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The effects of loaded bored piles on existing tunnels

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ABSTRACT: This paper presents the development of a series of centrifuge tests carried out to investigate the effects of loading of bored piles on existing tunnels. The apparatus was designed to monitor the tunnel lining deformation while a live loading was applied. Four facts were considered: rate of loading the pile, pile base level relative to the existing tunnel, the ratio of the depth of clay cover to tunnel diameter, and the distance between the pile and tunnel.

1 INTRODUCTION

High-rise buildings with deep pile foundations are more and more used in the fast developing urban environment. Inevitable disturbance to the ground and surrounding underground structures caused by their construction and subsequent loading may have significant impact in terms of settlement and deformation.

Over the last thirty to forty years, tunnel owners have become concerned about this possibility, and an exclusion zone was introduced to protect the tunnels. However, these guidelines, are mainly based on their empirical correlations from similar projects, and generally apply limits on the minimum distance between the existing tunnels and new pile foundations. (Chudleigh et al. 1999).

Many researchers have summarised the pile-tunnel interaction problems (Schroeder, 2002; Yao et al 2006), which can be categorised into two groups: effects of tunnelling on piles and effects of piling on tunnels, where the second group received less attention. Some field case studies have been presented, which investigated the effect of piling on existing tunnels (Chapman et al, 2001, Higgins et al, 1999, and Benton & Phillips, 1991). Schroeder (2002a, 2002b) also conducted a set of FE analyses to investigate the interaction between pile foundations and existing tunnels. Yao et al (2006) described a series of centrifuge tests designed to investigate the effect of bored pile excavation on existing tunnels.

The effect of bored pile foundations on existing tunnels can be categorised into two parts: pile installation and the post piling period. In this project, the main objective is focused on the post piling period, which is the investigation on the effect of pile loading on existing tunnels.

The paper presents the centrifuge apparatus design, the centrifuge test results and some preliminary analysis of the results. All the tests presented are solely with regards to post piling; the influence of pile excavation is not considered.

2 CENTRIFUGE MODELLING

The apparatus was designed to meet five requirements: the pile could be loaded at anytime, a range of loading rates, the applied load could be recorded, pile settlement could be recorded and the rate of loading could be changed during the test.

2.1 *Model overview*

Figure 1 shows a picture of the model on the centrifuge swing. The centrifuge strongbox is constructed from aluminium with a transparent Perspex window in the front to enable a view of the experiment in progress. A tunnel lining with an internal deflection gauge system installed in the centre of the sample, two rub bags were used to seal the tunnel at the two ends of the tunnel lining (Yao et al, 2006) and a pile loading apparatus was fastened on top of the model container. Druck PDCR81 pore pressure transducers were used to monitor the pore water pressure in the model and air pressure in the tunnel lining system during the centrifuge testing. Digital image processing was used to trace the deformation at the front surface of the model.

All the tests were conducted in the Geotechnical Engineering Research Centre at City University, London. The Acutronic 661 centrifuge with a maximum payload of 200 kg at 200 g and radius of 1.8 m is described in detail by Schofield and Taylor, (1988). All tests presented in this paper were conducted at

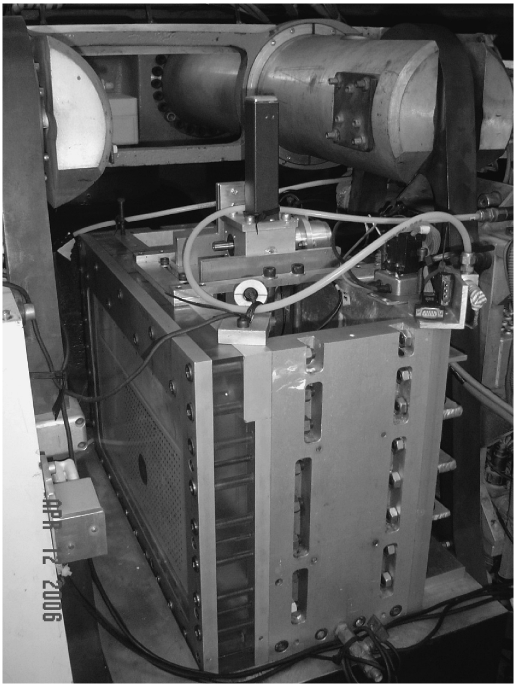

Figure 1. Model on centrifuge swing prier to test.

