Soft ground tunnelling with New Austrian Tunnelling Method in Taipei

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ABSTRACT

This paper reported on tunnels constructed with the New Austrian Tunnelling Method (NATM) for lot CH221 of Hsin-tien Line of Taipei MRT. The sequence of tunnelling, construction of cutoff wall, breakthrough of diaphragm wall, installation of air locks, excavation under compressed air, and construction of waterproofing membrane and final lining were introduced. Based on 24 sets of field data reported in the literature, this paper recommended empirical values regarding the thickness of sprayed concrete lining and the thickness of the final lining for a tunnel driven with the NATM in soft ground.

Keywords: New Austrian Tunnelling Method; settlement; soft ground; sprayed concrete lining; tunnel

1 INTRODUCTION

In recent years, due to the rapid development of urban areas, many public facilities such as the Mass Rapid Transit (MRT) systems had been constructed. The tunnelling methods commonly adopted in soft grounds in urban areas included: (1) cut-and-cover method; (2) shield tunnelling method; and (3) New Austrian Tunnelling Method (NATM).

The Institution of Civil Engineers (1996) described, in soft ground in urban areas, that which is referred to as NATM is primarily the application of sprayed concrete as primary support, followed at a predetermined later date by installation of a permanent support. The use of sprayed concrete lining (SCL) permits the adoption of non-circular shape and by providing a rapidly installed temporary lining, permits flexibility and speed in the construction of complex tunnel structures. Chang (1991) stated that, at the initial stage of construction, tunnelling with NATM required less equipment investment. If the tunnel was less than 500 m-long, tunnelling with NATM would be more economic. However, for a tunnel longer than 500 m, the shield tunnelling method would be more economic. The Heathrow tunnel collapse was reported by Clayton (2008). It was mentioned that, once completed, NATM tunnels are as safe as any other tunnel. A comprehensive review of sprayed concrete lined tunnels with particular reference to London clay was made by the Health and Safety Executive (HSE) in 2014.

To alleviate the traffic problems that had plagued the Taipei metropolitan area, the first stage of the Taipei Mass Rapid Transit (Taipei MRT) network was approved by the Executive Yuan of the Republic of China (ROC) government in 1986. The tunnels constructed with NATM for lot CH221 of Hsin-tien Line of Taipei MRT was located at the intersection of Roosevelt Road and Shingsheng South Road as illustrated in Fig. 1. The owner of this project was the Department of Rapid Transit Systems (DORTS) of Taipei City Government.

Based on 24 sets of field data reported in the literature, empirical design recommendations were made regarding the thickness of sprayer concrete lining and the thickness of the final lining for tunnels excavated with NATM in soft grounds.

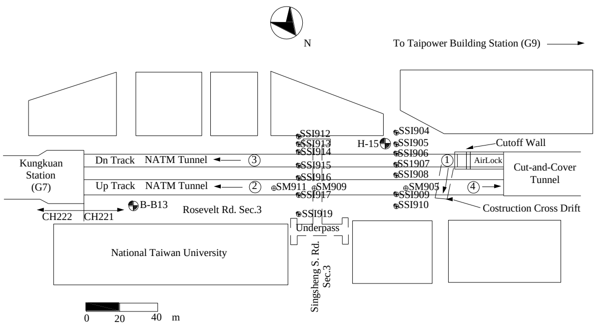

Fig. 1. Location of tunnels bored with New Austrian Tunneling Method.

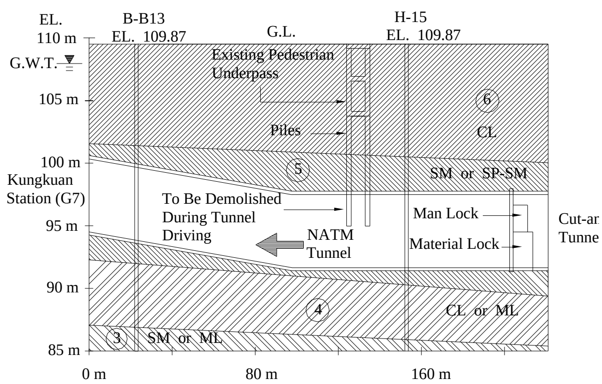

Fig. 2. Geological profile between kungkuan station and cut-and-

cover tunnel.

