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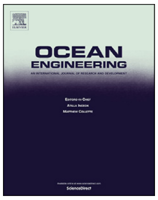

Comparison of monotonic and cyclic lateral response between monopod and tripod bucket foundations in medium dense sand

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ABSTRACT

The increasing trend of offshore wind turbines in deeper waters has necessitated the usage of alternative foundations such as the bucket foundation (including monopod and tripod). To investigate and compare the lateral monotonic and cyclic behaviour of the monopod and tripod, a series of centrifuge tests were carried out in medium dense sand, which were fabricated with an identical amount of material. The monotonic centrifuge tests were back-analysed using an advanced hypoplastic model to offer further insights into the test results. Under a monotonic lateral loading, the tripod exhibits a 78% higher initial lateral stiffness than the monopod, but it yields at a 71.4% smaller rotation, suggesting a more brittle response. While subjected to lateral cycling, the rotation of the monopod increases with number of cycles but at a decreasing rate, following a power function. Similarly, the dynamic stiffness of the monopod also increases with number of cycles. Differing from the monopod, the tripod exhibited a "self-healing" behaviour. Both the rotation and dynamic stiffness increases during the first few hundreds of cycling but decreases thereafter, leading to little variation. This unique feature in cumulative rotation and dynamic stiffness of the tripod makes it superior to the monopod.

1. Introduction

The cost of foundations for offshore wind farm developments is a significant fraction of the overall installation cost (current estimates suggest between 15% and 40%), which plays an important role in financial viability of offshore wind turbine farm projects (Houlsby and Byrne, 2000; Byrne and Houlsby, 2003; EWEA, 2016). As summarized by EWEA, 2016, most existing offshore wind turbines are constructed in a water depth less than 50 m. While the monopile is widely adopted for current wind turbine foundation design, the bucket foundation has been considered as a promising option for its easier installation, reusable and economy in deeper water depth (Byrne and Houlsby, 2006; Achmus et al., 2013; Houlsby et al., 2005a; Randolph and Gourvenec, 2011; Tjelta, 2015). The bucket foundations are commonly designed in the forms of monopod (Houlsby et al., 2005a; Ibsen and Liingaard, 2005; Guo et al., 2015) and tripod (Ehrmann et al., 2016). Basically, the monopod bucket foundation is believed to be suitable for water depth up to 40 m (Deb, & SIingh, 2016), while the tripod is well suited for offshore sites with water depth ranging from 20 to 50 m (Kim and Oh, 2014).

To meet the serviceability of an offshore wind turbine, which is a slender structure subjected to various cyclic offshore environmental loadings, two principal aspects governing the foundation design are cumulative rotation and dynamic stiffness of the foundation. Because any misalignment and resonance of the turbine structure could significantly reduce the design life of the various structural elements in the turbine. For these reasons, the cumulative rotation of the slender structure is limited to 0.25° in service (Peire et al., 2009; Det Norske Veritas, 2002), while the modal frequencies are required to differ by 10% to those of the periodic wind, wave, current and vortex loads (Det Norske Veritas, 2002). Fig. 1 presents a summary of typical loading frequency applied to the offshore wind turbine (Jonkman et al., 2009). In the figure, the 1P and 3P denotes the rotational frequency of the turbine and the blade-passing frequency, respectively. To avoid any resonance, the natural frequency of the system should be designed to be lower than 1P (i.e., 'soft–soft'), between 1P and 3P (i.e., 'soft–stiff') or larger than 3P (i.e., 'stiff–stiff' regions). Typically, the initial natural frequency of most offshore wind turbines is designed to be 'soft–stiff' accounting for the cost and design feasibility (Yu et al., 2015). However, the variation of the dynamic foundation stiffness under long-term cyclic loading may shift the natural frequency to approach one of the excitation frequency (i.e., 1P or 3P), leading to resonance (Bhattacharya et al., 2013). Despite the significance of cumulative rotation and dynamic stiffness, little track

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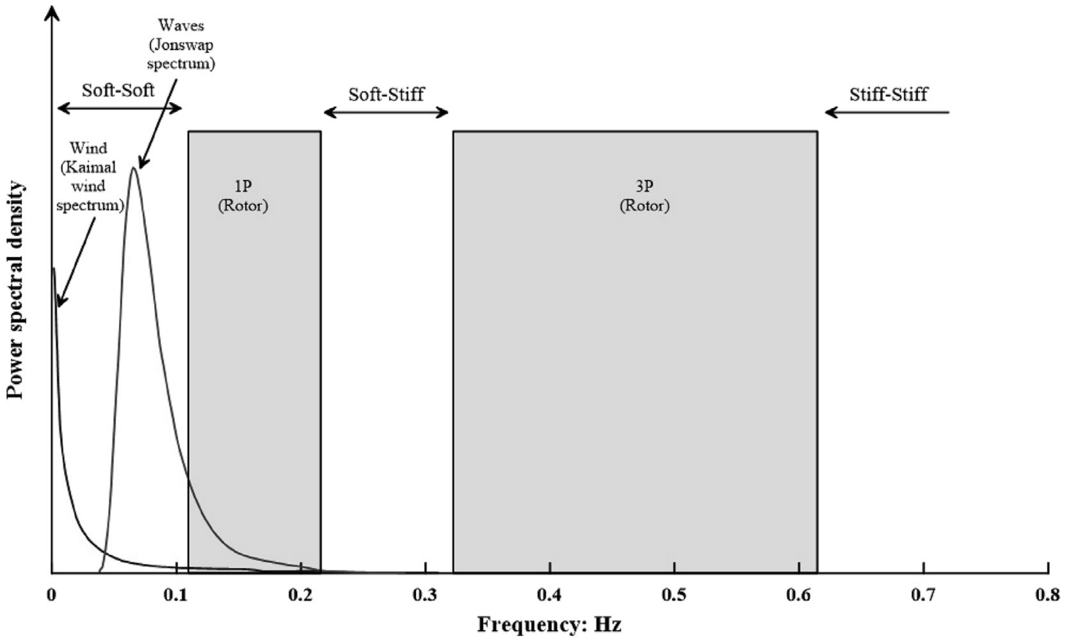

