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Numerical Evaluation of Surface Settlement Induced by Improper Muck Control of EPB Shield TBM

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ABSTRACT

The Shield TBM method can build the tunnel with least ground deformation through continuous and repetitive excavation and support. However, the surface settlement during Shield TBM excavation still happens, and it causes severe economic loss. The key factor of surface settlement during Shield TBM excavation is known as improper muck control, such as groundwater leakage or excessive excavation irrespective of TBM advance. In this study, the ground loss determined by the muck volume was identified, and its contribution to the surface settlement was evaluated through numerical experiments. It is anticipated to contribute to the settlement prediction model construction from these results.

1. INTRODUCTION

The Shield TBM (Tunnel Boring Machine) method is known as one of the advanced excavation method which generates less vibration, noise and dust than traditional blasting method. The major strength of Shield TBM is its ability to construct the tunnel with less ground deformation by continuous and repetitive excavation and support. The EPB (Earth Pressure Balanced) Shield TBM is a type of Shield TBM which can secure the balance of tunnel face with pressed muck inside the chamber. Still, the surface settlement due to Shield TBM excavation has been occurred, and caused severe economic loss. The key parameters triggering the surface settlement is various: diameter and depth of the tunnel (Melis et al., 2002; Chakeri et al., 2013), ground properties (Selby, 1988), face pressure (Lambrughi et al., 2012; Comodromos et al., 2014), and tail void backfill pressure and injection point (Suwansawat and Einstein, 2007). However, the magnitude of surface settlement due to those parameters of ordinary construction sequence is not significant than that from the accident. The accident such as groundwater inflow to the excavated tunnel, or excessive excavation irrespective to TBM advance can bring out enormous surface settlement. In this study,

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the contribution of the improper muck control to the surface settlement was evaluated through the numerical experiments. The numerical modelling was validated with comparison with the data from literature, which described ordinary excavation sequence. The relationship between ground loss determined by the muck volume and settlement was clarified.

2. NUMERICAL EXPERIMENTS

2.1 Validation of numerical modelling of EPB Shield TBM excavation sequence

In this study, the FDM based numerical computational software of FLAC3D was used which developed by Itasca C.G., Inc. The target site was selected from Teheran Metro Line 7 (Chakeri et al., 2013). The ground had no groundwater and composed with 4 layers of soils. The ground is assumed to have homogenous and isotropic with an elasto-plastic behavior following Mohr-Coulomb criterion. Detailed ground properties of target site is tabulated in Table 1.

Table 1. Ground properties of target site (Chakeri et al., 2013)

Ground layer	Classification (BSCS)	Thickness [m]	Unit weight [kg/m³]	Cohesion [kPa]	Internal friction angle [degree]	Elastic modulus [MPa]	Poisson's ratio
Layer 1	Filling	1.2	1900	29	35	15	0.30
Layer 2	ML, CL	8		40	27	30	0.35
Layer 3	GML, GCL	11.6		30	35	80	0.27
Layer 4	GWM, GML	Base		20	38	100	0.27

Note. ML: Silt, CL: Clay, GML: Silt with gravel, GCL: Clay with gravel, GWM: Well graded silty gravel

The EPB Shield TBM applied on the site had a diameter of 9.2m, shield length of 9.0m. Segment lining had 8.85m of external diameter, 1.5m of span, 0.35m of thickness. In this study, the external diameter of segment was chosen as 8.90m for convenience of mesh construction. The properties of Shield TBM, segment, and tail void grouts are tabulated on Table 2. All of three structures were described as Shell elements, and Zone elements are duplicated on segment and grouts to see the deformation of thickness direction.

Table 2. Input properties of structures (Chakeri et al., 2013)

	Elastic modulus [GPa]	Poisson's ratio	Unit weight [kg/m³]	Shear modulus [GPa]	Thickness [m]
Shield	200	0.25	7840	80	0.50
Segment	27	0.2	2400	11.25	0.35
Grouts	1	0.25	1200	0.4	0.15

For assumption of infinite ground, the model geometry was selected as 90m (>H+4D) on y-axis (longitudinal direction to excavation), 90m (>H+4D) on x-axis (transversal direction to excavation), and 60m (>H+4D) on z-axis, considering the diameter of tunnel (D) and the cover depth of tunnel (H) (Lambrughi et al., 2012). All nodes were fixed with orthogonal direction to boundary.

