Finite element analysis of basal heave stability for braced excavations in clays

Zhang Fanⁱ⁾ and Anthony T. C. Gohⁱⁱ⁾ⁱ⁾ PhD Graduate Student, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.ⁱⁱ⁾ Associate Professor, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

ABSTRACT

The basal heave stability of braced excavations in clay soils is one of the key considerations in both design and during construction. The finite element method with shear strength reduction (SSR) is increasingly being used for estimating the safety factor for geotechnical engineering problems. In this paper, results of basal heave stability for deep narrow braced excavations in terms of factor of safety (FS) and stability number (N_s) using two-dimensional finite element method with SSR are presented. Total stress finite element simulations are carried out to parametrically analyse the effects of system stiffness, undrained shear strength and excavation geometry on the base stability of braced excavations in different clay soils. For the cases considered, the study shows that the system stiffness has minimal influence on the factor of safety against basal heave. The stability number N_s calculated from finite element analysis is independent of the undrained shear strength of clays. Also, the N_s value decreases almost linearly as the ratio of the depth to the width of the excavation increases. The failure zone from finite element analysis is more extensive than that proposed by Terzaghi. Comparison of the factor of safety between the calculations from conventional methods and from finite element analysis indicate that the modified Terzaghi's method that considers the wall embedment depth are in close agreement with the results based on the plane strain finite element analyses.

Keywords: basal heave stability, finite element analysis, braced excavations, clays

1 INTRODUCTION

The basal heave stability assessment for deep braced excavations in clay soils is important and necessary to carry out in practice. Conventional methods such as Terzaghi's method (Terzaghi 1943) are commonly used, but many of these classical methods were developed decades ago, when the computation technology was not as developed as today. The finite element method (FEM) with shear strength reduction (SSR) has been recognised as a robust approach (Matsui and San 1992, Griffiths and Lane 1999, Do et. al. 2013, *etc.*) for estimating the safety factor for geotechnical engineering problems. But there has been limited literature reported on the assessment of the factor of safety for deep braced excavations in clay soils using this approach. Besides, it is useful to compare the factor of safety between numerical calculations and conventional methods, so that guidelines can be highlighted for engineering design and practice.

In this paper, the investigation of basal heave stability for deep narrow braced excavations using finite element analysis is carried out through assessing the factor of safety (FS) and the stability number (N_s). A total of 72 plane strain FE calculations are conducted to analyse various factors affecting the base stability of

braced excavations in different clay soils. The factors considered include the system stiffness, the undrained shear strength of the clay soils and the geometry of the excavation and wall. A comparison of the factor of safety FS between FEM and several conventional methods is also carried out.

2 CONVENTIONAL METHODS FOR BASAL HEAVE STABILITY – AN OVERVIEW

Terzaghi (1943) first proposed a failure mechanism for basal heave stability for wide excavations, which was developed for wide excavations with sheetpile walls. One of the modifications suggested by Terzaghi (1943) also takes the wall embedment depth D into account. Bjerrum and Eide (1956) provided an approach for determining the factor of safety for narrow excavations to complement Terzaghi's method. A bearing capacity factor N_c is introduced, which can be determined as a function of the H/B ratio and L/B ratio, where H refers to the excavation depth, L refers to the excavation length and B refers to the excavation width. Goh (1994) studied the basal heave stability for wide braced excavations in soft clay by conducting a series of finite element analysis using the nodal displacement method proposed by Goh (1990). Multiplier factors are

proposed which take the clay thickness, the wall penetration depth and the wall stiffness into consideration. These methods are summarised in Table 1.

