

CONSTRUCTION OF THE TAIPEI RAPID TRANSIT SYSTEMS

by

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Construction of the Taipei Rapid Transit Systems

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Abstract

Construction of the Taipei Rapid Transit Systems began in 1987. Two of the six lines in the Initial Network, namely, the Mucha and the Tamshui Lines were completed in 1996 and 1997, respectively. The remaining four lines, ie., the Hsintien, Chungho, Nankang and the Panchiao Lines, are still under construction at the time this paper was prepared (June, 1998). The Initial Network has a total route length of 86.8 kilometers of which 31.6 kilometers is elevated, 9.5 kilometers is at-grade and the remaining 45.7 kilometers is totally underground. Because the ground conditions in the Taipei Basin are poor, it is not surprising to encounter numerous technical problems during the constructions. Presented herein are cases related to the geological features unique to the Taipei Basin, represented by groundwater problems caused by a very permeable and water-rich gravelly stratum underlying the young sediments in which the transit lines are buried.

Introduction

The City of Taipei was promoted to be a special municipality in 1967 and has been funded by the central government to become an international city since then. It soon became the commercial, cultural as well as political center of Taiwan and possesses the densest population on the island. As the city expanded, it gradually absorbed its suburbs to become a metropolis. As can be noted from Figure 1 that the Taipei Metropolis includes the 12 administrative districts of the City of Taipei and the 16 nearby townships in the Taipei County with a total area of 837 square kilometers. It is roughly 15 kilometers in radius measured from the Taipei Main

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Station. Accompanied by the economic boom in the 70's and 80's, the number of vehicles in the metropolis increased dramatically. Similar to all other major cities around the world, traffic jam has become a daily nightmare for the citizens of Taipei. The population in the Taipei City alone has increased by 1 million in the past three decades to the present metropolitan area population of 3.5 million in 1998, and the number of passenger cars has increased by 38 times during the same period. On the other hand, the road surface shared by each car decreased by an annual rate of 5.4%. These figures clearly indicate the seriousness of the traffic problem in the city.

The TRTS Networks

The Department of Rapid Transit Systems (DORTS) was set up on 23 January 1987 to be responsible for the planning, design and construction of the Taipei Rapid

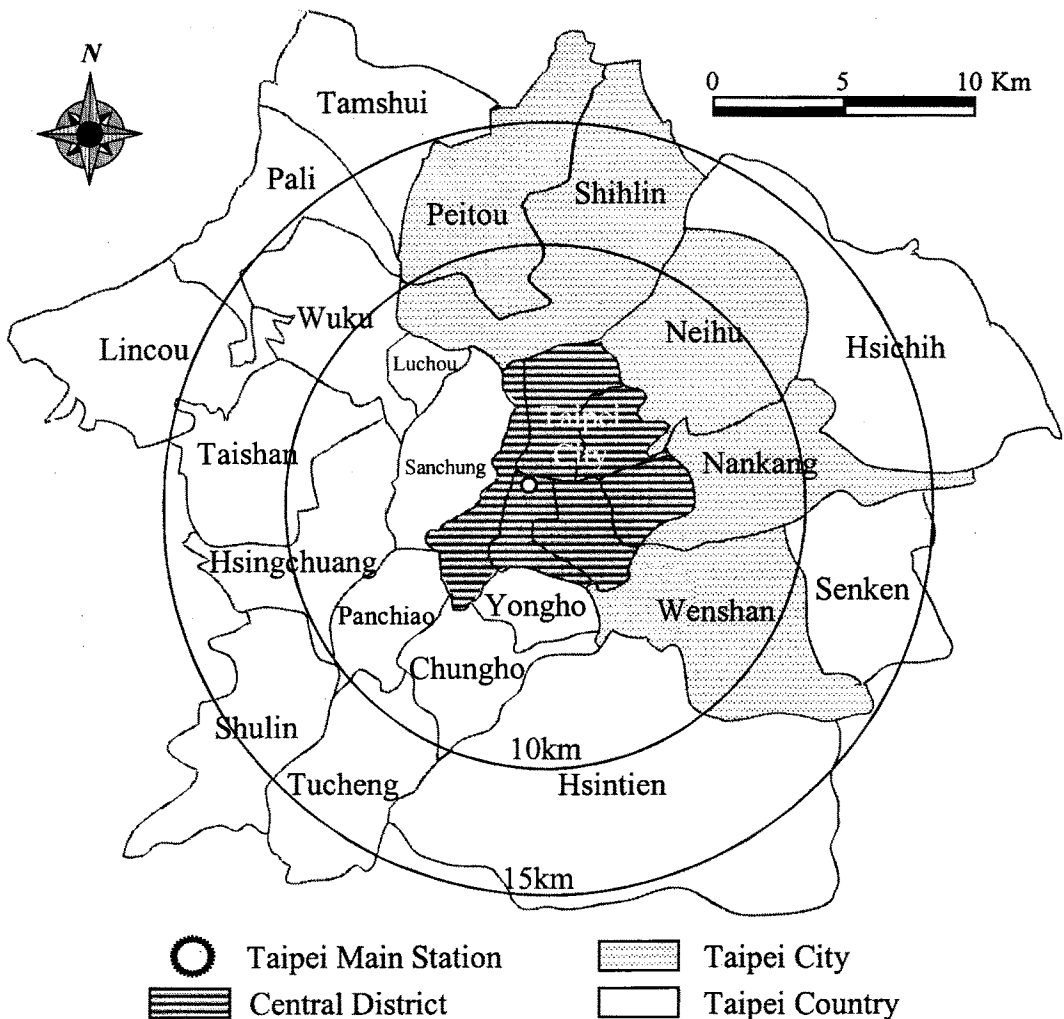


Fig. 1 Taipei Metropolitan Area

Transit Systems (TRTS), the first rapid transit system in Taiwan, to alleviate the growing problem of traffic jam in the City of Taipei. DORTS has set the year of 2021 as the target year for the completion of the entire program which is to be implemented in two phases. As depicted in Figure 2, the Initial Network comprise 6 lines with a total of 79 stations for a total budget of NT\$440 billion (US\$16 billion in 1990). Of the total route length of 86.8 kilometers in the Initial Network, 31.6 kilometers is elevated, 9.5 kilometers at-graded and 45.7 kilometers underground. The so-called Long-Term Network comprises 6 more lines and is 83.5 kilometers in length. There are 67 stations in the Long-Term Network.

