SETTLEMENTS OVER TUNNELS
- TRTS EXPERIENCE

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SYNOPSIS: For the construction of the Initial Network of the Taipei Rapid Transit Systems, there are a total of 68 shield tunnels and by the time this paper was prepared more than a half of them have been completed. The performance of some of these drives is discussed herein with emphasis on ground settlements induced as a result of tunnelling.

INTRODUCTION

The Initial Network of the Taipei Rapid Transit Systems (TRTS), as depicted in Fig. 1, consists of seven lines, namely, the Tamshui, Mucha, Hsintien, Nankang, Panchiao and Chungho, and Maintenance Lines. With the extension of the Panchiao Line to Tuchen and the extension of Mucha Line to Neihu, there are a total of 68 tunnel drives, with a total length of roughly 48 km. At the time this paper was prepared (December, 1995), more than a half of these tunnel drives had been completed. For studying ground response to tunnelling, numerous geotechnical instruments were available along the routes. The overall performance of a few tunnel drives which have been completed are discussed herein with emphasis on ground settlements induced as a result of tunnelling.

GEOLOGY OF TAIPEI BASIN

Taipei Basin is characterized by a well defined sequence of clay and sand alternations in the so-called Sungshan Formation, underlain by a thick bed of dense sands and gravels, i.e., the so-called Chingmei Formation. The stratigraphy of subsoils on the east of Tamshui and Hsintien Rivers has been extensively studied (Moh and Ou, 1979; Moh and Chin. 1991; Woo and Moh, 1990) and the central city area, as shown in Fig. 2, is geologically divided into seven zones, i.e., the T1, T2 and T3 Zones along the Tamshui River, K1 and K2 Zones along the Keelung River and H1 and H2 Zones along the Hsintien River. A typical soil profile in the central city area obtained by using a piezocone is given in Fig. 3. Figures 4, 5 and 6 show cross sections along the Nankang, Hsintien and Panchiao Lines. The six-layer sequence is the most distinct in the T2 Zone where the city center, represented by the Taipei Main Station, is. The sandy sublayers thin out toward the east (Fig. 4) and at some places are totally missing. Toward Hsintien (Fig. 5), sands and gravels were retained by Chanchu Shan (Chanchu Mountain) and toward Panchiao and Tuchen (Fig. 6), sandy layers predominate. Typical soil properties of individual sublayers in the Sungshan Formation are available in Table 1 for information.

