Geotechnical Aspects of Underground Construction in Soft Ground – Yoo, Park, Kim & Ban (Eds)

3-Dimensional numerical modeling of SPB shield TBM tunneling-induced ground settlement considering volume loss processes

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ABSTRACT: In this paper, a practical 3-dimensional numerical model was proposed for prediction of ground settlement in slurry shield TBM tunneling. The model was developed using commercial finite element program PLAXIS 3D, where the volume loss process around shield TBM was modeled by implementing ground loss estimation schemes of Gap model. For weathered granite ground conditions, a series of numerical simulations were carried out and the predicted results were discussed by comparing with 2-dimensional solution.

Keywords: SPB Shield TBM, volume loss, ground settlement, numerical analysis

1 INTRODUCTION

Tunneling induces stress release in neighboring ground and consequent convergence. Actual excavation volume should be larger than theoretical one, and the difference between them is generally called volume loss. The volume loss causes ground settlement and, in the case of undrained condition, volume loss is thought to be identical to the volume of ground settlement. According to literature (Peck 1969), the volume loss is nearly proportional to the ground settlement and thus, its reliable estimation is of great importance.

However, volume loss values adopted in shield TBM tunneling practices are mostly referred to empirical estimations that have been usually obtained from observations of actual construction cases. Thus, they are thought to be applicable to particular geology, machine, and workmanship conditions. For instance, construction authorities in Hong Kong, Singapore, US provide guidelines of volume loss for settlement control during TBM operation with qualitative consideration of geology and workmanship.

In slurry shield TBM tunneling, volume loss occurs in three different mechanisms. Face loss is the first encountered ground loss caused by a movement or squeezing of ground into face as a result of excavation. Then, as shield advances, shield loss occurs as a radial contraction of ground due to overcut at cutter head and conicity of shield skin. At last, tail loss develops as a radial contraction of ground, which is caused by geometric difference in outer diameters of shield skin and segment lining. It develops during tail void grouting process and its hardening time.

Above indicates that volume loss in slurry shield TBM tunneling is not only a process of ground but also interactions among ground, machine, slurry, and backfill grout. Rowe and Lee (1983) proposed Gap model for generalized evaluation of volume loss and ground settlement in 2-dimensional numerical analysis of shield TBM tunneling, where summation of ground loss at face, physical gap at shield tail, and overcut at cutterhead were estimated as a Gap parameter. The model has been modified by several researchers (Rowe & Lee 1992; Lee et al. 1992; Lee 1989) and, in recent, Loganathan (2009) proposed practical methods combining improved Gap model consistent with actual phenomena related to ground losses around shield skin and tail and ground settlement evaluation method of Loganathan and Poulos (1998).

On the other hand, because the shield TBM tunneling is a 3-dimensional process, sophisticated numerical models has been adopted in detailed settlement analyses (Kasper & Meschke 2006). However, the models require huge calculation resources and there are some uncertainties in their simulation schemes that may not be consistent with actual volume loss process around slurry TBM and design methods adopted in practice.

In this paper, practical 3-dimensional numerical model was proposed for prediction of ground settlement in slurry shield TBM tunneling. The model was developed using commercial finite element program PLAXIS 3D, where the volume loss process was modeled by implementing ground loss estimation schemes in Gap model. A series of simulations were carried out and the predicted settlement results were discussed by comparing with 2-dimensional solution.

2 NUMERICAL MODELING

2.1 *Ground condition and tunneling details*

Typical weathered granite soil and rock (G4, G6 type in Singapore) conditions described in Park et al. (2013)

Table 1. Geotechnical properties of ground.

Properties	G4	G6
Total Unit Weight γ (kN/m^3)	18.5	23.0
Young's modulus E (MPa)	69	300
Poisson's ratio v	0.30	0.25
Friction angel φ (°)	30	35
Cohesion c (kPa)	3	50
Undrained shear strength C_u (kPa)	245	1750

Table 2. Shield TBM and segment specifications.