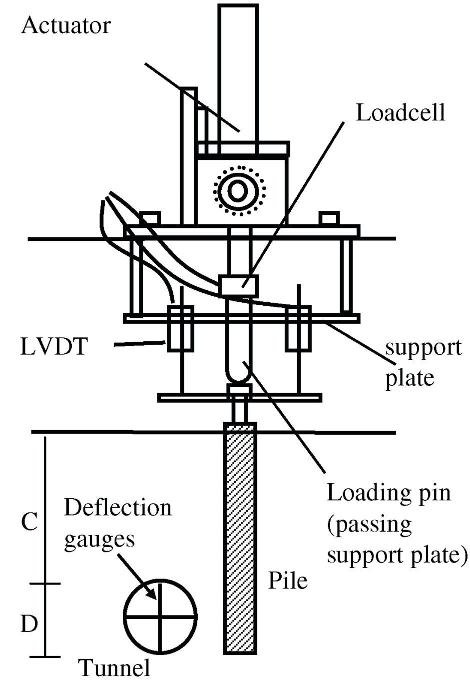

Figure 2. Schematic of the loading unit. C: depth of the cover above tunnel, D: diameter of the tunnel.

an acceleration level of 100 g, according to scaling law (Taylor, 1995), 1 cm in the model equals to 1m at prototype scale. Kaolin clay was used for modelling (Al Tabba, 1987).

2.2 *Pile loading unit*

A pile loading system was designed to load the pre-installed pile during the centrifuge test, and also provide the facilities to measure the settlement of the pile and applied load. Figure 2 shows a schematic of the pile loading unit, which consist a model pile (pre-installed in the model), an actuator, two LVDTs, a load cell, and support units.

For ease of centrifuge operation, the pile was pre-installed into the model during model preparation. Having a pile pre-installed has two important requirements:

– No settlement would occur due to the self weight of pile
– The pile must be strong enough to withstand the applied load

A 22 mm outer diameter, 10 mm internal diameter aluminium tube with two ends sealed was selected as the model pile. Two different lengths were made for different pile base levels and cover to tunnel diameter (C/D) ratios. The model pile was made to have a lower density than the clay sample, so it would not cause any settlements during centrifuge testing without any applied load. As can be seen from Figure 2, a loading pin sitting on top of the pile cap, which had two LVDTs (Linearly variable differential transformers) installed on either of it to monitor the settlement of the pile. The entire loading unit will stop the pile being pushed out due to the lighter density.

The actuator contains a ø35 mm 90 watt motor, RE35-118783, a planetary Gearhead GP 42 C gear box, and an aluminium screw jack, MSZ-Alu. The actuator fitted directly above the pile was supported by a channel unit sitting on top of the strongbox as can be seen from Figures 1 and 2. The loading pin was attached to it, to apply the load to the pile. A load cell was used to monitor the load applied to the pile. It was mounted between the loading pin and the screw jack.

2.3 *Deflection gauge tunnel system*

Figure 3 shows the cross section of the model in plan, which has similar layout to the pile excavation tests carried out by Yao et al (2006). The tunnel diameter was 50 mm with the thickness of 0.15 mm, and was made of carbon fibre. A 16 mm diameter titanium tube was used to support the tunnel unit and provide the pathway for all the wires and cables. The tunnel was sealed by two air-pressurised rubber bags at the two ends. Tunnel lining deformation detector was attached to it.

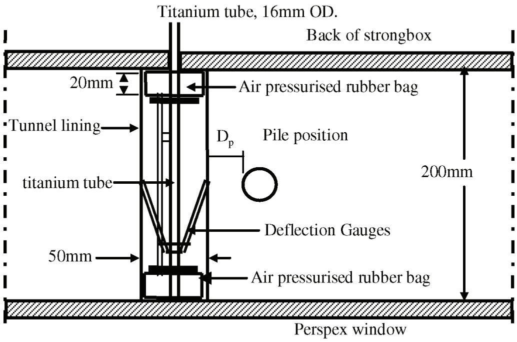

Figure 3. Cross section of the model, showing the deflection gauges and pile borehole(s). D_p is applied pile-tunnel spacing during test (22 or 44 mm).

