Shaft Resistances of Jacked Open-ended PHC Pipe Piles

Xiao-long Zhou[1], Hai-lei Kou[2,], Chang-hong Li[3]
[1,3]*School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[2]*College of Engineering, Ocean University of China, Qingdao 266100, China*
[2]*School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore*
[3]*E-mail*: zxl_89@126.com

ABSTRACT: The shaft resistance of open-ended pipe piles during installation and static loading test plays an important role in the design of pile foundation. One open-ended Pre-stressed High-strength Concrete (PHC) instrumented with sensors was jacked to investigate the performance of shaft resistance during installation and loading test. Test results indicated that the shaft resistances gradually transferred along depth during installation, and the magnitude is closely related to soil properties. The shaft resistance at the same depth decrease with jacked cycles. After five jacked cycles, the shaft resistances in sand silt at 6 m depth decreased about 58.8%. The decrement of silty clay at 10 m depth was about 12.1% after three jacked cycles. In the loading test, the shaft resistance of test pile were gradually mobilized from up to down.

KEYWORDS: Open-ended PHC piles; Shaft resistance; Installation; Static loading test

1. INTRODUCTION

Pre-stressed High-strength Concrete (PHC) pipe piles are usually used as deep foundation in China as its construction convenience, high bearing capacity and less environmental pollution and so on (Zhang and Wang, 2007,2009). Comparing with other construction methods, jacking method is preferred because it is free from noise, vibration and slurry handing, and is particularly suitable for installing piles in urban areas (Kou et al, 2016). As small displacement pile, the behavior of jacked open-ended PHC pile became more complicated considering the soil plugging during installation.

During installation, the soil is displaced predominately radially along the shaft while some vertical displacement along the shaft may also occur. The zone where soil is displaced and disturbed during installation is known as the shear zone (Kou et al, 2015). The soil properties in the shear zone are different from those of undisturbed soil. The behavior of pile and around soil during installation and static loading test became complicated as the existence of shear zone. The variations in the shear zone predominately play an important impact in subsequent pile performance after installation, especially on setup, which is related to pore pressure dissipation, soil aging, thixotropy and secondary compression (Komurka et al. 2003).

A number of previous studies have been reported to discuss the pile-soil interaction behavior in filed and lab tests. Vesic (1970) and Lehane et al (1993) investigated the behavior of displacement piles in sand and found that the reduction in the radial effective stress at a given horizon will be greater as the pile penetrates deeper. Such degradation of shaft resistance has been recognized for decades and is generally referred to as “friction fatigue” (Heerema, 1980; White and Lehane, 2004). The friction fatigue is likely to be closely related to the persistent contraction of shear zone during pile penetration. Lehane et al. (2005) described the behavior of displacement piles in sand and revealed that the equilibrium radial effective stress depend on relative density, the depth of the particular layer, and the relative position of the tip (h/R). Randolph et al (1994，2003，2005) Randolph et al (1994, 2003, 2005) suggested to introduce degradation factor into pile design to evaluate the impacts of friction fatigue. White and Lehane (2004) studied the friction fatigue using centrifuge model piles equipped withlateral stress sensors and found that the primary mechanism controlling friction fatigue is the cyclic history imparted during pile installation to soil elements at the pile-sand interface. Gavin and O'Kelly (2007) indicated that the increase of soil stiffness below pile end would improve the lateral friction in the static loading test. Yu and Yang (2012a, 2012b) discussed the interface behavior between open-ended steel pipe piles and soil in sands during pile installation and static loading.

To better understand the interaction between pile and soil around, an open-ended PHC pipe pile instrumented with strain sensors was jacked into silty clay. The shear stress between pile and soil during installation was monitored and analysed. The data collected from static loading test was also compared with that of during installation. The goal of this study was to further understand the pile-soil behavior during the whole process.

