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Research Paper

Pile responses to side-by-side twin tunnelling in stiff clay: Effects of different tunnel depths relative to pile

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ABSTRACT

In densely built areas, the development of underground transportation systems often involves twin tunnels, which are sometimes unavoidably constructed adjacent to existing piled foundations. Because soil stiffness degrades with induced stress release and shear strain during tunnelling, it is vital to investigate the pile responses to subsequent tunnels after the first tunnel in a twin-tunnel transportation system. To gain new insights into single pile responses to side-by-side twin tunnelling in saturated stiff clay, a three-dimensional coupled-consolidation numerical parametric study is carried out. An advanced hypoplasticity (clay) constitutive model with small-strain stiffness is adopted. The effects of each tunnel depth relative to pile are investigated by simulating the twin tunnels either near the mid-depth of the pile shaft or adjacent to or below the pile toe. The model parameters are calibrated against centrifuge test results in stiff clay reported in literature. It is found the second tunnelling in each case resulted in larger settlement than that due to the first tunnelling with a maximum percentage difference of 175% in the case of twin tunnelling near the mid-depth of the shaft. This is because of the degradation of clay stiffness around the pile during the first tunnelling. Conversely, the first tunnelling-induced bending moment was reduced substantially during the second tunnelling. The most critical location of twin tunnels relative to the pile was found to be the tunnels below the pile toe. This is because the entire pile was located within the major influence zone of the twin tunnelling. Two distinct load transfer mechanisms can be identified in the pile, namely downward load transfer in case of tunnels near mid-depth of the pile shaft and next to the pile toe and upward load transfer in case of twin-tunnelling below the pile toe. These two transfer mechanisms can be useful for practitioner to assess the pile performance due to twin tunnelling.

1. Introduction

A piled foundation transfers the load of the structure into the ground, generating stresses in the surrounding soil [55]. In contrast, tunnel excavation induces stress relief to the surrounding soil and results in ground movements around the tunnel, which propagate through the soil to the ground surface. Owing to the inherent lack of surface space in congested urban areas, new metro tunnels and larger-diameter sewers are inevitably constructed adjacent to existing pile foundations supporting high-rise buildings.

To understand the pile–soil–tunnel interaction mechanism, many researchers have conducted field monitoring studies and centrifuge model tests [7,8,29,18,51,25,21,31,32,41–44,53]. Moreover, this problem has also been studied by proposing analytical solutions and numerical modelling by some researchers [10,11,15,17,22–25,27,33,39,53]. 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. The magnitudes of likely depended on 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 fact, twin tunnelling is particularly favoured across the world when developing underground transportation systems [16,47,51]. Pang [47] carried out field monitoring on a metro project in Singapore (i.e., North-East Line Contract 704). A maximum dragload of up to 42% and 66% of the pile structural capacity was observed after single tunnel

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and twin tunnel advancement, respectively. In this case history, field measurements include only axial load and bending moments along a limited portion of the pile shafts. Other important pile responses, such as settlement of the pile foundation, were also not reported. 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 [17,42,43]. 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 almost completely the tilting of the existing pile group caused by the first tunnelling.

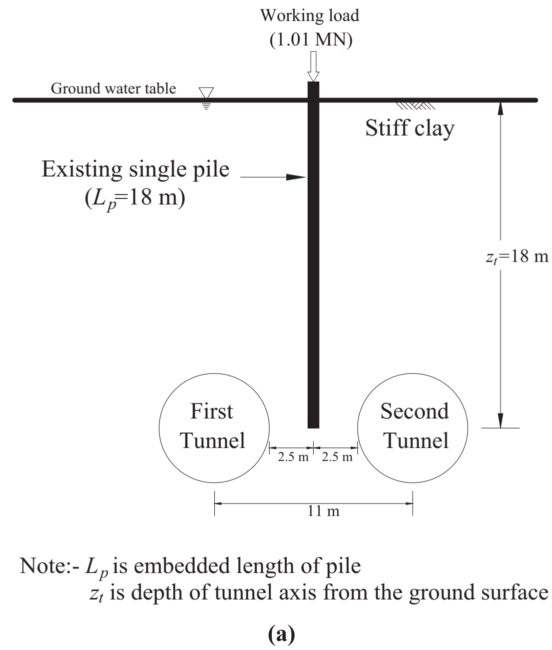
It is well recognised that the stress-strain relationship of soils is highly nonlinear even at very small strain. The stiffness of most soils decreases as strain increases and depends on the recent stress or strain history of the soil [3,4]. Owing to non-linear soil behaviour, a tunnel excavation can cause reduction in the stiffness of the ground. Therefore, it is vital to investigate the pile responses not only to first tunnel but also subsequent tunnel in clay in a twin-tunnelling transportation system. To obtain a satisfactory numerical model of the single pile responses to side-by-side twin-tunnelling, the analysis needs to take account of the small strain non-linearity of soil.

