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Three-dimensional centrifuge modelling of the effects of twin tunnelling on an existing pile

C.W.W. Ng, H. Lu *, S.Y. Peng

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

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ABSTRACT

Tunnelling activity inevitably induces soil stress changes and ground deformation, which may affect nearby existing pile foundations. Although a number of studies have been carried out to investigate the effects of tunnelling on existing piles, the excavation of only one tunnel is often considered. The fundamental interaction between twin tunnel construction and an existing pile foundation has not been thoroughly studied. In this study, a series of three-dimensional centrifuge model tests investigating the effects of twin tunnel construction on an existing single pile in dry sand were conducted. The influence of the depth of each tunnel relative to the pile was investigated by constructing the twin tunnels either close to the mid-depth of the pile shaft or near the pile toe. The pile settlement induced by the excavation of the twin tunnels is found to be closely related to the depth of each tunnel relative to the pile. The measured cumulative pile settlement due to tunnelling near the toe is about 2.2 times of that due to tunnelling near the mid-depth of the pile shaft. Apparent losses of pile capacity of 36% and 20% are identified due to the construction of twin tunnels near the pile toe and at the mid-depth of the pile, respectively. Although there is an increase in the axial force induced in the pile when a tunnel is constructed at the mid-depth of the pile, significant increases in bending moment is not observed in any of the tests.

1. Introduction

Tunnel construction inevitably causes soil stress changes in the ground and hence induces ground movements. Uncontrolled ground movements induced by tunnelling may cause cracking in buildings and gas mains, or induce additional loads on piles of nearby structures. In urban cities, it is not uncommon to encounter existing piles during tunnel constructions. Estimation of the effects of tunnelling on existing pile foundations of buildings poses a major challenge to designers. It is particularly vital to estimate the tunnelling effects when two new tunnels are to be built near an existing pile.

Bezuijen and Schrier (1994) studied the influence of bored tunnels on pile foundations. They pointed out that the pile settlement can be quite significant if the distance between pile and tunnel is less than the tunnel diameter. Loganathan et al. (2000) assessed tunnelling-induced ground deformations and their adverse effects on pile foundations in clay. Tunnelling-induced bending moment and axial force in the piles of a pile group were investigated by modelling volume loss of a tunnel in a single stage. They concluded that the tunnelling-induced bending moment may be critical when the centerline of the tunnel is located near the pile toe. Jacobsz et al. (2004) investigated the adverse effects of tunnelling beneath a pile in dry sand. An influence zone was identified above and around the tunnel in which the pile could suffer significant settlement, depending on the volume loss induced by the tunnelling. Lee and Chiang (2007) studied the tunnelling-induced bending moment and axial force in a single pile in saturated sand. Tunnels were embedded at various cover-to-diameter ratios. The authors concluded that the depth of the tunnel relative to the pile has a significant influence on the distribution of the bending moment along the pile. As far as the authors are aware, the three-dimensional centrifuge modelling of the effects of twin tunnelling on a single pile has not been reported.

Mroueh and Shahrour (2002) carried out three-dimensional elastoplastic finite element analyses to study the influence of a tunnel construction on a single pile as well as on pile groups. The numerical results showed that there is a significant reduction in the tunnelling-induced axial force and bending moment in the piles furthest away from the tunnel due to the group effect. Lee and Ng (2005) carried out a three-dimensional, elasto-plastic, coupled-consolidation numerical analysis to investigate the effects of an open face tunnel excavation on an existing loaded pile. It is shown that the factor of safety (FOS) of a pile can be reduced from 3.0 to 1.5 due to the additional settlement of a pile induced by tunnelling when a settlement-based failure criterion (Ng et al., 2001a) is used.

* Corresponding author. Tel.: +852 5104 8252; fax: +852 2243 0040.
E-mail addresses: cecwwng@ust.hk (C.W.W. Ng), luhu@ust.hk (H. Lu), muffinpp@ust.hk (S.Y. Peng).

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The effects of tunnel construction on the nearby pile foundations are obviously three dimensional. A fundamental understanding of the three-dimensional tunnel-soil-pile interaction is needed. In addition, few researchers have investigated the effects of twin tunnelling on piles, except Pang (2007), who reported the field monitoring and numerical study of the effects of twin tunnelling on an adjacent pile foundation in Singapore. A northbound tunnel and a southbound tunnel were constructed near piles one after the other. The smallest clear distance between the tunnels and piles was 1.6 m. Results of the field study showed that the piles were subjected to a large dragload due to an induced soil settlement in residual soil. However, strain gauges are only instrumented along pile portion near tunnels. The pile settlement due to tunnelling is not reported.

In this study, a series of three-dimensional centrifuge model tests were performed to investigate the behavior of a single pile due to the construction of twin tunnels one after the other. The effects of the three-dimensional tunnel excavation process were simulated in-flight by controlling the volume loss at 1.0% in each stage of the three-dimensional excavation of each tunnel. The twin tunnels in each test are located at either mid-depth of the pile or the pile toe. In addition to measurements of ground surface settlement and pile settlement, the bending moment and axial force induced in the pile by the tunnelling in different stages of construction were captured. The objective of this study is to investigate the response of an existing pile when a new tunnel excavation is to be carried out nearby. It is intended that results from this study can assist engineers and designers to choose and design the location (i.e., the depth) of the new tunnel.