The six lines in the Initial Network are as follows:

- Tamshui Line - running from Tamshui Station (R33) to National Taiwan University Hospital Station (R12), is 22.8 kilometers in length and has a total of 20 stations and one depot which is the main depot of the entire TRTS system. The portion of the route in the city, 2.8 km in length, is underground. The rest of route is partly at-grade and partly elevated.
- Hsintien Line - running from National Taiwan University Hospital Station (R12) to Hsintien Station (G01), is 10.3 kilometers in length and has a total of 11 stations and one depot. The entire line is underground.
- Nankang Line - running from Hsimen Station (BL6) to Qungyang Station (BL16), is 11.5 kilometers in length and has a total of 12 stations and one depot. It will be extended to Hsichih Park Station (BL18) at a later date. The entire line is underground.
- Panchiao Line - running from Hsimen Station (BL6) to Panchiao Station (BL1) is 7 kilometers in length and has 5 stations and one depot. The Tochen Extension to Yungning Station (BL37) is 5.5 kilometers in length and has 4 stations. The entire line is underground.
- Chungho Line - running from Chungho Depot and Nanshih Chiao Station (O19) to Kuting Station (O15/G10) of the Hsintien Line, is 5.4 kilometers in length and has a total of 4 stations and a depot. The entire line is underground.
- Mucha Line - running from Taipei City Zoo Station (BR13) to Chungshan Middle School Station (BR2), is 10.9 kilometers in length and has 12 stations and one depot. The entire line is elevated. It may be extended to Neihu in the future with a length of 12.9 kilometers and a total of 11 stations and one depot. Whether this extension is to be elevated or underground is yet to be decided.

A 1.6 kilometer Maintenance Track will run from Hsimen Station (BL6) to Chiang Kai Shek Memorial Hall Station (G11) to facilitate trains serving the Nankang and Panchiao Lines to transfer to the Peitou Main Depot for maintenance purposes. There is only one station (G12: Hsiao Nanmen Station) along the route.

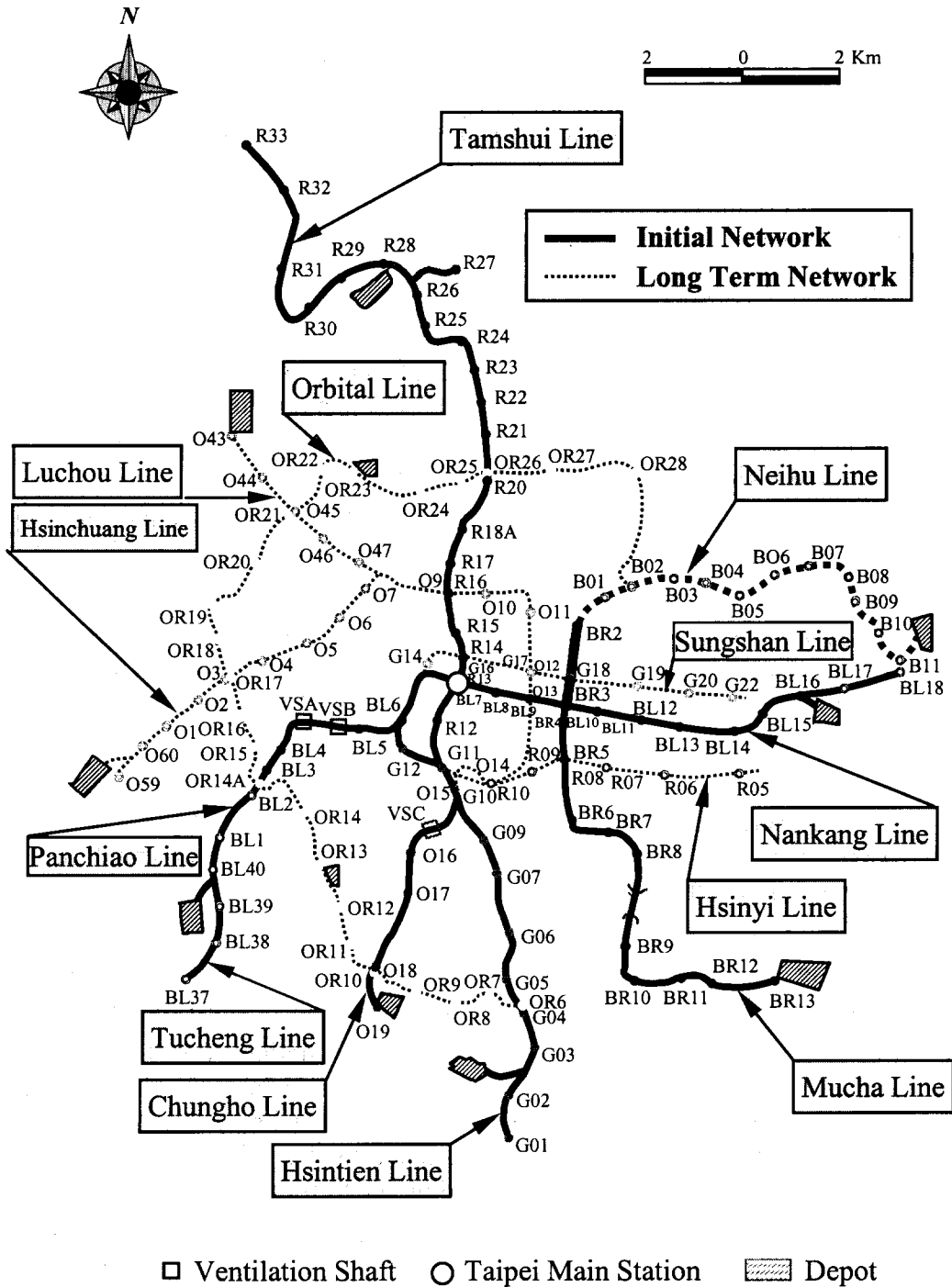


Fig. 2 The Taipei Rapid Transit System

Mucha Line is a line for medium-capacity trains with a capacity of transporting 30,000 passengers per hour in each direction and all the rest of the lines are for heavy-capacity trains with a capacity of transporting 50,000 passengers per hour.

The Mucha Line was opened for revenue services in March, 1996 and the Tamshui Line was opened in March, 1997. The Chungho Line and the northern section of the Hsintien Line, between Station O15/G10 and Station R13, are scheduled to be opened at the end of 1998 so trains will be able to run from Tamshui in the very north to Chungho in the very south. The whole Hsintien Line is scheduled to be in service at the end of 1999 and the western half of the Nankang Line, between R13/BL7 Station and BL10 Station, will be available at the same time to link the Mucha Line with Tamshui/Hsintien/Chungho Lines. The entire Nankang and Panchiao Lines, except the extensions at the east and the west ends, will be opened in the year of 2000.

