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Lateral bearing capacity of hybrid monopile-friction wheel foundation for offshore wind turbines by centrifuge modelling

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ABSTRACT

The hybrid monopile-friction wheel foundation is an innovative alternative for offshore wind turbines. The concept has wider adaptability and can be used as reinforcement method for existing monopiles. A series of centrifuge tests was performed to investigate the lateral bearing capacities of the hybrid foundation under monotonic loads. Five foundation models and two soil types were considered. According to the recorded responses, the hybrid foundation demonstrated better lateral behaviors that both lateral bearing capacity and stiffness are enhanced. Two analytical methods were proposed and compared with the centrifuge test results. The bearing capacity of the hybrid foundation is smaller than the sum of individual pile and friction wheel, and a reduction factor is suggested for both friction wheels. The friction wheel restrains rotations of monopile and provides extra restoring moments; their effects are idealized as equivalent moments acting on the pile head. The analytical results provide possible solutions in estimating the lateral bearing capacity of the innovative hybrid foundation system for offshore wind turbines by using traditional theories.

1. Introduction

The production of wind energy has experienced rapid growth during the last decade. Wind energy is considered to be one of the most promising forms of renewable energy (Li and Yu, 2015; Leung and Yang, 2012; Li and Yu, 2017b). In the United States, the total installed wind energy capacity was 74 GW by the end of 2015, which accounted for 4.7% of the total electricity generation; it is expected to increase to over 30% by 2050 (Adib, 2015; Li and Yu, 2017a). Offshore wind shows great potential with steadier speeds, and the power output for offshore wind is estimated to be 1.7 times more than onshore wind; generally, the energy production will continue increasing by going further from land (Kaldellis et al., 2016; Li and Yu, 2017b). The evolution of offshore wind industry in Europe where 91% offshore wind farms located is presented in Fig. 1 (Association, 2017; Wang et al., 2017b). Besides the increasing new installed wind capacity, the offshore wind farm tend to build in further and deeper sea, which aims to harvesting better wind resources.

There are several types of substructures for offshore wind turbines, and they are selected according to water depths, geotechnical conditions and wind turbine capacity (Arany et al., 2017; Sun et al., 2012). The technique for offshore wind foundation experiences rapid developments; besides the fixed foundation types, the floating foundation for offshore wind turbines has been proposed to adapt to more severe environmental or seabed conditions (Castro-Santos and Diaz-Casas, 2015; Li et al., 2014). The most widely applied foundation concept for offshore wind industry is the monopile foundation. There are 2301 monopile supported offshore wind turbines in Europe by the end of 2014, which consumed 79% of all installed offshore wind turbines (Brown et al., 2015; Ho et al., 2015). The foundations are steel piles with large diameters, total lengths of 20 m-50 m and driven 40%–50% of the total lengths into the seabed to provide resistances (Arany et al., 2015c; Standard, 2007). The offshore wind turbines are mainly subjected to large lateral loads and overturning moments caused by wind, wave and ice, but relatively smaller vertical loads. For a typical monopile foundation, the vertical capacity is satisfactory if the requirements of lateral and overturning stabilities are guaranteed (Arany et al., 2017). Meanwhile, the offshore wind turbines are dynamically sensitive structure, and their natural frequencies are close to the excitation frequencies. The loads induced by the vibrations at the hub level as well as those caused by blade shadowing effects are considered in the design phase. The effects of these external loadings could be transformed into bending moment spectrum at the mudline (Arany et al., 2015b). The dynamic response of the offshore wind turbines is a concern (Wang et al., 2017d); a proper system frequency is selected to avoid resonance, and hence the soft-stiff design is the most commonly used method in the offshore wind industry (Arany et al., 2015a). The natural frequency of the offshore wind turbine may change

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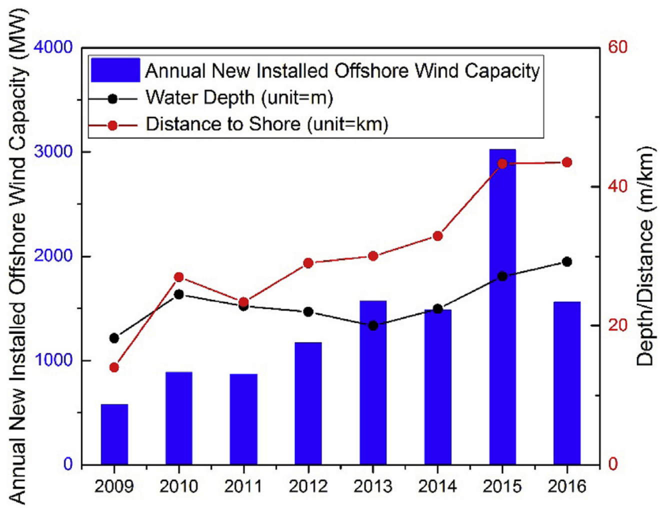

Fig. 1. Evolution of offshore wind industry in Europe.

with the dynamic loadings, which will enhance the dynamic amplification and increase the fatigue damage on the structure. By moving the offshore wind farm into deeper seas, environmental conditions are more severe and the capacities of wind turbines are higher, which results in more challenges for geotechnical design of the foundations. The original monopile foundation is likely to be not sufficient to support the new generation of offshore wind structures, and therefore improved foundation concepts are necessary.