2. Centrifuge modelling

2.1. Experimental program and setup

The fundamental principle of centrifuge modelling is to recreate the stress conditions, which would exist in a full-scale problem, in a model of a greatly reduced scale. This is done by subjecting model components to an enhanced body force, which is provided by centripetal acceleration ($r\omega^2$) when a centrifuge rotates at a constant angular velocity (ω) about the center of the centrifuge arm with radius, r. For instance, an 100 m prototype stress conditions can be replicated in a centrifuge by an 1 m height model when the Earth's gravity (g) is enhanced by 100 times (i.e., $r\omega^2 = Ng = 100g$). Thus, centrifuge is suitable for simulating stress-dependent materials such as soils. More details, scaling laws and centrifuge applications are given by Schofield (1980), Taylor (1995) and Ng et al. (2006). Table 1 summarizes all the relevant scale laws in this study.

In total, four centrifuge model tests were carried out at the Geotechnical Centrifuge Facility of the Hong Kong University of Science and Technology (Ng et al., 2001b, 2002). The 400g ton centrifuge has an arm radius of 4.2 m and is equipped with a two-dimensional hydraulic shaking table and a four-axis robotic manipulator. All of the centrifuge tests were carried out at an acceleration of 40g.

Table 1
Centrifuge scaling factor.

Physical quantity	Scaling factor (model/prototype)
Gravitational acceleration	n
Length	$1/n$
Area	$1/n^2$
Volume	$1/n^3$
Settlement	n
Stress	1
Strain	1
Force	$1/n^2$
Density	1
Mass	$1/n^3$
Flexural stiffness	$1/n^4$
Bending moment	$1/n^3$

Fig. 1a shows the schematic elevation view of Test T. A single pile is located at the center of each model container. Test T is designed to investigate the behavior of a pile due to a single tunnel constructed near pile toe in dry sand. The model pile had a diameter of 20 mm (0.8 m in prototype) and was 600 mm long (24.0 m in prototype). The pile cap was elevated by 110 mm and therefore the embedded depth of each pile was 490 mm (19.6 m in prototype). The tunnel diameter (D) was 152 mm (6.08 m in prototype). The C/D ratio (cover-to-diameter ratio) of the tunnel is 2.7. The horizontal distance from the centerline of the tunnel to the pile was 0.75D. In addition, a separate test (Test L) is carried out to obtain the load settlement curve of the single pile without tunnelling effects. This test has the same configuration of Test T but only without the model tunnel.

As shown in Fig. 1b, Test TT was designed to study the effects on the pile induced by the construction of twin tunnels, one after the other, near the pile toe. The C/D ratio of each tunnel is 2.7, same as that in Test T. Fig. 1c shows the schematic elevation view of Test SS. This test was designed to investigate pile responses induced by the construction of twin tunnels near the mid-depth of pile shaft. The C/D ratio of each tunnel is 1.5. A summary of the test program is given in Table 2.

Fig. 2a and b shows the plan views for Test T and Tests TT and SS, respectively. In Test T, the model tunnel had a length of 228 mm, which was equal to 1.5D. The three-dimensional tunnel construction was simulated in three stages, with the tunnel face advancing by a distance of 0.5D in each stage. In Tests TT and SS, the longitudinal length of each tunnel was 380 mm, which was equivalent to 2.5D. The tunnel excavation was simulated in five stages, again with the tunnel face advancing by a distance of 0.5D in each stage. A photograph of the model package is shown in Fig. 3a.

2.2. Simulation of tunnel construction

In simulating of tunnel advancement, it is common to model overall volume loss resulting from tunnelling effects in practice (Taylor, 1995; Mair, 2008), rather than trying to simulate different construction steps in centrifuge. Obviously, this implies that some construction details like erection and deformation of tunnel liners, stiffness of liners and workmanship are not simulated separately. Only the overall result like volume loss due to actual tunnelling is simulated. Obviously, this type of modelling is not ideal. However, it does capture the essential effects (i.e., volume loss) of tunnelling and can meet the comparative objective of different simulated cases in this paper.

In the single tunnel test, the model tunnel consisted of three cylindrical rubber bags. In the twin tunnel tests, each model tunnel consisted of five cylindrical rubber bags (see Fig. 3b). Between two rubber bags was a rigid aluminum divider to control and separate the volumes of water inside so that volume change in each rubber (i.e., the tunnel volume loss) can be controlled independently. Each rubber bag was filled with de-aired water. Three-dimensional tunnel construction was simulated in-flight by draining away a controlled amount of water from each rubber bag one by one. The amount of water drained away was controlled as 1.0% of the total volume of the cylindrical rubber bag. This is to simulate an equivalent volume loss of 1.0% of excavated cross section area of the tunnel face during each stage of tunnel construction. Since the effects of tunnel excavation were modelled by inducing an equivalent volume loss resulting from various construction factors and tunnel