Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48475-6

Analysis of the factors influencing foundation pit deformations

Y.Q. Li
Department of Civil Engineering, Shanghai University, Shanghai, P.R. China

K.H. Xie
Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, P.R. China

J. Zhou & X.L. Kong
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, P.R. China
Department of Geotechnical Engineering, Tongji University, Shanghai, P.R. China

ABSTRACT: Due to the complexity of excavation and groundwater seepage, the behavior of foundation pits is not yet well understood. In this paper, based on three-dimensional (3D) Biot's consolidation theory and nonlinear Duncan-Chang's model, finite element equations considering the coupling of groundwater seepage and soil skeleton deformation during excavation are deduced and a corresponding three-dimensional finite element program is developed. Using the program, the influence of soil permeability, rigidity and tiers of supports, rigidity of retaining wall and construction period of excavation on ground surface settlement, wall horizontal displacement and pit base heave are analyzed in detail. Some useful conclusions are drawn by analyzing the influence of these factors on the excavation deformations, which are very significant for guiding design and construction of excavations.

1 INTRODUCTION

In urban areas, more and more underground space is utilized with the fast development of city construction, and thus a lot of excavation engineering appears. However, the pit deformations induced by excavation greatly influence the safety of not only the pit itself but also the buildings and municipal facilities around it. Therefore, study of the behavior of foundation pits has received much attention. Whittle et al. (1993) described the application of a finite element analysis for modelling the top-down construction of a seven-storey, underground parking garage at Post Office Square in Boston. The results demonstrated that reliable and consistent predictions of soil deformations and groundwater flow can be achieved by advanced methods of analysis without recourse to parametric iteration, but emphasized the need for adequate characterization of engineering properties for the entire soil profile. Vaziri (1996) described a simple, efficient and practical numerical model for analysis of cantilevered and strutted flexible retaining walls. The model had incorporated a variety of features that affected the performance of the retaining walls in the field such as installation and removal of struts, application of surcharge, changes in groundwater table, changes in soil properties and simulation of staged excavations. The model can be used effectively to perform a broad suite of parametric studies in the design stage and also as a reliable tool for predicting performance. Ou et al. (1996) further proposed a nonlinear, 3D finite element technique for deep excavation analysis. The technique as well as the analytical procedures for modeling the excavation processes were coded into a computer program, and the accuracy of the program was assessed. The case of an irregularly-shaped excavation with field measurements of wall deflection was studied and the results showed close agreement with field measurements. Zdravkovic et al. (2005) studied the effect of excavation on the surrounding areas and provided a detailed assessment of wall and ground movements.

There have been a few studies on the influencing factors of foundation pit deformations. In this paper, 3D consolidation finite element equations are derived, and the corresponding finite element program is developed. Some useful conclusions are drawn by analyzing the influence of factors such as soil permeability, rigidity and tiers of supports, rigidity of retaining wall and construction period of excavation on the pit deformations, which are beneficial to optimisation of excavation design.

2 FINITE ELEMENT EQUATIONS

Based on Biot's 3D consolidation finite element equations (Xie & Zhou 2002), and considering groundwater seepage induced by the water head difference between the inside and outside of a pit, the finite element equations of excavation are as follows:

$$\begin{bmatrix} [\mathbf{K}_{eij}] & [\mathbf{K}_{cij}] \\ [\mathbf{K}_{cji}] & -\theta \Delta t K_{sij} \end{bmatrix} \begin{Bmatrix} \Delta u_i \\ \Delta v_i \\ \Delta w_i \\ P_{i(n+1)} \end{Bmatrix} = \begin{Bmatrix} \Delta R'_{xi} \\ \Delta R'_{yi} \\ \Delta R'_{zi} \\ \Delta R'_{pi} \end{Bmatrix}$$

$$(i, j = 1, 2, \ldots, 8) \qquad (1)$$

where θ is an integral constant; Δt is the time increment; $[\mathbf{K}_{eij}]$ and $[\mathbf{K}_{cij}]$ are respectively the submatrices of the stiffness matrix and the coupling matrix; K_{sij} is an element of seepage matrix; Δu_i, Δv_i and Δw_i are the displacement increments of element node i; $P_{i(n+1)}$ is the soil water potential of element node i at $t = t_{n+1}$; $\Delta R'_{xi} = \Delta R_{xi} + [\mathbf{K}_{cij}]P_{i(n)}$, $\Delta R'_{yi} = \Delta R_{yi} + [\mathbf{K}_{cij}]P_{i(n)}$, $\Delta R'_{zi} = \Delta R_{zi} + [\mathbf{K}_{cij}]P_{i(n)}$, and $\Delta R'_{pi} = \Delta R_{pi} - \theta \Delta t K_{sij} P_{i(n)}$, ΔR_{xi}, ΔR_{yi} and ΔR_{zi} are the equivalent load increments of element node i, and ΔR_{pi} is the equivalent water runoff increment of element node i, $P_{i(n)}$ is the soil water potential of element node i at $t = t_n$.