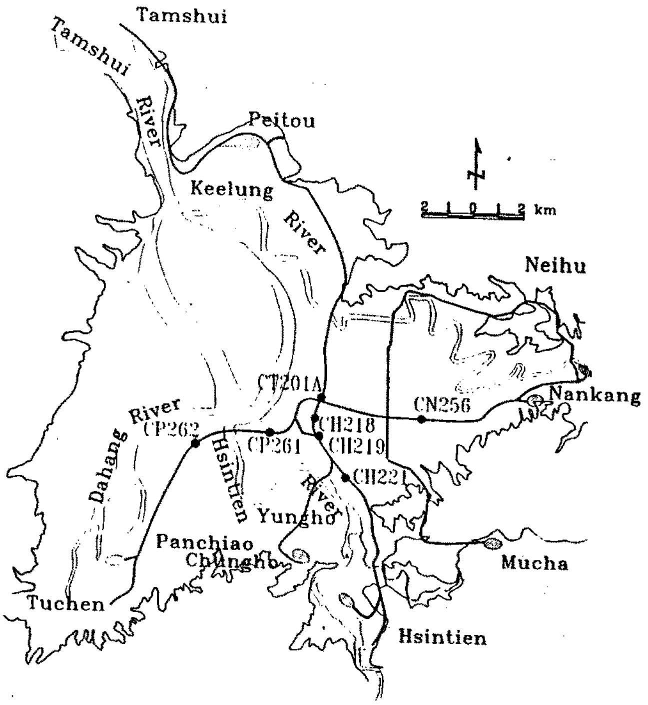


Fig. 1 Initial Network of Taipei Rapid Transit Systems

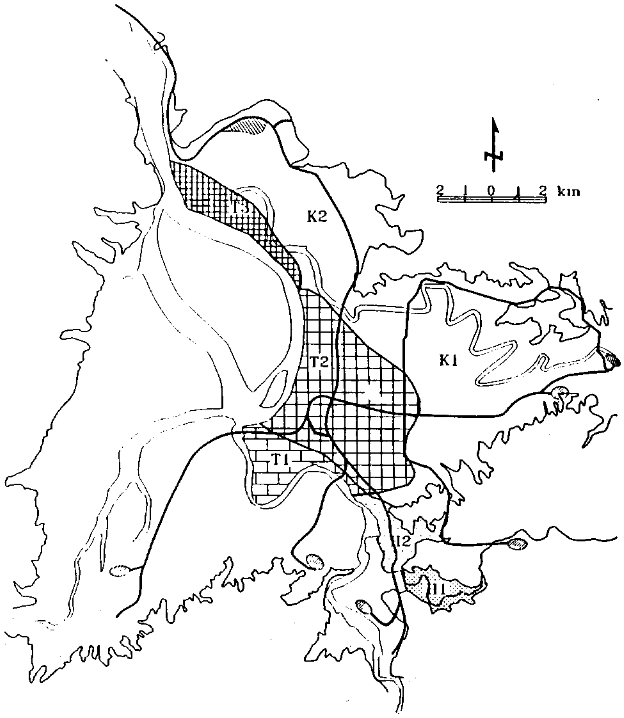


Fig. 2 Geological Subdivisions in the Taipei Basin

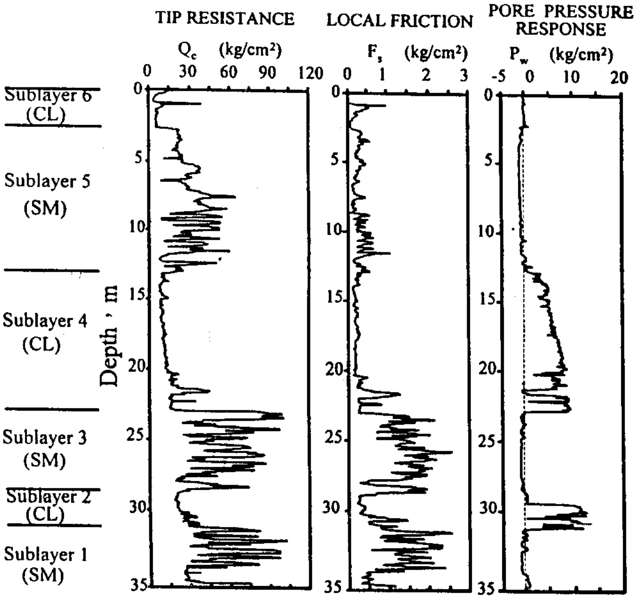


Fig. 3 Soil Profile in the T2 Zone

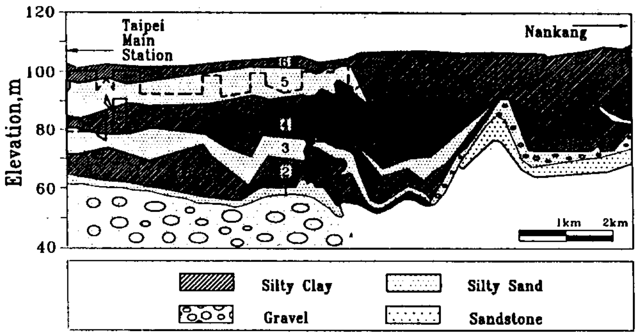


Fig. 4 Soil Profile along the Nankang Line

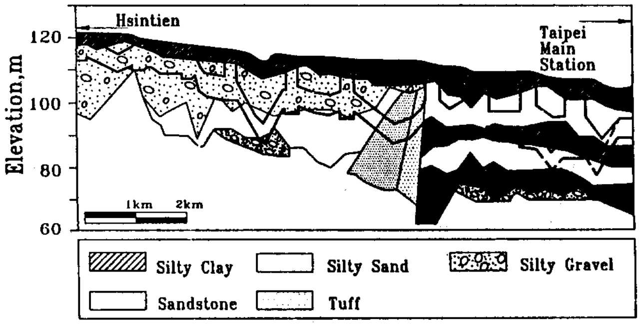


Fig. 5 Soil Profile along the Hsintien Line

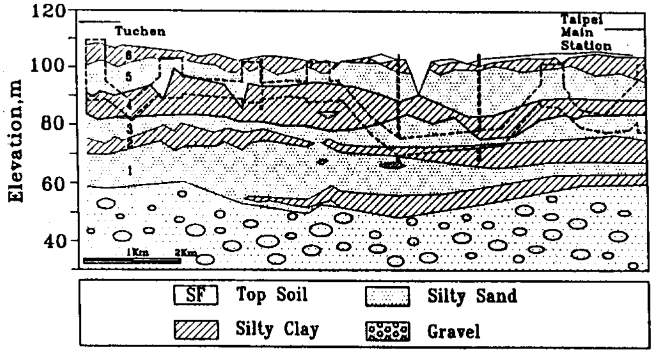


Fig. 6 Soil Profile along the Panchiao Line

Table 1 Soil Properties at Tunnel Levels

	Taipei Silt in T2 Zone		
	Sublayer 5	Sublayer 4	Sublayer 3
Soil Type	SM/ML	CL/ML	SM/ML
Water Content %	26	32	24
Unit Weight kN/m^3	18-20	18-19	19-20
Liquid Limit %		34	
Plastic Limit %		22	
Plasticity Index %		12	
Liquidity Index		0.8-1.0	
Sensitivity		3.5-4	
OCR		1.6	
Particle Sizes			
Gravel %	1	0	0
Sand %	75	10	60
Silt %	19	60	34
Clay %	5	30	6
Su kN/m^2	20-40	50	50-70
Cc		0.3-0.4	
Coeff. of Sec. Comp.		0.02	
Cv m^2/sec		20	
References	(1)Woo and Moh, 1990 (2)Chin, Crooks and Moh, 1994		

METHODS OF TUNNELLING

Except a 222m section of twin tunnels, which is to be bored by using the so-called NATM method, of the Hsintien Line, the rest of tunnels in the TRTS routes are to be driven by using shield machines. Most of the tunnels are to be driven through Sublayer 4 and Sublayer 5, with only a few deep ones to be driven in Sublayer 3. Sublayer 4 consists of silty clay (CL) with SPT N-values typically in the range of 3 to 7 and Sublayer 5 consists of silty sands with N-values in the range of 5 to 15. The poor strengths of subsoils together with a high ground water table call for the use of closed-face shields. The shield machines adopted by the contractors are either: (a) the earth pressure balancing type, or (b) the slurry type. The choice between the two is very close. The former is thought to be more suitable for clayey soils and the latter is believed to perform better in sandy soils. For the TRTS tunnels, the tunnel axes are usually at depths of 12m or so at the two ends and 18 to 20m in the middle sections. Therefore, the shield machines must be able to cope with both sand and clay (refer to Figs. 4, 5, 6 for soil stratigraphy). All the contractors, except the one for Contract CH221 of the Hsintien Line, have chosen earth pressure balancing machines (EPB) because it is extremely difficult to have worksites sufficiently large in the congested city area to house the slurry treatment plants required for slurry machines. To deal with variable ground conditions and to increase workability when necessary, all the earth pressure balancing shield machines have the provision of injecting slurry/chemical into the earth chambers.

