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MECHANISM OF GROUND SETTLEMENTS AND HEAVES DUE TO SHIELD TUNNELING

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ABSTRACT

One of the tunnel sections in Construction Contract CB420 of Taipei Metro passed underneath the runway and the taxiways of the Taipei Songshan Airport and it was very necessary to reduce potential risks during tunneling so flights would not be interrupted. The Contractor adopted various measures to minimize ground settlements and closely monitored the ground response to tunneling. Abundant data of high quality were obtained for studying the effectiveness of the measures adopted. The mechanism of ground heaves and settlements is discussed herein. It has been found quantitatively that ground settlements are closely related to the imbalance of the materials taken out of the tunnel and the materials put into the tunnel. Long-term settlements are mainly due to bleeding of the grout injected at the tail. The possibility for the slurry in the earth chamber to flow to the tail is also discussed.

Key words: Settlement, tunneling, runway, airport, ground loss.

1. INTRODUCTION

As depicted in Fig. 1, one of the tunnel sections in Construction Contract CB420 of the Neihu Line of the Taipei Metro System passes underneath the runway and the taxiway of Taipei Songshan Airport. Because the operation of the airport should in no case be disrupted, stringent criteria were adopted to regulate the ground settlements induced. To minimize ground settlements, settlements were closely monitored and various measures were attempted.

As depicted in Fig. 1, the shield machine was launched from the ventilation shaft located at the northern end of the tunnel section. It passed under an open area, the runway, a lawn, a hardstand, the taxiway and the apron and ended at the east end of Station BR1 (Songshan Airport Station). The articulated shield machine was 7.395 m in length and 6.150 m in outer diameter. The reinforced-concrete segmental linings are 6,000 mm in their outer diameter and 5,400 mm in their inner diameter and are 1 m in length.

Construction for the down-track tunnel commenced at the beginning of November 2003 and ended at the end of June 2004. The locations of the 11 sections designated for studying the performance of tunnelling are shown in Fig. 1. The sections are identified by the 4-digit numbers denoting the chainage of the sections and the type of section. There were 11 shallow settlement indicators (SSI) in each of Type A sections and 9 in each of Type B sections. Extensometers (EXM) were installed in all the Type B sections and piezometers (ELP) were installed in selective Type B sections, a typical instrument layout of which is depicted in Fig. 2.

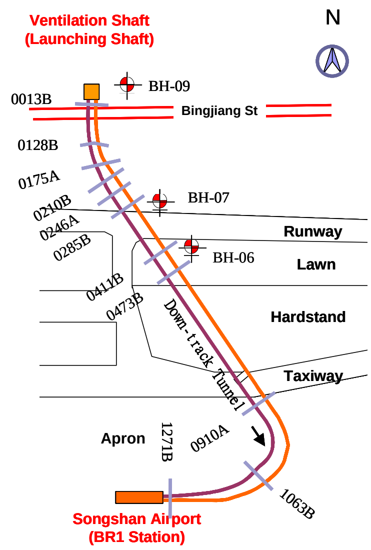

Fig. 1 Locations of research sections

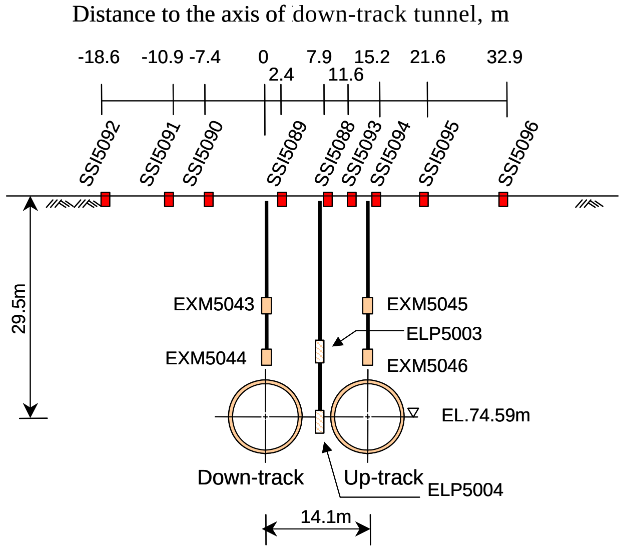

Fig. 2 Layout of instruments, Section 0128B

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2. GROUND SETTLEMENTS

The airport is located in the K1 Zone of the Taipei Basin. A longitudinal section along the tunnel alignment is shown in Fig. 3 and a representative soil profile is shown in Fig. 4. The soils at the depth of tunnel consist of soft to medium soft clay with N-values varying from 4 to 8 and water contents varying from 30% to 40% which are very close to the liquid limits. These soils are easy to loose their strengths once disturbed. The groundwater table is at a depth of 2 m below surface. However, the piezometric level in the sand seam at a depth of 40 m was found to be at a depth of 6 m.

2.1 Method of Analyses

Because ground settlements induced by tunnelling may drag on for a very long period of time, it is essential to evaluate ground settlements in different cases with a consistent time scale. The Logarithmic model, as depicted in Fig. 5, was adopted for studying the settlements induced in the case of interest (Hwang *et al*., 1995; Hwang and Moh, 2007). In short, ground settlements over tunnels can be categorized into 3 phases with the passing of the head of shield as the beginning of the timeline. Phase 1 settlements occur during passing of the shield machine and Phase 2 settlements are mainly due to the closure of tail voids. In fact, distinction between Phase 1 and Phase 2 settlements is academic because usually it takes only a couple of hours for the shield to pass a section and it is thus very difficult to differentiate the two from each other. It will be appropriate to consider them together as "short-term settlement" which is a term adopted simply for convenience.

In most cases, settlement-versus-time curves will become linear in semi-log plots after a certain period subsequent to the passing of the shield machine. The beginning of the linear portion of settlement curve can be considered the end of Phase 2 settlements and the beginning of Phase 3 settlements for practical purposes. For tunneling in the Taipei Basin, it has been observed that such transitions from Phase 2 to Phase 3 usually occur within 7 to 10 days after the passing of shield machines and it will be appropriate to assume the settlements induced in 10 days, denoted as δ_{10}, after the passing of shield as "short-term settlements" for all practical purposes. Unless denoted otherwise, δ_{10} always refers to the short-term settlements directly above the longitudinal axes of tunnels.

It has been proposed to express Phase 3 settlements in terms of the slope, which is denoted as α and is referred to as "index of Phase 3 settlements", of the line corresponding to Phase 3 settlements. Since Phase 3 settlements are, presumably, due to consolidation of soils, α is sometimes referred to as "index of consolidation settlements".

