

Numerical study of long-term settlement induced in shield tunneling

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ABSTRACT

The objective of this study is to examine the mechanism of the long-term settlement induced in shield tunneling. A series of finite element analysis were conducted using PLAXIS 3D on a well document shield tunneling case in Taipei Mass Rapid Transit System. Various simulation were executed assessing the impact of consolidation on long-term settlement using Soft Soil and Hardening Soil with Small-strain models. Simulation to assess the impact of the creep behavior of the soil on the long-term settlement was also executed using the Soft Soil Creep model. The computed surface settlements were compared to the field measurements. It was found from this study that the computed settlement matched the field measurement when creep behavior of the soft soil was considered but if creep was not accounted for, the computed settlement undervalued the field measurements.

Keywords: consolidation; creep; shield tunneling; long-term settlement

1 INTRODUCTION

Ground settlement is an inevitable consequence during the construction of a tunnel. The settlements induced in shield tunneling can be categorized into the short-term and long-term settlements. The short-term settlement is mainly caused by the relief of the in situ ground stresses (Peck et al., 1969). Because of the possible significance of the differential displacement, short-term settlements are often monitored as part of the routine measures to protect the superjacent structures and the adjacent underground conduits from damage during tunneling.

The long-term settlement may increase with time, which is also a great concern, especially in soft clay (e.g., Ng et al., 2013; Meng et al., 2018). The long-term settlement can be induced by the equilibration of the stresses and dissipation of excess pore pressures in the clayey layer around the tunnel, which is associated with a new drainage condition imposed by the tunnel. It may also be caused by the creep behavior of the soft soil around the tunnel or in the soil layers. For long-term settlement, most of the existing studies interpreted them in terms of consolidation theory, in which the soil layers are considered as an elastoplastic material. However, it may also stem from creep phenomenon (Wang et al., 2012).

In this paper, a series of FE analysis was conducted using PLAXIS 3D to investigate the long-term settlement induced in shield tunneling. Various simulations were executed assessing the impact of consolidation on long-term settlement using Soft Soil and Hardening Soil with Small-strain model. The contribution of the creep behavior of the soil on the

long-term settlement was also examined by executing simulation using the Soft Soil Creep model.

2 ANALYSIS OF TUNNELING CASE

2.1 The CK570H tunneling project description

The CK570H is the tunnel section of the XinYi Line (Red Line) that is part of the tunneling case in the Taipei Mass Rapid Transit (Taipei MRT). It consists of the construction of two tunnels, namely, the up-track and down-track tunnel. The tunnels are circular in shape and each ring is consist of six segments. The segments are 25cm thick and are connected together via curve bolts. The total length of the tunnel section is 390m for both the down-track and up-track tunnel. The depth of the centerline of the up-track and down-track tunnel is 26.5m and 28.5m deep, respectively. The diameter of both tunnels is 6.10m.

In this case, the construction of the tunnels was executed by one TBM. Construction of the down-track tunnel was commenced and upon its completion, the construction of the up-track tunnel began. As excavation of the tunnel is executed at the face of the tunnel, simultaneously erection of the tunnel lining is also done at the rear of the TBM. Upon the erection of the concrete lining, the void is immediately injected with grouting material.

The monitoring instrumentation is implanted along the intersection between Aiguo east road and Hangzhou south road. The deformation measured is in the transverse cross-section. There is no monitoring instrumentation in longitudinal cross-section. Furthermore, there is approximately 18 datum selected with implanted measuring instruments. The settlement

induced is measured for 1, 90 and 365 days after the passage of the TBM through the monitoring section Based on the velocity of the TBM. The TBM will had passed the monitored section about a distance of 5m in 1 day.

Fig. 1 depicts the schematic cross-sectional diagram of the TBM pressure and soil profile used in this analysis. The pressures involved in the shield tunneling of the real case were calculated in accordance with the construction specifications of the Department of Rapid Transit Systems of Taipei. Due to page limitation, the detail properties of the soil profile are not shown here. For interested readers could refer to Jallow (2018).

