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The Behavior of a Single Pile under Cyclic Axial Loads

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ABSTRACT: Many piled foundations have been destroyed under significant cyclic loads in earthquakes. Centrifuge modelling of a single pile subjected to cyclic loads has been conducted to investigate the influence of cyclic loads on the axial performance of the single pile. Different pile installation procedures were applied to compare the axial behaviour of different piles under cyclic loads. Pile head permanent settlements accumulated due to cyclic axial loads, and these increased with the increasing load amplitude. Also the pile head axial secant stiffness decreased with the increasing number of axial load cycles, and with increasing amplitude. Furthermore, the axial pile performance is influenced significantly by different installation methods.

INTRODUCTION

Piled foundations are often subjected to significant cyclic loads arising from the swaying and rocking motions of superstructures during earthquakes. These cyclic loads caused the cyclic degradation of axial pile head stiffness and accumulated permanent settlements. Consequently, many piled foundations have failed catastrophically owing to these cyclic loads, causing destructions of major pile-supported structures.

For monotonically loaded pile behaviour, dynamically-driven piles are stiffer than bored piles caused by the influence of penetration on the stress state of soil surrounding piles. Nowadays jacked piles become more popular to be used in urban construction due to the minimal noise and ground vibration. Compared to bored and driven piles, jacked piles show a stiffer base response due to stiffening effect of the final jacking stroke, and exhibit a stiffer shaft response resulting from enhanced shaft resistances without friction fatigue effect (White & Deeks, 2007).

Many researchers have paid much attention to the axial performance of bored or driven piles subjected to cyclic axial loads (e.g. Poulos, 1989). Nevertheless, the axial behaviour of jacked piles under cyclic loads is still not well understood at present.

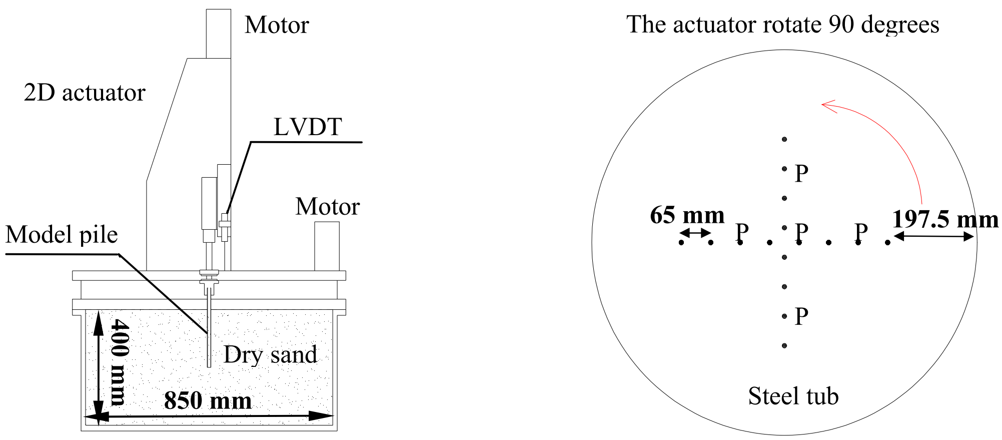
In this research, a series of cyclically loaded pile tests was conducted in the centrifuge environment. Different pile installation methods were applied to capture the full range of construction-induced soil conditions available in the field. The pile head axial load-displacement response under cyclic loads is described; the pile head stiffness degradation and accumulated permanent settlements are also discussed.

METHODOLOGY

Test Apparatus and Model Pile

Single pile tests were conducted at 50g in the Turner beam centrifuge at the Schofield Centre, Cambridge University. The whole test package is presented in FIG 1(a). A new two-axis servo actuator was designed to apply vertical loads to the model pile. An introduction to the actuator is described in Haigh et al. (2010).

A stainless steel tubular model pile was used, with an outsider diameter of 12.7 mm and an internal diameter of 11.3 mm. The embedment depth and total length of the pile are 200mm and 250mm respectively. The pile tip is flat and close-ended. The shaft surface is smooth, and the pile head is fixed without any rotation. The pile was instrumented with a load cells at the pile head to measure axial forces, lateral forces and bending moments.



