Stability Evaluation of TBM Pilot Tunnels to Rear Blasting Using the Protection Shield

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Abstract: Recent studies have increasingly investigated construction methods for tunnel excavation because of growing underground space development. Although the New Austrian tunneling method (NATM)—a representative tunnel excavation method—can be applied to various ground conditions, as well as having good constructability and economic feasibility, it suffers from problems such as vibration and noise. By contrast, excavation using a tunnel boring machine (TBM)—a representative mechanized construction method—affords advantages such as stable excavation, minimized ground and environmental damage, noise, and vibration. However, it cannot be applied easily to various ground conditions, and it suffers from problems such as high construction costs and delays owing to equipment defects. Therefore, the simultaneous pilot tunnel excavation using the TBM—which affords advantages such as constructability, economic feasibility, and minimized noise and vibration—and rear enlargement blasting using NATM was investigated in this study. A protection shield was installed to minimize accidents occurring from equipment defects (a disadvantage of TBM) and analyze the decrease in the effect of NATM blasting, which depends on the use of the protection shield and the separation distance through 3D numerical analysis.

Keywords: tunnel boring machine (TBM); New Austrian tunneling method (NATM); protection shield; pilot tunnel; 3D numerical analysis

1. Introduction

Recently, underground space development has attracted increased interest. In particular, developments in tunnel excavation technology have enabled more economical and rational planning of tunnels. Studies have investigated the stability and economic feasibility of tunnel excavation. Initially, tunnel excavation was widely performed using a small sectionally divided excavation method with considerable manpower and small equipment. In more recent years, advancements have been made in mechanized construction, including tunnel boring machines (TBM) and ground reinforcement technology, and excavation methods that are advantageous in terms of economic feasibility and constructability have been developed.

The simultaneous excavation method, which uses a TBM pilot and New Austrian tunneling method (NATM) enlargement, involves excavating a pilot tunnel with a small-diameter TBM before excavating the full face of the tunnel without producing large disturbances in the surrounding rock mass. Therefore, there are advantages to investigating, analyzing, and evaluating the ground conditions in advance before performing the main NATM enlargement excavation; simultaneously, the blasting vibration greatly reduces because the center-cut blasting that produces a large vibration can be avoided (Figure 1). In addition, economic efficiency increases because the construction period is shortened...
by appropriately controlling the pre-excavation and using a TBM with a high excavation speed and enlargement blasting/excavation stages.

Figure 1. Simultaneous excavation using tunnel boring machines (TBM) and New Austrian tunneling method (NATM) enlargement with protection shield.

However, the required separation distance between the NATM blasting point and TBM, as well as the minimization of the effect on the TBM during the simultaneous excavation of the TBM pilot and NATM enlargement, remain understudied issues. Therefore, this study used a 3D numerical analysis to predict the effect of NATM enlargement blasting on the TBM pilot tunnel with the use of a protection shield in the middle of the TBM and NATM enlargement blasting points. Further, we aimed to shorten the construction period and improve construction safety by presenting the minimum required distance between the NATM enlargement blasting point and the protection shield.

2. Literature Review

NATM is based on the equilibrium theory in which an equilibrium state is induced in an elastic or elastoplastic state; by contrast, a conventional tunnel is designed and constructed based on the tunnel load theory [1]. Because the surrounding ground primarily supports the tunnel in NATM, the strength of the rock mass should be preserved as much as possible and support materials, such as rock bolts and shotcrete, should be installed to minimize the ground deformation during tunnel excavation. In addition, NATM affords good constructability and economic efficiency because it can be easily applied to a wide range of cross sections and it is widely used owing to its adaptability to changes in ground conditions and its versatility with auxiliary construction methods. Therefore, as NATM construction methods are finding increased use, studies have focused more on the development of NATM-based excavation methods and their support materials [2–6].

TBM is widely used for excavation because it affords advantages such as high-speed and stable excavation, minimization of ground and environmental damage, noise, and vibration. Therefore, TBM has been increasingly used for tunnel construction worldwide [7,8]. Although TBM is an effective tunnel excavation method, it requires equipment to be setup according to the ground and site conditions, and accidents have often occurred due to unexpected ground conditions and equipment defects during construction. Therefore, many studies have investigated TBM tunnel excavation designs [9–11].

