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# Lessons learnt from unusual ground settlement during Double-O-Tube tunnelling in soft ground



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## ABSTRACT

The DOT (Double-O-Tube) tunnelling method has been adopted in the construction of various types of tunnels in soft ground both in Japan and in China. Recently, an unexpected ground surface settlement of approximately 0.8 m was observed in a DOT construction site in Shanghai, China. The backfill grouting injection rate had to be increased by up to 500% to control the settlement. In order to find out the reasons for the large settlement, and to reduce it to an acceptable level, in-situ monitoring, including surface settlement and subsurface settlement, was undertaken to obtain the change in ground deformation during DOT machine driving. It was found that the conventional settlement control methods, such as adjusting the earth pressure balance on the cutter face, and simultaneous backfill grouting at a normally acceptable injection rate, could not reduce the large settlement. It was also noticed that the settlement started as the DOT machine was passing, as well as after the tail had passed through. Subsequent field investigations found cement accumulation attaching to the skin plate. This was due to improper backfill grouting at the early construction stage, and the concave shape of the DOT machine. The mechanism for large settlements due to improper immediate backfill grouting was analysed. After taking countermeasures, the ground settlement was reduced to approximately 0.02 m.

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## 1. Introduction

The DOT (Double-O-Tube) tunnelling method can be employed to construct two tunnels simultaneously using one shield machine. It provides economic advantages by shortening construction time and reducing discharged soil volume. After its first application in Japan in 1989, it has been adopted successfully in the construction of several types of tunnels in soft ground, both in Japan (Moriya, 2000; Sakakibara and Watanabe, 2001; Koyama, 2003) and in China (Chow, 2006). Unexpectedly, a ground settlement of approximately 0.8 m took place during DOT tunnelling in Shanghai recently. The aim of this paper is to clarify the mechanism of this unusual settlement and to suggest countermeasures.

Due to the large cutter face and the two interlocking spoke-type cutters, the ground settlement and the rolling associated with DOT machines have been the main focus of attention for engineers. In

Japan, most of the DOT tunnels have been constructed in hard ground, such as silty sand in Hiroshima city, and sandy ground in Nagoya city (The Shield Tunnelling Association of Japan, 2004). A multipurpose underground utility conduit (Yokoyama and Yonei, 1995) in the Ariake-kita district of the Tokyo metropolitan area was constructed in diluvial cohesive soil using a large diameter DOT machine (9.36 m in diameter and 15.86 m in width). The ground conditions were the softest of those investigated, but were more suited to DOT tunnelling than those of Shanghai. The in-situ monitoring data in Tokyo showed that the final ground surface settlement was around 0.02 m. A part of the Taoyuan International Airport Access MRT (Mass Rapid Transit) in Taiwan (Fang et al., 2012) was constructed in silty sand and silty clay layers using a DOT machine 6.42 m in diameter, and 11.62 m in width. The observed maximum settlement during the construction period was less than 0.04 m.

In Shanghai, the subsoils up to a depth of 30 m are soft silty clays. The ground conditions are difficult for single-circular shield tunnelling (e.g., Wang, 1982; Xu et al., 2011; Shen et al., 2014; Bai et al., 2014), as well as for DOT tunnelling. Parts of Shanghai Metro Lines M8 (2003–2004) and M6 (2004–2005) were

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constructed using a DOT machine. Since then, settlement and rolling problems have been the biggest challenge for DOT engineers (Shen et al., 2009, 2010). Chow (2006) summarised the construction experiences of the M8 Line and concluded that the maximum ground surface settlement, and the width of the ground surface settlement trough, were almost equal to that created by two single circular shield tunnels. Gui and Chen (2013) also found similar results for the Taiwan DOT project. Based on the monitoring data for the utility conduit in Tokyo and the Shanghai M6 Line, Yokoyama and Yonei (1995), Sun (2007) suggested that the DOT-induced ground settlement can be approximated to that resulting from a single-circular tunnel which has the same cross-sectional area. The general settlement over Shanghai metro tunnels (diameter 6.34 m, single-circular) during construction was less than 0.03 m. The settlement of a 15.43 m diameter shield tunnel in Shanghai was around 0.05–0.06 m (Wu et al., 2010). According to the above approximation methods, the estimated DOT-induced settlement should be around 0.06 m. This is consistent with the typical observed settlement of 0.04 m (<1% volume loss) for the M8 and M6 Lines (Chow, 2006; Sun, 2007). Apart from the collapse of a Shanghai metro tunnel due to an accident in 2003 (Xu et al., 2009), no reports of large settlements over 0.1 m during tunnelling construction have been recorded in Shanghai.

In this paper, a systematic in-situ monitoring programme, including ground surface settlement and subsurface settlement, was carried out to investigate the mechanism of the unusual settlement observed during DOT tunnelling. The major factors, such as the earth pressure balance on the cutter face and the backfill grouting, are analysed carefully. The countermeasures are also provided.

## 2. Background

In preparation for the 2010 Shanghai World Expo, Shanghai Metro Line 2 was expanded east to the Pudong International Airport. The length of the extension line is 29.9 km. Three sections (CS-A, -B, and -C) were constructed by the DOT method, as shown in Fig. 1. The construction commenced on July 2007, and was completed by the end of 2009.

Three earth pressure balance DOT machines (Fig. 2) with a spoke-type cutter face were used in the three sections. The shield machine was 6.52 m in diameter and 11.12 m in width and the tunnel was 6.30 m in diameter and 10.90 m in width. Reinforced



Fig. 2. DOT machine used in the construction of the Shanghai Metro.

concrete segments were assembled in a stagger-jointed arrangement. Each ring was separated into 8 segments. The thickness and the width of the segments were 300 mm and 1200 mm, respectively.

A simultaneous backfill grouting system with a two-component grouting liquid was employed in the DOT machines. The simultaneous backfill grouting was carried out in shield tunnelling for the first time in 1982 in the construction of the No. 4 line of the Osaka Subway in Japan, and has been proven to be an effective measure for reducing shield-induced settlement in soft ground (Hashimoto et al., 2004). Two simultaneous backfill grouting pipes (35 mm dia.) were installed in the top and bottom concave 'seagull' (the V shape formed at the centre of the DOT where the two tubes meet) respectively, with one pipe in each 'seagull'.

It is important to highlight two factors relating to the research topic. Firstly, the DOT machines had previously been used in the construction of the Shanghai Metro Line M8 (2003) and Line M6 (2004). They were reused in the current project after a basic and hurried maintenance. In the first few months, the advance of the TBM had to be stopped frequently for the repair or replacement of worn parts, such as sensors, valves and hydraulic tubes, and due to the simultaneous backfill grouting pipes becoming blocked. Secondly, since many tunnels were undergoing construction

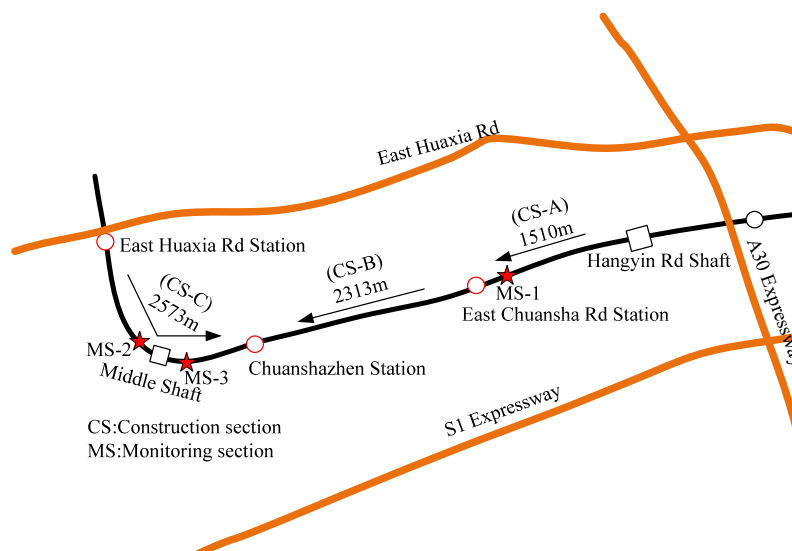


Fig. 1. Layout of tunnels constructed by DOT in the eastward extension of Shanghai Metro Line 2.

