Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

RELIABILITY ASSESSMENT OF GROUND SURFACE SETTLEMENT INDUCED BY BRACED EXCAVATION SUBJECTED TO A SIGNIFICANT GROUNDWATER DRAWDOWN

RUNHONG ZHANG [1] WENGANG ZHANG [2*] and ZHONGJIE HOU[3]

[1] *School of Civil Engineering, Chongqing University, Chongqing, China.*
E-mail: ZhangRH@cqu.edu.cn
[2] *Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongqing University, Chongqing, China.*
Corresponding author, E-mail:cheungwg@126.com
[3]*School of Civil Engineering, Chongqing University, Chongqing, China*
E-mail: azonger@163.com

Braced excavation systems are commonly required to ensure stability in the construction of basements for shopping malls and underground transportation facilities. For excavations in deposits of soft clays, stiff retaining wall systems such as diaphragm walls help to restrain ground movements and wall deflections in order to prevent damage to nearby buildings and utilities. The ground surface settlement behind the excavation is closely associated with the magnitude of basal heave and the wall deflections and is influenced by the possible ground water drawdown. This paper numerically investigates the influences of excavation geometries, the system stiffness, the soil properties and water drawdown on ground surface settlement and develops a simplified maximum surface settlement model. Considering the uncertainties of the design parameters, a probabilistic framework combining the estimation model with First-order Reliability Method (FORM) is proposed to determine the probability that a threshold surface settlement is exceeded.

Keywords: reliability, ground surface settlement, braced excavation, FORM, groundwater drawdown

1 Introduction

One of the main concerns in a braced excavation in an urban area is the risk of damages to adjacent infrastructures caused by the excavation-induced ground movements. Evaluating the magnitude and distribution of ground movements adjacent to a supported excavation is an important part of the design process. Although numerical modeling is a powerful tool in many design situations, it can be costly and requires considerable training to implement and interpret results. Therefore, empirical/semi-empirical methods are most commonly used to predict induced ground movements due to a supported excavation.

There are many empirical/semi-empirical methods for estimating the excavation-induced maximum wall deflections (Mana and Clough 1981, Wong and Broms 1989, Clough and O'Rourke 1990, Hashash and Whittle 1996, Addenbrooke et al. 2000, Kung et al. 2007, Zhang et al. 2015, Goh et al. 2017). However, when it comes to the estimation of the excavation-induced ground surface settlements, apart from the previous charts proposed during the last century (Peck 1969, Clough and O'Rourke 1990, Ou et al. 1993, Hsieh and Ou 1998), limited approaches can be referred to (Hsieh and Ou 1998, Kung et al. 2007, Cham and Goh 2011, Zhang et al. 2015, Goh et al. 2017). The reasons might lie in that: firstly the ground surface settlement response is more complicated and is generally monitored by settlement markers at different distances from behind the wall while for wall deflection, the wall inclinometer instrumentation is much easier; secondly, it is generally accepted that the maximum ground surface settlement is generally within 0.5–1.0 time the maximum wall deflections for braced excavations (Mana and Clough 1981, O'Rourke 1981, Goh et al. 2017). Nevertheless, the latter is true only when the ground surface settlement is solely caused by the wall deflection through the deformation compatibility mechanism. For cases with considerable groundwater drawdown behind the excavation, consolidation settlements are introduced due to the increased effective stresses as a result of the water drawdown, under which circumstance the measured sum ground surface settlement would be much greater.

This paper numerically investigates the influences of excavation geometries, the system stiffness, the soil properties and the groundwater drawdown on the ground surface settlement and develops a simplified maximum surface settlement model. Considering the uncertainties of the design parameters, a probabilistic framework combining the estimation model with FORM is proposed to determine the probability that a threshold surface settlement is exceeded.

