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Basal heave stability of supported circular excavations in clay

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ABSTRACT

Deep circular shafts are commonly used for example to construct access shafts for transit tunnels, pump stations for wastewater tunnels, and launch shafts for tunnel boring machines. Since the earth pressures acting on a circular shaft subjects the shaft support to ring compression, the reinforcement in the structural elements can be reduced and the need for internal support is eliminated, thereby speeding up excavation. The design of circular support systems for excavations in clays involves assessing the ground stresses and ground movements, the capacity of the structural elements, and the basal heave stability. This study focused on assessing the basal heave stability of diaphragm wall supported circular excavations in clays using the finite element method. The analyses have shown that the basal heave factor of safety is dependent on the undrained shear strength of the clay, the geometrical properties of the excavation system and the thickness of the soil stratum. Based on these results, a simplified method is proposed for assessing the basal heave factor of safety for axisymmetric supported excavations in clay.

1. Introduction

Tunnelling projects for transit railway and sewage systems often require the construction of deep excavation shafts to facilitate the launching of tunnel boring machines as well as for access and ventilation purposes. These shafts can be either rectangular or circular in shape. Circular shafts are becoming increasingly popular due to improvements in construction methods and equipment. Circular shafts are often preferred because their high structural stiffness through hoop forces can lead to less reinforcement in the structural elements and also minimize the ground displacement during excavation. In addition, the shafts can be constructed without the use of internal struts, hence providing a relatively obstruction free area for excavation works.

As with rectangular-shaped excavations, the design of circular excavations in clays involves the assessment of the ground stresses and ground movements, the capacity of the structural elements, and the basal heave stability. The majority of the studies involving circular excavations have focused on the performance of the wall system and associated ground movements (Parashar et al., 2007; Arai et al., 2007; McNamara et al., 2008; Kim et al., 2013; Tan and Wang, 2015; Schwamb et al., 2014). While a number of researchers have examined the basal heave stability of rectangular braced excavation systems (Bjerrum and Eide, 1956; Goh, 1994; Faheem et al., 2003, 2004), only limited studies (e.g., Cai et al., 2002) have been carried out for circular supported excavations. Most of the studies on the basal heave stability of circular excavations in clays have focused on open and unsupported excavations using similar numerical techniques (Salencon and Matar, 1982; Britto and Kusakabe, 1983; Khatri and Kumar, 2010).

In this study, extensive finite element analyses were carried out to assess the basal heave factor of safety for circular excavations supported by diaphragm walls. The parametric study was performed using the finite element software Plaxis (Brinkgreve et al., 2011). Based on these results, a simplified method is proposed for assessing the basal heave factor of safety for axisymmetric supported excavations in clay.

2. Numerical study

Fig. 1 shows schematically the cross section of the excavation system, with a simplified soil profile comprising of a thick normally consolidated clay deposit. The Mohr Coulomb constitutive relationship was used to model the undrained behavior of the clay. For this study, cases with a homogeneous clay layer with constant undrained shear strength c_u and cases with c_u linearly increasing with depth were considered. The soil is assumed to be subjected to undrained shearing during excavation. The thickness of the clay below the final excavation level is denoted as T in Fig. 1.

The analyses considered an axisymmetric excavation of diameter B supported by a stiff diaphragm wall system. Because of symmetry, only half the cross-section was considered. The soil was modeled by 15-noded triangular elements. The wall structural elements were assumed to be linear elastic and were modeled by

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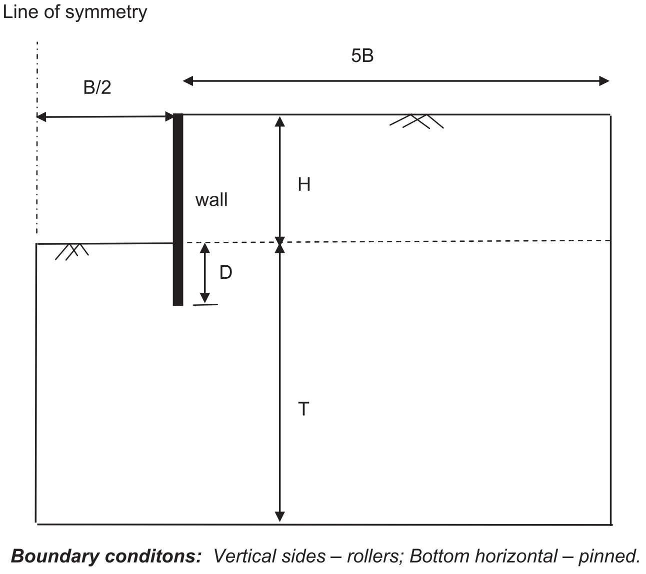

Fig. 1. Cross-sectional soil and wall profile.