2. FIELD TEST

2.1 Soil conditions

One open-ended PHC pipe pile, with outer diameter of 400 mm and wall thickness of 75 mm, was jacked into clay soil layer to investigate the shaft resistance. The site is underlain in sequence by 1.8 m fill layer and 14.2 m marine deposits. The fill layer is mainly composed of silty clay with shell fragments. The marine deposits consist of silty and cohesive soil with some shell fragments. The properties of the soil layers are summarized in Table 1. The cohesion and friction angle were measured using quick shear tests. The water table was at 1.5 m below the ground surface and the pore pressure distribution was hydrostatic.

Table 1 Subsoil properties

Soil Layer	Thickness (m)	Water content w (%)	Void ratio e_0 (%)	Unit weight γ (kN/m^3)	Cohesion c (kPa)	Friction angle φ (°)
Fill	0-1.8	/	/	/	/	/
Silty clay	1.8-4.8	25.7	0.73	19.36	14.0	21.5
Sandy silt	4.8-7.3	31.2	0.87	18.52	7.1	29.4
Muddy clay	7.3-9.8	44.8	1.28	17.07	15.8	8.0
Silty clay	9.8-16.0	23.4	0.67	19.77	28.5	22.8

2.2 Pile Instrumentation

The test pile was instrumented with Fiber Bragg Grating (FBG) sensors before installation to monitor the shaft resistance of test pile. The arrangement of FBG sensors along test piles is shown in Figure 1. Seven levels of FBG sensors are mounted along test pile and most of the sensors are installed in 2.5 m intervals. The distance from pile toe or head to the nearest strain gauge is kept as 0.25 m, as illustrated in Figure 1.

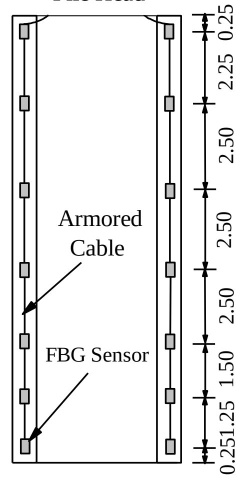

Figure 1 Arrangement of strain sensors on test piles

The test pile was installed by the jacking machine. The final jacking force was about 727 kN. Static loading test was carried out on the test pile at 17 days after installation according to the Chinese Technical Code for Testing of Building Foundation Piles (JGJ106-2014).A loading platform with fill was used to provide the reaction force, and the pile head settlements were measured by using two displacement transducers located at the pile head.

3. TEST RESULTS AND DISCUSSION

3.1 Shaft resistance during installation

Figure 2 shows the axial force distribution along test pile during installation. It is indicated that the axial force transmission is closely related to the soil properties around pile. Along with penetration depth, the base resistance gradually increase as the soil strength is larger with installation depth. The shaft resistance can be calculated using the records of adjacent sensors along test pile, as shown in Figure 3.

