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Investigation of effects of different construction sequences on settlement and load transfer mechanism of single pile due to twin stacked tunnelling

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ABSTRACT

Construction of tunnels in urban cities may induce excessive settlement and tilting of nearby existing pile foundations. Various studies reported in the literature have investigated the tunnel-soil-pile interaction by means of field monitoring, centrifuge and numerical modelling, but the influence of construction sequence of twin stacked tunnelling on an existing pile is seldom reported in the literature. This paper presents a 3D coupled-consolidation numerical parametric analysis to understand settlement and load transfer mechanism in single pile due to twin stacked tunnelling with different construction sequences in stiff saturated clay. To accurately capture the tunnelling induced ground deformation, path- and strain-dependent soil stiffness at small strains were taken into account in each numerical analysis, by adopting an advanced hypoplastic clay model coupled with the intergranular strain formulation. Twin stacked tunnelling was simulated one after the other with the first tunnel excavated near the mid-depth of the pile shift and the second either next to the toe of the pile (case ST) or below the pile (case SB). In addition, two more analyses were performed with change of construction sequence of twin stacked tunnels (i.e. cases TS and BS). The first tunnel was excavated either near the pile toe (case TS) or below the pile (case BS) and second tunnel near the mid-depth of the pile shaft. The different construction sequence of twin stacked tunnels at different depth had a substantial effect on induced pile deflection and settlement. In contrast, no significant effect was found on load transfer mechanism in the pile due to the change in construction sequence of tunnels.

1. Introduction

It is well-known fact that a pile supports the load of superstructure by transferring it to the ground resulting in generation of stresses surrounding the pile. On the contrary, tunnelling is a stress relief process which results in ground movements (which propagate through the soil to the ground surface) around the tunnel (Shi et al., 2019a). The expansion of cities and urban areas is resulting in an increased demand for environmentally and economically sustainable transport and services infrastructure (e.g. water, waste, etc.). Underground construction and infrastructure that often require the excavation of tunnels represent an ideal solution to satisfy these needs. However, tunnel construction is increasingly taking place in close proximity to buried and surface structures.

To understand the pile–soil–tunnel interaction mechanism, many researchers have conducted field monitoring studies and centrifuge model tests (Jacobsz et al., 2004; Marshall and Mair, 2011; Franza and Marshall, 2017a; Franza and Marshall, 2017b; Franza and Marshall, 2018; Lee and Chiang, 2007; Coutts and Wang, 2000; Dias and Bezuijen, 2015; Ng et al., 2014; Ng et al., 2015; Pang et al., 2005; Selemetas, 2005; Loganathan et al., 2000; Boonyarak et al., 2014). Moreover, Franza and Marshall (2018, 2019) conducted a series of centrifuge experiments designed to simulate the effect of excavating a tunnel beneath piled structures in dry sand. The measured results illustrate that pile settlement and failure mechanisms are highly dependent on the pre-tunnelling loads and the load redistribution that occurs between piles during tunnel volume loss, which are related to structure weight and stiffness. Moreover, this problem has also been studied by proposing analytical solutions and numerical modelling by some researchers (Marshall, 2012; Marshall and Haji, 2015; Franza et al., 2017c; Soomro et al., 2015; Soomro et al., 2017; Mroueh and Shahrour, 2002; Loganathan et al., 2001; Lee and Ng, 2005; Lee, 2012a; Lee,

