Case Record:

A BORED TUNNEL ON KAOHSIUNG RAPID TRANSIT SYSTEM, CONTRACT CR2

Benson Bin-Chen Hsiung[1] and Kuan-Lin Lu[2]

ABSTRACT

Shield-machine bored tunnels are used for a variety of purposes in urban areas. Construction of these bored tunnels in soft ground can induce ground movement and cause damage to adjacent structures. Observation of soft ground tunnels in clay have been popularly discussed but there is limited literature on soft ground tunnels constructed in sand. A complete case record is given in this paper based on tunnels on Contract CR2 of the Kaohsiung Metro. It shows the accumulated maximum surface settlement induced by tunnelling can be up to 40 mm and that the ground becomes stable 20 to 40 days after the shield has passed. This paper explores the effects from two factors on the transverse surface settlement trough, ground loss rate (V) and settlement trough factor (K). Back-analyses indicate that approximately 0.31 to 1.85% of V and 0.4 to 0.9 of K were induced by the tunnelling works. In addition, three construction parameters, chamber pressure coefficient (P_r), backfill rate and backfill pressure were calculated and discussed. It is observed that P_r is mainly in the range of 0.7 to 0.9, backfill rate varies from 100 to 150% and the applied backfill pressure varies from 200 to 500 kPa during the construction. Due to limited data, no firm relationship could be established between construction parameters and V therefore further investigation is required.

Key words: Tunnelling in sand, settlement, ground loss, settlement trough factor.

1. INTRODUCTION

Bored tunnels are commonly used for transportation, water supply, sewers and common conduits in urban areas. Generally, soft ground tunnels are bored using earth-pressure-balance (EPB) or slurry type shield-machines, as shown in Fig. 1. However, unfavourable ground movements induced by the construction of bored tunnels can cause damage to adjacent structures. Ground behaviour induced by construction of bored tunnels in clay have been widely explored and discussed (Fang and Chen, 1990; Fang, *et al.*, 1994; Hwang, *et al*., 1995) but there are limited references for similar examinations of tunnels constructed in sand. This paper presents a complete case record of bored tunnels constructed in sand in a densely populated urban area. It is expected this will provide an effective foundation for research of ground and structural behaviour of bored tunnels in sand.

2. PROJECT BACKGROUND AND CONSTRUCTION PROCEDURE

Kaohsiung is the political and economic centre in southern Taiwan. Kaohsiung began design of their new metro system in the 90’s and construction commenced in 2002. Two lines, Red-line and Orange-line are constructed and the total route length of the system is 42.8 km and includes 37 stations, 28 underground. All underground stations employ open-cut construction. Shield-machine bored tunnels connect the stations and there are 28 single-track twin tunnels in the whole system.

Contract CR2 on the Red-line is located in the CianJen district in Kaohsiung city, and has three underground stations, R4A, R5, and R6. It also has four twin bored tunnels, LUR10, LUR11, LUR12, and LUR13 as well as eight cross-passages (two of them with sumps). The construction sequence for these tunnels is presented in Table 1 and Fig. 2.

Three EPB shield-machines were employed for construction of tunnels at CR2. The diameter of the shield was 6.34 m and the inner and outer diameter of the tunnel lining was 5.6 m and 6.16 m, respectively, the rings were 1.2 m wide reinforced concrete. Each ring consisted of six segments (three A-type segments, two B-type segments and one K-type segment) and the total weight of each ring was 14.9 tons.

Backfill grouting was injected in order to fill the tail voids. At CR2, the grout comprised cement/bentonite and sodium silicate and was injected as soon as each ring left the shield. The injection pressures were typically 350 to 450 kPa maximum and the target volume of grout fill was 2,756 litres per ring.

3. GROUND CONDITIONS

The construction site is located in the alluvium area of CianJen River, which mainly comprises silty sand and silty clay. Figures 3 to 6 present the ground profile along the route of Contract CR2 and a simplified description is given in Tables 2 to 5.

At Contract CR2, the groundwater level is observed at 2 to 5 m below ground level and remains in the same hydrostatic condition as before tunnel construction.

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[1] Assistant Professor (corresponding author), Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan 807 (e-mail: benson@cc.kuas.edu.tw)

[2] Postgraduate student, Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan 807.