As can be noted from Figure 2 that the Long-Term Network includes the Hsinyi, Sungshan, Sanchung-Hsinchung, Luchou, and Orbital Lines. Also included in the Network is a link (not shown in the figure) to the Chiang Kai Shek International Airport (about 30 km to the west of the city center). This is to be a build-operate-transfer (BOT) project to be completed in five years. A contractor was selected as a candidate for negotiation this May and the contract award is expected at the end of the year.

Generally speaking, all the lines in the Initial and the Long-Term Networks, except the Orbital Line, focus on transferring commuters to, and/or away from, the central city area. The Orbital Line, on the other hand, links the suburbs so people can travel to neighboring townships without entering the city. The ultimate goal is to develop these townships to become satellite cities to disperse the population.

Regional Geology and Groundwater Conditions

The City of Taipei is located in the Basin which is a structural basin formed by the subsidence of napes between thrusts in the foothill range of northwestern Taiwan as a result of tectonic movements during the Pliocene or Pleistocene eras. The Basin is approximately 243 square kilometers in area. As shown in the geological map in Figure 3, it is enclosed by the Tatun Volcanic Group on the north, Lincou Tableland on the west, and a hilly terrain of Tertiary Sedimentary rock on the southeast. It is dissected by the Tamshui River and its three tributaries, i.e., the Keelung River, Tahan Creek and the Hsintien Creek.

As depicted in Figure 4, there are five major faults running across the Basin: the Hsinchuang, Kanchiao, Keelung, Taipei, and the Hsintien Faults. These faults are generally northeast or east-northeast in bearing. The Basin is filled with recent alluvium and the Quaternary unconsolidated materials, which are underlain by the Tertiary Sedimentary rock, except that in part of the Peitou area the unconsolidated

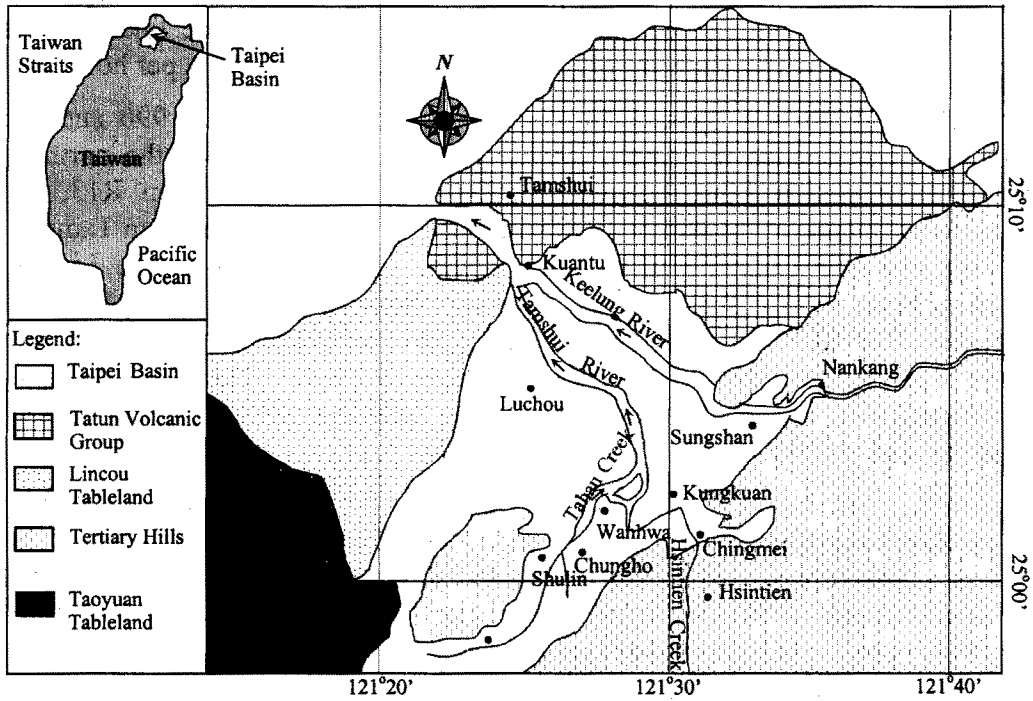


Fig. 3 The Taipei Basin and Its Surroundings

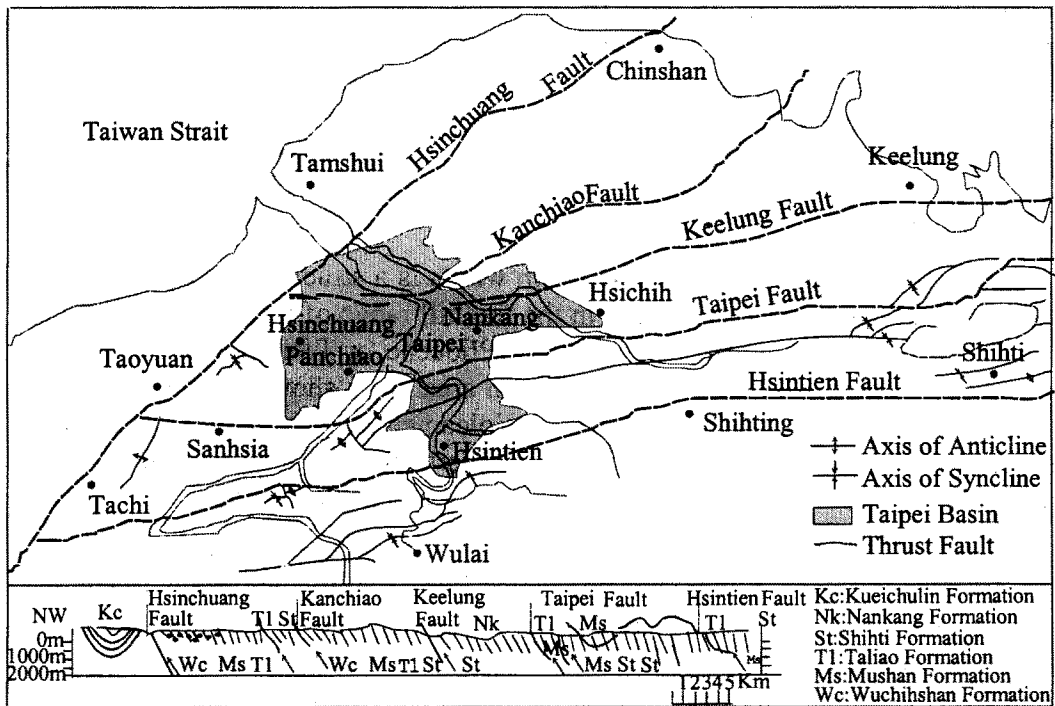


Fig. 4 The Tectonic Map of Taipei Basin Area

materials are underlain by the volcanic rock of the Tatun Volcanic Group. The thickness of the unconsolidated materials reaches a maximum of 500 meters. These unconsolidated materials in the basin can be divided into four major formations: the Hsinchuang Formation, Chingmei Formation, Sungshan Formation and the top soil in an ascending order. Please refer to Figure 5 for descriptions of these formations.