The soil water potential of a saturated soil can be expressed using the following equation when the solute potential of the soil is neglected:

$$P = p + \gamma_w z \qquad (2)$$

where the spatial coordinate z is upwards positive; P is soil water potential of saturated soil; p is the sum of the pressure potential and the load potential, i.e. the total pore water pressure; and $\gamma_w z$ is the gravity potential.

3 ANALYSIS OF THE INFLUENCING FACTORS OF PIT DEFORMATIONS

In order to analyze the parametric influence on the pit deformations, a 3D consolidation finite element program is developed on the basis of the finite element equations derived. Using a numerical example given below, the main factors influencing the pit deformations such as soil permeability, rigidity and tiers of supports, rigidity of retaining wall and construction period of excavation are analyzed respectively.

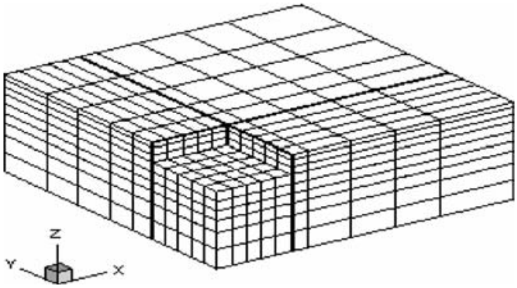

Figure 1. Mesh of finite elements.

Table 1. Duncan-Chang model parameters of soil.

Parameters	Values
K	150
n	0.7
R_f	0.85
c'	15 kPa
φ'	35°
F	0.15
G	0.35
D	3.5
K_{ur}	300

3.1 *Reference case numerical example*

The excavated length, width and depth of the foundation pit in a certain homogenous and isotropic stratum of soft soil are 60 m, 50 m and 8 m respectively. The soil's vertical and horizontal permeability coefficients are both 2.0×10^{-6} cm/s and the effective unit weight of the soil is $9.0\,\mathrm{kN/m^3}$. The retaining wall is 0.6 m thick and embedded 16 m deep in soft soil. Reinforced concrete supports are installed at different excavation stages and the horizontal spacing between supports along the pit's long side (i.e. y-direction) and short side (i.e. x-direction) is 6 m and 5 m respectively in every tier.

In order to minimize the boundary effects and improve the computational efficiency, the calculation domains in x-, y- and z-direction are 100 m, 100 m and 40 m respectively in consideration of the symmetry about the pit centerline. The finite element mesh of the soil mass and retaining wall are shown in Figure 1.

All soil units are discretized using eight-node hexahedral isoparametric elements, modelled using the nonlinear Duncan-Chang model with parameters listed in Table 1, where c' and φ' are the effective cohesion and the effective friction angle of the soil respectively, R_f is the failure ratio, and K, n, F, G, D and K_{ur} are some parameters determined by tests. The retaining wall adopts Wilson non-harmony elements, modelled as a linear elastic model, whose modulus of elasticity and Poisson's ratio are 25 GPa and 0.167 respectively. A row of 0.1 m thick interfaces, connecting the soil mass and the retaining wall is at the two sides of retaining wall, adopting 3D thin interface elements derived from Yin's rigid plastic model (Yin et al. 1995) with the outer friction angle = 1.0° and cohesion = 0.5 kPa, and its other model parameters are the same as those of the soil mass elements. The supports are modelled using a linear elastic model and spatial bar elements, with 0.6 m × 0.6 m cross section, whose elasticity modulus is 23 GPa.

The excavation involves three stages. The detailed description of the staged excavation of the pit is as follows:

1. Stage 1: 2.0 m excavation depth without supports for four days, and four days' excavation intermission for installing supports at the next excavation stage. The z value is -1.5 m for the first tier of supports and -2.0 m for the corresponding excavation level below the supports.
2. Stage 2: 3.0 m excavation depth (excavation to 5.0 m deep) with a tier of supports in six days, and six days' excavation intermission for installing the next tier of supports. The z value is -4.5 m for the second tier of supports and -5.0 m for the corresponding excavation level below the supports.
3. Stage 3: 3.0 m excavation depth (full excavation to 8.0 m deep) with two tiers of supports in eight days, and twenty days' excavation intermission for casting the pit base concrete.

