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Three-dimensional centrifuge modelling of pile group responses to side-by-side twin tunnelling

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ABSTRACT

Development of underground transportation systems inevitably involves tunnels, which may have to be constructed in close proximity to existing piles and pile groups in densely built areas. Since many previous studies mainly focus on the responses of single piles subjected to single tunnelling, the effects of twin tunnelling on pile groups are not well investigated and understood. In this study, a series of three-dimensional centrifuge tests were carried out to investigate the response of a pile group under a working load subjected to the advancement of twin tunnels in dry sand. Side-by-side twin tunnels (excavated one after the other on both sides of the pile group) were simulated in-flight by controlling 1% volume loss at three critical locations relative to the pile group, namely near the mid-depth of pile shaft (Test SS), next to (Test TT), and below the toe of the pile group (Test BB). In addition, an in-flight pile load test was carried out to determine the pile group capacity. Among the three tunnelling tests, twin tunnelling below the pile toe (Test BB) caused the largest settlement of the pile group (2.4% of pile diameter), resulting in an apparent loss of capacity of 40%. On the other hand, the largest induced transverse tilting of the pile cap of 0.2% reached the limit suggested by Eurocode 7 and the most significant bending moment exceeded the ultimate capacity by 6% were measured near the pile head due to the advancement of the first tunnel near the pile toe. In spite of the severely bending moments induced by tunnelling, no more than 15% increase in axial force was observed in piles in all the tests.

1. Introduction

The rapidly increasing demand for underground transportation systems in urban areas has been driving the construction of tunnels, which are possibly excavated adjacent to existing piles. The effects of tunnelling on piled foundations have received particular attention recently, and has been investigated numerically or analytically by a number of researchers (Chen et al., 1999; Mroueh and Shahrour, 2002; Lee, 2004; Kitiyodom et al., 2005; Lee and Ng, 2005; Cheng et al., 2007; Huang et al., 2009; Lee et al., 2010; Devriendt and Williamson, 2011; Lee, 2012). In addition, some centrifuge model tests have also been carried out to study the responses of pile foundations due to single tunnelling (Bezuijen and Van der Schrier, 1994; Loganathan et al., 2000; Jacobsz et al., 2004; Lee and Chiang, 2007). In the centrifuge tests reported by Loganathan et al. (2000), they investigated the responses of an axially loaded (working load = 4.55 MN in prototype) 2×2 pile group in stiff clay subjected to the excavation of 6 m diameter single tunnel near the mid-depth of the pile shaft and next to the toe of the pile group. The diameter and length of each pile was 0.8 m and 18 m, respectively. Their test results revealed that tunnelling adjacent to existing pile foundations resulted in additional loading and deformation of the piles. The pile responses were found to be mainly governed by the locations of the tunnel relative to the pile. However, the effects of twin tunnelling on piled foundations have not been the focus of the above studies.

In fact, twin tunnelling is particularly favoured when developing underground transportation systems all over the world (Hu et al., 2003; Pang et al., 2005; Selemetas, 2005; Ng et al., 2012; Ng and Lu, 2014). Ng et al. (2013a) carried out centrifuge tests for twin tunnelling effects on an existing single pile in dry sand. Side-by-side twin tunnels were simulated in-flight, either next to, or below the pile toe. It was concluded that due to twin tunnelling, no significant bending moment was induced in both cases (i.e., no more than 17% of its bending moment capacity). In addition, the twin tunnelling resulted in a maximum increase of axial

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force in the single pile by 27%, due to load transfer within the pile. Nevertheless, these conclusions are not thought to be applicable to pile groups subjected to twin tunnelling. Significant bending moments may be induced near pile heads when the rigid pile cap tilts due to tunnelling. Regarding axial force in a pile group, load transfer occurs not only within a pile, but also among piles. Clearly, tunnelling induced change of axial force in a single pile would be different from that in a pile group.

As far as the authors are aware, the subject of twin tunnelling effects on an existing pile group has only been explored by Pang et al. (2005), based on a metro project in Singapore (i.e., North-East Line Contract 704). Fig. 1 illustrates a typical sectional view of the project, where side-by-side twin tunnels were constructed adjacent to an existing pile group. In this case history, field measurements only include axial load and bending moment along a limited portion of the pile shafts. Bending moment near the pile head, which might be the most critical (Loganathan et al., 2000), remain unknown. Other important pile responses, such as settlement and tilting of the pile group, were also not reported.