**Table 1**

General information for three DOT tunnels before field investigation.

Construction section	(CS-A) Hangyin Rd shaft ~ East Chuansha Rd	(CS-B) East Chuansha Rd ~ Chuanshazhen	(CS-C) East Huaxia Rd ~ Chuanshazhen
Contractor	S company	S company	J company
TBM manufacturer	IHI	Mitsubishi	IHI
Backfill grouting	Two-liquid, from segment, up to 20 m <sup>3</sup> /ring max.	Two-liquid, from segment, 6–8 m <sup>3</sup> /ring	Two-liquid, from segment, 6–8 m <sup>3</sup> /ring
Earth pressure balance at cutter face	$\lambda = 0.8–0.9$ $\lambda$ is the coefficient of lateral earth pressure in terms of total stress	$\lambda = 0.8–0.9$	$\lambda = 1.3–1.4$ (malfunctioning pressure gauges)
Advancing speed	6–10 rings/day	4–6 rings/day	8–10 rings/day
Max. ground settlement	0.5 m	<0.1 m	0.8 m

**Table 2**

Factors in ground deformation due to shield tunnelling.

Stage	Factors
(1) 1D before cutter face arrives	The imbalance between the lateral earth pressure and the chamber pressure of the machine
(2) Shield machine passing through	Mainly the friction between the shield machine and the ground, and the overcut in curved advancing
(3) 1D after tail passes	Settlement due to stress release by tail void or heaving due to the excessive backfill grouting pressure
(4) Long-term settlement	Mainly due to the consolidation of the disturbed soil

Note: D is the overburden of tunnel.

during that period in preparation for the World Expo 2010, there was a lack of qualified operators and labourers, particularly for the DOT. These factors placed additional risks on the tunnelling operation.

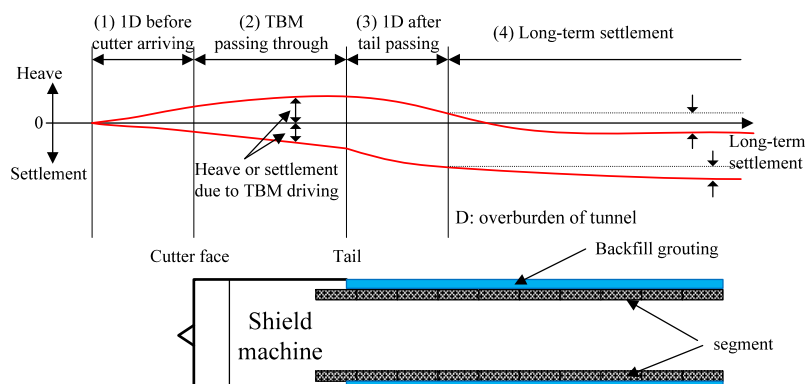
After advancing several hundred metres, unusual settlements, up to 0.8 m, were reported from CS-A and CS-C. The ground conditions, the TBM machines and the construction methods were similar in all three sections, as summarised in Table 1. Both contractors (J company and S company) had successful experience in M8 and M6 DOT tunnel construction. The settlement at CS-B was less than 0.1 m, and the backfill injection rate was 150–200% of the theoretical volume of the tail void. This required the injection of 6–8 m<sup>3</sup>/ring. Compared to the theoretical tail void of 4 m<sup>3</sup>/ring, a backfill injection rate of 6–8 m<sup>3</sup>/ring was acceptable in Shanghai soft ground. At CS-A, the backfill injection rate was increased to 500% (20 m<sup>3</sup>/ring) when passing through the settlement restricted locations. Since the TBM machine had to pass below a 6-storey building in the second half of CS-C, it was essential to carry out field investigations and in-situ monitoring to clarify the mechanism of such unusual large settlement, and this is described below.

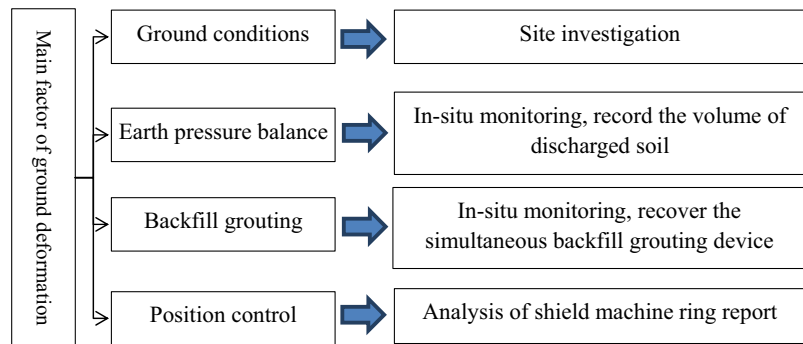
### 3. Outline of investigation

The DOT method is a multi-face shield tunnelling method. The basic mechanism of ground deformation during DOT shield tunnelling is the same as that when using a conventional single-face machine. The deformation stages and the major factors are shown in Fig. 3 and Table 2. The unbalanced earth pressure on the cutter face (1), the skin plate friction and position control (2), the tail void grouting (3) and the consolidation of disturbed soil (4), are the main factors in ground deformation. As the large settlement occurred in the construction stage in this Shanghai DOT project, factor (4) is excluded. Therefore, the investigation was focused on factors (1)–(3) and on the ground conditions. In-situ monitoring of ground surface settlement and subsurface deformation, and analysis of shield machine ring reports were carried out in the investigation, as shown in Fig. 4. Due to the blockage of the simultaneous backfill grouting pipes inside the skin plate, and the unworkable pumps, immediate backfill grouting (injection from the grouting holes of the segments) was used in the three DOT tunnels, as shown in Fig. 5. Immediate backfill grouting is considered to be one of the major factors in reducing ground settlement in modern shield tunnelling (Research Association on New Shield Tunneling Technology, 1998).

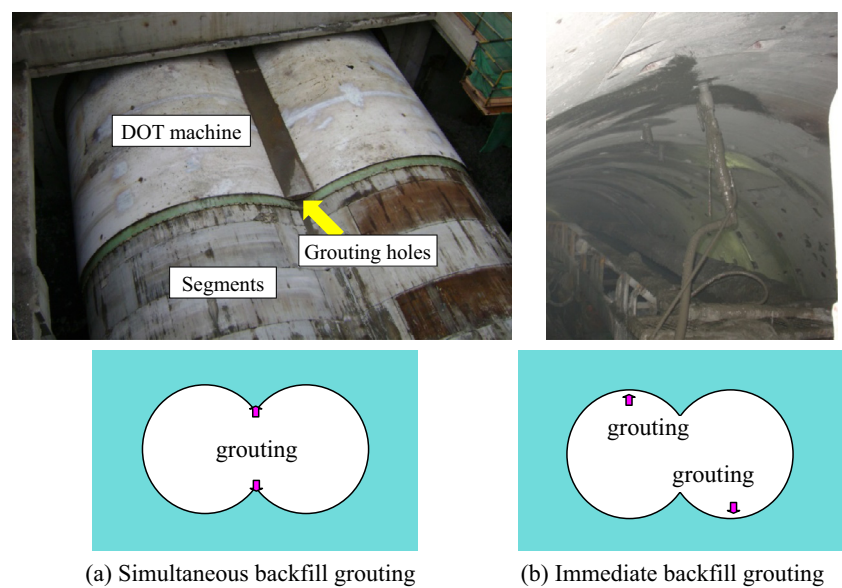
### 4. Ground conditions

The subsoils along the tunnel are mainly soft Shanghai clays comprising quaternary alluvial and marine deposits (Wu et al., 2014). In the Shanghai area, the soil layers are almost horizontally deposited (Chen et al., 2013a, 2013b). Site investigations with borehole sampling had been done for the project. These showed that there was no noticeable difference between the three construction sections. The detailed engineering properties of the soils in the construction site are given in Table 3. In general, the soil

