SOFT GROUND TUNNELING FOR TAIPEI RAPID TRANSIT SYSTEMS

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Soft Ground Tunneling for Taipei Rapid Transit Systems

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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. Also discussed are two cases in which the New Austrian Tunneling Method was used in soft ground. In one of these two cases, compressed air was used as an auxiliary measure for maintaining the face stability, and in the other ground improvement was applied. Although settlements were large, the success well proves the applicability of the method in very poor ground.

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. In addition to shield tunneling, the New Austrian Tunneling Method was used to mine two sections of routes of considerable lengths with success. In one of these cases, compressed air was used, and in the other ground improvement was applied, as auxiliary measures for maintaining face stability.

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In view of the soft nature of subsoils, these two cases are indeed milestones in the history of soft ground tunneling in Taiwan.

Taipei Rapid Transit System

The Initial Network, refer to Figure 1, of the Taipei Rapid Transit Systems consists of six lines, namely, the Mucha, Tamshui, Hsintien, Nankang, Panchiao and Chungho Lines, with a total of 79 stations and a total length of route of 86.8 km. The Mucha Line was open to revenue services in March, 1996 and the Tamshui and Chungho Lines were open in December of 1997 and 1998, respectively. The total ridership of all these three lines passed the mark of 100 million on 23 December, 1998. The rest of lines, except the extension of Panchio Line to Tuchen & the extension of Mucha Line to Neihu, will be open in the year of 2000. The Mucha Line is a medium-capacity system while the rest of lines are heavy- capacity systems. Mucha Line is now carrying an average of 40,000 passengers and Tamshui and Chungho

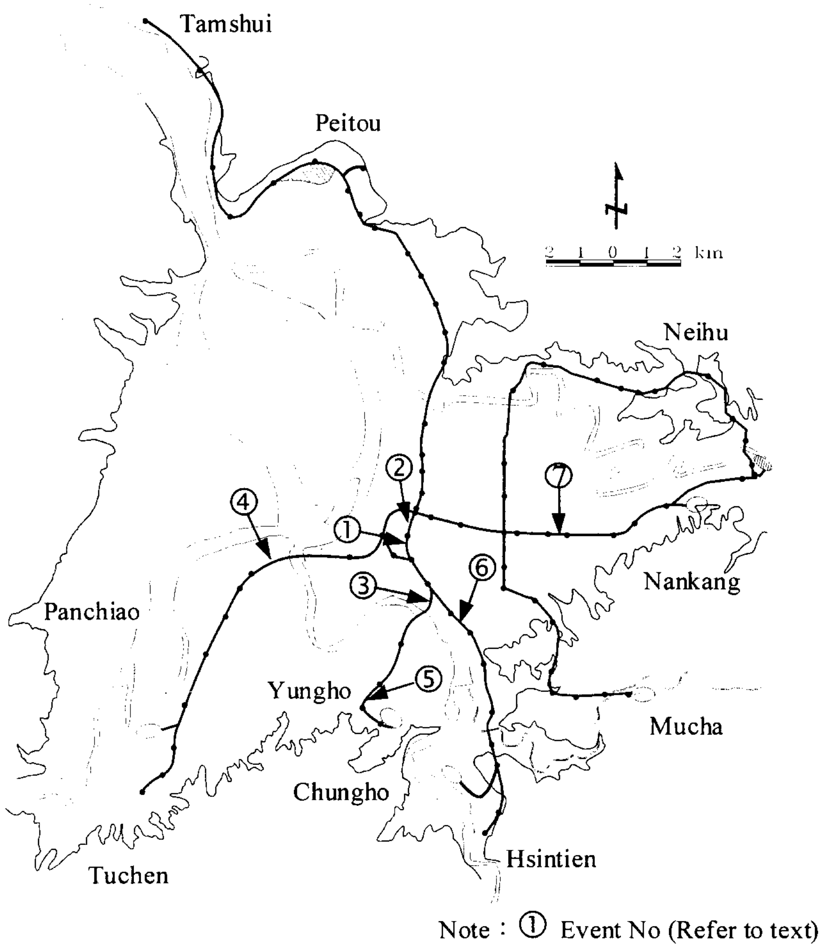

Figure 1. Initial Network of Taipei Rapid Transit Systems

Lines, together, are carrying an average of 200,000 passengers on each weekday.