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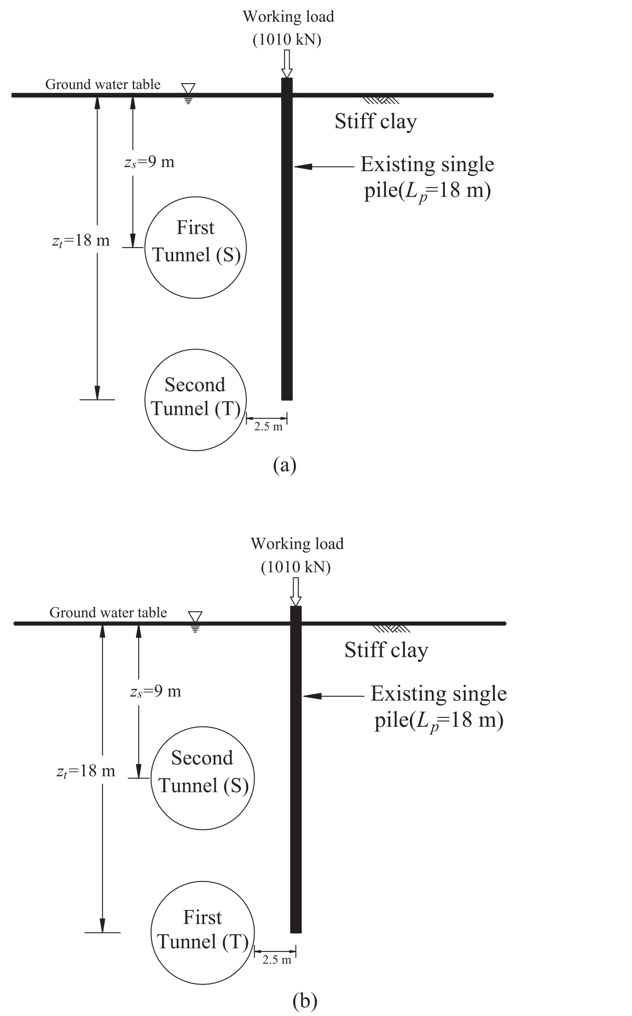
2012b; Lee, 2013; Huang et al., 2009; Zhang et al., 2011; Hong et al., 2015a; Shi et al., 2019b). They all concluded that tunnelling adjacent to existing pile foundations caused pile settlement, additional axial load on piles and induced bending moments along piles, which is unfavourable for piled foundations and their magnitudes depend upon the relative locations of tunnels and piles. However, most previous studies have focused on the effects of a single tunnel on single piles and pile groups in dry sand. In fact, twin tunnelling is particularly favoured across the world when developing underground transportation systems (Pang et al., 2005). To further explore twin tunnelling effects on an existing single pile and a pile group in dry sand, some centrifuge model tests and back-analysis of the tests were also carried out at the Hong Kong University of Science and Technology (Ng and Lu, 2013; Ng et al, 2013). Side-by-side twin tunnels were simulated in-flight, either adjacent to or below the pile toe. The existing single pile and pile group stood between the twin tunnels, which were excavated one after the other. It was concluded that owing to twin tunnelling, no significant bending moment was induced in either case (i.e., no more than 17% of the pile bending moment capacity). In addition, the twin tunnelling resulted in a maximum increase in axial force in the single pile by 27%, due to load transfer within the pile. Furthermore, the second tunnelling reversed the tilting of the existing pile group caused by the first tunnelling. Moreover, Ng and Lu (2013) carried out a series of three-dimensional centrifuge model tests and numerical back-analyses to investigate the effects of construction sequence of twin tunnels on an existing pile in dry sand. Two tunnelling sequences were investigated: (*i*) a sequence involving tunnelling near the pile toe followed by tunnelling near the mid-depth of the pile shaft (i.e., test TS); (*ii*) sequence involving tunnelling near the mid-depth of the pile shaft followed by tunnelling near the pile toe (i.e., test ST). The measured cumulative pile settlement was about 33% greater for tunnelling sequence ST than for tunnelling sequence TS. They used simplified elasto-plastic model with Mohr-Coulomb failure criterion (with little consideration of path dependency) in their numerical simulations. Since soil stiffness is highly nonlinear, and it is substantially affected by stress level, strain level and reversal of stress path, it is necessary to understand the stiffness degradation of the ground with change of construction sequence of tunnelling. In addition, the ground conditions can have a significant influence on pile-soil-tunnel interaction. Apart from Ng and Lu (2013)'s study, authors are not aware of any other research related to effect of construction sequence of twin tunnelling on piles in the literature. Therefore, there is a lack of systematic research on the behaviour of an existing pile due to twin stacked tunnelling with different construction sequences in saturated clay.

In view of the aforementioned issues, this study aims at systematically investigating the effects of different construction sequence on settlement and load transfer mechanism of an existing single pile due to twin stacked tunnels in saturated stiff clay. To achieve these objectives, a series of three-dimensional coupled-consolidation numerical analyses were performed to investigate the influences of twin stacked tunnelling with different construction sequences on an existing single pile. Soil responses were simulated by a hypoplastic soil model with intergranular strain concept which has the ability to capture the small-strain soil stiffness. The soil parameters were calibrated by centrifuge test results (Loganathan et al., 2000). Settlement, lateral movement, axial load distribution along the pile, stress and stiffness changes in the ground during twin stacked tunnelling advancement are reported and discussed.

2. Three dimensional numerical modelling

2.1. Numerical analysis program

To understand settlement and load transfer mechanism in single pile due to twin stacked tunnelling with different construction sequences in stiff saturated clay, this study conducts a three-dimensional coupled-



Note:- L_p is embedded length of pile
z_t is depth of tunnel axis from the ground surface

Fig. 1. Elevation view of configuration of numerical simulations in cases of (a) ST (b) TS.

consolidation numerical parametric study. To facilitate validation of the numerical model, the tunnel diameter, pile diameter and embedded length and clear distance between the pile and the tunnel were identical (in prototype scale) to those in the centrifuge test reported by Loganathan et al., 2000 (details of the test are given in Section 3).

In this study, numerical parametric study was conducted to investigate the influences of twin stacked tunnelling with different construction sequences on an existing single pile. The tunnels were located near mid-depth of the pile shaft (tunnel S) and either next to (tunnel T) or below the pile toe (tunnel B). Two tunnelling construction sequences were investigated (*i*) sequence involving construction of tunnel near the mid-depth of the pile shaft (tunnel S) followed by tunnelling next to the pile toe (tunnel T) in case of ST and below the pile toe (tunnel B) in case of SB; (*ii*) sequence involving construction of tunnel next to the pile toe (tunnel T) and below the pile toe (tunnel B) followed by tunnelling near mid-depth of the pile shaft (tunnel S) in cases of TS and BS, respectively.

Figs. 1(a) & (b) and 2(a) & (b) show the elevation views of the configuration of numerical simulations of cases of ST, TS, SB and BS, respectively. The diameter (D) of each tunnel was taken as 6 m. Cover to-diameter ratios (C/D) of the tunnels located near the mid depth of the pile shaft and the pile toe were 1.0 and 2.5, respectively. The closest distance between the centreline of the tunnel and the pile was 5.5 m, equivalent to 0.92D. The embedded length (L_p) and diameter (d_p) of the