The index of Phase 3 settlements is the settlement over one full cycle in a semi-log plot, or, simply, the difference between the settlement obtained in 100 days and the 10th day after the passing of the shield machine. Such a definition has the merit that settlements increases, roughly, by 0.5 α each time the elapse time increases by a factor of 3, for example, from 10 days to a month, from a month to 100 days, from 100 days to a year, so on and so forth. Unless denoted otherwise, α refers to the long-term settlements directly above the axes of tunnels.

The straight line representing undisturbed Phase 3 settlements is referred to as the "α Line" and can be used to predict future settlements. It has been proposed to assume that settlements last for a year, therefore, long-term consolidation settlements will approximately equal to 1.5 α.

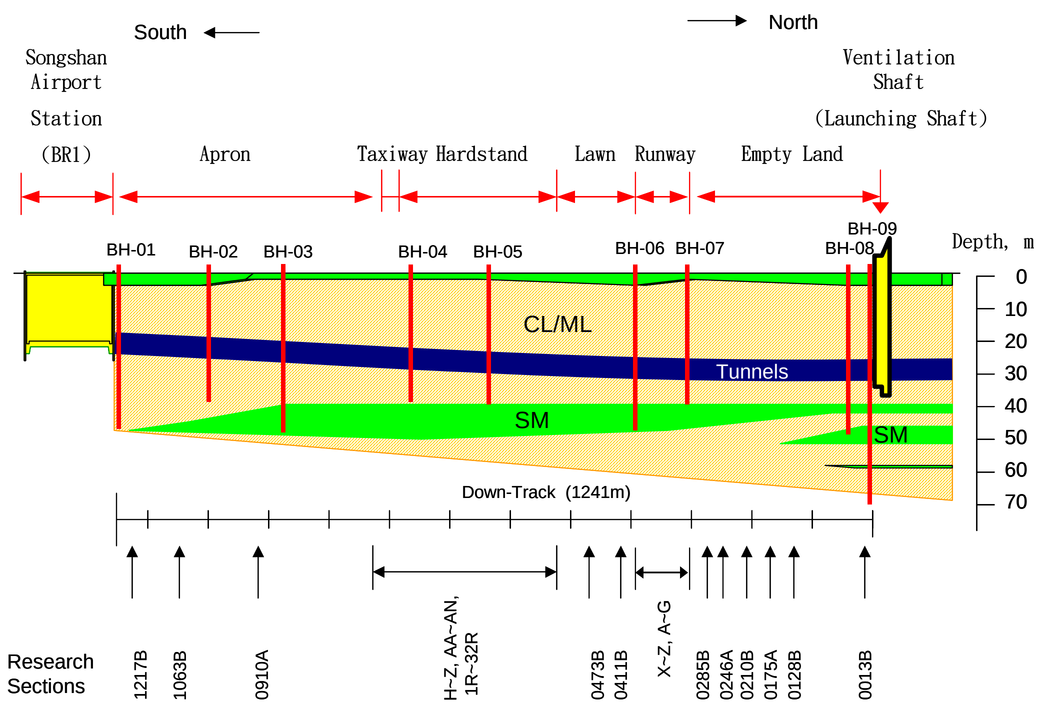


Fig. 3 Longitudinal section along tunnel alignment

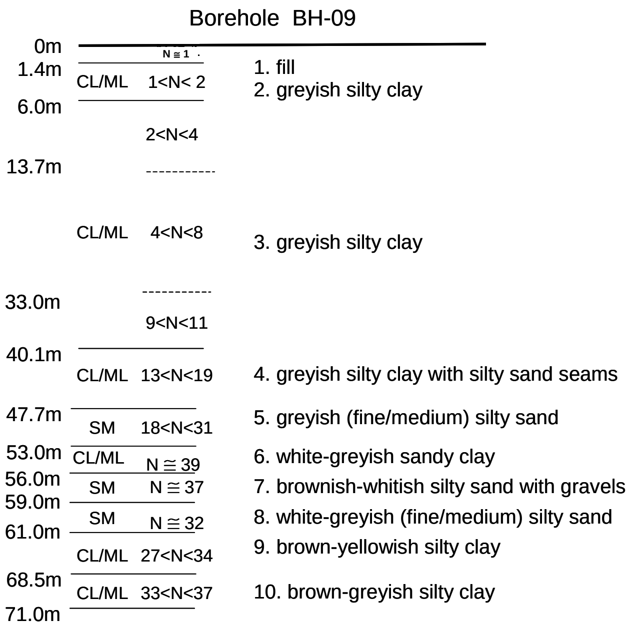


Fig. 4 Representative soil profile

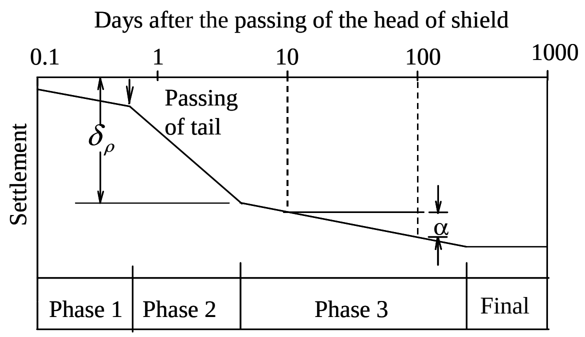


Fig. 5 Logarithmic model for simulating settlement curves

2.2 Short-term Settlements

To illustrate the applications of the Logarithmic model, Fig. 6 shows the readings of ground settlements obtained in Section 0128B, the instrument layout of which is shown in Fig. 2. As can be noted, a maximum settlement of 13 mm was obtained in 10 days at SSI5089 which is not far from the tunnel axis. Even at a distance of 32.9 m away from the axis, a settlement of 2 mm was obtained at SSI5096.