The TBM and NATM simultaneous excavation method is safe because the ground conditions can be investigated through the TBM pilot tunnel, and the support material can be installed in advance when a fracture zone is observed. Further, vibration and noise reduction effects can be obtained because the free face can be secured from the pilot tunnel, and center-cut blasting can be avoided. In addition, it provides the advantages of both NATM blasting and TBM excavation, such as shortening the construction period through simultaneous excavation. However, if a certain excavation length is not secured, the relatively high initial cost of using the TBM results in poor economic feasibility. The TBM and NATM simultaneous excavation method was first developed by the Italian Railways Authority in 1982. This method can reduce construction costs by 50% per unit volume.
compared to those of NATM blasting for high-grade rock (e.g., rock mass with a high RMR or Q classification score) [12]. Further, the constructability can be improved when the TBM pilot tunnel has a small diameter of 3.5–5 m; in particular, the construction cost can be reduced by 20% due to the pre-ground investigation of the pilot tunnel [13]. The TBM and NATM simultaneous excavation method has already been applied worldwide. For example, a railroad tunnel in Canada was constructed by simultaneously using NATM in the lower half of the excavation and TBM in the upper half. In Korea, the TBM and NATM simultaneous excavation method has been used in the construction of the Seoul subway, an urban expressway in northern Seoul, and a bypass in Busan Haeundae. However, the overall number of construction cases and studies remain insufficient. Further, the current TBM and NATM simultaneous excavation method does not prevent NATM enlargement blasting from causing some faults in the TBM and backup installations.

In this light, this study fabricated and installed a protection shield between a NATM blasting point and a TBM. In keeping with previous studies, we used a TBM with a small diameter of 3 m. Further, the stability of the TBM and NATM simultaneous excavation method with the protection shield was evaluated by analyzing the required minimum distance and its effect on the ground behavior. A follow-up field test was conducted under the same conditions to accurately examine the practical applicability and economic feasibility of this method.

3. Numerical Analysis

Because soil in the ground is an anisotropic material that behaves nonlinearly over time, its behavior is extremely difficult to predict without conducting a numerical analysis of the ground because its interaction with the ground structure is extremely complex. In this study, the simultaneous excavation of a TBM pilot and NATM enlargement using a protection shield was analyzed through Plaxis 3D, a geotechnical numerical analysis program developed by the Delft University of Technology in 1987. Plaxis 3D analyzes the deformation and stability of the ground based on finite element analysis, and it is often used for conducting deformation and stability analyses of ground structures such as tunnels, foundations, and levees [14].

3.1. Target Ground and Protection Shield Design

It is extremely important to understand the conditions of the target ground before evaluating the stability of a tunnel. The material parameters of the ground at the construction site of the high-speed railroad in Seoul were applied in this study (Table 1). The ground parameters found in the geotechnical survey report of the target site were referenced for use as the material parameters of the ground in the analysis, and the site boring logs were referenced to determine the boundary between soil and rocks [15]. A numerical analysis was conducted using a Mohr–Coulomb model for soil constitutive modeling and an elastic model for protection shield constitutive modeling. Figure 2 shows the design plan for the protection shield; the analysis was performed by modeling a steel frame with a diameter of 2.3 m and a length of 4.0 m and an inflator (polyester mat) with a diameter of 3 m according to the design plan. The material parameters of iron were used for the protection shield frame. The weight values were obtained through an experiment conducted by the Korea Conformity Laboratories. The material parameters of polyester were obtained through the literature and applied to the inflator, as shown in Table 2. The material parameters of the TBM were the same as those of the protection shield frame. In the future, more accurate material parameters will be input to analyze the effect on TBM itself.