Fig. 1. Typical loading frequencies and dynamically sensitive regions of a NREL 5 MW turbine structure (Jonkman et al., 2009).

record of long term performance is available for monopod and tripod, which are new types of foundation to support offshore wind turbine.

The current understandings of the cyclic behaviour (i.e., cumulative rotation and dynamic stiffness) of a laterally loaded monopod in sand were mainly obtained through small scale tests at 1*g* (Byrne, 2000; Foglia and Ibsen, 2014; Villalobos Jara, 2006; Zhu et al., 2012, 2014), large scale field trials (Houlsby et al., 2006) and centrifuge model tests (Zhang et al., 2007; Cox et al., 2014). It was found that under the fully drained condition, the cumulative rotation of a laterally loaded model pod generally increased with number of cycles, which can be fitted by a power relationship (Zhu et al., 2012; Cox et al., 2014). On the other hand, the evolution of the unloading stiffness with the loading cycles may broadly follow a logarithmic relationship (Cox et al., 2014).

Comparing with the monopod, cyclic response of a laterally loaded tripod foundation in sand are rarely investigated. The existing studies mainly focused on vertical cyclic behaviour of a monopod, which was intended to mimic the behaviour of one pod in a laterally loaded tripod (Byrne and Houlsby, 2004; Houlsby et al., 2005b; Kelly et al., 2006; Gao et al., 2013). This simplification was made by assuming that a lateral load imposed to a tripod was thoroughly transformed into either vertical tensile or compressive loadings to the suction buckets (Senders and Randolph, 2009). Although the studies based on this simplification have shed insights into the cyclic vertical behaviour that may be exhibited by one suction bucket in a tripod, the cumulative rotation and variation of dynamic stiffness of a tripod foundation cannot be directly obtained. The validity of the simplification also remained to be justified. Kim et al. (2014) is probably one of the first to directly investigate the lateral cyclic response of a tripod. Displacement-controlled centrifuge model tests were performed to simulate a tripod under limited numbers of lateral cycling in silt sand. For engineering purpose, the cyclic behaviour (including cumulative rotation and dynamic stiffness) of a tripod may be more realistically obtained by performing load-controlled long-term cyclic load tests. In addition, it is vital to understand the different characteristics of cumulative rotation and dynamic stiffness between the monopod and the tripod through a systematic comparative study, to optimise the bucket foundation design for offshore wind turbine.

In view of the aforementioned issues, a series of centrifuge model tests were carried out in this study to directly compare the monotonic and cyclic lateral behaviour of a monopod and a tripod foundation, which were fabricated with the same amount of material. The measured data was interpreted with attentions specifically paid to the push-over bearing capacity, cyclic accumulation of rotation and evolution of dynamic stiffness of the two types of foundation. Moreover, preliminary finite element analysis was performed to back-analyse the monotonic lateral behaviour of the monopod and the tripod, with the principal objectives to verify the push-pull mechanism of the tripod and to de-couple foundation stiffness under the combined loading of horizontal force and overturning moment.

2. Centrifuge modelling

All of the centrifuge model tests reported in this paper were carried out at the geotechnical centrifuge facility of Zhejiang University, China. The beam centrifuge, which has a rotation arm of 4.5 m and a maximum payload of 400 *g*t, can be operated up to 150 *g* (Chen et al., 2010). Scaling factors relevant to the centrifuge tests reported herein are summarized in Table 1 (Taylor, 2003).

2.1. Test programme

The experimental programme consists of four centrifuge tests, including one monotonic loading test and one multi-stage cyclic loading test for each of the two model foundations (i.e., monopod and tripod). All the centrifuge tests were carried out in medium dense dry sand, at a centrifugal acceleration of 100 *g*.

Table 1
Scaling factors relevant to centrifuge tests in this study (Taylor, 2003).

Physical quantity	Scaling factor (Model/Prototype)
Gravitational acceleration	n
Length	1/n
Area	$1/n^2$
Volume	$1/n^3$
Settlement	n
Stress	1
Strain	1
Force	$1/n^2$
Density	1
Mass	$1/n^3$
Flexural rigidity	$1/n^4$
Bending moment	$1/n^3$