**Fig. 3.** Mechanism of ground deformation due to shield tunnelling (after Hashimoto et al., 1999).



**Fig. 4.** Main factors of ground deformation in DOT tunnels and the corresponding investigation scheme.



**Fig. 5.** Backfill grouting of DOT machine.

**Table 3**  
Engineering properties of soils along the DOT tunnels.

Soil layer name	$\gamma$ (kN/m <sup>3</sup> )	$e_0$	$w_n$ (%)	$w_l$ (%)	$w_p$ (%)	$c_{cu}$ (kPa)	$\phi_{cu}$ (°)	$c_{u(v)}$ (kPa)	SPT-N	$S_t$
2. Silty clay	18.5	0.914	31.9	36.2	20.3	19	20.6	49.6	2.0	4.1
3. Soft silty clay	17.6	1.133	40.1	34.9	20.1	12	18.9	28.4	0.8	4.0
3-T. Sandy silt	18.5	0.854	29.8						7.3	
4. Very soft silty clay	16.7	1.426	50.2	44.4	23.5	12	13.3	31.3	1.2	4.4
5–1. Clay	17.3	1.229	42.9	42.5	22.4	15	15.8	52.4	3.4	4.4
5–3. Hard silty clay	17.9	1.023	35.2	36.1	20.7	18	19.6		5.1	

Note:  $\gamma$  = unit weight;  $e_0$  = void ratio;  $w_n$  = natural water content;  $w_l$  = liquid limit;  $w_p$  = plastic limit;  $c_{cu}$  = cohesion of consolidated undrained triaxial compression test;  $\phi_{cu}$  = friction angle of consolidated undrained triaxial compression test;  $c_{u(v)}$  = shear strength obtained from field vane shear test; SPT-N = number of Standard Penetration Test;  $S_t$  = sensitivity obtained from field vane shear test.

surrounding the tunnels is very soft silty clay with a Standard Penetration Test value (SPT-N) < 2. The ground water level is about 0.5–1.0 m below the ground surface.

### 5. In-situ monitoring of ground deformation

Based on the construction schedule and the site conditions, three monitoring sections were instrumented to study the DOT induced ground movement. The locations of the three monitoring sections are shown in Fig. 1.

- (1) Monitoring section 1 (MS-1) was located at Ring No. 1014 within the CS-A section (Hangyin Rd shaft to East Chuansha Rd), which was to be constructed first. The earth pressure balance on the cutter face was adjusted to achieve a good balance. In addition, a simultaneous backfill grouting with a normal grouting volume of 6–8 m<sup>3</sup>/ring was tested.
- (2) Monitoring sections 2 and 3 (MS-2, MS-3) were located at Ring Nos. 983 and 1162 of the CS-C section (East Huaxia Rd to Chuanshazhen) respectively. There was a middle shaft for ventilation in CS-C. After the cause of the large settlements was discovered, countermeasures were carried out



in the shaft. In addition to the monitoring in MS-1, MS-2 was used to analyse the features of the ground response caused by the planned shield driving parameters. MS-3 was used to check the effect of the improved shield driving.

Accordingly, both the ground surface settlements and subsurface ground movements were monitored in MS-1 and MS-2, while only the ground surface settlements were monitored in MS-3. The ground profiles and instrumentation of MS-1 and MS-2 are shown in Figs. 6 and 7. The ground profile of MS-3 is almost the same as that of MS-2; there is only a slight difference of 0.1–0.2 m between the thicknesses of soil layers of the two sections.

Magnet extensometers were installed to measure the subsurface deformation in MS-1 and MS-2. Magnetic rings for settlement in the ground (symbol  $\blacklozenge$  in the figures) were installed inside the bored holes at an interval of 2 m. The positions and lengths of the extensometers are shown in Figs. 6 and 7. Three extensometers were placed above the centre line and the two axial lines of the tunnels. The fourth extensometer was installed on the side of the tunnel at a distance of 1 m from the tunnel. As discussed later, the PVC (Polyvinyl chloride) pipes of the extensometers in MS-1 were destroyed by the large deformation, and so two improvements were applied in MS-2. Firstly, more flexible PE (Polyethylene) pipes were used instead of PVC ones. Secondly, the space between the bottom of the extensometers and the shield machine, which was 1 m in MS-1, was increased to 2 m in MS-2.

Ten rows of ground surface settlement gauges were placed before and after each monitoring section. The relative positions of each row of settlement gauges to the tunnel were the same as the caps of the extensometers: two gauges above the axial lines of the two tunnels, and another gauge at the edge of the tunnel.

The distance between the two adjacent rows was approximately 3 m. In total, 30 gauges were set up in each monitoring section.

## 6. Monitoring results in MS-1 and MS-2

In this section, the in-situ monitoring data from MS-1 and MS-2, together with the construction data is analysed.

### 6.1. Construction data

The shield driving data for 70 rings (Ring Nos. 960–1030) around the monitoring section MS-1 (Ring No. 1014) is summarised in Fig. 8 and Table 4. The earth pressure on the cutter face and the backfill grouting were adjusted at 4 steps (marked as 'i'–'iv' in Fig. 8) based on the monitoring results.

- (1) The earth pressure at the middle of the left chamber was a reference for the shield operation. The earth pressure was 245 kPa initially, then reduced to 210 kPa at Ring No. 987 (marked as 'i' in the figure), and further reduced to 190 kPa at Ring No. 998 (marked as 'ii'), becoming much closer to the theoretical value of 183 kPa at the middle of the chamber. The theoretical earth pressure is calculated using the coefficient of lateral earth pressure in terms of total stress,  $\lambda = 0.8$ .
- (2) The simultaneous backfill grouting device was repaired and put back into operation at Ring No. 1003 (marked as 'iii'). Prior to this, the grouting was injected from two points at the segment immediately after the segment passed through the last tail brush (approximately the 3rd to the 5th segment). Two injection points were located at the top left

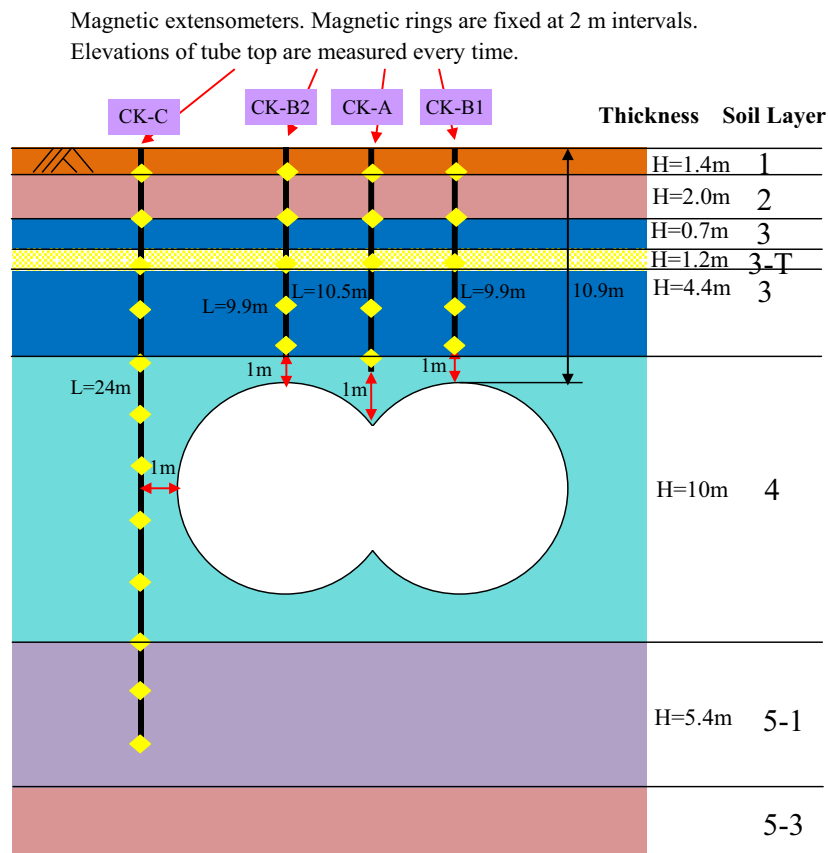


Fig. 6. Ground profile and instrumentation in monitoring section MS-1.

