Exploration of factors affecting settlements induced by tunneling in loose to medium dense sands

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ABSTRACT

Due to fast development of the urban area in the city, it simultaneously generates some problems too, such as excessively dense population and traffic jam. For solving these problems, additional underground space is needed for the use of public sector, such as road, metro, water supply and sewer systems etc. and tunneling, especially shield tunneling is widely to be used since it is fully constructed below surface level and any construction activity would not interrupt daily life of human being and traffic on ground if it operates adequately. In this paper, a case of shield-machine- bored tunnel in loose to medium dense sand is selected as research background. Measured settlement data are first undertaken to explore behavior induced by tunnel construction in both transverse and longitudinal directions. Moreover, three- dimensional finite element method (FEM) analyses are conducted using software PLAXIS 3D to evaluate ground and structural stress and deformations induced by tunneling. Various constitutive models are selected, then analytical results are compared and reviewed. In addition, some shield operating parameters and material properties are used as inputs for tunneling excavation simulation instead of a non- physical parameter, such as ground convergence ratio which used often previously. Further, parametric studies are delivered to evaluate impacts on displacements from different parameters. Finally, discussions on change of the soil stress in terms of stress paths and stresses on reinforcement segment caused by tunneling are carried out.

Keywords: Tunnel in loose to medium dense sand, three- dimensional FEM analyses, constitutive models, shield operating parameters and material properties, stress- path, stresses on tunnel segments

1 INTRODUCTION

Previously, attentions are mainly focused on studies of behaviors and stresses induced by shield- machine bored tunnel in clay instead of sand (Peck, 1969; Clough and O'Rourke, 1981). Further, most discussions are conducted regarding settlements in transverse direction, not in longitudinal direction and influences from tunnel construction progress are not considered either. In this study, first of all, three- dimensional analyses using different constitutive models are delivered and analytical results are compared and discussed. In order to simulate three- dimensional ground behavior induced by tunneling, computer software PLAXIS 3D (version 2016) is selected and influences from soil features in the aspects of unloading and small strain level are addressed. Further, some shield operation parameters, such as face pressure, backfill grouting pressure and material properties of backfill grout are considered but these parameters are not included in previous studies. Analyses including parameters stated above are therefore undertaken and outcomes are compared with conventional analyses based on ground convergence ratio. Moreover, impacts on displacements from operation parameters stated above are explored. At the end, the change of ground stress is interpreted in terms of stress path. Structural stresses on tunnel segments, such as bending moment and axial forces are also evaluated.

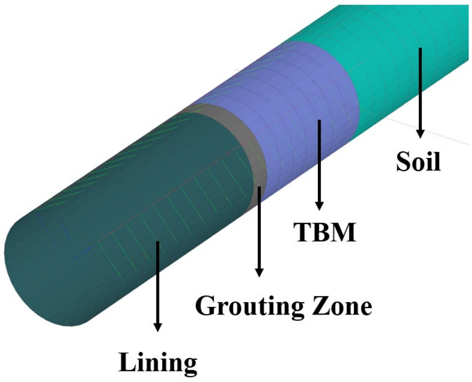


Fig. 1. Layout of the shield, grouting zone and tunnel segments in the model

In order to examine issues listed above using 3-dimensional analyses, a 120m × 120m × 45m model was built and layout of bored tunnel itself in the model is shown in Figure 1.

2 PROJECT BACKGROUND

2.1 CASE BACKGROUND

In this study, one twin- parallel bored tunnel among one of underground construction packages in a metro project is selected as research background.

Total track length of the tunnel chosen is 851.8m (includes both the up- track and the down- track). Figure 2 shows the tunnel layout and profile in longitudinal direction. It is noted that the tunnel is a twin-bored tunnel but the shield actually moves toward in one direction in one tunnel, has a U-turn at the end and then moves in the other direction for next tunnel which can lead to difficulties for a full simulation of construction of a twin-tunnel. Therefore, only construction of a single-tunnel (up- track one) is selected for simulation.

For tunnel construction, an EPB (Earth Pressure Balance) shield- machine is selected. In theory, said machine maintains the lateral earth pressures equilibrium outside the chamber using face pressure in order to proceed tunnel excavation.

