Geotechnical Aspects of Underground Construction in Soft Ground – Yoo, Park, Kim & Ban (Eds)

Ground settlement trough due to DOT shield tunneling

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ABSTRACT: In this paper, the tunneling with a Double-O-Tube (DOT) shield for the construction of Taoyuan International Airport Access Mass Rapid Transit in Taiwan was introduced. The DOT shield machine and tunneling operation was summarized. Based on the field data, it was found the backfill grouting rate decreased with increasing tunnel depth. This was probably due to: at a deeper location, the pressure to close the tail void was greater, therefore high backfill grouting rate was hard to achieve. Eleven sets of field data collected from six cases indicated that, the maximum settlement due to DOT shield tunneling decreased with increasing tunnel depth.It was also found that the width of settlement trough increased with increasing tunnel depth.

1 INTRODUCTION

Due to the rapid development of urban areas in recent years, many public facilities such as the Mass Rapid Transit (MRT) systems and underground sewerage systems have been constructed. Because of the disruptive effects of the cut-and-cover method, it is becoming more popular to employ the shield tunneling method. The Double-O-Tube shield tunneling has a minimized section area, and enables the most efficient use of underground space. As compared with circular twin-tube tunnels, the DOT shield tunnel may pass narrow underground corridors, and the impact on nearby structures is minimized (Sterling, 1992).

In this paper, the DOT shield tunneling for the construction of Taoyuan International Airport Access (TIAA) MRT is introduced. This is the first DOT shield machine employed in Taiwan.The location and geological condition of the DOT tunneling project was briefly described. The DOT shield machine and tunneling operation was summarized. The range of backfill grouting rate obtained from Lot 450A of TIAA MRT was compared with those measured from six DOT tunneling cases conducted in Japan and China. In the final part of this paper, an empirical method was proposed to estimate the maximum surface settlement and the width of settlement rough due to DOT shield tunneling.

2 DOT SHIELD TUNNELING IN TAIPEI

The objective of Taoyuan International Airport Access MRT is to provide airport passengers with a safe, convenient,comfortable and high quality transit service. TIAA MRT system will link the Taoyuan International Airport to the Taiwan High Speed Rail (HSR), Taiwan railway systems, and Taipei MRT systems. In Figure 1, the project starts from Taipei Main Station (A1 Station), passes through Sanchong, Sinjhuang, Linkou, Taoyuan International Airport (A12 to A14a Stations), and terminates at Jhongli Train Station (A21 Station). The total route length is 51.03 km, consisting of 10.92 km of underground section and 40.11 km of elevated section.

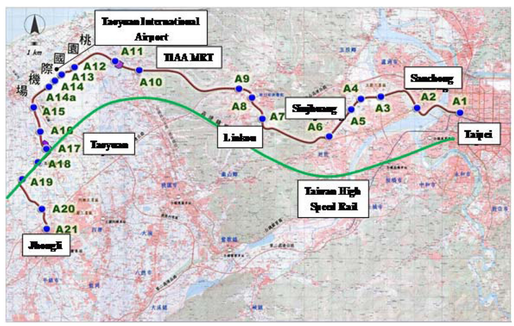

Figure 1. Taoyuan International Airport Access MRT system.

Lot CA450A is located between Station A1 and A2, and the tunnel passes under Danshuei River. To avoid the difficulties and potential risks associated with the excavation of three cross-passages between two single-circular tunnels under Danshuei River, the DOT shield tunneling method was selected.

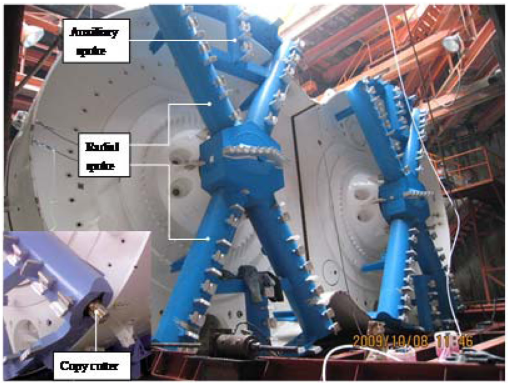

Figure 2. Cutter heads of DOT shield machine.

