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SOFT GROUND TUNNELING IN TAIPEI – PROBLEMS AND SOLUTIONS

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Abstract

This paper discusses a few problems encountered during shield tunneling for constructing the rapid transit systems in the City of Taipei. Most of these problems involved leakage at the interfaces between tunnels and shafts either during launching or arriving of shield machines. The situations were aggravated by the presence of a highly permeable water-bearing stratum at a close proximity of the tunnel portals where openings were made on diaphragm walls. The rest of problems were related to encounter of obstacles during driving of shield machines. Also discussed herein is the successful application of NATM tunneling in two sections of the route. The success per se is a milestone in the history of underground construction in Taipei in view of the poor ground conditions encountered.

Keywords: underground, tunneling, accident, groundwater, freezing, Taipei, Metro, MRT, TRTS

1. Introduction

The laying of the sewerage line along Mingtsu Road in the City of Taipei in 1976 is believed to be the first application of shield tunneling technique in Taiwan. Since then, the number of shield machines used, mainly for laying sewer lines and water mains, increased drastically year by year and reached its peak in 1994 when the construction of the Taipei Rapid Transit Systems (TRTS) was the most active. For constructing the Initial Network of TRTS alone, for example, 30 shield tunneling machines have been used up to now. There were quite a few problems encountered during tunnel driving and some of them led to catastrophic consequences. The occurrence of these problems was related to the presence of a highly permeable water bearing stratum at a close proximity to the tunnel portals, leading to excessive leakage. Furthermore, large tree trunks were encountered at a few places and as they were forced by the shield machines the face became unstable resulting in ground collapse.

This paper discusses the nature of these problems and the remedial measures taken. Also discussed is the NATM tunneling in two sections of the route. Its success is a milestone in the history of soft ground tunneling in Taipei Basin.

2. Geology

A system map of the Initial Network of TRTS is depicted in Figure 1 [1] and soil profiles across the Taipei Basin are presented in Figure 2. As can be noted that at the surface is a thick layer of the Sungshan Formation. Toward the east and the north, silty clay dominates while in the central city area, where the Taipei Main Station is located, the six-sublayer sequence is evident. Toward the west, the way the various strata are interbedded becomes rather complex. Toward the south, ground becomes gravelly. A typical CPT profile obtained in the central city area of Taipei is shown in Figure 3 and the soil strengths obtained in laboratory tests are given in Figure 4. The soft nature of subsoils in the Sungshan Formation is readily apparent.

The Sungshan Formation is underlain by a water-bearing stratum, the so-called Chingmei Gravels, which contains gravels and sands of various sizes and is extremely permeable. This gravelly layer was the sole water supply for the entire Taipei City prior to the 70's. This tells how ample the water reserve is in this layer. It was responsible for several major failures during the underground construction of the Taipei Rapid Transit Systems [2,3,4,5].

3. Tunneling for Taipei Rapid Transit Systems

Of a total length of 86.8 km in the Initial Network, 19 km was completed by shield tunneling. There were 58 tunnel drives, averaging 655m per drive, mined by using

