Tunnelling and Underground Space Technology 45 (2015) 63–72

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Load transfer mechanism in pile group due to single tunnel advancement in stiff clay

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ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form 8 May 2014
Accepted 5 August 2014

Keywords:
Three-dimensional
Tunnelling
Capacity
Load transfer
Pile group

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. However, the load transfer mechanism between piles in a group, the induced settlement and the tilting of a pile group due to tunnel advancement has not been investigated systematically and is not well understood. This study conducts three-dimensional, coupled-consolidation finite element analyses to investigate tunnelling effects on an existing 2×2 pile group. The construction of a 6 m diameter (D) tunnel in saturated stiff clay is simulated. Responses of the pile group located at a clear distance of 2.1 m (0.35D) from a tunnel constructed at three different cover-to-diameter-of-tunnel ratios (C/D) of 1.5, 2.5 and 3.5 are investigated. The computed results are compared to published data based on field monitoring. It is found that the most critical stage for settlement, tilting and induced bending moment of pile group due to tunnelling is when the tunnel face is close to the pile group rather than at the end of tunnel excavation. The depth of the tunnel relative to the pile group has a vital influence on the settlement, tilting of pile group and the load transfer mechanism between piles in pile group induced by tunnel excavation. Tunnelling near the mid-depth of the pile group (i.e. $C/D = 1.5$) induces the largest bending moment in the piles, but the settlement and tilting of the pile group are relatively small. Based on a settlement criterion, apparent loss of capacity of the pile group is 14% and 23% for tunnels constructed at depths of $C/D = 1.5$ and at both $C/D = 2.5$ and 3.5, respectively. The largest load redistribution between the front and rear piles in the group and the largest tilting of the pile cap towards the tunnel occurs when tunnel excavated at $C/D = 2.5$.

1. Introduction

Nowadays, tunnelling is a very popular technique to facilitate congested urban traffic systems in big cities like London, Hong Kong and Singapore. Since the construction of tunnels inevitably induces soil movement and stress changes in the ground, it may cause additional settlement and tilting to nearby existing piled foundations (Ng et al., 2014a, Ng et al., 2014b, Hong et al., 2014). Tunnelling remains a big challenge for geotechnical engineers, particularly when a tunnel is to be excavated in soft ground.

Various studies have investigated the tunnel–soil–pile interaction by means field monitoring. Mair (1993) described the effects of a 7.5 m tunnel excavated in stiff London clay on a bored piled foundation. The clear spacing between the springline of the tunnel and the nearest 1.2 m diameter pile was only 1 m. The measured horizontal movements of the piles and ground were similar. The maximum horizontal displacement of 10 mm of the nearest pile towards the tunnel was reported. Forth and Thorley (1996) reported the measured settlement of a building due to the excavation of a 7.9 m diameter tunnel in Hong Kong. The building was supported by 2 m diameter bored piles varying in length from 41 m to 64 m. The depth of the tunnel was above the level of the pile toe. The maximum settlement of the building was recorded as 12 mm due to tunnel construction. Coutts and Wang (2000) reported measured results of the effects of 6.5 m diameter shield tunnelling on the adjacent piled foundations of bridge piers in Singapore. The piers were supported by 2×2 pile group of 1.2 m diameter and 62 m long piles. The piles were embedded in completely weathered material (residual soil) with SPT values varying from 15 to 100. The nearest distance between the tunnel and pile foundation was 1.6 m. The depth of the tunnel was located at about

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http://dx.doi.org/10.1016/j.tust.2014.08.001
0886-7798/© 2014 Published by Elsevier Ltd.

the mid depth of the piles (i.e. 21 m). The maximum volume loss due to the tunnel excavation was reported as high as 1.5%. The monitoring results showed that the piles were subjected to large dragload, and the maximum induced bending moment in the piles was at the tunnel springline due to advancement of the tunnel.

Some centrifuge tests were also carried out to study tunnel pile interaction. (Bezuijen and van der Schrier, 1994; Loganathan et al., 2000; Jacobsz et al., 2004; Ng et al., 2013; Ng and Lu, 2014). New findings and insights have been reported. Moreover, some analytical solutions were also proposed as well as finite element analyses that were conducted by some researchers to investigate tunnelling effects on piled foundation (Chen et al., 1999; Loganathan and Polous, 1999; Mroueh and Shahrour, 2002; Lee and Ng, 2005). Mroueh and Shahrour (2002) carried out three-dimensional elasto-plastic analyses to study the effects of a tunnel on a single pile and a 2 × 2 pile group pile group at different cover-to-tunnel diameter (C/D) ratios. Computed results showed that there was significant reduction of the induced axial force and bending moment due to tunnelling on the pile furthest away from the tunnel (i.e., the rear pile) due to the group effect. However, the settlement, tilting of the pile group and the load transfer mechanism between the piles in the group due to tunnelling was not reported.

In previous studies, researchers were mostly interested in the tunnelling-induced axial forces and bending moments in piles due to tunnel excavation. The load transfer within the piles of a group and the induced tilting due to the advancement of a tunnel has not been reported and is not well understood. Besides this, the location of a tunnel relative to a pile foundation has not been studied systematically.