2.1 *Subsoil conditions*

The DOT tunneling for Lot CA450A was carried out in Taipei basin. In descending order, properties of the subsoil layers are as follows:

(1) Topsoil: A layer of surface fill, located at 0 to 3.0 m below ground level, with Standard Penetration Test (SPT) N-value ranging from 1 to 5.
(2) Sungshan Formation: Inter-layers of silty clay (classified as CL, N = 4 to 7) and silty sand (classified as SM, N = 8 to 18), located at 3 to 50 m below ground level.
(3) Chingmei Formation: A layer of silty gravel (classified as GM, N > 50), located at about 50 m below ground level.

The ground water table was typically 2.9 to 5.0 m below ground level. DOT tunneling for Lot CA450A was entirely carried out in the silty sand and silty clay layers of the Sungshan Formation.

2.2 *Tunnel construction*

The mud-injection Earth-Pressure-Balance (EPB) type DOT shield machine adapted for this project is shown in Figure 2. This articulated shield machine was designed and manufactured by Ishikawajima-Harima Heavy Industries (IHI), and has the outside dimensions of Φ 6.42 m × W 11.62 m. Each cutter head is equipped with two copy cutters (shown in lower left of Figure 2) with the stroke of 150 mm. A total of 32 shield jacks were installed in the shield, including 20 upper jacks with 2,000 kN capacity each, and 12 lower jacks with 2,500 kN capacity each.

Each ring of tunnel lining consists of 11 segments (Figure 3), and the segments are connected with straight steel bolts. Four types of lining segments used to fabricate a tunnel section are shown in Figure 4 (a) to (d). The reinforced concrete Type Asegmentis 0.3 m thick and 1.2 m long.

The tail void of the DOT shield is 0.11 m thick. To reduce the ground settlement due to tail void closure, when the lining segments were pushed out of the shield, backfill grouting was conducted through the grouting hole on the segment (see Figure 5), to fill the newly generated tail void space. For more information regarding the tunnel construction with DOT shield machine in Taipei, the readers are referred to Fang et al. (2012).

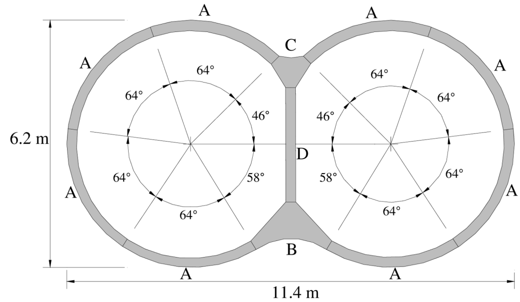

Figure 3. Section of DOT tunnel.

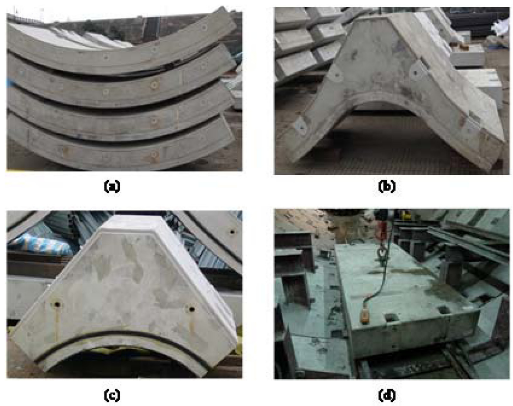

Figure 4. Lining segments for DOT shield: (a) Type A; (b) Type B; (c) Type C, (d) Type D.

Figure 5. Segment backfill grouting.

Table 1. Projects constructed with DOT shield tunneling method (abridged from Fang et al. 2012).

