

복합지반에서 TBM 굴진 진동을 고려한 지표침하에 대한 수치모델링

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Numerical simulation for surface settlement considering face vibration of TBM tunnelling in mixed-face condition

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ABSTRACT: In this paper, the surface settlement resulted from the shallow TBM tunnelling has been numerically simulated. TBM tunnelling is especially used in urban area to avoid serious vibration and noise caused by explosion in NATM. Surface settlement is one of the most important problems encountered in all tunnelling and critical in urban areas. In this study, face vibration of TBM excavation is considered to estimate surface settlement trend according to TBM extrusion. The dynamic excavation forces are calculated by total torque on the TBM cutterhead in mixed-face of soil and weathered rock condition with shallow depth. A 3-dimensional FDM code is employed to simulate TBM tunnelling and mechanical-dynamic coupling analysis is performed. The 3D numerical analysis results showed that dynamic settlement histories and trend of surface settlement successfully. The maximum settlement occurred at the excavation point located at 2.5D behind the face, and the effect of face vibration on the surface settlement was verified in this study.

Keywords: Surface settlement, TBM, Face vibration, Mixed-face, Mechanical-dynamic coupling analysis

초 록: 본 연구는 도심지 천층터널에서 현재까지 해석에서 무시되던 막장면 진동이 주위 구조물에 가장 큰 영향을 미치는 지표 침하에 대하여 3차원 수치해석을 이용하여 모델링하였다. 풍화도와 풍화암이 각각 50%의 비율로 구성된 복합지반을 고려하여 TBM 커터헤드에 발생하는 굴착시 토크를 산정하여 이를 시간에 따라 막장면에 재하함으로써 그 영향을 수치해석적으로 관찰하였다. 3차원 유한차분해석법을 이용하여 역학-동역학 연계해석을 통하여 지표침하 발생이력 및 분포도를 산정하였다. 연구결과, 3차원 수치해석을 통하여 막장면 진동하중에 의한 지표침하 발생경향을 성공적으로 모델링할 수 있었으며 최대 침하는 막장면에서 2.5D 후방에서 발생함을 확인하였고, 막장면 진동이 실제 지표침하에 영향을 미치는 것을 확인하였다.

주요어: 지표침하, TBM, 막장면 진동, 복합지반, 역학-동역학 연계해석

1. Introduction

The TBM tunnelling technology has found widespread applications and appropriateness in underground

excavations for decades. Difficult soil conditions, locations, and depth have been applicable as the TBM technology evolves. Urban tunnels are often excavated adjacent to buildings, beneath roads, railroads, and other civil structures. The increasing need for urban tunnelling in such congested areas are leading engineers to investigate more sophisticated solutions to predict surface settlement which affects the stability of adjacent

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Received April 20, 2015; Revised May 1, 2015;
Accepted May 6, 2015

structures. The static analyses to estimate effect of tunnel excavation on the surface settlement have been performed in various conditions, however, dynamic effect from face vibration has been overlooked.

A certain serious limitation is represented by varying ground conditions, such as faults, weakness zones or soil/soft rock, combined with hard rock. This is commonly referred to as mixed-face condition (Zhang et al., 2010). Mixed-face condition is defined as the difference in uniaxial compression strength between the weakest and the strongest layer of a minimum of 1:10 (Steingrímsson et al., 2002). The ground constitution of tunnel face is critical to the excavation torque and one of the most significant factors that influence the machine’s overall performance. It has been reported that mixed-face condition may lead to frequent TBM stoppages and even failures of the drive motor (Jafari et al., 2009). Zhang et al. (2010) analyzed the dynamic characteristics of TBM tunnelling in mixed-face condition and the results are utilized in the numerical simulation of this study. Kim et al. (2013) performed an experimental study on shield TBM tunnel face stability in soft ground, and Kim (2004) conducted 2 dimensional numerical analysis.

In this study, the dynamic effect of face vibration induced by TBM extrusion is simulated in the mixed-face condition. A 3-dimensional FDM code is employed to simulate TBM tunnelling, and mechanical-dynamic coupling analysis is performed to investigate the trend of surface settlement according to tunnel extrusion.