The Hsinchuang Formation exists at a depth too great to be a concern. The Chingmei Formation consists of gravels, and sometimes boulders, intercalated by sand layers and is about 140m maximum in thickness. The diameter of the boulders in the Chingmei Formation may even exceed 600mm. The Chingmei Formation is the bearing stratum for most of the pile foundations supporting the TRTS structures.

The Sungshan Formation overlying the Chingmei Formation, comprises an alternation of silty sand (SM/ML) and silty clay (CL/ML). It is, refer to the east-west profile shown in Figure 6, the major formation in which the TRTS structures are buried. The thickness of the Sungshan Formation ranges from 40 to 70 meters in the city area. A typical profile obtained in the central city area by using piezocone is given in Figure 7 and, as can be noted, the various sublayers are clearly identifiable. The undrained shearing strengths of the clayey layers are depicted in Figure 8. The

Formation		Thickness, m		Soil Description
SF	Top Soil CL,CL-ML	1-6	6	Yellowish brown clay
Sungshan Formation	Sublayer 6, ML	2-8	40-70	Grayish black silt
	Sublayer 5, SM	2-20		Gray silt fine sand
	Sublayer 4, CL,ML	6-29		Gray silt clay($\leq 10\%$ sand)
	Sublayer 3, SM	0-19		Gray medium dense silt fine sand with shells
	Sublayer 2, CL/ML	0-19		Gray silt clay(45%~70% silt)
	Sublayer 1, SM	0-15		Medium dense to dense sand with about 20% fine content
	Chingmei Formation	0-140		Yellowish brown gravel $\phi = 100-200$ mm
	Hsinchuang Formation	0-120		Gray-blue silt clay intercalated by 5-15m thickness of gravel
Tertiary Sedimentary Rock (Volcanic Rock in part of Peiton-Area)				

Fig. 5 Logging of Central City Area of Taipei

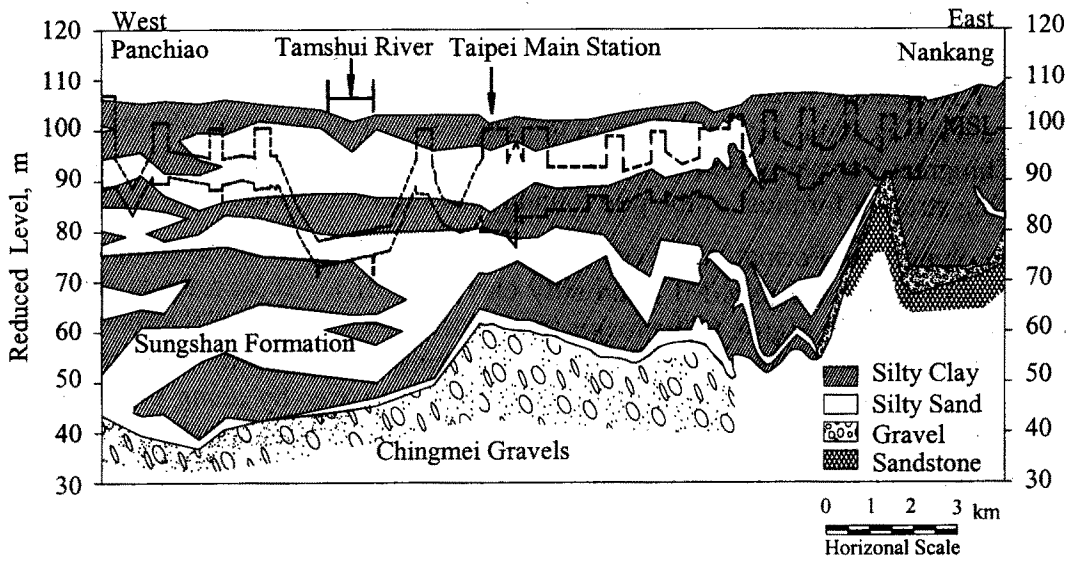


Fig. 6 Geological profile of the Taipei Basin

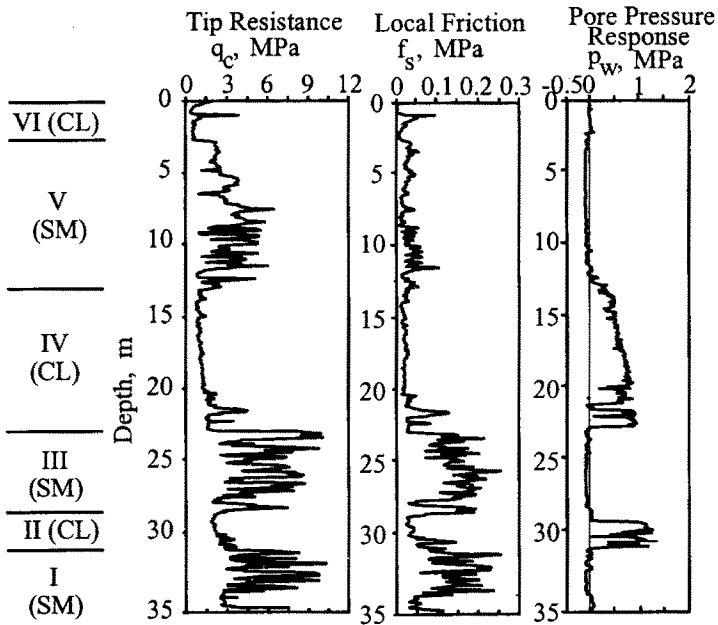


Fig. 7 CPT profile in Central Taipei in the Sungshan Formation

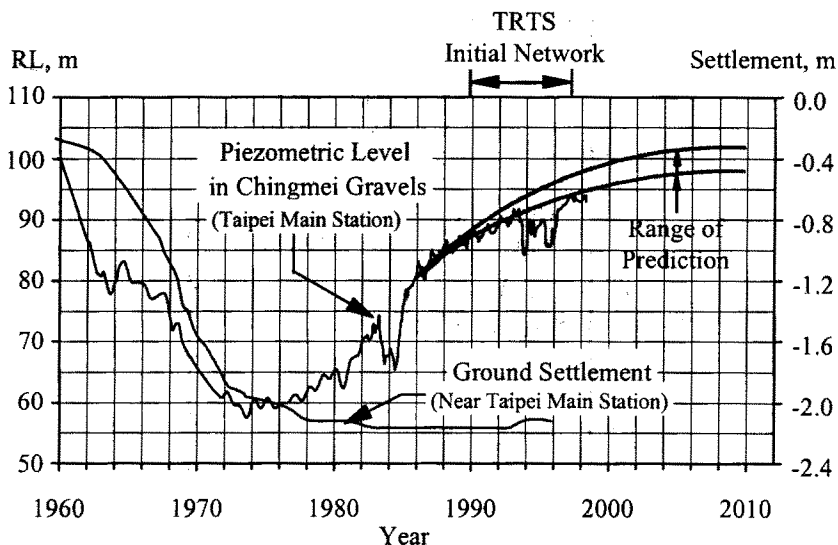


Fig. 9 Piezometric levels in the Chingmei Gravels and historical ground settlement in Central Taipei

