Challenges in recent underground construction in Taiwan

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ABSTRACT

Discussed herein are the challenges met in the underground constructions of two major infrastructure projects carried out in recent years in Taiwan, i.e., Taoyuan International Airport Access MRT System and the Green Line of the Taipei Metro. Taoyuan International Airport Access MRT System is an airport link transit system connecting the Taoyuan International Airport with surrounding transportation hubs. To avoid the high risk of constructing crosspassages under water, a Double-O-Tube (DOT) shield machine was successfully adopted for the very first time in Taiwan for tunneling the section of the route under the Tamsui River. For constructing Taipei Main Station, pumping with a record high flow rate was carried out to lower the piezometric head in the underlying gravelly water-bearing stratum in order to maintain the stability of the bottom of excavation. While constructing Beimen Station of the Green Line of Taipei Metro, a historical building, which was designated as a cultural heritage by Taipei City Government, had to be temporarily relocated before construction and moved back to its original location after the station was completed. Furthermore, the shield machines in the two tunnels had to go through two SMW walls and one diaphragm wall underneath existing tunnel boxes of Taiwan Railways and High Speed Rail. Extensive ground treatment was carried out to enable openings to be made on these walls for the shield machines to go through and the H-piles in one of these walls to be removed.

Keywords: excavation, tunneling, heritage, preservation, dewatering, ground treatment

1. INTRODUCTION

Underground construction in difficult situations has always been challenging to geotechnical engineers. Introduced herein are some of the problems encountered in the underground construction of two major infrastructure projects recently carried out in Taiwan, together with the solutions worked out.

2. TAOYUAN INTERNATIONAL AIRPORT ACCESS MRT SYSTEM

Taoyuan International Airport Access (TIAA) MRT System is an airport link transit system connecting the Taoyuan International Airport with surrounding transportation networks, i.e., Taipei Metro, Taiwan Railways, High Speed Rail and Taoyuan Metro. It was originally planned to be the Purple Line of Taipei Metro linking Taipei Main Station and Taoyuan International Airport, as depicted in Figure 1 (reproduced from BHSR web site), with a total length of only 35.7km. It was later combined with the Blue Line of Taoyuan Metro to give a total length of 51.3km. Bureau of High Speed Rail (BHSR) of the Ministry of Transportation and Communications (MOTC) is responsible for the construction and Taoyuan Metro Corporation (TMC) will be responsible for the operation of the entire system. Except the short section at its very southern end, i.e., between A21 (Huanbei Station) and A23 (Zhongli Railway Stations), the system is scheduled to be available for revenue services at the end of 2015.

Check-in and porter services will be provided at Stations A1 (Taipei Main Station), A3 (New Taipei Industrial Park Station) and A18 (Taoyuan High Speed Rail Station). As a result, some current airline check-in counters at the airport will be moved to the downtown area, and stations in the city center will become part of the airport. Passengers can then check-in baggage and get boarding passes in advance before getting to the airport. They may continue shopping or doing business without heavy baggage.

Currently, it takes about 70 minutes for passengers to travel from the city to the airport, or vice versa. It will take only 35 minutes for the express trains to travel between Taipei Main Station (A1 Station) and Taoyuan International Airport (A14 Station), with short stops at A3, A8, A12, and A13 Stations. Not only is the traveling time to the airport reduced, but the freeway congestion will also be relieved. Commuter trains will...
stop at every station and will take 70 minutes to run between Taipei Main Station (A1 Station) and Jhongli Station (A23 Station). Train services will be provided at 6-minute intervals, with 5 express trains and 5 commuter trains every hour (BHSR web site).

2.1 Tamsui River Crossing and DOT shield

Upon the completion of the entire MRT line, there will be a total of 22 new stations with A1, A7, A12 to A14a, and A21 to A23 being underground and the rest elevated. The very northern segment of the line was originally planned to be elevated. This plan was opposed by the city government of Taipei as it would lead to unpleasant visual impact in the City. It was then revised to be underground on the condition that the extra construction costs would be borne by the City. The construction of the section between the first two stations, i.e., Taipei Main Station (A1 Station) and Sanchung Station (A2 Station) also became the responsibility of the City and the job was assigned to the Department of Rapid Transit Systems (DORTS) which is responsible for the construction of Taipei Metro.