Geology

An east-west and a north-south 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 stratigraphy becomes complex with silty sand and silty clay seams interbedded in a rather complicated manner. 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 the so-called Chingmei Gravels which contains gravels and sands of various sizes and is extremely permeable and rich in water reserve. This gravelly layer was the sole water supply for the entire Taipei City prior to the 70's. It was responsible for several major failures during the underground construction of TRTS.

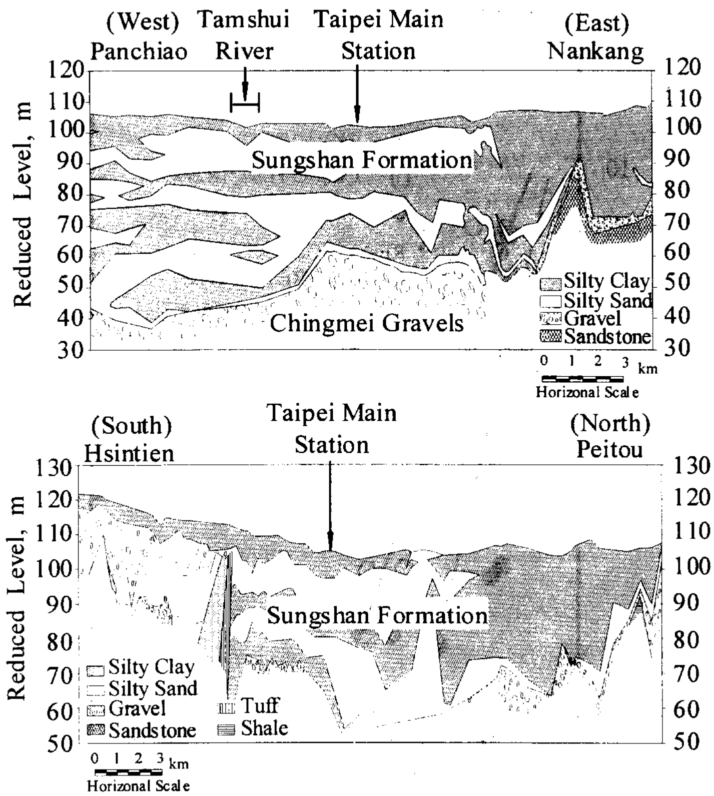

Figure 2. Geological profiles of the Taipei Basin

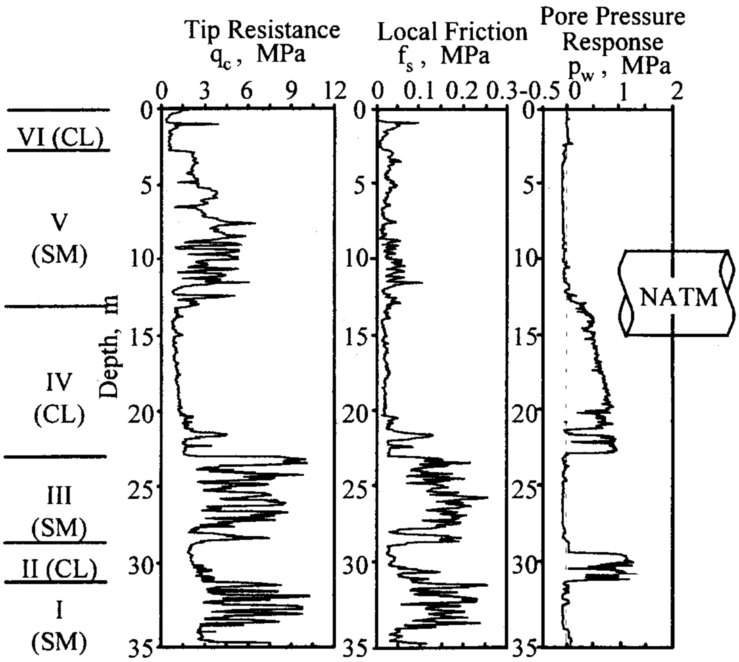

Figure 3. CPT profile in Central Taipei

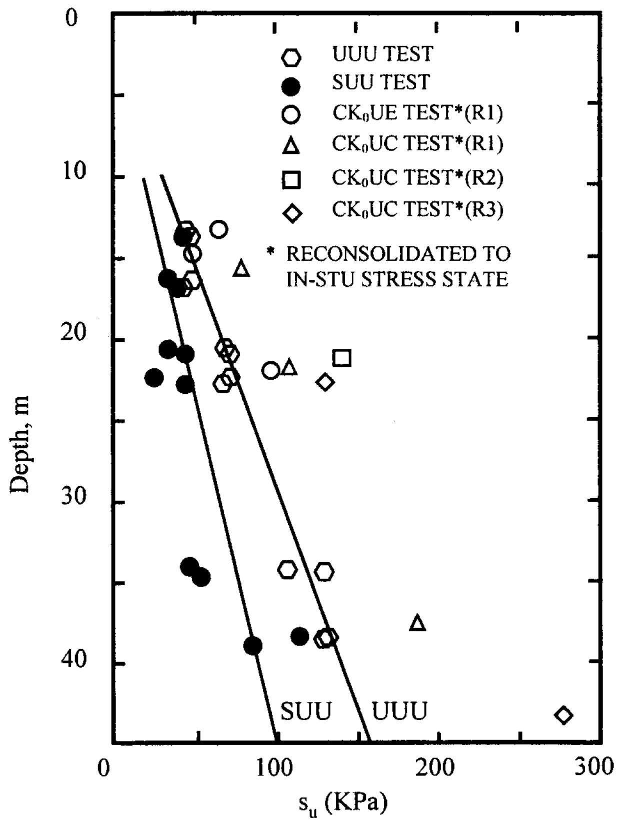

Figure 4. Undrained shearing strength of clays in the Sungshan Formation

Shield tunneling

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 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. The progress of tunneling was in general satisfactory except that at a few locations the progress was much hampered by obstacles. The first major obstacle was a 125mm (5 in.) diameter steel casing of a borehole left in place in a previous