5-noded beam elements. 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. A typical very refined mesh comprising 3834 elements and 31,337 nodes is shown in Fig. 2. The right vertical boundary which extends far from the excavation (~5B) to minimize the effects of the boundary restraints, is not shown in Fig. 2. The range of geometrical properties of the excavation that were considered, and the assumed wall and soil properties are shown in Table 1.

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 in 2 m intervals until the final depth H is reached. The stability of the vertical shaft was then determined using the shear strength reduction technique. This technique has been used by various authors including Matsui and San (1992), Griffiths and Lane (1999), Hammah et al. (2007), Zhang and Goh (2012), and Do et al. (2013). The method is now available in many commercial finite element and finite difference programs.

The shear strength reduction method involves progressively reducing the shear strength of the soil until the geotechnical structure such as a slope or retaining wall is on the verge of global failure. The reciprocal of this reduction factor F is identified as the factor of safety. The iterative procedure to determine factor of safety starts with assigning $F_i = F_0 = 1$. Subsequently, F_i is increased by ΔF to $F_{i+1} = F_i + \Delta F$ where typically ΔF is set to 0.1. With the updated F, for a Mohr-Coulomb material, the cohesion c and tangent of the friction angle ($\tan\phi$) are reduced as follows:

Table 1
Summary of soil, wall and geometrical properties.

Parameter	Symbol	Range of values
Wall diameter (m)	B	10–100
Final excavation depth (m)	H	16–24
Wall penetration depth (m)	D	0–24
Thickness to hard stratum (m)	T	7–120
Wall stiffness (kN m^2)	EI	5×10^6
Soil unit weight (kN/m^3)	γ	16
Soil undrained shear strength (kPa)	c_u	50–100
Soil friction angle (degrees)	ϕ_u	0
Soil undrained stiffness ratio	E_u/c_u	300
Soil Poisson's ratio	υ	0.495

$$c_{i+1} = \frac{c}{F_{i+1}} \tag{1}$$

$$\tan\phi_{i+1} = \frac{\tan\phi}{F_{i+1}} \tag{2}$$

Using the reduced strength parameters, a new equilibrium is sought by carrying out an elastic-plastic finite element (FE) analysis. If a new equilibrium is found, i.e. the analysis converges, then F is increased and a new equilibrium is sought again with reduced strength parameters. The process is repeated until the analysis does not converge or F remains constant with continuing deformation, within a certain specified number of iterations. In this study, this was set to the default of 100 iterations. This is described in detail in Brinkgreve and Bakker (1991), Matsui and San (1992), and Brinkgreve et al. (2011). This critical strength reduction value is taken to be the vertical shaft basal heave factor of safety FS_{FE}. Fig. 3 shows the results of a typical finite element (FE) shear strength reduction analysis to compute the FS_{FE} for a circular excavation.

3. Results

For brevity, only some general trends are highlighted. The influence of the diameter of the supported shaft B is shown in Fig. 4 for two cases with H = 16 m, T = 60 m and c_u = 50 kPa. The basal heave factor of safety FS_{FE} decreases with the increase of the shaft

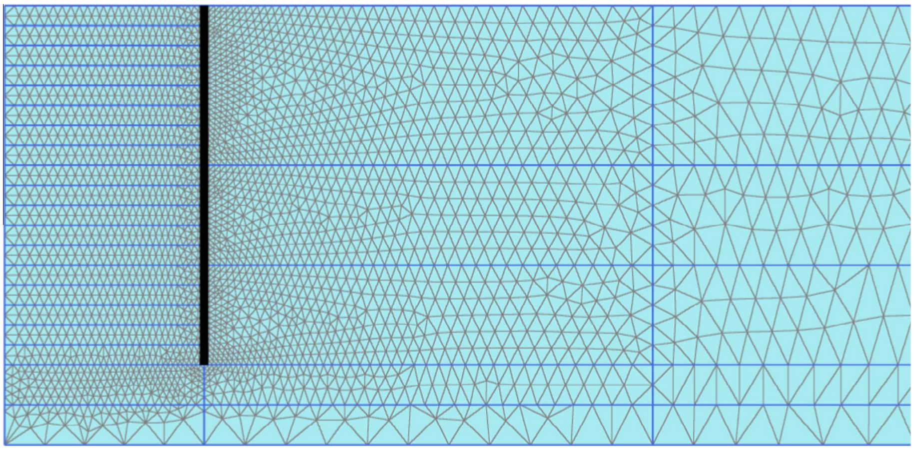

Fig. 2. Partial finite element mesh.