The shield machine which employed in this study is 6.23m in diameter. The outer and internal diameter of tunnel behind the shield are 6.1m and 5.6m, respectively. The prefabricated reinforcement concrete lining rings are 1.2m wide, 0.25m thick, and each ring contains of three types of segment. (six pieces in total; three A-type, two B- type and one K- type)

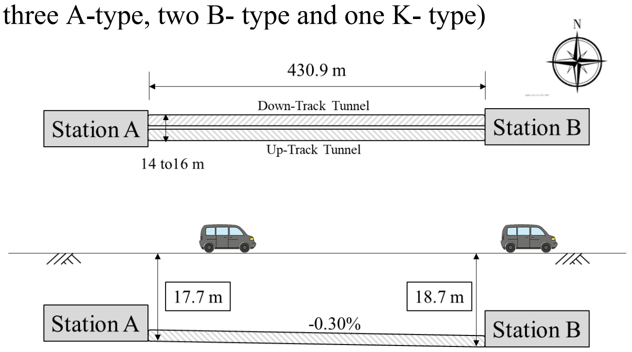


Figure 2. The layout and profile in longitudinal direction of the tunnel

2.2 GROUND CONDITIONS

Considering details from borehole log and geotechnical interpretation report, the ground is mainly a very thick loose to medium dense sand with some thick layers of clay. The groundwater level was observed from 2.58m to 4.8m below ground level. Ground profile was detailed described in Hsiung (2011).

2.3 MONITORING RESULTS

Representative and reliable observed monitoring data for surface settlement induced by tunnel construction are selected first as a base of this study and such data in both transverse and longitudinal directions was presented in Hsiung (2011 and 2019) and not shown in here due to limit of paper length.

3 ANALYTICAL METHODS

Two different analytical methods, Method A and Method B are selected to be adopted in this study. For details of Method A, please refer to Hsiung (2019) as well as other references (Park et al., 2014 and Chen et al. 2016). Convergence ratio is the key input but said ratio is not capable to be physically defined by any shield machine control parameters. In contrast, an innovated approach, Method B in which ground convergence ratio is not applied in the simulation and details of the method was stated in Hsiung (2019) and Figure 3. Hwang et al. (1995) indicated that ground movement is mainly caused by tail void so elastic modulus and pressure of backfill grout are used in the simulation. Real shield operation parameters are adopted to replace convergence ratio as inputs of the model.

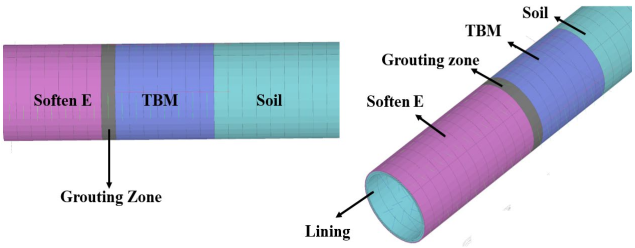


Figure. 3. Simulation of Method B

In this study, Hardening Soil – small strain (HSS) which small strain soil behavior can be concerned are selected for analyses. Additional 2 parameters have to be used in HSS rather than Hardening Soil (HS) model which is G_0^{ref} and $\gamma^{0.7}$. Due to limit of paper length, Table 1 presents soil parameters used for analyses using both HS and HSS model.

Table 1. The soil parameters used for analyses using HS and HSS model

Layer	Type	Thickness (m)	$\varnothing'$ °	γ_t (kN/m³)	ν –	Su (kN/m²)
1	SM	6.5	31	19.6	0.3	—
2	CL	2	—	18.9	0.45	42
3	SM	14.5	32	20	0.3	—
4	CL	2	—	19.3	0.45	91
5	SM	20	33	19.8	0.3	—
Layer	**Type**	**Eu (kN/m²)**	**E (kN/m²)**	**E_{50}^{ref} (kN/m²)**	**$\gamma^{0.7}$ –**	**G_0^{ref} (kN/m²)**
1	SM	—	16188	27472	1×10^{-4}	165592
2	CL	21000	—	—	—	—
3	SM	—	31813	24790	1×10^{-4}	141083
4	CL	45500	—	—	—	—
5	SM	—	55875	29571	1×10^{-4}	161203