Item	Value
Shield Length (m)	12.0
Cutterhead diameter (m)	7.0
Shield outer diameter (m)	6.9
Shield inner diameter (m)	6.7
Segment ring length (m)	1.5
Segment outer diameter (m)	6.6
Segment inner diameter (m)	6.0

were referred in our analyses. Their geotechnical properties are summarized in Table 1. Ground water table was assumed to be located at ground surface.

Table 2 presents specifications of shield TBM machine and segment lining. Tunnel was considered to be constructed at 21 m below ground surface, which ensures a cover depth equal to 3 times of excavation diameter. As TBM operation conditions, 250 kPa of face pressure and 100 kPa of backfill pressure were imposed.

2.2 *Determination of volume loss parameters*

The method proposed by Loganathan (2009) was adopted in the volume loss estimation. The face loss V_f was calculated using Equation 1 where, α is the coefficient representing the resistance between the intruding soil and the TBM chamber skin, β is the dimensionless axial displacement ahead of the tunnel face, P_0 is the total stress removal at the spring line level on tunnel face, and E_U is the undrained Young's modulus of soil at tunnel face.

$$V_f = \alpha\beta P_0 / E_U \tag{1}$$

The coefficients α and β can be determined from Equation 2 and 3, respectively.

$$\alpha = \begin{cases} 0.7 & \text{stiff ground } (q_u > 100\text{kPa}) \\ 0.9 & \text{soft ground } (25\text{kPa} < q_u < 100\text{kPa}) \\ 1.0 & \text{very soft ground } (q_u < 25\text{kPa}) \end{cases} \tag{2}$$

$$\beta = \begin{cases} 1.12 & \text{for } N_R < 3 \\ 0.63N_R - 0.77 & \text{for } 3 < N_R < 5 \\ 1.07N_R - 2.55 & \text{for } N_R > 3 \end{cases} \tag{3}$$

Table 3. Estimated volume loss parameters*.

Items	G4	G6
Face loss V_f (%)	0.02 (5)	0.06 (8)
Shield loss V_{sh} (%)	0.09 (20)	0.26 (35)
Tail loss V_v (%)	0.34 (75)	0.43 (57)
Total loss V_L (%)	0.45 (100)	0.75 (100)

*Number in parentheses means relative ratio to total loss in %.

In above equations, q_u is the unconfined uniaxial strength, N_R is the stability number defined as Equation 4, where γ is the total unit weight of ground, H is the depth of tunnel spring line, P_i the face pressure, and C_u is the undrained shear strength.

$$N_R = (\gamma H - p_i) / C_u \tag{4}$$

Then, the shield loss V_{sh} was estimated as smaller one between those derived from physically and from convergence of tunnel cavity as denoted in Equation 5, where U_s is the cavity convergence, v is the poisson's ratio, p_w is the pore water pressure at tunnel spring line level, t_b is the overcut thickness, t_t is the amount of shield taper.

$$V_{sh} = \begin{cases} 0.5(t_b + t_t), \text{if } U_s > t_b + t_t \\ 0.5U_s \quad\quad , \text{if } U_s \le t_b + t_t \end{cases} \tag{5}$$

Finally, considering shrink of backfill grout during its hydration process (Ingles 1928), the tail loss V_v was determined as Equation 6, where t_v is thickness of tail void, and U_v is the cavity convergence with backfill pressure. Equation 6 is slightly modified from original one, because tail loss estimation of Loganathan (2009) may result in overestimation for rock condition.

$$V_v = \begin{cases} 0.1 \cdot t_v, \text{if } U_v > 0.1 \cdot t_v \\ U_v, \quad \text{if } U_v < 0.1 \cdot t_v \end{cases} \tag{6}$$

Table 3 summarizes the calculated volume loss parameters. The stiffer the ground, the less total volume loss was estimated. On the other hand, the tail loss was found to be most influencing factor and its proportion to total value increases as ground become stiffer due to decreasing of face and shield losses.