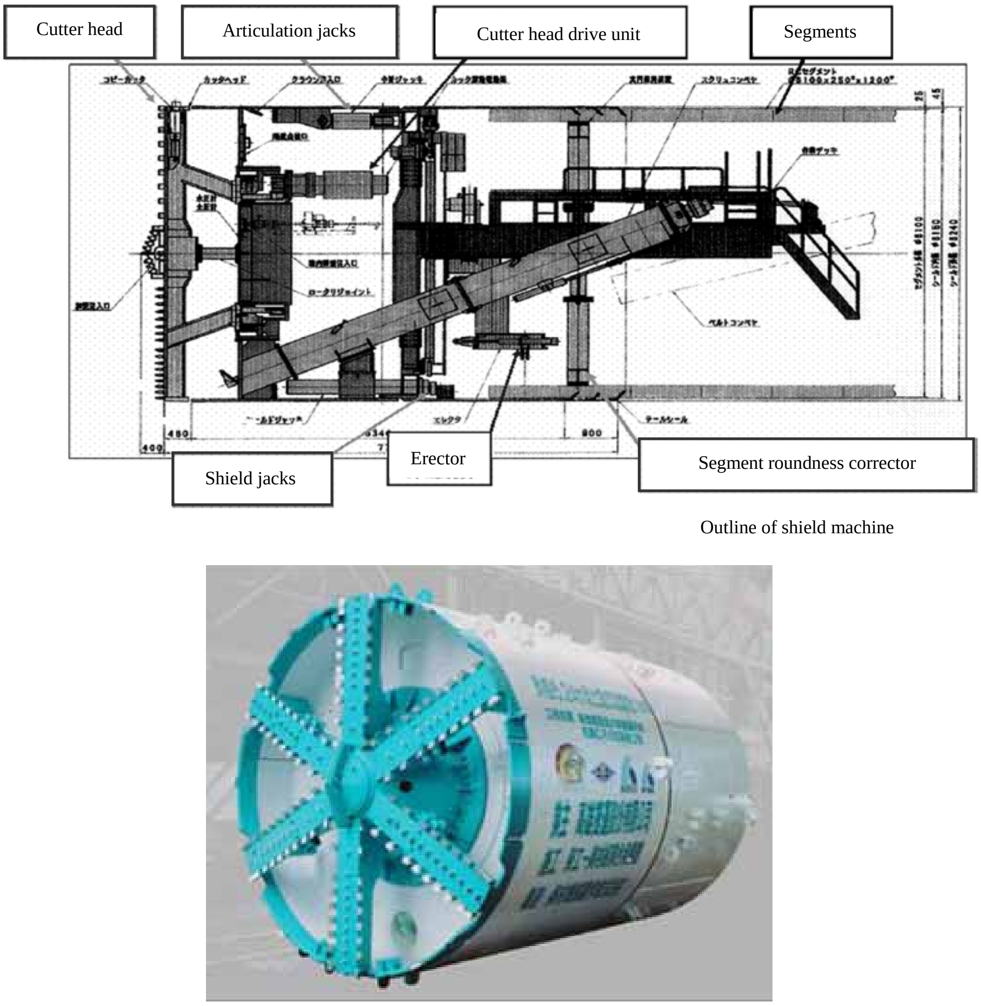
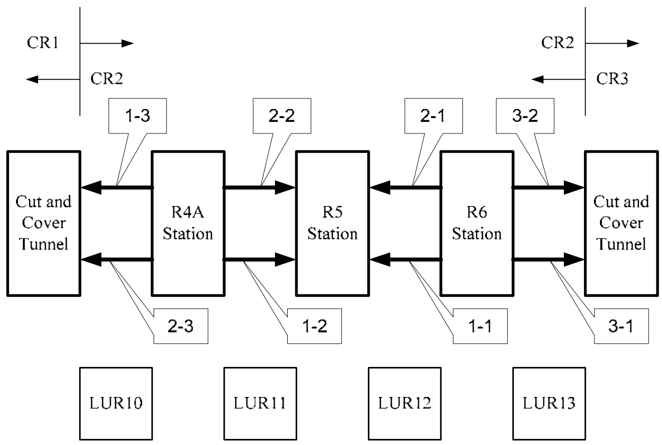


Fig. 1 Shield machine used for soft ground tunnels

Table 1 Details and construction sequence of tunnels at CR2

Name of tunnel	Exit from	Entry to	Date of start of construction (year/month/day)	Date of end of construction (year/month/day)
LUR10 (down-line)	South end of Station R4A	Cut-and-cover tunnel at CR1	2004/10/15	2005/01/18
LUR10 (up-line)	South end of Station R4A	Cut-and-cover tunnel at CR1	2004/12/11	2005/02/25
LUR11 (down-line)	North end of Station R4A	South end of Station R5	2004/01/19	2004/08/13
LUR11 (up-line)	North end of Station R4A	South end of Station R5	2004/05/02	2004/10/03
LUR12 (down-line)	South end of Station R6	North end of Station R5	2003/06/10	2004/03/16
LUR12 (up-line)	South end of Station R6	North end of Station R5	2003/03/28	2004/01/18
LUR13 (down-line)	North end of Station R6	Cut-and-cover tunnel at CR3	2004/07/10	2004/11/04
LUR13 (up-line)	North end of Station R6	Cut-and-cover tunnel at CR3	2004/10/14	2005/04/20