Note

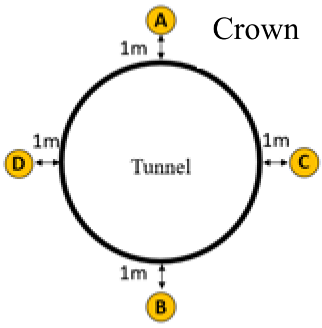
1. γ_t is saturated soil unit weight ;
2. $E_{50}^{ref} = E_{oed}^{ref}$; $E_{ur}^{ref} = 3E_{50}^{ref}$; ν is effective poisson ratio and k_0 is lateral earth pressure coefficient at rest ;
3. m and P_{ref} used for interpretation of E_{50}^{ref} and G_0^{ref} from E_{50} and G_0 are assumed to be "1" and "100 kPa" ;
4. $G_0^{ref} = G_0/(\sigma_3'/p^{ref})$ and $E_{50} = E_{50}^{ref}(\sigma_3'/p^{ref})^m$;
5. σ_3' is effective horizontal stress ;
6. G_0 is shear modulus of soil at small strain level and $\gamma_{0.7}$ is shear strain for shear modulus of soils equals to 70% of G_0 ;
7. E_u and E is undrained and drained elastic modulus of soil, respectively.

4 RESULT&DISCUSSION

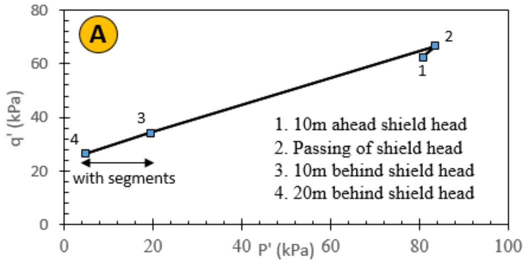
Except HS and HSS model, Mohr- Coulomb (MC) model is also selected for a comparison purpose and outcomes in the aspect of surface settlement are compared and discussed. Only outputs of stresses of tunnel segments from Method A are presented and compared with the ones from Method B, not for others so the rest results are all from Method B simulation. It is found that MC model has comparatively worse performances since a large ground heave is seen but can't be observed the same from the monitoring data.

Impacts from different shield operation parameters are conducted for parametric study. Details of analytical outputs and discussions are presented in Hsiung (2019). In short, surface settlement is not much changed when raising the face pressure as long as face pressure could reach a certain level but increasing backfill pressure of grout would decrease the value of surface settlement.

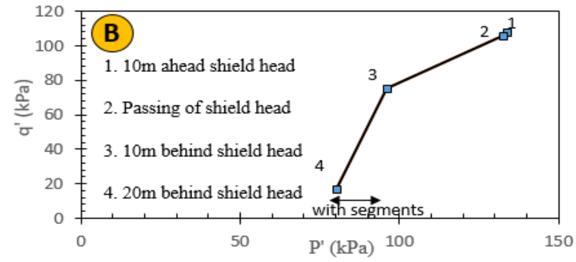
Moreover, stress status of soils around tunnel induced by tunnel construction are presented in Figure 4. Points at top, bottom and 2 sides, very close to the tunnel (approximately 1 m away; refer to Figure 4a) are selected.



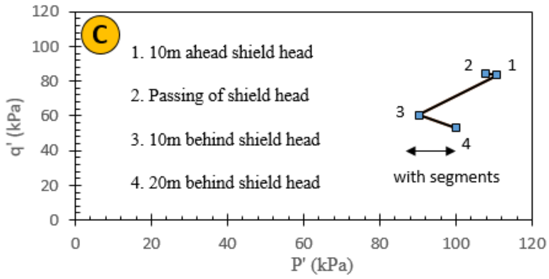
(a) Location of four points



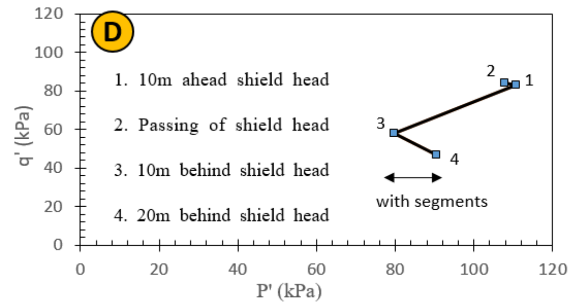
(b) Stress path of top point



(c) Stress path of bottom point



(d) Stress path of right side point

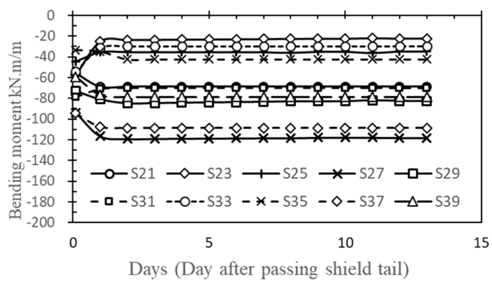


(e) Stress path of left side point

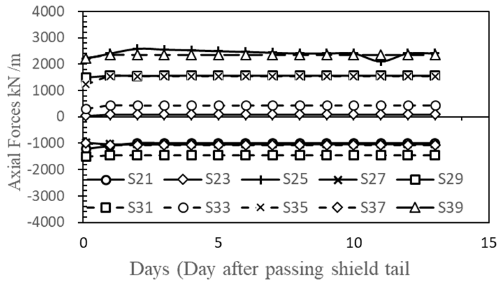
Figure. 4. Stress path for four points selected

