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Mechanical behaviors of SD and CFA piles using BOTDA-based fiber optic sensor system: A comparative field test study

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ABSTRACT

Screw displacement (SD) pile and continuous flight auger (CFA) pile are two similar deep foundation technologies, and new developed SD piles are used for the first time in Anhui Province, China. In order to investigate the differences of their mechanical behaviors under the load, field static load tests were performed. The distributed strains along the full length of piles were measured using fiber optic sensor (FOS) system based on Brillouin optical time domain analysis (BOTDA) technology. The axial fore, shaft resistance and tip resistance were calculated using the measured axial strains according to the stress calculation method. Thereby, the load transfer mechanism and bearing capacity of SD and CFA piles were compared. The test results indicate that FOS system is an alternative method to measure the mechanical behaviors of the pile. When the ultimate load exerted on the pile top is reached, the pile tip force of SD pile is about 7.8% of the total load, which means that SD pile works as an end bearing friction pile. The ultimate bearing capacity of SD pile is 66.7% higher than that of CFA pile in this case study. The change of stress state of soil element induced by pile installation shows that the densification and shear strength improvement of surrounding soil is the main reason why the bearing behaviors of SD pile is better than that of CFA pile.

1. Introduction

Screw displacement (SD) pile and continuous flight auger (CFA) pile are two types of deep foundation technologies with similar construction sequence and construction equipment [1,2]. These two types of pile, particularly the new developed SD pile, have been widely used in Europe and US for last decades, and are becoming increasingly popular in China [3,4].

Several laboratory model tests and field tests for SD and CFA piles were carried out by Krasiński [5–9], Cavin [10–12], Brown [13] and Farrell [14]. In tests reported in the above-mentioned literatures, the axial force and strain of pile were measured using force cells and strain gauges which were embedded at intervals in the pile. It is impossible to obtain the continuous distribution of axial force and load transfer along pile shaft through this kind of discrete point measurement. Additionally, the output value of an electrical or mechanical-based sensor is liable to be interfered by electromagnetic fields and external unfavorable factors. More seriously, the implantations of these sensors also adversely affect the pile integrity, and then weaken the pile working performance [15–17].

Recent developments of distributed fiber optic sensor (FOS) provide an alternative for pile performance monitoring due to its advantages of light weight, small volume, waterproof, anti-corrosion, anti-jamming, good durability, high resolution and long-distance transmission [18–20]. FOS has an increasing application in health monitoring of geotechnical structures such as slope [21–22], tunnel [23], pile foundation [24–26], deep excavation [27,28], embankment [29], etc.

In this study, SD piles are used for the first time in Anhui Province, China. The actual performance at the site is unclear. In order to investigate its mechanical behaviors under the load and compare that with CFA pile at the same site, field static load tests were performed, in which the distributed strains of SD and CFA piles were measured using a FOS system based on Brillouin optical time domain analysis (BOTDA) technology. Then, the axial force, shaft resistance and tip resistance were calculated based on the measured strains. Thereby, the load transfer mechanism and bearing capacity of SD and CFA piles were compared.

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2. Description of CFA and SD piles

2.1. CFA pile

The CFA pile, also known as auger cast-in-place (ACIP) pile in North America, enjoys significant increase in use in recent years due to its advantages of rapid construction and good economy [1]. To install a CFA pile, a continuous flight auger is drilled into the ground by torque and a downward force. After the desired depth is reached, concrete or grout is pumped through the hollow stem to the base while withdrawing the auger from the ground. Then, a reinforcement cage is inserted or vibrated down into the concrete or grout to complete a pile. The installation sequence is illustrated in Fig. 1. With the current construction equipment available in the market, CFA pile can be installed with a diameter ranging from 0.3 to 1.0 m and a length up to 40 m [30]. During the process of advancing auger to the desired depth, the control of auger rotation rate and penetration rate is important. If the rotation rate of auger is too fast with respect to penetration rate, most of soil within borehole would be transported to the ground surface by the auger flight, which would result in a lateral movement of the surrounding soil towards the borehole [1,2].

2.2. SD pile

The SD pile, also known as drilled displacement (DD) pile or augered displacement pile, evolves from CFA pile. Basu [3] overviewed different types of drilled displacement pile, e.g., the Atlas, Dewaal, Fundex, Oliver, Omega, etc., and their installation techniques in North America. In this study, SD piles were installed using a specially designed displacement auger which was drilled into the ground by combining vertical force and torque, as shown in Fig. 2. During the penetration process, a displacement body horizontally displaced soil within the ground. After the auger tip reached the desired depth, concrete or grout was poured through a hollow stem as the displacement auger was extracted from the ground. Then, a reinforcement cage was inserted into concrete by vibration until a pile being completed. The installation sequence is illustrated in Fig. 3. Compared with CFA pile, minimal soil was transported to the ground surface induced by SD pile installation.