2 Soil model

The hardening-soil (HS) model is an advanced constitutive model for simulating the behavior of soils. The model involves frictional hardening characteristics to model plastic shear strain in deviatoric loading, and cap hardening to model plastic volumetric strain in primary compression. Failure is still defined by the MC failure criterion. In view that at low strain levels most soils exhibit a higher stiffness than at engineering strain levels for braced excavation problems, and this stiffness varies non-linearly with strain. The hardening-soil with small strain (HSS) is an improvement based on the HS model, accounting for the increased stiffness of soils at small strains with introduction of two additional parameters. For brevity, the use of HSS model and the determination of HSS model parameters are not included. More details can be referred in Zhang and Goh (2015) and Liang and Jia (2017).

3 Finite element analysis

Parametric studies have been carried out using the HSS model for the soft clay with emphasis on the ground surface settlements. Figure 1 shows schematically the cross section of the excavation system, with a slightly simplified soil profile comprising of a thick normally consolidated soft clay layer overlying a stiff clay layer, typical of soil conditions in many coastal areas. The MC constitutive relationship was used to model the stiff clay (γ = 20 kN/m^3, c_u = 500 kPa, E_u = 250 MPa) underlying the soft clay deposit. The soft clay thickness is denoted as T in Figure 1.The penetration depth of the wall into the stiff layer was 5 m which is proved to be sufficient.

The analyses considered a plane strain excavation supported by a retaining wall system. Considering symmetry, only half the cross-section was considered. The soil was modeled by 15-noded triangular elements. The structural elements were assumed to be linear elastic with the wall represented by 5-noded beam elements and 3-noded bar elements were used for the 6 levels of struts located at depths of 1 m, 4 m, 7 m, 10 m, 13 m and 16 m below the original ground surface. The nodes along the side boundaries of the mesh were constrained from displacing horizontally while the nodes along the bottom boundary were constrained from moving horizontally and vertically. The right vertical boundary extends far from the excavation to minimize the effects of the boundary restraints. The ranges of properties varied are shown in

Table 1. The various φ, K_0, and E_{50}^{ref} values derived from the commonly used empirical equations (Zhang 2015, Liang 2017) are listed in Table 2.

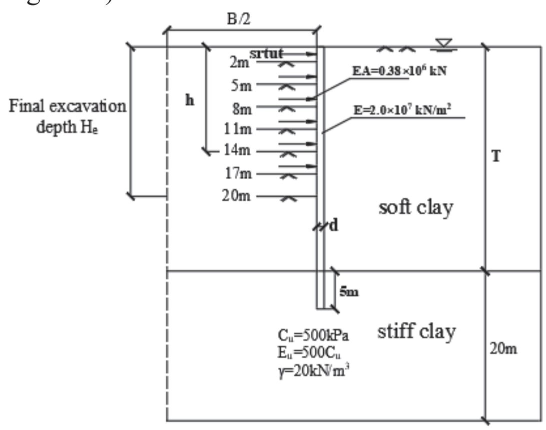

Figure 1 Cross-sectional soil and wall profile

Table 1 Parameters considered and the ranges

Parameter	Ranges	Parameter	Ranges
Relative shear strength ratio c_u/σ'_v	0.25, 0.30, 0.35	Excavation width B (m)	30, 40
Relative soil stiffness ratio E_{50}/c_u	100, 200, 300	Soft clay thickness T (m)	25, 30
Groundwater drawdown d_w (m)	0.3, 6.0, 12.0	Excavation depth H_e (m)	14, 17, 20
*System stiffness S	7.309，8.176，8.846		

* Influence of wall stiffness was studied by varying wall thickness d while keeping the Young's modulus of the wall constant (E = 2.0×10^7 kN/m^2). The corresponding natural logarithm of the system stiffness $\ln(EI/\gamma_w h^4_{avg})$, denoted by S for the wall thickness of 0.9, 1.2 and 1.5 m with average vertical strut spacing h_{avg}=3m are 7.309，8.176，8.846, respectively.

Table 2 ϕ K_0 and E_{50}^{ref} values for soft clay in HSS model

c_u/σ'_v		0.25	0.30	0.35
φ(°)		22.3	26.4	30.4
K_0		0.621	0.555	0.494
E_{50}^{ref} (kPa)	E_{50}/c_u=100	4026	5405	7085
	E_{50}/c_u=200	8052	10811	14170
	E_{50}/c_u=300	12077	16216	21255

The strut stiffness per meter EA is assumed as a constant at 3.80×10^{6}kN/m since the influence of strut stiffness on wall deflection is not very significant when the strut is stiff (Poh and Wong 1997). A total of 746 hypothetical cases were analyzed.

