ARTICLE IN PRESS

ENGEO-04431; No of Pages 13

Engineering Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Geology

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

Numerical investigations on pore-pressure response of suction anchors under cyclic tensile loadings

Kanmin Shen [a], Lizhong Wang [a], Zhen Guo [a,*], Dong-sheng Jeng [b]

[a] Key Laboratory of Offshore Geotechnics and Material of Zhejiang Province, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China

[b] Griffith School of Engineering, Griffith University Gold Coast Campus, QLD 4222, Australia

ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 17 November 2016
Accepted 5 December 2016
Available online xxxx

Keywords:
Suction anchor
Floating offshore wind turbine
Cyclic loading
Oscillatory pore-pressure
Residual pore-pressure
Pullout capacity

ABSTRACT

The suction anchor is an effective option for the anchor foundations of floating offshore wind turbines (FOWTs). During its long-term service, in addition to the static pretension load, the suction anchor is subjected to a series of cyclic loads that are caused by waves, currents and the continuous motions of the floating structure. Thus, excess pore-pressure will accumulate within the soil around the embedded anchor, and the anchor capacity tends to be reduced. In this paper, by introducing the oscillatory and residual mechanisms, a novel numerical model is proposed to predict the instantaneous variations and accumulations of excess pore-pressures around a suction anchor that is subjected to long-term vertical cyclic loads. The results indicate that excess pore-pressure builds up mainly in the shallow soil near the external anchor wall. As a consequence, the effective soil stress in this region decreases along with the interface friction between the external wall and the soil. Detailed parametric studies reveal that the accumulation of excess pore-pressure is obvious for a larger load magnitude and smaller load period. With a lower permeability, smaller shear modulus or smaller relative density of the seabed soil, the pore-pressure accumulation outside the anchor increases significantly.

1. Introduction

Wind is a rapidly growing renewable energy source both onshore and offshore for the last decade. Vast sea areas in China with stronger and steadier winds show a potential to develop offshore wind turbines (OWTs) in the future. Currently, offshore wind turbines are always supported by the monopiles but limited to a shallow water depth up to approximately 30 m. For deep water, only floating platform systems are expected to be economically and technically feasible. The foundation design for FOWTs in varying water depths is shown in Fig. 1. Mooring line stabilized Tension Leg Platform (TLP) is one of effective choices for FOWTs in water depths exceeding 50 m. The TLP consists of a floating structure connected to the seafloor with by a group of mooring lines or tendons attached to the anchor foundations (Ronalds, 2002). The reserve buoyancy for the floater is transferred to the suction anchors embedded in the seabed (Sclavounos et al., 2010). Suction anchor is made of steel and resembles a large over-turned bucket. The typical length of a suction anchor ranges from 5 to 30 m, with a length-diameter ratio of 3 to 6 (Randolph and Gourvenec, 2011). Compared with other anchors (*e.g.*, drag embedded anchor, pile anchor), the advantages of suction anchors include the accommodation of a variety of soil conditions (clay or sand), accurate positioning, and the ease of installation and retrieval for reutilization.

As shown in Fig. 2, during the installation process, the suction anchor penetrates into the seabed by its dead weight and by applying suction in sequence until it reaches the target depth below the seabed surface. After anchor installation and set-up (full dissipation of excess pore-pressure), the mooring line is gradually tensioned to remove the line slack. A specific degree of pretension load is always required to provide adequate constraint to the floating structure. The capacity of the embedded anchor must be large enough to sustain the loads passed from the attached mooring line. Most previous works (DNV, 2005; Houlsby and Byrne, 2005; Guo et al., 2014) have studied the monotonic capacity of suction anchors. For the drained condition, the vertical pullout resistance of a suction anchor only consists of its submerged self-weight and the soil frictions on the external and internal sides of the caisson wall (Deng and Carter, 1999; Randolph and House, 2002). This is the minimum pullout capacity of a suction anchor that determines the safe load limit of an embedded suction anchor.

In fact, a suction anchor in service is subjected to long-term cyclic vertical loads produced by waves, currents and the continuous motions of the floating structure. This kind of cyclic load is mainly composed of wave-frequency and low-frequency components, which may last for a few hours, days or even weeks (Clukey et al., 1995). Therefore, the load cycles can be counted by thousands. Under this long-term effect of cyclic loads, the excess pore-pressure will build up within the soil

* Corresponding author.
E-mail addresses: shenkanmin@163.com (K. Shen), wlzzju@163.com (L. Wang), nehzoug@163.com (Z. Guo), d.jeng@griffith.edu.au (D. Jeng).