It is a common practice to approximate settlement troughs by error functions as follows (Peck, 1969):

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

where

δ = settlement

δ_{max} = maximum settlement

x = horizontal distance to tunnel axis

i = width parameter of the settlement trough

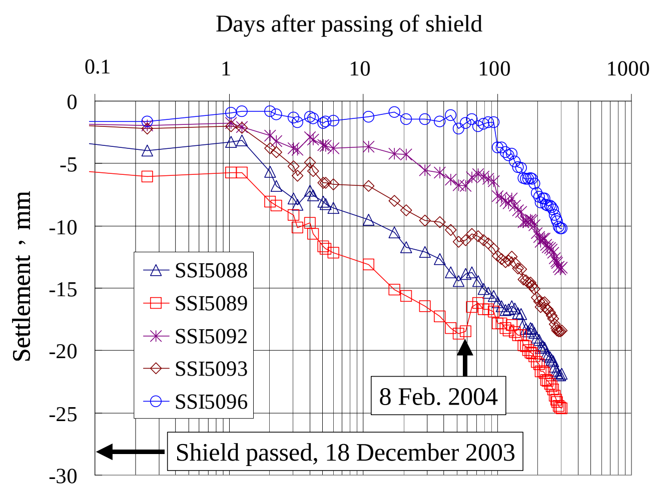


Fig. 6 Ground settlements, Section 0128B

As depicted in Fig. 7, the width parameter, i, is the distance from the axis of tunnel to the point of inflexion where the slope is the maximum. The maximum settlement, δ_{max}, can be computer as follows:

$$\delta_{max} = \left(\frac{vA}{2.5i}\right) \tag{2}$$

where

v = ground loss

A = sectional area of tunnel

Figure 8 shows the settlements obtained in 10 days, 51 days and 300 days at the location of Section 0128B and Fig. 9 shows the idealized settlement troughs. For settlements induced in 10 days, the same maximum settlement of 13 mm was obtained above the axis of the tunnel and is considered as representative short-term settlement, *i.e.*, δ_{10} for this section. The idealized settlement trough corresponds to a ground loss, v = 1.2% and a width parameter, i = 10 m.

Ground did not always settle in Phases 1 and 2. Heaves were observed at Section 0285B, for example, on 3 January before the arrival of the shield as shown in Fig. 10. In fact, heaves occurred concurrently at Sections 0175A, 0210B, and 0246A as depicted in Figs. 11 to 13. And their layout of instruments also depicted in Figs. 11(a) to 13(a). Table 1 lists the ground losses and width parameters corresponding to the short-term settlements at these sections. Sections 0013B and 1217B are excluded because they were too close to the shafts at the two ends and the readings were affected by ground treatments. As can be noted from the table, the ground losses were comparatively smaller at Sections 0210B, 0246A and 0285B due to the heaves. The ground losses at Sections 0910A and 1063B were also small, presumably, because of the stiffness of pavement in the apron.

The average ground loss of 0.68% obtained in the case of interest is comparable to the value of 0.66%, refer to Table 2 (Chen *et al.*, 2002), for the K1 Zone obtained in a previous study. The large standard deviations obtained, 0.45% for the case of interested and 0.55% in the previous study, indicate the great diverseness of data. The fact that the standard deviations of

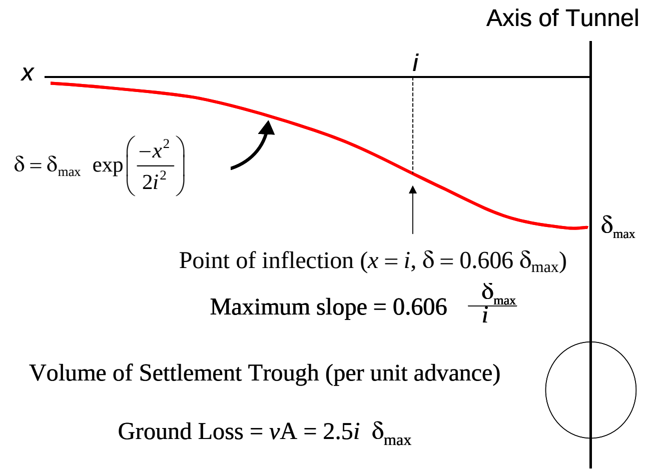


Fig. 7 Idealized settlement trough expressed as error function

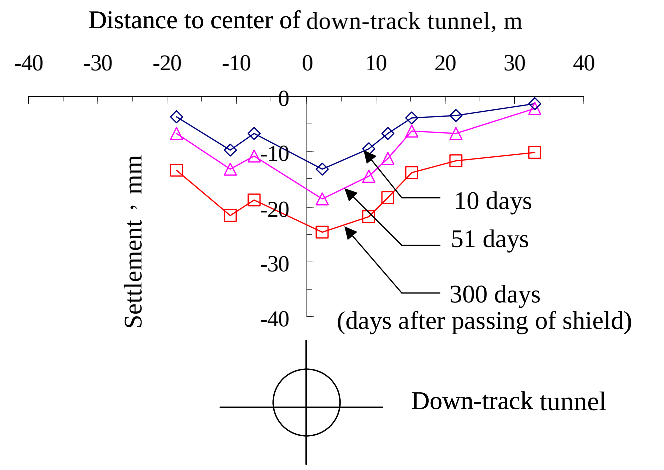


Fig. 8 Settlement troughs, Section 0128B

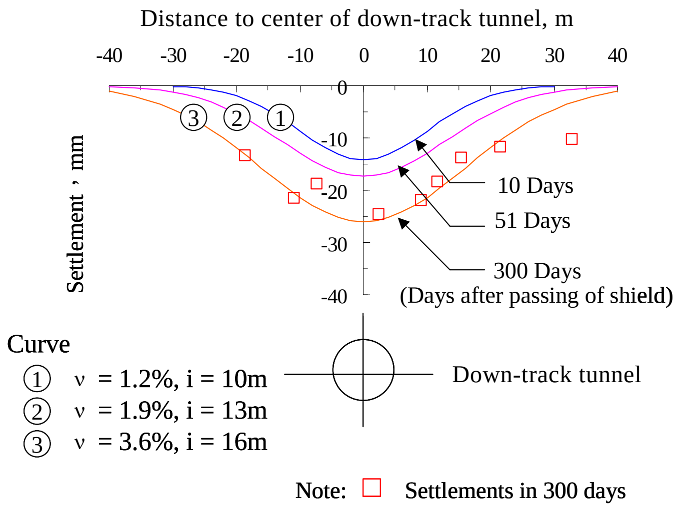
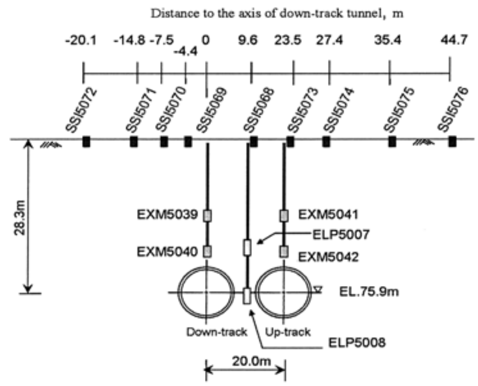