2 SUBSOIL CONDITIONS

Woo and Moh (1990) studied the geological history at the Taipei basin. In ascending order, the alluvial deposits consisted of the Hsin-chuang Formation (0 to 120 m thick), the Ching-mei Formation (0 to 140 m thick), the Sung-shan Formation (40 t0 70 m thick), and a topsoil layer (1 to 6 m thick). Most underground projects in Taipei were located at less than 40 m below ground level; hence most construction works were carried out in the topsoil and the Shun-shan Formation. Hung (1966) proposed that the Sung-shan Formation can be further divided into six sublayers.

Based on information obtained from bore holes B-B13 and H-15 shown in Fig. 1, a typical soil profile near the NATM tunnels was illustrated in Fig. 2. In the figure, the ground water table was located at about 2 m below ground level. In descending order, the sublayers involved with the project were described as follows:

(a) Topsoil and sublayer 6. The topsoil was 0.5 to 1.0 m thick. The sublayer 6 comprised soft silty clay with low plasticity (classified as CL). Characteristics of the soil were summarized in Table 1, if available. Due to its low permeability, this silty clay was expected to block the possible leakage of compressed-air adopted for tunnel excavation.

(b) Sublayer 5. Beneath the silty clay was a layer of loose to medium dense silty sand (classified as SM). It was clear in Fig. 2 that for this project the tunnelling was conducted entirely in sublayer 5 of the Sung-shan Formation.

(c) Sublayer 4. It comprised soft to stiff clayey silt or silty clay with low plasticity (classified as ML or CL).

3 REASONS TO SELECT NATM

The main reasons considered to select NATM were as follows:

1. The total length of the tunnel was only 222 m. It would be uneconomic to construct the tunnels with the shield tunnelling method, because the shield machines were quite expensive.

2. As indicated in Fig. 2, at about 120 m from the Kungkuan Station, piles to support the existing pedestrian underpass would be encountered during tunnel driving. It would be difficult for a close-type shield machine to handle the underground obstacles.

3. Fig. 1 showed the tunnels were located at the intersection of the heavily trafficked Roosevelt Road and Singsheng South Road. In the densely populated urban area, it would be inadequate to construct a tunnel with the cut-and-cover method.

4 CONSTRUCTION OF NATM TUNNELS

Fig. 1 showed a pair of soft ground tunnels was bored from the cut-and-cover tunnel to the Kungkuan Station (G7 Station) with the New Austrian Tunnelling Method. Major construction steps were briefly described as follows.

Table 1. Characteristics of sublayers of Sung-Shan Formation.

Soil layer	Soil type and classification	Soil properties
Topsoil and sublayer 6	Silty clay (CL)	N = 1-6, w = 26-36% e = 0.6-1.1 w_L = 25-45, w_P = 17-29 c = 39.2 kN/m^2 k = 0.58-3.4 x 10^{-7} cm/sec
Sublayer 5	Silty sand (SM or P-SM)	N = 14-18, w = 25-27% e = 0.6-0.8 ϕ = 30°
Sublayer 4	Clayey silt or silty clay (ML or CL)	N = 4-12, w = 22-30% e = 0.7-1.0 w_L = 25-40, w_P = 19-24 c = 39.2 kN/m^2 k = 1.0x10^{-7} cm/sec

The cement-bentonite cutoff wall was constructed to protect the initial part of the bored tunnel. Fig. 3 showed the cutoff walls penetrated 26.5 m into the soft ground. After the cutoff walls were fabricated, a circular opening with a diameter of 6.56 m was broken on the diaphragm wall. The soils at the top-heading level were excavated and lattice girders were placed to support the tunnel as indicated in Fig. 4. As a pre-support, 2 m-long steel lagging sheets were driven into the ground along the upper boundary of the top-heading zone as illustrated in Fig. 4 (b). In Fig. 4 (a), the inclination angle between the tunnel and the lagging sheets was 10°. With the lattice arches and lagging sheets, the shotcrete was sprayed to form a composite support. After the length of the top-heading tunnel advanced about 3.5 m, the bench and invert parts of the diaphragm wall were demolished. Steel wire mesh and sprayed concrete were placed as indicated in Fig. 4.

During tunnelling, compressed air was applied in the tunnel to balance the hydrostatic groundwater pressure in the permeable sandy soil. Air locks were used to equalize the compressed air inside the NATM tunnel as well as the outside air to permit passage of men and materials. The air locks included a men lock on top of a material lock. A picture of the material lock was shown in Fig. 5. It should be mentioned that if the rate of pressure change was too fast, the health of the personal in the air lock could be endangered.

