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Time-dependent bearing capacity of a jacked pile: An analytical approach based on effective stress method

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ABSTRACT

Complex stress changes occur in the soil adjacent to a jacked pile during pile installation, equalization and loading, but the corresponding effects on the bearing performance of the jacked pile are not well understood at present. This paper performs a theoretical study on the time-dependent bearing capacity of a jacked pile by considering the entire stress history of the surrounding soil. The pile installation process is modeled by the undrained expansion of a spherical cavity at the pile tip and a cylindrical cavity around the pile shaft, respectively. A K_0-based anisotropic modified Cam-clay (K_0-AMCC) model is employed in the cavity expansion solution to evaluate the stress state of the surrounding soil immediately after pile installation. The dissipation of the jacking-induced excess pore water pressure is modeled by the governing equation of radial consolidation theory. The change of the effective stress in the surrounding soil is obtained by solving the governing equation and taking the soil relaxation effects into consideration. A time-dependent empirical reduction factor is introduced to incorporate the thixotropic effect on the friction angle between the soil and pile interface. An analytical approach, based on the effective stress method, is presented to predict the time-dependent bearing capacity of published centrifuge model pile tests and field pile tests. The predicted results agree well with the measured data. It demonstrates that the present approach can be applied to capture the time-dependent bearing capacity of a jacked pile in clay effectively.

1. Introduction

The stress state of soil adjacent to a jacked pile is largely affected by the pile installation (Dijkstra et al., 2011; Lim and Lehane, 2015). Especially, significant excess pore water pressures are induced by the pile installation in saturated clayey soils (Randolph and Wroth, 1979; Basu et al., 2014). It is well known that the bearing capacity of a pile is in fact an effective stress problem (Esrig et al., 1997; O'Neill, 2001). Hence, excess pore water pressures in the soil adjacent to a jacked pile have a pronounced effect on the bearing performance of the pile (Svinkin and Skov, 2000; Zheng et al., 2010). Generally, the bearing capacity of a jacked pile in saturated clays increases with the dissipation of excess pore water pressures and exhibits a time-dependent property after pile installation.

The effect of pile installation on the bearing capacity of the jacked pile is always a topic of interest for many researchers (e.g., Randolph et al., 1979; Bond and Jardine, 1991; Jardine et al., 1998; Guo, 2000; Paikowsky and Hajduk, 2004; Basu et al., 2014; Abu-Farsakh et al., 2015). Extensive field and laboratory tests have been performed to investigate the changes of the effective stress in the surrounding soil and the corresponding effects on the bearing behaviour of a jacked pile (e.g. Cooke et al., 1979; Roy et al., 1981; Konrad and Roy, 1987; Bond and Jardine, 1991; Ng et al., 2013). Those tests have provided a better understanding of the stress changes in the surrounding soil that occur during pile installation and subsequent consolidation, thus leading to more rational design approaches for calculating the bearing capacity of jacked piles in saturated clayey soils (Saldiva and Jardine, 2005). However, because of the extreme complexity of the stress changes during the pile installation, equalization and loading, the installation effects are not directly incorporated in the current design methods (Dijkstra et al., 2011). As a consequence, most of the prevalent design methods implicitly considered the installation effects through empirical correlations (Randolph, 2003). However, many of these empirical approaches have limitations, because they were developed for the specific geological conditions (O'Neill, 2001; Doherty and Gavin, 2011). Additionally, the time-dependent performance of jacked piles

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Abbreviations: K_0-AMCC, K_0-based anisotropic modified Cam-clay model; MCC, Modified Cam-clay model; FEA, Finite element analysis; OCR, Over-consolidated ratio; EP, Elastic-plastic