http://dx.doi.org/10.1016/j.enggeo.2016.12.001
0013-7952/

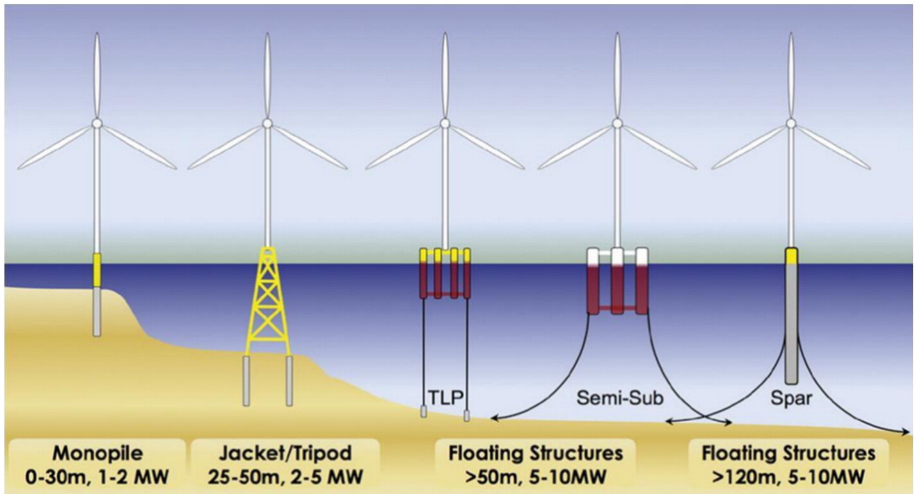

Fig. 1. Foundations for the OWTs with varying water depths.

near the anchor. The accumulated excess pore-pressure can reduce the effective soil stress, thus reducing the interface friction between the anchor wall and the surrounding soil. Consequently, the pullout capacity of suction anchor is reduced. Kelly et al. (2006a,b) carries out model tests of suction caissons under vertical monotonic and cyclic loading, as well as a comparison with field data, showing the positive pore pressure increases with the rate of cycling. Zhu et al. (2013) presents the 1 g laboratory cyclic loading tests with approximately 10,000 cycles to investigate the long-term lateral cyclic response of suction bucket foundations in sand.

In order to predict excess pore-pressure response of offshore foundations and its effect on the bearing capacity, two numerical methodologies are adopted with different advantages. The first one is to apply advanced constitutive soil models to describe the plastic volumetric strain and stiffness of soil element within every load cycle, which require complex constitutive equations and numerous parameters. Thieken et al. (2014) describe the numerical simulation of suction bucket under variable tension loadings in sand. Cerfontaine et al. (2015) adopt the Prevost elasto-plastic model to estimate the response of a suction caisson embedded in dense sand under monotonic and cyclic vertical loading. Applications of these advanced models can be limited due to the determination of parameters and massive calculation steps involving hundreds or thousands of load cycles. The other approach is a semi-analytical method based on simplified constitutive model incorporated with laboratory tests to evaluate the effects of cyclic loading. Taiebat and Carter (2000) present a method for the development of pore-pressure build up in seabed to predict the liquefaction analysis of a tank during a storm with time duration of 6 h. The semi-analytical method is efficient for cyclic response of offshore foundations facing numerous load cycles.

To accurately predict the responses of the pore-pressure around the suction anchor, two mechanisms (the oscillatory and residual mechanisms) are used to simulate the instantaneous variation and accumulation of excess pore-pressures, respectively. Based on these two mechanisms, a novel numerical model is proposed for an embedded suction anchor under long-term vertical cyclic loadings. In this paper, the development and characteristics of the excess pore-pressure along the caisson wall are first studied, and then, the influences of different load and seabed parameters are investigated in detail.

2. Theoretical formulations

As shown in Fig. 3, there are two different mechanisms controlling the pore-pressure responses in the seabed soil (Zen and Yamazaki, 1990): the oscillatory and residual mechanisms. Therefore, the overall pore water pressure p can be expressed as

$$p = p_{osc} + p_{res} \tag{1}$$

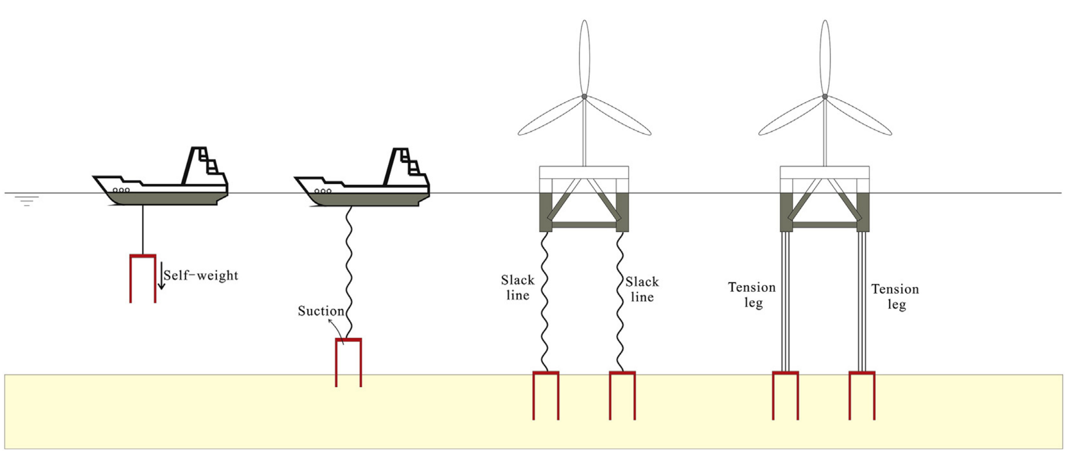

Fig. 2. Suction anchors used for a moored FOWT.