The excavation sequence adopted for the tunnelling with NATM at lot CH-221 was illustrated in Fig. 6. The bench-type excavation was used. In Fig. 6, the remaining bench and invert soil mass provided a passive earth pressure to balance the invading earth pressure at the face.

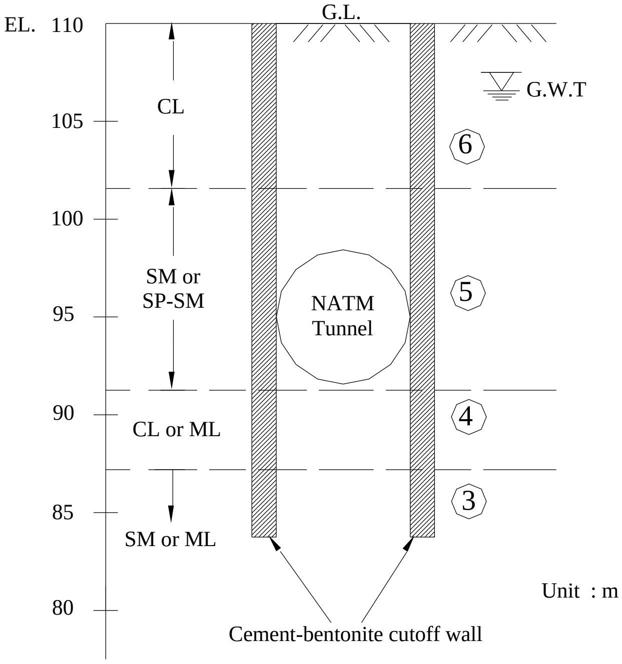

Fig. 3. Section of cement-bentonite cutoff walls.

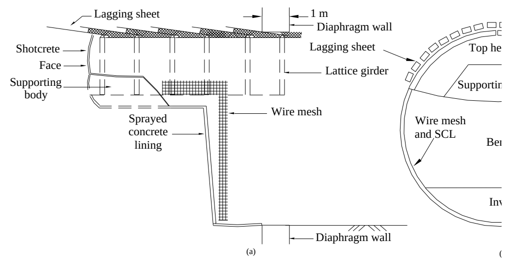

Fig. 4. Excavation and support of NATM tunnel.

Fig. 5. Material lock.

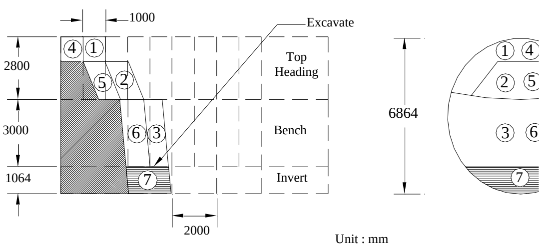

Fig. 6. Excavation sequence for tunnelling of lot CH221.

Fig. 7. Excavation of top-heading.

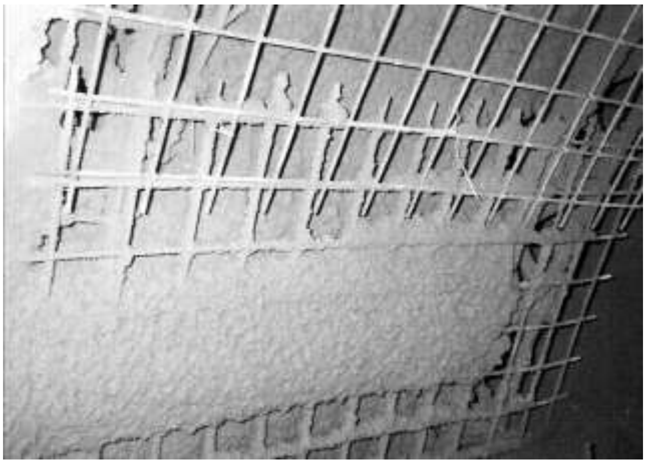

Fig. 8. Steel wire mesh and sprayed concrete lining.

Fig. 6 showed each shift of stage 3 and 6 required 1.0 m of soil excavation along the tunnel alignment. The removing of the bench soils, a layer of 100 mm and a layer of 30 mm-thick shotcrete was sprayed on the tunnel wall and face, respectively. Then a second layer of 100 mm-thick shotcrete was sprayed on the tunnel wall. Fig. 7 showed the excavation of the top-heading zone. After putting on the steel wire mesh, a third layer of 100 mm-thick shotcrete was sprayed on the tunnel wall as shown in Fig. 8.