3.2 *Influencing factors*

3.2.1 *Soil permeability*

In this section, the influence of soil permeability on the pit deformations at the $y = 0$ section after the third excavation stage is studied. The soil permeability for the reference case is 2.0×10^{-6} cm/s. Four more analyses are carried out for soil permeability of 2.0×10^{-5} cm/s, 5.0×10^{-6} cm/s, 5.0×10^{-7} cm/s and 2.0×10^{-7} cm/s. Figures 2–4 show the influence of soil permeability represented by permeability coefficient k on the wall horizontal displacement, ground settlement and pit base heave. With the soil permeability increasing, the vertical effective stresses outside the foundation pit also increase, but those beneath the pit base decrease, so ground settlement and pit base heave increase, which are shown in Figures 3–4. For the wall horizontal displacement, with the soil permeability increasing, the horizontal effective stresses inside and outside the pit both increase, and the wall horizontal displacement decreases as a result of the greater influence of lateral pressures acting on the wall inside the pit, which can be seen in Figure 2.

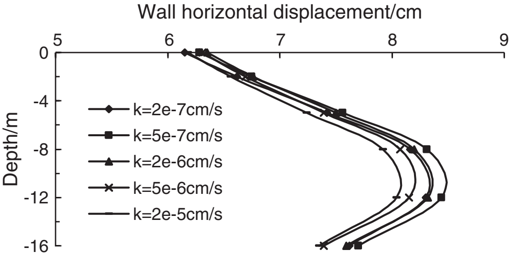

Figure 2. Influence of soil permeability on wall displacement.

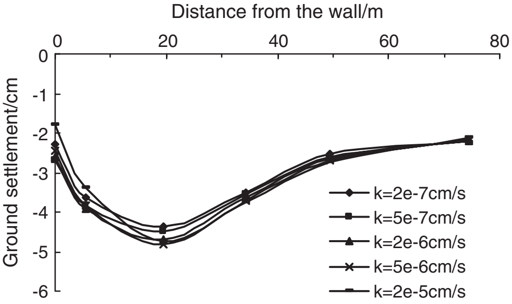

Figure 3. Influence of soil permeability on ground settlement.

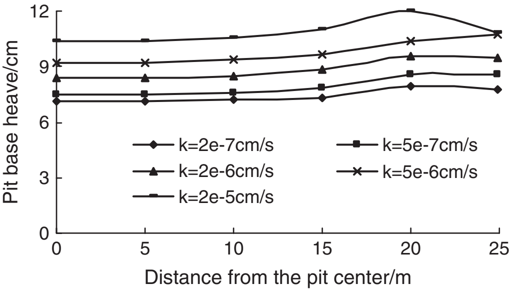

Figure 4. Influence of soil permeability on pit base heave.

3.2.2 *Rigidity of supports*

The influence of support rigidity on wall horizontal displacement, ground settlement and pit base heave at the $y = 0$ section after the third excavation stage are shown in Figures 5–7. When the support rigidity becomes larger, the retaining wall movement is more restricted, so the wall horizontal displacement is smaller. However, the influence of support rigidity on ground settlement and pit base heave is relatively insignificant.

3.2.3 *Tiers of supports*

The influence of support tiers on the pit deformations at the $y = 0$ section after the third excavation

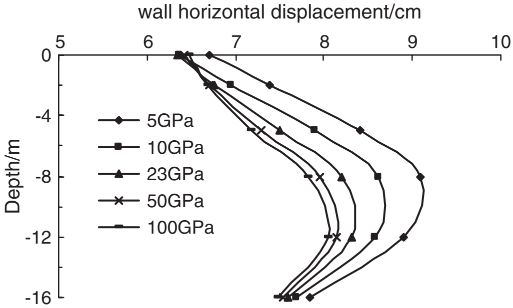

Figure 5. Influence of support rigidity on wall displacement.

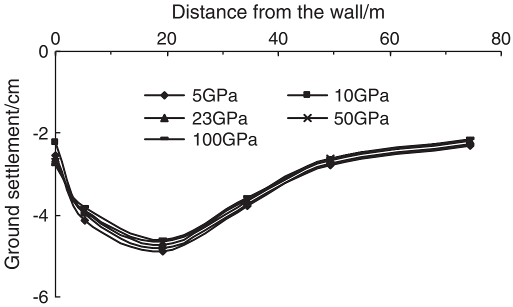

Figure 6. Influence of support rigidity on ground settlement.