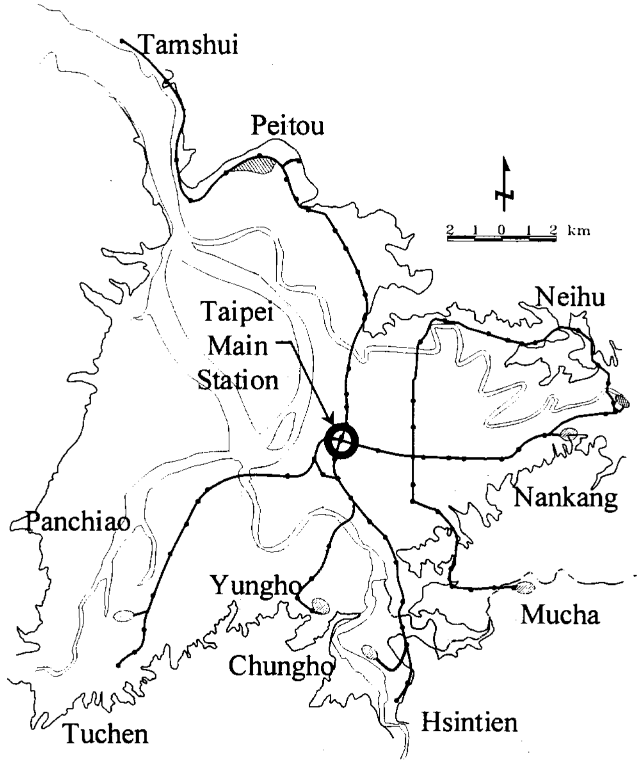

Figure 1 Initial Network of Taipei Rapid Transit Systems

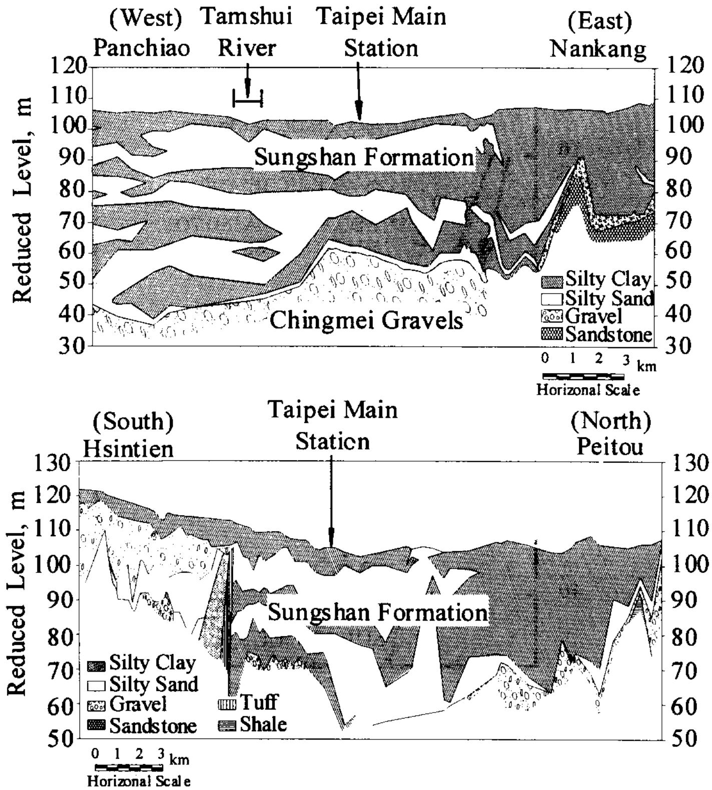

Figure 2 Geological profiles of the Taipei Basin

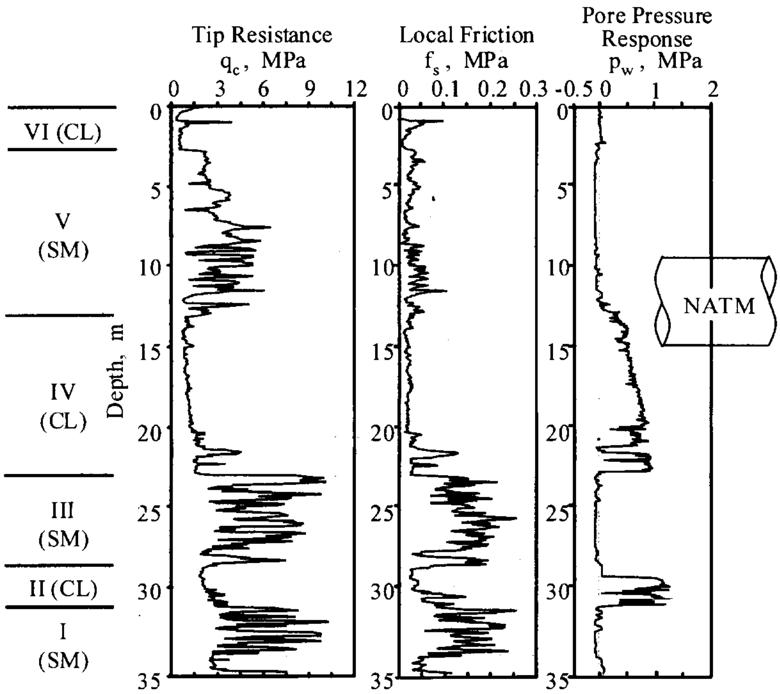

Figure 3. CPT profile in Central Taipei

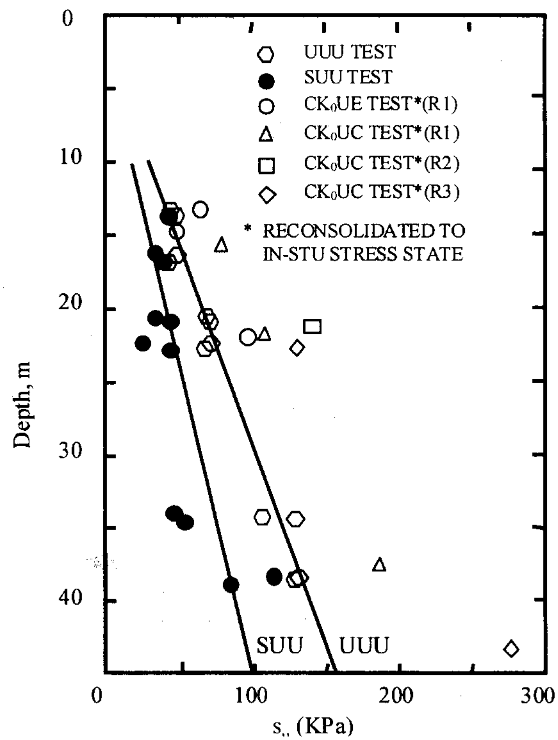

Figure 4. Undrained Shearing Strength of clays in the Sungshan Formation

28 earthpressure balancing type and 2 slurry type shield machines. Tunnels are either 5.4m or 5.6m in their inner diameters and reinforced concrete segments are typically 250mm in thickness and 1m in length. Tunnels are generally buried at depths of 10m to 20m below ground surface, with a few exceptions in which the tunnel inverts were as deep as 35m.

4. Problem with Methane

Methane was encountered in several boreholes during site investigations. Its presence is related to the capture of gas in dooms, mostly in Sublayer I, encapped by impermeable Sublayer II in the Sungshan Formation [6]. In one case, when drilling reached a depth of 28.65m, the eruption sent a jet of methane-water mixture to a maximum height of about 10m into the air and continued for more than 3 days. The concentration of methane was about 5% in this incident. Contractors have been warned of the possibility of encountering methane in tunnel drives and potential hazards. As a precaution, specifications require the concentration of methane be continuously monitored during tunneling and shield machines be equipped with detective devices and alarm systems. The power supply shall be automatically cut off when the concentration of methane reaches 1.25% and resume only after the concentration drops to 1% or below. To further reduce the risk, 11 holes were drilled along the route of the Chungho Line in an attempt to release the methane, if any. The capacity of ventilation in tunnels was increased form 780 cubic meters per minutes to twice as much during driving. Although methane was encountered at locations all over the Taipei Basin during site investigation, the problems, to the author's knowledge, were limited to the Chungho Line during TRTS constructions.

