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Behavior of closely spaced double-pile-supported jacket foundations for offshore wind energy converters

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ABSTRACT

As the offshore wind energy production units move to deeper waters the design of their foundations demand more creative and complex approaches especially for large turbines (i.e. ~5–7 MW). In this article, a novel piled foundation alternative with closely spaced double piles at the edges of the jacket is studied for various pile spacing and lengths. A numerical parametric study was carried out to understand the effects of pile spacing and pile length on the behavior of the novel supporting system under monotonic combined loading in very dense sand. Prior to the analysis, the numerical model is validated in field tests with single-pile and double-pile configurations. The contribution of closely spaced double piles to the overall foundation response and load distribution among the piles were investigated. The response of the foundation was evaluated considering the horizontal load-head displacement, moment-head rotation, and initial stiffness of the soil-pile system. It is found that the response of the recommended foundation system is superior to that of a rather conventional system with single piles at the edges. The results indicate that the piles on the tension loading side evidently carried lower loads than those on the compression side. Moreover, the disposition of the piles is more important on the tension side, as the trailing piles carried considerably lower loads than the leading piles. It is found that the double pile system with a pile embedment length L/2 and a pile spacing of S = 5D, 6D provides better response, where L is the embedded pile length of conventional system and D is the diameter of pile.

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1. Introduction

The importance of renewable energy is significantly increasing, and the utilization of offshore wind energy has been growing. Within the next few decades, a vast number of offshore wind energy converters (OWECs) shall be erected to supply a large portion of our energy needs [1]. It is stated in the report of European Wind Energy Association [2] that the next step for wind energy is offshore wind farms in deep waters, and projects of deep OWECs are being developed in Europe. In this respect, selecting and designing an appropriate OWEC foundation type is an essential challenge for geotechnical engineers, as the foundation is the critical part of the design of OWECs. Therefore, the design of OWEC foundations has been the focus of several studies [3–5]. Gravity, monopile, and monopod suction bucket foundations are suitable for shallow and moderate water depths up to 25 m. Conversely, there is a need to enhance existing foundation systems for large wind turbines in deep waters (deeper than 30 m). Thus, innovative substructure concepts regarding multi-footing configurations have recently been under research and development [6,7]. Kim et al. [6] performed a parametric study to understand the group effect of tripod bucket foundations on the bearing capacity. The behavior of a three-bucket jacket substructure under long-term cyclic loading was investigated by Lupea et al. [7]. Shi et al. [8] stated that the jacket foundation is becoming progressively more interesting and is a good option for water depths between 30 and 80 m. Achmus et al. [9] indicated that for larger water depths, tripod and jacket foundations are more appropriate. However, the combined horizontal and vertical loading applied to individual piles of tripod and jacket foundations significantly increase with the water depth. In this regard, the foundation of wind turbines should ensure an adequate bearing capacity against such loading conditions in deep waters. Consequently, this study is focused on a novel supporting system of the jacket foundation for OWECs in deep waters. The conventional jacket foundation is supported by four piles positioned at the edges of the construction (Fig. 1a). For the recommended innovative foundation, the available jacket foundation system was supported using closely spaced double piles for each edge (Fig. 1b). To keep the symmetry of the foundation system on both the x- and y-axes, each leg was designed with closely spaced double piles