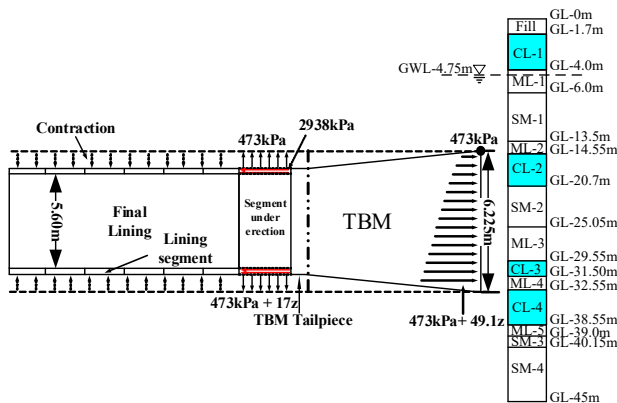


Fig. 1. Shield conicity and cross-sectional diagram of TBM pressures applied for the down-track tunnel (Note: z stands for depth in meters)

2.2 Soil constitutive models and structural parameters

The Hardening Soil with Small-strain (HSS) model (Benz et al., 2009) was one of the models adopted to simulate the soil behavior, including clay (CL); silts (ML) and Sand (SM) under the undrained and drained condition, respectively. The stiffness parameters of HSS are the secant stiffness (E_{50}^{ref}) corresponding to the reference stress, p^{ref} , the tangent referential stiffness for primary oedometer loading (E_{oed}^{ref}), the unloading/reloading referential stiffness (E_{ur}^{ref}). The power law to determine stress-level dependency is define by parameter, m . Furthermore, two addition parameters like reference shear modulus at very small strains, G_0^{ref} , and the shear strain at the shear modulus equivalent to 0.7 of the shear modulus at very small strain ($\gamma_{0.7}$) defines the small strain parameters of the model.

The Soft Soil (SS) (Stolle et al., 1997) and Soft Soil Creep (SSC) models (Vermeer et al., 2000) were

adopted to simulate the soil behavior of clay soil under the undrained condition, respectively. The SS and SSC stiffness parameters includes, modified swelling index, κ^* , modified compressive index, λ^* . However, the SSC model has an addition parameter that distinguishes it from the SS model name, modified creep index, μ^* . Due to page limitation, the determination and detail of input parameters are not shown here. For interested readers could refer to Jallow (2018).

In the analysis, the structural components, such as TBM, and tunnel lining was assumed to behave as linear-elastic material. The TBM was modelled with a plate element, while the tunnel lining was simulated as a soil body. The stiffness of the tunnel lining was reduced by 20% of its nominal value to account for cracks in the concrete lining and bolted joint. The input parameter for the TBM and tunnel lining are illustrated in Table 1 and Table 2, respectively.

Table 1. Input Parameter for TBM

Parameter	Index		Unit
Thickness	t_{TBM}	0.045	m
Length	L_{TBM}	9	m
Young's Modulus	E_{TBM}	210000000	kPa
Unit weight	γ_{TBM}	76	kN/m ³
Equivalent thickness	d	0.045	m
Poisson's ratio	ν_{TBM}	0	
Shear Modulus	G_{TBM}	10500000	kPa

Table 2. Input Parameter for tunnel lining

Parameter	Index		Unit
Young's Modulus	E	25.5×10^6	kPa
Poisson's ratio	ν	0.15	-
Unit weight	γ_t	24	kN/m ³
Void ratio	e	0.5	-
Interface	R_{inter}	1	-