In view of the aforementioned issues, this study aims at systematically investigating the settlement and load transfer mechanism of an existing single pile due to side-by-side twin tunnels in saturated stiff clay. To achieve these objectives, a three-dimensional coupled-consolidation numerical parametric study was carried out by varying the twin tunnel depths relative to the pile. Settlement, axial load distribution along the pile, stress changes and excessive pore pressure generation during twin tunnelling advancement are reported and discussed.

2. Three-dimensional coupled consolidation analysis

To gain new insights into single pile responses to side-by-side twin tunnelling in stiff saturated clay, this study conducts a three-dimensional coupled 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. [29] (details of the test are given in Section 3.1). Fig. 1(a) shows the elevation view of the configuration of a typical numerical simulation in which twin tunnels were excavated adjacent to the pile toe. The diameter of each tunnel (D) was 6 m. The embedded length (L_p) and diameter (d_p) of the pile were 18 m and 0.8 m, respectively. The modelled pile represents a cylindrical reinforced concrete (grade 40, reinforcement ratio = 1) with a bending moment capacity of 800 kN m. The centre-to-centre distance between each tunnel and the pile was 5.5 m (0.92D). It is worth noting that, in reality, high-rise buildings are unlikely to be built on a single pile. This hypothesised study is a more virtual case [18,29,31]. This simplification is made to understand the settlement and load transfer mechanism clearly.

Fig. 1(b) illustrates the plan view of the configuration of the numerical simulation. The length of each model tunnel (along its longitudinal direction) is 72 m, which is equivalent to 12D. Each tunnel excavation was simulated in 28 steps. At each step, the tunnel advanced a distance of 2.5 m (0.42D) [8,22,36]. The time increment of one day for each step was adopted in the finite element analysis. A monitoring section was selected at the transverse centreline of the pile (i.e., $y/D = 0$) as a reference for the tunnel advancements.



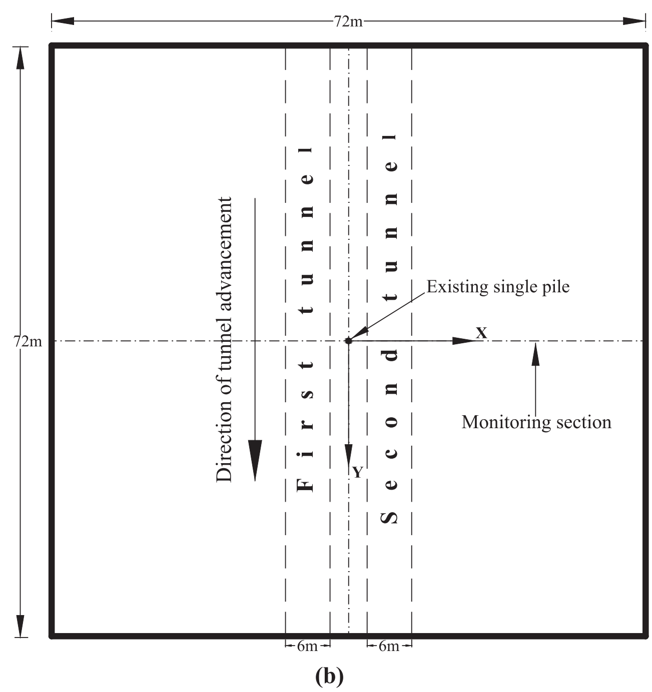


Fig. 1. Configuration of a typical numerical run representing case of $z_t/L_p = 1.00$; (a) elevation view (b) plan view.

The parametric study consisted of nine different numerical simulations (in total) in which the existing single pile was located between the twin tunnels, which were excavated one after the other on either side of the pile at various depths of tunnels (z_t) relative to the pile length (L_p) namely, near the pile shaft ($z_t/L_p = 0.67$ and 0.83), adjacent to the pile toe ($z_t/L_p = 1.00$) and below the pile toe ($z_t/L_p = 1.17$, 1.33, 1.50, 1.67, 1.83 and 2.00). In addition to these simulations, a pile load test (L) was conducted numerically in "greenfield" conditions (i.e., no tunnels are present) to obtain the