Small strain model based method for analysis of pile responses induced by excavation

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ABSTRACT

Estimating damage potential on buildings induced by excavations is required because more and more foundation pits are excavated near existing building. Thus, displacement control becomes a critical indicator of excavation design. Unfortunately, there is nearly no simplified method that can estimate the influence of excavation on existing building supported by deep foundations and can be easy to be used. Small strain behavior of soil should also be considered when establishing method to estimate influence of excavation on adjacent building for the strain of the soil is very small under displacement control design. In order to fit the requirement for simplified method to estimate the influence of excavations on existing buildings supported by pile foundations, a two-stage method is proposed herein to estimate the responses of piles adjacent to excavations. Firstly, the empirical method based on small strain behavior of soil proposed by Mu and Huang (2013) is employed to calculate three-dimensional free-field soil displacement induced by excavation. Then, an elastic theory method is proposed to calculate the vertical and horizontal pile responses in layered soil. The method is verified through comparison with results from FEM.

Keywords: excavation, pile, small strain, simplified method

1 INTRODUCTION

Cities, especially those large cities, are extreme shortage of urban space in China due to the rapid development of urban constructions. And underground space are strongly developed in those cities. More and more foundation pits, which are basically needed by underground constructions, for example constructions of subway stations and basements, are carried out near existing buildings. In order to protect the nearby buildings, many researches on estimating the potential damage of buildings induced by excavations are carried out in recent years.

The finite element method (FEM) is now the main method employed to estimate the influence of excavations on adjacent buildings (Finno et al. 1991, Iliadis 2006) due to the complexity of the foundation pit and the diversity of the excavation of adjacent structures. The deformation of excavations are controlled in a small range based on the protection requirement of adjacent building, when the soil surrounding the excavations are kept in a small strain range (Burland 1989). A lot of researches are carried out to study the small strain behaviour of soils (Hryciw 1990, Bellotti et al. 1996, Hoyos et al. 2011, Clayton 2011) after Burland (1989) pointed out that behaviours of foundations were strongly influenced by the small strain behaviour of soils. And it is well recognized that the deformations induced by excavations are strongly influenced by the small strain behaviour now (Whittle et al. 1993, Kung et al. 2009, Xuan et al. 2009). Thus, in order to estimate the influence of excavations on adjacent buildings accurately it is very important to consider the small strain behaviour of the soil in the analysis. However, most researches which studied the influence of excavations on adjacent building by FEM did not considered the small strain behaviour of the soil (Kung et al. 2009, Xuan et al. 2009). The validity and the accuracy of FEM depend on the rationality of the model and the rationality of input parameters of FEM which are difficult to be guaranteed. Identifying reasonable small strain parameters for soil model with small strain behaviour is a more difficult task for researchers. And it is even hard for engineers to obtain reasonable results from FEM. In additionally, three dimensional FEM considering small strain behaviour of soil would take a lot of time. Thus, a simplified method which can be used to estimate influence of excavation on adjacent structures is urgently needed.

In order to estimate the potential damage of adjacent structures induced by excavation, it is necessary to estimate the soil movement induced by excavation firstly. Many model tests and in-situ tests are carried out to study the deformations of soils surrounding the excavation induced by excavation (Leung et al. 2000, Leung et al. 2003, Goh et al. 2003, Ong et al. 2006, Leung et al. 2006) to find an feasible empirical method to calculate the soil movement induced by excavation. Due to the type of foundations of the adjacent buildings, the adjacent buildings can be divide into two types: 1. Buildings supported by shallow foundation, 2. Buildings supported by deep foundations like pile foundations. For buildings supported by shallow foundation, the additional
deformations of the buildings induced by excavations can be obtained directly from the settlement of the ground surface induced by excavation (Boone 1996). And many empirical methods have been proposed to calculate ground surface settlement induced excavations based on tests data since now (Hsieh and Ou 1998, Finno et al. 2007, Kung et al. 2007). For the buildings supported by pile foundations, there is almost no simplified method to calculate the additional deformations of buildings induced by excavations because that there is few method can be used to calculate the underground soil movement induced by excavation except FEM. And none of the published method calculating effect of excavations on adjacent buildings considered the small strain behaviour of soil. The author (Mu and Huang 2013) present a simplified method to calculate soil movement induced by excavations in a previous paper which provides a potential way to calculate the influence of excavation on adjacent underground structures.