Fig. 9 Idealized settlement troughs, Section 0128B



(a) Layout of instruments, Section 0285B

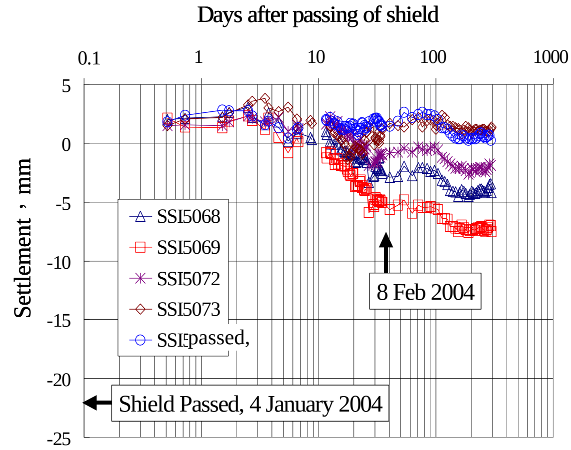
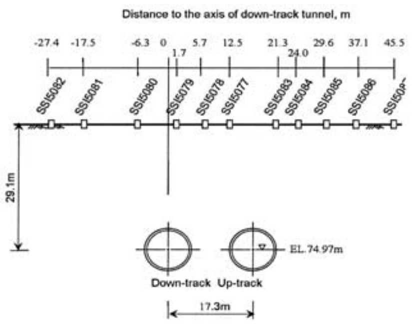


Fig. 10 Ground settlements, Section 0285B



(a) Layout of instruments, Section 0175A

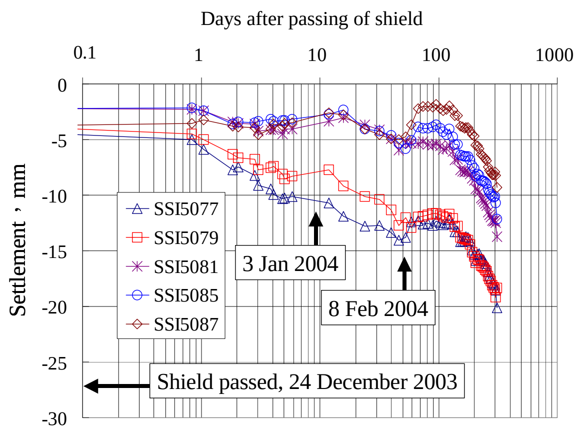
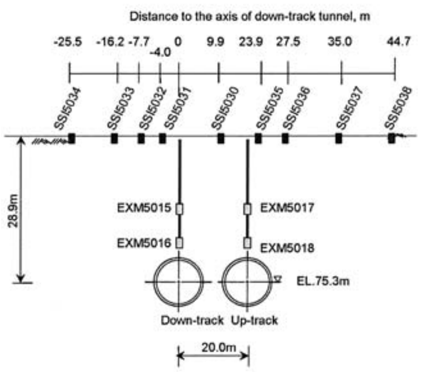


Fig. 11 Ground settlements, Section 0175A



(a) Layout of instruments, Section 0210B

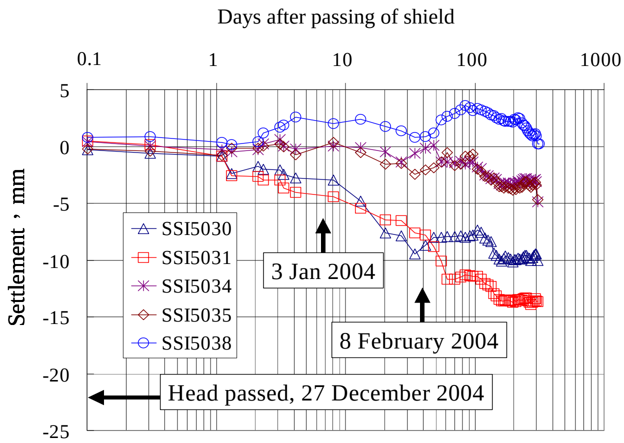
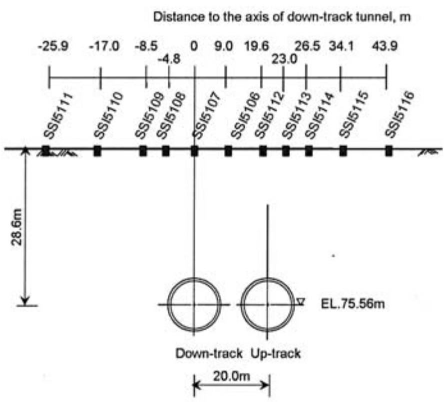


Fig. 12 Ground settlements, Section 0210B



(a) Layout of instruments, Section 0246A

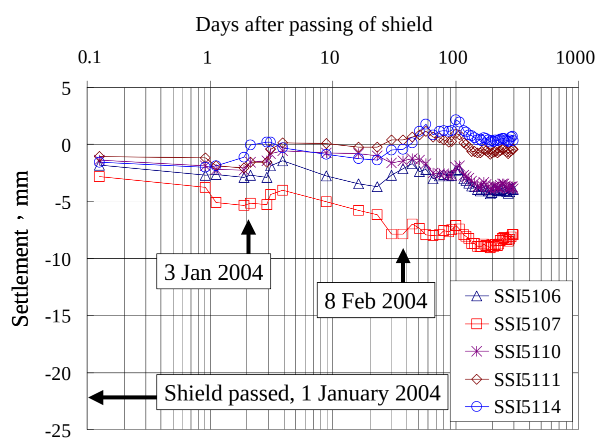


Fig. 13 Ground settlements, Section 0246A

Table 1 Ground settlements at research sections

	Idealized trough			Readings at axis	
	Phases 1 + 2			Phase 3 α (#1) (mm)	Final (#2) (mm)
Section	δ_{10} (mm)	ν_{10} (%)	i (m)		
0013B	(#3)	(#3)		(#3)	
0128B	14.3	1.2	10	8.9	27.7
0175A	11.9 (#4)	1.2	12	7.9	23.8
0210B	5.2	0.35	13	10.0 (#4)	20.2
0246A	5.2	0.35	8	3.0	9.7
0285B	0	0	18	9.2	13.8
0411B	7.9	0.6	9	3.0	11.65
0473B	11.9	1.2	12	4.5 (#4)	18.65
0910A	4.0 (#4)	0.4	17	9.8 (#4)	18.7
1063B	8.0	0.8	12	6.6	17.9
1217B	(#3)	(#3)		(#3)	
Average	7.6	0.68	12.3	7.0	18.1
Standard deviation	4.5	0.45	3.4	2.8	5.7

Notes:
#1 For settlement markers closest to the axis
#2 Equal to short-term settlement plus 1.5 α
#3 Affected by ground treatment
#4 Settlement troughs are asymmetrical

Table 2 Short-term settlements observed in the Taipei Basin (after Chen *et al.*, 2002)

Geological zone	No. of sections	Average ground loss ν_{10} (%)	Standard deviation (%)
T1	17	0.70	0.23
T2	21	0.64	0.54
TK2	3	0.70	0.35
K1	34	0.66	0.55
H1	6	0.76	0.17
YH	13	0.89	0.41
B1	19	0.86	0.42
B2	62	0.63	0.45
C	5	1.42	0.26
Summary	180	0.71	

ground losses are large in comparison with the averages for individual zones indicates that short-term settlements are sensitive to workmanship. On the other hand, the averages are quite uniform among various zones except the *C* Zone, indicating that short-term settlements are not sensitive to ground conditions. It is to the authors' knowledge, the excessive ground settlements observed in the B1 and *C* Zones were due to improper tunnelling operation and should be excluded from statistical analyses. The average of 0.71%, however, was obtained by including the data for all the zones.