Because of this change, the two tunnels had to pass under the Tamsui River, refer to Figure 2. To avoid the high risk of constructing crosspassages at shallow depth under a river, a DOT shield machine, as shown in Figure 3, was adopted for the very first time in Taiwan. This shield machine has a height of 6,420mm and a width of 11,600mm. The two circular sections are 5,200mm apart, center to center. The reinforced concrete lining is 300mm in thickness, and each ring has a width of 1,200 mm and is composed of 11 panels. To cope with the sharp turns with a minimum radius of 277m, the shield machine is also articulated (DORTS, 2009; 2011b).

Tunneling started from the launching shaft located on the west bank of Tamsui River and terminated at the western end of the cut-and-cover tunnel box which was integrated into G14 Station of Taipei Metro and constructed as a part of the station box. It took a total of 284 days to complete the tunnel drive over a total length of 1,584m and a maximum daily production rate of 10 rings was achieved.

This section of the route runs through the central region of the Taipei Basin where the ground consists of alternating silty clay and silty sand layers with low strength except a thin sand seam at a depth of 20m or so as depicted in Figure 4. The cover above the tunnel crown varied from 7.6m to 26m, and the minimum cover under the river was 11m. Large timbers were frequently encountered in the early stage of metro
construction and caused difficulties in tunneling in several incidents. Provisions have been made for the shield machine to deal with this potential problem, including large openings in the face and facilities for grouting to solidify the ground, so that workers could remove timbers in a stable earth chamber. However, there were no incidents associated with timbers during tunneling.

Within a short distance from the launching shaft, the alignment swings from the west side of Huan Ho Bei Road (Riverside North Expressway) to the east side of the expressway and the shield machine had to go underneath one of the piers, i.e., Pier P64, supporting the viaduct of the expressway (refer to Figure 2 for location). The 9 bored cast-in-place piles, 1.5m in diameter and 60m in length, supporting the pier had to be removed to make way for the machine to pass. As depicted in Figure 5, diaphragm walls and sheet piles were first installed to retain the working shaft. Ground treatment was carried out to solidify the soil.
surrounding these piles. A steel frame was erected on the two diaphragm walls and the loads were transferred to this steel frame and the column of the pier was cut. The existing pile cap was demolished and the foundation piles were removed. A RC deck was then cast on top of the two diaphragm walls and connection was made between the shortened column and this new deck. The loads were transferred from the steel frame to this new deck which is supported on the two diaphragm walls. Finally, the steel frame was removed and the pit backfilled (DORTS 2011a; Wu, et al., 2011; Lee, et al., 2011).

On the east bank of the river, the alignment crosses Huan Ho Nan Road (Riverside South Expressway) and the tunnels passed in-between the piers supporting the viaduct. As depicted in Figure 6, the piles were protected by ground treatment by using the double-packer technique. Ground treatment was also conducted to protect a swimming pool and a hospital building below which the tunnels passed.

To minimize ground movements induced by shield driving, the shield machine had a provision for simultaneous grouting as it advanced. Furthermore, the face pressure and volume of spoil discharged were closely monitored and regulated. Ground settlements were able to be maintained within 50mm as shown in Figure 7.

2.2 Largest dewatering scheme in the Taipei Basin

Taipei Main Station (A1 Station in TIAA MRT System) is a 4-level underground complex. Airport boarding services are available at B1 level which is also a transfer level connecting the Airport Access MRT System to High Speed Rail, Taiwan Railways and Taipei Metro as depicted in Figure 8. Taiwan Railways and High Speed Rail share the same cut-and-cover tunnel box, side by side, as will be discussed in Section 3.2. The concourse for the Airport Access MRT System is located at the B2 level, and platforms are located at the B3 level for passengers to get on/off trains. Public parking facilities are provided at the B4 level.

Fig. 7. Settlements induced by DOT tunneling

![Fig. 7. Settlements induced by DOT tunneling](image)

Fig. 8. Location of A1 Station in relation to Taiwan Railways, High Speed Rail and Taipei Metro

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The area surrounding the station is designated as Taipei Main Station Special District by the City of Taipei with the aim of serving as a gateway to the city. Two skyscrapers, i.e., C1 (56 stories for a height of 241.5m) and D1 (76 stories for a height of 320.7m), will be constructed on top of A1 Station as depicted in Figure 9. The first two stories of these two skyscrapers are part of the station and will be available when the station is open for service (end of 2015). The commercial developments above these two stories were originally tendered as a Build-Operate-Transfer package. However, the tender was not successful and the city government decided to take over the responsibility for construction. To prepare for these future developments, as depicted in Figure 10, barrettes were installed to take the heavy loads by using the diaphragm walling technique.

