Stability analysis of face-reinforced Divide Shield Method (DSM) using test chamber and its numerical verification for shallow-embedded tunneling

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ABSTRACT

Tunneling under roadway/railroad in a busy urban area is not an easy work due to a hostile environment involving weak ground and a shallow embedded condition and resulting in a great possibility of tunnel face stability problems. Divided Shield Method (DSM) is one of techniques to reduce the instability of the tunnel face using divided steel plates as a shield for tunneling. This study investigated the effectiveness of layers of the horizontal pipe grouting at the face of DSM tunneling on the stability and construction speed. The investigation was undertaken by the test chamber and its numerical verification. Surface deflection of the chamber fill and the stability of the tunnel face were measured with the excavation sequence. Numerical analyses of the chamber test were conducted to predict further behaviors of DSM tunneling. The results of the study show that DSM tunneling reinforced by horizontal pipe grouting reduced the ground movement and construction time, and enhanced the stability of the tunnel face significantly. Using the test and analysis results, the potential development of a new method that can reduce the construction period was discussed in detail.

Keywords: Divided Shield Method, ground settlement, horizontal pipe grouting, MIDAS, numerical analysis, soil chamber, tunnel face stability

1 INTRODUCTION

Usable land is being rapidly depleted as the industrialization of society grows. As a result, various structures for engineering have been built in underground such as the subways and cable tunnels ¹). Upon a crowded city with higher traffic and population, open cut excavation for the underground construction may not be suitable but tunneling could be a solution. Therefore, a wide range of tunneling method for many different conditions and special needs has been researched and developed. In large rocky area, New Austrian Tunneling method (NATM) is a theoretically safe and very economical choice for the underground construction. It cannot, however, applicable to the rather shallow soil deposits ²). Especially, the stability of the tunnel face is one of the most important factors to be considered in tunneling through the relatively soft ground. Divided Shield Method (DSM) is gaining popularity with its provision of the safety and cost-effectiveness. The method applies many divided plates as a shield during tunneling after umbrella arch reinforcement over the crown to prevent failure of the arc sliding at the face. Each plate advances with a hydraulic jacking device ³). Due to the additional instability of the tunnel face during the method application, every step of shield advancing involves a retaining wall construction at the tunnel face. The construction and removal of the installed retaining wall is time-consuming process. It is still needed to investigate a new methodology for enhancing the construction period of the DSM.

Pipe grouting for reinforcing is well known methodology to increase of the stability of the face ⁴, ⁵). In this study, the possible use of pipe reinforcing for tunnel heading to remove the construction stage of the retaining wall was investigated through a chamber test and its numerical verification. ½ size reduced DSM tunnel was constructed in a test chamber. With tunneling, surface settlement was measured and its result was compared with numerical analysis using commercially available software.

2 DIVIDED SHIELS METHOD (DSM)

DSM (Divided Shield Method) is originally based upon the Messer Shield method. Mess in German stands for knife. Messer Shield method uses the steel...
sheet piles to support the crown of the tunnel face. One of the first applications of the method was the sewer tunnel at the suburban area of Bonn, Germany in 1950s. Then subway construction München, Germany used again the method\(^6\). In Japan, many tunneling sites adapted and develop further Messer Shield\(^7\). The first application of the method in Korea was the 99m tunneling of the Seoul Metropolitan subway in 1983. After then a company developed an upgraded Messer Shield method and named it as DSM. Until now, it has many patents and specification certificate for new technology from the Ministry of Land, Infrastructure and Transport. Fig. 1 shows various recent DSM applications.

General procedure for DSM construction is shown in Fig. 2. The major step goes as follows. First, reinforce the outer side of the tunnel face using umbrella arch reinforcing method. Then, place a reaction supports and DSM plates. Third, propel the shields, dig a tunnel, and locate a retaining wall at the face. Finalize the tunneling with 1st lining and main structures.