site investigation encountered in the Down-Track Tunnel in the Hsintien Line (Event 1 in Figure 1). Steel fragments choked the screw 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 serious 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 5 shows a situation encountered during tunneling in constructing the Tamshuei Line (Event 2 in Figure 1). A sinkhole of roughly 3m (10 in.) in depth and 75 m^3 ($1m^3 = 1.3$ cubic yard) 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 machine. 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 (140°F). It is postulated that, as the cutter reached the end of the treated zone, a mixed-face situation was encountered. As most of the face was still in the treated ground, the shield advanced rather slowly. On the other hand, portion of the face was already in

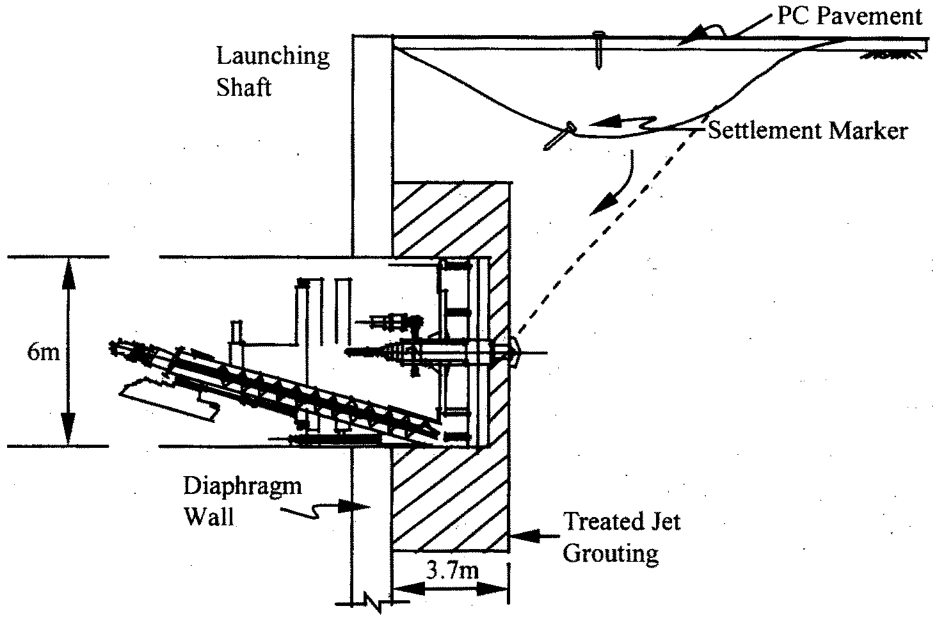

Figure 5. Problem with Ground Treatment during Launching of Shield Machine

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 4 MPa (40 tsf) or above, shield driving is likely to encounter difficulties. This, however, certainly will depend on the capacity of the machine used and the uniformity of ground treatment. 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.