Note 1: " → " means the drive direction of shield machine

Note 2: a-b , "a" means number of shield machine; "b" means number of drive

Fig. 2 Construction sequence of tunnels at Contract CR2

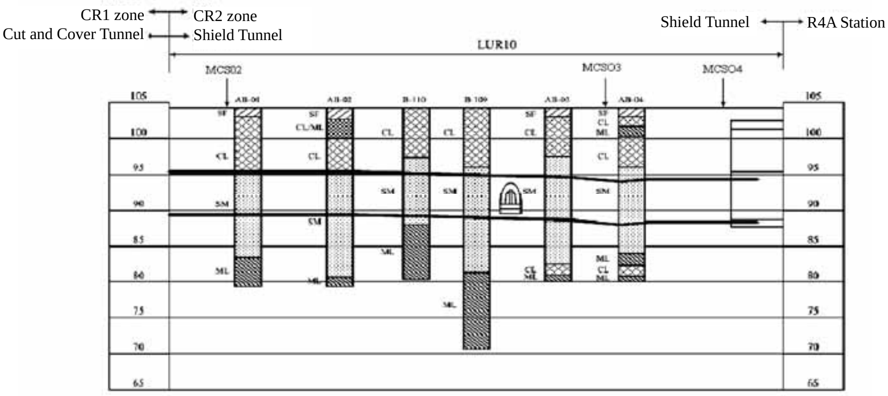


Fig. 3 Ground profile at LUR10

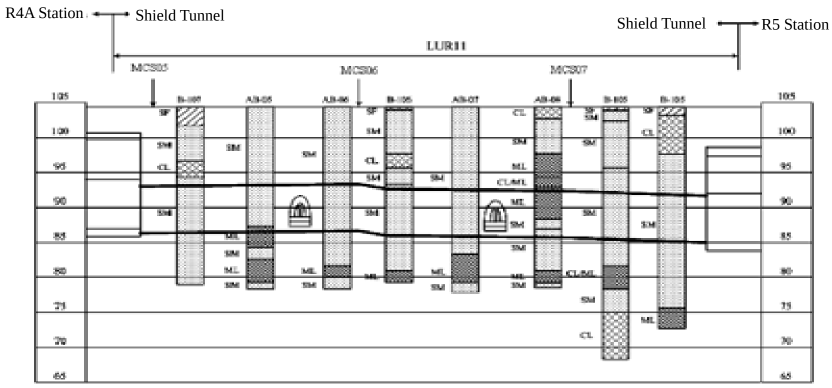


Fig. 4 Ground profile at LUR11

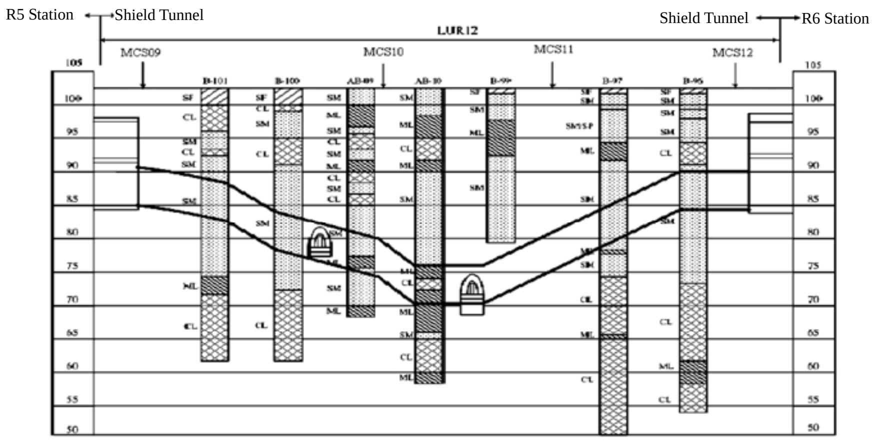


Fig. 5 Ground profile at LUR12

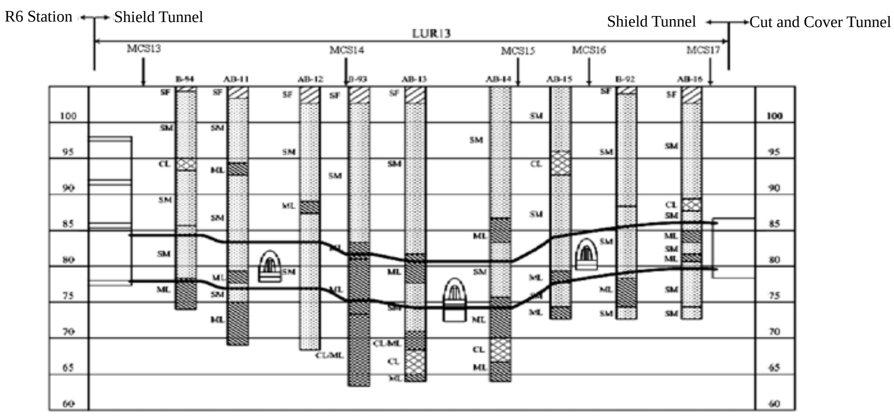


Fig. 6 Ground profile at LUR13

Table 2 The ground strata of LUR10

Layer	Description of ground	Depth	Total unit weight (kN/m^3)	SPT-N value
I	Gray silty clay occasionally with silt and sand	Surface to 9.9 m below; groundwater level observed at 2.0 m below ground level	Approximately 19.0	4 to 12
II	Gray silty fine sand occasionally with sandy silt	In the range of 9.9 m to 23.6 m below the ground surface	Approximately 19.1	20 to 26
III	Gray sandy silt	Beneath 23.6 m below the ground surface	Approximately 19.9	27 to 36

Table 3 The ground strata of LUR11

Layer	Description of ground	Depth	Total unit weight (kN/m^3)	SPT-N value
I	Gray silty sand occasionally with clayey silt and silt clay	Surface to 9.6 m below; groundwater level observed at 5.0 m below ground level	Approximately 19.6	2 to 20
II	Gray silty sand occasionally with sandy silt	In the range of 9.6 m to 23.8 m below the ground surface	Approximately 19.0	13 to 32
III	Gray sandy silt with silty sand or silty clay	Beneath 23.8 m below the ground surface	Approximately 19.0	15 to 27

Table 4 The ground strata of LUR12

Layer	Description of ground	Depth	Total unit weight (kN/m^3)	SPT-N value
I	Silty sand with sandy silt and silty clay. Backfill materials are observed on surface in some locations.	Surface to 9.0 m below; groundwater level observed at 2.0 m below ground level	Approximately 19.1	4 to 12
II	Silty sand	In the range of 9.0 m to 31.5 m below the ground surface	Approximately 19.2	5 to 21
III	Silt	Beneath 31.5 m below the ground surface	Approximately 19.8	22 to 35