In this paper, a two-stage method is proposed to calculate the effect of excavations on adjacent piles. At the first stage, the method proposed by Mu and Huang(2013) is employ to calculate three dimensional free-field soil movement induced by excavation. At the second stage, the free-field soil movement is applied on to the pile to obtain the pile responses.

2 ANALYSIS METHOD

2.1 Free-field Soil Movement Induced by Excavation

Considering the small strain behavior of soil, Mu and Huang (2013) presented a simplified method to calculate three-dimensional soil movements caused by excavations based on an inverse analysis technique coupled with FEM analysis with HS-small soil model. This method reflected the small strain behavior of soil. And the behavior of soil in a range of small strain are similar to an elastic material. Thus, this method can be used in an elastic method. The equations of the method are expressed as:

$$u(x, y, z) = u_{max} \cdot e^{\left(\frac{\frac{x-h}{R}}{c_i}\right)^2}$$

$$w(x, y, z) = 0.8w_{max} \cdot e^{\left(\frac{\frac{z-H}{R}}{c_i}\right)^2}$$

$$v(x, y, z) = 0.8v_{max} \cdot e^{\left(\frac{\frac{y}{R}}{c_i}\right)^2}$$

where $u_{max}$ is the maximum lateral wall deflection,

$$a_x = 1 + e^{-10.47\frac{x}{H}}^{0.76}$$

$$b_x = e^{-6.45\frac{x}{H}+2.76}$$

$$c_x = e^{-20.58\frac{x}{H}+2.64}$$

As shown in Figure 2, according to elastic theory method the vertical and horizontal pile equilibrium equations are given as:

$$\mathbf{I} - \frac{d^2E}{4d^2I_p} \mathbf{I} \mathbf{I} \mathbf{I} \mathbf{I} \mathbf{I} = \mathbf{Y}$$

$$\mathbf{I} + \frac{E_1J}{\delta^2} \mathbf{I} \mathbf{I} \mathbf{I} \mathbf{I} \mathbf{I} = \mathbf{Y}_h$$
where \( E_p \) is the Young’s modulus of pile, \( I_p \) is the section inertia moment of the pile, \( d \) is diameter of the pile, \( p \) is the horizontal nodal soil resistance force vector of the pile, \( q \) is the vertical nodal soil resistance force vector of the pile,

\[
\mathbf{Y} = \left[ \begin{array}{ccc} \frac{Q}{2\delta L} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right],
\]

\[
\mathbf{Y}_L = \left( \begin{array}{ccc} \frac{2\delta^2 T + 2\delta^2 M}{E_p I_p} & -\frac{\delta^2 M}{E_p I_p} \\ 0 & 0 & 0 \end{array} \right), \quad \delta = L/n ;
\]

\( L \) is the pile length, \( n \) is the number of the element along the pile, \( \mathbf{I}_s \) is the vertical pile flexibility matrix of the pile, \( \mathbf{I}_{sl} \) is the horizontal pile flexibility matrix of the pile, \( \mathbf{I}_s \) and \( \mathbf{I}_{sl} \) are the vertical and horizontal soil flexibility matrices for the pile.

Assuming the vertical free-field soil deformation induced by excavation at the position of the pile is \( \mathbf{w}_s \), the horizontal free-field soil deformation induced by excavation at the position of the pile is \( \mathbf{u}_s \) and no separation and slipping occur between the pile and the soil, the vertical and horizontal pile equilibrium equations can be express as:

\[
\begin{bmatrix} \mathbf{I} - \frac{d^2 E_p}{4\delta^2 E_s} \mathbf{I}_p \mathbf{L}_s \\ \mathbf{I} + \frac{E_s I_p}{\delta^2} \mathbf{I}_s \mathbf{I}_{sl} \end{bmatrix} \mathbf{p} = \mathbf{Y} + \frac{d E_p}{4\delta^2 E_s} \mathbf{I}_p \mathbf{w}_s \quad (5)
\]

\[
\begin{bmatrix} \mathbf{I} + \frac{E_s I_p}{\delta^2} \mathbf{I}_s \mathbf{I}_{sl} \end{bmatrix} \mathbf{q} = \mathbf{Y}_L - \frac{E_s I_p}{\delta^4} \mathbf{I}_{sl} \mathbf{u}_s \quad (6)
\]