The construction sequence comprised the following steps: (1) the wall is installed ("wished into place") without any disturbance in the surrounding soil; (2) the soil is excavated uniformly 1 m below each strut level prior to adding the strut support with struts at 3 m vertical spacing until the final depth H_e is reached. The groundwater table was at the ground level when the excavation started. As excavation proceeds, the water head inside excavation drop to the excavation level with each stage. The groundwater drawdown outside excavation may be caused by wall leakage, flow from beneath wall and perched water, flow along wall interface or poor D-wall panel connections. The maximum drawdown is considered as 12m, 6m and 0.3m, respectively, the drawdown curve is determined through the steady state seepage pattern (Wen and Lin 2002).

Figure 2 presents the wall deflections and ground surface settlements corresponding to different excavation stages for the case of B=30 m, H_e=20 m, c_u/σ'_v=0.35, E_{50}/c_u=200, S=8.176, d_w=0.3m and T=30 m with a penetration depth of 5 m. Both the maximum wall deflection δ_{hm} and the maximum ground surface settlement δ_{vm} increases as excavation proceeds.

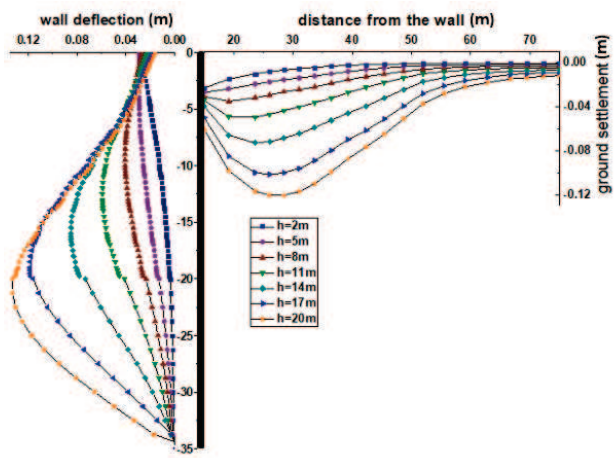

Figure 2 Wall deflections and ground surface settlements

For brevity, only some general trends of the ground surface settlements are highlighted. The influence of the soil stiffness ratio E_{50}/c_u and the shear strength ratio c_u/σ'_v is shown in Figure 3 for cases with B=30 m, T=25 m, H_e=17m, S=8.176 for c_u/σ'_v = 0.25, 0.3 and 0.35 and for E_{50}/c_u = 100, 200 and 300 respectively. It is obvious that the ground settlement decreases with the increase of the relative soil stiffness ratio E_{50}/c_u and the soil shear strength ratio c_u/σ'_v. In addition, the influence of water drawdown d_w is also significant as the ground surface settlement increases obviously with the increase of d_w.

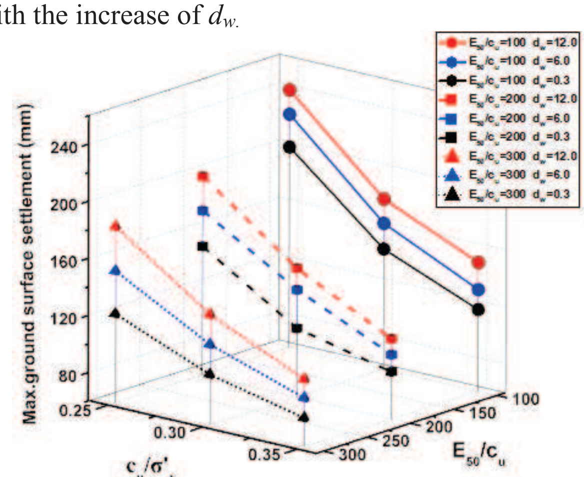

Figure 3 Effect of soil shear strength ratio on ground settlement

4 Ground surface settlement estimation model

Based on the results, an Exponential Polynomial Regression (EPR) model has been developed for estimating the maximum ground surface settlement δ_{vm} as a function of seven input parameters: B, T, H_e, c_u/σ'_v, E_{50}/c_u, S, and d_w. The optimal regression equation with coefficient of determination of R^2=0.925 for δ_{vm} takes the following form:

