Tunnelling and Underground Space Technology 52 (2016) 168–181

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Influence of deep excavation induced ground movements on adjacent piles

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 28 October 2015
Accepted 24 November 2015
Available online 18 December 2015

Keywords:
Deep excavations
Ground movements
Wall support systems
Finite element method
Pile behaviour

ABSTRACT

In urban areas, excavations for cut-and-cover tunnels and basement construction cause detrimental effects on adjacent existing piles. Hence quantifying the excavation induced lateral deformations and bending moments on piles are important to ensure the stability of structures. In this paper, behaviour of a single pile subjected to excavation induced ground movements is analysed using the finite element method, which has the ability to simulate the construction sequence comprising soil excavation, deformations due to dewatering within the excavation and installation of struts. A fully coupled analysis is carried out based on the effective stress principle. The numerical model was verified using the centrifuge test data found in the literature. A parametric study was carried out to establish the excavation induced pile behaviour varying the depth of the excavation, soil properties, wall support system, pile fixity conditions and pile location with respect to the excavation. Increasing axial load does not have a significant influence on the pile behaviour. However, pile head fixity condition, and stiffness and spacing of the wall support system have a significant influence on the pile behaviour adjacent to the excavation. Finally, based on the parametric study, a set of design charts are developed to predict the pile behaviour by taking into account the depth of excavation, undrained shear strength, width of the pile, spring stiffness, spacing of vertical supports, and unsupported depth of the excavation. The capability of the proposed design charts are demonstrated using a three-dimensional finite element analysis, a case study from the literature and a previously published simplified analysis procedure.

1. Introduction

The need for urban construction involving deep excavations for basement construction and underground infrastructure such as mass rapid transit and cut and cover tunnels are increasing due to rapid urbanisation. Stress release caused by these deep excavations may lead to excessive lateral ground movements. The interaction of these lateral ground movements with nearby existing pile foundations develop additional loading on them. These additional loads will induce extra bending moments and lateral deformations on nearby existing pile foundations and they should be taken into account to ensure the integrity of the foundations as well as the structures supported by them.

Case studies with proper instrumentation (Finno et al., 1991; Goh et al., 2003) are very useful to gain a clear insight into the pile behaviour during nearby excavations. Also they can be used to verify numerical models. However, applying instrumentation along an existing pile shaft is not feasible prior to a nearby excavation. Hence the amount of data available is limited for existing pile behaviour during nearby deep excavations.

For problems similar to this, where it is not possible to instrument existing pile foundations, centrifuge tests play a major role. They can be used to investigate the pile behaviour and subsequently, measured response can be used to calibrate numerical models. Leung et al. (2000) and Ong et al. (2006) carried out centrifuge tests to investigate single pile response near excavations in sand and clay, respectively. Leung et al. (2000) found that the maximum induced bending moment and lateral deformation of the pile reduce exponentially with increasing distance from the excavation face and the provision of restraints at the pile head induce additional bending moments and shear forces. Ong et al. (2006) found that the wall and soil continue to move towards the excavation even after completion of the excavation due to the dissipation of excess pore water pressures. As a result, bending moment and pile lateral deformation increases with time even after the completion of the excavation. They identified a significant soil deformation zone, which is bounded by the wall and a line drawn from the bottom of the clay layer to the ground surface, 45° inclined to the wall. When the pile length within the significant

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http://dx.doi.org/10.1016/j.tust.2015.11.019
0886-7798/

zone decreases (pile moves away from the wall), excavation induced pile response significantly decreases. Centrifuge tests discussed above did not consider the influence of axial loads applied on piles during nearby excavations. Guo and Ghee (2006) carried out scaled model tests in sand to investigate pile behaviour due to lateral ground movements incorporating axial loads supported by piles. They concluded that the axial load imposed on a pile head tends to decrease the induced bending moment, soil reaction and pile lateral deformation.

When performing parametric studies, numerical analyses are very cost effective compared to experimental modelling. The tools like finite element method can be used to simulate the construction sequence, wall support system, water drawdown, nonlinear soil behaviour, pore pressure effects and pile-soil interaction. In addition, actual geometry and three-dimensional nature of the problem can be taken into account. However, the three-dimensional finite element analyses require high computational effort and time. Therefore, in majority of finite element analyses, the analysis was carried out in two stages decoupling the ground response due to excavation and pile response. In the first step of these analyses, the free field movements are calculated using the finite element method or analytical solutions independent of the presence of the pile. In the second step, pile response will be computed by applying the computed free field movements to the soil adjacent to the pile, where soil–pile interaction is represented by a series of spring elements or *p*–*y* curves.