(a). Elevation view of the test package **(b). Test arrangement**

FIG. 1. Centrifuge test plan.

Instrumentation

Pile head axial displacements were measured using a Linearly Variable Differential Transformer (LVDT) mounted on the 2D actuator, with a maximum stroke length of 22 mm. Also the pile head vertical and horizontal displacements were recorded by two encoders fixed on the track of the 2D actuator.

Sand and Container

Dry Fraction E silica sand was used in this project, and it should have behaved like a continuum as would be the case in the prototype. The sand was pluviated into a cylindrical steel tub (850mm diameter and 400mm deep) by an automatic sand-pouring machine, and a dense homogeneous sand specimen with a relative density of 83% was achieved. The steel tub is large enough to ignore the boundary effect ($D_{container}/D_{pile}$=67).

CYCLIC AXIAL LOAD TESTS

Test Procedure

All test locations are presented in FIG 1(b). The interspaces between successive tests were about 15 times the pile diameter to nullify any effects due to effective stresses induced in the sand by preceding tests. The pile was pre-jacked into sand at 1g to simulate undisturbed soil conditions surrounding bored piles, or monotonically jacked at 50g, or cyclically jacked at 50g to model jacked piles in the field. After installation, ten displacement-controlled axial load cycles with an amplitude of 0.52mm or 1.3mm were conducted; and ten force-controlled load cycles were conducted subsequently, in which the pile head axial maximum and minimum force in each cycle was equal to those in the tenth displacement-controlled cycle.

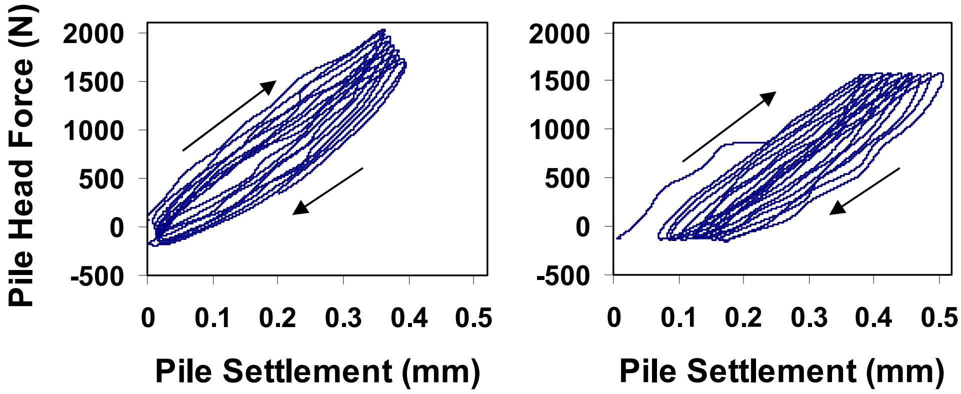
Displacement-Controlled Load Cycles

Pile head axial force-settlement curves in the first ten displacement-controlled cycles for the jacked pile are shown in FIG 2(a). In these load cycles, pile head minimum force (P_{min}) had little change; while pile head maximum force (P_{max}) reduced with increasing number of cycles but at a reducing rate, as shown in FIG 3. The greatest reduction took place within the first ten cycles, which is consistent with Poulos' (1989) test results.

This reduction of P_{max} mainly derives from the loss of pile shaft friction. When the pile is subjected to cyclic axial loads, the pile shaft friction reduces due to a decrease in the normal stress caused by cumulative contraction of the sand within the shear zone close to the pile-soil interface (White & Lehane, 2004). In each load cycle, although dilation occurs in the shear zone firstly, the shear band contracts significantly after reversal of the loading direction, leading to some net contraction per cycle.