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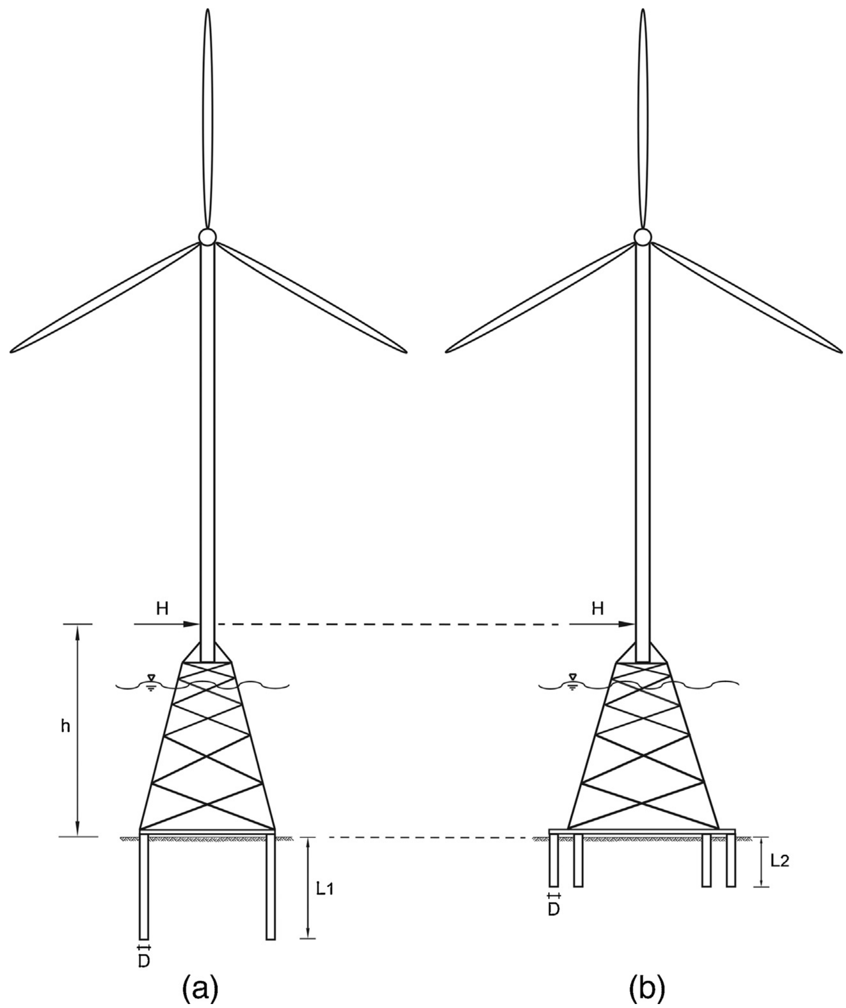

Fig 1. Schematic sketch of OWEC on foundation systems: (a) conventional pile-supported jacket (L1 = 12.5D); (b) jacket with closely spaced double piles (L2 = 6.25D, S = 3D).

arranged diagonally. In some cases, the depth profile of the seabed shows that chalky soil layers can exist beneath the sand/clay layers, i.e., in the Baltic Sea north of Ruegen, large chalk deposits are found beneath the glacial till [12]. It is noted in the study of Dührkopf and Barbosa [13] that the pile destroys the chalk during installation, and it is estimated that the destroyed chalk around the pile characterizes the response of the foundation system under cyclic loading. The results of a cyclic test on chalk obtained from the Wikinger Site show an obvious decrease in the shear stress during cycling [13], which demonstrates the dilative nature of chalk when sheared. In this respect, the recommended relatively short closely spaced piles promise a fine solution to avoid installing the piles into chalky soil.

Moments arising from wind and wave loading are transferred to vertical loads on the individual piles. Thereby, the individual piles of the jacket foundations are exposed to horizontal and vertical combined loading, that is, combined tension and compression loading. The effects of combined loading on the behavior of piles are scarce in the literature, especially for offshore structures, and have not been studied yet for closely spaced piles. The study of Achmus and Thieken [10] regarding monopile behavior under combined horizontal and vertical loading indicates that combined compression loading leads to favorable and combined tension loading mostly unfavorable influences on the system stiffness. Akdag and Özden [11] found that a vertical load significantly improved the performance of the reinforced concrete (RC) and RC-with steel fiber piles, according to lateral loading and lateral + axial loading model pile test results.

Although there have been several experimental and numerical based studies on the behavior of closely spaced piles [14–16], the response of closely spaced piles for an OWEC foundation has not been studied yet. It is well known that the efficiency of the pile is considerably affected when the piles are installed close to each other due to overlapping soil reaction zones. McVay et al. [14] found that the group efficiency at pile spacing (S) of 3D was 22% less than the group efficiency at a spacing of 5D according to centrifuge tests conducted on the closely spaced piles, where D and S are the pile diameter and the center-to-center distance between the piles, respectively. The influence of the pile spacing and the number of piles on the behavior of closely spaced piles was investigated using the finite element method [15]. The behavior of the piles in the group was compared with the behavior of a single pile, and the variation of the displacement amplification factor was quantified. It was determined that the displacement amplification factor depends on the horizontal load level, and the factor attains its maximum value at the initial load level [15]. Model pile tests were performed in various closely spaced pile layouts by Kim and Yoon [16]. It was emphasized that group interaction effects in closely spaced piles reduce the load-carrying capacity for all rows (i.e., trailing row, middle row, and leading row) relative to the single pile response. It was also observed from the tests that the soil reaction strongly depends on the closely spaced pile layout and pile spacing. It was remarked that load reduction factors to compute the load carried by each pile depend on the pile position in closely spaced piles [17]. Brown et al. [18] found that the piles in the leading row supported

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