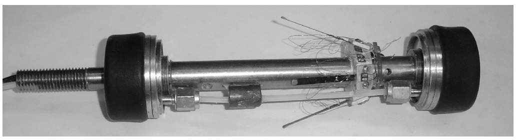

Figure 4. Assembled deflection gauges system.

Figure 4 shows the deflection detector unit developed by Yao et al (2006). That was made of four deflection gauges, which were calibrated strain gauged carbon fibre cantilevers, and their output was recorded via an onboard PC. In order to measure both inward and outward deformation, the deflection gauges were given a 4 mm pre-deformation.

2.4 *Other equipment*

Strongbox: The centrifuge model was set up within an aluminium alloy strongbox, which had an inner plan area of 550 mm × 200 mm, and can contain a solid model up to 300 mm high, a 80 mm width Perspex window at the front to enable the model to be viewed during the test.

Water was supplied from a stand-pipe sitting on the centrifuge swing, and the pore pressure in the clay model was monitored using pore pressure transducers pre-installed into the sample before the test. Details of this equipment have been well discussed by a number of researchers at City University, London. (Taylor et al, 1998, McNamara, 2001).

A pile cutter set was used to excavate the bore hole for the model pile. The cutter was made of 22 mm stainless steel thin walled tube.

2.5 *Sample preparation and test procedure*

Kaolin slurry with a water content of 120% was poured into the strongbox, which had a 3 mm thick porous plastic sheet with a 0.5 mm thick filter paper in the bottom. The strongbox was transferred into a consolidation press, and loaded up to a vertical effective stress of 500 kPa. Upon completion of normal consolidation it was swelled back to 250 kPa. The bulk unit weight of the kaolin was about 17.44 kN/m^3. A de-aired and calibrated pore pressure transducer was installed into the sample after the swelling period.

A typical sample set-up and test procedure consisted of the following steps:

- Free water at the top of the model was removed after closing the drainage taps closed at the base of the strongbox; this was to avoid clay swelling back.
- The applied vertical stress was reduced to zero and the strongbox removed from the consolidation press.
- The front wall was removed, so the front surface of the Kaolin sample could be cleaned to ensure a better image process, and the top of the sample was trimmed to the required height.
- Tunnel was cut and pre-assembled tunnel unit was installed into the model.
- Marker beads for image processing were pushed into the sample front surface on a 10 mm grid.
- The Perspex window was then bolted onto the strongbox.
- The pile shaft hole was excavated and pile was pre-installed into the model.
- The pile loading unit was mounted on top of the strongbox; loading pin was driven down to the pile cap.
- The strongbox was weighed and placed on centrifuge swing.
- The model was accelerated to 100 g on the centrifuge, and left over night to reach the pore pressure equilibrium.
- Air pressure in the rubber bags at the ends of the tunnel was reduced
- Load applied to the pile using the actuator.

The tunnel lining deformations, pore pressure in the model, load applied, pile settlements and air pressure in the rubber bags, were monitored and data stored on the computer in the control room. Global movement around the tunnel was measured using the image processing system. However, the results of digital image analysis will not be discussed in this paper.

3 TEST RESULTS AND DISCUSSION

Eight tests were carried out, of which 2 were trial tests used to commission and improve the apparatus. Table 1 summarises all the tests:

- Pile was installed at two different tunnel-pile clear spacing: 22 mm and 44 mm.
- Two different C/D ratios were used: 2 and 3.
- Pile base was installed at two different levels relative to the tunnel position: tunnel crown level and invert level.
- Only a single pile was tested.

Table 1. Table of tests.

Test ID	C/D	Pile Length	Pile base	Spacing
JY13	2	100 mm	Crown	2.2
JY14	2	100 mm	Crown	2.2
JY15	2	150 mm	Invert	4.4
JY16	2	100 mm	Crown	2.2
JY17	2	150 mm	Invert	2.2
JY18	2	100 mm	Crown	4.4
JY19	3	150 mm	Crown	2.2
JY20	3	150 mm	Crown	4.4

*Spacing is the minimum distance between the outsides of the tunnel and pile (m in prototype scale).