2.3 Evaluation of volume loss

In order to determine the volume loss during shield tunneling, back analysis of field measurements was performed using Loganathan and Poulos (1998) method. The execution was done assuming that after 1 day of the field measurement to be a result of short-term settlement (Differential deformation). Meaning both creep induced and consolidation influence on the settlement after 1 day is neglected. However, the heave points observed in the field measurement are ignored during the back analysis. In the back analysis, the gap parameter was calculated for each settlement point by assuming an influenced range using Eq. (1). After obtaining all the gap parameter, g , for each settlement point, the volume loss (Ω_0) is calculated using Eq. (2)

$$u_y = R^2 \left\{ \begin{aligned} &-\frac{y-H}{x^2 + (y+H)^2} + (3-4\nu) \frac{y+H}{x^2 + (y+H)^2} \\ &\frac{2y[x^2 - (y+H)^2]}{[x^2 + (y+H)^2]^2} \end{aligned} \right\} \quad (1)$$

$$\times \frac{4gR + g^2}{4R^2} \exp \left\{ - \left[\frac{3.12x^2}{(R + H \tan \beta)^2} + \frac{0.69y^2}{H^2} \right] \right\}$$

where g is the gap parameter, u_y is the settlement, H is tunnel depth, β is the influence angle, R is tunnel radius, x and y coordinate, and ν is the Poisson's ratio.

$$\Omega_0 = \frac{4gR + g^2}{4R^2} \quad (2)$$

where R = tunnel radius.

Table 3 illustrates the result acquired from the back analysis. The volume loss obtained was quite reasonable, as it is approximately equivalent to ground loss acquired by previous researchers about tunneling in the Taipei basin.

Table 3. Result of the back analysis

Parameter	Index		Unit
Gap parameter	g	13.26	mm
Influence angle	β	68.2	deg
Volume loss	Ω_0	0.44	%

2.4 Model geometry, mesh and boundary conditions

Fig. 2 shows a three-dimensional finite element mesh and the boundary condition used to conduct the analysis. The total length of the tunnel is 95m, which is one-fourth of the original length of the tunnel in the real case. The length and width of the geometry were assumed to be 95m and 100m, respectively. The depth of the down-track (1st tunnel) and up-track (2nd tunnel) tunnel are 28.5m and 26.5m, respectively. The height of the geometry was assumed to be 45m.

This analysis was executed with the assumption of a Greenfield condition. The boundary of the TBM and tunnel lining was assumed to impermeable. The boundary in both x -direction and y -direction are closed to prevent groundwater flow. The boundaries in the z -direction are opened to facilitate groundwater flow.

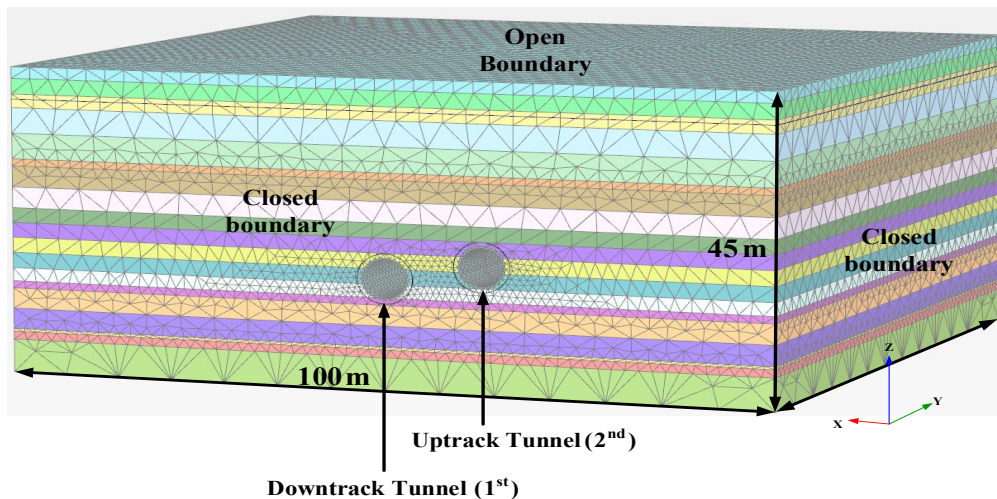


Fig. 2 Three-dimensional finite element mesh used in this analysis

3 RESULTS AND DISCUSSION

The computed short-term settlement from all the three soil constitutive models is portrayed in Fig. 3. The analyzed settlement depicts that HSS, SS and SSC models matched the ground surface settlement quite closely. SS and SSC models gave an identical result in the short-term proving that, the only difference between the two models was the creep phenomenon in the long-term condition, which was not accounted for in the SS model. The close reflection of the field measurement by HSS, SS and SSC model proves that the volume loss from back analysis was reasonable since the immediate settlement induced is due to volume loss. Additionally, it proved that the stiffness parameters related were calibrated.