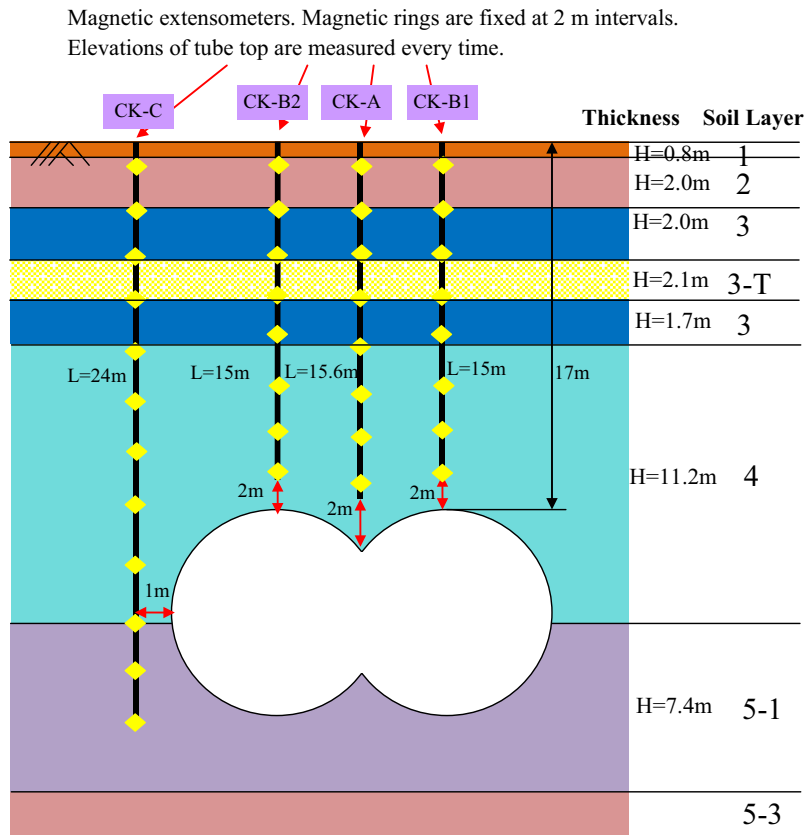


Fig. 7. Ground profile and instrumentation in monitoring section MS-2 (Note: ground profile in MS-3 is the same).

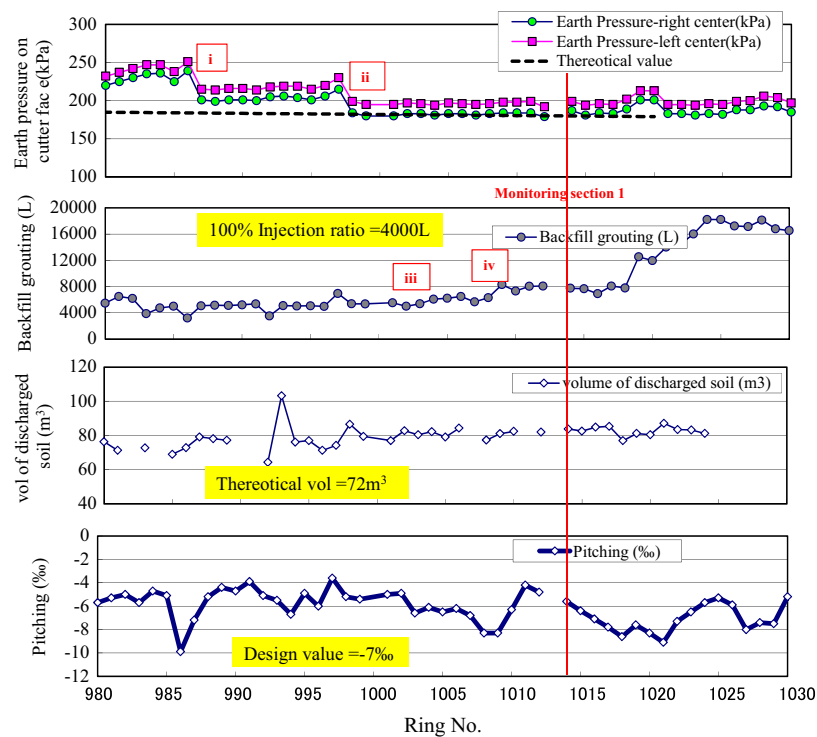


Fig. 8. Shield machine data at monitoring section MS-1 (i–iv are four major construction conditions. (i) Ring #987, earth pressure reduced to 210 kPa. (ii) Ring #998, earth pressure reduced to 190 kPa. (iii) Ring #1003, backfill grouting method changed from immediate to simultaneous, injected 6 m<sup>3</sup>/ring from top only. (iv) Ring #1008, backfill grouting volume increased from 6 m<sup>3</sup>/ring to 8 m<sup>3</sup>/ring, 6 m<sup>3</sup> from top, 2 m<sup>3</sup> from bottom).

**Table 4**

Key construction information for MS-1 and MS-2 during in-situ monitoring.

Monitoring section	MS-1 (refer to Fig. 8)	MS-2
Earth pressure balance at cutter face	Before Ring No. 987: 245 kPa. Reduced to 210 kPa at Ring No. 987 (marked as 'i' in Fig. 8). Further reduced to 190 kPa at Ring No. 998 (marked as 'ii')	Determined by trial-and-error at the early construction stage, due to malfunctioning earth pressure gauge
Backfill grouting	Two-liquid. Backfill grouting method changed from immediate to simultaneous, injected 6 m <sup>3</sup> /ring from top only. iv: Ring #1005, backfill grouting volume increased from 6 m <sup>3</sup> /ring to 8 m <sup>3</sup> /ring, 6 m <sup>3</sup> from top, 2 m <sup>3</sup> from bottom). Before Ring No. 1003 (marked as 'iii'): 150% (6 m <sup>3</sup> /ring). Increased to 200% (8 m <sup>3</sup> /ring) at Ring No. 1008 (marked as 'iv')	Two-liquid, from segment, 300% (12 m <sup>3</sup> /ring)
Discharged soil volume	Theoretical value = 72 m <sup>3</sup> /ring. Increased gradually from 72 m <sup>3</sup> /ring to 82 m <sup>3</sup> /ring (volume loose ratio = 1.2–1.45 for soft soils)	/
Position control	The pitching was close to the design value, and the rotation was small	/

and bottom right of the tunnel (position is defined as face towards the machine advancing direction). It was thought that this kind of injection method could reduce the rotation of the whole tunnel. A two-component grouting with a gel time of less than 10 s was used. Since an optimal backfill injection rate (equal to the volume of grouting per ring/volume of tail void per ring  $\times 100\%$ ) of 150% was used in the M8 and M6 Lines (Zhang et al., 2006), the backfill grouting rate was 150% (6 m<sup>3</sup>/ring) initially. It was then increased to 200% (8 m<sup>3</sup>/ring) at Ring No. 1008 (marked as 'iv'), higher than the theoretical backfill void of 4 m<sup>3</sup>/ring.

