International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 25, No. 2, June 2015, pp. 134–144; http://dx.doi.org/10.17736/ijope.2015.cg09

http://www.isope.org/publications/publications.htm

Evaluation of *p-y* Approaches for Large-Diameter Monopiles in Sand

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For the design of monopile foundations, the soil resistance is usually modeled by the subgrade reaction method. The commonly used *p-y* approach described in the offshore guidelines is generally assumed to be sufficiently accurate for slender piles with diameters $D \leq 2$ m. However, several investigations indicate that the pile deflections of large-diameter monopiles are underestimated for extreme loads but overestimated for small operational loads. A three-dimensional finite element (FE) model is presented to evaluate the currently used *p-y* approach for piles in sand under static loading conditions in dependence on the pile dimensions and the soil's relative density. In addition, modified *p-y* formulations to account for the effect of the pile diameter are compared to the FE results.

INTRODUCTION

Monopiles are currently the preferred support structure for offshore wind energy converters (OWECs) in water depths of less than 30 meters. The cost-effective and relatively simple manufacturing and installation process is a great advantage in comparison to lattice structures like jackets or tripods. A monopile foundation (see Fig. 1) consists of a single steel pipe pile driven into the seabed. These large-diameter monopiles have to withstand large and discontinuous horizontal forces H and bending moments M caused by wind and wave actions. Large water depths and sizable wind turbines necessitate large pile dimensions. Pile diameters more than $D = 6$ m have already been realized, and diameters up to $D = 8$ m are currently planned. The relative pile length, i.e., the ratio of embedded pile length L to diameter D, lies usually at approximately $L/D = 5$.

In the design of the wind turbine, the ultimate limit state (ULS) and the serviceability limit state (SLS) design proofs have to be fulfilled. In the ULS proof, a sufficient soil resistance has to be guaranteed to ensure the structural safety of the wind turbine. Thereby, effects of cyclic loading have to be considered; i.e., degradation in soil resistance has to be accounted for. For the SLS proof, the deflections and rotations under the characteristic extreme load cases (hereinafter referred to as "extreme loads") have to stay below certain serviceability limits. In that, the accumulation of deflection due to cyclic loading also has to be considered (cf. Achmus et al., 2008). Besides these geotechnical design proofs, the stiffness of the monopile foundation system under operational loads has to be determined. Considering this stiffness in a dynamic analysis of the whole OWEC structure, it has to be ensured that the eigenfrequencies of the wind turbine have a sufficient distance to the main excitation frequencies of the dynamic loading. In that, neither an overestimation nor an underestimation of foundation stiffness is generally conservative. An incorrect estimation of foundation stiffness results in an increase of uncertainties and leads to additional but unnecessary costs. Moreover, in the worst case it could have a negative influence on the structural lifetime of the structure (Kallehave et al., 2012).

In all design proofs, it is common practice to use the subgrade reaction method to simulate the occurring soil resistance p in dependence on the horizontal displacement y. The soil is herein replaced by a number of spring elements along the pile shaft (Fig. 1). In most cases the so-called *p-y* method, recommended in the offshore guidelines (OGL) of the American Petroleum Institute (API, 2007) and Det Norske Veritas (DNV, 2013), is used. Based on experience in the oil and gas industry, the *p-y* method seems to be sufficiently accurate for slender piles with diameters up to $D = 2$ m. For larger pile diameters, several investigations showed that the horizontal deflections of monopiles are underestimated for extreme loads (cf. Achmus, 2011). In contrast, experience from operating offshore wind farms with monopiles indicates that the foundation stiffnesses for small operational loads are significantly underestimated (Hald et al., 2009; Kallehave et al., 2012). The authors are unaware of any investigations on the accuracy of predicting the ultimate resistance in dependence on the pile diameter. However, Thieken et al. (2014) showed that the ultimate bedding resistance of the *p-y* method is, independent of the pile diameter, conservative in conjunction with the German standard for earth pressure (DIN, 2007).

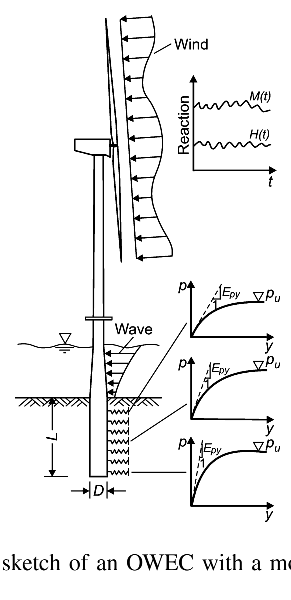

Fig. 1 Schematic sketch of an OWEC with a monopile foundation

Received August 5, 2014; updated and further revised manuscript received by the editors December 22, 2014. The original version (prior to the final updated and revised manuscript) was presented at the Twenty-fourth International Ocean and Polar Engineering Conference (ISOPE-2014), Busan, Korea, June 15–20, 2014.

KEY WORDS: Wind energy converter, monopile, *p-y* curve, sand, foundation stiffness, small strain stiffness