There were a few major collapses of ground which occurred either during launching from shafts or during arriving of shield machines at shafts. Although ground treatment is routinely carried out as illustrated in Figure 5, 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 reserve. Therefore, if the opening made on diaphragm wall is too close to the Chingmei Gravels, soil surrounding the water path quickly liquefied once leakage occurred and the flow usually became uncontrollable in hours. In one case in which leakage occurred when the tunnel portal was enlarged for installing the flexible joint (Event 3 in Figure 1), ground subsided by several meters and a section of tunnel was damaged. A total of 23 rings were seriously distorted and had to be replaced (Hwang, et. al., 1998). In another case in which ground subsided by several meters when the shield machine was making the breakthrough on the diaphragm wall (Event 4 in Figure 4), 39 rings in one tunnel drive and 34 in the other were damaged and two shield machines were submerged (Ju, Duann and Tsai, 1998).

Large tree trunks, up to 1.5m in diameter and 5m in length, were often encountered, usually at depths of 10m to 20m, during deep excavations (Ju, Kung and Duann, 1997). During TRTS constructions, pieces of wood were frequently removed from the spoil during tunneling, however, few problems were reported. A large tree trunk nevertheless did stop the shield machine during excavation for the Up-Track tunnel of the Chungho Line (Event 5 in Figure 1). It was reported that the daily progress rate was reduced from 43 rings (1m per ring) to 4 rings on the day prior to the event. It appears that this tree trunk had been pushed by the shield machine by more than ten meters. As the advancement of the shield machine was obstructed, the earthpressure balancing mechanism was destroyed and soil was "sucked" into the earth chamber in a manner similar to what was observed in Event 2 (refer to Figure 5). A sinkhole of 5m (16 ft) in diameter occurred right above the head of the shield machine. Jet grouting was carried out in front of the shield and compressed air was applied for workers to enter the earth chamber to free the cutter. Two pieces of drift wood, 500mm (20 in.) and 400mm (16 in.) in length, were recovered in the earth chamber.

NATM Tunneling

In this part of the world, the so-called "New Austrian Tunneling Method" appears to have deviated from its original context of being principally an observational method for tunneling and has been adopted to mean nearly all types of tunneling without using shields. However, the essence of the method is missing in the way that contracts are rigid and do not allow for the flexibility of varying the designs during constructions.

The twin tunnels in a 222m section in th Contract CH221 of the Hsintien Line were bored by using the NATM method (Event 6 in Figure 1). They were buried in the Sungshan Formation with their crowns at depths varying from 8m to 11m below the ground surface, refer to Figure 3 for profile. The soft ground called for the use of compressed air to a maximum of 1.35 bar. Construction was carried out in such a way that the two tunnels were inter-connected, as shown in Figure 6, by a cross drift so that both tunnels were able to be pressurized by using a single set of compressed air facility. Excavation was carried out in five stages. Stage 1 excavation was carried out in free air for providing a space to house the compressed air plant. The rest of excavation was carried out in compressed air. Air pressure was not released till both tunnels were fully excavated and primary lining was completed.

The upper heading was kept at a distance of 2m to 4m ahead of the lower heading. As depicted in Figure 7, lattice girders were installed at 1m intervals and the tunnels were protected by shotcrete, 250mm in thickness, and wire mesh as primary lining. For maintaining the stability of the headings, steel lagging sheets, 6mm in thickness, 200mm (8 in.) to 300mm (12 in.) in width and 2m (6 ft) in length, were closely spaced to make a canopy. The tunnels were finally lined by 350mm (14 in.) reinforced concrete as permanent lining.

