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Stress paths in deep excavations under undrained conditions and its influence on deformation analysis

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ABSTRACT

The objective of this study is to examine the stress state of soils during deep excavation, in relation to the determination of appropriate soil parameters for deformation analysis of a deep excavation case using the finite element method. Two well documented case histories of a deep excavation were utilized for the validation of the analysis procedure and the selection of soil stiffness parameters. Results from the Hardening Soil model showed that the out-of-plane stress has significance influences to the direction of soil effective stress path. In addition, most of the soil inside and outside excavation zone is in the elastic behavior. Even though the effective stress path of soils adjacent to the diaphragm wall have undergone yield, but the characteristics of those soils are still dominated by the elastic behavior. Hence, the unloading/reloading parameters are predominant in a deformation analysis of an excavation case. When the undrained shear strength and unloading/reloading modulus were precisely specified, even the Mohr-Coulomb model could obtain good prediction of the wall deflections. Moreover, a hypothetical case was employed to investigate the performance of the computed ground surface settlements. The result showed that the computed ground settlement from Mohr-Coulomb model was close to the result from the Hardening Soil Small model if the layer of soft soil is deep enough and a layer of small strain stiffness zone is introduced at bottom of the model geometry.

1. Introduction

The necessity of underground space in dense urban areas, such as Taipei, Shanghai and Singapore is imperative. In the last decades there are clear trends using underground space in urban development, for example, as part of buildings mainly for parking and commercial uses (a basement) or for underground metro system (Zhao and Künzli, 2016). The deep excavation method is usually performed to construct a basement or the cut-and-cover tunnel. In some cases, a deep excavation is located close to existing underground metro tunnels or adjacent buildings (Shi et al., 2015; Hsieh et al., 2015; Hong et al., 2015; Chen et al., 2016). Obviously, the design and construction of a deep excavation should be carefully executed in order to avoid excessive wall deflections and ground surface settlements, or even the collapse of the retaining wall, for example the Nicoll Highway failure case (Whittle and Davies, 2006).

Nowadays, many approaches can be used for design and analysis of a deep excavation, such as the earth pressure method, the numerical method, and the robust geotechnical design (RGD) method (Wang et al., 2014), a new design method that involves the theory of reliability and uncertainty in geotechnical engineering. However, the numerical method, such as the finite element method, seems still a popular method in design and analysis of a deep excavation, because not only it can simulate the stage construction procedures of excavation, but also there are a lot of soil constitutive models can be adopted to model the soil behavior. Due to many soil constitutive models available in the finite element method, it also been utilized by some researchers to study the soil behavior (Surarak et al., 2012; Ho and Hsieh, 2013).

Plenteous soil constitutive models have been developed to simulate the effective stress-strain-strength behavior of clay soil. Initiated with the Mohr-Coulomb model, a classic but widely performed in practical geotechnical engineering, until the extension of the Hypoplasticity Cam-Clay model with considering stiffness anisotropy (Mašín, 2014), a sophisticated soil model with

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twelve input soil parameters deduced from advanced laboratory testing apparatus such as a hollow cylinder apparatus, or the MIT-E3 model (Whittle and Kavvadas, 1994), which requires fifteen input soil parameters obtained from at least five types of testing such as 1D consolidation tests, K_0-oedometer or K_0 triaxial tests, undrained triaxial shear tests (both axial compression and axial extension conditions), shear wave velocity tests, and drained triaxial tests.

Although the MIT-E3 and/or the Hypolasticity-clay models could provide reasonable prediction of an excavation deformation behavior (Mašín, 2005; Whittle and Davies, 2006; Corral and Whittle, 2010; Mašín et al., 2011), but most of the engineers might adopt it reluctantly because the input parameters are not easily to be justified from conventional soil tests. In geotechnical engineering practice, the Mohr-Coulomb model is yet a popular model to be applied because it is simple and most of engineers have good experiences and confidence to utilize this model. One concern of this model is the input parameters such as the Young's modulus and the shear strength of soil for analysis need to be adjusted based on a local experiences or from back analysis (Ng and Lings, 1995; Whittle and Davies, 2006; Lim et al., 2010; Hwang et al., 2012).

As the deformation characteristic of an excavation system is influenced by the stress state and stress history of the soil, understanding the stress path during an excavation process is essential. Powrie et al. (1998) investigated the stress-strain relations appropriate to diaphragm wall in clay by performing a series of triaxial test on speswhite Kaolin. The stress paths imposed in the triaxial testing program intended to simulate those that would be experienced in reality by soil elements at a depth of 12 m, behind and in front of an in situ retaining wall, during wall installation and main excavation. However, their results were limited to the stress path in which no significant principal stress rotation occurred, as it might be significant at the soil element near the wall toe or at the excavation bottom.