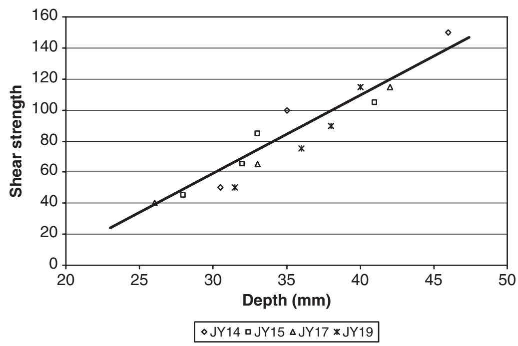

Figure 5. Undrained shear strength measured against depth in model.

All the data presented in the paper are intended to demonstrate the design of this research and the basic data obtained from the centrifuge test.

3.1 *Rate of loading the pile*

The main purpose of two initial trial tests was to testify the loading unit and to determine the best rate at which to load the pile.

Burland et al (1966) produced a simple method to predict the load/settlement curve. It is assumed that the curve is linear up to full mobilisation with takes place at a settlement of about 0.5% of the shaft diameter. Brown et al (2002) presented a series of Statnamic tests to investigate the influence of loading rate on pile behaviour in clay. The pile bearing capacity was found to be particularly sensitive to pile deformation rate. Dayal & Allen (1975) found the similar response. Frischmann & Fleming (1962) stated that the recorded settlement was largely elastic. All settlement was assumed to be as a direct result of shear strains. Skempton (1951) presented the similar result:

$$\rho_s = \frac{p_s \cdot \ln(\frac{r_m}{r_o})}{2 \cdot \pi \cdot L \cdot G_{ave}}$$

where: ρ_s = shaft settlement, p_s = load applied to pile shaft-soil interface, L = effective length of pile shaft, G_{ave} = mean shear modulus of soil along pile shaft, r_m = radius from pile at which strain becomes negligible (Randolph & Wroth, 1978) and r_o = pile radius. Whitaker & Cooke (1966) stated that when the settlement is about 0.5 per cent of the shaft diameter, the pile shaft frictional resistance develops rapidly and linearly with the settlement.

The speed of pile displacement also affects the pore pressure at the base of the pile, which can be understood as on increase in magnitude of excess pore pressure with increasing penetration rate (Brown et al, 2002). The rate of loading used in the centrifuge tests were designed to create undrained conditions. The loading speed of 2 mm per minute was selected on the basis of the trial tests.

The ultimate load of a pile can be defined as either the load at which the pile settlement continues to increase without further increase of resistance, or the load at which pile settlement reaches 10% of the pile base diameter (Fleming et al, 1992). For most soil conditions, the second category is more likely to be the controlling factor for end bearing resistance (Burland et al, 1966). In this research, the ultimate load is defined as the load which causes a settlement of 10% of pile foundation base diameter. The ultimate load capacity of piles can be estimated in terms of undrained strength (S_u), in this research measured from quick undrained tests direct taken after the test, and undrained pile shaft adhesion factor, which was chosen as 0.6 in this paper. Figure 5 shows the measured undrained shear strength again depth directly taken after four tests.

Figure 6 shows the recorded load applied in the test JY16. Half of the maximum calculated load reached as soon as the load applied, then increased more gradually towards the maximum. The load only achieved 85% of the designed ultimate load. Applying the factor of safety of 1.5 to 2, the achieved load was acceptable for our research purposes.