Case no.	Project name	Case no.	Project name
1	Rijo tunnel, 54th national route Hiroshima, Japan	11	Yagoto south district 4th line, high speed transit, Nagoya, Japan
2	Kikutagawa 2ndsewer main, Narashino, Chiba, Japan	12	East-terrain line, 1st district, Aichi, Japan
3	Ariakekita common conduit, Tokyo, Japan	13	East-terrain line, Aichi, Japan
4	Underground line, coastline high speed transit, Kobe, Japan	14	Nenjiang Rd. St. to Xiangyin Rd. St. to Huangxing greenbelt St., line 8 Shanghai Metro, China
5	East district of Sunadahashi, 4th line high speed transit, Nagoya, Japan	15	Kairu Rd. St. to Nenjiang Rd. St., line 8, Shanghai Metro, China
6	Chayagasaka park district, 4th line, high speed transit, Nagoya, Japan	16	Lot 9, line 6, Shanghai Metro, China
7	Yamamoto north district, 4th line, high speed transit, Nagoya, Japan	17	Lot 10, line 6, Shanghai Metro, China
8	South district of Nagoya University, 4th line, high speed transit, Nagoya, Japan	18	Lot 11, line 6, Shanghai Metro, China
9	Yagoto north district, 4th line, high speed transit, Nagoya, Japan	19	Lot 10, line 3, Shanghai Metro, China
10	Yamashitadori south district, 4th line, high speed transit, Nagoya, Japan	20	Lot CA450A, Taoyuau International Airport Access MRT, Taiwan

3 BACKFILL GROUTING RATE

The variation of backfill grouting rate for different shield diameters and tunnel depths was investigated in this study. The backfill grout material consisted of a mixture of grout A and grout B as indicated in Figure 5. For every cubic meter of mixture, grout A consisted of 250 kg of cement, 30 kg of bentonite, 3 liter of stabilizer, and 820 liter of water. Grout B consisted of 85 liter of water glass. The amount of grout used per ring was determined with the backfill grouting rate (BGR), which is defined as follows:

$$\text{BGR} = \frac{\text{Volume of grout backfilled per ring}}{\text{Volume of tail void per ring}} \times 100\% \qquad (1)$$

Fang et al. (2012) reported from 1989 to 2010, as summarized in Table 1, twenty tunneling projects were constructed with DOT shield tunneling method. The first thirteen cases were carried out in Japan, the next six cases were conducted in China, and the latest one was constructed in Taiwan.

The range of backfill grouting rate obtained from Lot 450A was compared with those measured from cases 1, 2, 3, 5, 11, 14 and 15. The diameter of the DOT shields used varied from 4.45 m (case 2) up to 9.36 m (case 3). The range of backfill grouting rate for those 8 tunnels bored with DOT shields was illustrated in Figure 6. In the figure, the minimum backfill grouting rate was 109%, the maximum rate was 200%, and the mean value was 153%. The mean rate plus and minus one standard deviation would be 125 and 180%, respectively. It was clear that the backfill grouting rate was not influenced by the diameter of the DOT shield.

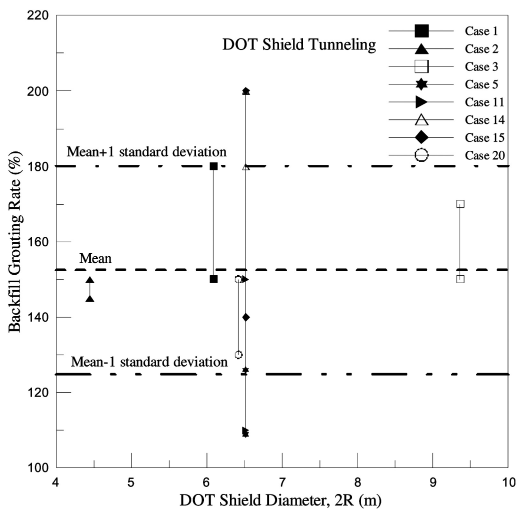

Figure 6. Backfill grouting rate with shield diameter.

Figure 7 showed the change of backfill grouting rate as a function of normalized tunnel depth Z/2R for 8 different cases. Based on the data in the figure, the backfill grouting rate decreased with increasing tunnel depth. This was probably due to: at a deeper location, the pressure to close the tail void was greater, therefore high backfill grouting rate was hard to achieve.