Table 1. Summary of conventional methods for the basal heave calculation

Factor of Safety	Notes	Reference
$FS_{T1} = \frac{5.7c_u B_1}{\gamma H B_1 - c_u H}$	Wide excavations ($B > H$) of rectangular shape	Terzaghi (1943)
$FS_{T2} = \frac{5.14c_u + \sqrt{2}(\frac{H_w}{B}) + 2c_u(\frac{D}{B})}{\gamma H}$	Embedded wall considered; Perfectly smooth footing ($N_c = 5.14$)	Terzaghi (1943)
$FS_{B\&E} = \frac{c_u N_c}{\gamma H + q}$	Narrow excavations ($B < H$)	Bjerrum & Eide (1956)
$FS_{Gh} = \frac{c_u N_h}{\gamma H + q} \mu_i \mu_d \mu_w$	Homogenous and constant c_u ; $H/B < 0.6$	Goh (1994)

3 DEVELOPMENT OF THE FINITE ELEMENT MODEL FOR BASAL HEAVE STABILITY

Plane strain finite element analyses using Plaxis 2011 (Brinkgreve et al., 2011) were carried out in which various geometrical factors, wall stiffness and undrained shear strength properties were varied. Total stress Mohr-Coulomb constitutive soil model was employed in the finite element analysis.

3.1 Geometry

The cross-section of the excavation is depicted in Fig. 1. The geometrical parameters that were varied included the excavation depth H (9 m, 12 m, 15 m and 16 m), the wall penetration depth D , the clay thickness below the current excavation level T , the net clay thickness at the final excavation level T_n (32 m, 14 m, 10 m), and the embedment depth at the final excavation level D_n (4 m, 0). For a wall of height H_w (20 m), as the excavation depth H is increased, there is a corresponding decrease in the depth of embedment D ($= H_w - H$). The notations T_n and D_n correspond to the special case when H was at the final excavation level. The excavation width B was 20 m for all the cases considered.

3.2 Properties of clay soils, retaining walls and retaining structures

Clays with three different undrained shear strengths (c_u) were assumed as shown in Table 2. The soil stress-strain behaviour was modelled using the Mohr-Coulomb soil model with a Poisson's ratio $\nu = 0.495$ and $E_u/c_u = 300$. Total stress analyses were carried out to determine the factor of safety using the SSR method. Fig. 2 shows a typical plot of the plastic points for the case with $H = 16$ m and $c_u = 40$ kPa.

Table 2. Mohr-Coulomb soil properties in basal heave stability analysis.

Soil	γ (kN/m ³)	c_u (kPa)	E_u (kN/m ²)
A	16	40	1.2E04
B	16	60	1.6E04
C	16	70	2.1E04

Table 3. Retaining wall properties.

Wall Type	System stiffness S	EI (kNm ² /m)	EA (kN/m)
Flexible	32	5.04E+04	3.427E+06
Medium	320	5.04E+05	3.427E+07
Stiff	3200	5.04E+06	3.427E+08

Fig. 1. Geometry of braced excavation.

Fig. 2. A typical plastic points (red dots) plot from FEM

To assess the influence of the wall stiffness on the basal heave stability, walls with three different system stiffnesses are employed and denoted as flexible, medium and stiff walls as shown in Table 3. The system stiffness S (Clough and O'Rourke, 1990) was defined as $EI/(\gamma_w H_{avg}^4)$, where EI is the wall stiffness and H_{avg} is the average vertical spacing of the struts.

To increase the accuracy of the results, very fine meshes are generated with a global error of 0.01 in the SSR evaluation, according to the Plaxis Manual (Brinkgreve et al., 2011).

4 EFFECTS OF VARIOUS FACTORS ON BASAL HEAVE STABILITY

4.1 Effect of system stiffness

Fig. 3 shows the results of the factor of safety versus system stiffness for various H/B ratios (0.45, 0.60, 0.75, 0.80) for the cases with $c_u = 40$ kPa, $D_n = 4$ m, $T_n = 32$ m. Similar trends were observed for $c_u = 60$ kPa and 70 kPa. The results indicate that system stiffness has minimal influence on the base stability of the excavation for the cases considered.

Fig. 3. Logarithm of system stiffness versus FS_{FE} ($c_u = 40$ kPa, $D_n = 4$ m, $T_n = 32$ m)

4.2 Effect of undrained shear strength

In order to assess the effects of the various parameters on the factor of safety for different undrained shear strength, a nondimensional stability number N_s is introduced. N_s is defined as:

$$N_s = \frac{FS \gamma H}{c_u} \quad (1)$$

Since the wall stiffness does not influence the FS from plane strain analysis, only N_s values from the cases with flexible walls are shown in Figure 4. From the figure, it can be seen that the stability number is almost independent of the undrained shear strength.