Table 1. Material parameters of ground.

| Soil            | Model | γ (kN/m³) | E (kN/m²) | ν  | c (kN/m²) | Φ' (°) |
|-----------------|-------|-----------|-----------|----|-----------|--------|
| Reclamation soil| M-C   | 18        | 13,000    | 0.3| 0         | 31     |
| Hard rock (Gneiss)| M-C | 27       | 12,900,000 | 0.2| 1890      | 40     |

γ: Unit weight of soil, E: Young’s modulus, ν: Poisson’s ratio, c: Cohesion, Φ': Angle of shearing resistance.
3.2. Calculation of Blasting Load

Various empirical equations are available for calculating the blasting load in numerical analysis. Among these, one of the most widely used is presented by the US National Highway Institute [16,17]:

\[
P = \frac{4.18 \times 10^{-7} \times C_S^2 \times \rho}{1 + 0.8 \times \rho},
\]

where \( C_S \) is the detonation velocity of gunpowder (m\(^2\)/s); \( \rho \) is the specific gravity of gunpowder (g/cm\(^3\)); and \( P \) is the detonation pressure (kbar).

The time history of the vibration caused by blasting needs to be considered in order to apply the dynamic load. The following hysteresis loop of Starfield and Pugliese is mainly used as the time history of the blasting load [18–21].

\[
P(t) = 4P\exp\left(\frac{-Bt}{\sqrt{2}}\right) - \exp\left(-\sqrt{2}Bt\right),
\]

where \( P(t) \) is the pressure according to time \( t \) (kg/cm\(^2\)); \( B \) is a load constant (16,338); and \( t \) is the travel time (0.06 µs).

The largest detonation pressure value of domestic emulsion explosives was used as the blasting load in this analysis; it was calculated as 4282 kg/cm\(^2\), equivalently converted when decoupling for 1 kg of charge [22]. Moreover, the duration was set to 0.001 s, and the equivalent frequency and damping ratio of the ground were 500 Hz and 1%, respectively [17,23].

3.3. Analysis Case and Measurement Location

This study compared cases with and without a protection shield and different separation distances from the NATM enlargement blasting point to the protection shield to determine the safe separation distance of the protection shield and to analyze the effect on the preceding pilot tunnel with the presence of a protection shield. The analysis was
performed for eight separation distances (2 m, 4 m, 8 m, and 20 m) between the NATM enlargement blasting point and the protection shield, which were repeated without the protection shield (Table 3).

Table 3. Classification of numerical analysis cases.

| Offset | With Protection Shield | Without Protection Shield |
|--------|------------------------|---------------------------|
| 2 m    | Case 1-1               | Case 2-1                  |
| 4 m    | Case 1-2               | Case 2-2                  |
| 8 m    | Case 1-3               | Case 2-3                  |
| 20 m   | Case 1-4               | Case 2-4                  |

The crown part of the ground (A) adjacent to the front of the protection shield and the crown part of the ground at the face of the pilot tunnel (B) were measured to analyze the effect on the preceding pilot tunnel owing to the enlargement blasting of NATM, as shown in Figure 3. In the future, the exact application of the material parameters to the TBM and deformation/axial force affecting the TBM will analyze the impact of blasting on TBM.

Figure 3. Measurement points A and B.

3.4. Modeling

The target ground was modeled using the ground of the high-speed rail construction site in Seoul; it consisted of reclamation soil and hard rock, as described in Section 3.1. The depth range of the hard rock was extended to ensure that the reflected wave had no influence owing to the blasting load during the analysis (Figure 4). In addition, the boundary condition in the X- and Y-directions (excavation direction) was set as viscous in the numerical analysis program to prevent the influence of reflected waves in all directions [24]. Figure 5 shows the modeling and mesh for the numerical analysis. The vibration-controlled blasting was considered a blasting load because the target ground was an urban area. A boring depth of 2.7 m and a boring interval of 1.5 m were applied for this purpose. This analysis (construction stage) was divided into four stages, as shown in Figure 6, i.e., initial stage, TBM excavation stage, protection shield installation stage, and NATM enlargement blast stage.

Figure 4. Ground and structure overview.
4. Numerical Analysis Results

This section presents the numerical analysis results of the optimum separation distance between the blasting point and the protection shield to minimize the effect on the latter and the effect on the safety of the preceding pilot tunnel depending on the presence of a protection shield after NATM enlargement blasting on the target ground.