is hard to predict. However, it is optimistic that they will rise to the Mean Sea Level, i.e., RL 100m, which is 2m below the ground surface, in the year of 2000.

The impervious clayey Sublayers 2 and 4 retain the water in the upper layers and divide the Sungshan Formation into three aquifers as illustrated in Figure 10. As mentioned previously, the groundwater in the Chingmei Formation was in an artesian condition in the old days. Therefore, the groundwater in Sublayer 3 was then at least at the ground surface in the central city area. Record indicated that the groundwater levels in Sublayer 3 were once lowered by at least 12m or so in responding to the drawdown in the Chingmei Formation. This had an unforeseen benefit of consolidating Sublayers 2 and 4 and, as depicted in Figure 9, the ground had settled by as much as 2m in the central city area where the Taipei Main Station (Station R13) is located. As a result, ground settlements during the TRTS constructions were much less than what could have been otherwise.

The coefficients of conduction of the Chingmei Formation range from 0.12 to 0.18 m/sec and coefficients of storage range from 0.001 to 0.004 (Moh, Chuay and Hwang, 1996), indicating that the Chingmei Formation is an excellent reservoir rich in water. In fact, it was the sole source of water supply for the City of Taipei for decades.

Cut-and-Cover Constructions

The cut-and-cover method was used for constructing all the stations, entrances, vent shafts and crossovers. A few short tunnels were also constructed by using the cut-and-cover methods. The pits were decked as soon as practical to lessen the

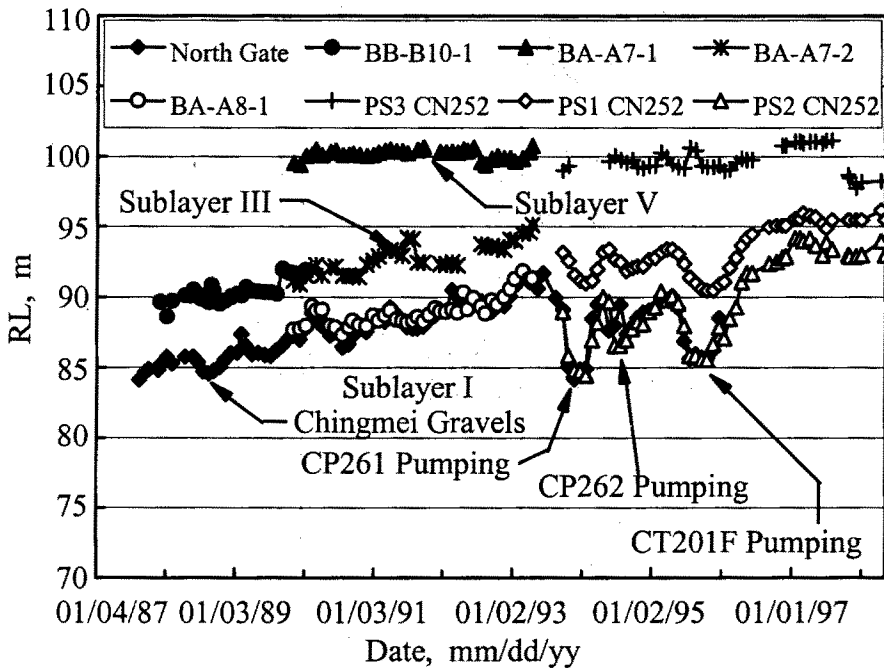


Fig. 10 Piezometric levels in the Sungshan Formation

impact on traffic. Excavations for two-level stations generally reached depths of 16m to 26m and those for three-level stations generally reached depths of 22m to 30m. There are only two stations with four levels underground. Of all the 34 underground stations, which have been constructed in the Initial Network, 23 were constructed by using the bottom-up method, 10 by using the semi-top-down method but only one by using the top-down method (Moh and Hwang, 1997). It is clear that the top-down method was not favored in the TRTS constructions.

There are three standing-alone ventilation shafts. The one between Stations G10/O15 and O16 of the Chungho Line, denoted as VSC (not an official designation, but used herein for convenience) in Figure 2, is a circular shaft excavated to a depth of 35m. As depicted in Figure 11, it was braced by two ring beams without other types of internal bracing. The bottom of excavation was right at the interface of the Chingmei Formation and the Sungshan Formation. It was thus necessary to extend the diaphragm wall deep into the Chingmei Formation and form a grouted plug for obtaining a sufficient factor of safety against blow-in and piping. The other two shafts, VSA and VSB, located between Stations BL4 and BL5 of the Panchiao Line were excavated to depths of 34m to 36.6m, respectively. Large scale pumping was carried out to lower the piezometric levels in the Chingmei Formation by as much as 12m for maintaining a sufficient factor of safety against blow-in during excavation (Moh, Chuay and Hwang, 1996). It is amazing that the pumping did cause the

