Tunnelling and Underground Space Technology 52 (2016) 12–22

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Small strain based method for predicting three-dimensional soil displacements induced by braced excavation

Linlong Mu *, Maosong Huang

Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 9 August 2014
Received in revised form 28 October 2015
Accepted 1 November 2015
Available online 14 November 2015

Keywords:
Excavation
Finite element analysis
Inverse analysis
Small strain
Soil movement

ABSTRACT

Displacement control is a critical indicator of foundation design. Maximum deformations of soil induced by excavations are controlled by the allowable deformations of the adjacent structures. In order to evaluate potential damage of surrounding structures, Finite Element Method (FEM) is commonly adopted, predicting soil responses caused by excavations. As the numerical results obtained from FEM are greatly influenced by input material parameters of soil, inverse analysis is an effective method to obtain these parameters, which is based on the results of on-site testing. In this paper, inverse analysis based on the data of on-site testing considering Chicago clays is firstly conducted to get material parameters of soil. Then, with these input parameters, considering Hardening Soil model with Small Strain stiffness (HSS model), FEM program PLAXIS is used for parameter studies, producing coefficients in the equations of attenuation law of the displacements of the soil. Finally, considering the coupled relationship between the soil and the retaining wall, an empirical method is proposed by the authors to predict the three-dimensional displacements of soil induced by braced excavations. Validation has been done by comparisons between the results obtained by the proposed method and by other methods in the literature.

1. Introduction

Considering excavation in urban areas, which induces soil deformation then influences surrounding structures, displacement control is a critical indicator of foundation design. The maximum lateral deformation of the retaining wall depends on (i) excavation depth, (ii) stiffness of supporting, (iii) material properties of the soil (Hashash and Whittle, 1996). Several methods (Mana and Clough, 1981; Ou et al., 1993; Kung et al., 2007) have been proposed correspondingly for predicting the maximum lateral wall deformation based on these three ingredients. The displacement induced by excavation shall be predicted for evaluation of the influence of excavation on the surrounding structures, providing information about further modification of the excavation plan to the designers.

Methods for predicting soil displacement induced by excavation has been researched for long (Hashash and Whittle, 1996; Osman and Bolton, 2006; Wang et al., 2010), including Finite Element Methods (FEM) (Finno and Harahap, 1991; Finno et al., 1991) and empirical methods (Ou et al., 1993; Roboski and Finno, 2006). With regarding to FEM, direct input of material parameters of soil given by laboratory experiments commonly results in unreliable results because those parameters depend on the quality of the samples and details of the experiments which are usually hard to guarantee. Furthermore, soil property at small strain level is important for FEM analysis of excavations, which is more difficult to obtained from laboratory experiments than soil property at conventional strain level (Burland, 1989; Whittle et al., 1993; Stallebrass and Taylor, 1997). Hence, inverse analysis methods based on results of on-site testing become an option for producing material parameters of soil used in FEM (Ou and Tang, 1994; Finno and Calvello, 2005; Rechea et al., 2008). With regarding to empirical methods, empirical methods are based on experimental results (Peck, 1969; O'Rourke, 1981; Finno and Roboski, 2005; Blackburn and Finno, 2007) or results from numerical parameter studies (Lambe, 1970; Clough, 1981; Finno et al., 2007; Kung et al., 2009). Most empirical methods aim at predicting deformations of the retaining wall and ground surface (Ou et al., 1993; Kung et al., 2007; Roboski and Finno, 2006; Clough and O'Rourke, 1990). An empirical method taking into account the underground soil movement is still missing.

In this paper, based on on-site testing data the authors firstly adopt inverse analysis to obtain the so-obtained material parameters for soil with HSS model. Then FEM analysis is conducted with

---

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China.

E-mail address: mulinlong@tongji.edu.cn (L. Mu).

http://dx.doi.org/10.1016/j.tust.2015.11.001
0886-7798/© 2015 Elsevier Ltd. All rights reserved.

the material parameters, considering different excavation depths. Finally an empirical method is given based on the numerical results, taking into account deformations of the underground soil. The empirical method is validated through comparison with results presented by other researchers.

The rest of this paper is organized as: in Section 2, details of inverse analysis are presented, including the site conditions, the soil model and the results, in Section 3, based on the results obtained by inverse analysis, a simplified method for predicting the soil movements induced by excavation is presented considering not only the deformation of the retaining wall and ground settlements but also the displacement of the underground soil. The presented simplified method is verified in Section 4, indicating agreements with FEM results as well as experimental results given in published papers. Finally, concluding remarks are given in Section 5.