2.3 *Finite element modeling*

2.3.1 *Finite element discretization*

Fig. 1 shows the finite element model developed for analyses. Considering symmetric condition of single tunnel, its half section was modeled with following dimensions: 60 m of width, 100 m of length, and 60 m of height.

Homogeneous ground condition was modeled by using 10-node tetrahedron continuum elements. Linear elastic-perfectly plastic behavior of the ground

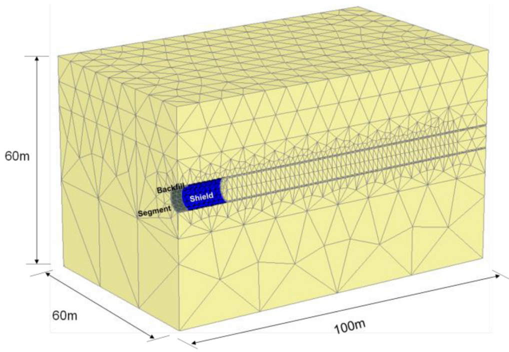


Figure 1. Finite element model developed for analyses.

Table 4. Material parameters of shield and concrete.

Properties	Shield	Concrete
Total Unit Weight γ (kN/m^3)	660*	24.0
Young's modulus E (GPa)	210	31
Poisson's ratio ν	0.1	0.1

*This value includes gross weight of shield skin and machine.

was assumed with obeying Mohr-Coulomb plasticity. Shield skin was modeled as elastic shell elements having equivalent weight and stiffness. Continuum elements with total stress formulation were applied to model concrete segment lining and backfill grout and their constitutive behavior was assumed to be elastic. Table 4 presents material parameters of shield and concrete.

On the other hand, in order to demonstrate hardening of backfill grout, guideline provided Nippon Civil Consultants (2001) given in Equation 7 was exploited to estimate time-dependent varying elastic modulus, where t is elapsed time in hour after completion of simultaneous backfilling.

$$E = 34 \cdot \left[0.0266 \times t + 0.01\right] + 16.0(MPa) \tag{7}$$

2.3.2 *Modeling of volume loss*

The volume losses obtained from Gap model were implemented in PLAXIS 3D program as described in Fig. 2. The face loss was modeled by imposing depth-dependent linearly increasing pressure to tunnel face, where gradient of pressure was assumed to be equal to slurry density 11.2 kN/m in vertical direction. Then, the shield loss was simulated by inducing forced contraction of shell elements corresponding to the shield loss V_{sh} obtained from Equation 5. Instead of imposing uniform contraction, the forced contraction was assigned to shell elements with longitudinal gradient as V_{sh} divided by shield length. On the other hand, the tail loss caused by shrink of backfill grout was simulated considering construction stages. In our analyses, the backfill grout was assumed to be fully shrunk and hardened in 4-ring installation period. Hence, in each stage, volumetric contraction of $V_v/4$ was imposed to 4-rings behind shield machine. Simultaneously, elastic modulus of backfill determined from Equation 7 was assigned according to construction step.

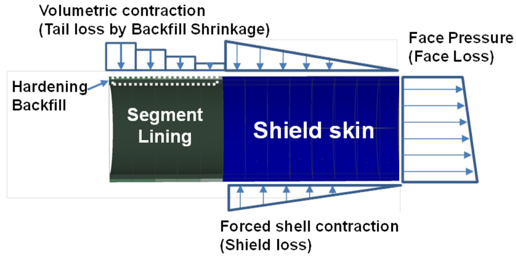
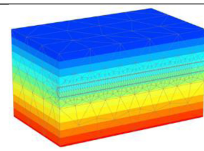
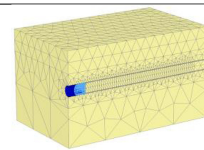
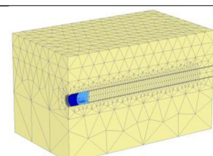
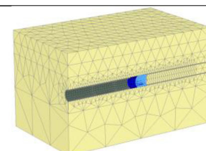


Figure 2. Modeling of volume losses in FE model.