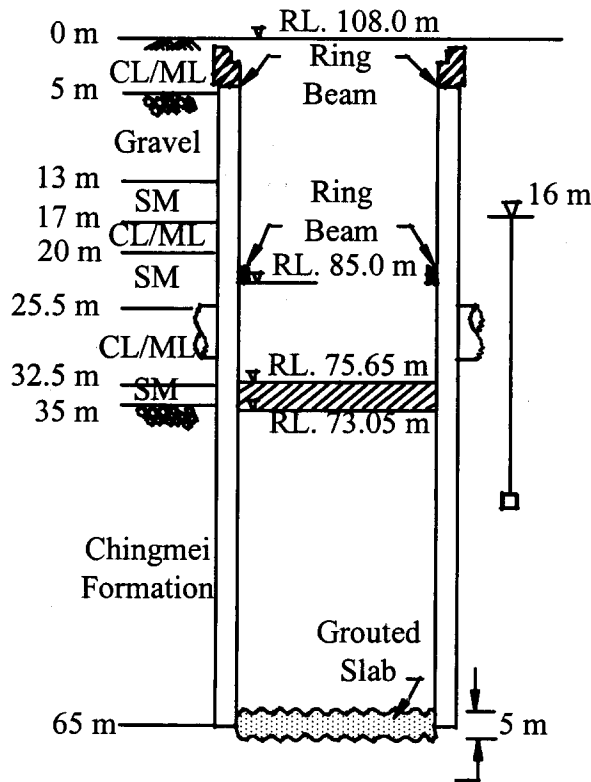


Fig. 11 Grouted plug at Ventilation Shaft C in Contract CH221

groundwater to drop by significant amounts at the Taipei Main Station, refer to Figures 9 and 10, which is at quite a distance away from these two sites. It was observed that even at a distance of 8 km away from where pumping was carried out, the drawdowns in the Chingmei Formation were as much as 2m. In these two cases, pumping was carried out to a maximum rate of 4,000 cubic meter per hour. This illustrates how permeable and how rich in water the Chingmei Formation is. Ground settlements due to pumping were, however, very little if any. Pumping was also carried out for constructing an annex of the Taipei Main Station and similar observations were obtained.

Tunneling

Short tunnels were generally constructed by using the cut-and-cover method and longer ones were bored by using the shield tunneling method. Two types of tunneling boring machines (TBM), i.e., the earthpressure balance type and the slurry type, were used. The ground conditions are not discriminative and the choice between the two appears to be governed by the availability of space for housing the slurry treatment plant. It is very difficult to find empty spaces sufficiently large for

the purpose in a city like Taipei, therefore, only one contractor opted the slurry type tunneling machine to bore 4 drives out of a total of more than 60. Tunnels bored by TBM are either 5.4m or 5.6m in their inner diameters. All the precast concrete segments are 250mm in thickness except that the segments for Contract 222 are 300mm thick.

The so-called New Austrian Tunneling Method (NATM) was used in two occasions. In this part of the world, the NATM method has 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 the contracts are rigid and do not allow for the flexibility of varying the designs during construction. In the first occasion, two adjoining sections, one of 225m in length and the other of 487m in length in the Mucha Line were mined through highly fractured shale. These two sections are separated by an open cut of only 32m in length. The twin tunnels have a horse-shoe shape with heights varying from 6.1m to 7.1m and a base varying from 9.2m to 9.5m in width and were lined with shotcrete of 100mm in thickness reinforced by wire meshes. Steel ribs were installed only as necessary. Rock bolts, 29mm in diameter and 4m in length, were installed at 1m intervals in the longitudinal direction and at 2m intervals in the transverse direction.

In the second occasion, the twin tunnels in a 222m section of the route, between Stations G09 and G07, of the Hsintien Line were bored by using the NATM method. They were buried in the Sungshan Formation, refer to Figures 7 and 8 for soil profile and soil strengths, with their crowns at depths varying from 8 to 11m below the ground surface. Compressed air with pressures up to 1.3 bar was applied for maintaining the stability of the ground. As depicted in Figure 12, the upper heading was protected by advanced roofing. The tunnels were supported by steel lattices and shotcrete during mining and lined with in-situ reinforced concrete subsequent to the breakthrough. Although there were problems (Moh and Hwang, 1997), the completion of these two tunnels is significant in the sense that this was the first successful NATM tunneling in poor ground in Taiwan. Subsequently, a section of tunnels between Stations B12 and B13, with a length of 54m for the Up-Track and 44m for the Down-Track, was completed by using the NATM method with ground treatment using JSG technique as a supplemental measure for maintaining the stability of the ground. In both cases, although ground settlements were quite large, exceeding 150mm, they were inconsequential.

The NATM method was in fact used to construct all the crosspassages, varying from 6m to 14m in length, between twin tunnels serving as fire escapes. Although ground was treated by high pressure jet grouting as a standard practice, leakage was observed in nearly all the cases because of the difficulty in solidifying the clays in the Sungshan Formation.

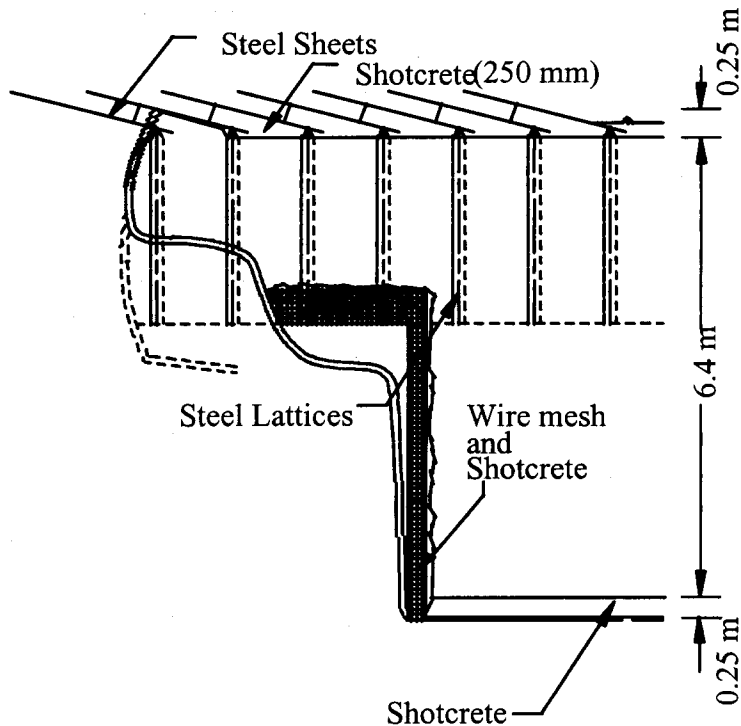


Fig. 12 Profile for NATM Tunnels in Contract CH221

Case Histories

During the construction, most of the accidents occurred as the tunneling machines were either leaving or arriving the launching/arrival shafts. Traditionally, high-pressure jet grouting was carried out to treat the ground in front of the shafts for the purpose of increasing its stability and reducing its permeability. However, because the clays in the Sungshan Formation are difficult to treat, minor leakage occurred at nearly all the tunnel eyes. The leakage usually was stopped by chemical grouting.