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Nomenclature

A_s	Area of pile base
C_{1n}, C_{2n}	Integration constants
C_h	Coefficient of horizontal consolidation
C_s	Perimeter of pile cross-section
f_s	Unit shaft resistance
$f_s(t=\infty)$	Long term unit shaft resistance
G	Shear modulus of the soil
J_i	Bessel functions of the first kinds and of order i ($i = 0, 1$)
K_0	Coefficient of earth pressure at rest
$K_c(t)$	Coefficient of earth pressure after pile installation
k_h	Coefficient of horizontal permeability
L	Pile length
M	Stress ratio at critical state
M^*	Relative stress ratio
N_c	End-bearing capacity factor
p'_0	Initial mean effective stress
p'_{cs}	Mean effective stress at critical state
$q_b(t)$	Time-dependent unit end resistance
$q_b(t=\infty)$	Long term time-dependent unit end resistance
$Q_{total}(t)$	Time-dependent total bearing capacity
$Q_{total}(t=\infty)$	Long term time-dependent total bearing capacity
r	Radial distance from pile centre
R	Radial distance of drainage boundary
r_0	Pile radius
r_p	Plastic zone radius
$S_u(t)$	Undrained shear strength after pile installation
T	Time factor
t	Time after pile installation
$u_e(t)$	Excess pore water pressure after pile installation
u_{e0}	Excess pore water pressure immediately after pile installation
υ'	Effective Poisson's ratio
Λ	Plastic volumetric strain ratio
Y_i	Bessel functions of the second kinds and of order i ($i = 0, 1$)
β	Shaft-bearing capacity parameter
γ_w	Unit weight of water
δ	Pile-soil interface friction angle
ζ, μ	Fitting parameters of soil relaxation
η_0	Initial stress ratio
η_p^*	Relative stress ratio at EP boundary
κ	Slope of swelling line
λ	Slopes of loading line
λ_n	Eigenvalues of Bessel function
ξ	Time required for full recovery of soil strength
σ'_{h0}, σ'_{v0}	In-situ effective horizontal and vertical stresses
σ'_r, σ'_θ, σ'_z	Effective stress components
$\sigma'_{rc}(t)$	Radial effective stress after pile installation
σ'_{rp}	Radial effective stress at EP boundary
τ_{rz}	Shear stress on pile-soil interface at failure state
υ	Specific volume
φ'	Effective internal friction angle of soil
χ	Relaxation ratio of soil
$\omega(\infty)$	Long term strength reduction parameter
$\omega(t)$	Time-dependent strength reduction factor
ω_0	Reduction parameter immediately after pile installation
ς	A parameter to simplify expression

has also not been taken into account in most of the empirical design methods. Therefore, these techniques cannot yet fully describe the entire stress history of the soil around a jacked pile.

Apart from experimental and empirical methods, many finite element analyses (FEA) have been performed to investigate the in-situ pile installation and subsequent bearing performance of a jacked pile (e.g., Sheng et al., 2005, 2009; Chakraborty and Kumar, 2013; Fakharian et al., 2014; Basu et al., 2014; Abu-Farsakh et al., 2015). Although finite element analyses could possibly model the complex procedure of pile installation, the modeling technology is complicated and high computational requirement. Moreover, most of these FEA mainly focused on different ground conditions and pile types, and the results were presented in different ways (Richards et al., 2006). It is therefore difficult to draw general conclusions and thus the applications in engineering practice have limitations.

This paper presents an effective stress based analytical approach to evaluate the time-dependent bearing capacity of a jacked close-ended pile in natural saturated clay. The in-situ properties of natural clay, the pile installation effects, the thixotropy and relaxation of the surrounding soil, which may significantly affect the bearing performance of a jacked pile after installation, are systematically incorporated in the proposed method. The presented approach is verified through comparing predicted results with data obtained from two published pile tests. A detailed discussion is also performed to investigate the time-dependent bearing behaviour of the jacked close-ended pile in various clays with different in-situ stress histories. The proposed analytical approach, with slight modifications by taking the soil plugging effects into consideration, can be applied to evaluate the time-dependent bearing capacity of jacked open-ended hollow piles in offshore engineering as well.

2. Cavity expansion model for pile installation

During pile installation, the soil adjacent to the jacked pile is primarily displaced radially outward, with strain fields similar to a spherical cavity expansion ahead of the pile tip and a cylindrical cavity expansion along the pile shaft (Randolph et al., 1979; Randolph, 2003). Although the soil near the pile may also be dragged downward as the pile penetrates, the cavity expansion theory provides reasonable predictions of the radial stress, displacement and the excess pore water pressures in the surrounding soil (Lehane and Gill, 2004). Moreover, the cavity expansion theory has the advantage that a closed-form solution is likely to model the stress changes during pile installation, which facilitates the analysis procedure for the subsequent consolidation. Therefore, the cavity expansion theory is adopted to model the process of pile installation in this study.

Given that the natural clay is mostly consolidated under the K_0 condition and the permeability coefficient of the clayey soil is generally very small, a K_0-AMCC model based undrained cylindrical cavity expansion solution (Li et al., 2016a) can be adopted to model the distributions of the radial stress and the excess pore water pressures in the soil around the pile shaft immediately after pile installation. This solution properly incorporates the properties of the initial stress anisotropy and initial stress-induced anisotropy of the natural clay, hence more realistic stress fields around the pile shaft can be obtained. However, the displacement of the soil around the pile tip is more similar to a spherical cavity expansion. To model the stress state around the pile tip with spherical cavity expansion theory, the isotropic assumption is essential because the solution to spherical cavity expansion should be based on the spherical symmetry condition (Yu, 2000). Hence, Approximately assuming that the three in-situ normal stress components around pile tip are equal to the mean effective stress, p'_0 ($=\sigma'_{ii0}/3$), the spherical cavity expansion solution presented by Cao et al. (2001) can be utilized to predict stress fields around the