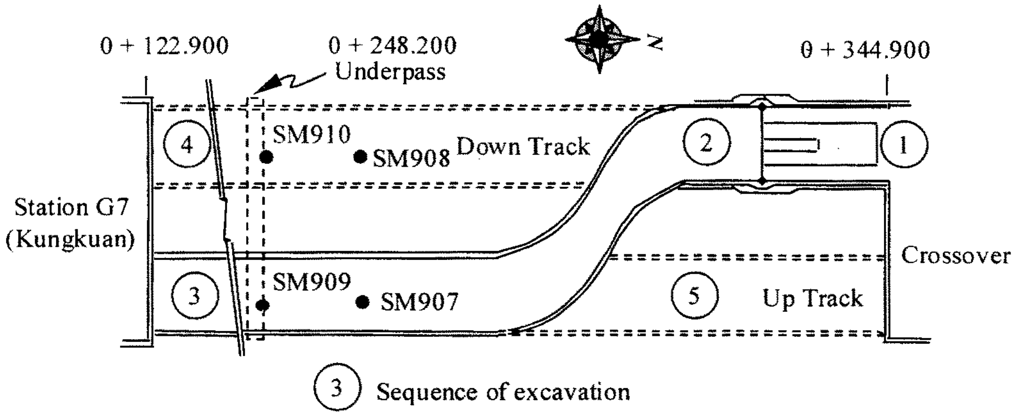

Figure 6. Plan of NATM tunnels in Contract CH221

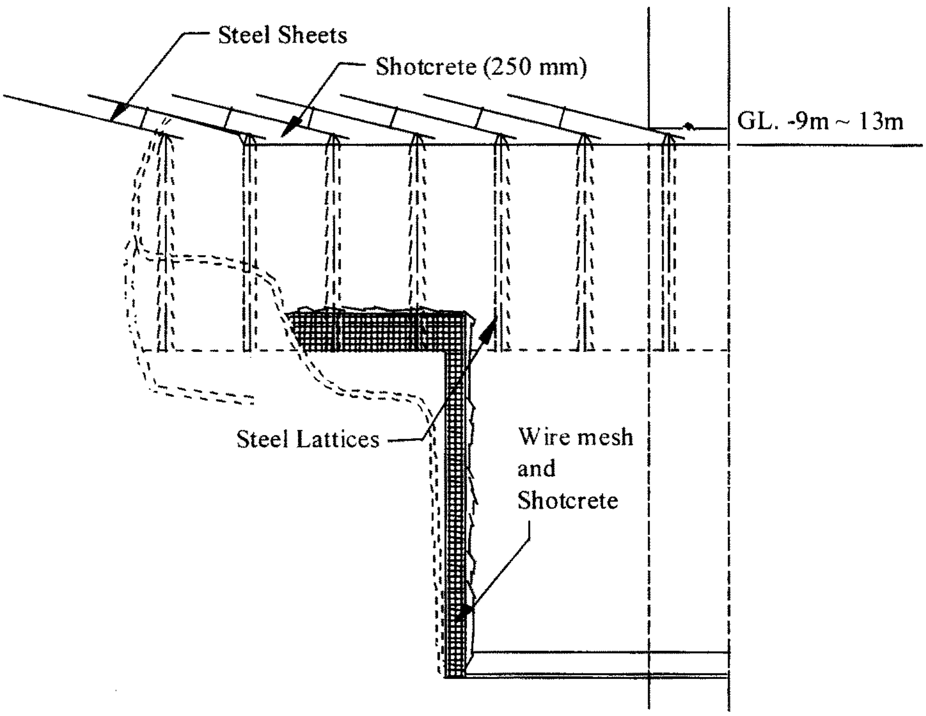

Figure 7. Profile for NATM tunnels in Contract CH221

The consumption of compressed air was about 110 m^3/min （1 cubic meters = 1.3 cubic yard）, refer to Figure 8, when tunneling was carried out in the Up-Track tunnel in Stages 2 and 3 excavation before a layer of gravel was first encountered at the face at the halfway of the drive. It increased to 270 m^3/min by the time the heading reached the end of drive of the Up-Track tunnel. It was maintained at 170 to 190 m^3/min during the Stage 4 excavation for mining the Down-Track tunnel. Again, as the gravel layer was encountered, the air consumption increased to a maximum of 280 m^3/min and the four compressors, with a power of 340 kilo-watts each, was fully loaded. As the tunnels were fully lined, the air consumption dropped to 140 m^3/mm.