\( \mathbf{p} \) and \( \mathbf{q} \) can be obtained from equations (5) and (6). Then the deformations can be obtained from equations (7) and (8).

\[
\mathbf{w}_p = \frac{d}{E_s} \mathbf{I}_p \mathbf{p} \quad (7)
\]

\[
\mathbf{u}_p = \mathbf{I}_{sl} \mathbf{q} \quad (8)
\]

where \( \mathbf{w}_p \) and \( \mathbf{u}_p \) are the vectors of vertical and horizontal deformations of the pile, respectively.

3 VERIFICATION

The method is verified through comparison with three dimensional FEM with HS-small strain soil model. As shown in Figure 3, a single pile adjacent to an excavation. The excavation depth is 15m and retaining system consisting of one-meter-thick slurry wall and five concrete struts. The soils, Sand, Clay crust, Tinely and Hardpan, are modeled as HS model in FEM, the other soils are modeled as HS-small model. For the deformation of the soil induced by the excavation are mainly influence by Blodgett, Deerfield and Park Ridge. The modulus of the soil locate at the center of each soil layer can be obtained from equation (9) when calculating the pile responses induced by the excavation using the method proposed herein. And the Young’s modulus of the soils can be calculated as \( 6E_{50} \) according to the experience in Chicago.

\[
E_{50} = E_{50}^{ref} \left( \frac{c \cos \phi - \sigma'_v \sin \phi}{c \cos \phi + p' \sin \phi} \right)^m \quad (9)
\]

Two cases are calculated:(1) the pile is 3m from the retaining wall,(2) the pile is 5.4m from the retaining wall. Figure 4 shows the free-field soil movement induced by excavation obtained from FEM and the method proposed herein. It can be seen, the horizontal soil deformations from the method proposed herein at both positions are nearly the same as those from FEM. The vertical soil deformations from the method proposed herein also agree well with those from FEM. However the vertical deformation calculated from the method proposed herein at 5.4m below the excavation base is a little larger than that from FEM.

Figure 5 shows the responses of the pile calculated from FEM and the proposed method. It can be seen, both the distributions and the maximum values of the vertical deformation, the horizontal deformation and the moment along the pile calculated from the proposed method agree very well with those from FEM. The distribution and maximum value of the axial force along the pile which is at the location of 3m away from the wall agree well with those from the FEM. While the location where the maximum value of axial force along the pile which is 5.4m from the wall from the proposed is higher than that from FEM. However the maximum value of the axial force of the pile is close to that from the FEM. This is mainly due to the difference of free-field vertical movement obtained from the proposed method and the FEM below the excavation base mentioned previous.
This study
FEM
0 -10 -20 -30
330
230
10
0
Depth(m)
Excavation Base

(a) lateral movement

0 -10 -20 -30
30
20
10
0
Depth(m)
Excavation Base

(b) vertical movement

Fig.4 Soil movement induced by excavation at the location of pile

Fig.5 pile responses induced by excavation

4 CONCLUSION
Based on a simplified method used to calculate free-field soil movement induced by excavation considering small strain behavior of soil and an elastic theory method for piles in layered soils, a semi-empirical method is proposed to calculate the influence of excavations on adjacent piles. And the method is verified through comparison with FEM. The verification shows the method is reasonable to calculate
pile responses induced by excavation. Small strain behavior of the soil is implied in the method. Thus, the method is reasonable to calculate the responses of the pile adjacent to an excavation of which the deformation is small. And most excavations in urban areas need to control its deformation in a specific small range. Thus, the method proposed herein can be used in most excavations conducted in cities.

ACKNOWLEDGMENTS

The authors would like to thank financial support provided by the National Natural Science Foundation of China through Grant No. 51208378. Also appreciate Professor Richard J Finno at Northwestern University in the work.

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