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Effects of tunneling-induced soil disturbance on the post-construction settlement in structured soft soils

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ABSTRACT

Earth pressure balanced shield machine (EPBS) is widely adopted for metro tunnel construction in urban areas. Support pressure on excavation face and grouting at the EPBS tail are the main measures to control the ground disturbance and settlement. The post-construction settlement is of significance to the serviceability of metro tunnel. By weakening the compression parameters of underlying soils related to soil disturbance degree (SDD) and using layer-wise summation method, this study developed a method to predict the post-construction ground and tunnel settlement. The SDD is quantitatively evaluated by the shear-strain state obtained from a series of isotropically consolidated undrained triaxial compression (CIU) tests. Based on a case history of metro tunnel constructed in structured soft soils, a suite of three dimensional finite-element analyses are performed to investigate soil disturbance during tunneling construction. The numerical simulation and the applicability of the proposed method are validated by comparing the numerical results with the field measurements. In addition, influences of support pressure and grout ratio on the tunneling-induced soil disturbance, ground and tunnel settlement are revealed. The SDD shows remarkable falloff within 0.32D above the tunnel crown, while 0.24D below the tunnel invert. Furthermore, within the above distance range, the linear relation between the SDD and distance from the tunnel crown or invert can be built. The analysis results show that the excessively high or low support pressure and grout ratio can both cause severe SDD which results in the significant post-construction settlement. Grout ratio of about 200% and support pressure of 2.2–2.4P_0 are effective for reducing both the post-construction ground and tunnel settlement. The research presented in this paper provides a reference for controlling the post-construction ground and tunnel settlement constructed in structured soft soils.

1. Introduction

Metro tunnels have been increasingly developed in urban areas where buildings and infrastructures are densely distributed. The post-construction tunnel settlement is of great concern for the serviceability in consideration of the significant continuous settlement with time (e.g. Schmidt and Grantz, 1979; Komiya et al., 2006; Ng et al., 2013; Di et al., 2016; Tan et al., 2016). Ng et al. (2013) reported that the post-construction settlement of Shanghai Metro Line 1 was continuous with time and reached a maximum of 288 mm after 12.5 years' operation.

The long-term settlement of shield tunnel constructed in the soft deposit is mainly caused by: the recompression settlement following construction, the secondary consolidation settlement, the train-load-induced settlement, the local leakage and/or nearby construction-induced settlement. Of all the causes, the recompression settlement contributes the most according to Di et al. (2016), in which a combination of the typical equivalent entity method and the layer-wise summation method was employed to obtain the recompression settlement. However, the effect of tunneling-induced soil disturbance on the compressibility of under-layered soils was not considered, which may led to non-conservative results.

The surrounding soils are inevitably disturbed due to the tunneling construction (e.g. Yi et al., 1993; Adachi et al., 2003; Xu et al., 2003; Gomes, 2013). The disturbance is severer in structured soft clays that are widely distributed in Eastern China. Burland (1990) indicated that natural sedimentary clays differed from the reconstituted soils both respect to fabric and bonding. The strength on a shear surface dropped rapidly to a reasonably steady value after only a few millimeters' relative displacement. Xu et al. (2003) defined the stress disturbance degree of Shanghai silty clay by the change of in situ effective stress before and just after tunneling, and developed the relationships between the mechanical properties and stress disturbance degree.

For the soil disturbance degree (SDD), Xu et al. (2003) pointed out that the soil disturbance during tunneling consists of two parts: stress

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Nomenclature

C	contraction ratio
c'	effective cohesion of soil
C_c	compression index for intact soil within remoulded range
C_{cd}	compression index for disturbed soil within remoulded range
C_{cr}	compression index for remoulded soil
C_g	contraction ratio for grout ratio simulation
C_s	compression index for intact soil within elastic range
C_{sd}	compression index for disturbed soil within elastic range
D	tunnel diameter
d_c	distance above the tunnel crown
d_i	distance below the tunnel invert
e	void ratio
e_0	initial void ratio for intact soil
E'	effective Young’s modulus
EPWP	excess pore-water pressure
Eref 50	reference secant stiffness of trial axial compression stress paths
Eref oed	reference stiffness from one-dimensional compression tests
Eref ur	reference stiffness for unloading/reloading stiffness
G_r	grout ratio
k_0	at-rest earth pressure coefficient
m	power that controls the stress dependency of stiffness
p'	mean effective stress
P_c	earth pressure acted on the tunnel crown
p_{co}	consolidation pressure
P_{inc}	increment of support pressure with depth
P_J	jacking thrust
P_{ref}	support pressure exerted on the top of the excavation face
P_s	support pressure
q	deviator stress
q_f	peak deviator stress;
R_{inter}	strength factor of interface element
SDD	soil disturbance degree
S_{pt}	post-construction tunnel settlement
SPT-N	N value of standard penetration test
s_u	undrained shear strength
R_f	failure ratio
w	water content
γ	unit weight
γ_s	shear strain
ν_{ur}	poisson's ratio of unloading/reloading
φ'	effective friction angle
Ψ	dilatancy angle
ν_{ur}	Poisson’s ratio of unloading/reloading
σ_{pc}	structured yield stress for intact soil
σ_{pd}	structured yield stress for disturbed soil
σ'_z	effective gravity stress
σ_{z0}	apparent gravity stress for intact soil
σ_{zd}	apparent gravity stress for disturbed soil