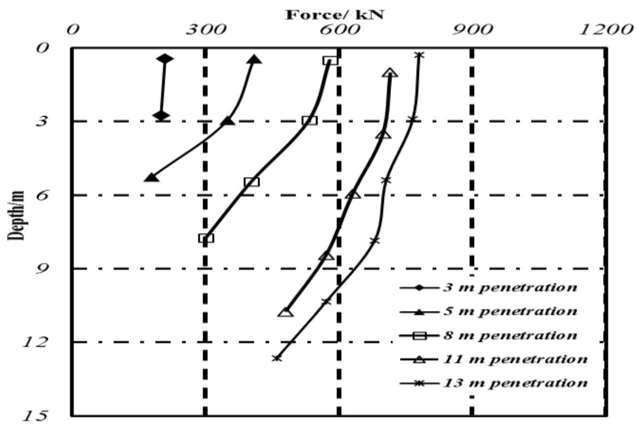

Figure 2 Axial force distribution with penetration depth

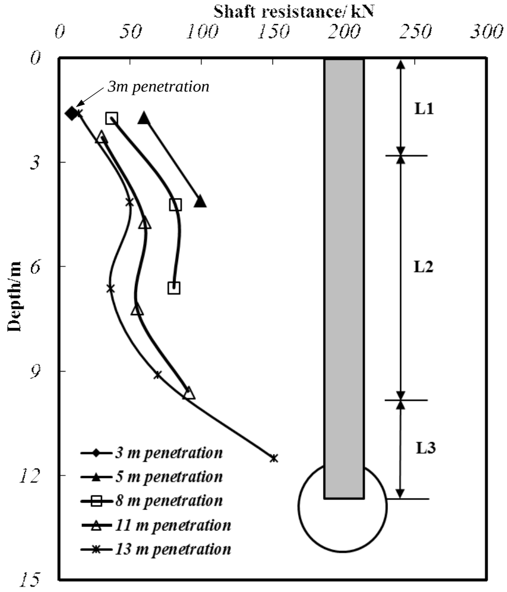

Figure 3 Shaft resistance with penetration depth

The changes of shaft resistances illustrate that the soil properties around pile has significant effects on pile behavior during installation. Taking the shaft resistance at 6 m depth as example, the shaft resistances were 80 kPa, 55 kPa and 43 kPa respectively when test piles penetrated in 8 m, 11 m and 13.0 m. After five penetration cycles, the shaft resistance at 6 m depth was reduced by 47 kPa, with decrease amplitude of 58.8%. After three penetration cycles, the shaft resistance at 10 m depth reduced from 91 kPa to 80 kPa. The decrease amplitude is about 12.1%.

3.2 Shaft resistance in static loading test

Before static loading test, the readings of FBG sensors were set to be zero. That is the residual forces locked in test pile after installation was ignored during static loading test. Figure 4 shows the overall load-displacement responses of the test pile. Using the Chinese Technical Code for Testing of Building Foundation Piles (JGJ106-2014), the ultimate bearing capacity of the pile can be determined as 1180 KN which is the load at which the settlement reaches 10% of the pile diameter. The ultimate base and shaft resistance can also be deduced respectively based on the data recorded by FBG sensors which are 382 and 818 KN. It is indicated that the load applied to the pile is mainly supported by the shaft resistance. The load is then gradually transferred to the pile toe.

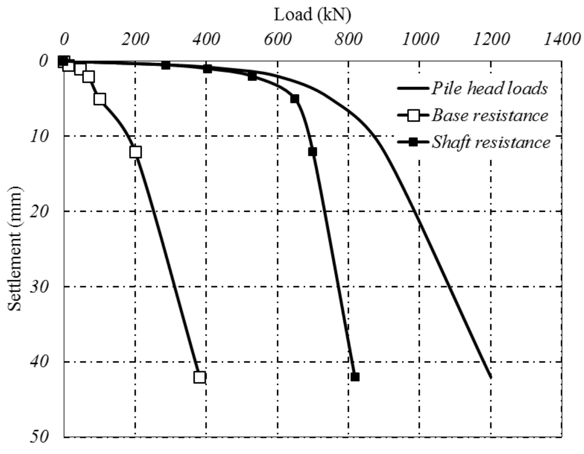

Figure. 4 Load vs displacement relationship at the pile head

Figure 5 shows the axial force distribution along test pile during static loading test. It is significant that, under small loadings, most of the pile head loads are balanced by the pile-soil interaction at top, and the lower pile shaft resistance were not fully mobilized. With the increase of pile head loads, the lower pile shaft resistance and base resistances are mobilized. The pile-soil interactions are gradually mobilized from top to bottom with the increase of pile head loads.