Table 5 The ground strata of LUR13

Layer	Description of ground	Depth	Total unit weight (kN/m^3)	SPT-N value
I	Sand with sandy silt. Backfill materials are observed on surface occasionally.	Surface to 8.7 m below; groundwater level observed at 2.0 m below ground level	Approximately 19.6	6 to 11
II	Silty sand	In the range of 8.7 m to 32.8 m below the ground surface	Approximately 18.7	9 to 20
III	Silty clay	Beneath 32.8 m below the ground surface	Approximately 18.6	15 to 26

4. MONITORING RESULTS AND DISCUSSION

Instruments installed on site included bench marks for surface level, tiltmeters, crack gauges, extensometers, observation wells and inclinometers. In this paper, the surface settlement measurement is addressed. The surface settlement points were installed at ground level exactly above the central axis of tunnel and were used to monitor surface settlements induced by tunnel excavation. Arrays at some sections were set perpendicular to the tunnel, as shown in Fig. 7 to measure transverse surface settlements at these sections during construction. Their locations (MCS02 ~ MCS17) are shown in Figs. 3 to 6.

Table 6 presents the depth to the centre of each tunnel at CR2. The depth to the centre of the tunnel is in the range of 8 to 29 m below ground level. Figures 8 to 13 present the time history of the settlement monitored at the surface level exactly above the centreline of each tunnel. It was observed that 4 to 20 mm of surface settlement was induced when driving the 1st tunnel. The adjacent second drive caused further settlement (except MCS06 on Tunnel LUR11, MCS12 on Tunnel LUR12 and MCS16 on Tunnel LUR13). The maximum accumulated surface settlement varied from 5 to 40 mm. Table 6 also indicates the average tunnel advance rate for each tunnel at CR2 which was from 3.2 to 8.8 m per day.

Hwang *et al*., (1995) suggested that the three phases (shield advancing, tail void and consolidation) of ground settlement could be clearly distinguished in Taipei. Figures 8 to 11 present accumulated surface settlements observed at different locations at CR2. As shown in Figs. 8 to 11 ground settlements induced during the phase of shield advance and tail void are observed but there was no consolidation settlement in the Kaohsiung tunnels. The main ground stratum in Taipei is soft clay, whereas in Kaohsiung it is silty sand hence the difference in the ground conditions are likely to be the main reason for the different settlement results.

As indicated in Figs. 8 to 11, on most sections the ground attained a stable condition 20 to 40 days after the shield had passed. Additional settlements (approximately 5 mm) at MCS02 were generated after the ground was stabilised (please refer to Down-Line tunnel on Fig. 8). Since this section is very close to a cut-and-cover tunnel LUR06, excavation inside LUR06 may have caused additional settlement at MCS02. Further movements were found 70 ~ 80 days after the ground had become stable at MCS15 and MCS16, as shown in Figs. 12 and 13, probably as a result of nearby cross-passage construction.

Also, Peck (1969) recommended that if two tunnels are driven adjacent to one another, the construction of the 2nd tunnel would generate significantly greater movements because of stress relief of the ground resulting from the construction of the 1st tunnel. However, this does not seem to apply at several locations on CR2 (refer to Figs. 9, 11, and 13). Apart from measurement error, improved operation of the shield-machine for the 2nd tunnel is a likely reason for the smaller settlements induced by the 2nd tunnel.

A transverse surface settlement trough was also measured at CR2. It was measured by several monitoring arrays but only twelve sets of data were selected for use in this paper because of a concern over reliability. Generally, as twin-tunnels run parallel horizontally, the centre of the array is defined as the mid point between two tunnels. Two settlement points in an array are installed above the centreline of each tunnel, and the array is extended to 35 m from the centre of the array perpendicular to the line of the tunnel.

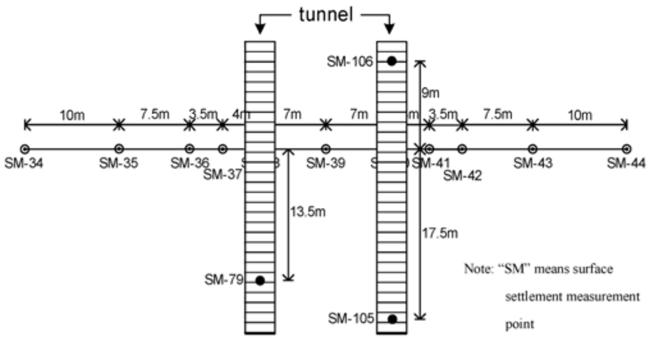


Fig. 7 The array for surface settlement measurement

Table 6 Depth to centre of tunnel and tunnel advance rate

Name of tunnel	Depth to centre of tunnel (m, below surface level)	Tunnel advance rate (m/day)
LUR10 (down-line)	8 ~ 12	7.9
LUR10 (up-line)	12 ~ 17	8.8
LUR11 (down-line)	8 ~ 12	4.6
LUR11 (up-line)	9 ~ 11	6.1
LUR12 (down-line)	18 ~ 29	3.4
LUR12 (up-line)	18 ~ 29	3.2
LUR13 (down-line)	17 ~ 27	7.1
LUR13 (up-line)	17 ~ 27	4.4