2. Conditions for simulation

2.1 Ground conditions

Mixed-face condition has been applied in this simulation which can represent one of the most difficult ground state in case of TBM excavation. The mixed-face consists of cohesionless weathered soil and weathered rock simultaneously. The interface between the soil and rock is simply assumed as a straight line as shown in Fig. 1. The engineering material properties of the ground are demonstrated in Table 1. α represents different area percentages of the soft part of ground formation in mixed-face condition, which directly affects the fluctuation frequency and amplitude of excavation torque.

2.2 Assessment of TBM vibration

Since TBM was originated from the idea to minimize the vibration and noise during the excavation, the

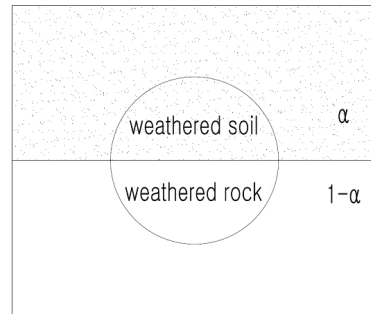


Fig. 1. Assumption of mixed-face condition

Table 1. Material properties of ground

| Material | Young’s modulus (MPa) | Friction angle (deg) | cohesion (kPa) | Density (kN/m ³) | Poisson’s ratio |
|----------------|-----------------------|----------------------|----------------|------------------------------|-----------------|
| Weathered soil | 35.0 | 30 | 15.0 | 19 | 0.3 |
| Weathered rock | 500.0 | 33 | 50.0 | 21 | 0.3 |

vibration resulted from the TBM will not be significant. However, the structures such as nuclear power plant, broadcasting station, hospital, etc. are critical to the vibration-induced ground settlement. Furthermore, the trend of settlement according to the face extrusion gives the useful information to predict ground movement in difficult soil conditions. In this study, the results of the previous study (Zhang et al., 2010) was utilized to assess the TBM vibration.

TBM is based on the mechanical excavation using cutterhead at the face, therefore dynamic torsional resistance on the cutterhead is the main source of vibration at the ground-machine interface. TBM cutterhead is driven by electric motors to apply excavation torque. Various cutters have been designed and mounted on the cutterhead to meet the demands for penetration performance in a number of geotechnical conditions. Fig. 2 displays a typical arrangement of cutters (Zhang et al., 2010). In this case, 20 disc cutters and 64 drag bits were applied.

Zhang et al. (2010) suggested the method to estimate the TBM excavation torque based on numerical analysis, which takes into account the speed-torque characteristic of variable frequency drive motor. Table

2 shows the specification of the TBM cutting system and the interface parameters.

The numerical simulation model suggested by Zhang et al. (2010) is able to estimate the fluctuation and amplitude of the total excavation torque under the mixed-face condition. In this study, the soil formation in mixed-face condition, α is 50%, and Fig. 3 demonstrates the calculated excavation torque. The cutting torque which stands for the total excavation torque applied on the cutterhead at some moment under mixed-face condition can be expressed as:

$$T_c = \sum_{j=1}^{n_d} F_{rj} \cdot R_j + \sum_{k=1}^{n_b} F_{tk} \cdot R_k \quad (1)$$

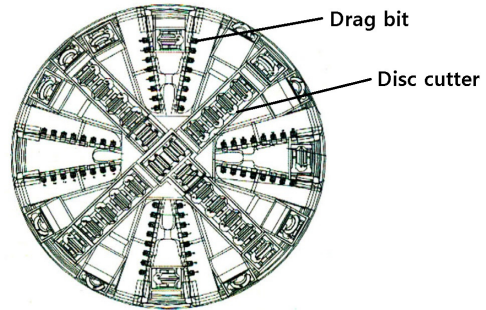


Fig. 2. Arrangement of cutters on the cutterhead (Modified after Zhang et al., 2010)

Table 2. Specification of the TBM cutting system (Zhang et al., 2010)

| Item | Component | Value |
|-------------|----------------------------|----------|
| Cutterhead | Rotation speed | 3 rpm |
| | Penetration per revolution | 5 mm/rev |
| Gear | Pinion radius | 0.175 m |
| | Gear radius | 1.3 m |
| Disc cutter | Radius | 216 mm |
| | Tip width | 20 mm |
| | Cutter spacing | 397.3 mm |
| Drag bit | Amount | 20 |
| | Width | 50 mm |
| | Amount | 64 |