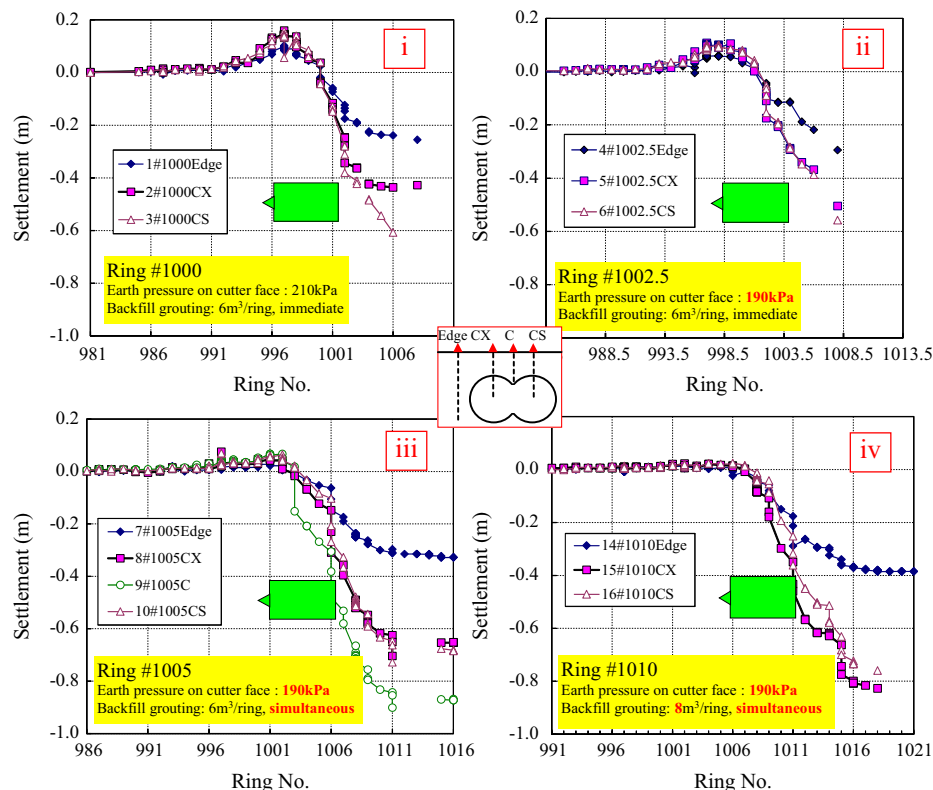
The shield driving data around monitoring section MS-2 (Ring No. 983) were slightly different, as shown in Table 4. The earth pressure gauges that were situated at the level of the tunnel springline were malfunctioning. The earth pressure was determined by trial-and-error at the early construction stage. Since the simultaneous backfill grouting pipes were clogged, the

grouting was injected from the grouting holes at the 3rd to the 5th segment. The backfill grouting rate was increased from 200% to 300% (12 m<sup>3</sup>/ring) under instruction.

## 6.2. In-situ monitoring results

Figs. 9–11 show the in-situ monitoring results. The horizontal axis of these figures is the ring number of the segment being assembled at the time of settlement measurement. Since the width of one ring is 1.2 m, the horizontal axis also represents the relative distance between the assembled segment and the monitoring section. The relative distance between the cutter face, the tail void and the monitoring section can also be obtained by plotting a schematic shield machine on the figure at the correct scale and position.

Fig. 9 shows the change in observed ground surface settlements around MS-1, corresponding to the four construction conditions shown in Fig. 3. The vertical axis is the settlement value. The



**Fig. 9.** Observed ground surface settlements at monitoring section MS-1 versus distance under different construction conditions. i–iv correspond to the construction conditions noted in Fig. 8. (Ring #xxxx: the location of the settlement gauges; Edge: 1 m to the left edge of tunnel; CX: left centre line; CS: right centre line).



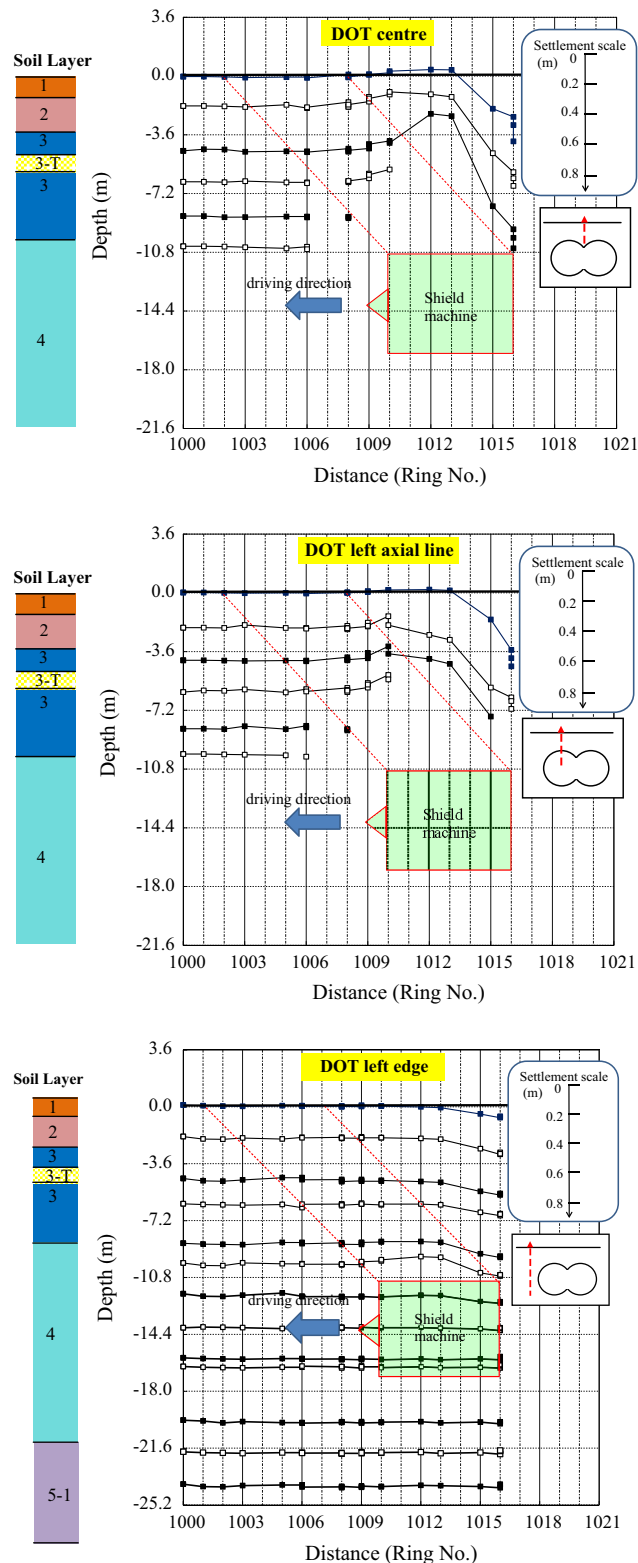


Fig. 10. Observed subsurface ground vertical deformation versus distance (monitoring section MS-1).

position of the shield machine is plotted in the figure. The ground surface settlement gauges at Ring No. 1000 showed that a heave of 0.15–0.18 m was observed under an earth pressure of 210 kPa. The heaving decreased gradually to almost zero after the earth pressure was reduced to 190 kPa (theoretical value is 183 kPa). However, after the cutter face had passed by, the ground surface began to

settle down dramatically. The large settlement still continued even after increasing the volume of simultaneous backfill grouting to 8 m<sup>3</sup>/ring (equivalent to 200% of the calculated tail void). These data indicate that neither the earth pressure balance on the cutter face nor the backfill grouting were the main reason for the large settlement.