GROUND SETTLEMENTS

Figure 7 shows an idealized settlement curve. Ground settlements can roughly be categorized as follows (Broms and Shirlaw, 1989, Hulme, Shirlaw and Hwang, 1990; Moh and Hwang, 1993; Moh, Hulme and Hwang, 1995; Hwang, Fan and Yang, 1995) :

Phase 1: due to face movements, overcutting and shield advancing
Phase 2: due to the closure and grouting of tail void, and dissipation of excess pore pressure
Phase 3: due to long-term consolidation

The distinction between Phase 1 and Phase 2 settlements is relatively easy. The settlements occurred before the passing of the tail must be due to face movement, overcutting and shoving of the shield. The sudden settlement immediately following the passing of the tail can certainly be attributed to the tail void closure. It has been frequently observed that the subsequent grouting for filling up the tail void heaved up ground slightly. A recent study indicated that the much excess pore pressures were induced in soils as a result of this grouting even before the arrival of the head (Moh, Hulme and Hwang, 1995), it is thus postulated that Phase 1 settlement may even contain ground heave as a result of grouting. The amount, however, is believed to be negligible.

The distinction between Phase 2 and Phase 3 settlements is not straightforward. The settlements which drag on for months towards the end are certainly the results of long-term consolidation, but exactly when the mode of settlement changed from Phase 2 to Phase 3 is hard to tell because the transition took place gradually.

To have a consistent definition so settlements in different phases can be evaluated separately, it is suggested to assume that long-term consolidation, i.e., Phase 3, starts as the time-settlement curve in a semi-log plot becomes a straight line.

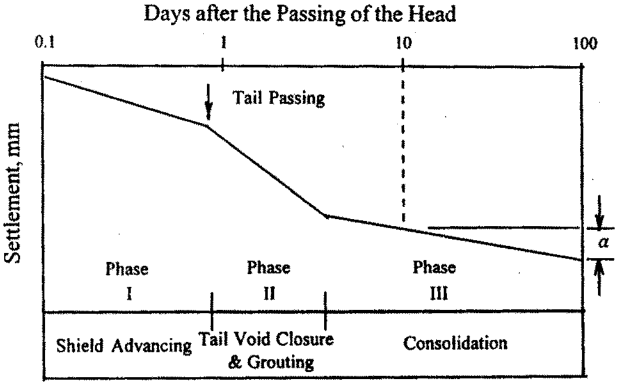


Fig. 7 Idealized Curve for Surface Settlement over Tunnels

Observations indicate that in usual cases this transition occurs in 4 to 10 days after the passing of shield. For practical purposes, it will be reasonable to assume that consolidation phase starts on the 10th day. The settlement induced prior to this date, denoted as δ_{10}, can be considered as immediate settlement to be used in constructing settlement trough and the corresponding ground loss is denoted as v_{10}. This settlement is conventionally referred to as ground loss settlement.

Consolidation settlement will be more conveniently evaluated by studying the slope of settlement curve in the semi-log plot, denoted as α , as an index for consolidation settlements. Index of consolidation is defined as the settlement in one log cycle or, simply, the settlement between the 10th day and the 100th day after the passing of the shield. This technique, together with the definition of ground loss settlement, makes studies much easier because only a few data points are required for obtaining δ_{10} and α values.

GROUND LOSS SETTLEMENTS IN TRTS PROJECT

In analyzing ground settlements over tunnels, Peck's approach (Peck, 1969) is commonly adopted and the settlements are assumed to follow a normal distribution so that

$$\delta = \frac{vA}{2.5i}\exp\left(\frac{-x^2}{2i^2}\right) \qquad \text{Eq. 1}$$

where v = ground loss, A = sectional area of excavation, and x = distance to the center, i = distance from the center to the point of inflection. The relationship suggested by Clough and Schmidt for estimating the distance to the point of inflection, i, (1981), i.e.,

$$i = \left(\frac{D}{2}\right)\left(\frac{Z}{D}\right)^{0.8} \qquad \text{Eq. 2}$$

where D = tunnel diameter, z = depth to the springline, is found to be applicable to surface settlements. For settlements in the regions very close to the tunnel, the use of this equation may result in much narrower troughs than what were observed (Moh and Hwang, 1993). Therefore, for example, it may be too conservative to estimate the sagging of a basement using Eq. 2.