For the pre-jacked pile, P_{max} rose to around 900N at a settlement of 0.52mm in the first cycle, and decreased to 450N after ten cycles; while P_{max} of the monotonically or cyclically jacked pile was around 2000N in the first cycle and reduced to 1600N after ten cycles with an amplitude of 0.52mm. In the first cycle, P_{max} of either the monotonically or cyclically jacked pile is twice as large as that of pre-jacked pile due to the larger soil radial stress around the pile shaft and higher soil shear modulus underneath the pile base. After ten cycles the reduction of P_{max} is similar for the pre-jacked, monotonically and cyclically jacked pile, attributed to the reduction of pile shaft friction as discussed above. This indicates that the cumulative contraction of the sand within the shear zone surrounding the interface is not influenced by the original radial stress level of sand, and is thus not changed by different pile installation methods.

For the monotonically jacked pile, P_{max} rose to around 3000N in the first cycle and reduced to 1700N after ten cycles with an amplitude of 1.3mm. Although this P_{max} value is 1.5 times that found using an amplitude of 0.52mm in the first cycle, it then decreased much more significantly and became comparable to that found using an amplitude of 0.52mm after ten cycles. Thus the reduction in P_{max} increases with increasing amplitude of cyclic load, indicating that the reduction in radial stress in the sand increases rapidly with increasing amplitude of cyclic displacement. However, the ultimate mobilized radial stresses of sand surrounding the pile shaft are similar for different cyclic displacement amplitudes.



(a). Displacement-controlled cycles **(b). Force-controlled cycles**

FIG. 2. Pile cyclic axial force-displacement curves.

Force-Controlled Load Cycles

In force-controlled axial load cycles, the pile head maximum and minimum displacements in each cycle increased with the increasing number of cycles but at a reducing rate, as shown in FIG 2(b). In each cycle, in order to counteract the effect of the accumulated contraction of sand around the pile-soil interface, an extra increment of pile head axial displacement is required to mobilize a given maximum load, thus inducing an accumulated permanent displacement, as shown in FIG 4.

Accumulated permanent settlement (S_a) of the pre-jacked pile is the largest with a value of 0.23mm, followed by the monotonically jacked pile and cyclically jacked pile with a value of 0.124 mm and 0.08mm respectively. The monotonically or cyclically jacked pile had a stiffer base response than the pre-jacked pile due to the pre-loaded soil under the pile base. Also they have higher shaft resistance and therefore higher stiffness caused by the larger radial stress in the soil surrounding the pile shaft. Thus, the accumulated settlement of the monotonically or cyclically jacked pile is much smaller than that of the pre-jacked pile during force-controlled load cycles.

Additionally, for the monotonically jacked pile, the permanent settlement S_a is influenced by the amplitude of previous displacement-controlled load cycles. S_a of the monotonically jacked pile, previously subjected to ten load cycles with an amplitude of 1.3mm, is 0.24mm, around twice as large as that of the monotonically jacked pile subject to ten load cycles with the amplitude of 0.52mm. Although the load amplitudes of these two piles are similar in load-controlled cycles, it seems that the larger amplitude of cyclic axial loads to which a pile has previously been subjected, the larger is the displacement needed to achieve the same P_{max}, thus the larger is the permanent settlement induced during force-controlled cycles.

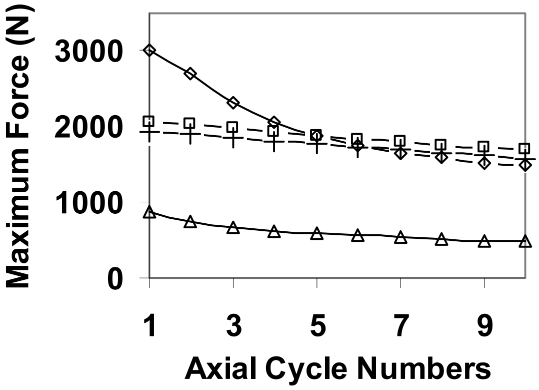


FIG. 3. The pile head maximum axial force.