As depicted in Figure 11, there exists a thick gravel layer, i.e., the Chingmei Formation which is extremely permeable and water-bearing, underlying the Sungshan Formation at depths of 40m to 60m in the central area of Taipei Basin. The presence of this water-bearing aquifer makes the geology of the Taipei Basin unique and very challenging to geotechnical engineers as it was responsible for several disastrous failures in the early stage of the construction of Taipei Metro (Moh, Ju and Hwang, 1997; Hwang, et al., 1998). Once water from the gravel finds its way to suddenly discharge into a pit, it is nearly impossible to stop the flow. Most of the disasters occurred during launching of shield machines at a launching shaft or during arrival of shield machines at reception shafts (Lin, et al., 1997). In another scenario, water suddenly discharged into a station excavation as a hole was made through the overlying Sungshan Formation to replace a malfunctioning piezometer installed in the Chingmei Formation. It became necessary to flood the whole pit by breaking a water main to discharge water into the pit to balance the groundwater pressure and stop the flow, and it was estimated that 70,000 m$^3$ of water was discharged into the pit in 18 hours (Moh, Ju and Hwang, 1997).

For the cut-and-cover construction for the R13S Station of Taipei Metro (Taipei Main Station for the Red Line, refer to Figure 8 for location), pumping was necessary to lower the piezometric level in the Chingmei Formation from EL. -10m to EL. -15.6m (i.e., a drop of 5.6m), in order to carry out excavation to EL. -24.6m (i.e., a depth of 29m below ground level) while maintaining stability at the base of excavation against piping or uplift. A maximum pumping rate of 2,450 m$^3$/hr was reached. Since the overlying Sungshan Formation is very thick, and is relatively impermeable by comparison, the Chingmei Formation can be considered as a confined aquifer. The drawdown of water level, $\delta$, is related to the flow rate of pumping, $Q$, transmissivity, $T$, storage coefficient, $S$, elapsed time, $t$, and distance to the pumping well, $r$, as follows

$$\delta = \frac{Q}{4\pi T} W(u)$$  \hspace{1cm} (1)

$$W(u) = \int_{u}^{\infty} \frac{e^{-u}}{u} \, du = -0.5772 - \ln u + u - \frac{u^2}{2\cdot2!} + \frac{u^3}{3\cdot3!} + \cdots$$  \hspace{1cm} (2)

$$u = \frac{r^2 S}{4 T t}$$  \hspace{1cm} (3)

For $u \leq 0.05$, the above equations can be reduced to

$$\delta = \frac{0.183 Q}{T} \log \frac{2.25 T t}{r^2 S}$$  \hspace{1cm} (4)
The two parameters, $T$ and $S$, can be obtained by curve-fitting based on the groundwater drawdown observed during pumping.

For R13S station, pumping lasted for 6 months (1 May to 25 November, 1995) and based on the data obtained, the transmissivity, $T$, was found to vary from 0.12 m$^2$/sec to 0.18 m$^2$/sec and the storage coefficient, $S$, to vary from 0.001 to 0.004 (Moh, Chuay and Hwang, 1996; Hwang, et al., 1996). This set of hydraulic properties of the Chingmei Formation is consistent with those obtained earlier at two other sites (Hwang, et al., 1996). The experience is very valuable as the analytical approach adopted has been followed ever since in nearly all the projects involving dewatering of the Chingmei Formation and the parameters obtained serve as important references for estimating pumping rates and preparing pumping programs.

The Chingmei Formation was once the sole source of water supply to the city. The piezometric level in the Chingmei Formation was above the ground level prior to the beginning of the 20th century (Wu 1968) and dropped by more than 40m in the 1970’s due to excessive extraction of groundwater. It was closely monitored by the Water Resources Planning Commission (WRPC) before the Commission merged into the Water Resources Bureau (WRB) in 1996. The Water Resources Bureau later merged into the Water Resources Agency (WRA) in 2002 and the monitoring has been continued up to the present. Figure 12 shows the piezometric level recorded at the observation well located near the southeast corner of G14 Station (WRA, 2013), refer to Figure 8 for location. As can be noted, the piezometric level gradually recovered since the mid-1970’s because pumping of groundwater was banned by the Government. The recovery of the piezometric level was affected by pumping carried out in the underground construction of several major infrastructure projects, particularly, the Taipei Metro.