2.3 Long-term Settlements

As can be noted from Figs. 6 and 10 to 13, the settlement curves indeed become linear subsequent to an elapsed time of 10 days after the passing of the shield. Unfortunately, heaves occurred concurrently at Sections 0128B to 0285B on 8 Feb. 2004 and made the analyses very complicated. The contours of heaves in the 3-month period between February and May of the year are shown in Fig. 14. Although the heaves were small in magnitudes, their occurrence was difficult to explain because of the lack of mechanism for them to happen. On 8 February, 350 rings had been completed and the shield machine was more than 60 m away from Section 0285B and more than 200 m away from Section 0128B. Field records do not reveal any activities which might cause ground heaves in the said period and the pattern of settlements shown in these figures rules out the possibility for the readings to be erroneous.

It is interesting to note from Fig. 15 that the ground started to settle again shortly afterward. The readings even fall below the α-Line. This implies that attempts, if any, to heave up the ground would only have short-term effects. The same phenomenon is also observed at Section 0175A as depicted in Fig. 11, but not at other 3 sections with ground heaves. Figures 16 and 17 show very different patterns of post-heave settlements observed at two markers, which were only 14 m apart in the same section. This illustrates the great difficulty in analyzing long-term settlements once ground is disturbed.

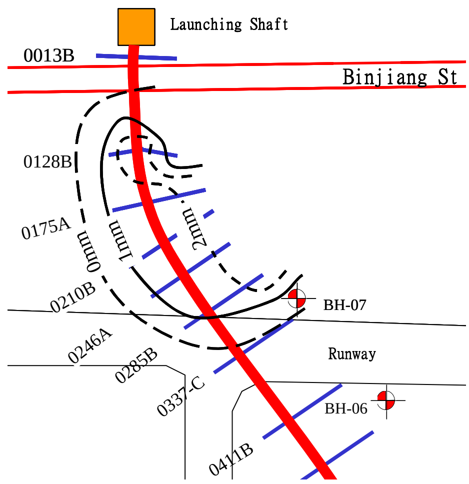


Fig. 14 Ground heave observed between 1 Feb. and 31 May, 2004

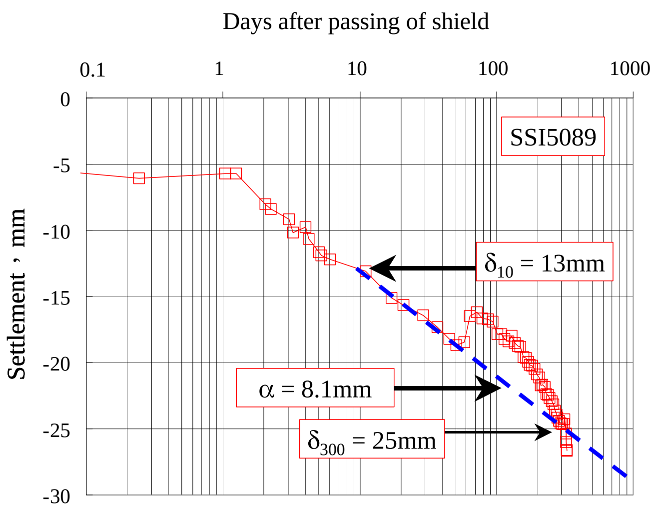


Fig. 15 Analyses of settlement, SSI5089, Section 0128B

Very fortunately, there are sufficient readings obtained prior to 8 February for predicting long-term settlements. Take Section 0128B again for example, an α value of 8.1 mm is obtained as depicted in Fig. 15 and extension of the α-Line to an elapsed time of 300 days gives a final settlement of 25 mm.

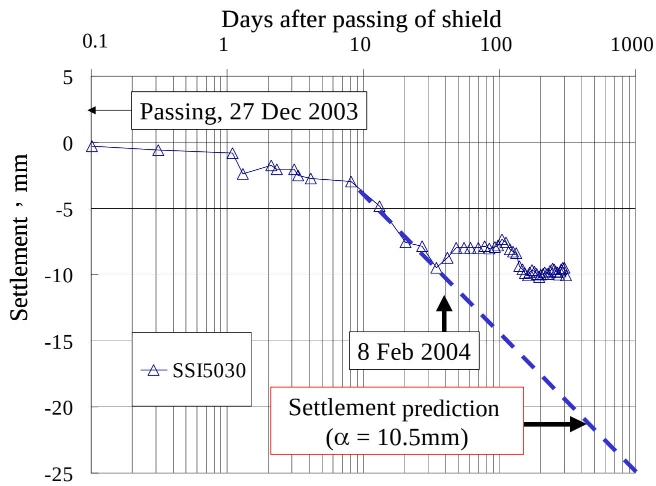


Fig. 16 Analyses of settlement, SSI5030, Section 0210B

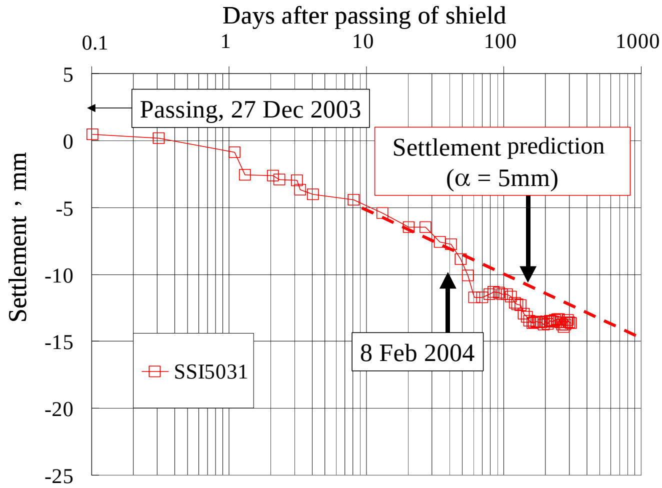


Fig. 17 Analyses of settlement, SSI5031, Section 0210B

Table 3 Indices of consolidation settlements observed in the Taipei Basin (after Chen *et al.*, 2002)