Fig. 10 shows the subsurface settlement of MS-1. The magnet extensometer positioned at the right axial line was broken before the TBM arrived, so only the data from the other three extensometers are analysed. The vertical axis is the depth below the ground surface. The settlement scale, position of the shield machine, ground profile, and the 45° influence lines of the cutter face and the tail void are plotted in the figure. The subsurface settlements are from a single line of extensometers at the monitoring section MS-1, and they are plotted against the advancing distance of the shield machine, rather than time. (1) The subsurface ground began to heave immediately before the cutter face arrived. The observed heaving in the DOT centre line was +0.077 m at the depth of –6 m, and 0.02 m at the ground surface. (2) The ground continued to heave while the first half of the TBM was passing. The maximum heave was +0.209 m at a depth of –4 m along the DOT centreline. Since some of the gauges below –4 m were destroyed, the heave in the region should have been greater than 0.209 m. The heave at the left edge was 0.0475 m, and it was much less on the ground surface. (3) The ground settled down in the rear half of the TBM machine. The maximum observed displacement was 0.824 m (heave of +0.209 m and settlement of –0.615 m) at a depth of –4 m in the DOT centre, leading to a final settlement of 0.615 m. All extensometer pipes were destroyed when the tail void passed through and no further data were available. (4) The maximum heave or settlement occurred in the DOT centre, where it was above the concave ‘seagull’ segment. The most unexpected phenomenon was the heaving and settlement whilst the TBM machine was passing through. Experience of shield tunnelling in soft ground suggests that ground heave is usually due to excessive earth pressure on the cutter face or redundant backfill grouting. However, neither of these factors will generate heave in the ground above the body of the TBM machine.

Fig. 11 shows the subsurface settlement in MS-2. The ground surface settlements in the DOT centre, the axial lines of the two tunnels, and the edge were 0.79 m, 0.73 m and 0.41 m, respectively. The main characteristic of ground deformation in this section is that the settlement did not take place until the tail had passed or was passing by.

- (1) Before the cutter face arrived, no obvious deformation could be seen in the ground, indicating that the chamber earth pressure was well balanced.
- (2) While the TBM machine was passing by, no obvious deformation could be seen. It seems that the ground within 2 m above the tunnel was not affected by the friction of the skin plate.
- (3) Immediately after the tail had passed by, a maximum upheaval of 0.167 m took place 2 m above the seagull segment (in the DOT centre). This upheaval was the consequence of immediate grouting. However, the ground 3 m above the tunnel remained unchanged and the ground 5 m above the tunnel began to settle. It is interesting to note that the ground at the right edge also began to subside. The magnet rings close to the tunnel were destroyed during this rapid deformation.
- (4) At a distance of two rings after the tail had passed by, the ground above the tunnel subsided. A maximum settlement of 0.92 m was observed 5 m above the DOT centre. At Ring No. 1000, the ground 5 m above the tunnel heaved several centimetres which was caused by the supplementary grouting from the segment.

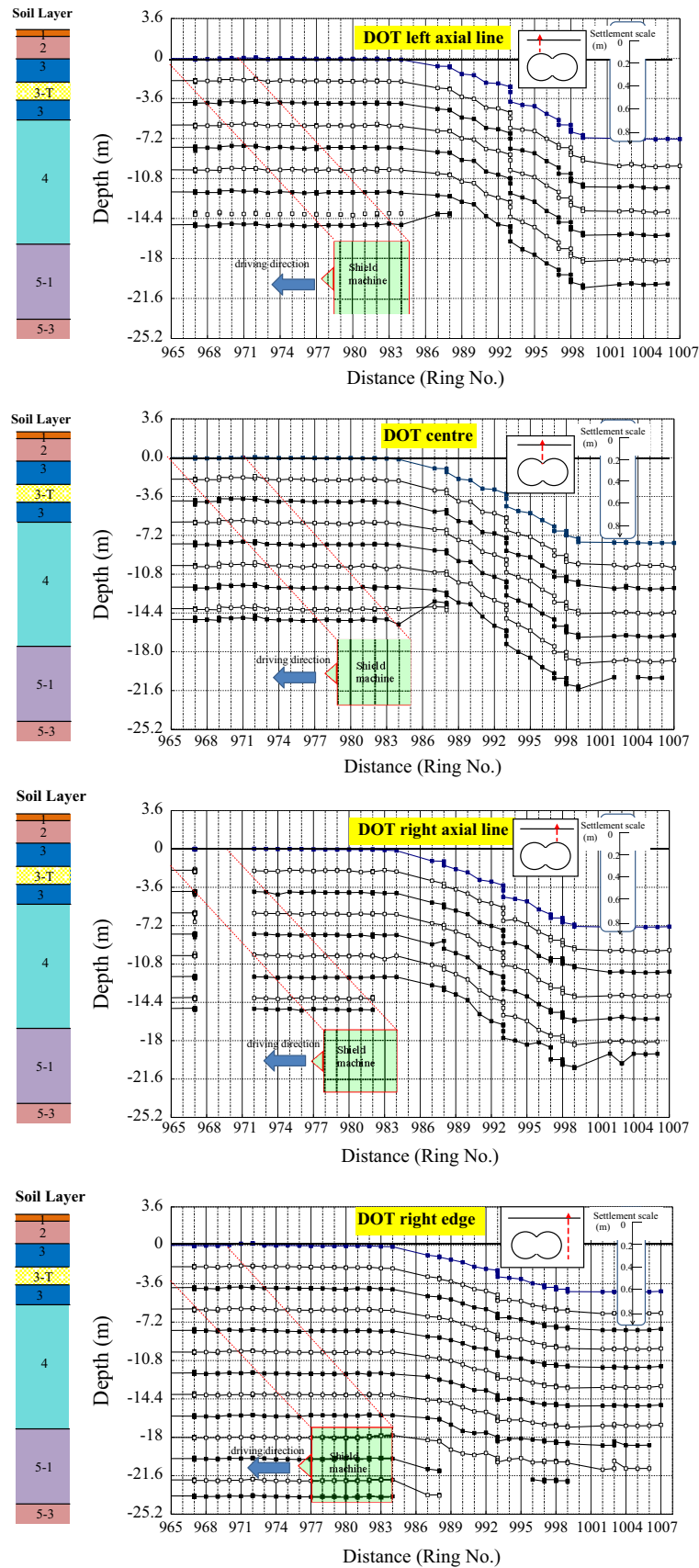


Fig. 11. Observed subsurface ground vertical deformation versus distance (monitoring section MS-2).

- (5) It can be seen that the settlements above the tunnel centre and the two tunnel axial lines were very close in magnitude, while those at the edge were reduced to half of these amounts. All settlements seemed to stop 16 rings after the tail had passed by.

Fig. 12 shows the observed ground surface settlement troughs at MS-1 and MS-2. The ground surface settlement trough induced by DOT tunnelling can be estimated using Peck's empirical equation (Peck, 1969) with the equivalent circle method (Gui and Chen, 2013). In Fig. 12, a theoretical settlement trough obtained using Peck's equation was plotted. Peck's empirical equation is:

$$S(x) = S_{\max} \exp\left(\frac{-x^2}{2i^2}\right) \quad (1)$$

$$S_{\max} = \frac{V_{\text{loss}}}{i\sqrt{2\pi}} \quad (2)$$

where  $S(x)$  is the ground surface settlement at a distance  $x$  from the tunnel centre;  $S_{\max}$  is the maximum ground surface settlement at the tunnel centre;  $V_{\text{loss}}$  is the ground volume loss, which normally is calculated from the tail void volume; Parameter  $i$  is the distance from the tunnel centre line to the point of inflexion of the trough. This parameter controls the width of the settlement trough. The tail void volume and the parameter  $i$  were determined by the best fitting curve method with the observed settlements. For MS-1,  $V_{\text{loss}} = 11.2 \text{ m}^3$ ,  $i = 5.5 \text{ m}$ ; For MS-2,  $V_{\text{loss}} = 12.5 \text{ m}^3$ ,  $i = 6.5 \text{ m}$ . It can be estimated from the figures that the widths of the settlement troughs are approximately 40–50 m. The widths are almost twice those of the monitoring data recorded in the M8 Line (Chow, 2006) and the M6 Line (Sun, 2007), but are close to the data recorded in the Taoyuan International Airport Access Mass Rapid Transit system in Taipei (Gui and Chen, 2013).

