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A simple prediction model for wall deflection caused by braced excavation in clays

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A R T I C L E I N F O

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A B S T R A C T

Deep excavations particularly in deep deposits of soft clay can cause excessive ground movements and result in damage to adjacent buildings. Extensive plane strain finite element analyses considering the small strain effect have been carried out to examine the wall deflections for excavations in soft clay deposits supported by retaining walls and bracing. The excavation geometry, soil strength and stiffness properties, and the wall stiffness were varied to study the wall deflection behavior. Based on these results, a simple Polynomial Regression (PR) model was developed for estimating the maximum wall deflection. Wall deflections computed by this method compare favorably with a number of field and published records.

1. Introduction

One of the key concerns in constructing an underground facility within a built-up environment is the impact of the associated ground movements on adjacent buildings. For excavations in ground that comprises of thick soft clays overlying stiff clay, braced walls are usually used to minimize ground movements. It is common to extend the wall length into the stiff clay layer to prevent basal heave failure and to reduce the movement of the wall toe. To ensure the serviceability limit state is satisfied, a common design criterion is to limit the maximum wall deflection to a fraction of the excavation depth H_e, typically in the range of 0.5–1.5% of H_e. Unnecessarily severe restrictions may lead to uneconomic design. Therefore, reliable estimates of wall deflections under working conditions are essential.

The finite element method and the empirical/semi-empirical method are two common approaches for estimating wall deflections induced by excavation. The finite element method is widely employed to model complex soil-structure interaction problems. For excavations in soft clays, the Mohr–Coulomb (MC) constitutive relationship is commonly used to model the clay stress–strain behavior, with no consideration of the soil small strain effect. The importance of modeling the soil small strain behavior for many geotechnical problems has been highlighted by Burland [1] and Jardine et al. [2]. The influence of the soil small strain effect on excavation problems which has been investigated through finite element analysis with some advanced small strain constitutive models [3–5] showed improvements in the predictions of wall deflection and ground movement.

Empirical and semi-empirical methods involve interpolating from a published empirical database or numerical analyses using finite elements. Several empirical and semi-empirical methods are available for estimating the excavation-induced maximum wall deflection [6–11]. However, many empirical methods that have been proposed for estimating wall movements assume that the wall is "floating" in the soft clay, without restraint at the wall toe. This paper focuses on the specific situation of the braced wall penetrating into the stiff stratum, since as mentioned previously it is common to extend the wall length into the stiff clay layer to prevent basal heave failure and to reduce the movement of the wall toe.

In this paper, parametric studies were carried out using the plane strain finite element (FE) software Plaxis [12] in which the soft clay stress–strain behavior was modeled using the hardening small strain (HSS) constitutive relationship that considers the small strain effect. Analyses were carried out to evaluate the behavior of excavations with braced walls in soft clays. Based on these results, this paper describes the use of a simple Polynomial Regression (PR) model for relating the maximum wall deflection to various parameters such as the excavation geometry, soil

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strength and stiffness parameters and the wall stiffness. Validations of the proposed PR model were also carried out through comparisons with well-documented excavation case histories.

2. Soil model

The hardening-soil (HS) model [13] 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. The main input parameters are E_{50}^{ref}, a reference secant modulus corresponding to the reference confining pressure p^{ref}, a power m for stress-dependent stiffness formulation, effective friction angle ϕ, cohesion c, failure ratio R_f, E_{ur}^{ref} the reference stiffness modulus for unloading and reloading corresponding to p^{ref}, and υ_{ur} the unloading and reloading Poisson's ratio. This model has been used for analyses of deep excavations by a number of researchers including Finno and Calvello [14] and Bryson and Zapata-Medina [15].

The main parameters of the HSS model include G_0^{ref}, ϕ, and E_{50}^{ref}. G_0^{ref} is a reference initial shear stiffness corresponding to the reference pressure p^{ref} and shear strain $\gamma_{0.7}$ at which the secant shear modulus is reduced to 70% of G_0. Following the approach recommended by Brinkgreve et al. [12], G_0^{ref} was obtained by first determining the E_0/E_{ur} ratio based on the chart by Alpan [16] and assuming $E_{ur} = 3\,E_{50}$, where E_0 is the small strain Young's modulus, and subsequently using the expression $G_0^{ref} = E_0^{ref}/(2(1+\upsilon_{ur}))$ with υ_{ur} assumed as a constant. Since the chart for estimating the parameter $\gamma_{0.7}$ based on Vucetic and Dobry [17] and reported in Brinkgreve et al. [12] shows that $\gamma_{0.7}$ only varies within a narrow range between 1×10^{-4} and 4×10^{-4}, in this paper $\gamma_{0.7} = 2\times10^{-4}$ was assumed. The G_0 is defined as:

$$G_0 = G_0^{ref}\left(\frac{c'\cos\phi - \sigma'_3\sin\phi}{c'\cos\phi + p^{ref}\sin\phi}\right)^m \tag{1}$$