3. Principle of BOTDA-based FOS system

3.1. Principle of BOTDA

BOTDA is an innovative technology that allows continuous strains measurement along the full length of pile using a standard optical fiber. It works by measuring the frequency shift of Brillouin scattered light which is stimulated by sending a pump light and probe light into the optical fiber separately from the two ends of optical fiber [31], as shown in Fig. 4. The measured frequency shift of Brillouin scattered light is associated with the local strain and temperature of optical fiber. It has been found that there is a linear relationship between the frequency shift, strain and temperature as follows [32–33]:

$$\upsilon_B(\varepsilon, T) = \upsilon_B(\varepsilon_0, T_0) + \frac{\partial \upsilon_B(\varepsilon, T)}{\partial \varepsilon}(\varepsilon - \varepsilon_0) + \frac{\partial \upsilon_B(\varepsilon, T)}{\partial T}(T - T_0) \qquad (1)$$

where $\upsilon_B(\varepsilon_0, T_0)$ and $\upsilon_B(\varepsilon, T)$ are the Brillouin frequency shifts before and after measurement, ε_0 and ε are the strains before and after measurement, T_0 and T are the temperatures before and after measurement, $\partial \upsilon_B(\varepsilon, T)/\partial \varepsilon$ is the proportional coefficient of strain, which is 505.5 MHz/% for a standard single mode fiber with 1550 nm wavelength according to the standard calibration test offered by Omnisens Company [34], $\partial \upsilon_B(\varepsilon, T)/\partial T$ is the proportional coefficient of temperature, which is about 1.2 MHz/°C [33].

The temperature changes influence the BOTDA strain reading. Thus, it is necessary to conduct temperature compensation to alleviate temperature influence [15]. This can be achieved by installing an additional unstrained temperature-sensing cable in the pile and obtaining its reading in the measurement. The cable can adopt a unitube cable, in which the optical fibers are free to move rather than carry strain [28]. Given the pile static load test in this paper didn't continue a long time (8.75 h for SD pile and 22 h for CFA pile), and the temperature along the optical cable in the pile can be assumed the constant [17,35,36]. We didn't install a temperature compensation cable in the pile to conduct temperature compensation. The Brillouin frequency shift is thought to be induced by external strain. Therefore, Eq. (1) can be simplified into Eq. (2) as follows:

$$\upsilon_B(\varepsilon, T) = \upsilon_B(\varepsilon_0, T_0) + \frac{\partial \upsilon_B(\varepsilon, T)}{\partial \varepsilon}(\varepsilon - \varepsilon_0) \qquad (2)$$

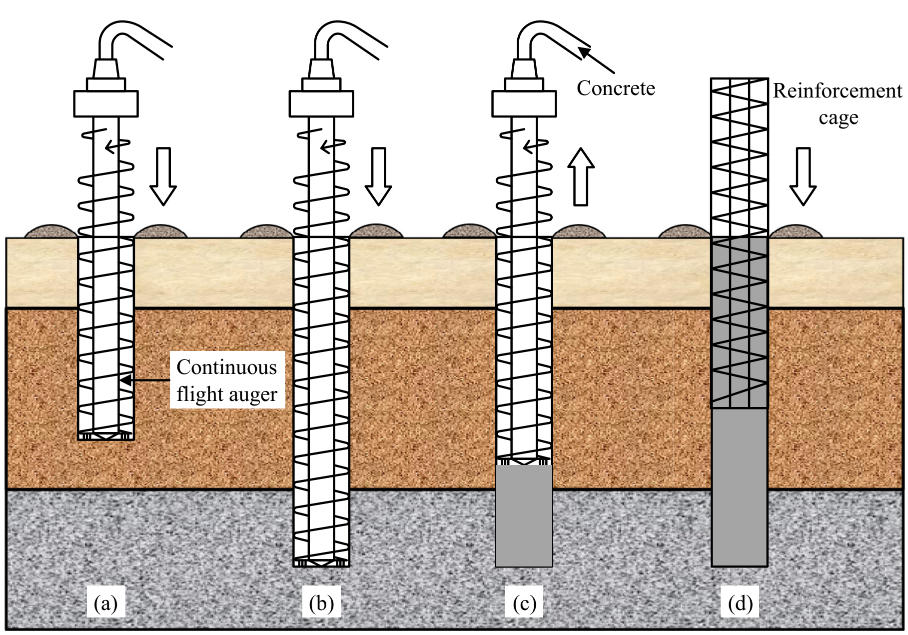

Fig. 1. Schematic of CFA pile installation.