4.1. Vibration Velocity

Because the blasting vibration impact is generally evaluated using the vibration velocity, the vibration velocities at two points, A and B, were compared in this analysis according to the presence of a protection shield and the separation distance from the...
blasting point. In the graphs below, the red and green lines indicate the analysis results of blasting without and with a protection shield, respectively. The vibration velocity decreased by 36.02%, 49.29%, 58.86%, and 65.85% as the separation distance between the blasting point and the protection shield was increased to 2 m, 4 m, 8 m, and 20 m, respectively, in the case of using a protection shield compared to the case of not using a protection shield (Figure 7). In addition, because the vibration velocity at the ground surface directly above point A was $3.27 \times 10^{-9}$ m/s, that is, the vibration was negligible and blasting was considered to have no effect if there was a structure above it (based on the blasting distance of 2 m when using a protection shield). The vibration velocity at point B was low regardless of the installation of the protection shield. This tendency was attributed to the sufficient separation distance between the blasting point and the face owing to the distance between the protection shield and the blasting point, length of the protection shield, length of the pilot tunnel, and length of the TBM.

![Graph A](image.png)

![Graph B](image.png)

**Figure 7.** Numerical analysis result of vibration velocity at measurement points (a) A and (b) B.

4.2. Plastic Zone

The stress on the excavation surface increased significantly due to the underground stress in the direction of the tunnel radius, and it was lost when the tunnel was excavated. Displacement of the excavation surface also occurred inside the excavation. At this time, if the tangential stress increased by excavation was less than the yield stress of the ground, the ground around the tunnel was stabilized; however, when the tangential stress exceeded the yield stress of the ground, plastic displacement occurred and the ground was destroyed. Figure 8 shows the stress at this time; it enabled us to define the plastic zone [18]. Because the tunnel stability can be determined by the generated stress in the plastic zone, the plastic
zone was compared in this analysis according to the installation location of the protection shield (i.e., distance between the blasting point and the protection shield), as shown in the following figures. Both the pilot tunnel and the TBM were within the plastic zone (red part) when the separation distance was below 2 m (Figure 9a). The pilot tunnel behind the protection shield was found to not lie within the plastic zone for a separation distance of 8 m (Figure 9c). Therefore, a separation distance of 8 m or higher was expected to be safe for the pilot tunnel and TBM.

![Figure 8. Definition of plastic zone.](image)

![Figure 9. Plastic zone according to separation distance between the blasting point and the protection shield: (a) Case 1-1, (b) Case 1-2, (c) Case 1-3, and (d) Case 1-4.](image)

4.3. Pilot Tunnel Underground Settlement

Regardless of the installation of a protection shield, the amount of settlement in the pilot tunnel (point A) during tunnel blasting did not exceed the standard value (10 mm) (Figure 10). The settlement decreased by 65.22% and 60.37% without and with a protection shield, respectively, when the separation distance between the blasting point and protection shield increased from 2 m to 4 m. Further, it decreased by around 93% and over 99% when the separation distance increased from 8 m and 20 m (Table 4). Accordingly, a separation distance of at least 8 m between the blasting point and protection shield was considered safe regardless of the installation of a protection shield. However, the installation of the protection shield was expected to affect the crown settlement of the tunnel as the separation distance between the blasting point and protection shield tended to decrease by up to 34.02% when the protection shield was installed (i.e., when the separation distance between the blasting point and the protection shield was 2 m).
Figure 10. Numerical analysis results of settlement of pilot tunnel (point A).

Table 4. Decreased rate of settlement at point A with an increase in separation distance between blasting point and protection shield.

| Offset | With Protection Shield | Without Protection Shield |
|--------|------------------------|---------------------------|
| 4 m    | 65.22%                 | 60.37%                    |
| 8 m    | 93.44%                 | 94.33%                    |
| 20 m   | 99.98%                 | 99.94%                    |

The low settlement values at point B (tunnel face) below 0.01 mm were measured regardless of the installation of a protection shield, as shown in Figure 11. The amount of settlement was considered to significantly reduce because the separation distance was equivalent to the length of the pilot tunnel (4 m) and the length of the TBM (9 m) behind the protection shield. However, a safer separation distance must be realized because the amount of settlement on the face decreased rapidly as the separation distance between the blasting point and the protection shield increased, as shown in Table 5. In the future, the effect of the blasting load and vibration on the TBM will be analyzed depending on the length of the pilot tunnel (i.e., distance between protection shield and TBM).

