Ocean Engineering 136 (2017) 209–217

Contents lists available at ScienceDirect

Ocean Engineering

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

Evolution of mechanical properties of soils subsequent to a pile jacked in natural saturated clays

Weibing Gong[a,b], Jingpei Li[a,b,*], Lin Li[a,b], Sheng Zhang[c]

[a] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China
[b] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
[c] School of Civil Engineering, Central South University, Changsha 410075, China

ARTICLE INFO

Keywords:
Variable coefficient of consolidation
K_0-AMCC model
Undrained shear strength
Thixotropic effect
Shear modulus

ABSTRACT

The mechanical properties of soils adjacent to a jacked pile significantly affect the bearing capacity and settlement of the pile. This paper investigates the evolution of the mechanical properties of the remolded soil surrounding a jacked pile by considering in-situ properties of natural clays, pile installation effects and variable coefficient of consolidation. The pile installation process is modeled by the undrained cylindrical cavity expansion. The distribution of excess pore pressures around the pile is derived by adopting the K_0-based anisotropic modified Cam-clay (K_0-AMCC) model, which can incorporate the initial stress anisotropy and the initial stress-induced anisotropy of natural clays. The Terzaghi's radial consolidation theory is further developed by introducing a variable coefficient of consolidation to the governing equation, which is solved by the variable separation method. The predicted results are in good agreement with the published test data. The variations of the mechanical properties of the remolded soil are studied with different variable coefficients of consolidation and the in-situ properties. The calculated results show that the variable coefficient of consolidation plays a significant role in the dissipation rate of excess pore pressures. The undrained shear strength considering thixotropic effect and the shear modulus of the remolded soil increase more rapidly with larger values of the introduced parameter α (related to the variable coefficient of consolidation). Moreover, the overconsolidation ratio has a pronounced effect on the undrained shear strength and the shear modulus of the remolded soil after pile installation.

1. Introduction

Compared with cast-in-situ piles, jacked piles are free of slurry handling and produce less noise and vibration in the installation process. The environmentally-friendly characteristic of jacked piles has increased their popularity in soft soil region in densely populated cities. Extensive experimental, field and numerical studies have been conducted to investigate the mechanical behaviours of jacked piles. Konrad and Roy (1987) investigated the shaft bearing capacity of short jacked piles by conducting a full-scale pile test. Pestana et al. (2002) studied the soil deformation due to pile driving and the dissipation of excess pore pressures after pile installation based on the well-documented field investigation. Liu et al. (2012) studied the construction effects of jacked piles in silt deposit by performing a field test program complemented with laboratory tests. Basu et al. (2013) explored the effects of undrained and residual shear strength on the shaft resistance and setup factors for jacked piles through a finite-element simulation. Zarrabi and Eslami (2016) investigated the effects of different installation methods on pile bearing capacity using the physical modeling method. It can be easily found that the changes of the mechanical properties of the soil due to pile jacking were not considered in the aforementioned studies. However, it is well-known that the mechanical properties of the soil adjacent to a jacked pile are critical for the pile bearing performance. Therefore, it is quite necessary to explore the evolution of the mechanical properties of the remolded soils surrounding jacked piles.

In addition, some researchers have performed a certain amount of research on the consolidation of the remolded soil surrounding the jacked pile with the cylindrical cavity expansion theory and the radial consolidation theory. For example, Randolph and Worth (1979) deduced pore water pressures and stress changes in the soil surrounding a jacked pile by theoretical study; Guo (2000) predicted the overall response of a pile following installation based on the closed-form solution for the radial consolidation equation; Zheng et al. (2010) studied the variations of the coefficient of consolidation and the dissipation of excess pore pressures by considering variable compres-

* Corresponding author at: Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China.
E-mail address: lijp2773@163.com (J. Li).

http://dx.doi.org/10.1016/j.oceaneng.2017.03.020
Received 16 May 2016; Received in revised form 20 January 2017; Accepted 13 March 2017

sibility and permeability of the soil. The reason for adopting the cylindrical cavity expansion theory in their studies is that the soil in the vicinity of the pile is moved outside during pile installation, and the generated strain field resembles cylindrical cavity expansion along the pile shaft, the rationality of which has been verified in Randolph's famous paper (2003). It is worth noting that the soils were all assumed isotropic in their studies and thus the anisotropic effects of the soils were neglected when modeling pile installation, which was inconsistent with actual conditions. Moreover, even though the cylindrical cavity expansion theory has gone a modest development in the recent decade, most of the theories still have not incorporated the anisotropic property of soils (e.g. Yu and Carter, 2002; Chen and Abousleiman, 2013; Li et al., 2016a).

In this paper, a solution for the undrained cylindrical cavity expansion based on the K_0-AMCC model is developed to model the behaviours of natural clays during pile installation. The governing equation considering variable coefficient of consolidation is derived for the consolidation of the remolded soil around the jacked pile, and the dissipation of the excess pore pressures along the pile shaft is obtained by solving the governing equation. The proposed solution is verified by comparing the predicted results with the published test data. The evolution of the mechanical properties of the remolded soil around the jacked pile, considering variable coefficient of consolidation, the in-situ properties and the thixotropic effect, is reasonably investigated based on the proposed solution.