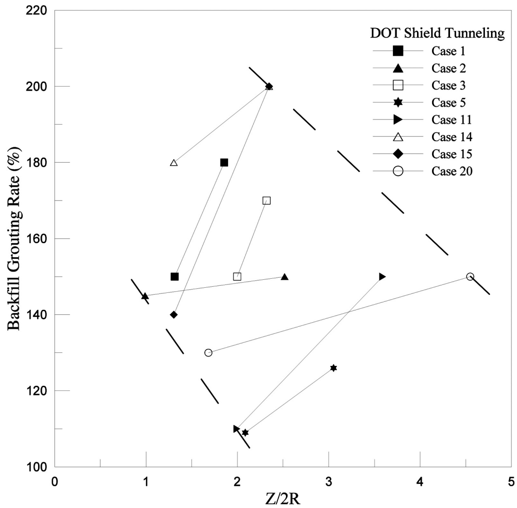

Figure 7. Backfill grouting rate with tunnel depth Z/2R.

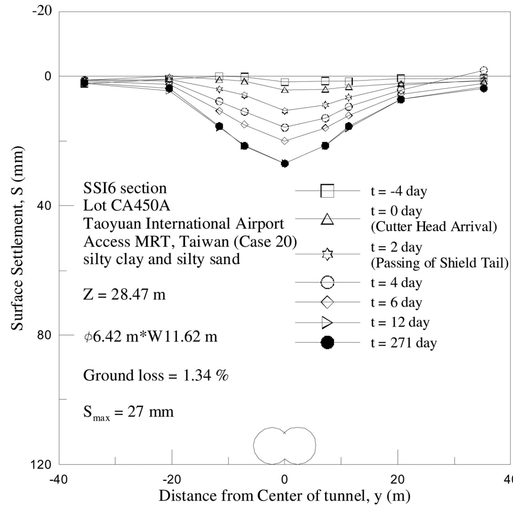

Figure 8. Surface settlement trough monitored at array SSI6.

4 GROUND SETTLEMENT TROUGHS

In this section, ground settlement troughs due to DOT shield tunneling measured in the field were reported. Based on field data, Peck (1969) suggested that the surface settlement trough over a single circular tunnel can usually be approximated by the error function or normal probability curve as follows:

$$S(y) = S_{max} \times \exp\left(\frac{-y^2}{2i^2}\right) \quad (2)$$

where S(y) is the settlement at offset distance y from the tunnel center line (tunnel axis), S_{max} is the maximum settlement above tunnel center line, and i is the distance from the inflection point of the trough to the center line. The parameter i is commonly used to represent the width of the settlement trough.

4.1 *Ground settlement measured at Lot CA450A*

In this study, the field data collected at monitoring section SSI6 of Lot CA450A were reported. Figure 8 showed the development of the settlement trough with time. Four days before the arrival of the face, a ground settlement of 2 mm was observed. When the cutter head arrived at SSI6, a roughly symmetrical settlement occurred. After the passage of the shield tail ($t = 2$ day), the maximum settlement was about 11 mm.

271 days after the passage of the face, the maximum settlement was 27 mm, which was identical to that measured at $t = 12$ day. For more information regarding the settlement-time relationship due to DOT shield tunneling, the readers are referred to Fang et al. (2013).

4.2 *Distribution of settlement trough*

In this study, since the two tunnels were always excavated together, it was assumed that the surface settlement tough due to shield tunneling could be approximated by the normal distribution curve (Equation 2) proposed by Peck (1969). The 271-day long term settlement trough indicated in Figure 8 was a good example.

Zhang (2007) suggested that the ground settlement due to DOT shield tunneling could be approximated with that due to a single-circular tunnel which has the same cross-sectional area as the DOT tunnel (equal area method). Fang et al. (2012) proposed that the principle of superposition may be used to estimate ground subsidence associated with the construction of DOT tunnels (superposition method). Six settlement troughs monitored at Ariakekita common conduit in Tokyo, Shanghai Metro, and Taoyuan International Airport Access MRT were compared with the settlement curves estimated with both the empirical equal-area and superposition methods (Fang et al. 2012).