5. Problems with Obstacles

Large tree trunks, up to 1.5m in diameter and 5m in length, were often encountered, usually at depths of 10m to 20m, during excavations for constructing basements and TRTS stations [7]. Pieces of wood were frequently removed from the spoil during tunneling, however, very few major problems were reported except that conveyors or pumps were sometimes jammed. A large tree trunk nevertheless did stop the shield machine during driving of the Up-Track tunnel of Contract CC277 of the Chungho Line. It was reported that the daily progress of tunneling was reduced from 43 rings

(1m per ring) on 14 June, to 10 rings on 15 June, and to 4 rings on 18 June, 1996. Chunks of wood were observed for many times at the conveyor during this period. In the morning of 19 June, the machine was totally stuck during the driving of Ring 696 and a sinkhole of 3m in depth and 36 cubic meters in volume was found at surface right in front of the shield. It appears that a tree trunk had been pushed by the shield machine for 14m or so. Jet grouting, refer to Figure 5, was carried out in front of the shield for maintaining the face stability to allow workers to enter the earth chamber to free the cutter [8]. Two pieces of drift wood, with dimensions of 500mm x 200mm x 150mm and 400mm x 200mm x 140mm, were recovered in the earth chamber. For the remaining tunneling work to be carried out safely, the ground was treated by cement-bentonite grout using the TAM method. Wood fragments were washed out from several holes drilled for grouting. More tree trunks were found during the subsequent tunneling, particular in the section between Ring 715 and Ring 721. However, these tree trunks were clamped by the treated ground and were able to be scraped away by the advancing tunneling machine.

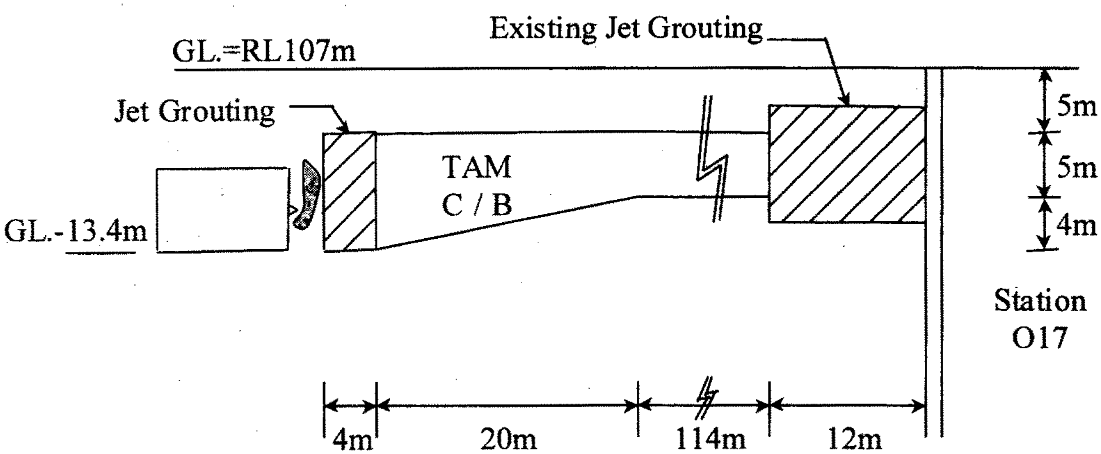

Figure 5 Ground Treatment at Up-Track Tunnel of Contract CC277

In another incident, a 125mm diameter steel casing of a borehole sunk during a previous site investigation encountered in the Down-Track Tunnel in the Hsintien Line choked the rotary conveyor and had to be removed by sending a worker into the earth chamber. This was much more difficult than what one might expect because of the high groundwater table together with high permeability of sands in Sublayer V (refer to Figure 3). Chemical grouting was attempted in vain in front of the face to stop water from entering the chamber. The operation was abandoned because of the fear that further grouting might glue the shield to the ground to the extent that driving would not be able to resume. Finally, pumping was carried out to lower the groundwater table to a level below the tunnel invert for the worker to be able to enter the chamber and to stay there safely for removing the steel fragments and repairing the damaged conveyer.

Steel fragments frequently appeared in spoil removed from tunnels, however, other than the one mentioned above, no problems were reported. This was due to the fact that modern shield tunneling machines have sufficient power and the cutters are strong enough to cut steel members as long as they are not too large in size. There were cases in which small RC piles and thin sheet piles were cut through. On the other hand, there were cases in which ground treated by jet grouting was too hard for shield machines to go through.