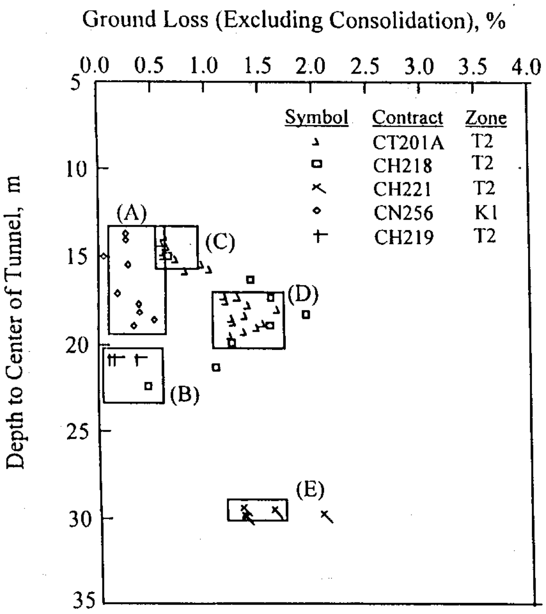


Fig. 8 Ground Losses for TRTS Contracts

Ground loss is an indicator commonly adopted for the performance of tunnelling. The ground losses for different geological zones are plotted versus depth in Fig. 8 (Hwang, Ju, Tsai and Fang, 1995). Data can be grouped into 5 clusters as follows (refer to Fig. 2 for geological zoning and Fig. 4, 5 and 6 for soil profile):

Case A	Ground loss is the smallest in the K1 zone in which the sandy sublayers in the Sungshan formation, namely, Sublayers 3 and 5 are mostly absent and clay dominates.
Case B	In the T2 Zone, ground loss is the same as that in the K1 Zone, i.e., Case A if the clayey cover above the tunnel crown is thick (say, 3m or more) .
Case C	If the clayey cover is totally absent, the ground loss is slightly greater than those for Cases A and B.
Case D	Ground loss is the greatest where a thin clay layer, say, a couple of meters or less, is present above the crown.
Case E	Slurry shield machines were used on the CH221 tunnel drives with both horizontal and vertical curves in the alignment.

In Cases A and B, it is conceived the clay in Sublayer 4 has a sufficient standup time to hold up the tail void. In Case C, presumably the sand in the Sublayer 5 has a high permeability to allow water to ingress into the tail void fast enough to equalize the water pressure. In the meanwhile, it has an optimum silt content to avoid internal erosion of particles, therefore, the closure of tail void is minimal. In Case D, water is unable to get into the void freely because of the low permeability of the clay cover, on the other hand, the clay cover is too thin to fully withstand the overburden pressures on the top. Therefore, the potential for the void to close-in is greater than that in the above cases. Case E can not be compared with other cases fairly because: (a) different type shield machines were used, (b) the drives have both horizontal and vertical curves, and (c) the depths are much greater.