Geological zone	No. of sections	Average α (mm)	Standard deviation (mm)
T1	16	2.00	0.70
T2	21	5.40	2.70
TK2	4	5.50	0.90
K1	44	8.90	4.30
H1	6	5.20	2.00
YH	12	6.80	2.80
B1	19	7.40	3.60
B2	74	5.10	2.80
C	6	5.00	1.60
Summary	202	6.04	

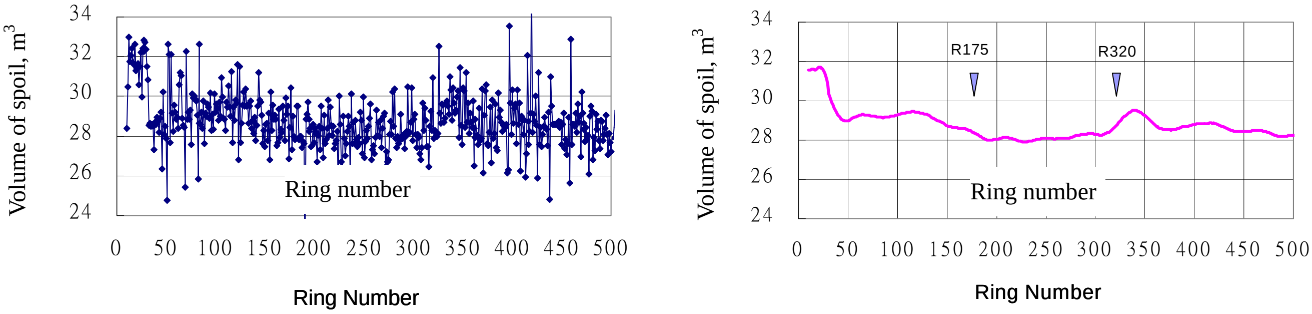
The indices of Phase 3 settlements, *i.e.*, the α values, for all the research sections are listed in Table 1. Sections 0013B and 1217B were excluded for the reason mentioned above. As can be noted from the table, the α values vary from 3 mm to 10 mm with an average of 7 mm and a standard deviation of 2.8 mm, which are somewhat smaller than those suggested by Chen *et al*. (2002) for the K1 Zone as depicted in Table 3.

Similar to short-term settlements, Table 3 indicates that the standard deviations for the α values for each geological zone vary in a large range indicating long-term settlements are sensitive to workmanship. However, unlike short-term settlements, the averages of individual zones also vary in a wide range. The smallest value, *i.e.*, α = 2 mm, was obtained for the T1 Zone in which the subsoils consist predominantly sands and the largest value, *i.e.*, α = 8.9 mm, was obtained for the K1 Zone in which subsoils consist predominantly clays. This indicates long-term settlements are sensitive to ground conditions.

3. MECHANISM OF SETTLEMENT AND HEAVE

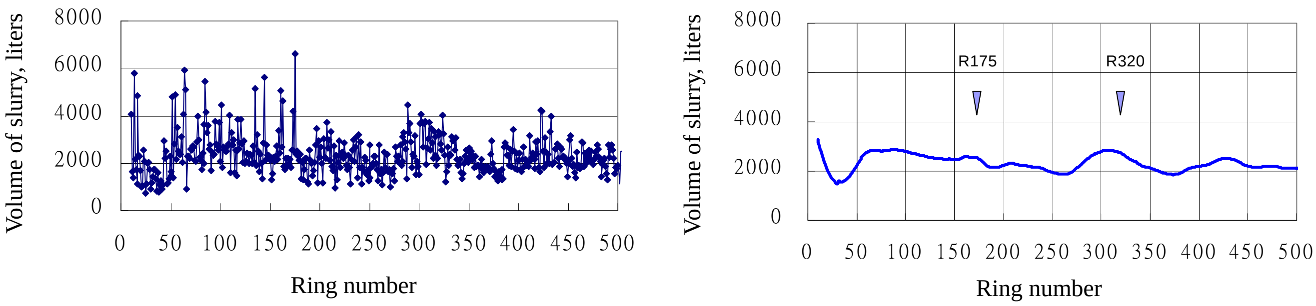
Ground settlement over tunnels are obviously induced by ground loss which is the imbalance of the volume of materials discharged from the tunnel and the total volume of materials inserted into the tunnel. The materials inserted into the tunnel include the tunnel tube, the grout injected for filling up the tail voids and the slurry injected into the earth chamber for reducing the torque required for driving the shield and for supporting the face. Sometimes, secondary grouting is used to reduce ground settlement, but the quantity of grout is very small and has insignificant influence on the imbalance. Ground movements are also affected by activities not related to tunnel driving as mentioned in Section 2.1. The discussion of the influences of such activities is, however, beyond the scope of this paper.

The volumes of the spoil discharged, the slurry injected into the earth chamber and the grout injected at the tail of the shield during the driving of the first 500 rings are shown in Figs. 18(a). 19(a) and 20(a) respectively. As can be noted from Table 4 that the average volume of materials, including the tunnel tube, inserted into the tunnel is 32.68 m^3 per ring which exceeds the average discharge of 28.82 m^3 per ring. Much ground heave would have been observed if these records were correct. The average discharge is smaller than the theoretical volume of cutting of 29.68 m^3 per ring for the shield with an outer diameter of 6.15 m even without considering the over-cutting by using the copy cutter. This was certainly impossible. It is therefore obvious that the readings of the flowmeter are misleading and have to be corrected. In the lack of better means, the readings can only be calibrated by correlating ground loss with ground movements.