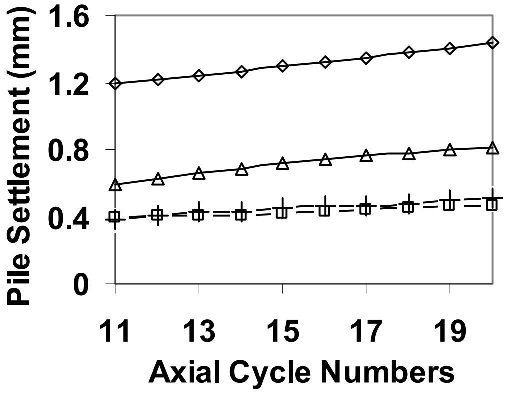


FIG. 4. The pile head settlement.

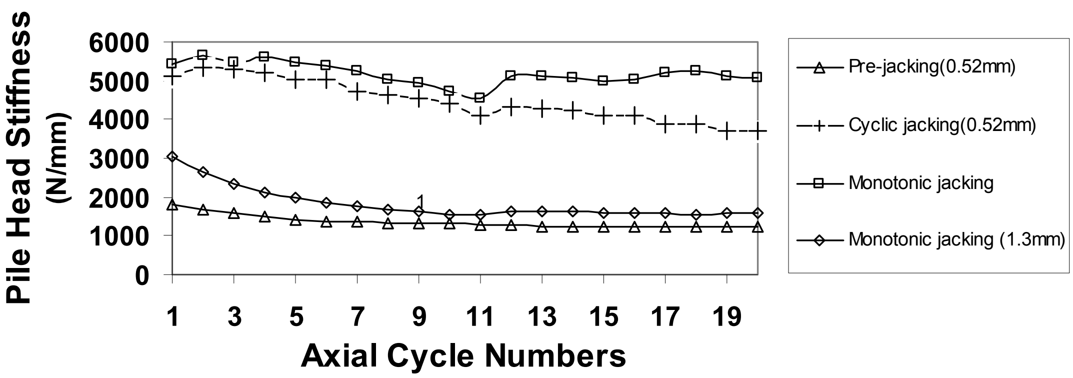


FIG. 5. Pile head axial secant stiffness.

Pile Head Axial Secant Stiffness

FIG 5 presents the pile head axial secant stiffnesses ($K_{s,a}$) obtained in cyclic axial load tests. In displacement-controlled axial load cycles, $K_{s,a}$ decreased with increasing number of axial load cycles; while in the succeeding force-controlled cycles, $K_{s,a}$ decreased very slowly with increasing number of cycles. Under cyclic axial loads with a given amplitude, the stiffness $K_{s,a}$ of the monotonically jacked pile is the largest, followed by the cyclically jacked pile and then the pre-jacked pile. This is because the jacking stroke creates the stiffer base response and higher radial stress along the shaft than the pre-jacked pile. Moreover, for the same type of pile, $K_{s,a}$ reduces with increasing amplitude of cyclic axial load.

CONCLUSION

A series of cyclically loaded axial pile tests was conducted in the beam centrifuge. Different pile installation methods were applied to investigate and compare the axial behaviour of different piles under cyclic loads.

Under displacement-controlled cyclic axial loads, the pile head maximum force (P_{max}) reduces with increasing number of axial load cycles, especially in the first ten cycles, due to the contraction and radial stress reduction of the sand within the shear zone close to the pile-soil interface. The decrement in P_{max} is not influenced by different pile installation methods, but it increases with increasing cyclic axial load amplitude, and the ultimate value of P_{max} is similar for different load amplitudes.

The accumulated displacement of the monotonically or cyclically jacked pile is much smaller than that of the pre-jacked pile during force-controlled load cycles due to the more highly stressed soil created by in-flight installation causing an increased stiffness in the soil surrounding the pile. Also the accumulated displacement increases with increasing load amplitude.

The pile head axial secant stiffness ($K_{s,a}$) of the monotonically jacked pile is the largest, followed by the cyclically jacked pile and then the pre-jacked pile. Also $K_{s,a}$ reduces with increasing cyclic axial load amplitudes.

These results provide a better understanding of the influence of cyclic loads on the performance of piled foundations, and offer an insight to further research to optimise construction methods and designs of piled foundations to resist live loads in service.

ACKNOWLEDGMENTS

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