The disastrous failures experienced in Stage 1 construction of Taipei Metro back in the 1990’s can be attributed to the facts that, firstly, the excavations were unprecedented at that time, as previous excavations were mostly for basements of less than 15m depth while the depths of metro excavations generally range from 20m to 30m, and secondly, the piezometric level in the Chingmei Formation had risen by 30m from its lowest level during the 1970’s. With the experience gained in the Stage 1 construction, designers and contractors were much more cautious in dealing with groundwater problems and no serious failure occurred in Stage 2 construction of Taipei Metro in the 2000’s.

As shown in Figure 12, the piezometric level in the Chingmei Formation had risen to El. -3m in 2010 when the excavation for A1 Station of TIAA was commenced. For C1 Zone, the excavation was to be carried out to EL. -23.2m (or a depth of 27.2m below ground level) and pumping was necessary to lower the piezometric level in the Chingmei Gravels to El. -14.5m (or a drop of 13m) to maintain stability of the base of the excavation against piping and uplift. Initially 14 wells (PW1, 3, 4, 7, 10, 12, 13, 15, 17, 20, 23, 24, 29 and 30, refer to Figure 13 for locations) were installed and a test was carried out for 3 days to confirm the adequacy of the pumping program. As depicted in Figure 14, the pumping rate reached 5,000 m$^3$/hr when the pumps in all the 14 wells were functioning and the piezometric level in the Chingmei Formation dropped to El. -9.4m. The piezometric levels rose by 2m within a few minutes after the test ended and returned to their original levels 5 days later. A transmissivity, $T$, of 0.18 m$^2$/sec and a storage coefficient, $S$, of 0.001 were deduced from the data obtained as depicted in Figure 15 (Yang, Lin and Huang, 2012).

![Fig. 12. Piezometric level in the Chingmei Formation at Beimen (North Gate)](image)

![Fig. 13. Locations of pumping wells and observation wells in C1 Zone](image)

Based on this set of parameters, it was estimated that 18 wells, with a maximum capacity of 6,480 m$^3$/hr, would be required for lowering the piezometric level to the desired elevation of EL. -14.5m. A test was again conducted after 4 additional wells were installed. The results, as depicted in Figure 16, indicated that the transmissivity, $T$ equaled 0.12 m$^2$/sec and storage
coefficient, $S$, varied from 0.001 to 0.004; and it was estimated that 15 wells, with a capacity of 5,400 m$^3$/hr, would be sufficient for the purpose. In fact, as depicted in Figure 17, the drawdown was even greater than what was predicted by using this set of parameters and only 11 wells were used at one time, with a maximum pumping rate of 5,000 m$^3$/hr in the subsequent excavation. Back analysis of the final results indicates that $T$ varied from 0.09 m$^2$/sec to 0.1 m$^2$/sec and $S$ equaled 0.001 (Yang, Lin and Huang, 2012).

In the case studied, a pumping rate of 6,480 m$^3$/hr would be required based on the results of the 14-well test while the actual pumping rate was only 5,000 m$^3$/hr. It appears that pumping tests with short durations tend to give conservative estimates of the pumping rates actually required. However, the 30% difference is well within the tolerance from a practical point of view and, in view of the many uncertainties to be faced, is absolutely necessary to ensure the success of the construction. It is hypothesized that, although the Chingmei Formation is widespread in the basin, the influence of pumping is also far reaching. As time goes by, the cone of drawdown (cone of depression) would approach the boundary of the gravelly water-bearing formation and the recharging of water became insufficient for balancing the outflow. This hypothesis is supported by the fact that the drawdown was very close, as depicted in Figures 16 and 17, to the prediction in the first couple of days and gradually exceeded the prediction in the later stage of pumping.

For D1 Zone, although excavation was to be carried out to the same depth as C1 Zone, it was necessary to lower the piezometric level to EL -22m (or a drop of 19m) because the overlying aquitard was thinner. A total of 22 wells were installed. As excavation was carried out at its bottom depth, 18 wells were used and the maximum pumping rate reached 7,000 m$^3$/hr. This pumping rate was unprecedented and is still being held as the record high in the Taipei Basin. It could well be the record on the entire island.