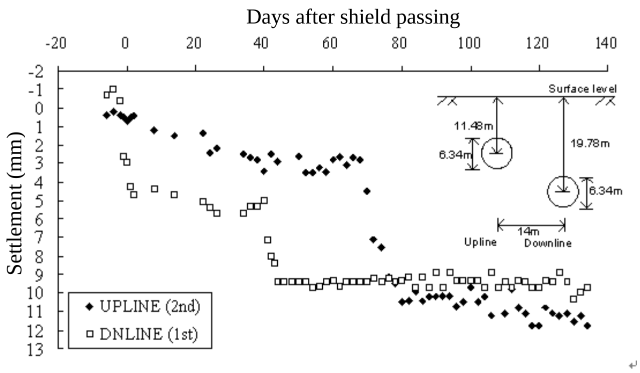


Fig. 8 Time history of surface settlement at LUR10-MCS02

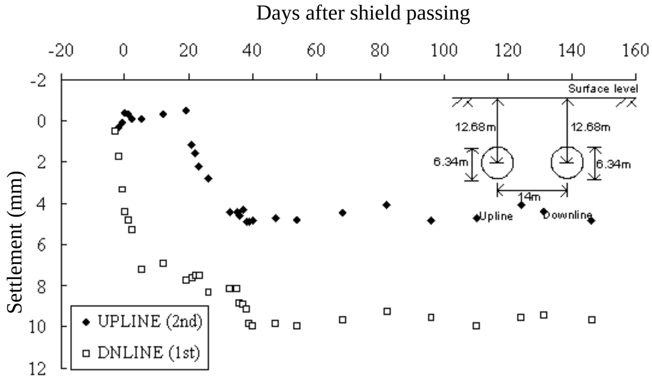


Fig. 9 Time history of surface settlement at LUR11-MCS06

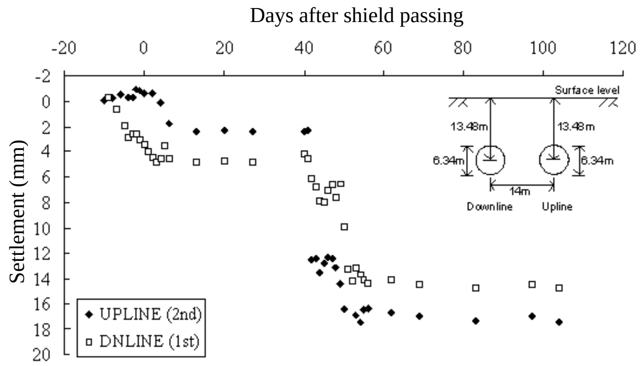


Fig. 10 Time history of surface settlement at LUR11-MCS07

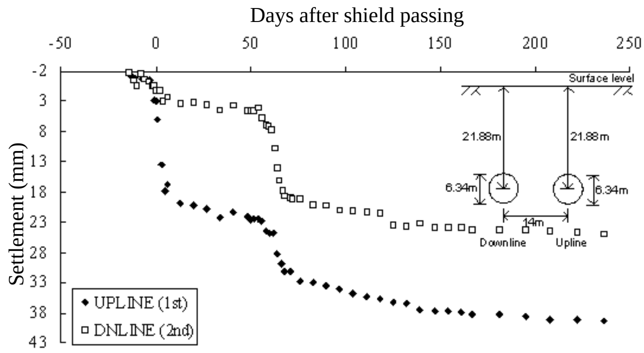


Fig. 11 Time history of surface settlement at LUR12-MCS12

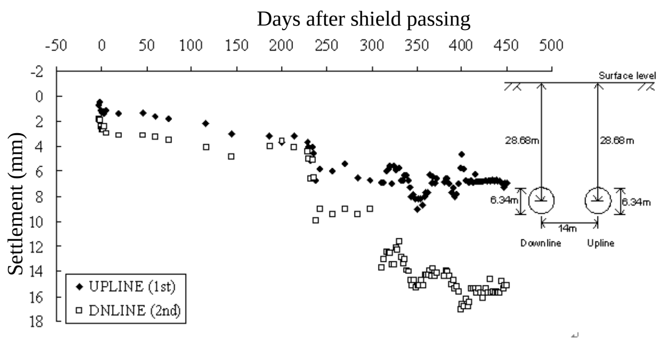


Fig. 12 Time history of surface settlement at LUR13-MCS15

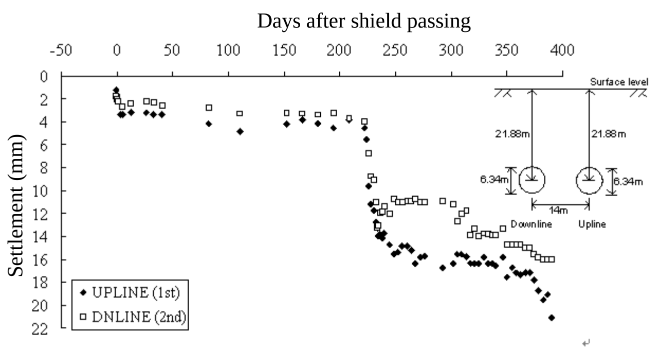


Fig. 13 Time history of surface settlement at LUR13-MCS16

Peck (1969) suggested that a normalised distribution curve can fit the transverse surface settlement induced by a single tunnel, as shown in Eq. (1).

$$\delta = \delta_{max} \exp\left(-\frac{X^2}{2i^2}\right) \quad (1)$$

in which δ is surface settlement at any location from the central axis of the tunnel; δ_{max} is the maximum surface settlement; X is the distance from the point having δ to the central axis of tunnel and i is called "width factor".