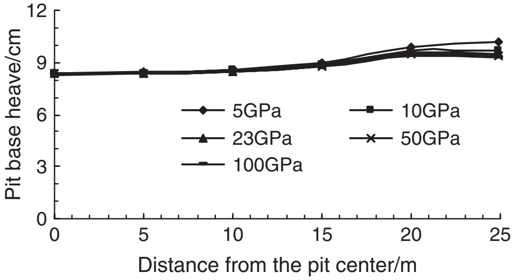

Figure 7. Influence of support rigidity on pit base heave.

stage is studied. The reference case has two tiers of support. Three more analyses are carried out: no support, one tier at 2.0 m excavation depth and one tier at 5.0 m excavation depth. Figures 8–10 show the influence of support tiers on wall horizontal displacement, ground settlement and pit base heave respectively. The deformations of the foundation pit during excavation with no support are the largest, and they evidently are smaller with adding support tiers. Tiers of support also influence the pit deformations, which for two-tier supports are less than those with one-tier. In addition, the position of the supports also greatly influences the pit deformations. The deformations with supports installed at a higher level are less than those with supports installed at a lower level under the same conditions, so the former approach is more effective for controlling the pit deformations.

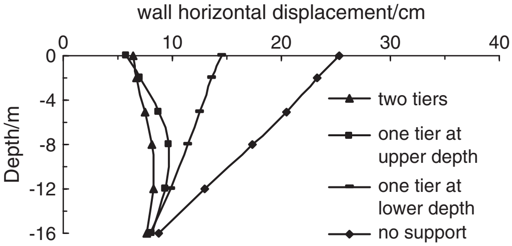

Figure 8. Influence of support tiers on wall displacement.

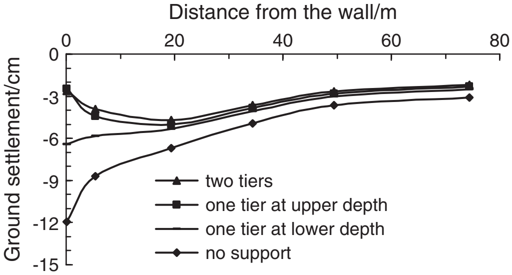

Figure 9. Influence of support tiers on ground settlement.

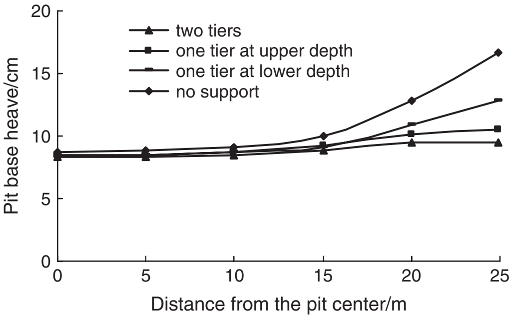

Figure 10. Influence of support tiers on pit base heave.

3.2.4 *Rigidity of retaining wall*

Figures 11–13 show the influence of rigidity of the retaining wall on wall horizontal displacement, ground settlement and pit base heave at the $y = 0$ section after the third excavation stage. The wall horizontal displacement will obviously decrease with an increase in the rigidity of the retaining wall. However, the

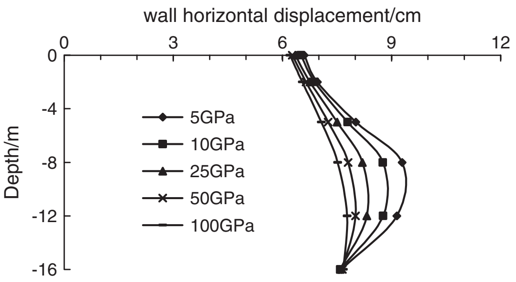

Figure 11. Influence of rigidity of retaining wall on wall displacement.

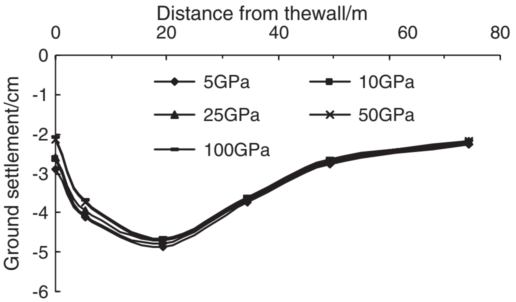

Figure 12. Influence of rigidity of retaining wall on ground settlement.