Fig. 14. Results of 14-well pumping test

![Graph of Number of Wells vs Date](image)

![Graph of Pumping Rate vs Date](image)

![Graph of Piezometric Level vs Date](image)

**Fig. 14.** Results of 14-well pumping test

**Fig. 15.** Back analysis of 14-well pumping test

**Fig. 16.** Back analysis of 18-well pumping test
3. GREEN LINE OF TAIPEI RAPID TRANSIT SYSTEMS (TAIPEI METRO)

The Green Line (Songshan-Xindian Line) is the newest line in the Taipei Metro System. In fact, the southern half of the line, from Xindian Station to CKS Memorial Hall Station, is one of the six lines constructed in the very first stage of the network and has been in operation since 1988. The section between CKS Memorial Hall Station to Songshan Station was open for revenue services on November 15, 2014. With this extension, the entire network comprising 107 stations and a total route length of 129.2 km, is now in operation and the daily patronage has reached a maximum of 3 million.

3.1 Preservation of a Historical Building

As shown in Figures 8 and 18, at the northeast corner of Beimen Station (G14 Station), there existed Taipei Workshop, which is a brick building constructed in 1909 for the maintenance of locomotives and trains. It was converted to an office building in 1935 as the workshop was moved. It is now being used as an auditorium by the Taiwan Railways Administration. What makes it particularly valuable from an archeological point of view, is the fact that the members of the truss supporting the roof are made from steel rails of the very first railway in Taiwan, which was completed in 1893.

In the original plan, the workshop was supposed to be demolished to facilitate metro construction and widening of a street. However, the city government designated it as a Class 3 historical heritage building on 7 June, 2005 and it became compulsory to preserve the building. Since by this time the detailed design was about to be finalized, the designer was requested to quickly propose schemes to preserve the workshop with minimum impact on the construction of G14 Station and TIAA MRT. Because of the site constraints and the urgency, to come up with a workable scheme which was satisfactory to all the parties and the public was an extremely challenging task to the designer.
The workshop occupies an area of 24.5m by 22.3m and weighs 1024 tons. As depicted in Figure 20, it is supported on brick footings with enlarged bases underlain by a layer of sand-cement mortar. The bottom of this cement mortar layer was at a depth of, roughly, 3m below ground surface. To move an object of this size horizontally would require excavation to a depth of 5m or so to provide space for installing jacks and a moving device and a retaining system would definitely be required to maintain the stability of the pit. However, it would be very difficult to brace the retaining walls because of the presence of the workshop and there was no space for tiebacks to be installed behind the walls. It was therefore decided to jack up the building by 1.5m to gain the space required. Excavation was reduced to a depth of only 3m and sheet piles were able to stand as cantilevers without lateral support.

After the excavation reached the desired depth and the footings were exposed, a 300mm reinforced concrete (RC) load bearing slab was cast at the bottom of excavation to serve as a reaction pad for jacks as depicted in Figure 20(a). Reinforced concrete ground beams were installed to tie all the footings together and were structurally integrated with these footings by installing rebars through them. Jacks, with a capacity of 50 tons each, were installed underneath these ground beams. The structure of the workshop was reinforced by using steel members to ensure its integrity. The entire assembly, now weighing 1500 tons, was jacked up, incrementally, by 1.5m by using 68 hydraulic jacks (DORTS 2008).

Once the assembly was raised to the desired height, as depicted in Figure 20(b), a RC slab was installed underneath the layer of mortar at the bottom of the footings and was structurally connected to the ground beams previously installed for protecting the footings. A RC base slab was installed at the bottom of excavation for providing reactions. Between these two RC slabs, a moving device was inserted. The moving device consisted of, from bottom to top, steel rails, steel bars (serving as rollers to reduce friction), steel plate, H beams and wood wedges.

Relocation of the building was commenced on 10 December, 2007 after the load was transferred to the moving devices and the jacking system was removed. Twelve jacks, with a capacity of 70 tons each, were used to push the workshop laterally toward its destination. The speed was limited to 1cm per minute and it took 9 days to complete the moving (DORTS, 2008). After the excavation for the station box of G14 was completed and the site restored, the workshop was moved back by a distance of 25.5m, 4.5m short from its original location to provide space for widening the street. A ceremony was held on 16 May, 2012 to mark the end of operation and, as a demonstration to show how the workshop was moved, the last 10cm of movement of the workshop was completed at the ceremony.
3.2 Tunneling through Obstacles

Figures 21 and 22 show the case in which shield machines of the Green Line were driven through two SMW (soil-mix-wall) walls and one diaphragm wall at a location, refer to Figure 8, to the south of G14 Station. The two soil-mix-walls, 600mm in thickness and approximately 23.5m in length, were installed for constructing the tunnel box for relocating this section of the TRA (Taiwan Railways Administration) tracks underground between 1983 and 1989. When the tunnel box for High Speed Rail was constructed between 2000 and 2006, a diaphragm wall of 800mm in thickness and 36m in length was added on the east to retain the pit.

