Computers and Geotechnics 68 (2015) 54–65

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Tunnelling under pile groups and rafts: Numerical parametric study on tension effects

Y. Hong [a], M.A. Soomro [b], C.W.W. Ng [c], L.Z. Wang [a,*], J.J. Yan [a], B. Li [d]

[a] College of Civil Engineering and Architecture, Zhejiang University, China
[b] Department of Civil Engineering, The Quaid-e-Awam University of Engineering, Science & Technology, Sindh, Pakistan
[c] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong Special Administrative Region
[d] School of Transportation, Wuhan University of Technology, China

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 21 February 2015
Accepted 22 February 2015
Available online 16 April 2015

Keywords:
Three-dimensional
Numerical parametric study
Hypoplasticity
Tunnelling
Pile group
Piled raft
Tensile force

ABSTRACT

Unfavourable tensile stress can be induced in piles due to tunnelling underneath, as observed in a few recent case histories. Systematic studies of the characteristics of the tunnelling-induced tensile force in pile groups and piled rafts, however, are rarely reported and compared in the literature. Moreover, it remains unclear as to how much working load is required to prevent the axial load in piles from experiencing tension. For this reason, two series (70 runs in total) of three-dimensional finite element analyses (using an advanced soil model) are carried out to simulate tunnelling directly underneath a 2 × 2 pile group and a 2 × 2 piled raft in sand. In each series, two variables are considered, namely tunnelling-induced volume loss and working loads acting on the pile cap/raft. The numerical results are verified by two centrifuge tests. It is revealed that due to tunnelling underneath a pile group, the lower part of the piles is dragged downward by the settling soil (by mobilising negative skin friction). The induced dragload (tensile force) is resisted by mobilising positive skin friction (i.e., PSF) along the upper part of the piles. Differing from the pile group, the tunnelling-induced dragload in a piled raft is mostly (up to 75%) resisted by the raft instead of by the PSF. Correspondingly, the neutral plane in the piled raft is located at a shallower depth (with percentage difference up to 36%) than that in a pile group. The maximum tensile stress in the pile group and piled raft is equivalent to 52% and 72% of the tensile strength of concrete, respectively. Larger tensile stress is induced in the piled raft because the raft tends to stop the piles from settling, resulting in larger downward relative soil–pile displacement than that observed in a pile group. To eliminate the tunnelling-induced tension, the working load required for the pile group and the piled raft is up to 73% and 82% of their axial capacity, respectively. The relatively high working load, however, can lead to significant tensile stress (up to 89% of the tensile strength of C50 concrete) at the crown of the tunnel lining.

1. Introduction

To further develop underground space in congested urban areas, it is unavoidable to construct tunnels directly underneath existing pile foundations [31,12,13,20,21,14,25,22]. Unfavourable tensile stress can be developed in the piles due to tunnelling underneath, as observed by Jacobsz et al. [13], based on field measurement from the Channel Tunnel Rail Link (CTRL) project in the UK. In this project, the 35-km long twin tunnels were constructed under a number of pile supported bridges, as illustrated in Fig. 1. Typical piles (see Pier 7 in Fig. 1(c)) were instrumented to measure changes in their axial strain during tunnelling. The measurements showed that the tunnelling-induced tensile stress (1.9 MPa) almost reached the ultimate tensile strength of C30 concrete for piles (2 MPa, according to MHUC [19]) when a volume loss of 0.3% was imposed by the tunnelling underneath.

Apart from the field evidence, tunnelling-induced tension in piles was also revealed from numerical analyses [14] and centrifuge model tests [25,26,9]. Lee [14] carried out three-dimensional numerical analyses to simulate tunnel excavation under a single pile and 3 × 3 and 5 × 5 groups of piles (without pile cap) in weak weathered rock. The computed results showed that the incremental tensile stress developed in the piles due to tunnelling can be up to 64% of the tensile strength of C30 concrete for piles (i.e., 2 MPa, according to MHUC [19]). Ng et al. [25,26] and Hong et al. [9] reported centrifuge tests simulating tunnelling below a

* Corresponding author.

http://dx.doi.org/10.1016/j.compgeo.2015.02.014
0266-352X/© 2015 Published by Elsevier Ltd.