Fig. 4. N_s values versus H/B ratio for different undrained shear strengths (flexible wall, $D_n = 4$ m, $T_n = 32$ m).

4.3 Effect of geometry

From Fig.4, it can also be seen that the H/B ratio is approximately linearly related to N_s , and significantly influences the basal heave stability. However, it is

worth noting that the range of the H/B ratio considered is only from 0.45 to 0.8.

Fig 5 indicates that the T/B ratio is also another important parameter affecting the basal heave stability. The N_s value decreases sharply particularly when the T/B ratio is less than 1.0. As shown in Table 4, the net embedment depth D_n is another important parameter as increasing D_n leads to the increase in N_s .

Fig. 5. N_s values versus T/B ratio (flexible wall, $D_n = 4$ m, $c_u = 40$ kPa).

Table 4. N_s values for different D_n (flexible wall, $T_n = 36$ m, $c_u = 40$ kPa)

H/B	N_s	
	$D_n = 0$	$D_n = 4$ m
0.45	6.65	7.23
0.60	6.39	7.06
0.75	6.14	6.75
0.80	-	6.64

5 COMPARISONS OF FACTOR OF SAFETY: FEM AND CONVENTIONAL METHODS

Comparisons are made between the factor of safety results from the finite element analysis and conventional methods.

As highlighted previously, the finite element analysis indicates that the wall stiffness has minimal effect on the factor of safety for the cases considered. Therefore, the FE results for the flexible wall cases are plotted in Fig 6. Also shown in Fig. 6 are the FS values determined using Terzaghi's method (FS_{T1}), Goh's method (FS_{Gh}), modified Terzaghi's method (FS_{T2}), and Bjerrum and Eide's method (FS_{BE}). One of the limitations of Goh's method is that it can only be used when H/B ratio is smaller than 0.6.

Generally, Terzaghi's method overestimates the factor of safety for the cases with $c_u = 60$ kPa and 70 kPa. The plastic points (red dots) plot in Fig 2 also suggests that the failure zone is beyond the side and bottom of that assumed in Terzaghi's method. The Bjerrum and Eide's method gives smaller FS values when H/B ratio is small. The results based on the modified Terzaghi's method are in close agreement with the results based on the plane strain finite element

analyses.

Fig. 6. Comparison of FS: FEM and conventional methods for $c_u = 40$ kPa, 60 kPa and 70 kPa ($D_n = 4$ m, $T_n = 32$ m)

6 CONCLUSIONS

In this paper, two-dimensional FE simulations for estimating the basal heave stability of braced excavations under total stress conditions are conducted. The Mohr-Coulomb constitutive soil model is employed. The parameters studied include the retaining system stiffness, the undrained shear strength of the clay soils and geometrical properties of the wall and excavation.

To conclude, the system stiffness has minimal influence on the factor of safety against basal heave calculated from two-dimensional finite element analysis for the cases considered. The stability number N_s values calculated from two-dimensional analysis are independent of undrained shear strength. The increase

of H/B ratio leads to a linear decrease in N_s values. Decreasing T/B ratio and increasing D_n helps to increase the basal heave stability. Comparisons between the FS from some conventional methods are made and summarised in Table 5.

Recent FEM studies by Do et. al. (2013) have shown that the intersection method are generally in good with field observations. The main limitation of this approach is the necessity to perform repeated analyses to obtain the FS. This will be considered in subsequent studies.

Table 5. Summary of comparisons between conventional methods and FEM

Conventional methods	Comments
Terzaghi (FS _{T1})	generally overestimates FS _{FE}
Modified Terzaghi (FS _{T2})	close agreement with FS _{FE}
Goh (FS _{Gh})	close agreement with FS _{FE} but only applicable when H/B is smaller than 0.6
Bjerrum and Eide's (FS _{BE})	underestimates when H/B is small

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