Figure 6 shows a situation encountered during tunneling in constructing the Tamshuei Line. A sinkhole of roughly 3m in depth and 75 m^3 in volume was found in front of the shield machine as the specialist subcontractor looked for a missing settlement rod installed for monitoring ground settlement. The cavity was covered by the RC pavement which did not show any signs of subsidence. In this case, jet grouting had been used to treat the ground at the back of the diaphragm wall to prepare for launching of the shield. Because the treated ground was too hard, driving of the shield was difficult since the very beginning and chemical had to be injected into the earth chamber as lubricant. Even so, worker had to go into the earth chamber to free the cutter from time to time. It was reported that the temperature of the spoil in the earth chamber was as much as 60°C. It is postulated that, as the cutter reached the end of the treated zone, a mixed-face situation was encountered. As most of the tunnel face was still in the treated ground, the shield advanced rather slowly. On the other hand, portion of the face was already in the natural ground and soil could easily be excavated and "sucked" into the earth chamber. From what was observed and experience learned elsewhere, it may be concluded that if the treated ground has an unconfined compressive strength of 40 MPa or above, shield driving is likely to encounter difficulties. This, however, certainly will depend on the capacity of the machine used. To avoid similar events from happening, it may be a good idea to have a transition zone with weaker strength at the end of the ground treated by jet grouting.

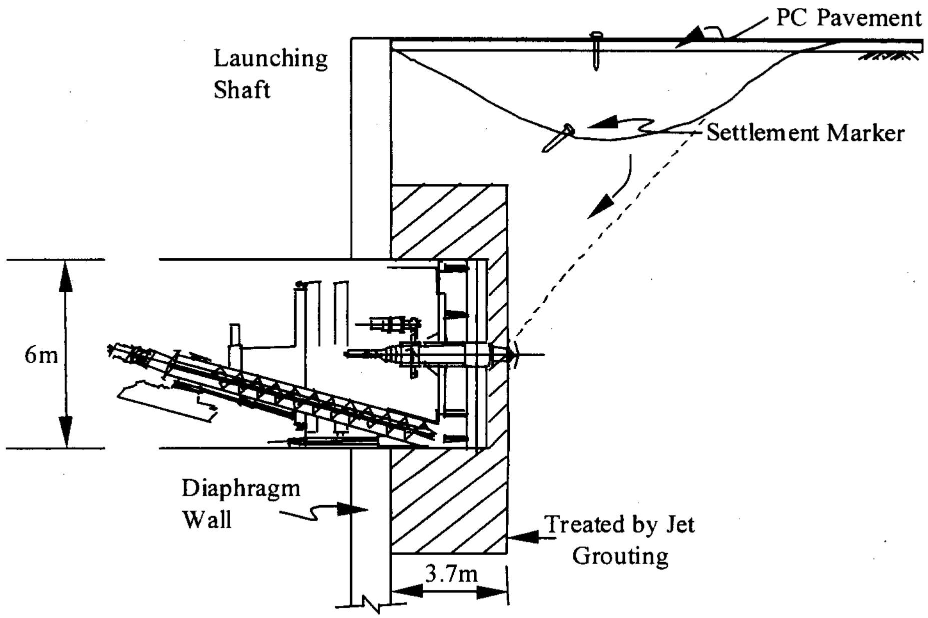

Figure 6 Tunneling Problem during Launching in Contract CT201A

6. Problems with Groundwater

There were a few major ground collapses which occurred either during launching from shafts or during arriving of shield machines at shafts. Although ground treatment is routinely carried out behind diaphragm walls, there is no way to ensure that treatment is uniform and the treated ground is perfectly watertight. The Chingmei Gravels is extremely permeable and is very rich in water. Therefore, if the opening made on diaphragm wall is too close to the Chingmei Gravels, once leakage occurred, soil surrounding the water path quickly liquefied and the flow usually became uncontrollable in hours. In the case shown in Figure 7, when the tunnel portal was enlarged for installing the flexible joint, ground subsided by several meters and a section of tunnel collapsed. As a result, 23 rings were seriously damaged and had to be replaced. Ground freezing was used to form a patching pad to seal off the portal for the shaft to be drained and cleaned. Subsequently, ground freezing was used again to form a shelter to surround the section of tunnel which was damaged for segments to be replaced [4].