δ_{max} is defined by

$$\delta_{max} = 0.0126\, V \frac{R^2}{i} \quad (2)$$

where V is ground loss rate and R is radius of tunnel.

In order to define i, O'Reilly and New (1982) suggested

$$i = K\ Z_0 \quad (3)$$

in which K is a settlement trough factor, a response to ground conditions and Z_0 is depth to the centre of the tunnel. Table 7 presents the use of K recommended by O'Reilly and New.

In order to realise the influence from a bored tunnel on surface levels as well as the use of the prediction of Peck to compare with the actual behaviour, the measurements were therefore interpreted and mapped to settlements induced by a single tunnel. Figures 14 and 15 present the interpreted transverse surface settlement of two of thirteen analytical sections. At LUR10-MCS02 and LUR12-MCS12, δ_{max} reaches 4 to 6 mm and 20 to 22 mm, respectively. Considering interpreted data, δ_{max} is mainly found above the central axis of the tunnel. Limited settlements were observed 35 m from the mid point of the tunnels. Table 8 summarises Z_0 and individual δ_{max} for each tunnel and it is seen that δ_{max} could be up to 22.4 mm.

Back-analyses using Eqs. (1) to (3) were carried out for interpreting parameters K and V at CR2. Results were also plotted in Figs. 14 to 15 and Tables 9 and 10 detail a range and average values of K and V. In order to deliver analyses, δ_{max} is fixed but K and V values on the analytical curve are adjusted to fit the rest of the observed data points on the plot. Two curves which could cover the range of most observed data points are selected for the upper and lower bounds so the maximum and minimum of K and V are defined herein. As shown in Figs. 14 and 15, interpreted observed settlement indicates a normalised distribution and it appears that the predicted settlement trough from back-analyses gives a good agreement with actual observations. Considering average values of analytical results, tunnels at CR2 caused approximately 0.31 to 1.85% of V and 0.4 to 0.9 of K. Bhogal (2005) reported that the design was based on presumed value of V of 0.8% to 1.2% with K of 0.35 to 0.45 in tunnelling works in Kaohsiung metro but V could be reduced to 0.5% if polymer was used as a soil conditioning agent. Interpreted results of K and V obtained from CR2 appear to be slightly higher than values reported previously.

Table 7 Recommended values for *K*

Ground conditions	*K*
Stiff clay with fissures	0.4 ~ 0.5
Glacial deposit	0.5 ~ 0.6
Soft clay	0.6 ~ 0.7
Granular material with groundwater	0.2 ~ 0.3
Granular material without groundwater	0.4 ~ 0.5

Table 8 Z_0 and δ_{max} induced by tunnels at CR2

Section	Up-line/ Down-line	Z_0 (m, below surface level)	δ_{max} (mm)	Section	Up-line/ down-line	Z_0 (m, below surface level)	δ_{max} (mm)
MCS-02	Up-line	11.48	4.2	MCS-11	Up-line	29.48	7.0
MCS-02	Down-line	19.48	5.7	MCS-11	Down-line	29.48	12.3
MCS-04	Up-line	14.28	5.8	MCS-12	Up-line	21.88	22.4
MCS-04	Down-line	14.28	6.4	MCS-12	Down-line	21.88	19.7
MCS-05	Up-line	15.08	6.4	MCS-14	Up-line	23.88	8.0
MCS-05	Down-line	12.28	4.8	MCS-14	Down-line	23.88	4.5
MCS-06	Up-line	12.68	5.8	MCS-15	Up-line	28.68	3.1
MCS-06	Down-line	12.68	7.3	MCS-15	Down-line	28.68	6.3
MCS-07	Up-line	13.48	14.5	MCS-16	Up-line	21.88	4.5
MCS-07	Down-line	13.48	4.7	MCS-16	Down-line	21.88	12.6
MCS-10	Up-line	23.88	12.3	MCS-17	Up-line	20.88	9.2
MCS-10	Down-line	23.88	6.5	MCS-17	Down-line	20.88	11.3

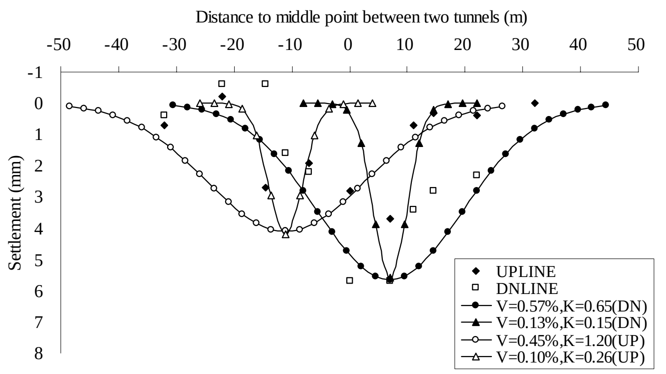


Fig. 14 Surface settlement trough and estimation of *K* and *V* at LUR10-MCS02

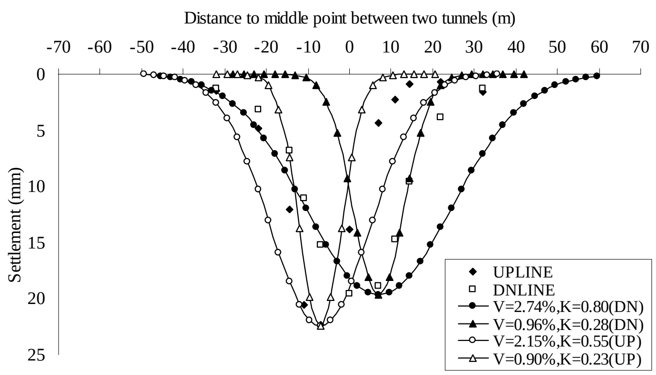


Fig. 15 Surface settlement trough and estimation of *K* and *V* at LUR12-MCS12

Parameters used for construction of shield-machine tunnels, chamber pressure, backfill rate and backfill pressure are explored in this paper. In order to control the applied chamber pressure, the upper limit (P_{fu}) and lower limit (P_{fl}) of chamber pressures are determined by

