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Evaluating the effect of soil structure on the ground response during shield tunnelling in Shanghai soft clay

Xia Bian [a,b,*], Zhen-Shun Hong [c], Jian-Wen Ding [c]

[a] *Geotechnical Research Institute, College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, PR China*
[b] *Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, PR China*
[c] *Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing 210096, PR China*

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ABSTRACT

When evaluating tunnel-induced ground response in Shanghai soft clay, the soil structure and its degradation behaviour of natural Shanghai soft clay during shield tunnelling should be properly considered. In this paper, a constitutive model that considers the initial soil structure and its destructuration is formulated within the framework of critical-state soil mechanics. The model is successfully calibrated and used to simulate the undrained behaviour of natural Shanghai soft clay. Based on the proposed model, finite-element analyses are conducted to simulate the short- and long-term ground responses induced by tunnelling at Shanghai metro line 2. The comparisons between numerical results and field measurements reported in literature indicate that the soil structure and the tunnel-induced destructuration significantly affects the magnitude and shape of the short-term surface settlement trough and horizontal displacement in Shanghai soft clay. The pore pressure variations around the tunnel are also affected by soil structure, which will significantly influence the long-term ground consolidation settlement in Shanghai soft clay.

1. Introduction

Shanghai located on the south bank of the estuary of Yangtze River, is a metropolitan and economic centre in China. With a major boost in economy in China during last three decades, the population and expanding urban areas of Shanghai increased several times. Hence, there is an increasing demand for underground tunnels used as efficiently alternative transportation. At present, there are 14 metro lines with a total length of approximately 560 km in operation in Shanghai. By the end of 2020, 22 metro lines, which comprise a total length of 880 km, will be operational (Zhang and Huang, 2014). The Shanghai metro lines are typically constructed using the shield tunnelling technology within a depth of 50 m. Over the upper 50 m of the Shanghai region, there distributes a typically 20 m thick soft clay layer. It has been well documented that the natural Shanghai soft clay is often highly structured with high compressibility and low strength (Ng et al., 2013; Shen et al., 2014). Tunnelling disturbance may degrade the soil structure, change the pore water pressure response, and decrease the stiffness and strength of the soil (Xu et al., 2003). Consequently, the variation in mechanical properties of soft clay around the tunnel may cause excessively large settlement and unpredictable long-term displacement, which may lead to the failure of soft clay foundations and tunnels. Hence, the effect of the soil structure on ground response during shield tunnelling is of practical importance.

Currently, numerical methods (FEM or DEM), which provide the flexibility of simulating different geometry and excavation sequences, and enable the application of advanced soil models, become the most popular method to analyse the ground response of tunnelling (e.g., Lee and Rowe, 1990a, 1990b; Addenbrooke, 1996; Grammatikopoulou, 2004; Wongsaroj et al., 2007; Jiang and Yin, 2012). Clough and Leca (1989) and Hejazi et al. (2008) noted that the soil constitutive model in numerical analyses significantly affected the simulation of tunnels. Previous studies primarily focused on soil features such as small-strain stiffness (e.g., Addenbrooke et al., 1997; Masin and Herle, 2005; Hejazi et al., 2008), stiffness anisotropy (Addenbrooke et al., 1997; Wongsaroj, 2005), recent stress history (Dasari, 1996) and elasto-plastic behaviour within the yield surface (Wongsaroj, 2005). All these features have been proved to significantly improve the prediction. It should be emphasized that although the constitutive modelling of natural soils, which incorporates the effect of the soil structure, has significantly progressed in recent years, there

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* Corresponding author at: Geotechnical Research Institute, College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, PR China.
E-mail addresses: bianxia2010@gmail.com, xia.bian@hhu.edu.cn (X. Bian).

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Nomenclature

e_0	in situ void ratio
G	shear modulus
G_0	small-strain shear modulus
ICL	Intrinsic Compression Line
I_v	void index
K'	bulk modulus
K_0	lateral earth pressure coefficient
M	critical state stress ratio
p'	mean effective stress
p^*_{ve}	intrinsic pressure at ICL
p^*_{ve0}	intrinsic pressure at yield stress
p'_0	the size of yield surface for natural clays
p'_{vy}	the mean effective yield stress
q	deviatoric stress
r	tunnel radius
R	subloading surface ratio
S_σ	current stress sensitivity
$S_{\sigma 0}$	stress sensitivity at yield stress
YSR	yield stress ratio $= \left(\sigma'_{vy}/\sigma'_{v0}\right)$
ε_d	soil structure degradation strain $\left(= \sqrt{\left(d\varepsilon_v^p\right)^2 + \left(d\varepsilon_s^p\right)^2}\right)$
ε_s^p	plastic shear strain
ε_v^p	plastic volumetric strain
κ^*	the gradient of the unloading-reloading line in $e - \log_{10}p'$ space
λ^*	the gradient of the normal consolidation line in $e - \log_{10}p'$ space
ρ^*_c	the gradient of the normal consolidation line in $\log_{10}e - \log_{10}p'$ space
ρ^*_r	the gradient of the unloading-reloading line in $\log_{10}e - \log_{10}p'$ space
ν'	Poisson's ratio
σ'_{vy}	vertical yield stress
σ^*_{v0}	vertical intrinsic pressure at yield stress