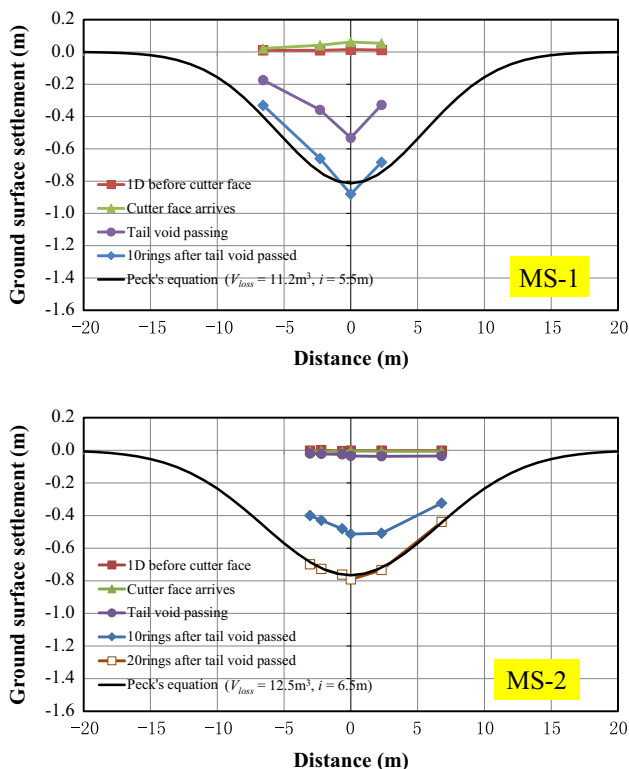


Fig. 12. Observed ground surface settlement troughs at MS-1 and MS-2.

## 7. Mechanism of unusual settlement due to DOT tunnelling

In this section, the major factors listed in Table 2 will be analysed with the in-situ monitoring results.

### 7.1. Unbalanced earth pressure on the cutter face

Monitoring results of subsurface settlement indicated that the earth balance on the cutter face in MS-1 was slightly excessive. However, the monitoring in MS-2 confirmed that this was not the main factor for the large settlement.

### 7.2. Skin plate friction and position control

Normally the friction force is distributed uniformly across the skin plate. It imposes a shearing effect on the surrounding soils. The shearing can disturb the soils and lead to a long-term settlement in soft ground, but a large heave or settlement, as was observed in the first half of the TBM machine in MS-1, is not likely to have been induced by the skin plate friction alone. The position control (pitching, yawing and rolling) was within the design values, and no overcut was conducted during the period of monitoring. These are also unlikely to be the cause of the large deformation.

### 7.3. Tail void grouting

Tail void grouting was considered at first to have been the most likely factor to be responsible for the large settlement. However, monitoring data showed that neither simultaneous backfill grouting with an injection rate of 150% and 200% in MS-1, nor immediate backfill grouting with an injection rate of 300% in MS-2 had any effect on reducing the settlement. Furthermore, the settlement had already started before the tail passed by in MS-1. The tail void grouting is also unlikely to be the main cause of settlement.

Therefore, there are likely to be some other unconventional reasons for the unusual settlement. It was observed that (1) the large

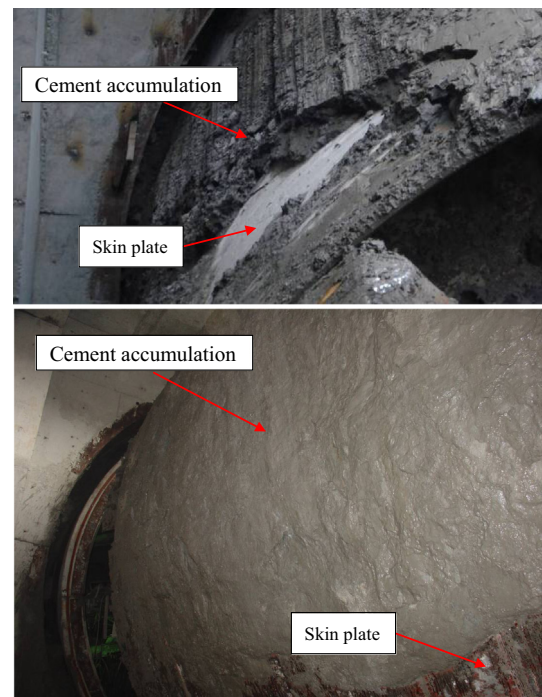


Fig. 13. Cement accumulation attached on the skin plate.

heaving and settlement developed as the first half of the TBM machine passed by MS-1; (2) The same magnitude of settlement took place after the tail had passed by in MS-2 without any preceding deformation and (3) A backfill grouting of 20 m<sup>3</sup>/ring (injection rate = 500%) was only just enough to control the ground settlement. In addition, the ground conditions were not largely different from other areas in Shanghai. This indicates that (1) the void volume is five times that of the design tail void; and (2) settlement can start while the TBM machine is passing by, not only after the tail has passed through. Therefore, the void is not induced by the physical tail void.

After the DOT shield machine entered a middle shaft, it was found that a layer of cement-like accumulation had attached onto the skin plate (Fig. 13). The maximum thickness of the accumulation was about 0.2 m. From an analysis of the accumulation, it was deduced that it had been cut by the entrance into the shaft.

It is described in section 6.1 that the volumes of backfill grouting in MS-1 and MS-2 were 8 m<sup>3</sup> and 12 m<sup>3</sup> per ring, respectively. It is also explained in section 6.2 that the ground volume losses of MS-1 and MS-2 were 11.2 m<sup>3</sup> and 12.5 m<sup>3</sup>, per ring respectively. Accordingly, the tail void volumes of MS-1 and MS-2 were 19.2 m<sup>3</sup> and 24.5 m<sup>3</sup>. The equivalent tail void heights of the two monitoring sections were  $h_{MS-1} = 0.31$  m and  $h_{MS-2} = 0.39$  m. Therefore, the original thickness of accumulation was speculated to be at least 0.3–0.4 m. The staff of the construction company confirmed that no other material had been added to the ground during the shield excavation, other than the bentonite slurry in the chamber and the backfill grouting. Therefore, the accumulation should be the cementation of the two-component backfill grouting.

The mechanism for the large ground settlement is illustrated in Fig. 14. (1) After the simultaneous backfill grouting pipes became clogged, the grouting was injected from the 3rd to the 5th ring of

