Mechanical behavior of ground due to EPB shield TBM tunnel excavation passing through fractured zone

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ABSTRACT: Recently, tunneling with shield tunnel boring machine (TBM) is getting popular for the construction of cable tunnel in urban area. Mechanized tunneling method using shield TBM has various advantages such as minimization of ground settlement and prevention of vibration induced by blasting that should be accompanied by conventional tunneling. In Korea, earth pressure balance (EPB) type of shield TBM has been mainly used. Despite the popularity of shield TBM for cable tunnel construction, studies on the mechanical behavior of cable tunnel driven by shield TBM passing through the fracture zone are insufficient. Thus, in this study, three dimensional numerical modelling of EPB shield TBM is presented. And, the effect of fractured zone ahead of tunnel face on the mechanical behavior of composite ground consisted with soil, weathered soil, weathered rock and fractured zone is investigated. The critical orientation of fractured zone ahead of tunnel face is derived based on the results obtained from the 3-dimensional numerical analysis.

1 INTRODUCTION

Recently, the use of electricity is rapidly increasing due to improving living standard and the industrial development in South Korea. To provide stable electricity to client, infrastructure such as ultra-high-voltage transmission line has been constructed to connect the power plant and substation in the urban area. However, the ultra-high-voltage transmission line generally causes noise issue, raises health problems, and brings harmful effects on nature. Thus, to prevent the problems accompanied by transmission line, underground cable tunnel can be the best solution to accommodate transmission line safely and environmentally friendly.

EPB type shield TBM tunneling has been used as the major tunneling method for cable tunnel construction in South Korea. However, despite the popularity of EPB shield TBM tunneling for cable tunnel construction, the study on the behavior of ground induced by EPB shield TBM excavation in composite ground is insufficient. Moreover, the behavior of shield TBM tunnel passing through the fractured zone has yet to be clearly investigated.

The prediction of fractured zone behavior in composite ground condition due to tunneling with shield TBM is very important. Because, the tunnel can be unstable due to excessive displacement at tunnel crown and tunnel face induced by localized settlement while passing through the fractured zone. In addition, reasonable 3-dimensional numerical modelling of EPB shield TBM has not been established yet (Kang, 2013).

In this study, we proposed a reasonable numerical simulation procedure for EPB shield TBM tunneling in composite ground passing through the fractured zone. In addition, the behavior of the fractured zone and vertical displacement at the ground surface due to tunneling is investigated with 3-dimensional finite element method, MIDAS-GTS NX. Orientation and width of fractured zone have been varied to derive critical situation for EPB shield TBM tunnel.

2 NUMERICAL SIMULATION

2.1 Background of numerical simulation

The most important purpose of numerical analysis on the EPB shield TBM excavation is to obtain the settlement of ground surface and stability of the segment during the tunnel excavation. The stability of the segment is associated with the internal displacement of the tunnel and stresses acting on the tunnel structures. If the excessive displacement is occurred while passing through the fractured zone, large force will act on the segment lining and cause tensile failure and crack in segment lining. With 3-dimensional FEM analysis, it is possible to get the settlement behavior of the surface ground as well as internal displacement of the tunnel at the same time. Moreover, we can get the stress acting on the segment lining while excavating.

Gap parameter is the quantity of the fictitious displacement due to the volume loss that occurs during the construction of the tunnel with the shield TBM. Gap
parameter should be estimated with following equation (1) and need to be imputed in the 2-dimensional numerical analysis (Lee et al., 1992).

\[
\text{Gap parameter} = 2\Delta + \delta + U^{*}_{3D} + W
\]

(1)

where \(\Delta\) is space between the segment lining and skin plate; \(\delta\) is space for installation of the segment lining; \(U^{*}_{3D}\) is 3-dimensional movement of the tunnel face due to volume loss and \(W\) is displacement resulted by over excavation.

In 2-dimensional numerical analysis for the simulation of EPB shield TBM, displacement control model (DCM) is mainly used. In DCM analysis, calculation or convergence is not controlled by force equilibrium but calculation proceeds until the pre-estimated excavation surface based on the gap parameter converges on the external diameter of segment lining. However, this method can’t simulate the actual behavior of EPB shield TBM and tends to overestimate the vertical subsidence since we need to assume the 3-dimentional ground movement. Furthermore, it is essential to assume the final convergence of the tunnel to estimate the load distribution factor.

On the other hand, the 3-dimensional numerical analysis is not necessary to assume the 3-dimensional movement of ground during the tunnel excavation and volume loss due to excavation. Therefore, estimation of gap parameter that needs few assumptions is not necessary in 3-dimentional numerical analysis. Moreover, not only subsidence and ground movement but also various stress and force components acting on the segment lining can be calculated with introduction of structural element using 3-dimentional numerical analysis. This study, we proposed a reasonable numerical simulation procedure for EPB shield TBM tunneling to obtain the behavior of ground as well as stress acting on the tunnel structure.

2.2 Modeling of EPB Shield TBM

Specifications of the EPB shield TBM tunnel and configuration of composite ground are referred to the ‘detailed design report’ of existing cable tunnel project. As shown in Figure 1, the ground is composed of landfill soil, weathered soil, weathered rock and soft rock. The external diameter of the tunnel is 3.55m and internal diameter is 3.4m. External diameter implies the drilling surface and internal diameter indicates an internal diameter of segment lining.