Figure 11. Results of settlement of the pilot tunnel through numerical analysis (point A).

Table 5. Decreased rate of settlement at point B with an increase in separation distance between blasting point and protection shield.

| Offset | With Protection Shield | Without Protection Shield |
|--------|------------------------|---------------------------|
| 4 m    | 60.14%                 | 60.34%                    |
| 8 m    | 95.25%                 | 95.24%                    |
| 20 m   | 99.99%                 | 99.98%                    |
5. Future Research Plan

In order to examine the safety and economy of simultaneous excavation using the TBM pilot and NATM enlargement with a protection shield, this study conducted a 3D numerical study to analyze the effect of NATM enlargement blasting on the TBM, backup installations, and TBM pilot tunnel. The ground behavior was also analyzed comparatively by varying the distance between the NATM enlargement blasting point and the TBM. Accordingly, the required minimum distance was predicted. This should be useful for a future analysis of economic feasibility. As a follow-up to this study, a field test was planned under the same conditions as those used in the numerical analysis, namely, a TBM with 3-m diameter and a protection shield. Figure 12 shows the protection shield currently under fabrication. It consists of a steel frame, a PVC tarpaulin, and a polyester mat. It will be able to stick close to a tunnel wall as it can gradually expand to accommodate different tunnel diameters. After completing the fabrication of the protection shield, a simulation test and field application will be conducted to analyze the safety and economic feasibility.

![Figure 12. Fabrication of protection shield.](image)

6. Conclusions

This study aimed to minimize the effect of NATM enlargement blasting on a pilot tunnel by using a protection shield during the simultaneous excavation of a TBM pilot and NATM enlargement. Accordingly, the effects of the presence of the protection shield and the separation distance between the blasting point and the protection shield were analyzed through the vibration velocity produced by blasting, the plastic zone, and the crown settlement. The following conclusions were derived from this study:

1. The vibration velocity at point A (i.e., crown part of the pilot tunnel in front of the protection shield) decreased by 36.02%, 49.29%, 58.86%, and 65.85% as the separation distance between the blasting point and the protection shield increased to 2 m, 4 m, 8 m, and 20 m, respectively, and there was almost no vibration on the ground surface directly above point A. In addition, minimal vibration was found to occur at point B (face) regardless of the use of the protection shield. Therefore, the use of a protection shield was considered beneficial in reducing the effect of the blasting on the pilot tunnel.

2. Comparisons of the plastic zone with different blasting distances showed that the plastic zone included the TBM location when the separation distance was 2 m. Further, the plastic zone did not reach the pilot tunnel and TBM behind the protection shield for a separation distance of 8 m or higher. Therefore, a distance of at least 8 m between the blasting point and the protection shield was predicted to be safe.

3. Although the underground settlement at point A was within the settlement range regardless of the use of the protection shield, it decreased by 34.02% when the protection shield was used (the result of comparing Case 1-1 and Case 2-1 with the closest separation distance). In addition, the difference in settlement amount depending on the use of a protection shield was not significant as the separation distance increased to 8 m or higher, and the difference was predicted to be insignificant at point B. Therefore, although the use of a protection shield is advantageous for stability, the pilot tunnel and TBM are considered safer if the separation distance is at least 8 m.
4. As a follow-up study, a simulation test will be conducted after fabricating the protection shield. A field test will be conducted using a TBM with the same size (i.e., 3 m diameter). In the field test, the field applicability and economic feasibility will be analyzed, and an optimal separation distance will be obtained. These results should enhance the reliability of the present study.

Author Contributions: S.-M.K. wrote the manuscript and performed the numerical analyses; S.-I.C. and S.-B.S. researched and analyzed existing literature and relevant data; H.L. and D.-W.O. investigated and reviewed the material parameters required for the numerical and other analyses; S.-W.L. was responsible for the research concept, design, supervision, and final review. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted by the research team for the “Development of high-speed excavation technology (20TBIP-C155615-01) for long tunnels using Protection Shield (simultaneous excavation of TBM pilot and NATM enlargement)” of the Ministry of Land, Infrastructure and Transport (Korea Agency for Infrastructure Technology Advancement) Technology Business Innovation Program. We would like to express our appreciation for their support on this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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