2. Inverse analysis of braced excavation

2.1. Site conditions

The results of on-site testing for inverse analysis is taken from Block 37 project located at down town in Chicago, details of the excavation can be found in Kern (2011) and Mu et al. (2015). The excavation is operated by partial top-down construction technique, with approximate size 110 m long, 110 m wide, and 15 m deep. The main purpose of the top-down construction is to build up as well as excavate down concurrently. This approach takes the excavation off the critical path of a project, and results in longer excavation times than conventional bottom-up construction. Usually, some sort of perimeter support is installed prior to any additional construction and then lateral supports are added as excavation progresses. Typical excavation progresses at a slower rate because of limited access; however, the construction up from ground level occurs at the same time, and overall a faster construction time is usually achieved. The Block 37 development deviated from a typical top-down construction system because the ground surface lateral support was not installed prior to any significant excavation; rather the first lateral support was placed after 6 m of excavation. The contractor made the decision to delay placement of the ground surface slab on the basis of construction expediency. The plan of the excavation is shown in Fig. 1. The excavation is supported by a 0.91 m-thick and 2 1 m-deep reinforced concrete slurry wall and four concrete slabs, with compressible soft/medium glacial clay as on-site soil, see Fig. 2. The water content of the stratigraphy is shown in Fig. 3. And the average index properties of the soils which mainly influence the deformation of the retaining wall are summarized in Table 1. The groundwater level is at a depth of 4 m below ground surface. The excavation processes of the foundation which are also the excavation sequence defined in PLAXIS are listed in Table 2.

Considering on-site testing, 23 inclinometers and settlement gauges were installed for recording the deformations of the retaining wall and the settlements of ground behind the retaining wall. The data of an inclinometer at the center of the north wall are shown in Fig. 4, indicating the importance to consider potholing in the simulation of the excavation. Most of the subsequent deformations occurred during the first stage, where a 6.2 m cut was made prior to placing any lateral support. The maximum lateral wall deformation at the final stage is about 45 mm.

Based on the characteristics of the soil layers (Finno and Chung, 1992), the authors took soil layer Blodgett, Deerfield and Park Ridge for inverse analysis, which are considered owing great influence on the ground displacement.

2.2. Soil model

In this paper, harden soil with small strain model (HSS) is taken for describing small strain behavior of the soil. HSS model (Benz et al., 2009) uses 13 parameters (see Table 3) for determination of mechanical properties of soil in which 11 parameters are the

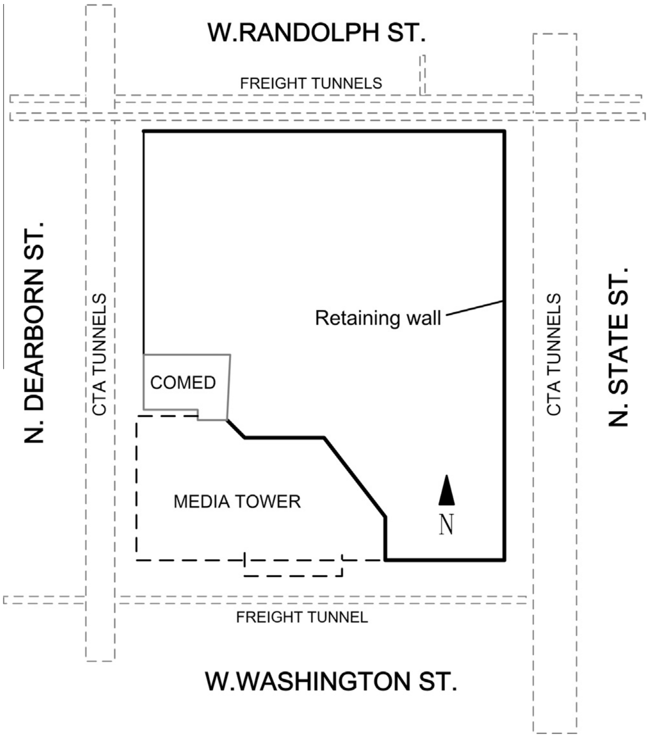

Fig. 1. Plan of Block 37.

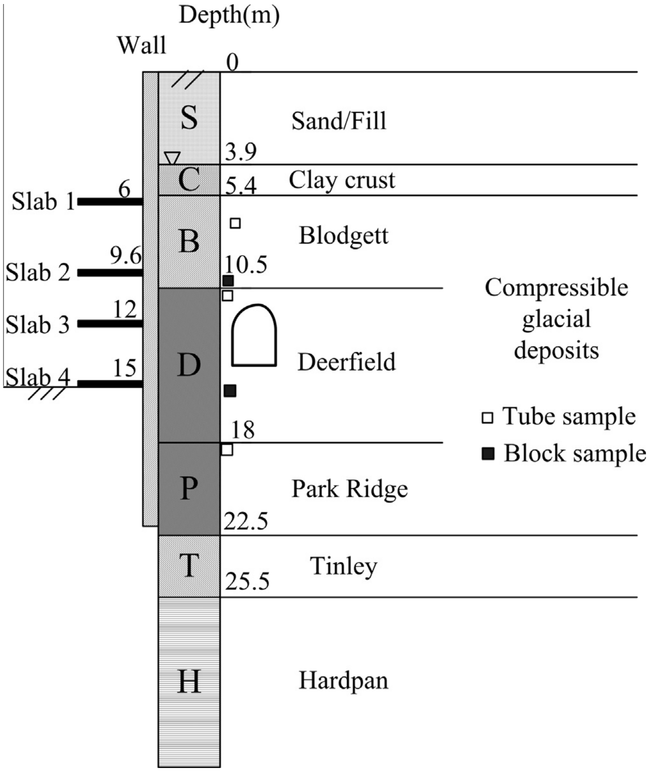

Fig. 2. Cross section and soil profile of Block 37.