accumulation. Besides installation, the cost savings depend on the design of the footing and buckling can be crucial. The rubble fill is shown to provide lateral restraint to the stiffeners, being beneficial for buckling prevention. Although seismic shaking is not critical in terms of capacity, it may lead to substantial accumulation of rotation and settlement. Combined with cyclic environmental loading, the latter may challenge the serviceability of the OWT, potentially leading to a reduction of its service life. To derive insights on the effect of seismic loading, two scenarios are investigated: (a) seismic loading; and (b) combined environmental and seismic loading. In the first case, even a $D=15$ m hybrid foundation may outperform the reference monopile. This is not the case for combined environmental and seismic loading, where a $D=20$ m hybrid system would be required to outperform the reference monopile.

1. Introduction

According to the latest forecasts, energy demand may double by 2015 due to the exponential growth of developing countries [28]. Even if resources were unlimited, this would lead to a proportionate increase in CO_2 emissions, which would not be environmentally sustainable. Moreover, such an increase in fossil fuel demand raises serious concerns over the security of supplies, which are not unlimited. To address this challenge, the energy industry is turning to renewable energy sources. Within this framework, the EU has set as a target 20% of its energy to be produced by renewable sources by 2020, and the UK is aiming at 60% reduction of CO_2 emissions by 2050 [14].

Wind power is recognized as one of the most promising such sources, and has seen major technological advances in recent years. Wind turbines are employed for this purpose, the majority of which have so far been installed onshore. Offshore wind turbines (OWT) offer certain advantages and are increasingly adopted by the industry. Offshore sites are more efficient and reliable, as they are characterized by stronger and more stable wind conditions [37]. Moreover, space is abundant offshore allowing the installation of larger wind farms. Due to their remoteness, offshore sites are also less sensitive to objections by residents, which have led to substantial delays or even cancellation of onshore wind farms.

Despite their advantages, the development of offshore wind farms is impeded by their cost. Such investments are currently not viable [32], and means to reduce the cost are urgently needed. The increased cost of offshore wind farms is due to: (a) the remoteness of the sites, due to which the grid infrastructure is not readily available and transportation costs are higher; (b) the harsh environmental conditions which dictate foundation design; and (c) the offshore installation which requires highly specialized vessels. As a result, the foundation cost may be as high as 35% of the total cost [14]. Hence, there is an urgent need for improved design and construction procedures and cost efficient solutions.

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http://dx.doi.org/10.1016/j.soildyn.2015.10.015
0267-7261/

Notation

Superstructure parameters

- d_R rotor diameter
- d_T tower cross section diameter
- h_0 wind loading height (taken from the lid of the foundation)
- h_W wave loading height (taken from the lid of the foundation)
- m_{NR} rotor-nacelle mass
- m_T tower mass
- t_T tower wall thickness

Foundation parameters

- A area of the footing
- d pile diameter
- D footing diameter
- q surcharge load
- L pile length
- t_p pile wall thickness

Soil properties and constitutive model parameters

- α backstress
- γ parameter determining the rate of decrease of the kinematic hardening with increasing plastic deformation
- ν Poisson's ratio
- ρ' effective unit weight
- σ_o stress at zero plastic strain
- σ_y yield stress
- C initial kinematic hardening modulus
- E Young's modulus
- k gradient of undrained shear strength increase with depth
- S_u undrained shear strength
- f_y yield stress of steel

Loads and deformations

- ϑ rotation
- ϑ_{max} maximum accumulated rotation
- H lateral load
- H_{ult} lateral loading capacity
- K_R secant rocking stiffness
- $K_{R,0}$ small strain (initial) rocking stiffness
- M overturning moment
- M_{ult} moment capacity
- N cycles of loading
- V vertical load
- V_{ult} bearing capacity under pure vertical loading
- w settlement

The design of OWT foundations is governed by wind and wave loading, which generates large overturning moments combined with low vertical loads. Several foundations have been proposed, including monopiles, footings, tripods, jacket structures, and suction caissons [13,26,27]. The vast majority of currently installed OWTs are founded on driven steel tube monopiles of 3.5–6 m in diameter and 30–40 m in length [37]. Pile lateral loading has been extensively studied in the literature [e.g., 38,40,44,41,42,19,51,21,45]. However, stiffness degradation and accumulation of pile deflections under cyclic loading governs the design of OWTs, rather than ultimate capacity [33]. In order to avoid excessive stiffness degradation, the strain level in the soil has to be reduced by increasing the foundation size. The threshold strain concept, proposed by [37], can be used for this purpose.

Currently, the design of monopiles relies on empirical data and the most commonly applied method is [6]. Despite its use in practice, the API method does not address the accumulation of deflections. The latter is crucial, as OWTs cannot tolerate more than 0.5° ($\approx$ 0.01 rad) of tilt [37]. Recognizing the need to develop reliable predictive methods, substantial effort has been devoted to gain insights on long-term cyclic performance and dynamic soil–structure interaction, applying experimental and numerical methods [10,2,33–37].

Monopiles with wings (or fins) have been proposed, aiming to enhance the capacity and reduce stiffness degradation at the upper and softer soil layers. Their effectiveness has been studied through physical and numerical modelling [11,18,39]. Although the rate of deflection accumulation is not reduced, the overall pile head displacement is substantially lower thanks to the increase of the initial stiffness. Hence, the addition of wings may enhance the efficiency of the monopile, allowing reduction of its length. However, the driving resistance is also increased in proportion to the area of the wings. Thus, there is a trade-off between the cost savings due to the reduction of the pile length and the additional installation cost.

Another alternative is a "hybrid" foundation, combining a monopile of diameter d and length L with a circular footing of diameter D. Such a scheme has been proposed by [47] and studied experimentally and analytically [20,48,8]. The footing provides a lateral restraint, due to which the moment capacity of the monopile can be increased by as much as 100%, provided that the footing is large ($D/d=6$) and heavily loaded (carrying a surcharge load $q \approx 200$ kPa). Its efficiency is enhanced when vertical movements are allowed between the pile and the footing. Such decoupling allows the footing to act independently, undertaking the entire surcharge load q.

Despite such promising results, the feasibility of the hybrid foundation is challenged by constructability issues. The construction, transportation, and installation of such a large and heavy footing can be costly. For a typical pile diameter $d=5$ m, a $D=30$ m footing would be required. Besides the excessive materials' cost, such a footing would have to be towed to the site. Most importantly, to achieve the necessary surcharge load, a substantial volume of ballast would be required: roughly 20 m of rubble placed on top of the footing. This paper attempts to address such issues, contributing towards the development of an alternative foundation system with the potential of offering cost savings.

2. Key elements of the hybrid system

The hybrid foundation is based on the concept of [47], but has a number of subtle differences which are believed to be crucial for its constructability. As shown in Fig. 1, the hybrid foundation comprises a steel monopile of diameter d and length L, and a circular footing of diameter D. The footing is a lightweight steel structure, consisting of a bottom plate (i), an external peripheral plate (ii), an internal peripheral plate forming a bore wall structure (iii), and radial stiffeners (iv). After installing the footing on the seabed, the compartments between the plates and the stiffeners are backfilled with rubble to increase the vertical load acting on the footing. The latter also offers scour