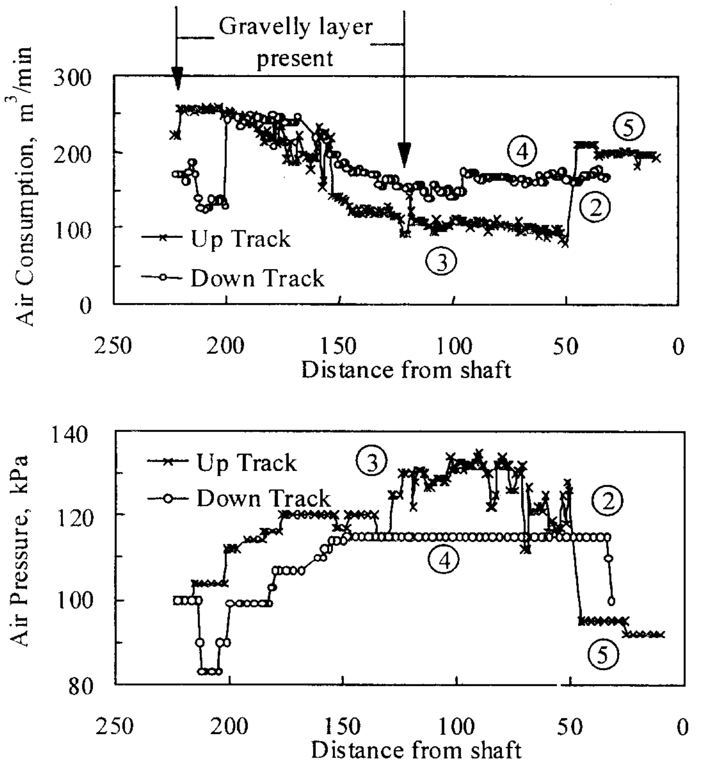

Figure 8. Air pressure and consumption for NATM tunnelling

Figure 9 shows the settlement records and, as can be noted that, ground settlements were significantly affected by two events. In the first event, an explosion due to the ignition of gas leaking from a gas line caused much panic of residents. As a precaution, the pressure of compressed air was lowered from 1.2 bar to 0.4 bar and was maintained at that level for about half a month. In the second event, a the malfunction of a transformer disrupted the electrical supply and the pressure of compressed air dropped to 0.2 bar in 12 hours before the transformer was replaced and the electrical supply was back to normal.

The second application of NATM Method in soft ground was in Contract CN256B of the Nankang Line, 54m (177 ft) for the Up-Track and 44m (144 ft) for the Down-Track (Event 7 in Figure 1). Figure 10 is a plan showing the layout of the tunnels and the locations of settlement markers. A longitudinal section of the Up-Track tunnel is given in Figure 11. Jet grouting to the west of the underpass was carried out previously and the shells of the two shield machines were left in place by the contractor of Contract CN256. Jet grouting underneath the underpass was carried out by the contractor of Contract CN256A when the underpass was constructed. Jet grouting to the east of the underpass was carried out by this contractor, i.e., the contractor of Contract CN256B.

The progress of the Up-Track tunnel was quite satisfactory with ground settlements in general less than 50mm (2 in.). Tunnel convergence and settlement of the crown were within 10mm (0.5 in.). Settlements above the Down-Track tunnel were rather large, up to 240mm (9.5 in.). The drastic difference in behavior between the two tunnel drives was due to the fact that ground treatment was difficult for the Down-Track tunnel because of the presence of utilities. The recovery of cores was 50% for the Up-Track tunnel and below 10% for the Down-Track tunnel.

Discussions

Notwithstanding the many difficulties encountered, the tunneling operation in the construction of the Taipei Rapid Transit Systems is deemed successful. Ground loss in general ranges from 1% to 2% which are far less than what were observed previously. The drastic improvement in performance was due to the prompt grouting of tail voids. In quite a few sections of routes, ground heaves were observed. Ground heaves were found to be caused by back grouting of tail voids, rather than by the pressure on the tunnel face. The progress of tunneling was impressive with a peak production rate of 47 rings a day. However, such an extraordinary rate is not advisable as ground settlements tend to become large because back grouting may not be able to catch up with the progress.

Although ground settlements were large in comparison, the successful completion of the two sections of tunnels using the NATM method was a remarkable achievement in consideration of the softness of subsoils. However, it must be admitted that NATM tunneling in soft ground shall be left as the last option because it is a highly risky operation. This is particularly true if compressed air is used as an auxiliary measure for maintaining face stability. Many labors suffered from diver's disease (aeroembolism) due to improper decompression. Ground treatment by grouting is a viable alternative. However, the quality of treatment is difficult to be ascertained, particularly in clays. Furthermore, the presence of utilities is often a major cause for poor treatment.