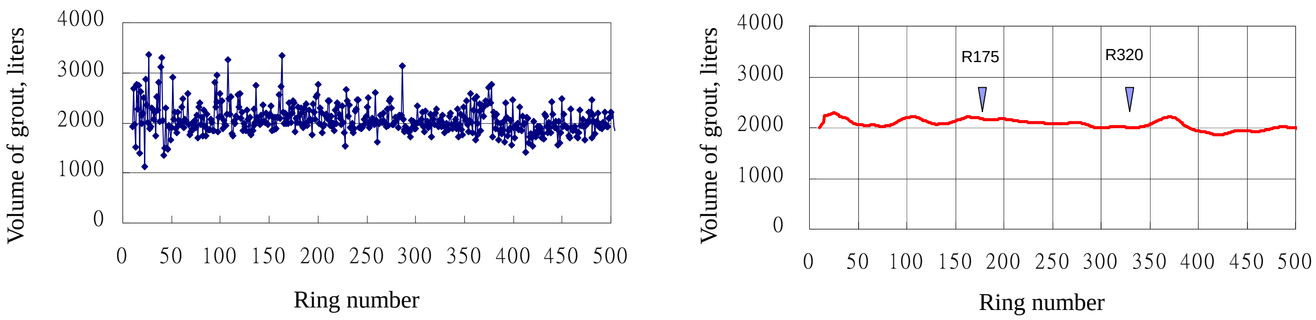
(a) Field Records (b) Weighted Averages

Fig. 18 Quantity of spoil discharged from tunnel



(a) Field Records (b) Weighted Averages

Fig. 19 Quantity of slurry injected into earth chamber



(a) Field Records (b) Weighted Averages

Fig. 20 Quantity of grout injected at the tail of shield

3.1 Correction of Flowmeter Readings

In the early morning of 9 January 2004, slurry was observed to have escaped to ground surface at a location near Ring 320 when the head of the shield reached Ring 325. Ground heaves were observed at Section 0246A and 0285B as early as 3 January as depicted in Figs. 10 and 13 respectively. The ground losses at these sections must be slightly negative. This offers an excellent, but rather unexpected, opportunity of calibrating the flowmeter readings.

The data points shown in Figs. 18(a), 19(a) and 20(a) for individual rings do scatter in wide ranges. It is therefore necessary to rationalize them for analyses to be meaningful. Ground movements at a particular section are an accumulation of the influences of ground losses during the driving of many rings ahead and many rings behind this section. The error function, suggested by Peck (1969) for expressing settlement troughs, *e.g.*, Fig. 7, in the transverse direction is expected to be equally applicable for expressing the influence of ground loss on settlements in the longitudinal direction of the tunnel. Figure 21 shows the influence of ground loss as a function of distance to the tunnel axis for i = 12 m which was the average of width parameters of troughs for short-term settlements as depicted in Table 1. For simplicity, the curve shown can be approximated by a trapezoid with a shorter base of 4 m and a longer base of 48 m. In other words, the weight will be 1 for the ring in the section of interest, and also for the two adjacent rings ahead and two adjacent rings behind the said section. The weights decrease linearly to zero to a distance of 24 m, *i.e.*, 2i, away from the axis of the tunnel.

The same function shown in Fig. 21 was adopted for computing the moving (weighted) averages of materials in and out of the tunnel as the shield progressed with the distance to tunnel axis replaced by the distance to the section of interest. The weighted averages of the volumes of spoil discharged, slurry injected into the earth chamber and the grout injected at the tail of the shield are shown in Figs. 18(b), 19(b) and 20(b) respectively and the imbalance of the volumes of materials in and out of the tunnel on 8 January and earlier is shown as Curve (a) in Fig. 22. The large negative imbalance would imply enormous ground heave ever since the beginning of tunneling. This certainly can not be true.

If a calibration factor of 1.16 is applied to the volumes of spoil discharged, *i.e.*, if the volumes of discharge are increased by 16%, the adjusted curve, *i.e.*, Curve (b) in Fig. 22, appears to agree with the observations well. As can be noted, ground losses

Table 4 Average volume of materials

Item	Volume (m^3)
Spoil discharged (magnetic flowmeter readings)	28.82
Tunnel tube (ϕ = 6m)	28.26
Slurry injected into earth chamber	2.34
Grouting at tail	2.08
Secondary grouting	negligible
Total infilling	32.68

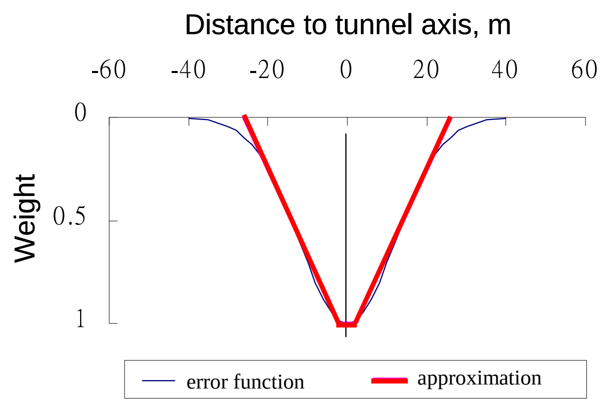


Fig. 21 Influence of volume imbalance on ground settlements

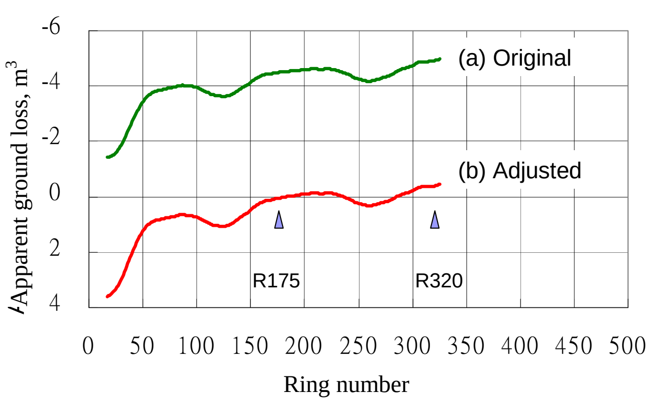


Fig. 22 Apparent ground losses

were very small, even slightly negative, starting from Ring 175 and onward. This is consistent with the fact that small heaves were observed at Sections 0175A, 0210B concurrently with Sections 0246A and 0285B. Since the quantities shown may not exactly be the true ground losses, they are referred to as "apparent ground losses".

3.2 Mechanism of Heaves

As shown in Fig. 18(b), the volumes of spoil discharged were comparatively low in the range between, say, Ring 175 and Ring 320. On the other hand, as can be noted from Fig. 19(b), the slurry injected into the earth chamber started to increase from Ring 280. As a result, the total volume of the materials inserted into the tunnel exceeded the volume of spoil discharged and the entire tunnel was "pressurized" as a balloon as illustrated in Fig. 23. Although the fact that the effects of such balloon-blowing reached Ring 175 at a distance of more than 100 m away may appear to be unbelievable, the data are nevertheless very convincing.