The hybrid monopile-friction wheel foundation is proposed to enhance the lateral bearing capacity of the original offshore monopile. The improved design is a combination of monopile foundation and gravity foundation. As shown schematically in Fig. 2, a circular friction wheel is added at the mudline to stiffen the pile responses laterally. The circular friction wheel can be a solid circular footing or a circular frame filled with gravels. The introduction of the friction wheel can provide additional shear stress to resist the lateral load and impart larger restoring moment to lower pile rotations (Clough and Duncan, 1973; Mokwa and Duncan, 2003). Moreover, the friction wheel brings larger vertical stresses to the foundation soil, and therefore increase the lateral resistance in front of the pile; additionally, if the friction wheel embeds into the foundation soil to some depth during the operation, the passive pressure in front of the wheel can further reduce its lateral deflections (Mokwa and Duncan, 2003). The hybrid monopile-friction wheel foundation can be an innovative alternative for offshore wind turbines located at areas with requirements of stronger substructures. This concept can also be a reinforcement method for existing monopile foundations: the fatigue of materials as well as the changing of seabed soil conditions may influence behaviors of the pile foundation in service, but it is unrealistic to rebuild the foundation, especially at offshore areas; therefore, a friction wheel can be applied to provide additional bearing capacities as an effective modification.

To investigate the lateral bearing behaviors of the hybrid monopile-friction wheel foundation system, both the response of a laterally loaded single pile and the bearing capacity of the friction wheel should be analyzed as a single unit. Several researcher have proposed different methods to investigate the lateral response of pile foundation (Broms, 1964a, b; Hansen et al., 1961; Matlock and Reese, 1960; McClelland and Focht, 1958; Mokwa and Duncan, 2001; Randolph, 1981; Reese et al., 1974). These analytical models are based on methods of Winkler approach, p-y theory, elasticity theory or finite element methods. Broms (Broms, 1964a, b) assumed a short-rigid pile rotated about a center without substantial pile deformations, and the lateral bearing capacity was estimated by the sum of earth pressures. Reese et, al (Reese, 1977; Reese et al., 1974). studied the behaviors of laterally loaded pile in saturated sand by considering the nonlinear responses of the ground soil, which was commonly known as the p-y method. To date, several p-y models for the analysis of laterally loaded piles have been proposed (Georgiadis et al., 1992; Murchison and O'Neill, 1984; Wesselink et al., 1988). API and DNV presented design codes for offshore monopile foundations based on p-y method for a service life of 25 years, which is widely used currently (Hao and Liu, 2017; Ma et al., 2017; RP2A-WSDA, 2000; Veritas, 2004). The idea of friction wheel part is come from concepts of offshore gravity foundations and pile caps (El-Marassi, 2011; Kim et al., 1979; Mokwa and Duncan, 2001, 2003). Mokwa and Duncan (2001) conducted a series of full-scale lateral load tests on single pile or group pile with pile caps, and it was demonstrated that the pile cap contributed significant amounts of lateral resistances (Mokwa and Duncan, 2001). Meanwhile, the lateral responses of offshore gravity foundation were investigated by large-scale tests and theoretical analysis (Andersen et al., 1989; Dyvik et al., 1989), and the design codes for gravity foundation for offshore wind turbines were recommended by DNV (Veritas, 2004). The base friction at the mudline is mainly depend on the vertical loads, friction coefficient of the connecting surface, contacting areas and properties of surrounding soil.

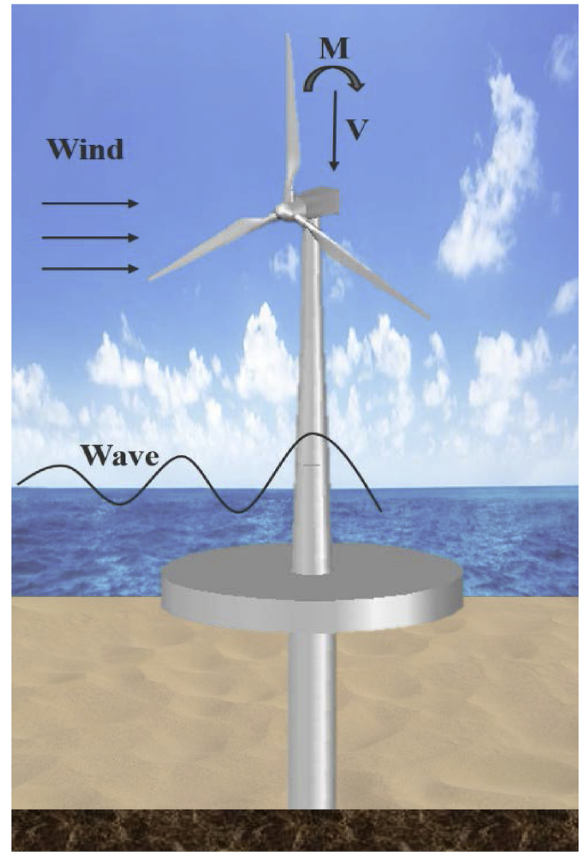

Fig. 2. Schematic of hybrid monopile-friction wheel foundation.

For the purpose of withstanding severe loading conditions, the monopile is strengthened by a friction wheel at the mudline to create an innovative hybrid foundation system. Some similar concepts have been studied previously. Stone and Arshi (Arshi and Stone, 2011; Arshi et al., 2013; Stone et al., 2007) conducted a series of 1-g tests of "monopiled circular footing"; it was demonstrated the hybrid footing foundation did show advantages in lateral and vertical bearing behaviors. The soil in front of the footing was found to be displaced and provided some passive earth pressure during the tests. Moreover, it was suggested if the vertical movements were allowed between the footing and the pile, the hybrid footing foundation was more effective since the two parts were acting