Waterproofing of the tunnel may be facilitated by providing a waterproofing membrane between the sprayed concrete lining sprayed concrete lining (SCL) support and the final lining. Fig. 9 showed the waterproofing membranes placed around the tunnel.

5 EMPIRICAL DESIGN RECOMMENDATIONS

Three methods commonly adopted by the designer includes: (1) empirical method; (2) numerical method; and (3) theoretical method. Based on the empirical method, an engineer must assume some of its dimensions, such as the thickness of SCL, and then the numerical and theoretical methods are used to analyze and check the adequacy of the trial section.

Based on 24 sets of field data reported by

Urban NATM Working Group (1985), Wallis (1990), McWilliams (1991), Aoki Construction and New Asia Construction and Development Corp. (1992), Way (1993), Wallis (1995) and Chao et al. (1997), this paper investigated the empirical values regarding the thickness of sprayed concrete lining (T_{SCL}) and the thickness of final lining (T_{FL}) for a tunnel driven with NATM in soft ground. The cases adopted for analysis were summarized in Table 2. The definition of H, T_{SCL}, T_{FL} and the length of pre-support L_{PS} were illustrated in Fig. 10.

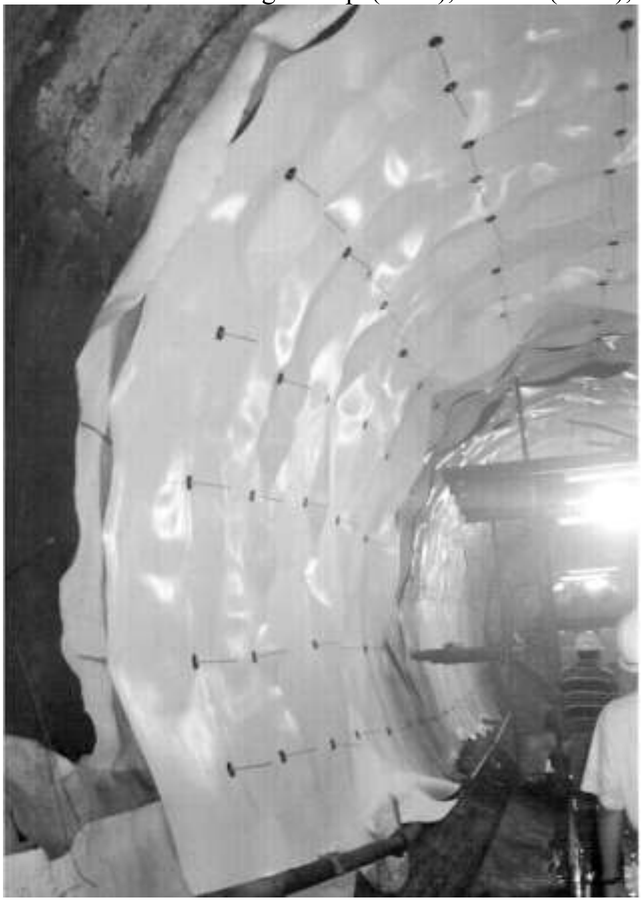

Fig. 9. Waterproofing membrane around tunnel.

Table 2. Cases of NATM tunnelling in soft ground.

Case No.	Tunnel location	Thickness of overburden H, (m)	Tunnel diameter D, (m)	Thickness of SCL T_{SCL}, (mm)	Thickness of final lining T_{FL}, (mm)	Length of pre-support L_{PS}, (m)
1	NT-2, Japan	22.0	5.6	150	N/A	N/A
2	NT-5, Japan	22.2	10.7	150	N/A	N/A
3	NT-14, Japan	7.0	10.7	200	N/A	N/A
4	NT-15, Japan	5.3	10.6	200	N/A	N/A
5	NT-16, Japan	8.2	10.7	200	N/A	N/A
6	NT-33, Japan	26.0	5.24	150	N/A	N/A
7	NT-35, Japan	27.0	9.6	200	N/A	N/A
8	NT-40, Japan	6.9	5.9	150	N/A	N/A
9	NT-42, Japan	4.0	11.0	250	N/A	N/A
10	NW-5, Japan	5.0	13.83	400	N/A	N/A
11	NW-6, Japan	17.5	8.6	200	N/A	N/A
12	NR-4, Japan	25.0	12.5	200	N/A	N/A
13	NR-22, Japan	18.0	12.0	200	N/A	N/A
14	NR-27, Japan	27.0	10.8	200	N/A	N/A
15	Lot CH221, Taipei MRT	10.0	6.8	250	350	2.0
16	Narashino Tunnel, Japan	8.0	9.57	250	450	2.75
17	Mitsuzawa-Kamicho Station, Japan	20.0	13.63	250	500	N/A
18	Kokubun River Diversion Channel, Japan	18.5	8.7	200	300	3.5
19	Ibuki Tunnel, Japan	19.0	11.6	200	600	1.5
20	Kita-Yobancho Tunnel, Japan	15.0	6.7	150	450	2.0
21	Munich Water Transport Tunnel, Germany	20.0	4.4	200	200	2.0
22	Rapid Transit Tunnel, Germany	3.5	7.8	450	500	N/A
23	Salzburg-Wogrl Rail Tunnel, Germany	23.0	11.5	300	250	1.5