The grouts injection pressure was applied to excavated perimeter surface orthogonally during 5 rings after simultaneous injection. The modulus was applied as 2, 3, 20, 40, 55, 65, 72, 80, 83, 86, 89, 100% of the one of final setting for each 5 rings (Lambrughi et al., 2012). EPB Shield TBM construction sequence was simulated assuming closed mode; continuous operation with face pressure application, segment ring building, and tail void backfilling. Unit excavation span was 1.5m same as segment span, and ring building with injection was simulated after 6 repeat, which is for Shield TBM length of 9.0m. Each advance was calculated with 1,000 steps.

The term of FPR and BPR was used to define the operational factor. The FPR is the ratio between face pressure and outer soil pressure, and the BPR is the ratio between backfill injection pressure and outer soil pressure. The operation setup of the field is not clear, but Chakeri et al. (2013) applied 88kPa of face pressure, which is very low. Thus, the control group for validation used FPR of 0.6 and BPR of 1.1. As the result, the maximum surface settlement of numerical prediction was 6.95mm, which is quite similar to the measured value of 6.9~7.1mm. Therefore, the numerical modelling was clarified to valid.

2.2 Parametric study on improper muck control

For the parametric study on improper muck control, other factors were fixed; FPR was 0.9, and BPR was 1.4. The wet ground densities were determined with considering representative porosity and permeability values. The tests were conducted with three conditions, excessive excavation on dry ground, groundwater inflow, and excessive excavation on wet ground. The excessive excavation was simulated by considering the sliding mechanism on tunnel face. The ground deformation in front of tunnel face shows prismatic wedge shape and the ground on that wedge has chimney shape as rectangular column (Horn, 1961). The inclination of the wedge is determined from internal friction angle of ground. Therefore, the excessive excavation of additional volume of 0.5 ring, 1.0 ring, and 2.0 ring was described with following the angle of the wedge as Fig. 1. The groundwater level was 1.2m below the ground surface. Groundwater inflow was modelled from 1 sec inflow to 10 sec inflow with applying uncoupled analysis.

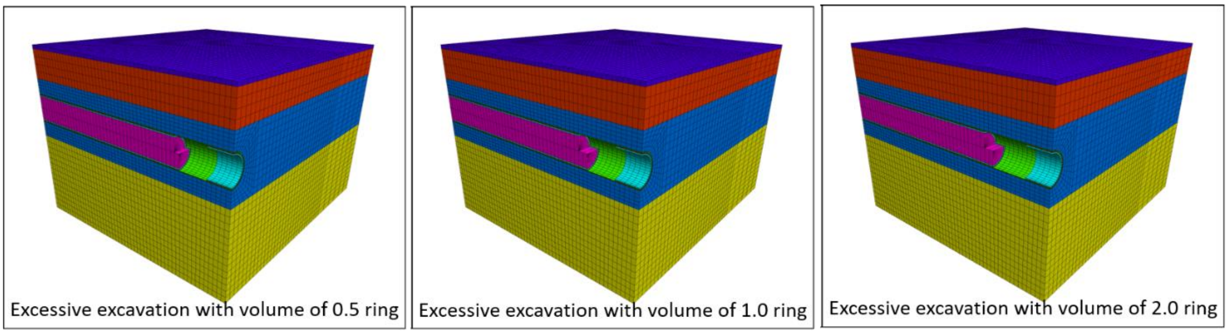

Fig. 1 Modelling of excessive excavation

The excavation sequences were as follow: a) following ordinary sequence until the tunnel face arrived at 27m, b) event of improper muck control happened, c) excavate until the tunnel face arrived at 51m.

