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Response of flexible monopile in marine clay under cyclic lateral load

Weiming Liao, Jianjing Zhang *, Jinbiao Wu, Kongming Yan

Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, PR China

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ABSTRACT

While monopile foundation is widely used at sandy site in Europe, it is designed and constructed in intertidal zone used only in China so far. Comparing with sandy site, intertidal site typically has different geological and environmental conditions due to upper layer consisting of soft marine clay and daily tide movement, which may lead to considerable difference in long-term behavior of monopile. In order to investigate the cyclic lateral behavior of monopile constructed in intertidal zone, several scaled model tests were conducted. The scaled monopile-soil system contained in-situ soil from intertidal zone was tested with a new designed loading device under static and cyclic lateral load. Behavior of monopile-soil system was obtained and analyzed, which includes assessment of cyclic deformation at pile-head, estimation of static and cyclic p-y curves, dissipation behavior of pore water pressure, evaluation of gapping effect and soil softening zone. Discussion and suggestion for available design are proposed based on the analysis work of test results.

1. Introduction

Offshore wind power has become a promising solution for global energy development. During 2014, nearly 92% offshore wind turbine had been constructed in European countries (GWEC 2014). Meanwhile, China had ranked fifth with installed capacity reaching 669.9 MW in 2014 (He et al., 2016). Although monopile is used widely in Europe, due to site condition and limitation of installation equipment, first offshore wind farm (Dong-Hai Bridge Wind Farm) constructed in China used high-rise pile group foundation. In the meantime, a unique compromise design by using monopile in intertidal zone was developed rapidly (Korsnes, 2014). In 2014, intertidal wind turbine (IWT) in China reached 56.69% of installed capacity which used monopile in general (CWEA 2014).

In current guidelines for offshore wind turbine (OWT), requirements of serviceability limit state (SLS) typically dominate the whole design (Arany et al., 2015). For assessment of lateral behavior of OWT during SLS, effects of cyclic loading should be considered with cautious to evaluate accumulated deformation and nature frequency change (Arany et al., 2017). At present, available design standards (e.g. API 2014 (American Petroleum Institute, 2014a; American Petroleum Institute, 2014b); DNV GL AS, 2016) only provide simplified p-y curve methods to assess the influence of cyclic effect on lateral behavior for OWT during SLS. The API code, which is based on analysis works from Matlock (1970) and Reese and Welch (1975), recommends considering cyclic effect by scaling maximum ultimate lateral resistance down by a factor of 0.72 within a specific depth for clayey site case. After that, Matlock (1979), Bhattacharya et al. (2006) proposed a modification by changing the factor from 0.72 to 0.5 to account for cyclic effect. However, available studies show a considerable difference between measured and recommended p-y curves (e.g. Murff and Hamilton, 1993; Jeanjean, 2009; Doherty and Gavin, 2011a; Gilbert et al., 2015). In addition, observation in model tests with OWT in clayey foundation also shows that stiffness of p-y curve (also consider as stiffness of pile-soil system) tends to decrease in shallow depth and leads to an observable zone of soil softening at soil surface around pile (e.g. Lombardi et al., 2013; Hamiltong and Murff, 1995; Zhang et al., 2011; Zakeri et al., 2015). Although conventional p-y method from API code has been questioned by many researchers, no generally accepted design procedure yet exists.

Estimation of lateral capacity of IWT during SLS remains using p-y curve method suggested by API in the present state of the art. Similar to OWT, IWT is slender columns with a heavy mass on top and therefore is dynamically sensitive structure. However, comparing with rigid monopile in sandy foundation (LeBlanc et al., 2010a; Doherty et al., 2012; Ahmed and Hawlader, 2016), monopile installed in intertidal area behaves mostly as flexible pile-soil system with large embedded length. Besides, intertidal site typically contains soft sensitive clayey soil at the top of foundation in general (e.g. Di et al., 2013), which could lead to

* Corresponding author. Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan Province, 610031, PR China.
E-mail address: jianzhang1102@swjtu.edu.cn (J. Zhang).

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Nomenclature

h	lever arm
H	horizontal load
λ	geometrical scale
L_c	critical length
L_P	prototype scale of length
L_M	model scale of length
$(EI)_P$	prototype scale of bending stiffness
$(EI)_M$	model scale of bending stiffness
f_P	prototype scale of loading frequency
f_M	model scale of loading frequency
F_P	prototype scale of horizontal load
F_M	model scale of horizontal load
ξ	cyclic load ratio
F_c	cyclic load
F_{USC}	ultimate static capacity
c	outer radius of the pile
Y_N	lateral displacement of n-th cycle
Y_0	lateral displacement induced by static load
S_c	stiffness of n-th cycle of load-deflection curve
S_{c0}	stiffness of 1-th cycle of load-deflection curve
$\Delta u'_N$	normalized pore water pressure
Δu_N	measured pore water pressure

unexpected cyclic degradation of pile-soil system under cyclic loading. Furthermore, environmental load of IWT is different from OWT in hydro-dynamic analysis due to daily tide movement, which could also induce severe scour around foundation. Therefore, using p-y curve method to estimate lateral behavior of IWT remains questionable and requires further verification.

This paper focuses on assessing the cumulative behavior of monopile installed in intertidal-like foundation subjected to one-way cyclic lateral load. A series of 1 g model tests were conducted to investigate the behavior of long fixed-bottom pile in overconsolidated marine clay subjected to cyclic lateral load. One static and three cyclic tests were carried out individually with the same pile-soil condition. Static test was

Fig. 1. Development of offshore wind power in different area in China (Li, 2010).

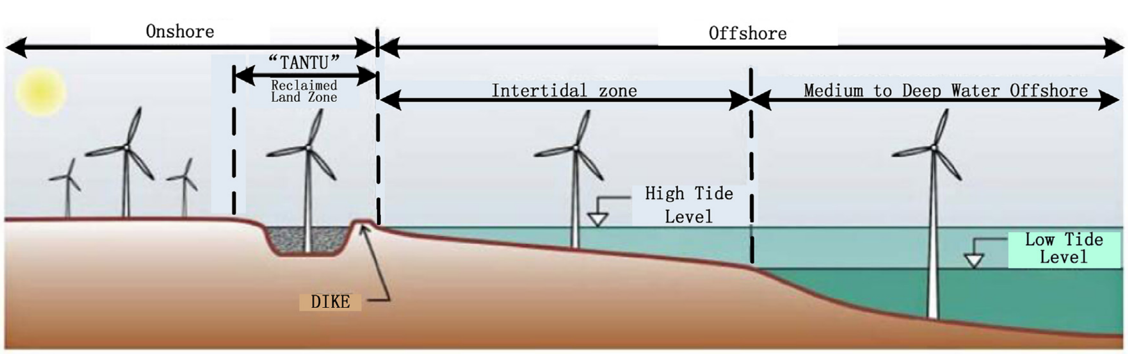

Fig. 2. Sketch map of different types of wind farms in China (Redraw from World Bank & NEA, 2010).