To obtain fundamental understanding of three-dimensional twin tunnelling effects on a pile group and to provide comprehensive and reliable physical data for numerical modellers to validate their analyses, we carried out a series of centrifuge tests. The test series consisted of one pile group load test in a "greenfield" site and three other tests with side-by-side tunnels constructed at three critical locations relative to an existing pile group (under working load). Measurements in the centrifuge tests include settlement and transverse tilting of the pile group, axial load and transverse bending moment in each pile at various tunnelling stages.

2. Centrifuge modelling

2.1. Experimental programme and setup

It is well recognised that soil behaviour is stress-dependent. Therefore, any physical model tests involving soils without correctly modelling the stress state and stress path will likely produce misleading or incorrect results. In geotechnical centrifuge tests, a proper stress field can be recreated in a small scale soil model, by increasing its gravitational acceleration. In centrifuge modelling, the relationship between a model and a prototype is generally derived through dimensional analysis, from the governing equations for a phenomenon, or from the principles of mechanical similarity. Scale factors (between prototype and model scale) relevant to this study are summarised in Table 1.

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; Ng et al., 2002; Ng, 2014). The 400 g-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 centrifuge tests reported herein were carried out at a centrifugal acceleration of 40 g (where g is the acceleration due to Earth gravity).

Fig. 2a shows the elevation view of the Test SS, which is intended to investigate the responses of a pile group due to twin tunnelling one after another near the mid-depth of pile shaft. The diameter of each model tunnel (D) is 152 mm (6 m in prototype). Cover-to-diameter ratios (C/D) of the tunnels are 1.5. The horizontal distance from the centerline of the tunnel to the nearest pile is 0.75D.

Fig. 2b and c shows the elevation view of Tests TT and BB, respectively. In these two tests, twin tunnelling was carried out near and below the toe of the pile group in test TT (i.e., $C/D = 2.7$) and BB (i.e., $C/D = 3.7$), respectively.

Fig. 3a illustrates the plan view of a typical centrifuge test. The length of each model tunnel (along its longitudinal direction) is 2.5D, which is equivalent to 380 mm. Each tunnel consists of five construction stages, with the tunnel face advancing a distance of 0.5D in each stage. A monitoring section is selected at the transverse centreline of the pile group (i.e., $y/D = 0$) for tunnel advancement reference.

In addition to the three tests described above, an in-flight pile group load test (Test L) is carried out to obtain the load settlement

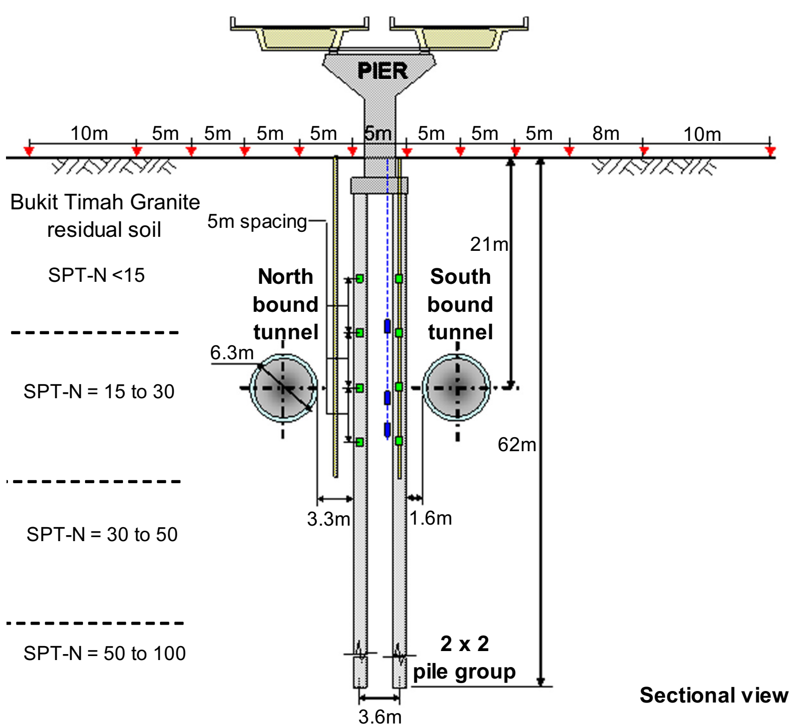

Fig. 1. A sectional view showing an existing pile group subjected to side-by-side twin tunnelling in Singapore (Pang et al., 2005).