$$P_{fu} = (1-\sin\phi')\times\gamma' Z_0 + u \qquad \text{in sand} \tag{4}$$

$$P_{fu} = (0.95-\sin\phi')\times\gamma' Z_0 + u \qquad \text{in clay} \tag{5}$$

and

$$P_{fl} = \gamma' Z_0 \tan^2\left(45-\frac{\phi'}{2}\right) - 2c'\times\tan\left(45-\frac{\phi'}{2}\right) + u \tag{6}$$

in which ϕ' is effective friction angle of soil, Z_0 is the depth to centre of tunnel, u is pore pressure and γ' is submerged unit weight of soil. c' is a constant and the value of c' for sand and inorganic silt is zero. For normally consolidated clay, c' can be approximated to zero. Over-consolidated clays have values of c' that are greater than zero. Tables 11 and 12 indicate typical values of c' and ϕ' on Contract CR2. It is noted that ϕ' varies from 29° to 33° here.

The magnitude of the chamber pressure during operation is generally managed between P_{fu} and P_{fl}. In order to effectively indicate the relationship of chamber pressure with other parameters, a chamber pressure coefficient (P_r) is defined by

$$P_r = \frac{P_{fc}}{P_{fu}} \tag{7}$$

in which P_{fc} is the chamber pressure used during construction.

Further, the backfill rate (R_b) is defined by

$$R_b = \frac{V_{fill}}{V_{tv}} \tag{8}$$

where V_{fill} is actual volume of grout used for backfill and V_{tv} is theoretical volume of tail void.

Table 9 Interpreted *K* and *V* for up-line tunnels at CR2

Section	Range of *K*	Average *K*	Range of *V* (%)	Average *V* (%)
MCS-02	0.26 ~ 1.20	0.73	0.10 ~ 0.45	0.28
MCS-03	0.36 ~ 0.85	0.61	0.20 ~ 0.47	0.34
MCS-04	0.30 ~ 0.75	0.53	0.22 ~ 0.55	0.39
MCS-05	0.30 ~ 1.20	0.75	0.14 ~ 0.56	0.35
MCS-06	0.23 ~ 0.60	0.42	0.17 ~ 0.44	0.31
MCS-07	0.47 ~ 0.95	0.71	0.24 ~ 0.48	0.36
MCS-10	0.26 ~ 1.00	0.63	0.61 ~ 2.34	1.48
MCS-11	0.25 ~ 0.65	0.45	0.41 ~ 1.07	0.74
MCS-12	0.23 ~ 0.55	0.39	0.90 ~ 2.15	1.53
MCS-14	0.40 ~ 0.80	0.60	0.61 ~ 1.21	0.91
MCS-15	0.17 ~ 0.65	0.41	0.12 ~ 0.46	0.29
MCS-16	0.27 ~ 0.75	0.51	0.21 ~ 0.59	0.40
MCS-17	0.23 ~ 0.60	0.42	0.34 ~ 0.89	0.29

On CR2, the shield diameter was 6.34 m and the outer diameter of the tunnel was 6.16 m, therefore V_{tv} per ring was 2.12 m^3 and R_b can be thus interpreted with V_{tv} and V_{fill} monitored during construction.

Figures 16 to 18 show the co-relationship between P_r, backfill rate and backfill pressure with *V* obtained at CR2. *V* is based on average *V* at different locations, as shown in Tables 9 and 10. It is seen that P_r is mainly in the range of 0.7 to 0.9, backfill rate varies from 100 to 150% and backfill pressure applied varies from 200 to 500 kPa. Due to limited data, no firm relationship could be established between construction parameters and *V* so further work is needed.

Table 10 Interpreted *K* and *V* for down-line tunnels at CR2

Section	Range of *K*	Average *K*	Range of *V* (%)	Average *V* (%)
MCS-02	0.15 ~ 0.65	0.40	0.13 ~ 0.57	0.35
MCS-03	0.42 ~ 0.65	0.54	0.23 ~ 0.36	0.30
MCS-04	0.30 ~ 0.85	0.58	0.20 ~ 0.56	0.38
MCS-05	0.30 ~ 1.15	0.73	0.23 ~ 0.83	0.53
MCS-06	0.24 ~ 1.30	0.77	0.13 ~ 0.70	0.42
MCS-07	0.60 ~ 1.20	0.90	0.94 ~ 1.87	1.41
MCS-10	0.31 ~ 0.60	0.46	0.26 ~ 0.74	0.50
MCS-11	0.25 ~ 0.62	0.44	0.72- 1.79	1.26
MCS-12	0.28 ~ 0.80	0.54	0.96 ~ 2.74	1.85
MCS-14	0.15 ~ 0.85	0.50	0.13 ~ 0.73	0.43
MCS-15	0.16 ~ 0.80	0.48	0.23 ~ 1.15	0.69
MCS-16	0.35 ~ 1.10	0.73	0.77 ~ 2.41	1.59
MCS-17	0.30 ~ 1.20	0.75	0.55 ~ 2.19	1.37