For the long-term condition, settlements were

computed for 90 and 365 days. The computed settlement from all three soil constitutive models after 90 days are depicted in Fig. 4. The computed settlement from the HSS and SS models portrayed undervalued the settlement monitored in the field. SS and HSS model underestimated the settlement probably because the dissipation of predominantly negative excess pore pressure (EPP) generated due to the unloading will result in a small settlement of the ground surface and the creep behavior of the clay soil was not accounted for in these models. The analyzed settlement from the SSC model agreed well with the measured settlement in trend and value (see: Fig. 4). For SSC model, the analyzed settlement agreed with the measured settlement because the complete dissipation of the EPP in 90 days resulted in a vast increase in the effective stress of the soil, resulting in the increase of creep-induced deformation. Furthermore, regeneration

of EPP was observed as well, this was due to the large creep-induced settlement observed. This behavior of EPP agreed with Lin et al. (1998) study. Therefore, the long-term settlement observed after 90 days was mostly due to the creep behavior of the soft soil.

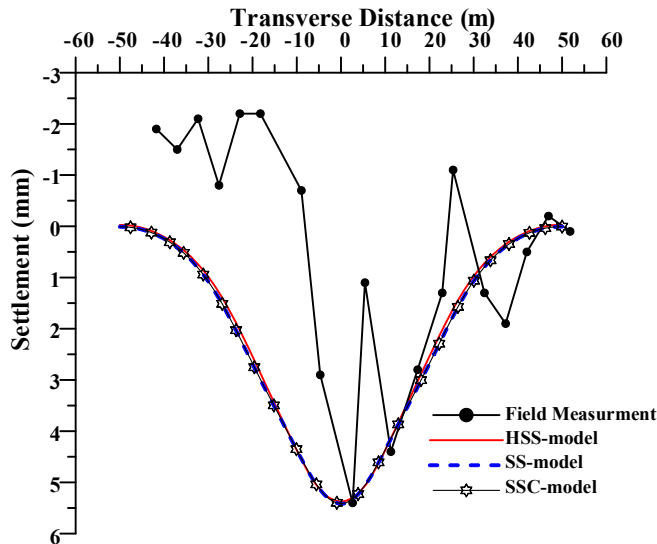


Fig. 3 Computed short – term settlement results compared to the field measurement from all three soil models (Note: (a). HSS stands for Hardening Soil with Small-Strain model. (b). SS stands for Soft Soil model. (c). SSC stands for Soft Soil Creep model)

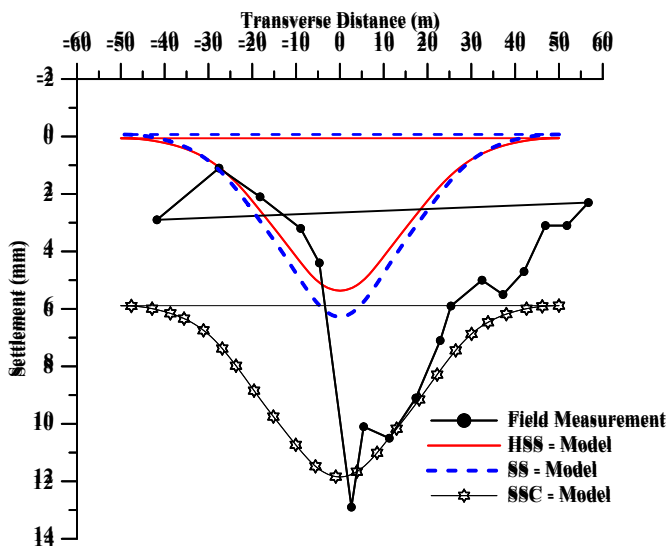


Fig. 4 Analyzed long-term settlement after 90 days compared to the field measurement (Note: (a). HSS stands for Hardening Soil with Small-Strain model. (b). SS stands for Soft Soil model. (c). SSC stands for Soft Soil Creep model)