where σ'_3 is the effective confining stress (assuming compressive stress is negative). The effective friction angle ϕ is computed using the correlation proposed by Wroth and Houlsby [18]:

$$\frac{c_u}{\sigma'_v} = 0.5743\frac{3\sin\phi}{3-\sin\phi} \tag{2}$$

in which c_u is the undrained shear strength and σ'_v is the vertical effective stress. When the ground water table is at the ground surface and assuming $m = 1$, $c_u/\sigma'_v = \alpha$, soil stiffness ratio $E_{50}/c_u = \beta$ and $\sigma'_3 = K_0\sigma'_1$ in the HSS model, E_{50}^{ref} can be expressed as:

$$E_{50}^{ref} = \frac{E_{50}}{\left(\frac{\sigma'_3}{p^{ref}}\right)^m} = \frac{\alpha c_u}{\left(\frac{K_0\times c_u}{\beta\times p^{ref}}\right)^m} = \frac{\alpha\beta p^{ref}}{K_0} \tag{3}$$

The HSS model accounts for the increased stiffness of soils at small strains. At low strain levels most soils exhibit a higher stiffness than at engineering strain levels, and this stiffness varies non-linearly with strain. In the TNEC case history back analysis, Kung et al. [5] used a small-strain constitutive model as well as a Modified Cam Clay (MCC) model for soft/medium clay. Their results indicated that the small-strain model was able to predict the wall lateral deflection and ground surface settlement fairly well, but that the MCC model could not predict accurately the surface settlement. Other publications in which small strain has been used to model excavation in soft/medium clay include Hashash and Whittle [9], Jen [19], Kung [20], Finno and Tu [21], Kung et al. [22], Lam [23], and Clayton [24].

The Plaxis default values are used to define the power for stress-level dependency of the stiffness m, the coefficient of earth pressure at-rest K_0^{nc}, the Poisson's ratio υ_{ur} and E_{ur} with $m = 1$, $K_0^{nc} = 1-\sin\phi$, $\upsilon_{ur} = 0.2$ and $E_{ur} = 3E_{50}$.

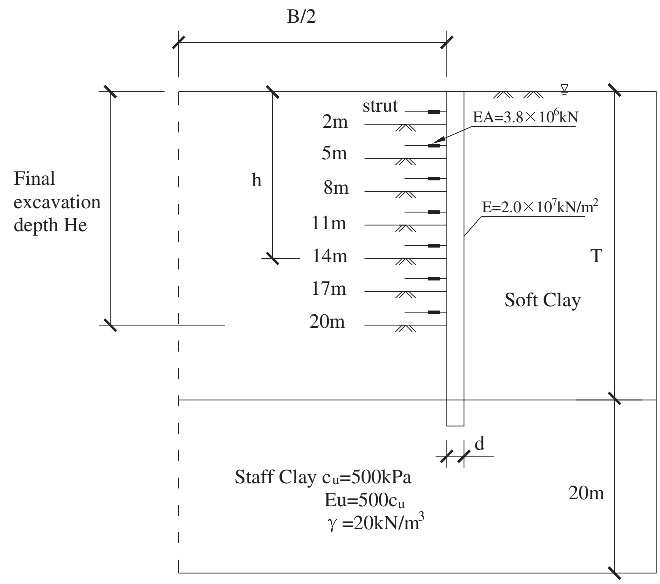

Fig. 1. Cross-sectional soil and wall profile.

3. Finite element analyses

Parametric studies have been carried out using the HSS model for the soft clay with emphasis on the maximum wall deflection predictions. Fig. 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

Table 1
Range of parameters.

Parameter	Range
Relative soil shear strength ratio c_u/σ'_v	0.21, 0.25, 0.29, 0.34
Relative soil stiffness ratio E_{50}/c_u	100, 200, 300
Soil unit weight γ (kN/m^3)	15, 17, 19
Soft clay thickness T (m)	25, 30, 35
Excavation width B (m)	20, 30, 40, 50, 60
Excavation depth H_e (m)	11, 14, 17, 20
Wall stiffness EI ($\times10^6$ kN m^2/m)	0.36, 1.21, 2.88, 5.63

Table 2
ϕ and K_0 values for soft clay in HSS model.

c_u/σ'_v	0.21	0.25	0.29	0.34
ϕ (°)	19	22.3	25.6	29.6
K_0	0.674	0.621	0.568	0.506

Table 3
E_{50}^{ref} values for soft clay in HSS model.

c_u/σ'_v	E_{50}^{ref} (kPa)			
	E_{50}/c_u = 100	E_{50}/c_u = 200	E_{50}/c_u = 300	E_{50}/c_u = 400
0.21	3114	6228	9342	12,456
0.25	4031	8062	12,093	16,124
0.29	5105	10,210	15,315	20,420
0.34	6721	13,442	20,163	26,884