Table 11 Simplified ground profile and related soil parameters at CR2-LUR10

Layer	Description of ground	Depth	c' (kN/m^2)	ϕ' (degree)
I	Gray silty clay occasionally with silt and sand	Surface to 9.9 m below	0	29
II	Gray silty fine sand occasionally with sandy silt	In the range of 9.9 m to 23.6 m below the ground surface	0	31
III	Gray sandy silt	Beneath 23.6 m below the ground surface	0	33

Table 12 Simplified ground profile and related soil parameters at CR2-LUR12

Layer	Description of ground	Depth	c' (kN/m^2)	ϕ' (degree)
I	Silty sand with sandy silt and silty clay. Backfill materials are observed on surface in some locations.	Surface to 9.0 m below	0	29
II	Silty sand	In the range of 9.0 m to 31.5 m below the ground surface	0	31
III	Silt	Beneath 31.5 m below the ground surface	0	33

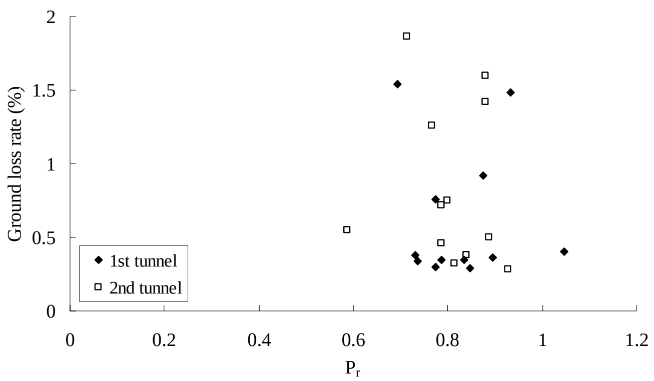


Fig. 16 The relationship between P_r and ground loss rate

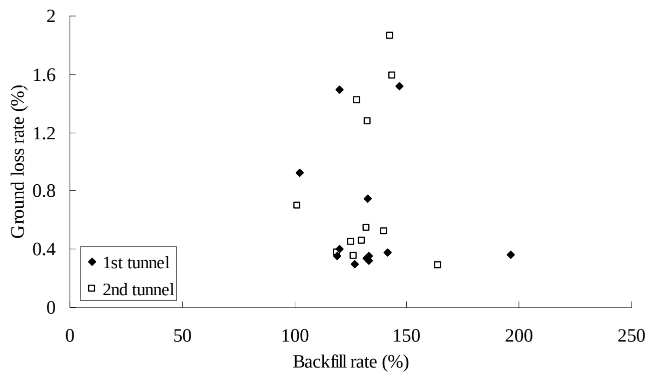


Fig. 17 The relationship between backfill rate and ground loss rate

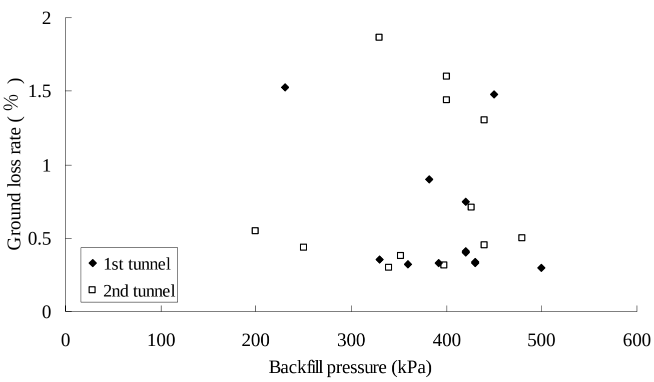


Fig. 18 The relationship between backfill pressure and ground loss rate

5. CONCLUSIONS

Shield-machine bored tunnels have been widely used for different purposes in urban areas. However, investigation of the ground behaviour induced by shield-machine bored tunnels in sand is very limited. A complete case record has been prepared in this paper based on tunnels on the Kaohsiung Metro system, Contract CR2. In this paper, time history of surface settlement is explored first. Observations show that driving the first bored tunnel induces up to 20 mm of surface settlement. The surface settlement might be further affected by construction of a second, adjacent tunnel and the accumulated maximum surface settlement may increase to 40 mm. Ground becomes stable 20 to 40 days after the shield has passed but construction of cross-passages or excavation of adjacent open-cut stations could induce further settlements. No consolidation settlement was observed in tunnels on CR2.

The transverse surface settlement trough at CR2 was also measured and discussed in this paper. The individual maximum surface settlement (δ_{max}) induced by a single tunnel could reach up to 22.4 mm. Back-analyses indicate that excavation of tunnels generates approximately 0.31 to 1.85% of V and 0.4 to 0.9 of K. In addition, the driving of the 2nd tunnel did not induce significantly more movement than the 1st tunnel at some places which is not consistent with observations of Peck (1969). This might be due to an improved operation of the shield-machine.

Three construction parameters for shield-machine bored tunnels, chamber pressure coefficient (P_r), backfill rate and backfill pressure are calculated and discussed. It is observed that P_r is mainly in the range of 0.7 to 0.9, backfill rate varies from 100 to 150% and backfill pressure applied varies from 200 to 500 kPa. The relationship between these parameters and V is also evaluated. However, due to limited data, no firm relationship could be established between construction parameters and V so further work is needed.

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