3 CHAMBER EXPERIEMNT AND ITS NUMERICAL VERIFICATION

A chamber test was conducted to investigate the stability of the DSM tunnel with a face reinforcing of pipe grouting. The chamber for the test has the depth of 2.5m and area of 7.5m\(^2\) (3.0m X 2.5m). It could contain a half size of the DSM cross tunnel under a two-lane expressway. The cross-sectional area of the tunnel face was 2.25m\(^2\) (1.5m X 1.5m). All tunneling equipment including bracing H-beams was prepared in ½ size. Major steps of testing were as the following. After placing the chamber on a pre-compacted ground, the chamber was filled with a granitic weathered soil that is common in the Korea peninsular. The physical properties of soil are summarized in Table 1. Then, 20 LVDT (The Linear Variable Differential Transformer) were placed at the top of fill to measure the surface settlements after tunneling. Tunneling of DSM was started as the regular process after 24 hours curing of face grouting with pipes.

| USCS   | Gs | Cohesion (kPa) | Friction (°) | Max. Dry Density (kN/m\(^3\)) | LL | PI |
|--------|----|----------------|-------------|-------------------------------|----|----|
| SP-SC  | 2.67 | 2              | 32          | 18.6                          | 33 | 13 |

A numerical analysis was undertaken after the chamber testing using a commercially available FEM program (MIDAS GTX form MIDAS IT Co., Ltd.). 3-D analysis performed with Mohr-Coulomb soil model and the material properties were set equal to the values of the test chamber. In the simulation, the tunnel face has two different types of soil caused by the pipe reinforcing. Fig. 4 shows the modeling steps for the numerical analysis. Fig. 5 shows the location of the measurements at the top of the chamber to obtain surface settlement after the test to compare with the simulation.
maximum value of the displacement vector is located at the center of the tunnel face. The location of the maximum flexural stress is at the center ceiling. Surface settlements of chamber fill from analysis were compared with those from the chamber testing in Fig. 7. Due to the complexity of the measuring, stresses in the shield during the chamber test could not be obtained. However, the figure shows a good agreement of surface settlement between the test and simulation. The values of the settlement and stress from the test and simulation were examined with the design code, and the range of the results seems to be within the safe side.

4 RESULT AND DISCUSSION

Fig. 6 shows typical results of the numerical analysis of this study. It is easily seen that the

5 COCLUSION

This study investigated the safety of horizontal pipe grouting of the DSM face using chamber testing and its numerical verification. The DSM tunnel was constructed in the soil chamber in ½ size of the tunnel for two-lane expressway. Surface settlement of the chamber and the stability of the tunnel face were measured with the excavation sequence. Using commercially available program, numerical analyses of the chamber test were performed and its results compared with the soil behaviors in the chamber of DSM tunneling. The results of the study show that pipe grout reinforced DSM tunneling might reduce the ground movement and construction time. It also enhances the stability of the tunnel face significantly. The test and analysis results shows that it could be drawn a conclusion of the potential use of the face reinforcing to grade DSM up.
REFERENCES

1) Derrick, P. (2001): Tunneling to the future: the story of the great subway expansion that saved New York, New York University Press.

2) Wood, A. M. (2002): Tunnelling: Management by Design, Taylor & Francis.

3) Jang, Y. S., Shin, S., and Heo, J. H. (2014): A field case study on construction of underground passageway with non-open excavation method, Geotechnical Aspects of Underground Construction in Soft Ground, Yoo, Park, and Ban (Eds), Korean Geotechnical Society, Korea.

4) Yoo, C. (2002): Finite-element analysis of tunnel face reinforced by longitudinal pipes, Computers and Geotechnics, 29(1), 73–94, doi:10.1016/S0266-352X(01)00020-9.

5) Shin, J. H., Choi, Y. K., Kwona, O. and Lee, S. (2007): Model testing for pipe-reinforced tunnel heading in a granular soil, Tunnelling and Underground Space Technology, 23(3), 241–250, doi:10.1016/j.tust.2007.04.012.

6) Lehmann, G and Bäppler, K. (2010): Development tendencies in mechanised tunnelling – Review and development tendencies for shield machines with slurry and earth pressure, Geomechanics and Tunnelling, 3(3), 245–255, doi:10.1002/geot.201000022.

7) Miura, K. (2003): Design and construction of mountain tunnels in Japan, Tunnelling and Underground Space Technology, 18(2-3), 115–126, doi:10.1016/S0886-7798(03)00038-5.

Fig. 7 Surface Settlements