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Effects of cyclic vertical loading on bearing and pullout capacities of piles with continuous helix wing

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Abstract

Laboratory and field tests were conducted to investigate the bearing and pullout capacities of steel piles with a continuous helix wing during cyclic loading. Both continuous helix and straight-sided piles were subjected to monotonic compressive, monotonic tensile, and cyclic reversal loading in the laboratory, while only the continuous helix pile was tested in the field. Both the laboratory and the field tests showed that the bearing and pullout capacities of the continuous helix pile under cyclic reversal loading decreased to approximately 60–80% of those of the pile under monotonic loading, with a larger reduction seen in the laboratory tests. The decrease in resistance was mainly due to the reduction in shaft friction, which was likely to be the result of soil disturbance and loosening around the pile with cyclic loading. The laboratory tests also showed that the tip resistance of the straight-sided pile under cyclic reversal loading was reduced, similarly due to the loosening of the soil, particularly underneath the pile tip. The tip resistance of the continuous helix pile, in contrast, did not degrade with cyclic loading, owing to the presence of the wing immediately above the pile tip that inhibited the loosening of the soil. These findings were supported by similar field test observations.

Keywords: Cyclic vertical loading; Helical pile; Bearing capacity; Pullout capacity; Model test; Full-scale test (**IGC**: E04/E14)

1. Introduction

Piles supporting slender buildings or tower-like structures, such as wind turbines, may suffer from cyclic reversal axial force due to excessive overturning moments induced by strong ground motions and/or wind-induced impact loading. Helical piles have been introduced and used in practice as a method to increase the bearing and pullout capacities without increasing the pile diameter. However, little is known on whether the current design formula (Architectural Institute of Japan, 2001), mainly based on monotonic loading tests, is applicable to helical piles subjected to cyclic reversal loading. It is therefore desirable to evaluate the bearing and pullout capacities of helical piles under cyclic loading and to incorporate the acquired knowledge into the design of pile foundations.

Helical piles can be classified into three types of steel pipe piles: (1) those with a helical wing attached near the tip, (2) those with several helical wings, and (3) those with a continuous helical wing fixed around a pipe shaft (hereafter referred to as “single helix”, “multi-helix”, and “continuous helix” piles, respectively). Many studies have been made to investigate the bearing and pullout capacities of these piles during monotonic loading (e.g., Ghaly et al., 1991; Saeki and Ohki, 2000; and Gavin et al., 2014). Rao et al. (1991) and Prasad and Rao (1994) conducted model tests on multi-helix piles and recommended that the ratio of the spacing of the helices to their diameter (“the helix

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Nomenclature

c	cohesion of soil
D_e	diameter of shear zone (= D_w for continuous helix pile or D_p for straight-sided pile)
D_p	diameter of pile shaft
D_r	relative density of sand tank
D_w	diameter of helical wing
D_{50}	mean grain size of silica sand #6
K	coefficient of earth pressure
K_p	coefficient of passive earth pressure
L	length of middle friction part
P	pitch of helical wing
G1-G4	strain gauges attached to inner pipe surface
h	height above pile tip
NF	negative friction
R	bearing and pullout resistance
r	radius of pile shaft (=$D_p/2$)
R_e	bearing and pullout resistance of pile end (= sum of R_{lf} and R_p)
$R_{e.max}$	maximum R_e at which pile head displacement reaches 10% of D_e under monotonic loading condition
R_{lf}	shaft friction of lower third of pile (= "bottom wing resistance" or "lower friction")
R_{mf}	shaft friction of middle third of pile (= "middle friction")
$R_{mf.max}$	maximum R_{mf} at which pile head displacement reaches 10% of D_e under monotonic loading condition
R_{mf}'	modified R_{mf} after accounting for NF
R_{max}	Maximum bearing and pullout resistance at which pile head displacement reaches 10% of D_e under monotonic loading condition
R_{max+}	R_{max} in compression phase
R_{max-}	R_{max} in tension phase
R_p	tip resistance of pile (= "tip resistance")
R_{uf}	shaft friction of upper third of pile (= "upper friction")
I	spacing of helical wings
U_c	uniformity coefficient of silica sand #6
z	depth from sand tank surface to center of middle friction part
z	unit weight of soil
ρ_{max}	maximum dry density of silica sand #6
ρ_{min}	minimum dry density of silica sand #6
ρ_s	soil particle density of silica sand #6
σ_v	overburden pressure of sand tank
τ_f	shear strength of soil
ϕ	internal or interface friction angle

Symbols for piles

B	symbol for continuous helix pile in field tests
H	symbol for continuous helix pile in laboratory tests
S	symbol for straight-sided pile in laboratory tests

spacing ratio" I/D_w (I: spacing of helical wings and D_w: helical wing diameter) be kept between 1.0 and 1.5 in soft to medium stiff clay in order to exert the maximum pullout resistance. In this case, the pullout resistance can be determined by the shear strength of the surface of the cylindrical helices ("the cylindrical shear method"). Livneh and El Nagger (2008) conducted full-scale load tests on piles with the helix spacing ratio I/D_w of 3.0 and showed that not only the pullout capacity, but also the bearing capacity, could be estimated by the cylindrical shear method. Wada et al. (2014, 2015) conducted both laboratory and field tests on continuous helix piles with the helical wing pitch ratio P/D_w (P: helical wing pitch and D_w: helical wing diameter) of about 1 and showed that the bearing and pullout capacities of the piles could also be estimated by the cylindrical shear method.

Unlike monotonic loading conditions, few studies have been carried out on these piles under cyclic loading conditions. Komatsu et al. (2003) suggested that the wing resistance of single helix piles becomes a major component against pullout after the shaft friction has been mobilized. Tokimatsu et al. (2012) and Suzuki et al. (2013) conducted centrifuge tests on single helix piles and suggested that, even with an increase in amplitude and in the number of cycles, the wing and tip resistances increase in the compression phase (i.e., pushing), but the former decreases in the tension phase (pullout). In the case of shaft friction, it decreases in both the compression and tension phases. El Nagger and Abdelghany (2007) conducted cyclic loading tests on helical piles with three helices, and reported that 15 cycles of loading with an amplitude of 1/3 of the ultimate capacity reduced the axial compression capacity of the pile by only less than 10%.

The objective of this study is to examine the basic performance of the bearing and pullout capacities of continuous helix piles under cyclic loading conditions in both laboratory and field tests. Both the continuous helix and straight-sided piles, of the same diameter, were tested in the laboratory under monotonic compressive, monotonic tensile, and cyclic reversal loading conditions, in order to facilitate a comparison of the performance between the two piles under various loading conditions. Only the continuous helix pile was tested in the field under similar loading conditions to validate the laboratory observations.

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