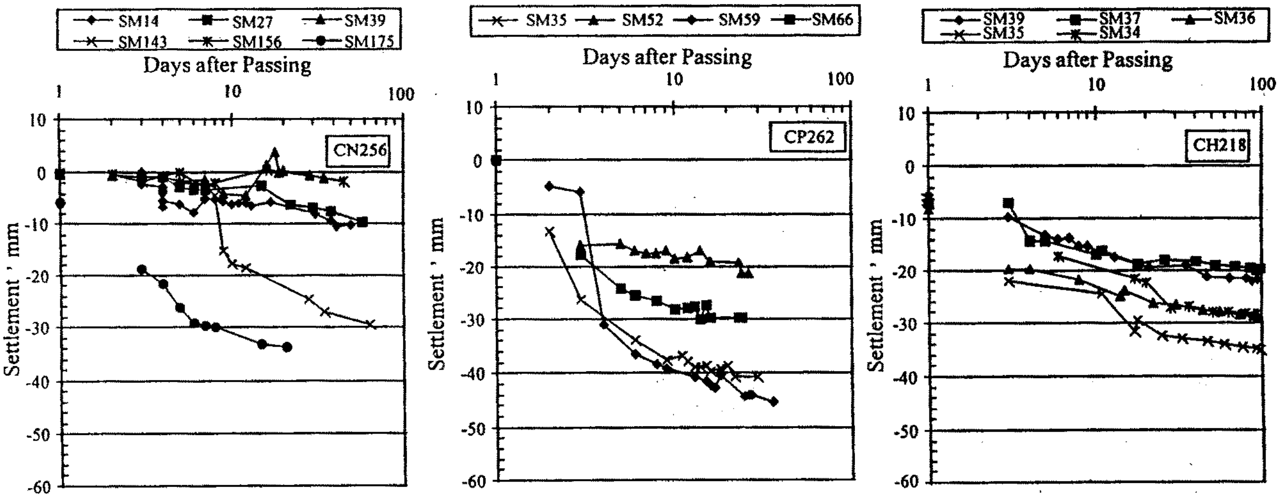
CONSOLIDATION SETTLEMENTS IN TRTS PROJECT

The time histories of surface settlements for a few TRTS contracts are shown in Fig. 9 (Moh, Hulme and Hwang, 1995) with detailed data given in Table 2. As can be noted that, although the ground losses vary in a very wide range, the indices of consolidation settlements, i.e., the α values, for the T1, T2 and K1 Zones are fairly consistent and fall in a narrow range of 5mm to 14mm per log cycle. This presumably is due to the fact that the presence of sand lenses in clays and clay lenses in sands reduces the contrast among different zones.

Consolidation settlements are obviously related to dissipation of excess pore pressures. Piezometers were available for monitoring pore pressure response. Part of the results have been published and can be referred to for better understanding of the mechanism (Moh, Hulme and Hwang, 1995; Hwang, Wu and Lee, 1995; Moh, Ju and Hwang, 1996; Hwang, Moh and Chen, 1996). The lack of space does not allow details to be presented herein.

Table 2 Ground Losses and Indices of Consolidation Settlements

Zone	Construction Contract	Marker	Depth (m)	Ground Loss v_{10} (%)	Index of Cons α (mm)
K1	CN256	SM 143	12.2	0.86	12
	CN256	SM 156	12.7		5
	CN256	SM 175	12.9	1.49	14
	CN256	SM 14	18.9	0.41	7
	CN256	SM 27	17.7	0.19	6
	CN256	SM 39	16.5		6
T1	CP262	SM 35	13.6	1.86	8
	CP262	SM 52	13.6	0.85	10
	CP262	SM 59	13.8	2.03	12
	CP262	SM 66	14.2	1.45	6
T2	CH218	SM 34	17.3	1.26	10
	CH218	SM 35	18.2	1.64	5
	CH218	SM 36	18.9	1.62	7
	CH218	SM 37	19.8	1.12	5
	CH218	SM 39	21.2	1.11	7



(a) K1 Zone (b) T1 Zone (c) T2 Zone

Fig. 9 Time Histories of Surface Settlements

CONCLUSIONS

The foregoing discussions lead to the following conclusions:

1. In the Taipei Basin, the ground losses corresponding to settlements induced in 10 days after the passing of the shield vary from 0.5% to 1% for tunnels in uniform ground, being either sandy or clayey, and for tunnels in sands with thick clay covers . The ground losses for tunnels in clay with thin clay covers range from 1% to 1.5%.

2. The indices of long-term consolidation settlement, i.e., the α value which is the slope of settlement curve in the semi-log plot, range from 5mm to 14mm in the T1, T2 and K1 Zones.

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