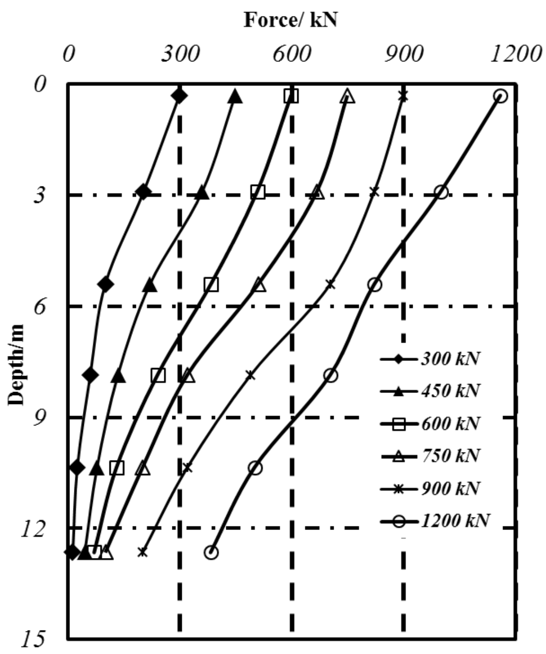

Figure 5 Axial force with depth in static loading test

The distribution of unit shaft resistance under each loading can be established according to the axial force in static test. To compare the shaft resistance during installation and the static loading test, the unit shaft resistance after installation were also presented in Figure 6.

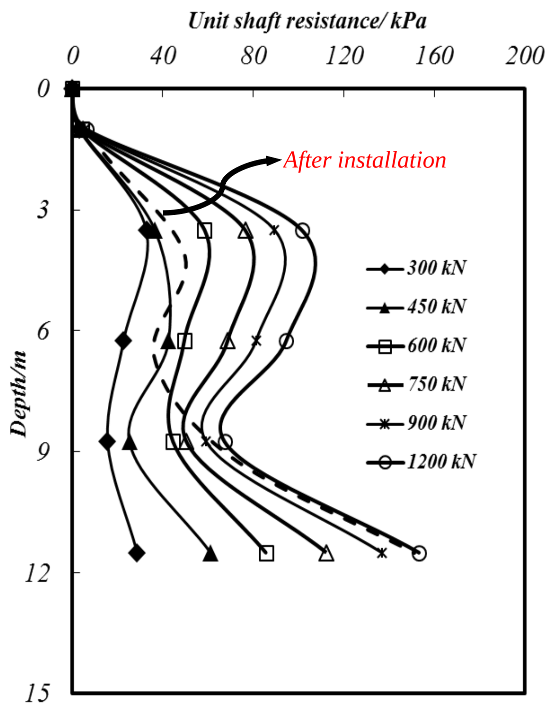

Figure 6 Shaft resistances with embedded depth

It is indicated that the unit shaft resistance gradually transfer from top to bottom with increase of pile head loads, which is similar with the transmission of axial forces. Compared with the distribution of shaft resistances after installation, the ultimate shaft resistance is larger due to the effect of set-up. Set-up is defined as the increase of pile bearing capacity over time after installation, and relaxation refers to the decrease of pile bearing capacity as time elapsed (Komurka et al., 2003). The set-up effect is mainly attributed to the dissipation of excess pore water pressure. The dissipation is associated with an increase in effective horizontal stress in surrounding soil as the surrounding soil consolidates and gains strength (Gavin et al., 2013). During installation, pile penetration is the steady state, in which the interaction between pile and around soil acts as sliding friction. The surrounding soil was be completely remodelled during installation. After installation, the surrounding soil will be re-consolidated. In the static loading test, the physical mechanical properties of the soil have been changed, and the pile-soil interaction displays as static characteristics.

4. CONCLUSION

The shaft resistance of open-ended PHC pile were measured during installation and static loading test based on fibre sensing technology. Based on the analysis of the field test results, the following conclusions can be reached.

(1) During installation, the axial forces and shaft resistances gradually transfers with penetration depth. The transfer behavior is closely related to the soil properties around pile.

(2) With the increase of penetration cycles, the shaft resistance at the same depth gradually decreases. After five penetration cycles, the shaft resistance at 6 m depth was decreased by 58.8 %. After three penetration cycles, the shaft resistance at 10 m depth was decreased by 12.1%.

(3) The shear mechanism at the stage of loading test is different from that of the installation phrase. The penetration process of PHC pipe pile is the steady-state penetration, which the interaction between pile and soil acts as sliding friction. In the static loading test, the pile-soil interaction is the static friction.

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