5.1 Thickness of sprayed concrete lining

The relationship between the thickness of SCL (T_{SCL}) and tunnel diameter D was investigated in this section. Tunnel diameters ranging from 4.4 to 17.6 m, and T_{SCL} varied from 150 to 450 mm were plotted in Fig. 11. Based on linear regression method, an empirical relationship between T_{SCL} and D was established with the following equation:

$$T_{SCL} = 12.8D + 102 \quad (1)$$

where T_{SCL} = thickness of sprayed concrete lining in mm; and D = excavated diameter of tunnel in m. It should be noted that equation 1 was applicable for the tunnel with a diameter ranging from 4.4 to 17.6 m.

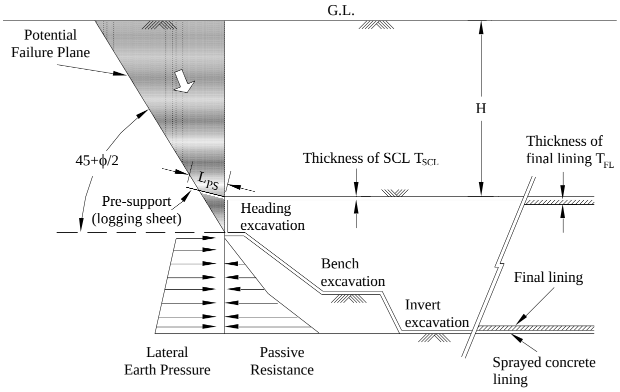

Fig. 10. Thickness of sprayed concrete lining T_{SCL} and length of pre-support L_{PS}

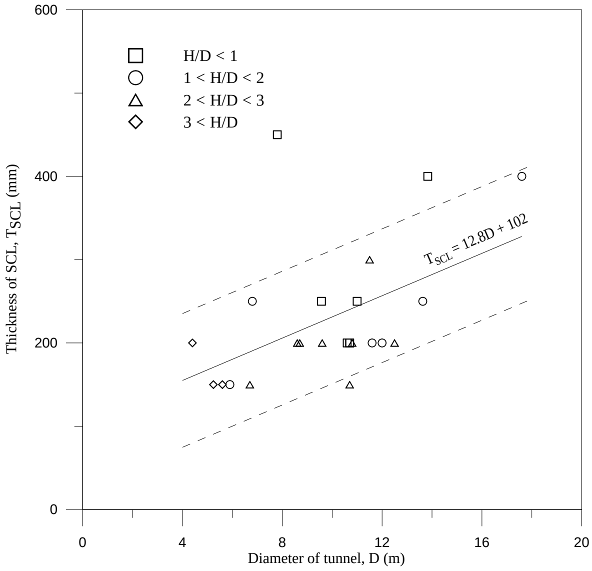

Fig. 11. Thickness of SCL as a function of tunnel diameter.

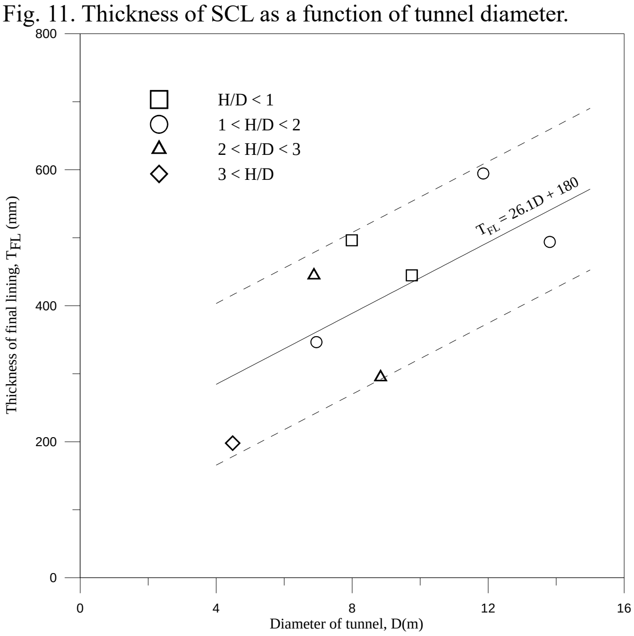

Fig. 12. Thickness of finial lining as a function of tunnel diameter.