3.2 *Tunnel lining deformations*

Tables 2 and 3 summarise the maximum deformations measured by the deflection gauges for tests JY13 to JY20, and positive values indicate movement towards the tunnel centre. During the pile excavation test carried out by Yao et al 2006, the tunnel crown was subjected to the greatest deformations for all cases, and moved towards the tunnel centre, but there was less effect at tunnel invert. As it can be seen, while the pile was under load, the crown was still affected the

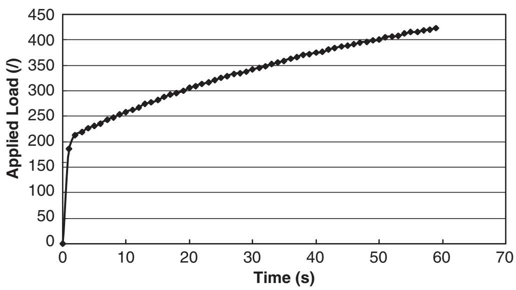

Figure 6. The recorded increasing of load against time.

Table 2. Summary of maximum tunnel lining deformations recorded during pile loading period (mm at prototype scale).

ID	Crown	Left	Right	Invert
JY15	11	−1	2	−8
JY16	18	−1	2	−12
JY17	22	−2	3	−19
JY18	10	−1	1	−9
JY19	24	−3	4	−18
JY20	16	−2	3	−14

Table 3. Summary of maximum deformations in percentage: deformation over tunnel diameter (δ/D).

ID	Crown	Left	Right	Invert
JY15	0.22	−0.02	0.04	−0.16
JY16	0.36	−0.02	0.04	−0.24
JY17	0.44	−0.04	0.06	−0.38
JY18	0.2	−0.02	0.02	−0.18
JY19	0.48	−0.06	0.08	−0.36
JY20	0.32	−0.04	0.06	−0.28

most, followed in turn by the invert, the right side and the left side of the tunnel. (The right side of the lining is the nearest site to the pile). Both right and left sides were always moved away from the pile.

Figure 7 shows the recorded tunnel lining deformation for test JY16. It can be seen that the tunnel lining did not start to move until the load reached half of its maximum. Together with Figure 6, it shows the relationship between the applied load, pile settlement and tunnel lining deformation. Similar results were found for most of the tests.

Figure 8 shows the relationship between applied load and pile settlements. The pile did not start to move until the load achieved half of its maximum.

Table 4 lists the change of diameter of the tunnel lining in the vertical and horizontal directions. Figure 9 shows the relationship between the tunnel lining deformation and pile-tunnel clear spacing and Figure 10

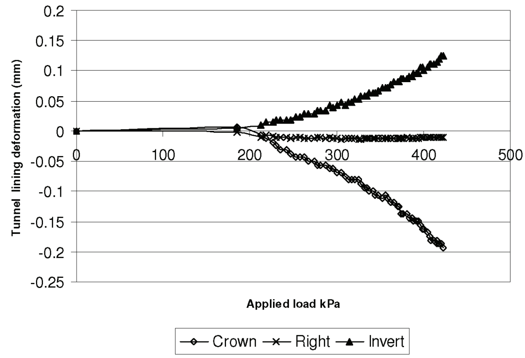

Figure 7. The tunnel lining deformations against the applied load. In all cases, positive values indicate movement towards tunnel centre, deformations at model scale, for test JY16.

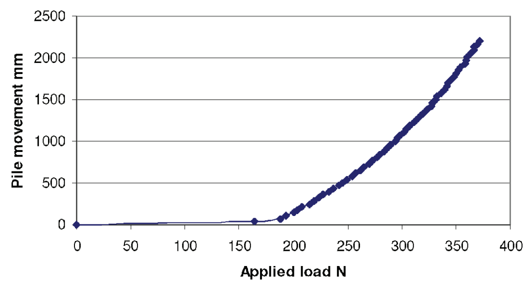

Figure 8. Applied loads against pile settlements, for test JY16.

Table 4. Change of tunnel diameter and tunnel centre position (in prototype).

