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Research Paper

Lateral response of single piles in cement-improved soil: numerical and theoretical investigation

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ABSTRACT

This study aims to investigate the lateral response of a single precast concrete pile reinforced with cement-improved soil through a series of theoretical studies and 3D finite element analyses using a concrete damage-plasticity model. Application of cement-improved soil around a pile can obviously reduce both lateral deflections and bending moments in the pile and can significantly increase the lateral capacity of the pile. Increasing soil resistance to limit pile deflection and preventing or delaying the development of tension-induced damage in the pile are reinforcement mechanisms. A modified *p–y* curve model is proposed to predict the lateral response of single piles in cement-improved soil.

1. Introduction

In the last several decades, various types of pile technologies such as concrete piles employing precast or cast-in-place construction, deep cement mixing (DCM) columns, and stone columns have been extensively used for soft ground improvement [1–5]. Although a concrete pile has many advantages with various applications, the strength of the concrete pile cannot be sufficiently utilized under either vertical or lateral loading, and failure caused by soil failure can always occur, which makes it uneconomical for use in soft ground improvement [6]. Instead, DCM column failure is commonly observed as the major failure mode when used in soft ground owing to its lower strength and stiffness [7–9]. To mitigate such problems, a novel type of concrete pile reinforced with cement-treated soil has recently been proposed [6,10,11]. Owing to the low cost and effectiveness, the pile foundation, which is constructed by inserting a high-strength concrete pile into a DCM column (see Fig. 1), has been widely used for soft ground improvement in the southeast coastal region of China [12–14].

To investigate the effectiveness of such cement-improved soil for improving the vertical capacity of concrete piles, a series of studies on side friction, load transfer, and failure modes has been performed based on full-scale pile load tests, numerical modelling, and theoretical models [7,15–18]. However, a pile foundation also tends to resist lateral loads induced by earth pressure, wind loading, hydrostatic and hydrodynamic pressure, and earthquake loading. Further studies are needed to evaluate the effects of cement-improved soil on the lateral performance of piles.

Rollins et al. [19] and Lin et al. [20] observed that the lateral resistance of existing pile group foundations can be significantly enhanced using jet-grouting and cement-mixing reinforcement. In addition, several field and numerical modelling investigations were reported on the use of jet-grouting-reinforced cast-in-place piles, including those by Wang et al. [21], He et al. [22,23], and Hong et al. [24]. These studies concluded that application of jet-grouting (with a shallow depth) around cast-in-place piles can greatly enhance lateral pile stiffness and reduce the residual pile deflection under both monotonic and cyclic loading. Although several field tests and numerical modelling of laterally loaded piles with jet-grouting or cement-mixing reinforcement have been reported, systematic studies of the use of cement-improved soil towards improving the lateral performance of precast concrete piles are still needed. Additionally, the *p–y* model for predicting lateral response of piles reinforced by cement-improved soil has been rarely reported.

This paper aims to conduct a comprehensive study on the lateral capacity of precast piles reinforced by cement-improved soil as well as the *p–y* model for predicting the lateral response under monotonic loading. To achieve the research objectives, three-dimensional (3D) numerical analyses that were first validated against field test results were performed using ABAQUS finite element software. A concrete damage-plasticity (CDP) model was developed to investigate the lateral performance of a single pile reinforced by cement-improved soil along with the reinforcing mechanisms. Moreover, a modified *p–y* curve

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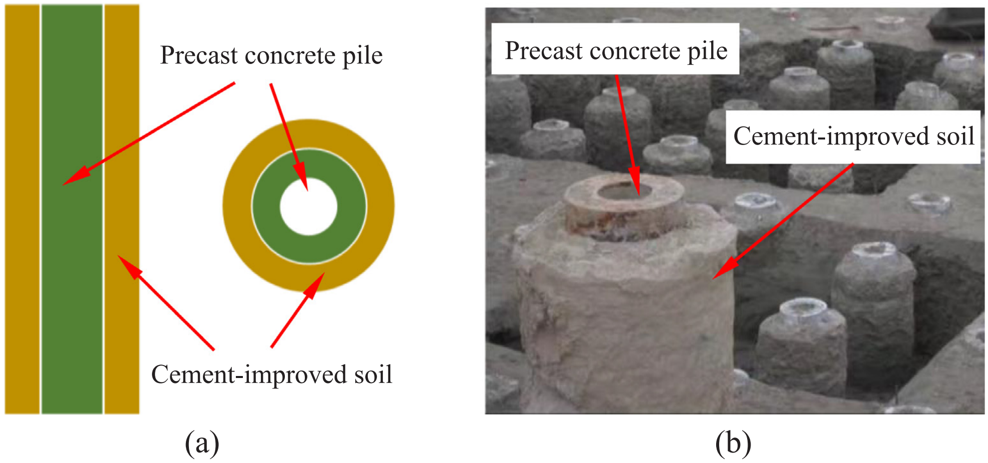

Fig. 1. (a) Schematic diagram of pile with cement-improved soil reinforcement; (b) photo of field excavation.

model is proposed for the reinforced piles within the cohesive soil, and the suitability of the proposed *p-y* curves for predicting the lateral responses of such reinforced piles was also assessed.