disturbance (defined by the change of effective stress) and strain disturbance (not defined in their study). The undrained shear strength (s_u) obtained from in-situ vane shear test was used for quantitatively evaluating the SDD (Chen et al., 2015). The SDD equals to the ratio of s_u under disturbed state to that for intact soil. However, the above evaluation method cannot be used to predict the tunneling-induced SDD before construction. Salehnia et al. (2015) employed shear strain localization, which was obtained from numerical simulation to predict the extent of excavation damage zone induced by tunneling construction. Similarly, it is reasonable to adopt γ_s to evaluate the SDD. Hence, the shear strain state is adopted to evaluate the SDD as expressed by the following formula:

$$\mathrm{SDD} = (\gamma_s/\gamma_f) \times 100\% \qquad (1)$$

where γ_s is the shear strain induced by tunneling construction, and γ_f is the failure shear strain that can be obtained from CIU tests.

Currently, some constitutive models (e.g. Rouainia and Muir Wood, 2000; Rocchi et al., 2013) have been reported to model the structured property of soft soils. However, the research on the constitutive model that implemented into the finite-element analysis code to calculate the ground deformation is rarely seen. For structured soft clays, the soil disturbance can naturally lead to the weakened soil compression indices (e.g. Santagata and Germaine, 2002) thus causes ground settlement. To date, tunneling-induced ground settlements were generally estimated by empirical methods (e.g. Peck, 1969; Attewell and Woodman, 1982), numerical methods (e.g. Kasper and Meschke, 2004; Hajjar et al., 2014) and analytical methods (e.g. Loganathan and Poulos, 1998; Park, 2004). Appropriate shield-driving parameters are effective for limiting the tunneling-induced volume loss and ground settlement. However, very limited research works were seen on the relationship between the tunneling-induced soil disturbance, and the post-construction ground settlement, not to say their correlations with the shield-driving parameters.

In summary, this study aims to develop a method for evaluating the tunneling-induced soil disturbance and post-construction tunnel settlement considering the following four aspects:

1. The shear strain state is adopted (obtained from CIU tests) to calculate the soil disturbance degree.
2. The distribution of shear strain induced by shield-tunneling is obtained by three-dimensional numerical simulation.
3. The compression parameters of underlying soils are quantitatively reduced based on the SDD distribution below tunnel invert.
4. The post-construction tunnel settlement is obtained by using layer-wise summation method.

2. Post-construction tunnel settlement considering soil disturbance

Fig. 1 depicts the $e - \log p'$ curve of structured soft soil under different disturbed states. For the intact soil (e.g. Schertmann, 1953; Nagaraj et al., 1990; Chen et al., 2007), the soil compression is negligible up to the effective gravity stress (σ_{z0}), beyond which sudden

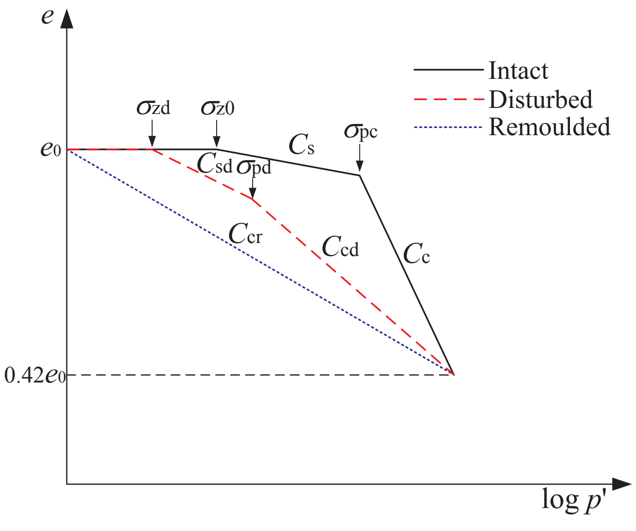

Fig. 1. $e - \log p'$ curves of structured soft soils at different disturbed states.