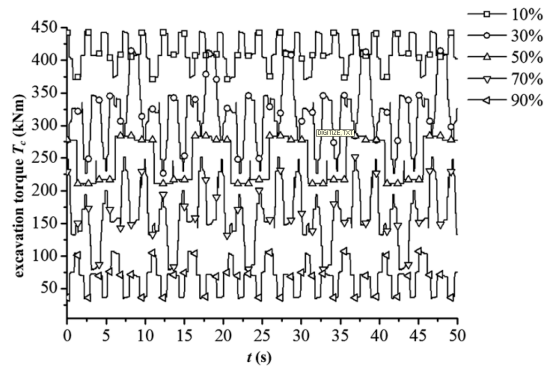


Fig. 3. Excavation torque at mixed-face condition (Zhang et al., 2010)

where, n_d is the number of disc cutters within the hard formation and n_b is the number of drag bits involved in the soft formation, R_j and R_k are the vertical distances from the locations of the j th disc cutter and the k th drag bit to the center of the cutterhead, respectively. For the total numbers of disc cutters (N_d) and drag bits (N_b) yield:

$$\begin{aligned} n_d &\leq N_d = 20 & (2) \\ n_b &\leq N_b = 64 \end{aligned}$$

If we consider 1 disc cutter line, the summation of the force evolving torque, F_{d1} is:

$$\begin{aligned} F_{d1} &= F_d 1d_1 + F_d 2d_1 + F_d 3d_1 + F_d 4d_1 & (3) \\ &= F_d d_1 (1 + 2 + 3 + 4) \\ &= 10F_d d_1 \end{aligned}$$

where, d_1 is the disc cutter spacing and F_d is force evolving torque at each disc cutter and assumed to be the same to each other. Therefore, the force by disc cutters is the summation of 4 disc cutter lines as:

$$\sum_{j=1}^{n_d} F_{rj} \cdot R_j = 40F_d d_1 \quad (4)$$

As the same procedure, the force by drag bits at 1 drag bit line, F_{b1} is:

$$\begin{aligned} F_{b1} &= F_b d_2 (1 + 2 + \dots + 7) & (5) \\ &= 28F_b d_2 \end{aligned}$$

where, d_2 is the drag bit spacing and F_b is force evolving torque at each disc cutter and assumed to be the same to each other. The force by drag bits is the summation of 8 drag bit lines as:

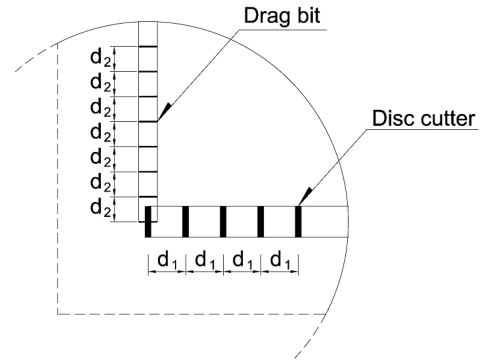


Fig. 4. Calculation concept of the total force evolving torque

$$\sum_{k=1}^{n_b} F_{lk} \cdot R_k = 224F_b d_2 \quad (6)$$

Fig. 4 displays the concept to estimate the total force evolving torque at disc cutters and drag bits.

d_2 is 397.3 mm as shown in Table 2, and d_1 is assumed to be the 1/2 of d_2 , 198 mm. The total excavation torque is between 212 to 282 kN•m based on Fig. 3 and F_b and F_d are assumed to be the same value to find the average conversion length of the moment-arm. Equation (7) yields 60.18 m of the average conversion length. Therefore, the face vibration pressure estimated by this procedure are displayed in Fig. 5.