In a second case, both of twin tunnels were damaged when the shield machine for

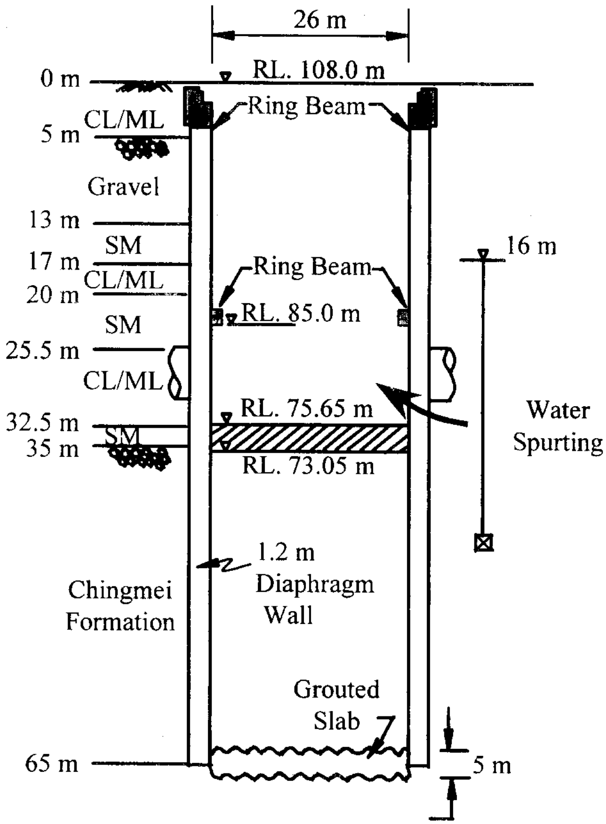

Figure 7 Grouted Plug at Ventilation Shaft in Contract CH221

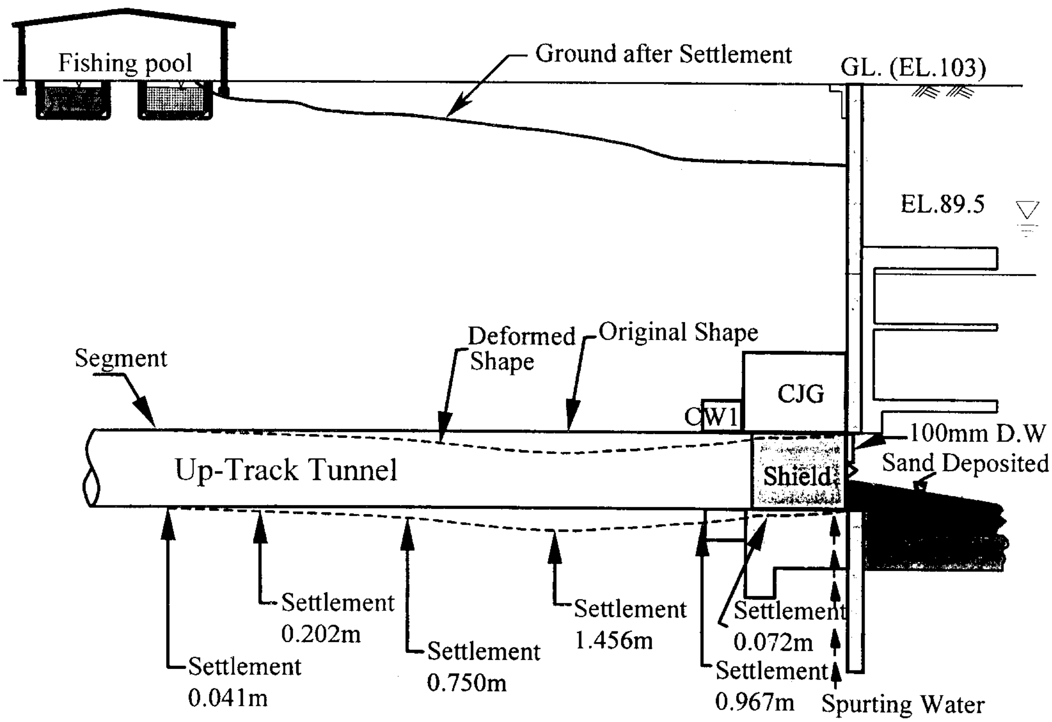

Figure 8 Settlement Profile at Arrival Shaft in Contract CP262

driving the Up-Track tunnel arrived and opening was made on the diaphragm wall of the shaft, refer to Figure 8. Ground freezing was adopted to seal off the hole and rehabilitation was carried out in compressed air [3]. A large piece of timber was found at where water spurted as the invert was exposed. Right next to this piece of timber is a pvc pipe which was presumably once used for drawing water from the Chingmei Gravels. It is postulated that as the shield machine pushed the timber, the integrity of the treated ground was destroyed resulting in leakage. The situation would not have been so serious if this pvc pipe were not there because the Chingmei Gravels is at a level of 20m below the invert. This pvc pipe, about 225mm in diameter, became a water channel connecting to the Chingmei Gravels [3,5].

7. Ground Settlements

Notwithstanding the many difficulties encountered, the tunneling operation in the Taipei Rapid Transit Systems is deemed successful. Ground loss in general ranges from 1% to 2% which are less than one-third of what were observed previously. Prompt grouting of the tail void made this drastic difference. Few problems were associated with ground settlements induced by shield tunneling. Heaves of an order of 10mm to 30mm were observed at quite a few places. Since in most of the tunnel drives, the pressures in the earth chambers were maintained at values corresponding to earthpressure coefficients of 0.5 to 0.7, heaves were unlikely to be related to driving of shields. On the other hand, there are convincing evidences that heaves were a result of grouting for filling up the voids at the tails of shields. They were more likely to occur during tunneling in clayey ground with overburden less than 12m. The pre-requisites for heave to occur are: 1) pressure greater than 350 kPa, and 2) volume of grout greater than 150% of the theoretical volume of the tail void.