Fig. 21. Location of conflict between Green Line, TRA and HSR

The H-piles in the western SMW wall were withdrawn as the TRA construction was completed, and the H-piles in the eastern SMW wall, i.e., the wall between TRA and HSR boxes, were left in place. These piles would become obstacles during shield driving for constructing the Green Line of the metro. To enable these H-piles to be removed from the earth chambers of shield machines, it is necessary to solidify the surrounding soils by using a ground treatment technique. The presence of the existing tunnel boxes made it impossible to carry out ground treatment from the ground surface. Two working shafts, i.e., CW Shaft on the down-track and CE Shaft on the up-track, were installed to enable horizontal grouting to be carried out. Besides, these work shafts could also be used to demolish the HSR diaphragm wall to make openings for the shield machines to pass.

Fig. 22. Configuration of TRA, HSR and Green Line

As depicted in Figure 23, these two shafts were retained by diaphragm walls sunk into the Chingmei Formation and were sealed at the bottom by sleeve grouting using cement/bentonite mix (CB) and silicalizer (SL). Excavation inside the shafts was carried out in 10 stages, with 9 levels of struts, to a depth of 28.8m, and ground treatment was carried out using JSG (Jumbo Special Grout) technique to form a buried slab to brace the two diaphragm walls at the bottom of excavation to minimize ground movements and, hence, to reduce the risk of damaging TRA and HSR structures which would interrupt the operation of TRA and HSR.

Ground treatment was also carried out outside the working shafts to enable openings be made through the diaphragm walls for the shield machines to pass safely. On the side away from the existing tunnel boxes, grouting (Task 3 in Figure 23) was able to be carried out from the ground surface and was carried out by using the RJP (Rodin Jet Pile) grouting technique to increase soil strength, followed by sleeve grouting for better watertightness. Underneath the existing tunnel boxes, horizontal sleeve grouting (Task 6) with double packers was carried out from the two shafts (Odagiri, et al., 2013a; 2013b).
To solidify the soils surrounding the eastern SMW wall so that H-piles could be removed from earth chambers as the shield machines arrived, sleeve grouting with double packers (Task 8) was carried out from the two shafts. H-piles were indeed encountered at the location where the eastern SMW wall intercepts the down-track tunnel during grouting from CW Shaft. Piles were not encountered along the alignment of the up-track tunnel during grouting from CE Shaft.

As the shield machine in the down-track tunnel arrived at the location where H-piles were encountered, a series of tests were conducted from the inside of the shield machine through the openings provided on the shield machine to ensure that the integrity of the treated ground would be adequate for workers to work in the earth chamber safely. The quality of the treated ground was indeed quite satisfactory and the removal of H-piles was carried out smoothly. A total of 12 piles were removed in 9 days (Odagiri, et al., 2013a, 2013b).

4. CHALLENGES

Tunnelling at shallow depth is always challenging, but more so when tunneling under a river because of the opportunity for significant water inflow. The risk can be reduced by use of appropriate tunneling shields, but the creation of cross-passages required for fire safety is usually done by hand mining, and hence a very high risk under a river. All of this was effectively managed by the use of a DOT machine, driving both tunnels in one go and removing the need for cross-passages altogether.

Groundwater is undoubtedly a threat to underground construction if subsoils are permeable and the groundwater table is high and/or if there exists a water-bearing stratum below the bottom of an excavation. On the other hand, it offers challenges to geotechnical engineers and makes geotechnical services valuable and demanding. In the Taipei Basin, sudden discharge of water from the underlying Chingmei Formation during deep excavations has indeed resulted in a number of disastrous accidents in the 1990’s. Methodology and procedures have since been established based on the experience gained and such problems associated with groundwater can now be handled with confidence.