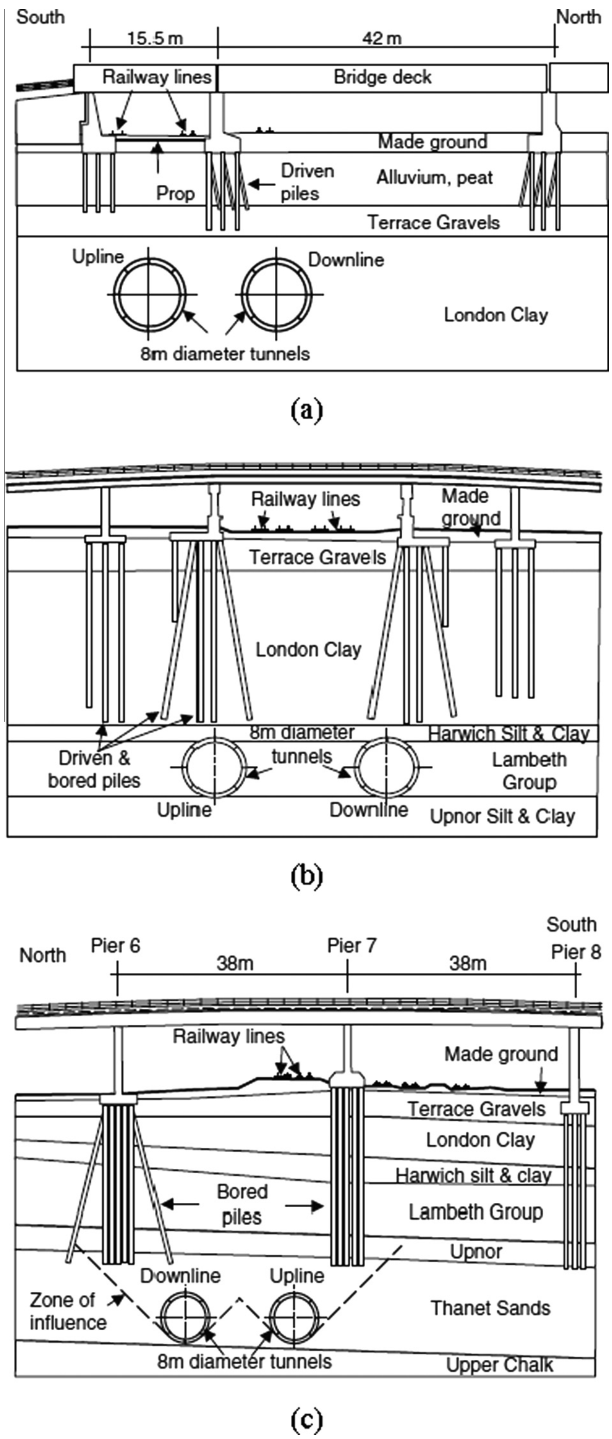

Fig. 1. Three typical sections showing tunnelling under (a) Renwick road bridge; (b) Ripple Road Flyover and (c) A406 viaduct bridge in piled bridges in the Channel Tunnel Rail Link project [13].

2×2 pile group in medium dense sand. Due to the tunnel excavation, substantial incremental tensile stress (up to 50% of the tensile strength of concrete) was also developed in the piles. In spite of the significant incremental tensile force (i.e., reduction in compressive force) caused by tunnelling, the piles are still under compression due to the relatively large working load acting on the pile cap.

Although the aforementioned studies have brought the attention that tension could be developed in piles due to tunnelling underneath, the characteristics (i.e., distribution and magnitude) of tunnelling-induced tensile force in pile groups and piled rafts have still not been systematically investigated and compared. In addition, it is still unclear how much working load is required to prevent the axial load in the piles from experiencing absolute tension. For these reasons, this study aims to investigate and compare (a) the characteristics of tunnelling-induced tensile force in a pile group and a piled raft, as well as the associated load transfer mechanism and (b) the working load required for a pile group and a piled raft to maintain the piles under compression after tunnelling.

To address the aforementioned objectives, three-dimensional numerical analyses (FEA) are carried out using the commercial finite element software package ABAQUS, which has been widely used to study the effect of tunnelling on existing structures in urban areas [17,23,33,3,15,35,32].

In total, two series of analyses (70 runs in total) are performed to simulate tunnel excavation directly under a pile group and a piled raft. In each parametric study series, two variables are considered, i.e., tunnelling-induced volume loss and working loads acting on the pile cap/raft. In the numerical parametric study, a hypoplastic sand model, which accounts for strain-dependent and path-dependent soil stiffness, is adopted. The hypoplastic model and its model parameters have been calibrated against stress-path triaxial tests and verified through centrifuge tests simulating tunnel–soil interaction in sand [25]. Based on the computed results, the responses of the pile group and the piled raft due to tunnelling underneath are interpreted, compared, and discussed. Calculation charts are developed for estimating the magnitude and location of the maximum tensile stress in pile groups and pile rafts due to tunnelling underneath and for the estimation of working load required to prevent the piles from experiencing tension.

2. Finite element analysis

2.1. Programme of numerical parametric study

Two series (70 runs in total) of numerical analyses were carried out to study the response of a pile group and a piled raft subjected to tunnelling. Each series consists of 35 numerical runs in which various volume losses and working loads acting on the pile group or piled raft are considered. Table 1 summaries all numerical analyses carried out in this study. The programme of numerical analyses in the table is equally applicable for the scenarios simulating tunnelling underneath a pile group or a piled raft. As shown in the table, the minimum working load adopted in this study (i.e., 1.5 MN), which is meant to represent a load acting on a bridge pier, is determined based on AASHTO LRFD Bridge design specifications

Table 1
A summary of numerical analyses simulating tunnelling underneath a pile group or a piled raft.

Variable		Objective
Volume loss: %	Working load: MN	
0.3 0.6 1.0 1.5 2.0	1.5	Effect of volume loss
0.3, 0.6, 1.0, 1.5, 2.0	2.5 3.5 4.5 5.5 6.5 7.5	Effect of working load

Note: The programme of numerical analyses in the table is equally applicable for the scenarios simulating tunnelling underneath a pile group and a piled raft.