2. Basic assumptions

The history of a jacked pile can be divided into three stages, which are installation of the pile, dissipation of the excess pore pressures and loading of the pile (Randolph, 2003). The first two stages will be explored in this study. In the first stage, the pile is jacked into the soil and excess pore pressures are generated. As mentioned above, the installation process of a jacked pile can be reasonably assumed as the undrained expansion of a cylindrical cavity. Fig. 1 shows a mechanical model of the cylindrical cavity expansion in the K_0-consolidated clay. As the pile is jacked into the natural clay, the internal pressure, σ_{h0}, increases to σ_h, and the initial radius of the cylindrical cavity, r_0, expands to the current radius, r_d (i.e. the radius of the jacked pile). The assumptions made for deriving the solutions for the cylindrical cavity expansion are in the following:

1. The anisotropic clay is saturated, and the compressive stress and strain are conventionally taken as positive.
2. The expansion of the cylindrical cavity is under the plane strain and undrained conditions.

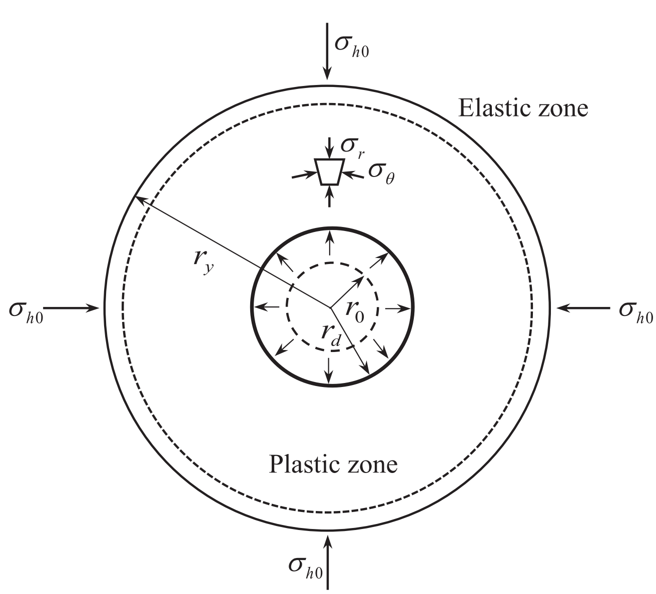

Fig. 1. Mechanical model of the cylindrical cavity expansion in K_0-consolidated clay.

Immediately after pile installation, an excess pore pressure field develops around the jacked pile. The generated excess pore pressures can be taken as the initial excess pore pressures for consolidation, given as

$$u|_{t=0} = \Delta u \tag{1}$$

where Δu are the excess pore pressures generated immediately after pile installation.

In the second stage, the pore water flows radially outwards from the pile (Randolph et al., 1979), resulting in the consolidation of the surrounding soil. The assumptions made for deriving the governing consolidation equation are as follows:

1. The jacked pile is rigid and impermeable. Hence, it follows that

$$\left.\frac{\partial u}{\partial r}\right|_{r=r_d} = 0,\ t > 0 \tag{2}$$

2. The pore water is incompressible and flows in accordance with Darcy's law. The excess pore pressures beyond the scope of the plastic zone are negligible (Zheng et al., 2010), i.e.

$$u|_{r\geq r_y} = 0,\ t > 0 \tag{3}$$

With the aforementioned assumptions, the solutions for the undrained cylindrical cavity expansion based on the K_0-AMCC model and the radial governing consolidation equation of the remolded soil around the jacked pile are derived detailedly in the following sections.

3. Solutions for the cylindrical cavity expansion based on the K_0-AMCC model

3.1. Elastic analysis

During pile installation, the equilibrium equation of a soil element at a radial distance, r, from the center of the cylindrical cavity in the cylindrical polar coordinate system can be expressed as

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{4}$$

in which σ_r and σ_θ are the radial and tangential stresses, respectively. Eq. (4) is applicable in both elastic and plastic zones.

Based on the relationship among the stress, strain and displacement, the stress distribution in the elastic zone can be obtained as (Cao et al., 2001)

$$\sigma_r = \sigma_{h0} + (\sigma_{ry} - \sigma_{h0})\left(\frac{r_y}{r}\right)^2 \tag{5a}$$

$$\sigma_\theta = \sigma_{h0} - (\sigma_{ry} - \sigma_{h0})\left(\frac{r_y}{r}\right)^2 \tag{5b}$$

$$\sigma_z = \sigma_{v0} \tag{5c}$$

where σ_{ry} is the radial stress acting on the elastic-plastic boundary.

Under the undrained condition, the soil volume remains constant during pile installation. In the $\upsilon - \ln p'$ plane, this is expressed as

$$d\upsilon = -\kappa \frac{dp'}{p'} = 0 \tag{6}$$

in which κ is the slope of the swelling line in the $\upsilon - \ln p'$ plane; and p' is the mean effective stress. It can be known from Eqs. (5a)–(5c) and Eq. (6) that the mean effective stress, p', as well as the total mean stress, p, remains constant in the elastic zone during pile installation.