The most serious accident, as far as financial loss is of concern, occurred at the Up-Track tunnel of Contract CP262 of the Panchiao Line when the shield machine was approaching Vent Shaft A. Figure 13 is a location map of the site and a typical soil profile and the configuration of the shaft are shown in Figure 14. Ground treatment had been carried out to provide protection prior to the arrival of the shield machine. Although the treated ground had been tested for leakage, water spurted at the invert when the opening was made on the diaphragm wall. The flow soon became uncontrollable and a sinkhole of roughly 4,000 cubic meter in volume was created. Figure 15 shows the settlement contours. As can be noted, ground settlements were significant to a distance of 70m or so. The shaft had to be flooded

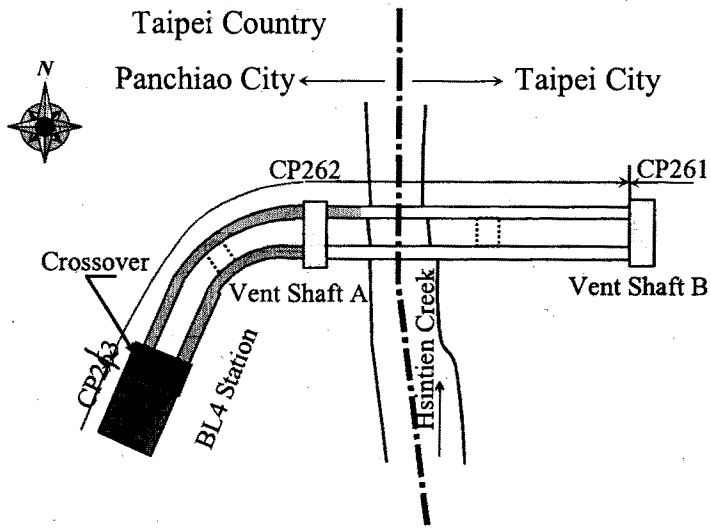


Fig. 13 plan of Panchiao Line Contract CP262

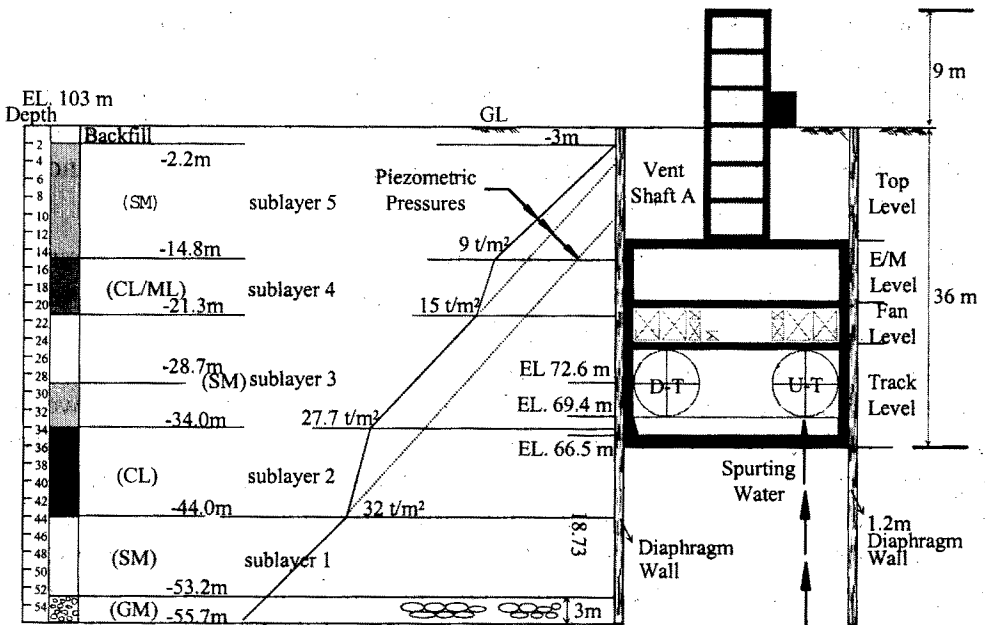


Fig. 14 Soil and Groundwater Conditions

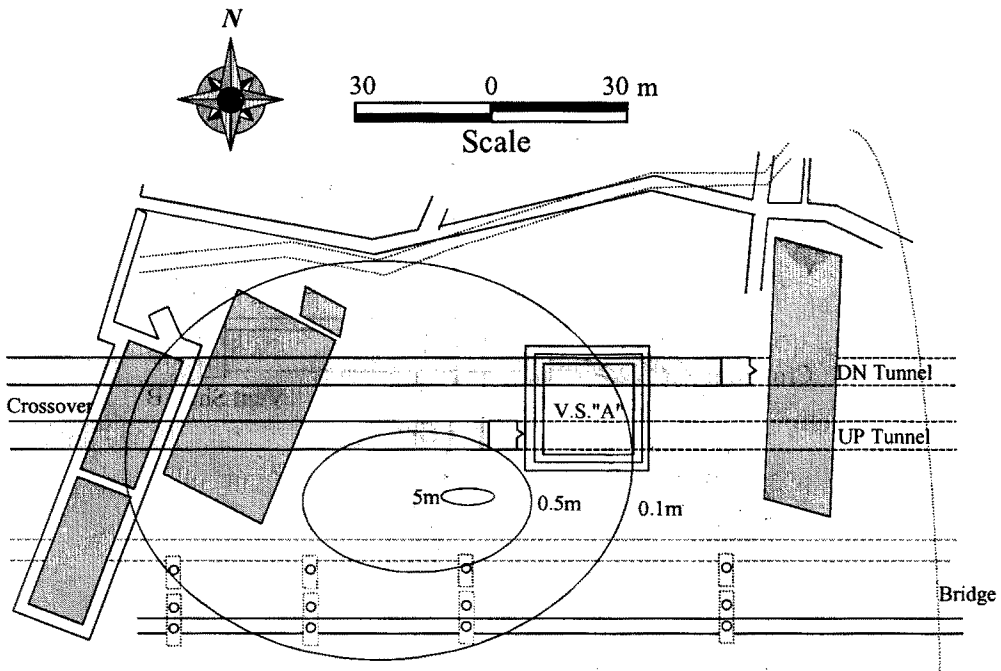


Fig. 15 Settlement Contours

to stop the inflow of water. At the time the accident occurred, the Down-Track tunnel had already passed through Vent Shaft A and had advanced by 25m in the second drive. The shield machines in both tunnels were thus totally submerged in water. The settlements of the tunnels were estimated by probing the crowns from the surface. It was found that, as depicted in Figure 16, the Up-Track tunnel had settled by 1.46m. The Down-Track tunnel settled by 0.34m (Lin, Ju and Hwang, 1997; Ju, Duann and Tsai, 1998).