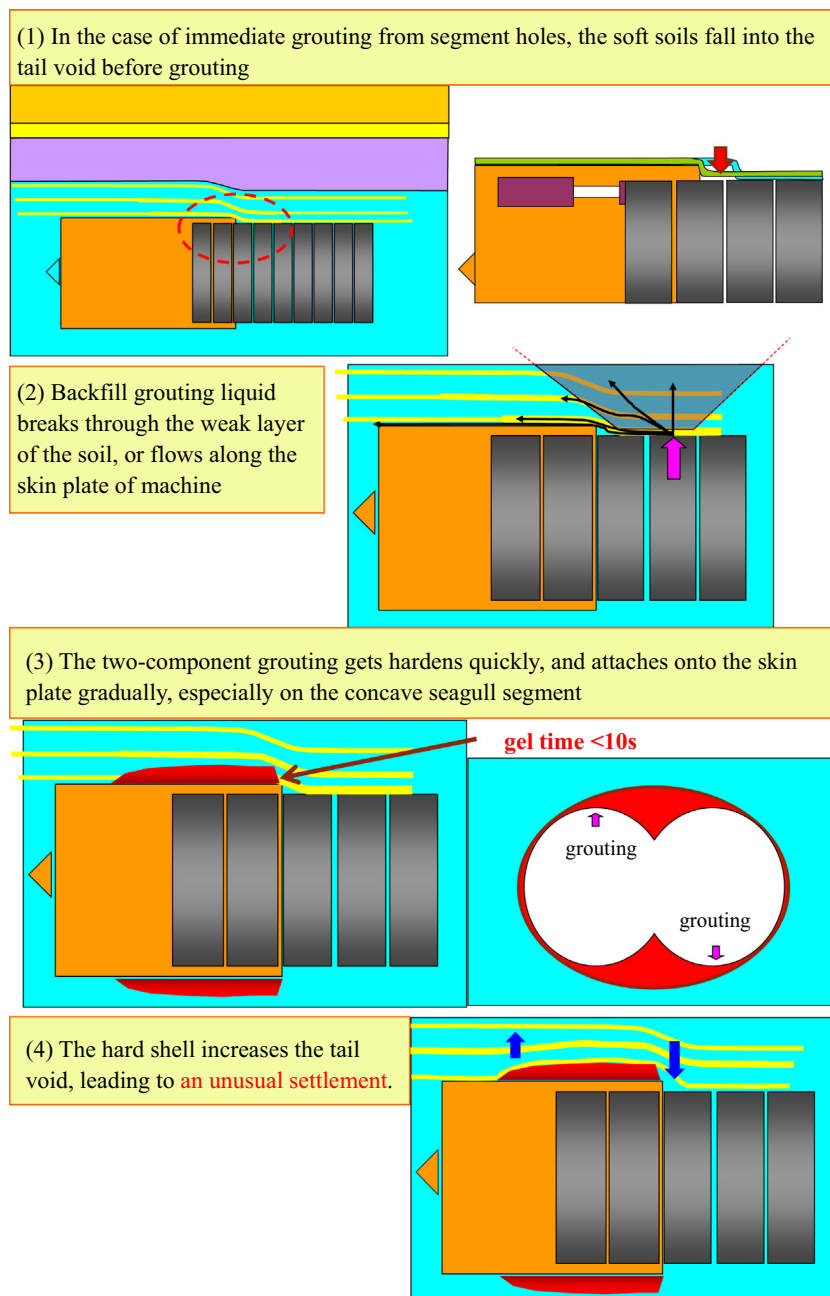


Fig. 14. Mechanism of unusual settlement due to improper backfill grouting of DOT.



**Table 5**  
Proportion of two-component backfill grouting.

Proportion				Properties			
Liquid A				Liquid B	Gel time (sec)		Uniaxial compression strength (N/mm <sup>2</sup> )
Cement (kg)	Bentonite (kg)	Retarder (L)	Water (L)	Water glass (L)			1 h28 days
300	100	0.5	750	75	<10		0.044.0

the segment. The soft ground had already fallen down to fill the tail void before the grouting from the segment had arrived. (2) The grouting broke through the weak zone of the ground, and ran back along the gap between the ground and the skin plate. This phenomenon would have been more serious when the machine had to be stopped frequently for maintenance in the early stages of construction. (3) The two-component grouting hardened quickly, and attached onto the skin plate gradually, particularly on the concave seagull segment. (4) Consequently, the tail void became much larger than the theoretical value, resulting in a large settlement. If the cement accumulation was concentrated at the front part of the skin plate, a settlement following an upheaval could be seen while the TBM machine was passing by, which was the scenario in MS-1. If the cement accumulation dispersed along the skin plate, the settlement could be seen after the tail had passed through, which was the scenario in MS-2.

### 8. Countermeasures and monitoring results of MS-3

#### 8.1. Countermeasures

The two-component grouting has the properties of high fluidity before hardening and early hardening after mixing, so that it is suitable for reducing the immediate and long-term settlements of soft ground. The two-component backfill grouting is composed of two liquids: Liquid A, which is mainly cement, and liquid B, which is mainly water glass (liquid sodium silicate). The proportions are shown in Table 5. In the DOT machine, both liquids were mixed together at the operation platform. Then the mixture was sent to the simultaneous injection pipe at the tail of the shield machine through a connecting pipe. The mixture was sent by injection pump to fill the tail void while the shield was advancing. The connecting pipe was about 6 m long. The gel time was less than 10 s. It is easy for the connecting pipe to become blocked if the pipe is not cleaned in time after the injection. In addition, the pump for liquid B frequently failed due to lack of maintenance.

In order to fill the tail void in time, and to avoid the accumulation of grouting material onto the skin plate, two countermeasures

were taken in the middle shaft of the construction section CS-C. Firstly, the two-component backfill grouting was changed to the one-component type. The one-component grouting is of a non-cement material, composed of fly ash, bentonite and fine sand, which will not harden and accumulate on the skin plate. The ratio of components by weight of grouting in terms of fly ash, bentonite, fine sand and water is 1:0.4:2:1.45, respectively. Secondly, a secondary injection of cement fluid was carried out from the segment on the first gantry, which is about 30 m away from the first ring. In this way, the long term strength of the grouting material can be enhanced.

In addition, the cement accumulation on the skin plate was cleaned off in the middle shaft.

#### 8.2. In-situ monitoring of MS-3

After the improvement, the shield advanced from the middle shaft towards the arrival shaft. In-situ monitoring was conducted in MS-3 to verify the effect of the improvement. Only ground surface settlements were monitored in MS-3. The shield machine data for 40 rings (Ring Nos. 1140–1180) around the MS-3 are summarised as follows:

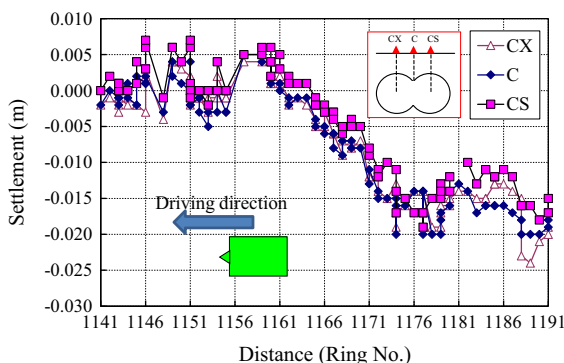
- (1) The earth pressure at the chamber was  $260 \pm 10$  kPa (middle left and middle right positions). It was within the rational range of the theoretical lateral earth pressure (286 kPa).
- (2) One-component simultaneous backfill grouting and secondary injection of cement fluid were conducted. The volumes of backfill grouting and secondary injection were  $6 \text{ m}^3/\text{ring}$  and  $0.5 \text{ m}^3/\text{ring}$  respectively, approximately half of that before improvement.
- (3) The advance speed of the shield was 30–40 mm/min.

As shown in Fig. 15, a vertical displacement of  $\pm 0.005$  m was observed before the shield arrival and while the TBM machine was passing by. A settlement occurred after the tail had passed by, and final settlement was approximately 0.02 m. Comparing it with Fig. 11, it can be seen that the countermeasures have reduced the settlement effectively.

### 9. Conclusions

In this study, in-situ monitoring and field investigations were carried out to investigate the reasons for an unusual settlement of approximately 0.8 m due to DOT tunnelling. The following lessons can be learnt from the study:

- (1) The cement accumulation on the skin plate due to improper backfill grouting at the early construction stage was the reason for the large settlement. Therefore, when adjustment of the earth pressure balance on the cutter face and backfill grouting within normally accepted ranges cannot reduce the settlement, accumulation of cement on the skin plate should be checked for, particularly in case of multi-circular shield tunnelling.



**Fig. 15.** Observed ground surface settlement versus distance (monitoring section MS-3).

- (2) The maintenance of the shield machines is important to avoid problems during construction, particularly where they are re-used several times for different tunnels. Some important parts, such as the earth pressure transducers and hydraulic valves and tubes, should be carefully inspected.
- (3) Two-component grouting is suitable for reducing the immediate and long-term settlements of soft ground. However, this requires a sophisticated management system of construction and machine maintenance. One-component grouting is relatively easily handled. It can fill the tail void in sufficient time so as to avoid a large settlement. After changing to one-component grouting, the ground settlement was reduced to approximately 0.02 m.
- (4) The current study acknowledges the flexibility of the use of the DOT tunnelling method and two-component backfill grouting in the soft ground of Shanghai. However, it can be concluded that a sophisticated management system of construction and maintenance is considered necessary for the application of DOT tunnelling to this type of ground.

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