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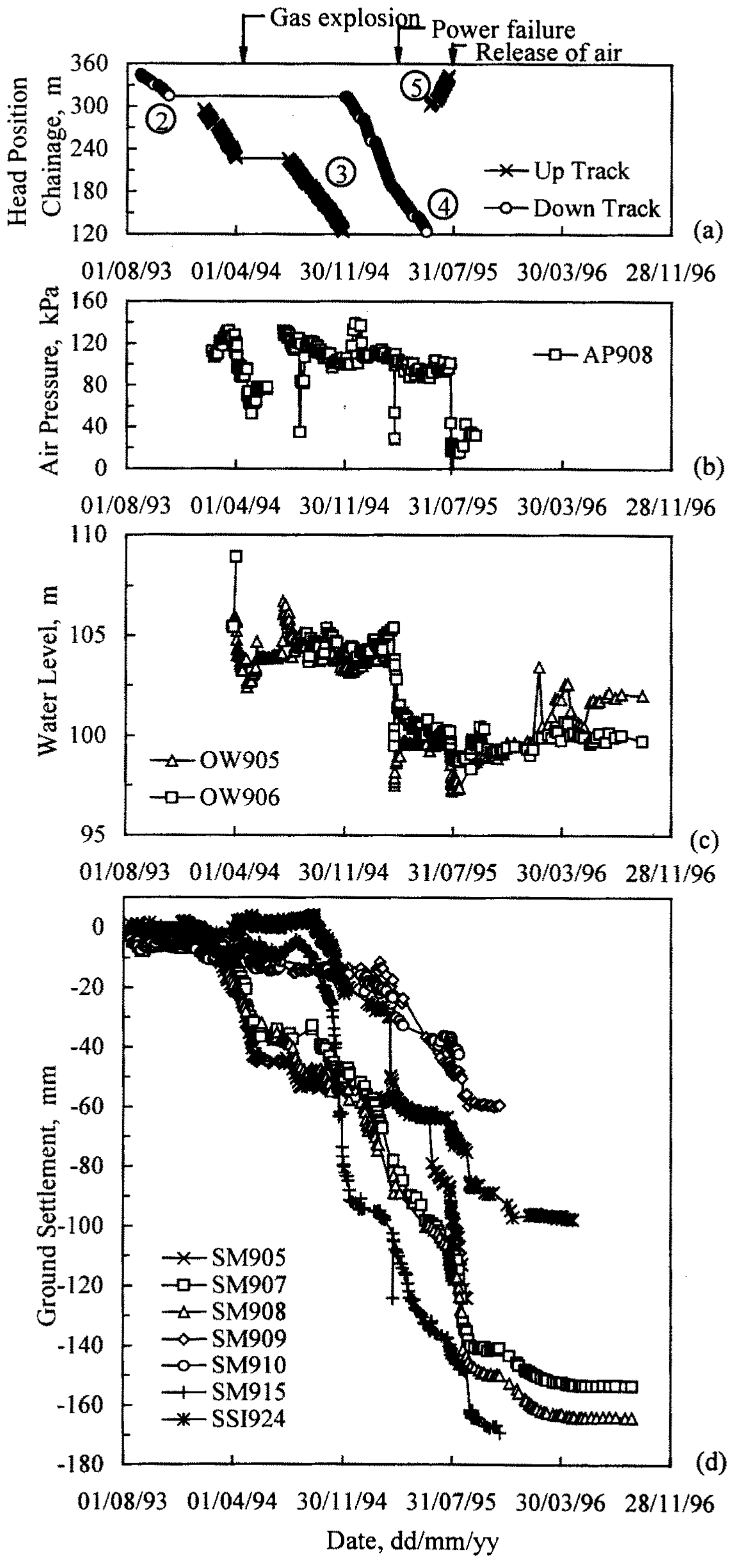