As shown in Figure 4, the deviator stress continues to decrease during tunneling process, it is likely to be connected with stress relief due to tunneling excavation. Again, increasing of mean effective stress at Points C and D might be connected with increasing of lateral stress during tunnel segment installation but said statement has to be confirmed further associated with additional reference, such as monitoring data from an intensive instrumentation system.

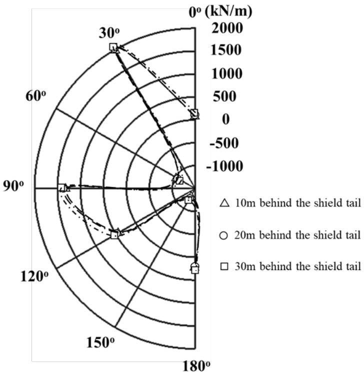
Figure 5 shows the simulation of axial forces, bending moment and stress of tunnel reinforcement segments at very locations using both Method A and Method B simulations. The soil constitutive model here chosen is HSS model. These results are compared with measured data taken from a tunnel constructed in similar soft alluvium material. It is found that outcomes from Method B are much closer to measured data. Therefore, it is able to conclude that though Method A is widely to be adopted in engineering practice and might have an opportunity to give an acceptable predicted settlement but the performance of Method B is even better which doesn't have to consider a "non-physical" parameter, ground convergence ratio and also could predict better in stresses of tunnel segments.



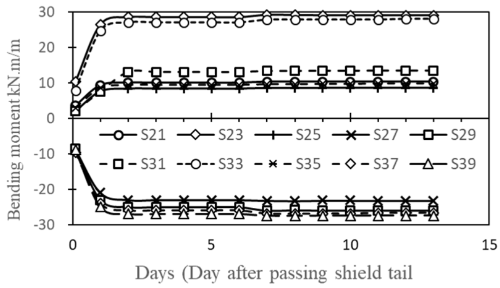
(a) Bending moment predicted from Method A



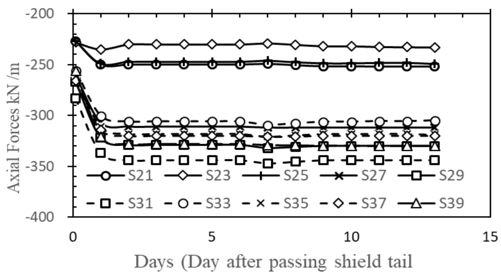
(b) Axial forces predicted from Method B



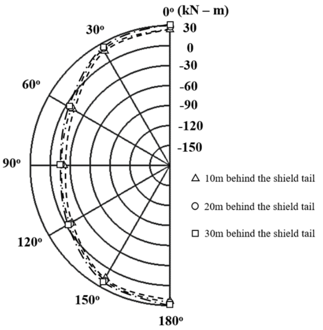
(c) Bending moment on tunnel segment at various locations using Method A



(d) Bending moment predicted using Method B



(e) Axial forces predicted using Method B



(f) Bending moment on tunnel segment at various locations using Method B

Figure. 5. Predicted stress on tunnel segment

5 CONCLUSION

In the aspect of constitutive model selection, it shows that although MC model get acceptable value from surface settlement but it can't give a consistence in ground heave in front of shield comparing with field monitoring data. This might be connected with MC model is a simple linear- perfect plastic model which is not eligible to include some soil characteristics due to stress relief of tunneling and also soil behavior at small strain level. In addition, the convergence distance seems to be longer of using both MC and HS models rather than the reality but HSS model simulation can provide much closer results. This is mainly connected with said model has a strain- dependent soil modulus function which can perform better rather than other two models.

Parametric studies of some shield operation parameters were conducted and it is concluded that the changes of face pressure is not eligible to lead to significant influence on surface settlement as long as the face pressure could reach a certain level. In contrast, impacts from the changes of backfill grouting pressure is more significantly larger.

At the end, stresses on tunnel reinforcement concrete segments are predicted by two different simulation methods and it is approved that the new method developed in this study (Method B) could perform better rather than works developed in previous study as well as conventional solution used in engineering practice.

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