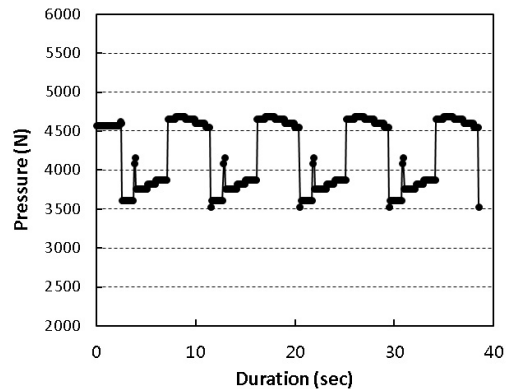


Fig. 5. Estimated face vibration pressure history

2.3 Numerical analysis conditions

All specific conditions for numerical analysis are described in Table 3. 3-dimensional FDM analysis is performed under the static-dynamic coupled condition. Boundary conditions are switched over from fixed to free-field according to the analysis stages.

Fig. 6 and 7 show the geometry and the surface monitoring points for displacement, acceleration, and

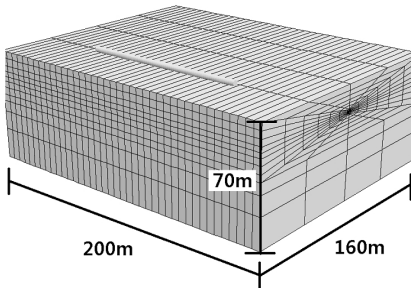


Fig. 6. Geometry and 3D mesh

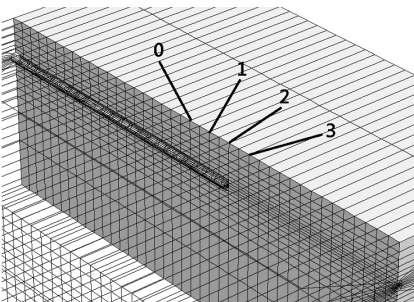


Fig. 7. Locations of surface monitoring points

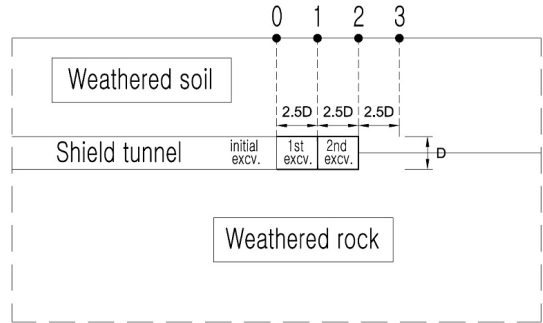


Fig. 8. Schematic of numerical analysis

velocity in the analysis.

The 2 stages of additional excavation are simulated after the initial excavation. At each stage, dynamic analysis is performed after static analysis to simulate practical construction procedures and the effect of excavation vibration at each stage. The longitudinal distance between each monitoring point is $2.5D$ as shown in Fig. 8.

3. Results

Fig. 9 displays the crown settlement-time histories according to the duration at each monitoring point. The the amount of settlement increased with duration and the fluctuation of settlement was observed at the initial stage of excavation due to the dynamic pressure load at tunnel face. The maximum measured settlement was 1.023 mm at point 1 and the minimum measured

Table 3. Numerical analysis conditions

| Item | Conditions | Remarks |
|-----------------------------|---|---|
| Analysis method | Finite Difference Method (FDM) | |
| Analysis code | FLAC3D Ver. 3.00 | |
| Boundary condition | Static : fixed Dynamic : free-field boundary | |
| Analysis sequence | Static-dynamic coupling | vibration (dynamic) after excavation (static) |
| Duration of loading | 21 sec | |
| Thickness of shield segment | 300 mm | |