8. NATM Tunneling

It is worthy of mentioning that the New Austrian Tunneling Method (NATM) was successfully used in boring two sections of the route which were too short for shield tunneling to be economical. In the first case, a 222m section of twin tunnels with crowns at depths varying from 8m to 11m, was driven in compressed air with air pressures up to 1.35 bar [9]. Although ground settlements were large, up to 170mm, the success was encouraging in consideration of the ground conditions as depicted in Figs. 3 and 4. The settlements would have been much less without the occurrence of two accidents, one caused by explosion of gas leaking from a gas pipe and the other caused by a power failure. Air pressures were partially lost during these two accidents. In the second case, a 54m section of the Up-Track tunnel and 44m of the Down-Track tunnel, with tunnel crowns at a depth of 10m, were dug with jet grouting as a auxiliary measure for maintaining the stability of face. The ground is clayey with an undrained strengths of about 50 kPa as depicted in Figure 4. Ground settlements were less than 50mm for the Up-Track tunnel and up to 200mm for the Down-Track tunnel. The poor performance for the Down-Track tunnel was due to the presence of utilities which made ground treatment difficult.

9. Conclusions

Much has been learned from tunneling in the construction of TRTS. Despite the many difficulties encountered, tunneling operation per se was successful. Nearly all the major accidents were associated with groundwater. Therefore, extra care shall be taken wherever there exist permeable water bearing strata at or near tunnel levels. The successful application of NATM tunneling is particularly encouraging in consideration of the poor nature of the subsoils. However, it shall be admitted that it is an extremely risky operation and success is not always warranted.

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