With the prime objective of investigating the effects of the tunnel location relative to the piled foundation, three-dimensional parametric coupled-consolidation finite element analyses were carried out at different cover-to-diameter-of-tunnel ratios (C/D = 1.5, 2.5 and 3.5). The effects of an advancing open face tunnel of 6 m in diameter on a 2 × 2 pile group in stiff saturated clay were investigated. Settlement, tilting of the pile group and load transfer among the piles in the group at various stages of tunnelling were reported and discussed.

2. Three-dimensional coupled-consolidation analyses

Three cases of tunnel excavation in stiff, non-homogeneous and overconsolidated saturated clay were modelled in this numerical parametric study. Fig. 1 shows the geometry and location of each tunnel and the 2 × 2 pile group. The diameter of each tunnel (D) was 6 m. Three separate tunnels were driven near the pile group at different cover depths (C) of 9 m, 15 m and 21 m. The cover-to-diameter (C/D) ratios were 1.5, 2.5 and 3.5, respectively. The net distance between the tunnels and the pile group was 2.1 m (0.35D). The length and diameter (d_p) of each pile were 19 m and 0.8 m, respectively. The heads of all four piles were rigidly embedded into a 4.5 m × 4.5 m × 1.0 m (length × width × thickness) pile cap. The pile spacing was 3.2d_p. The pile cap was elevated by 1 m from the ground surface and each pile was installed 18 m into the ground. It is worth noting that, in reality, the pile cap is likely to be attached to a surface structure, making it potentially more restrained. The pile group with an elevated cap modelled in this study probably represents the worst case scenario encountered in engineering practice. The tunnels were located at z = 12 m (near the pile shaft), 18 m (at the toes of the piles) and 24 m (below the toes of the piles), where z is the distance from the ground surface, in the cases of C/D = 1.5, 2.5 and 3.5, respectively. The finite element programme ABAQUS version 6.8-2 (Hibbitt et al., 2008) was used to carry out the numerical analyses.

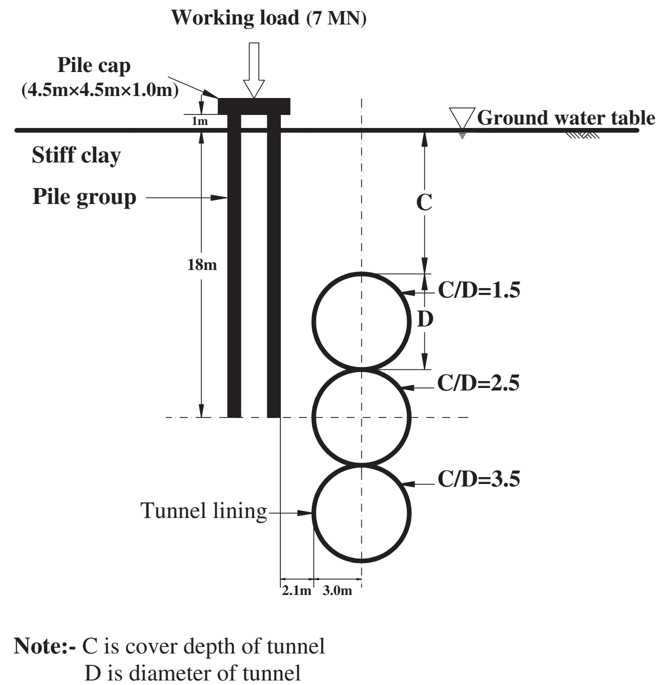

Fig. 1. Geometry of the problem in the analyses.

2.1. Finite element mesh and boundary conditions

Fig. 2 shows a typical three-dimensional finite element mesh adopted for the case of C/D = 2.5. A hypothetical tunnel excavation was modelled, and it is assumed that there were two identical loaded pile groups on both sides of the tunnel. Therefore, only half of the problem is modelled, since a symmetrical plane could easily be identified at the tunnel centre line. The length (along the y-axis), width (along the x-axis) and depth (along the z-axis) of the mesh were 60 m, 60 m and 36 m, respectively. These dimensions were sufficiently large to minimise boundary effects in the numerical simulation, because further increasing the dimensions of the finite element mesh did not lead to any change in the computed results. This mesh consists of 17,732 elements and 20,072 nodes. Eight-noded brick elements, four-noded shell elements and two-noded beam elements were used to model the soil, the lining and the cap, and the piles, respectively. A monitoring section was selected at the centre line of the pile group (i.e. y = 0) for reference.

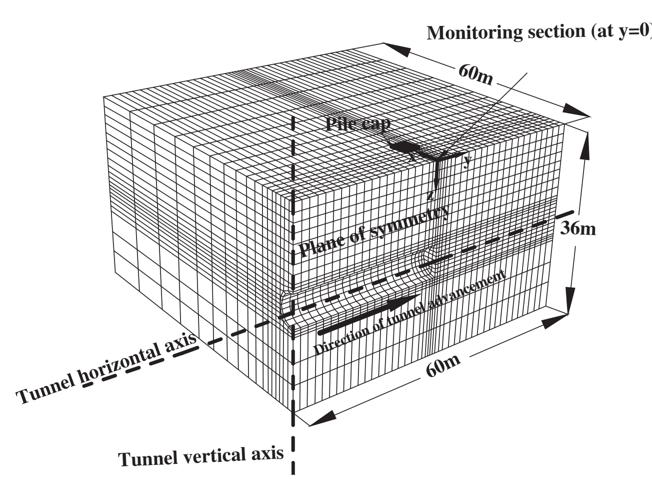

Fig. 2. A typical three-dimensional finite element mesh (C/D = 2.5).