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A numerical study on the lateral loading behaviour of offshore tetrapod piled jacket foundations in clay

Bin Zhu*, Kai Wen, Deqiong Kong, Zhoujie Zhu, Lujun Wang

MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou, 310058, China

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ABSTRACT

Jacket foundations for offshore wind turbines, typically having three or four latticework legs, are mainly subjected to lateral loads induced by winds, waves and currents during their service life. An accurate assessment of the bearing capacity of these foundations is of great importance in the design. This paper presents a study into the monotonic lateral loading behavior of tetrapod piled jacket foundations in undrained clay, with the complex lateral loads being simplified to an equivalent lateral load acting at a certain height of the jacket. A centrifuge testing programme was undertaken to provide high-quality validation data for the development of a three-dimensional finite element model established using ABAQUS. The key parameters investigated are the spacing and embedment of the piles, the height to which the equivalent lateral load acts and the angle between the direction of this load and the orthogonal line of the jacket in the horizontal plane. The parametric study aims to provide guidance to the optimal design of jacket piled foundations: for instance, to examine the critical pile embedment beyond which limited improvement of the bearing capacity of the foundation can be achieved and to define the most unfavorable lateral loading direction. In addition, the limitations of the commonly assumed constant *p*-multiplier, regardless of the lateral deflection of the pile and the depth along it, are critically discussed. Then an improved analytical model is proposed, based on the existing model used in design and the parametric study results, to quantify the variation of *p*-multiplier with depth and with pile deflection.

1. Introduction

The development of offshore wind power has gained increasing popularity throughout the world recently, leading to the construction of an ever-growing number of offshore wind turbines [1]. The foundations of offshore wind turbines are mainly subjected to lateral loads (as the weight of the upper-structure is relatively low) induced by winds, waves, currents, *etc*. When assessing the bearing capacity of these foundations against the lateral loads and the resulted overturning moments, these loads are usually represented by an equivalent lateral load applied at a certain height at the upper-structure [2–4], for the sake of simplicity. Among the commonly used foundation types for offshore engineering (*e.g.* piles, suction buckets and gravity foundation), pile foundations are the most popular due to the fact that their responses under combined loading scenarios are well investigated.

Recently, tetrapod piled jacket (TPJ) foundations are considered to be an attractive solution for offshore wind turbines in waters with depths ranging from 20 m to 50 m [5] due to the optimized loading characteristics (*i.e.* very low overturning moment for each pile and small wave loading) and the improved anti-impact performance under low-energy collisions [6]. In general, a TPJ foundation can be taken as a special form of commonly used pile group foundations with an evenly spaced pile layout of 2×2 but with relatively large spacing, so that the self-weight of the upper-structure as well as the pullout resistance of the piles can contribute greatly to the overturning bearing capacity of the foundation. Regarding the loading characteristics of each pile, distinctly different behaviours of the former from the latter can be envisaged [4] as that the lateral loads on the upper structure of a TPJ foundation could result in sufficiently large axial forces along the piles, which greatly affects the lateral pile–soil interaction. Moreover, due to the complex sea environments, the loading scenarios (*e.g.* directions, amplitudes, *etc.*) of the upper structure and consequently of the piles could change drastically during the service life of the foundation.

Both experimental and numerical approaches for jacket foundations, either in a tetrapod or tripod form, have been widely pursued, providing valuable insights into their loading behaviours. These studies, however, either have been limited to specific foundation parameters (*e.g.* pile diameter D, pile length L, pile spacing s, *etc.*) and can hardly be generalised [7,8], or concentrated primarily on the overall responses of the foundation [9–11,6] without examining the detailed

* Corresponding author.
E-mail addresses: binzhu@zju.edu.cn (B. Zhu), wenkai@zju.edu.cn (K. Wen), deqiong_kong@zju.edu.cn (D. Kong), zhu_zj@ecidi.com (Z. Zhu), lujunwang@zju.edu.cn (L. Wang).