remains a lack of experience in evaluating the effect of the soil structure on tunnelling. Several studies analysed the effect of the soil structure on the tunnel-induced ground response in overconsolidated stiff clays (e.g., Dang and Meguid, 2008; González et al., 2012; Zhu et al., 2013). Note that these limited studies may lead to contradictory results, because it is difficult to distinguish the effect of OCR from the soil structure for stiff clays. More importantly, extensive research work on the effect of soil structure in natural soft clay during tunnelling appears to be sparse.

The objective of this study is to investigate the effect of the soil structure of natural soft clay on the ground response induced by shield tunnelling. Firstly, based on the critical-state theory, an advanced soil model is proposed that evaluates the stress-strain relationship of natural clay and incorporates the effect of the soil structure through the sensitivity framework. Secondly, the performance of the proposed model is validated by comparing the simulations with laboratory experimental results for natural Shanghai soft clay. Finally, the finite element method is used to evaluate the effect of the soil structure on the short- and long-term tunnel-induced ground response at Shanghai metro line 2 by implementing the advanced soil model. For simplicity, all the analyses in this study are conducted in the plane strain conditions.

2. Soil model

2.1. Description of the soil model

There are several different approaches to represent the soil structure within a constitutive modelling framework. One of the most popular methods is to introduce a quantitative parameter, which represents the difference between natural and reconstituted clay, and to modify the hardening rule by adding a destructuration law based on the Modified Cam Clay (MCC) model (e.g., Rouainia and Muir Wood, 2000; Gajo and Muir Wood, 2001; Liu and Carter, 2002; Baudet and Stallebrass, 2004; Masin, 2007; Liu et al., 2013). Following these approaches, the sensitivity framework proposed by Chandler (2000) is adopted to quantify the effect of the soil structure in this study. As shown in Fig. 1, the ratio of the yield stress of natural clay to the vertical stress on the Intrinsic Compression Line (ICL) at the same void ratio $\left(p'_{vy}/p^*_{ve0}\right)$ is defined as the "stress sensitivity" ($S_{\sigma 0}$) and can be considered as a parameter quantifying the effect of the soil structure. Callisto and Rampello (2004) noted that this definition only accounted for the initial degree of structure and did not account for a continuous change in structure during destructuration. Hence, a current S_σ can be defined as the ratio of the current vertical stress between natural clay and the ICL at the same void ratio (Gasparre and Coop, 2008) as follows,

$$S_\sigma = \frac{p'_0}{p^*_{ve}} \tag{1}$$

where p'_0 and p^*_{ve} represent the current stress level of the natural clay and its ICL at the same void index, respectively.

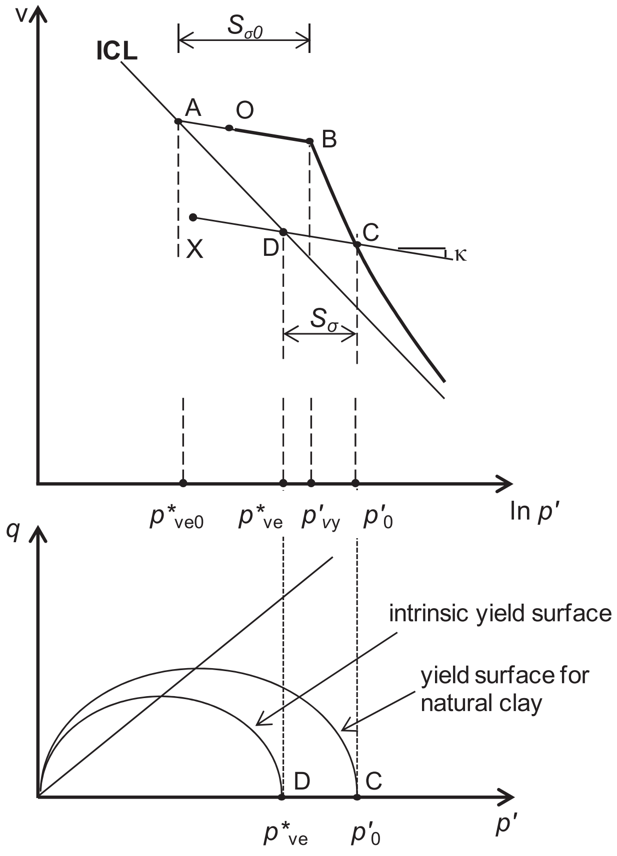

Fig. 1. Schematic diagram of the definition of stress sensitivity.