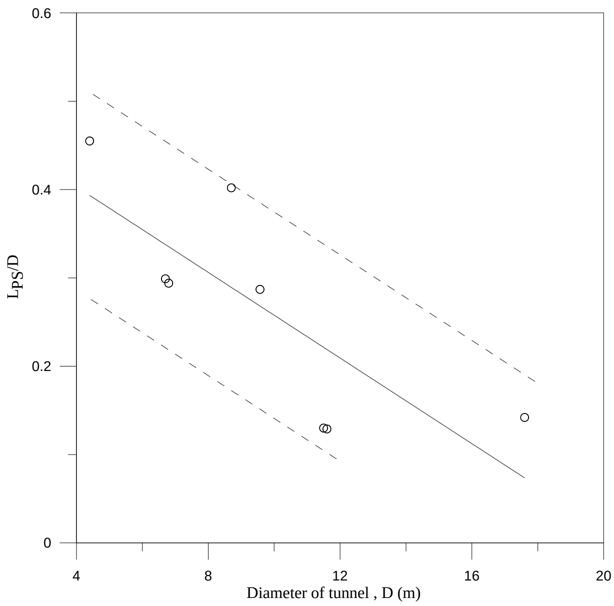

Fig. 13. Length of pre-support as a function of tunnel diameter.

For the convenience of construction, in all cases the thickness of SCL was designed as a multiple of 50 mm, such as 150, 200, 250, 300, 350, 400 and 450 mm. Fig. 11 indicated that the selection of T_{SCL} was also influenced by the H/D ratio of the tunnel. The NATM tunnel with a thin overburden H and a large tunnel diameter D could be less stable. It was suggested that for the design of a tunnel with a low H/D ratio, a thicker T_{SCL} value should be selected. From a practical point of view, no T_{SCL} less than 150 mm was observed in Fig. 11.

5.2 Thickness of final lining

An empirical relationship between the thickness of final lining T_{FL} and tunnel diameter D was studied. Based on the field data summarized in Table 2, Fig. 12 was drawn. In the figure, the T_{FL} varied from 200 to 600 mm. Based on the field data, the empirical equation between T_{FL} and D was suggested as follows:

$$T_{FL} = 26.1D + 180 \qquad (2)$$

where T_{FL} = thickness of final lining in mm; and D = excavated diameter of tunnel in m. Equation 2 was only applicable for tunnels with diameters ranging from 4.4 to 13.6 m.

In all cases, the thickness of the final lining was designed as a multiple of 50 mm. It was suggested that for the tunnel with a thin overburden and a large tunnel diameter (low H/D ratio), a thicker T_{FL} value should be considered.

5.3 Length of pre-support

As indicated in Fig. 4 and Fig. 10, during the excavation of a NATM tunnel, pre-supports were often constructed to prevent the collapse and inflow of soils above and in front of the face. Pre-supports were generally fabricated with steel pipes, or steel sheet piles.

The length of the pre-support L_{PS} should be long enough to block the movement of the potential collapse zone, and to protect the excavation at top-heading. For all cases studied in this article, the length of pre-support L_{PS} varied from 1.5 to 3.5 m. Fig. 13 showed the L_{PS} varied from 0.14D to 0.45D.

The solid line in Fig. 13 indicated that the L_{PS}/D ratio decreased with increasing tunnel diameter D. The dashed lines in the figure indicated the mean L_{PS}/D ratio plus and minus one standard deviation. No recommendation was made regarding the value of L_{PS} because of insufficient data in Table 2.

6 CONCLUSIONS

This paper reported on tunnels constructed with the New Austrian Tunnelling Method for lot CH221 of Hsin-tien Line of Taipei MRT. Based on 24 sets of field data reported in the literatures, this paper recommended empirical values regarding the thickness of sprayed concrete lining T_{SCL} and the thickness of the final lining T_{FL} for a tunnel driven with the NATM in soft ground. With the assumed empirical value, an engineer can use the numerical and theoretical methods to analyze and check the adequacy of the trial section.

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