The accident had occurred so suddenly and it took only a few hours for the inflow to become uncontrollable. The large flow rate indicates that water path indeed connected to the underlying Chingmei Formation which is extremely permeable and water rich. It was quite puzzling how this could have happened because the thick clay layer, Sublayer 2 in Figure 14, beneath the tunnels would have served as an impervious blanket to effectively cut off seepage flow from the Chingmei Formation down below. It was later observed during the restoration that there was indeed a pvc pipe right at where the cutter was and this pipe could have formed a water path for the water to rush from the Chingmei Formation to the opening made on the diaphragm wall. This pipe is believed to have been used in the old days for pumping water from the Chingmei Formation for the irrigation purpose.

The portal was sealed by a gravity type concrete retaining wall and the damaged

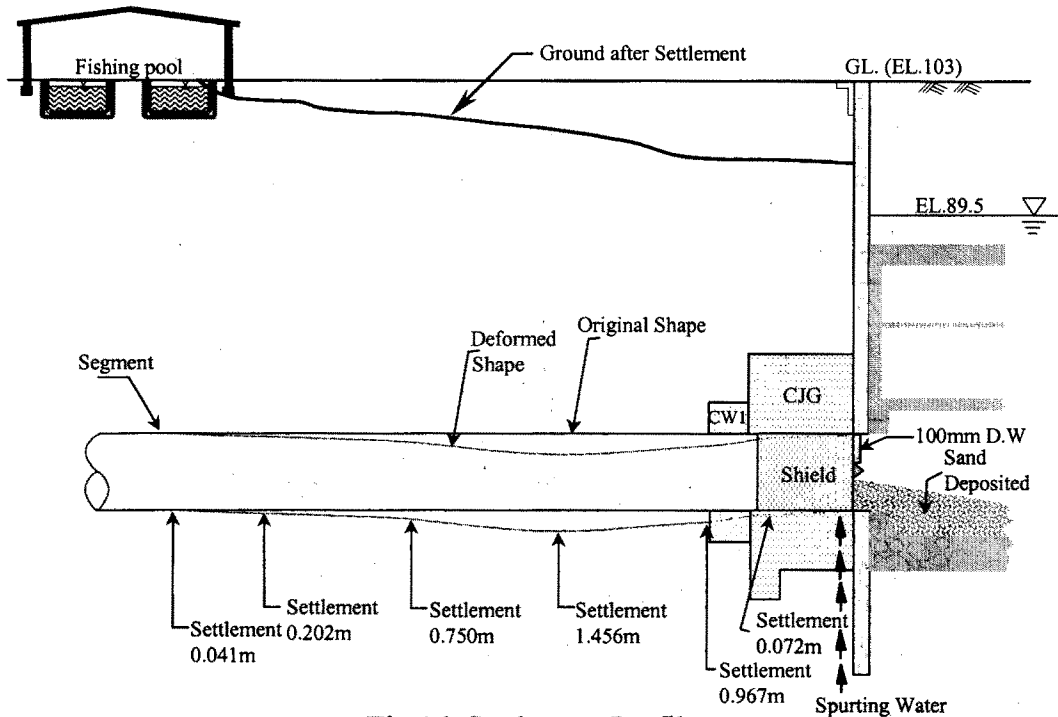


Fig.16 Settlement Profile

tunnels were restored in compressed air. Ground freezing was applied to seal off the water path at the invert to enable the portal to be re-opened (Ju, Duann and Tsai, 1998). It took two years to complete the rehabilitation of the Up-Track tunnel.

As a result of this accident, it became a standard practice to apply chemical grouting at the contact between the diaphragm wall of the shaft and the treated ground to fill up the gaps prior to the arrival of shield. Furthermore, a chamber was installed at the tunnel eye prior to the making of the opening on the diaphragm wall. If leakage did become uncontrollable, the chamber would be sealed and compressed air would be applied to stop the groundwater from flowing. In addition to ground treatment, freezing was adopted to treat the ground in contact with the shaft wherever there exist water bearing strata near the opening. With these measures, quite a few potential problems were avoided.

Another case history, which is less serious as the one presented above in terms of financial loss but is as interesting, is the piping failure at Station BL6. A hole made for replacing a malfunctioning piezometer led to flooding of the entire station excavation (Moh, Ju and Hwang, 1997). Figure 17 is a schematic presentation of the case. At the time the incident occurred, excavation had already reached the bottom and the base slab had been cast in more than a half of the station. As drilling reached the top of the Chingmei Formation, a large quantity of water spurting into the excavation. A total of 80,000 metric tonnes of water was released into this

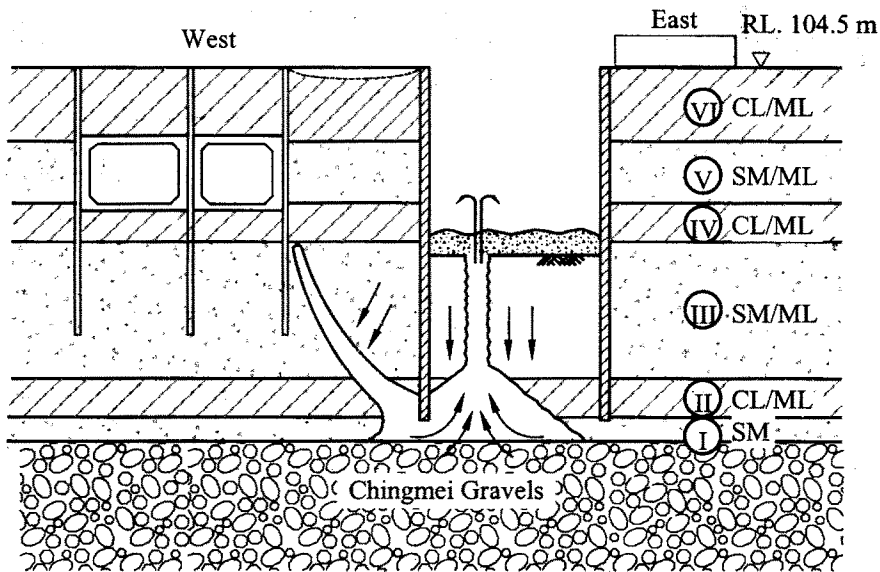


Fig. 17 Scenario of the Incident during Station BL6 Construction

pit from a watermain and a pool of 20m in width and 500m in length was formed with water to a depth of 8m. It took 6 months to mend the damaged ground by grouting.

Conclusions

The two case histories presented above clearly demonstrate how dangerous underground constructions could be. Groundwater is potentially detrimental and understanding of local geological features is a key to a safe construction. Wherever there exists a water-rich stratum, the design shall be performed in a conservative manner and construction shall be carried out with extra caution. More importantly, contingency measures shall be planned in advance and a good monitoring system is always helpful.

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