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Nomenclature

D	Pile diameter
h	Lateral loading height above the mudline
h_0	Height of the jacket top
H_{ult}	Lateral bearing capacity of the foundation
J	Dimensionless empirical constant
k	Gradient of undrained shear strength of soil with depth
L	Pile embedment
n	Acceleration level of the centrifuge model test
p_m	p-multiplier for pile group foundations (and for TPJ foundation)
p	Soil resistance per unit length
s	Pile spacing of the tetrapod piled jacket foundation
s_{cri}	Critical spacing beyond which pile group effect can be ignored
s_u	Undrained shear strength of soil
s_{um}	Undrained shear strength at the mudline
y	Lateral pile deflection
u_j	Horizontal displacement at jacket top
w	Vertical displacement at pile head
w_1	Vertical displacement at the top of the front-row piles
w_2	Vertical displacement at the top of the back-row piles
x_c	Horizontal distance from the central line of jacket
z	Soil depth
z_c	Depth of the rotation centre
z_{cri}	Critical soil depth beyond which pile group effect can be ignored
β	Lateral loading angle
ε_{50}	Strain which occurs at one-half the maximum stress on undrained compression tests

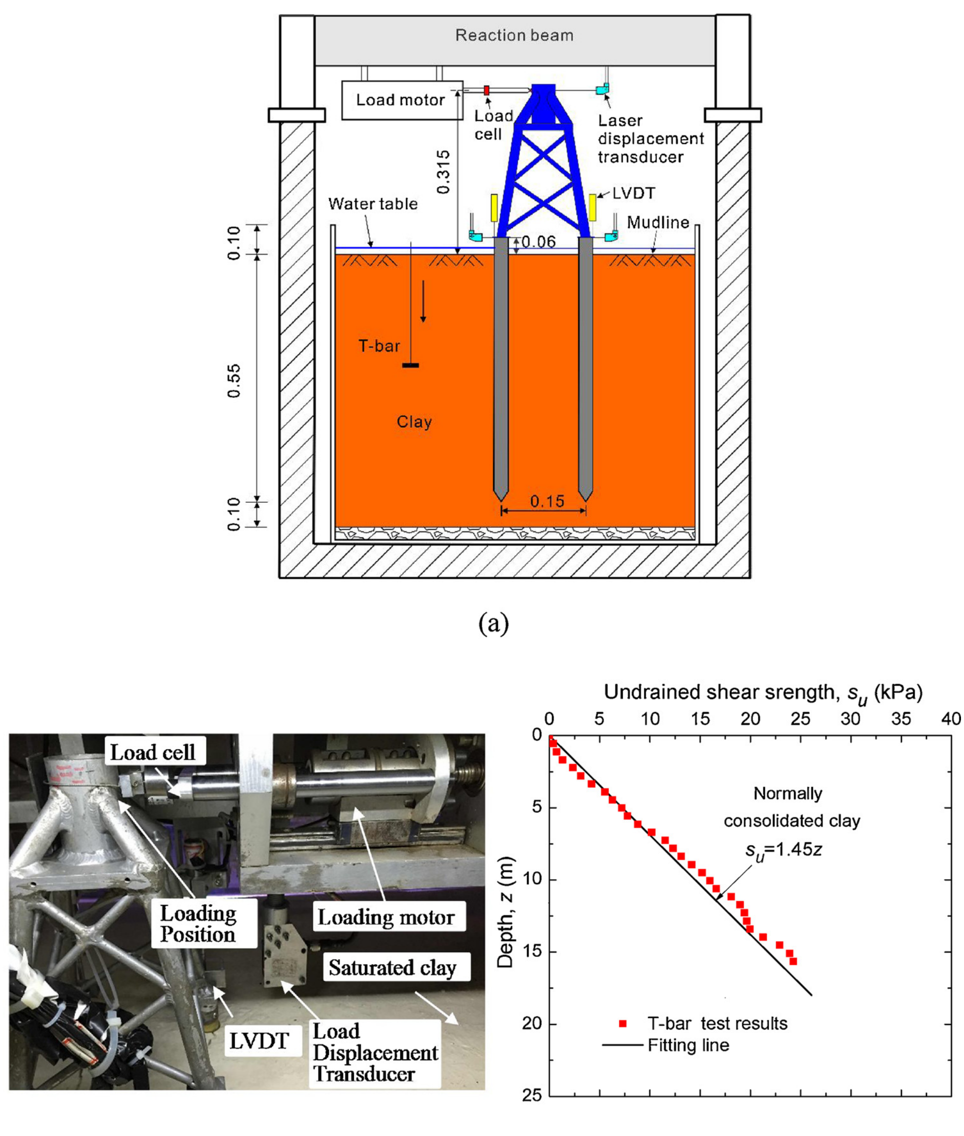

Fig. 1. (a) Set-up of the centrifuge model test programme (unit: m); (b) The model foundation after the lateral loading; (c) Undrained soil shear strength from T-bar test.