The incident of 9 January was a result of hydraulic fracturing due to injecting slurry at a pressure much exceeding the overburden pressure. This leads to the speculation that the slurry could have flowed to the tail of the shield and pressurized the tunnel for quite a length. The excavated section is always slightly larger than the cross-section of the shield due to over-cutting for reducing frictional resistance and there exists, theoretically, an annular space for the slurry to spill over. This annular space will be kept open if the fluid pressure of slurry is constantly greater than the overburden pressure. Even without over-cutting, the slurry at high fluid pressures is still able to flow to the tail through the fissure between the tunnel wall and the shield skin. Such a phenomenon was reported in Bezuijen and Talmon (2008) but unfortunately no details were available. It will take some time for the grout at the back of the linings to harden. Therefore, at an average progress rate of 10 rings per day, it is expected that the grout will be in a semi-solid state and will be able to transmit pressure over quite a distance.

Excessive back grouting at tail may also cause ground heaves. Ground heaves were observed at quite a few locations during the construction of the Nankang Line of Taipei Metro and were attributed to back grouting at tail (Moh and Hwang, 1997). At one location cracks were observed at ground surface with the presence of escaped grout.

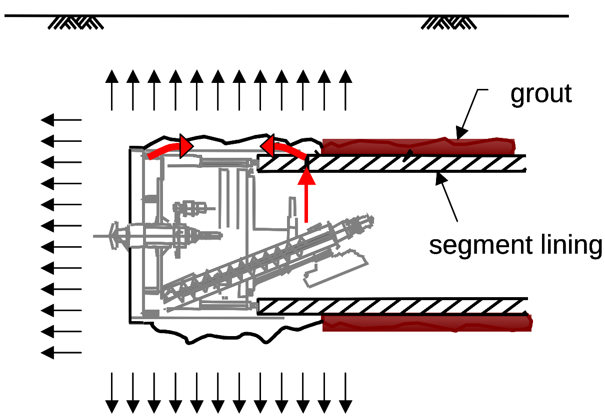


Fig. 23 Mechanism of ground heave

3.3 Mechanism of Short-term Settlements

With a calibration factor of 1.16 on the discharge, the adjusted apparent ground losses for the first 500 rings are shown in Fig. 24. Also shown in the figure are the short-term settlements above the tunnel axis. As can be noted, the short-term settlements correlate with apparent ground losses very well. It is therefore evident that short-term settlements are primarily affected by the imbalance of materials in and out of the tunnel.

3.4 Mechanism of Long-term Settlements

Long-term settlements can be attributed to consolidation of soil surrounding the tunnel and bleeding of grout, *i.e.*, loss of the water in the grout into the surrounding soil, injected for filling up the tail void. A very interesting study on the so-called bleeding of grout was conducted by Komiya *et al*. (2001). A given volume of grout was poured between heavily overconsolidated soil samples placed at the top and the bottom of a large consolidometer. After waiting for gel hardening, the composite soil-grout sample was consolidated at a vertical pressure of 235 kPa. It was observed that 30% of the volume was lost if Type I grout, refer to Table 5 for compositions, was used. The volume loss was reduced to 7% if Type II grout, which contained less water and was more viscous than Type I grout, was used.

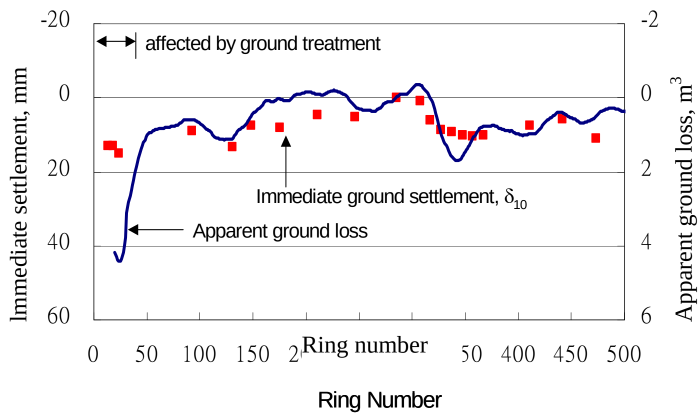


Fig. 24 Influence of ground loss on settlements

Table 5 Composition of the grout (Komiya *et al.*, 2001)

	Material	Type I grout	Type II grout	
			A solution	B solution
Proportion by weight	Cement	1		1
	Water	3.43	1	2.2
	Water Glass	1.25	1	
	Bentonite			0.15
	Chemical Hardener			0.5
Gel Time		120s	20s	
Unconfined compressive strength (1 day curing)		75 kPa	143 kPa	

Table 6 Composition of the grout (this study)

Material	Mass (kg)	Specific gravity	Volume (liters)
Cement	220	3.10	71.0
Bentonite	37	2.50	14.8
Stabilizer	8.6	1.79	4.8
Water	845	1.00	845
Water Glass	87.75	1.35	65
Total	1198.35		1000.6

As can be noted from Table 6, water accounted for 85% of the volume for the grout used for the case studied herein in comparison with only 73% for Type I grout. For an average unit weight of 18 kN/m^3 and a minimum depth of 26 m, the overburden pressures exceeded 468 kPa, in comparison with 235 kPa in the laboratory test conducted by Komiya *et al*. (2001). Therefore, the volume loss due to bleeding for the case studied herein is expected to exceed 30%.

The mechanism of consolidation of soils surrounding the tunnel is far too complicated to be discussed herein. In any case, the combined volume loss due to soil consolidation and due to bleeding of the grout at the tail is expected to be much larger than 30% of the volume of the grout. However, it should be noted, soil consolidation and bleeding took place immediately after grouting and some of the settlements associated with consolidation and bleeding already occurred during the 10-day period assumed for short-term settlements.

As shown in Table 4, an average volume of 2080 liters, which was 145% of the theoretical volume of the tail void, of grout was injected at the tail for each ring. A 30% loss of the volume of the grout, or 624 liters per ring, corresponds to a ground loss of 2%. If this indeed was the case, the unit weight of the grout would increase from 12 kN/m^3 to 15 kN/m^3 as a result of bleeding. It will be interesting to confirm this inference in future by measuring the unit weight of the hardened grout adhered to the segments which are removed to make openings on tunnels for constructing crosspassages.

4. CONCLUSIONS

The foregoing discussions lead to the following conclusions:

1. Short-term settlements over tunnels induced are due to ground loss which is the imbalance of the volume of the spoil discharged and the volume of materials inserted into the tunnel. Settlements can be minimized by carefully keeping the ground loss to a minimal.
2. Long-term settlements are due to loss of water in the grout injected at the tail and can be minimized by using thicker grout.
3. It is possible for the slurry in the earth chamber to flow to the tail of the shield and fill up the tail void. This may be an effective way to reduce ground settlements.

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