Figure 9. Progress of CH221 NATM tunnelling and instrument readings

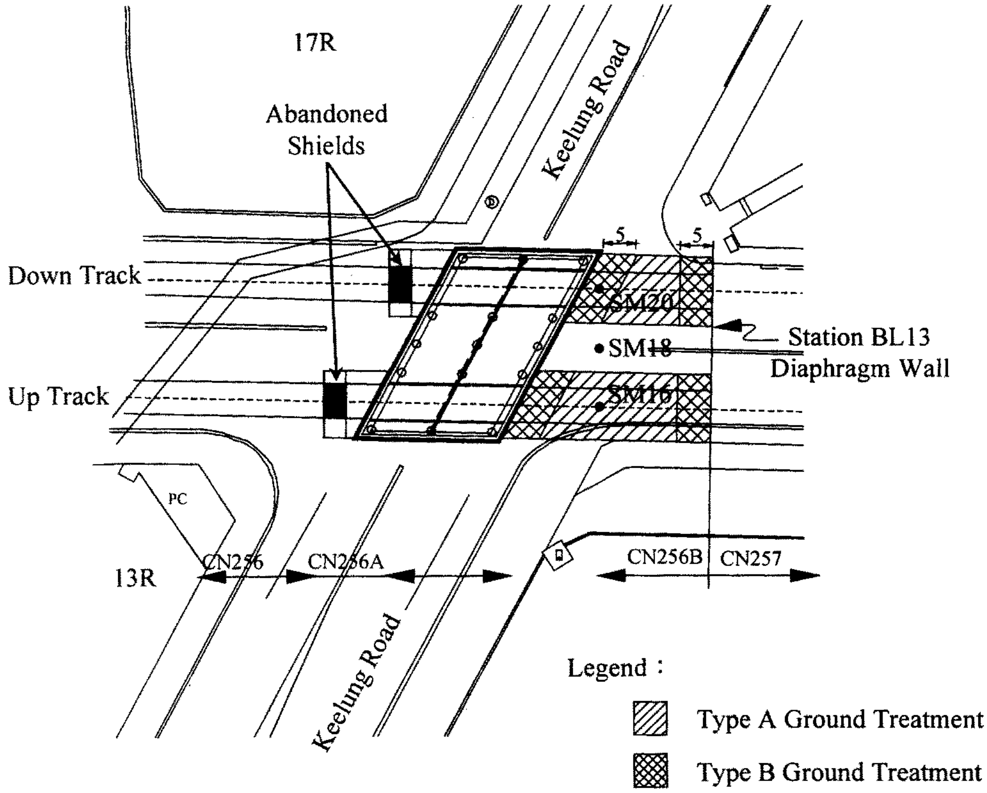

Figure 10. Layout of CN256B NATM tunnelling

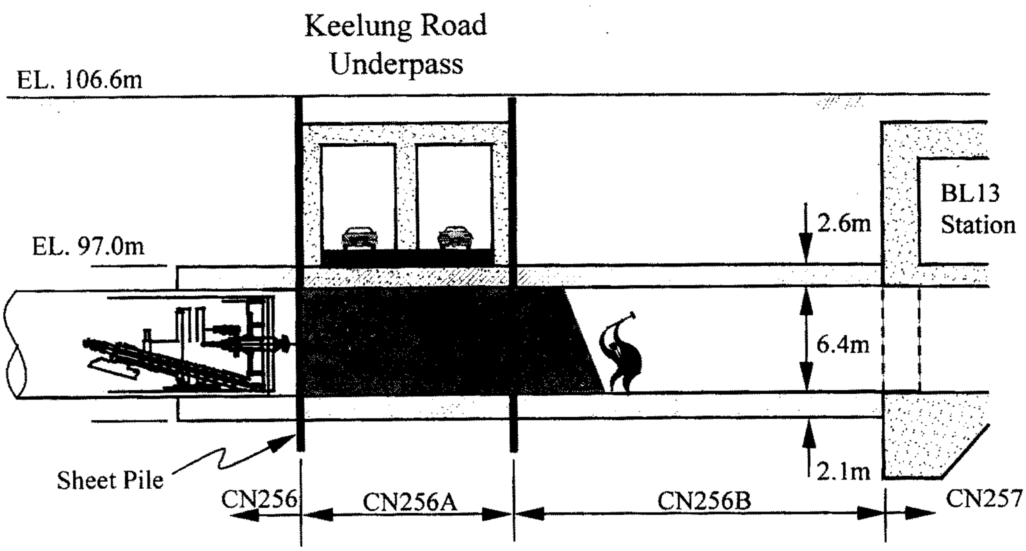

Figure 11. Schematic view of CN256B NATM tunnelling