ID	δv	$\delta v/D$	δh	$\delta h/D$	Cv	Ch
JY15	3	0.06	1	0.02	9.5	−1.5
JY16	6	0.12	1	0.02	15	−1.5
JY17	3	0.06	1	0.02	20.5	−2.5
JY18	1	0.02	0	0	9.5	−1
JY19	6	0.12	1	0.02	21	−3.5
JY20	2	0.04	1	0.02	15	−2.5

δ_v and δ_h: Change of tunnel diameter at vertical/ horizontal direction (mm); C_v and C_h: Change of tunnel centre position at vertical/ horizontal direction (mm), C_v move towards pile opening and C_h move downward.

presents the relationship between the lining deformation and pile base position. It can be seen from changes of the diameter, that deformation of the tunnel lining is non-uniform. The changes of the tunnel centre position in the vertical and horizontal direction are also summarised in Table 4. Figure 11 shows the change in positions of the tunnel centre for each case. Both crown and invert were subjected to significant impact for test JY17 and JY19 where long pile with larger C/D ratio

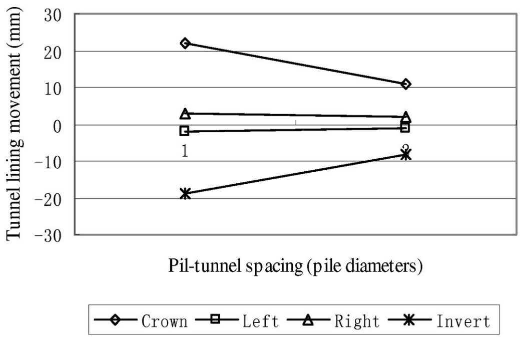

Figure 9. The change of movement due to change of the pile-tunnel clear spacing(C/D = 2).

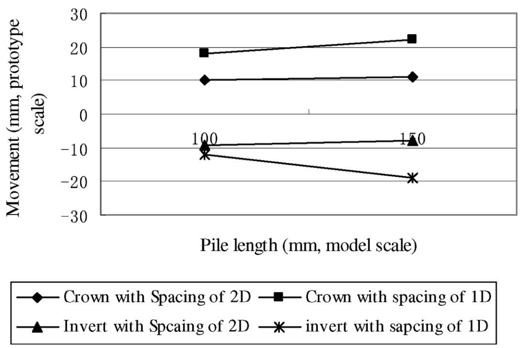

Figure 10. The change of movement due to change of pile base position (C/D = 2).

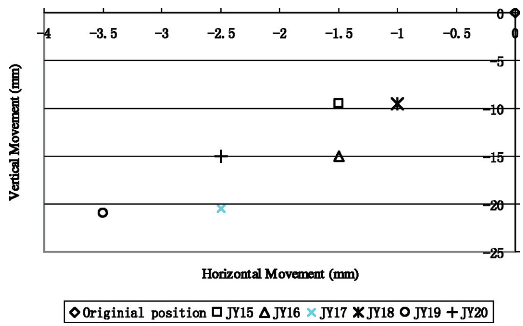

Figure 11. The positions of tunnel centre for all cases. Movement on X axis is towards pile opening, movement on Y axis is towards the bottom of the strongbox.

was used. Movements up to 0.48% of tunnel diameter were recorded on the crown when the long pile was installed together with deeper cover. For the same C/D ratio and tunnel-pile clear spacing, in test JY16 and JY17 a movement of 0.08% of the tunnel diameter was recorded for the longer pile. Summarizing the tables and the figures, it can be see that in general, as clear space increased, the deformation reduced; the deeper the pile bases level or the longer the pile length, the more the effect of the pile at the tunnel.

4 CONCLUSIONS

This paper presents a study of the influence of pile loading on an existing tunnel, which is a part of a research on the effect of bored pile installation and subsequent loading on an existing tunnel. The design of the model and preliminary analysis of the results were presented.

Based on the literature review and the centrifuge model tests, the following observations were made.

– By reviewing previous research and based on two trial tests, the rate of the loading was chosen as 2 mm per minute. The trial tests also confirmed that increasing in the rate of loading will increase the load achieved on the pile.
– Pile settlement has a linear relationship with increasing of the applied load once the load exceeds half of the maximum designed ultimate load.
– Tunnel lining response to the pile movement as observed from the results shows that the tunnel centre always move downwards and away from the pile.
– Increasing the pile-tunnel clear spacing will reduce the deformation of the tunnel lining.
– Using the long length pile will have more effect on the tunnel lining regardless of the C/D ratio.
– Tunnel crown is always subject to significant movement due to either pile excavation (Yao et al, 2006) or pile loading. Tunnel invert affected more from pile loading than pile excavation.

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