Pumping with rates exceeding 2,000 m³/hr, and even up to 7,000 m³/hr, has been successfully carried out at 7 sites to reduce the piezometric levels in the underlying Chingmei Formation, to enable deep excavations to be carried out safely. However, as discussed in Section 2.2, even with previous experience at a nearby site and with the results of large scale pumping tests, prediction of required pumping rate was still off by 30%. It is not surprising for designers to err by 100% or more in prediction at sites without previous experience. Therefore, prediction of drawdown remains a challenge to designers.

In the case of underpinning of Pier P64, the challenge lay in creating a new foundation for the elevated structure without affecting the traffic on the expressway. Similarly, for ground treatment carried out underneath the TRA/HSR tunnel boxes, it was absolutely necessary to ensure that the services of the railway and High Speed Rail would not be interrupted. As thousands of commuters would be affected, interruption to the traffic would not only impact the progress of the project, it would have unacceptable social and political implications. This is particularly true for High Speed Rail, for which the tolerance to movement is very small.

Relocation of the Taipei Workshop was not only technically challenging, it drew much attention from various parties, including historians, social workers, archeologists and even politicians. To work out a scheme satisfactory to all these parties challenged the wisdom of the project owner, i.e., DORTS, the designer and the contractor.

5. RISK MANAGEMENT

The risk associated with groundwater exists even without the presence of an underlying water bearing stratum. Water may suddenly discharge from openings made in underground structures if subsoils are permeable and the groundwater table is high. Moh and Hwang (2007) discussed disastrous failures in Asia-Pacific during the period between 2001 and 2006, and 4 out of the 5 cases discussed were associated with sudden discharge of water during excavations in permeable sandy soils. Because of these precedents, the probability of failure was rated high if crosspassages were to be constructed under the Tamsui River. Since the consequence of failure would be disastrous, the associated risk was rated unacceptable. As a risk reduction measure, a DOT shield machine was adopted for tunneling underneath the Tamsui River to avoid the risk of constructing crosspassages under water. Furthermore, because this is the first time a DOT shield machine had been adopted, DORTS engaged a Risk Management Consultant to ensure the success of the works (Chao, et al., 2012).

For the case of ground treatment underneath the TRA/HSR tunnel boxes for removing H-piles in a SMW wall, it was technically feasible to conduct grouting from the grout holes provided in the shield. However, it would have been difficult to ensure the quality of treatment. Because of the seriousness of the consequences if something went wrong, it was decided to sink two shafts and to carry out horizontal grouting from these shafts, again as a risk reduction measure.

Instrumentation and monitoring are vital elements in risk management. In all the cases mentioned herein, movements of the ground and structures, particularly, the HSR tracks, were closely monitored and the data were carefully interpreted and reviewed. The progress
of works was adjusted based on the data obtained and, where necessary, corrective measures were taken to prevent adverse events from happening.

The contractors were also requested to prepare contingency programs to deal with unexpected incidents. In fact, it is routine nowadays in all major construction projects to ask designers and contractors to identify potential risks and prepare contingency programs. In addition, independent panels of experts were engaged to safeguard the structures of special concern, i.e., Pier P64, Taipei Workshop and TRA/HSR tunnel boxes, in the cases presented herein.

6. CONCLUSIONS

Underground construction is risky but is also challenging to geotechnical engineers. The risks must be properly managed and the success of underground construction relies on team work of the project owner, designer and contractor. The above-mentioned cases lead to the following conclusions:

(1) The use of a DOT machine effectively eliminated the risks associated with constructing crosspassages at shallow depth beneath a river. The satisfactory performance of this machine makes it a viable option for tunneling in difficult geotechnical and/or environmental situations.

(2) The transmissivity and storage coefficient deduced from the observed groundwater drawdown are affected by not only the pumping rate, but also the duration of pumping.

(3) By using appropriate skills and techniques, a new foundation was created for a major highway under live traffic, and a 100-year building was successfully picked up in one piece, moved laterally about 30 m, and moved back again once the station construction was completed.

(4) With proper understanding of the geotechnical, social and even political constraints, challenges are essentially opportunities for geotechnical engineers. The valuable experience gained will benefit future construction in urban areas with congested underground structures and utilities.

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REFERENCES


2) DORTS (2008) Protection of a historical monument at Beimen MRT Station, the reality of historical memory – Taipei Workshop, MRT Constructions, no. 27, Taipei, Taiwan (in Chinese)


4) DORTS (2011a) Underpinning method applied to a shield tunnel of the Taiwan Taoyuan International Airport Access MRT System, MRT Construction, no. 43, Taipei, Taiwan (in Chinese)