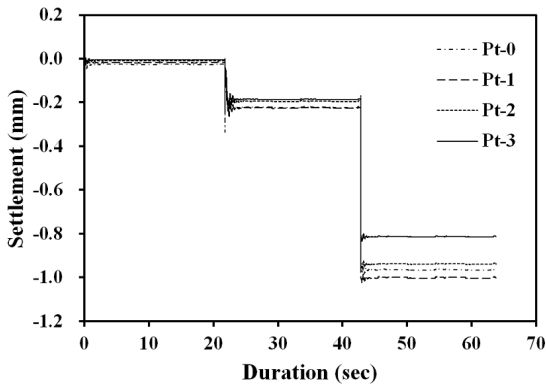


Fig. 9. Crown settlement histories at monitoring points

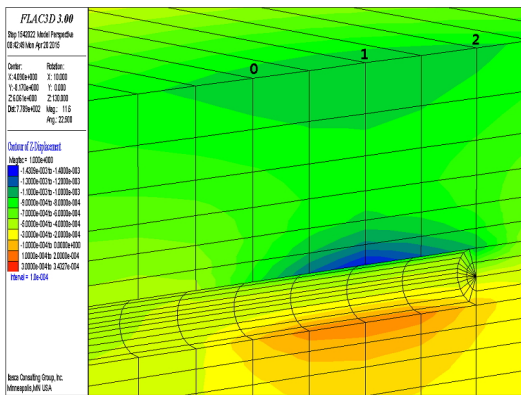


Fig. 10. Contour of settlement

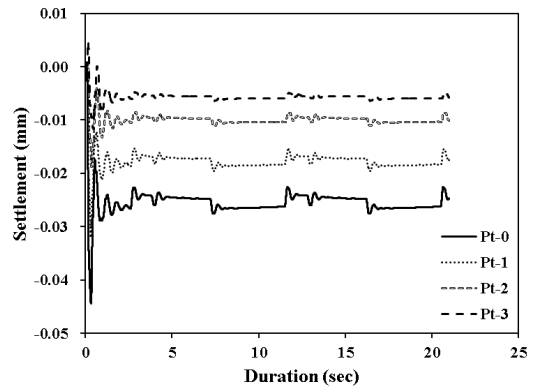
value was 0.884 mm at point 3.

Fig. 10 demonstrates the contour of settlement around face. Maximum crown settlement and invert heaving occurred after 2 stages of excavation at point 2.

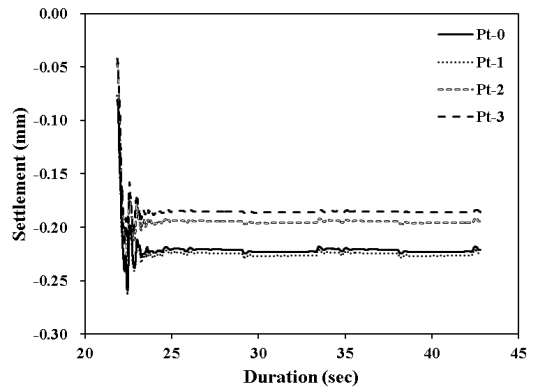
Fig. 11 shows the crown settlement histories at each point, divided by the excavation stages. After

Table 4. Maximum settlement

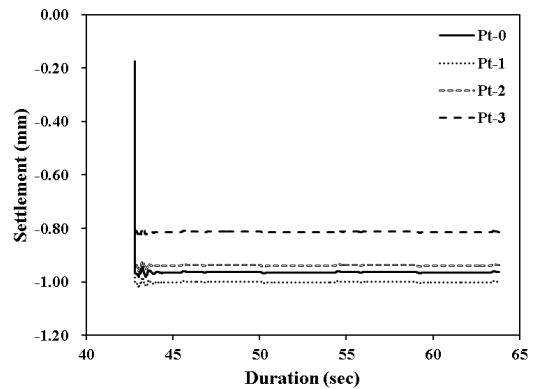
| Monitoring point | Maximum settlement (mm) | Remarks |
|------------------|-------------------------|---------|
| 0 | 0.9816 | |
| 1 | 1.0230 | Maximum |
| 2 | 0.9611 | |
| 3 | 0.8339 | Minimum |



(a) Stage 0 (initial excavation)



(b) Stage 1 (1st excavation)



(c) Stage 2 (2nd excavation)

Fig. 11. Contour of settlement

the initial fluctuation, the settlement histories displays similar shape as shield pressure history as shown in Fig. 5, and Table 4 demonstrates the maximum settlement at each points.

4. Conclusions

In this study, face vibration of TBM excavation was considered to estimate surface settlement trend according to TBM extrusion since the surface settlement is one of the most important problems encountered on tunnelling in urban areas. The dynamic excavation forces were calculated by total torque on the TBM cutterhead in mixed-face of soil and weathered rock condition with shallow depth. The 3D numerical analysis results showed that dynamic settlement histories and trend of surface settlement successfully. The maximum settlement occurred at the excavation point located at 2.5D behind the face and the effect of face vibration on the surface settlement was verified in this study.

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: 13CCTI-T01)

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