Gap parameter estimated considering the mechanical error of shield TBM is 0.075 m. In this study, backfill grout is assumed as elastic body. Segment lining is reinforced concrete and skin plate is metallic structure. To obtain the stresses and forces acting on the structural components, structural element such as shell element should be introduced. Segment lining is simulated with shell element; also the thin cylindrical skin plate is simulated with shell element in this study. Backfill grout and composite ground are simulated with solid element.

The orientation of fractured zone varied from against direction (Figure 2) to with direction (Figure 3). Width of the fractured zone varied 1L, 3L and 5L (e.g., the length of the segment, L = 1.2 m). As shown in Table 1, properties of shield TBM and ground used in numerical analysis are summarized.

It is necessary to determine the management face pressure that should be applied on the EPB shield TBM face as a boundary condition. Determination of optimum management face pressure is very important to secure the stability of EPB shield TBM. After the study based on the results of the field, setting the management face pressure must be determined by referring to the results of various monitoring conditions at the site (Kim, 2013). In this study, if we assume that the lateral earth pressure coefficient as \(K_0 = 0.5\), 77.12 kN/m\(^2\) of management face pressure is estimated and applied onto the EPB shield TBM face.

In this study, we focused on the displacement of the ground surface and fractured zone during the EPB shield TBM excavation passing through the fractured zone. The effect of orientation of fractured zone and the thickness of fractured zone is investigated. The length of the skin plate is 6m. Injection method assumed in this study is concurrent-injection method that backfill grout installed at the same time with the segment. After the skin plate has been fitted to the ground, the segment and backfill grout is installed. Maximum amount of subsidence is measured by the index point of maximum subsidence after 60 m excavation. Result of
Table 1. Properties used for numerical analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>Element</th>
<th>Elastic Modulus $\text{kN/m}^2$</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin plate</td>
<td>Elastic</td>
<td>Shell</td>
<td>$2.5e8$</td>
<td>0.20</td>
</tr>
<tr>
<td>Segment</td>
<td>Elastic</td>
<td>Shell</td>
<td>$2.1e7$</td>
<td>0.25</td>
</tr>
<tr>
<td>Backfill grout</td>
<td>D-P</td>
<td>Solid</td>
<td>$1.0e7$</td>
<td>0.30</td>
</tr>
<tr>
<td>Soft rock</td>
<td>D-P</td>
<td>Solid</td>
<td>$2.4e6$</td>
<td>0.30</td>
</tr>
<tr>
<td>Weathered rock</td>
<td>D-P</td>
<td>Solid</td>
<td>$1.0e5$</td>
<td>0.30</td>
</tr>
<tr>
<td>Weathered soil</td>
<td>D-P</td>
<td>Solid</td>
<td>$5.0e4$</td>
<td>0.35</td>
</tr>
<tr>
<td>Landfill soil</td>
<td>D-P</td>
<td>Solid</td>
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<td>0.38</td>
</tr>
<tr>
<td>Fractured zone</td>
<td>D-P</td>
<td>Solid</td>
<td>$1.0e4$</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Note: D-P denotes Druker-Prager model.

displacement obtained from 3-dimensional numerical analysis will be presented in following section.

3 RESULTS AND DISCUSSIONS

3.1 Displacement of the ground surface

Settlement of the ground surface shows a maximum subsidence near the fractured zone. Results of the numerical analysis are presented in Figure 4 and 5. Displacement is continuously measured according to the tunnel construction stage. Measurement point is located at the top of the model along the central axis of the tunnel.

When 5L wide fractured zone is inclined 60 degrees with direction of tunnel advancing, settlement at the ground surface shows a maximum displacement of 9.93 mm as it is shown in Figure 4.

When 5L wide fractured zone is inclined 30 degrees against direction of tunnel advancing, settlement at the ground surface shows a maximum displacement of 10.04 mm as it is shown in Figure 5. As the inclination angle increases from 60 degrees to 90 degrees, displacement of the ground surface decreases. As the width of fractured zone increases, settlement of ground surface increases regardless of the orientation of fractured zone. Especially, when 5L wide fractured zone is inclined 30 degrees against direction of tunnel advancing, settlement shows the maximum displacement.

3.2 Displacement of the fractured zone

When EPB shield TBM excavation passes through the fractured zone, vertical displacement in fractured zone is relatively bigger than that obtained from settlement at the ground surface. This result is based on the relationship between the ground surface and volume loss at the shield TBM face. Results of the numerical analysis are presented in Figure 6 and 7. Displacement is continuously measured according to the tunnel construction stage at the right above the tunnel crown along the central axis of the tunnel.

As a result, displacement of fractured zone is greater when the fractured zone is with direction of tunnel advancing than when the fractured zone is against direction of tunnel advancing. Vertical displacement in fractured zone which is against direction of tunnel advancing is about 75% of vertical displacement obtained fractured zone which is with direction of tunnel advancing. Due to subsidence suppression effect
induced by the face pressure acting on the shield TBM face is governed by the orientation of fractured zone. As the width of fractured zone increases, the vertical displacement in the fractured zone increases when the orientation of fractured zone is against the direction of tunnel advancing. When the inclination of fractured zone is 30 degrees, vertical displacement shows maximum value regardless of the direction. This is somewhat different from conventional understanding. In general, it is unfavorable condition when the fractured zone is against the direction of tunnel advancing. However, in continuum numerical analysis, displacement of the fractured zone is suppressed due to the face pressure imposed on the shield TBM face. To overcome the limitation of continuum analysis, discrete analysis should be carried out in the future.

It is expected that the results of this study are used as a basis to select the appropriate reinforcement method in accordance with the direction and width of the fractured zone in composite ground.

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