2. Field test

2.1. Subsoil conditions and project overview

A sluice foundation project was executed at a site in Nantong, which is located along the southeast coast of China. The site landform, which is classified as a coastal plain in the floodplain district of the lower Yangtze River, is essentially covered by Quaternary marine deposits. Extensive field tests there and laboratory tests were performed to characterize the subsoil conditions of the upper and lower layers. Specifically, conventional laboratory soil tests were carried out to determine the unit weight (γ), void ratio (e), compression modulus (E_s) and relevant shear parameters of the soil mass. Moreover, a Cone Penetration Test (CPT), which is one of the most commonly used field test methods in geotechnical investigations, was performed to determine the ultimate unit skin friction (f_s) and tip resistance (q_c). The soil profile and engineering properties of the test site are presented in Fig. 2. It can be seen that the soil profile near the ground surface consists of a marine silty clay layer underlain by a silty sand deposit. Specifically, the upper silty clay layer has a thickness of 8 m and can be characterized as a high compressibility and low strength layer, which is undoubtedly classified as the soft ground. Below the layer, there is a loose silty sand layer with a relatively higher strength. It is worth noting that the upper silty clay layer is of great interest for this study, not only because of its engineering properties for soft ground but also because the lateral resistance of pile is mostly contributed by the upper soil layer, which has a depth 7–10 times the diameter of the pile [25,26].

Given the geological conditions at the project site, the cast-in-place pile foundation may result in severe pollution due to the cement as well as a prolonged construction duration and elevated costs, whereas an ordinary precast pile requires a relatively deep bearing stratum (i.e., longer piles) and squeezing effects (disturbances) from the pile driving process on the silty clay and silty sand would result from the precast pile. Therefore, pretensioned high-strength concrete (PHC) pipe piles with cement-treated soil reinforcement were adopted for this project to improve the bearing capacity of the soft ground. DCM columns (cement-improved soil by dry-jet-mixing) having a cement content of 200–250 kg per cubic meter of soil were first constructed, and PHC pipe piles were then driven into the DCM columns using small-scale vibrating equipment prior to initial setting of the cement paste. The outer DCM column has a diameter (D) of 0.8 m and a length (L) of 12 m, and detailed information on the inner PHC pipe pile is summarized in

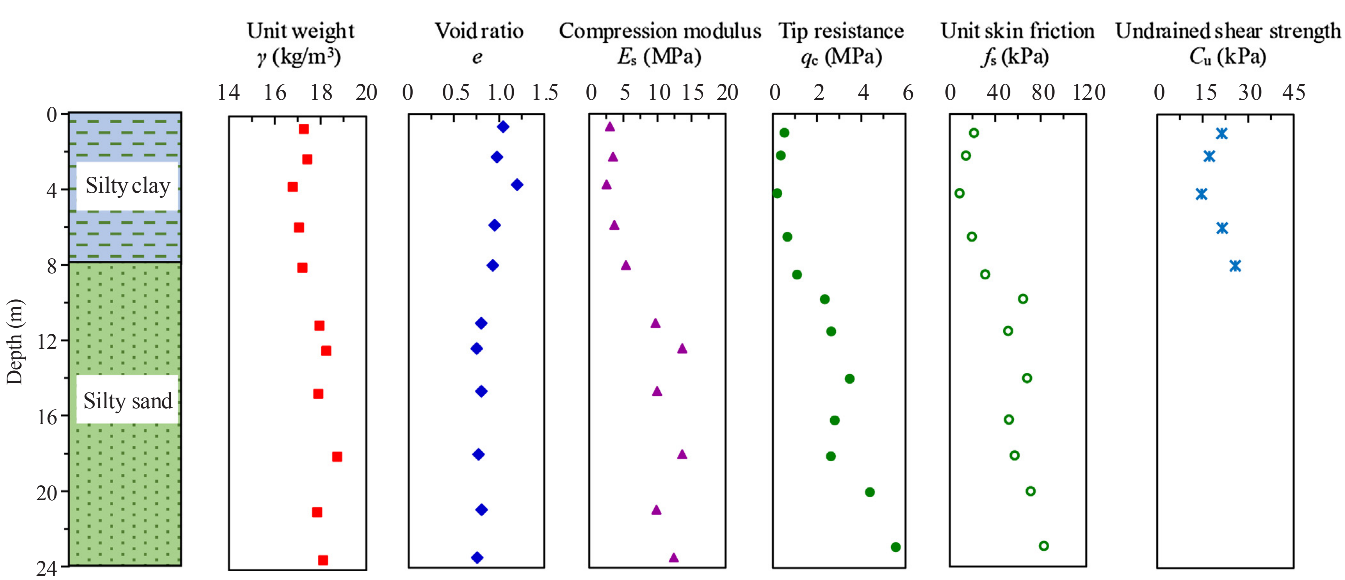

Fig. 2. Soil profile and engineering properties of the test site.