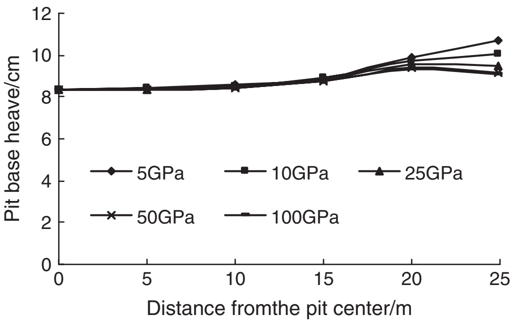

Figure 13. Influence of rigidity of retaining wall on pit base heave.

influence of rigidity of retaining wall on ground settlement and pit base heave is not significant. Therefore, increasing the rigidity of the retaining wall can effectively reduce the wall horizontal displacement and is beneficial to the safety of excavations.

3.2.5 *Construction period*

The construction period includes the excavation period and intermissions at all excavation stages, which is 48 d in the reference case. Four more analyses were carried out for construction period of 24 d, 36 d, 60 d and 72 d.

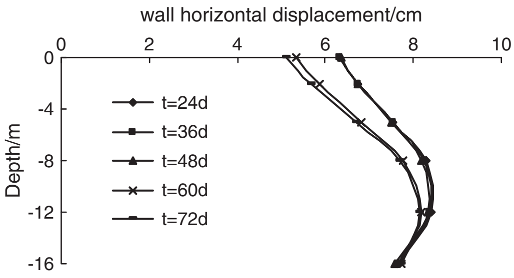

Figure 14. Influence of construction period of excavation on wall displacement.

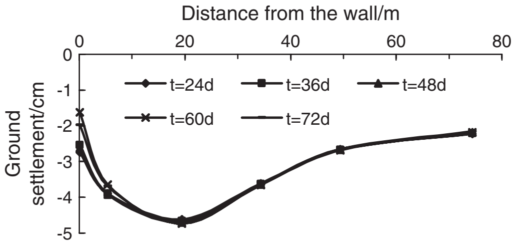

Figure 15. Influence of construction period of excavation on ground settlement.

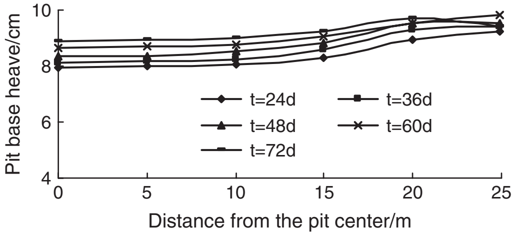

Figure 16. Influence of construction period of excavation on pit base heave.

The influence of construction period on wall horizontal displacement, ground settlement and pit base heave at the $y = 0$ section after the third excavation stage is shown in Figures 14–16. On the one hand, with the construction period increasing, the excess pore water pressures have a longer time to dissipate, and the soil strata can achieve a higher degree of consolidation, gaining higher strength and stiffness, thus the wall horizontal displacement decreases to a certain extent. On the other hand, the pit base heave increases with an increase in construction period. The influence of construction period on ground settlement is relatively insignificant.

4 CONCLUSION

Based on Biot's consolidation theory, finite element equations were deduced and a computer program was developed. The influence of the key parameters such as soil permeability, rigidity and tiers of supports, rigidity of the retaining wall, and the construction period on pit deformations is studied using the finite element program. The study and the results reported in this paper are helpful to guide excavation engineering.

ACKNOWLEDGEMENTS

This research project was supported by the China Postdoctoral Science Foundation (No. 20060400672) and Innovation Fund of Shanghai University, China.

REFERENCES

Ou, C.Y., Chiou, D.C. & Wu, T.S. 1996. Three-dimensional finite element analysis of deep excavation. *Journal of Geotechnical Engineering, ASCE* 122(5):337–345.

Vaziri, H.H. 1996. A simple numerical model for analysis of propped embedded retaining walls. *International Journal of Solids Structures* 33(16):2357–2376.

Whittle, A.J., Hashash, Y.M.A. & Whitman, R.V. 1993. Analysis of deep excavation in Boston. *Journal of Geotechnical Engineering, ASCE* 119(1):69–90.

Xie, K.H. & Zhou, J. 2002. *Theory and Application of Finite Element Analysis in Geotechnical Engineering*. Science Press, Beijing.

Yin, Z.Z., Zhu, H. & Xu, G.H. 1995. A study of deformation in the interface between soil and concrete. *Computers and Geotechnics* 17:75–92.

Zdravkovic, L., Potts, D.M. & St John, H.D. 2005. Modelling of a 3D excavation in finite element analysis. *Geotechnique* 55(7):497–513.