2.3 Results and analysis

At dry ground, the excessive excavation caused enlarged maximum surface settlement as 8% more at additional 0.5 ring, 27% more at additional 1.0 ring, and 58% more at additional 2.0 rings. Still, the longitudinal settlement trough along the tunnel centerline remained same except the point of excessive excavation occurred. At wet ground, although the trend was similar with dry condition, the maximum surface settlement increased as 8% more at additional 0.5 ring, 67% more at additional 1.0 ring, and 372% more at additional 2.0 rings. When only groundwater inflow occurred, the maximum settlement was slightly increased but did not show significant impact due to short fluid time. However, the settlement occurred more at adjacent ground.

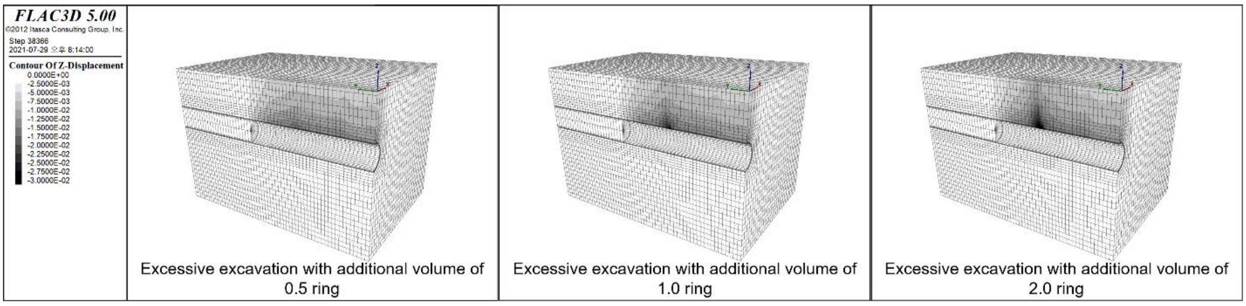

Fig. 2 Settlement diagram when excessive excavation occurred at dry ground

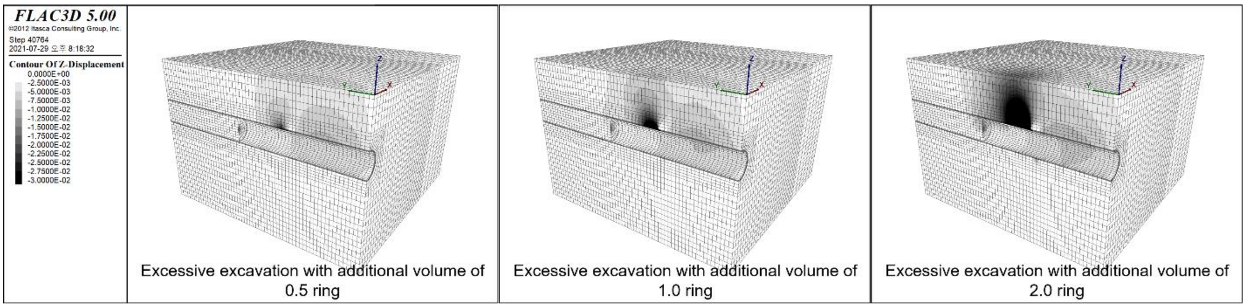

Fig. 3 Settlement diagram when excessive excavation occurred at wet ground

The groundwater drain makes the pore pressure diminished and effective stress increased. Thus, even though the groundwater inflow did not show significant impact itself, it showed critical as simultaneously occurred with excessive excavation. So, proper muck control should be conducted when the Shield TBM advances on wet ground.

3. CONCLUSIONS

The accident such as groundwater inflow to the excavated tunnel, or excessive excavation irrespective to TBM advance can bring out enormous surface settlement. In this study, the contribution of the improper muck control to the surface settlement was evaluated through the numerical experiments. The impact on maximum surface settlement was increased from groundwater inflow, excessive excavation on dry ground, and excessive excavation on wet ground. The groundwater inflow during the excessive excavation was especially significant factor.

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