Settlement induced in 365 days was because of not one but two tunnel excavations. An assumption was made as to when the construction of the 2nd tunnel

began. However, from the case study, the 2nd tunnel passes the monitored section on the 300th day. Therefore, construction of the 2nd tunnel was commenced after the completion of the 1st tunnel in this analysis. A total length of 104m was completely erected upon the passage of the 2nd tunnel at the monitored section in the real case. Regeneration of the EPP was observed due to the construction of the 2nd tunnel. Subsequent to the passage of the tunnel at the monitored section, a consolidation and creep analysis was performed for 65 days totaling to 365 days. For settlement after 365 days, both HSS and SS model computed results undervalued the monitored settlement while the SSC model computed settlement agreed well with the measured settlement in the field as illustrated in Fig. 5. SS and HSS model underestimated the settlement because all the EPP has completely dissipated in 90days and the creep behavior of the clay soil was not accounted for in these subsequent models. However, the increase in the analyzed settlement was due to the passage of the 2nd tunnel. Nonetheless, with the construction of the 2nd tunnel, regeneration of EPP due to unloading and deformation of the soil toward the tunnel void was observed. The EPP generated is predominantly negative. Therefore, its dissipation will result in a trivial increase in the settlement. The computed settlement from SSC model agreed well with the measured settlement (see: Fig. 5) because of the rapid dissipation of EPP in tandem with the vast increase of the effective stress of the soil resulted in the increase of the creep-induced deformation of the soft soil. The regenerated EPP observed was due to large creep-induced deformation. Furthermore, the settlement observed after 365 days was predominantly due to the creep behavior of the soil.

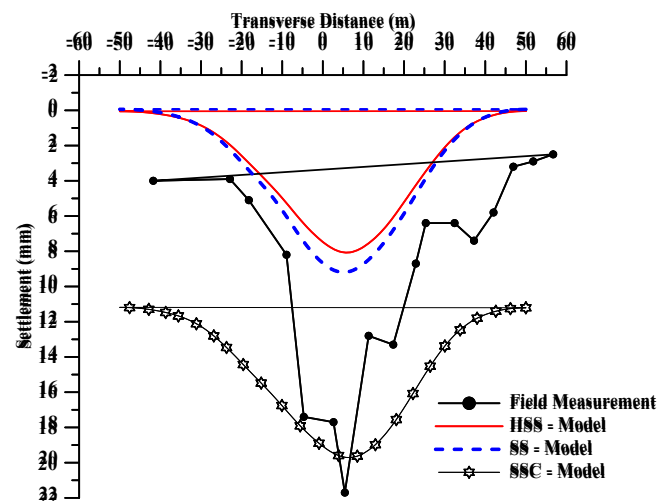


Fig. 5 Analyzed long-term settlement after 365 days compared to the field measurement (Note: (a). HSS stands for Hardening Soil with Small-Strain. (b). SS stands for Soft Soil. (c). SSC stands for Soft Soil Creep)

4 CONCLUSION

In this case, where the subsurface soil deposit comprise mainly sand and silt with thin clays layers embedded inbetween, short term, consolidation, and creep behavior of the soil constitutes 47%, 10% and 43% of the total settlement observed respectively, prior to the construction of the 2nd tunnel in the long-term condition. Additionally, with passage of the 2nd tunnel, the settlement subsequently increase as well. In conclusion, the long-term settlement in shield tunneling is greatly governed by the creep behavior of the soft soil.

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