Table 5. Analysis sequence.

① Initial condition	② Shield intrusion
	
③ Simultaneous excavation, backfill injection and segment lining installation → Repeat	
	

2.3.3 *Simulation of tunneling procedure*

The tunneling of 57 m, which includes TBM intrude and installation of 24 segment rings, was simulated in undrained condition. Detailed analysis sequence is described in Table 5.

3 RESULTS AND DISCUSSION

Fig. 3 shows the numerically predicted maximum ground settlement with the TBM driving distance. It can be seen that, after 50 meters of advance, the maximum ground settlements nearly converged. Because the tunneling is 3-dimensional process, the converged settlement can be interpreted as the maximum settlement developed in plane strain condition.

The numerically predicted ground settlements in transversal direction at the end of analyses were compared with the 2-dimensional solution of Loganathan and Poulos (1998) as expressed in Equation 8, where x is the lateral distance from tunnel axis.

$$U_{z=0} = V_L R^2 \cdot \frac{4H(1-\nu)}{H^2 + x^2} \cdot exp\left\{-\frac{1.38x^2}{\left(H cot\left(45+\phi/2\right)+R\right)^2}\right\} \tag{7}$$

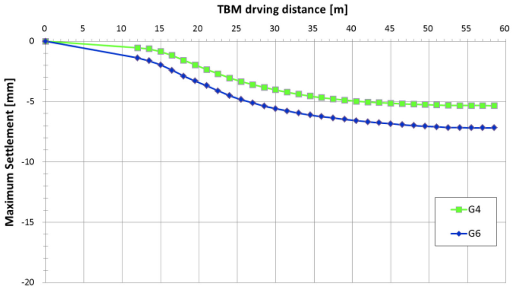


Figure 3. Maximum settlement with tunneling distance.

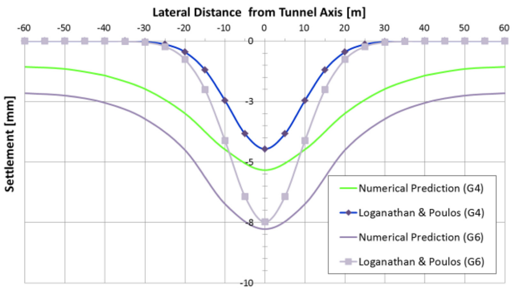


Figure 4. Comparisons of settlement predictions.

Comparison results are plotted in Fig. 4. There are favorable coincidences in the predictions of maximum ground settlement. It may imply that numerical model proposed in this study reasonably demonstrates volume loss process over tunnel crown, which is mainly related to maximum settlement. However, considerable differences are found in their settlement troughs. 2D solutions denote much steeper increase of settlement around tunnel and narrower range of settlement than numerical calculations. This might be caused by the uniform radial contractions over shield and unset backfill grout assumed in the numerical model, which may not be realistic in non-isotropic stress condition. Because of that, wider range of settlement was resulted in the numerical calculations. Moreover, the predicted results also indicate that numerical results provide conservative estimation of different settlement near tunnel.

For better numerical modeling, realistic process of volume loss should be investigated and reflected in the simulation by considering effect of earth pressure condition, soil-backfill grout interaction, shape of ground loss around shield skin etc.

4 CONCLUSIONS

In this paper, a 3-dimensional numerical model for the simulation of ground settlement induced by SPB TBM driving considering volume loss processes. Simulation results indicated that the proposed model is suitable for prediction of maximum settlement but the volume loss modeling should be improved for realistic estimation of settlement trough.

ACKNOWLEDGEMENT

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 13 Construction Research T01).

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