Poulos and Chen (1996, 1997) established design charts based on results from a two-stage analysis procedure. First they used a plane-strain finite element analysis to obtain ground deformations due to excavations. Then a pile analysis based on the boundary element method was carried out applying computed lateral soil movements as input. They investigated influence factors such as depth of excavation, stiffness and spacing of the support system, soil properties, pile head condition and pile diameter on maximum bending moment and maximum lateral deformation of a single pile adjacent to an excavation in undrained clay. Also they considered both unsupported and braced excavations. Xu and Poulos (2000) and Zhang et al. (2011) used a source-sink imaging technique proposed by Sagaseta (1987) to calculate the free-field soil movements. These calculated free-field movements are applied to soil adjacent to the pile, where soil–pile interaction is represented by a series of springs or *p*–*y* curves. They found that with an increase in working load acting over pile, the excavation induced pile settlement increases but the applied working load does not have much influence on the lateral response of the pile.

Poulos (2005) investigated the effect of excavations for a new pile cap adjacent to an axially loaded pile with different pressures over ground surface to simulate the loads applied by an existing building using the finite difference method. It was found that substantially higher lateral movements and bending moments are induced in the pile when the surface pressure is high. There is a higher chance for the induced moments to exceed the design capacity of the pile. Also he showed that the bending moments and shear forces due to induced lateral deformations are significant compared to those due to induced vertical deformations.

In this paper, a three-dimensional finite element analysis is carried out, which takes into account the coupling of ground movements due to excavations on pile response. The main aim of this paper is to investigate the pile behaviour due to lateral ground deformations caused by nearby excavations and to develop some design charts to predict pile behaviour. Hence soil anisotropy effects are not incorporated in this analysis owing to the large number of empirical parameters involved in those constitutive models, which might hinder the main purpose of this research. The shear modulus variation with strain level is incorporated in the parametric study carried out using the Modified Cam Clay (MCC) model. Prior to the parametric study, the model verification is carried out using centrifuge test results reported by Ong et al. (2006) for pile bending moments and lateral deformations. In the parametric study, pile behaviour is investigated during a nearby excavation by varying the spacing and stiffness of the wall support system, pile location, pile fixity conditions, over consolidation ratio of soil and axial load applied on the pile head. Based on the results from the parametric study, a set of design charts are developed considering the influence of depth of excavation, undrained shear strength, width of the pile, stiffness and spacing of struts supporting the wall, and unsupported depth of excavation on the pile response. Finally the design charts are validated using the results from a three-dimensional finite element analysis, case study from the literature (Finno et al., 1991) and a simplified method based on the design charts proposed by Poulos and Chen (1997).

2. Validation of three-dimensional finite element model using centrifuge data

The finite element model used in this analysis is verified using the centrifuge test results reported by Ong et al. (2006) to investigate whether the approaches used to model the wall, pile, and wall–soil and pile–soil interactions are appropriate to investigate the pile behaviour during an adjacent deep excavation.

2.1. Description of the centrifuge test

Centrifuge tests used for model validation were performed to investigate the behaviour of a single pile founded in clay, closer to an excavation behind an unsupported stable wall. Tests were carried out using the geotechnical centrifuge facility at the National University of Singapore at a centrifugal acceleration of 50*g*. The model container used for these tests has dimensions of 540 mm × 200 mm × 470 mm. The Malaysian kaolin clay was filled up to a depth of 130 mm above a Toyoura sand layer, which has a thickness of 120 mm. Fig. 1 shows the variation of undrained shear strength of the clay with depth obtained using a T-bar penetrometer test (Ong et al., 2006). The distribution shows that the top 2.5 m soil crust was over consolidated and soil below the crust was normally consolidated. The soil region that needs to be excavated was replaced by a Latex bag filled with a $ZnCl_2$ solution, which has a unit weight equivalent to clay. The excavation was

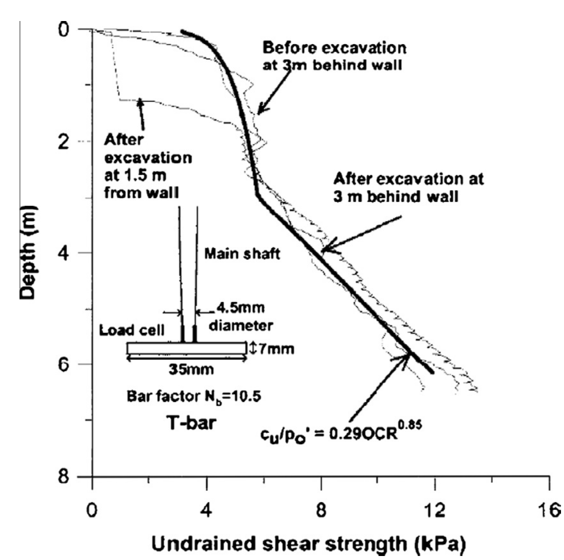

Fig. 1. Variation of undrained shear strength with depth (Ong et al., 2006).