In this article, a proper investigation of the soil stress paths during excavation was performed based on finite element simulation of the deep excavation case history by adopting the Hardening Soil Model. It is a common practice in the deep excavation modelling that the diaphragm wall is assumed to be wished-in-place and analysis results are reasonable (Ng and Lings, 1995; Lim et al., 2010; Zhang et al., 2015). Thus, the soil stress paths during construction of the diaphragm wall are not discussed here. Two well documented case histories were simulated to validate the proposed procedure of parameter determination, especially the soil modulus. In addition, a logic and systematic procedure of parameters determination, directly derived from the conventional laboratory tests and in-situ tests results, was used to accommodate the Mohr-Coulomb model effective stress approach. Besides, a hypothetical case was performed to examine the profile of ground surface settlements with considering a layer of small strain stiffness zone.

2. Finite element analysis and soil constitutive models

The PLAXIS v.2010 (Brinkgreve et al., 2010) computer software was used to perform the finite element analysis with various soil constitutive models. Based on the evaluation performed by Lim et al. (2010), three soil constitutive models were selected, such as the Hardening Soil Model (Schanz et al., 1999), the Hardening Soil-Small model (Benz et al., 2009), and the Mohr-Coulomb model, to simulate the clay soil behaviors with the effective stress undrained analysis. Furthermore, the effective stress drained analysis with the Mohr-Coulomb model was selected to model the sandy soil. Since those prominent models are well developed, thus only essential description will be highlighted to ease discussion of research results.

The Hardening Soil model, abbreviated as the HS model, is a true second order model for soil in general (soft to stiff types of soil). The model involves frictional hardening characteristics to model the plastic shear strain in deviatoric loading, and cap hardening characteristics to model the plastic volumetric strain in the primary compression. The failure is defined by the Mohr-Coulomb failure criterion. The basic characteristics of the model are a Mohr–Coulomb failure with input parameters c, φ and dilatancy angle, ψ, stress-dependent stiffness according to a power law defined by input parameter, m, plastic straining resulting from primary deviatoric loading with an input parameter, E_{50}^{ref}, and plastic straining from primary compression with an input parameter E_{oed}^{ref}, elastic unloading/reloading is defined by input parameters E_{ur}^{ref} and unloading/reloading Poisson's ratio, υ_{ur}. Fig. 1 displays the shear yield surface and cap yield surface in the Hardening Soil Model for soil with no cohesion ($c' = 0$). In this paper, the soil yield is defined as the stress state of soil which is located in the shear hardening zone. Meanwhile, the soil failure is defined as the stress state of soil which reaches to the Mohr-Coulomb failure line.

It should be noted that, the HS model is difficult to accurately predict the drop in the deviator stress, which represents a strain softening response of soil behavior. Nevertheless, in terms of an effective stress path, the typical shape of the normally consolidated clay stress paths, and their undrained shear strength, are handled very well by the HS model predictions (Surarak et al., 2012). In other words, the HS model can represent real soil behavior as long as the soil response is a strain hardening behavior.

The Hardening Soil Small-strain model, abbreviated as the HSS model, evolves from the HS model with the consideration of small strain characteristics of soil. In the HSS model, two additional parameters are required in addition to those in the HS model. The two additional parameters are the reference shear modulus at very small strains (G_0^{ref}) and the shear strain at shear modulus equal to 0.7 shear modulus at very small strain ($\gamma_{0.7}$). The Mohr-Coulomb Model, abbreviated as the MC model, is an elastic perfectly plastic model and in fact, a combination of the Hooke's law and the generalized form of Mohr-Coulomb failure criterion. The model involves four input parameters, such as two pseudo-elastic parameters from the Hooke's law (Young's modulus (E), and Poisson's ratio (υ)), and the two parameters from the Mohr-Coulomb failure criterion (the friction angle (φ), and cohesion intercept (c)). For the MC model, the effective stress undrained analysis can be performed with combination of the effective shear strength parameters ($c = c'$ and $\varphi = \varphi'$), referred to as the Undrained A approach, or combination of the total strength param-

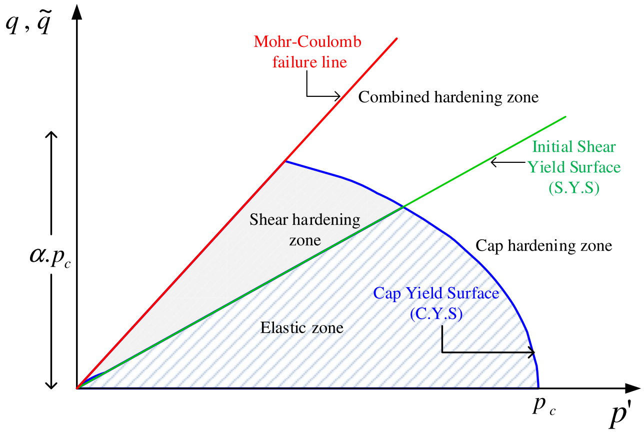

Fig. 1. Shear yield surface and cap yield surface in the Hardening Soil Model (*modified from* Brinkgreve et al., 2010).