$$\delta_{vm}=24.26B^{0.3747}T^{0.7251}(H_e)^{1.2032}(c_u/\sigma'_v)^{-1.4687}(E_{50}/c_u)^{-0.5479}S^{-2.2223}(d_w)^{0.1013} \quad (1)$$

5 FORM reliability analyses

With determination of the performance function Eq. (1), reliability assessment of ground surface settlement can be performed using First-order reliability method (FORM), as shown in Fig. 4. B, T, H_e, S and d_w are treated as deterministic since the values of these five variables can be determined easily. The relative soil shear strength ratio and stiffness ratio are regarded as random variables. The coefficient of variation (COV) for these two parameters is assumed to changing from 0.05 to 0.4 in consideration of the different variation degree. Failure occurs if the predicted maximum ground surface settlement is greater than the threshold values.

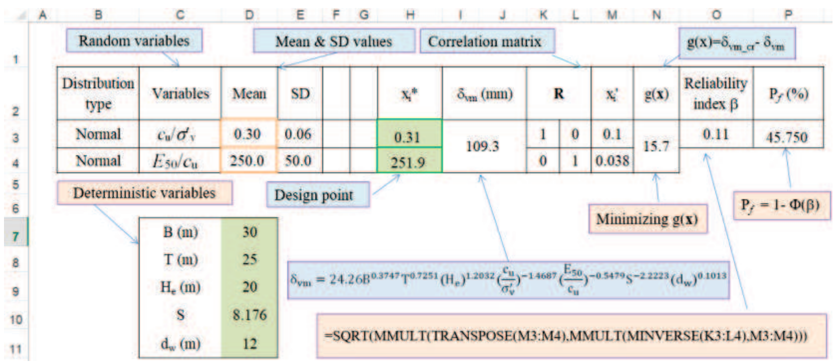

Fig. 4 Implementation of EPR model into FORM Spreadsheet for reliability analyses

For illustrative purpose, Table 3 lists two synthetic cases used for reliability index.

Table 3 Two synthetic cases for reliability analysis

Case No	Parameter combination
1	B=30 m, T=25 m, H_e=17 m, S=8.176, d_w=0.5 m, 6 m and 12 m, average c_u/σ'_v=0.30, E_{50}/c_u=200, COV of both c_u/σ'_v and E_{50}/c_u = 0.05, 0.10,0.15,0.20,0.25,0.30,0.35,0.40
2	B=30 m, T=25 m, H_e=20 m, S=8.176, d_w=0.5 m, 6 m and 12 m, average c_u/σ'_v=0.30, E_{50}/c_u=250, COV of both c_u/σ'_v and E_{50}/c_u = 0.05, 0.10,0.15,0.20,0.25,0.30,0.35,0.40

Fig. 5a plots the changes of β with the COV values for groundwater drawdowns of 0.5, 6.0 and 12.0 m, respectively, for the two cases. It is obvious that β decreases as the variation becomes greater. In addition, the case with greater drawdown is more prone to failure. Fig. 5b indicates that the choice of threshold ground surface settlement is also important since the greater the threshold is set, the smaller probability that this value can be exceeded.

6 Summary and conclusions

Based on the numerical results, this paper proposes an EPR model for maximum surface settlement estimation. A probabilistic framework combining the estimation model with FORM approach is proposed to determine the probability that a threshold surface settlement is exceeded, allowing engineers to take mitigation works such as recharging or fissure grouting to meet the different target reliability indices.