4.3 *Maximum surface settlement*

Eleven sets of maximum surface settlement S_{max} collected from cases 3, 14, 16, 18, 19 and 20 were summarized in Figure 9. In this figure, the vertical coordinate is the normalized tunnel depth Z/2R, and the horizontal coordinate is the normalized maximum settlement S_{max}/R. The dash lines are the upper and lower bounds of the field data. In Figure 9, the maximum settlement due to DOT shield tunneling decreased with increasing tunnel depth. This was probably due to: with increasing tunnel depth, the overburden thickness increased, therefore the ground arching effect increased.

Figure 9 may be used to predict the range of maximum surface settlement before tunneling. For example, for $Z/2R = 2.0$, the range of S_{max} due to DOT shield excavation is expected to vary from 0.0049R to 0.0126R.

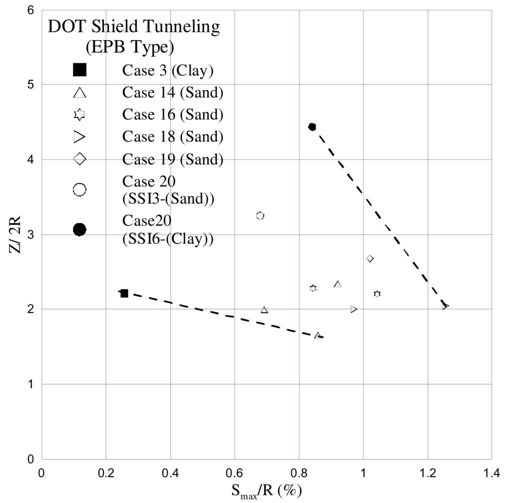

Figure 9. Relationship between maximum settlement S_{max}/R and tunnel depth Z/2R.

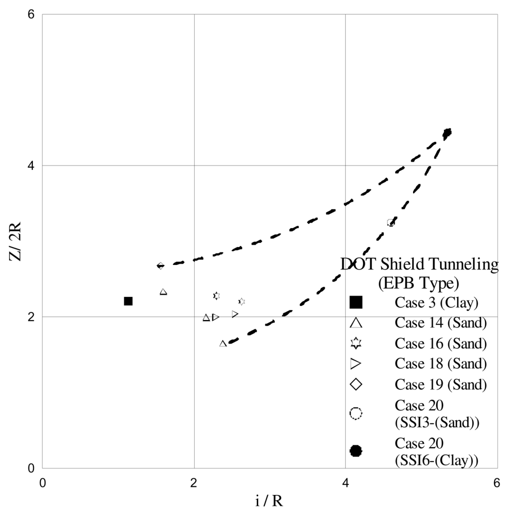

Figure 10. Relationship between settlement trough width i/R and tunnel depth Z/2R.

4.4 *Width of settlement trough*

Based on the normal distribution of ground settlement, the settlement trough width parameters i for 11 sets of data obtained from cases 3, 14, 16, 18, 19 and 20 were summarized. In Figure 10, the horizontal coordinate is the normalized width parameter i/R, and the vertical coordinate is the normalized tunnel depth Z/2R. The dash lines are the upper and lower bounds of these data. In this figure, the width of settlement trough increased with increasing tunnel depth.

Figure 10 may be used to estimate the range of settlement trough width before tunneling. The results are only applicable for tunnels driven with earth-pressure-balance DOT shield machines.

5 CONCLUSIONS

The backfill grouting rate obtained from the DOT shield tunneling of Lot 450A was compared with those measured from seven other cases. It was found that the range of backfill grouting rate varied from 109 to 200%, and the mean value was 153%. The backfill grouting rate decreased with increasing tunnel depth. This was probably due to: at a deeper location, the pressure to close the tail void was greater, therefore high backfill grouting rate was hard to achieve

Eleven sets of surface settlement data collected from six cases indicated that the maximum settlement due to DOT shield tunneling decreased with increasing tunnel depth. This was probably due to: with increasing tunnel depth, the overburden thickness increased, therefore the ground arching effect increased. It was also found that the width of settlement trough increased with increasing tunnel depth.

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