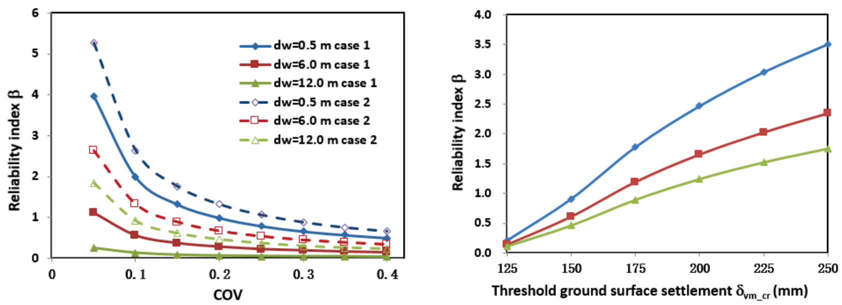

Fig. 5 Influence of (a) COV and d_w, (b) threshold ground surface settlement on β

References

AddenbrookeTI, Potts DM, Dabee B. Displacement flexibility number for multiple retaining wall design.*Journal of Geotechnical andGeoenvironmentalEngineering*, 126(8): 718–726, 2000.

Clough, GW, and O'Rourke TD, Construction induced movements of in-situ walls. Design and Performance of Earth Retaining Structure, *Geotechnical Special Publication No. 25, ASCE, New York*, 439-470, 1990.

Clough GW, O'Rourke TD. Construction induced movements of in situ walls. *Design and Performance of Earth Retaining Structures,ASCE Special Conference* 439–470, Ithaca, New York, 1990

Cham W M, and Goh K H, Prediction of ground settlement due to adjacent deep excavation works. *Underground Singapore* , 94-103, NUS, Singapore,2011.

Goh ATC, Zhang F, Zhang WG, Zhang YM, Liu Hl. A simple estimation model for 3D braced excavation wall deflection. *Computers and Geotechnics* 83: 106-113,2017.

Hashash YMA,Whittle AJ. Ground movement prediction for deep excavations in soft clay.*Journalof Geotechnical Engineering*, 122 (6): 474–486, 1996.

Hsieh PG, and Ou CY, Shape of ground surface settlement profiles caused by excavation.*Can. Geotech*. , 35(6), 1004-1017, 1998.

Kung GTC, Juang CH, Hsiao ECL, Hashash YMA. Simplified model for wall deflection and ground-surface settlement caused by braced excavation in clays.*Journal of Geotechnical and Geoenvironmental Engineering*,133(6): 731–747,2007.

Liang FY, Jia YJ. Experimental study on parameters of HSS model for soft soils in Shanghai. *Chinese Journal of Geotechnical Engineering*, 39(2):269-278, 2017.

Mana AI, Clough GW. Prediction of movement for braced cuts in clay. *Journal of Geotechnical and GeoenvironmentalEngineering*, 107 (6): 759–777, 1981.

O'Rourke TD, Ground movements caused by braced excavations. *Journal of Geotehcncial Engineering Division ASCE*, 107(9): 1159-1178, 1981..

Ou, CY, Hsieh, PG, and Chiou DC,. Characteristics of ground surface settlement during excavation. *Can. Geotech*., 30(5), 758-767,1993.

Peck RB,Deep excavation and tunneling in soft ground, *7th Int. Conf. on Soil Mechanics and Foundation Engineering*, Sociedad Mexicana de Mecanica, Mexico City, 225-290,1969.

Poh TY, Wong IH, Chandrasekaran B, Performance of two propped diaphragm walls in stiff residual soils. *Journal of Performance of Constructed Facilities*, 11(4): 190–199,1997.

Wong KS, Broms BB. Lateral wall deflections of braced excavation in clay. *Journal of Geotechnical Engineering*, 115 (6): 853–870,1989.

Wen DZ and Lin KQ. The effect of deep excavation on pore water pressure cahnges in the Old Alluvium and under-drainage of marine clay in Singapore.*Geotechnical Aspects of Underground Construction in Soft Ground*.Specifique,Lyon.ISBN 2-9510416-3-2, 2002.

Zhang WG, Goh ATC. A simple prediction model for wall deflection caused by braced excavation in clay. *Computers and Geotechnics* .63: 67-72, 2015.