Geotechnical Challenges for Urban Section of the Taoyuan MRT Green Line

Guang Syun Li
CTCI Resources Engineering Inc.
Guangsyun.li@ctci.com

Yen Chun Liu [2], Chen Jia Jiang [3], Hui Sheng Liao [4]
CTCI Resources Engineering Inc.

Chien Chih Kuo [5]
Futsu Construction Co., Ltd & Obayashi Corporation Taiwan Branch (Japan) & Continental Engineering Corporation Joint Venture

Zhen Yuan Liao [6]
Taoyuan City Government MRT Engineering Bureau

ABSTRACT

Aiming at serving Taoyuan Metropolis, Taoyuan MRT Green line GC03 Underground Civil Turnkey Project located in Taoyuan downtown from Taoyuan Train Station, crossing over Taoyuan City along Zhongzheng Road(中正路), and finally passing through be National Highway No.1. Overall, the GC03 project includes 6 stations, 7.1 kilometers Φ5.6m shield tunnel, and 5.8 kilometers Φ7.5m shield tunnel. Due to the solid cobble gravel and sandstone formations in Taoyuan area, heavy traffic in downtown and limited construction space, the project faces a huge challenge in both engineering design and construction phases.

This article intends to reveal key geological engineering issues of GC03 project, which includes the diaphragm wall construction, deep excavation and dewatering operations in cobble gravel and sandstone formations; long-distance and large-section shield tunnels; adjacent construction numerical analysis, monitoring and protection measures for the shield tunnels that constructed through the National Highway No.1 and the historic site Jinfu temple(景福宮); the separated platform design of G08/G09 station, which is first adopted in Taiwan MRT system; the top-down construction planning of G07 station, the deepest underground MRT station that co-constructed with Taiwan Railway Taoyuan Station, etc. Furthermore, the construction conditions, design principles, and current status of each issue will be clarified as well.

The civil construction of GC03 project (both stations and shield tunnels) are currently in progress; therefore, this article attempts to provide the latest empirical data and feedback for the engineering design and construction of future underground metro projects.

KEYWORDS: MRT design, cobble gravel layer, large-section shield tunnel, top-down construction

1. Project Overview

Under the framework of "Forward-Looking Infrastructure Plan", Taoyuan City Government has put efforts into a cross-boundary transportation plan that contribute to "One-hour living circle" where every destination in the Greater Taipei Metropolitan Area, which includes Taipei City, New Taipei City, Keelung City and Taoyuan City, is accessible within an hour of commute.

In order to strengthen the connectivity of Taoyuan and other core cities in Greater Taipei Metropolitan Area, and create a connective, circular MRT network, Taoyuan City Government has proposed an overall upgrade for several transportation projects, which includes the undergroundization project of Taiwan Railway System Taoyuan section, and the extension of Taoyuan Airport MRT and the Green Line MRT. Owing to the urban spatial development plan, in particular the Taoyuan Green Line has been put into priority for construction due to its core location and connecting nodes. As shown as Figure 1.

Six underground stations are incorporated within GC03 section, with a total length of approximately 5.8 kilometres. The route of GC03 section starts from Taoyuan Railway Station and goes alone Zhongzheng Road, passing several well-known hotspot in Taoyuan City, which includes historical site JingFu Temple (景福宮), Yonghe Market (永和市場), Taoyuan night market, and Zhong zheng Arts District (中正藝文特區). As shown as Figure 2.

The first half of Zhongzheng Road, where G07~G09 station located, is relatively narrow but preserves abundant local characteristics and historical buildings; in the meantime, the second half of Zhongzheng Road, where G10~ G12 station will be positioned, presents a modern city landscape with greening. GC03 route eventually crosses the National Highway No.1, unearthed at Zhongzheng N Road, and connects with GC01 viaduct.

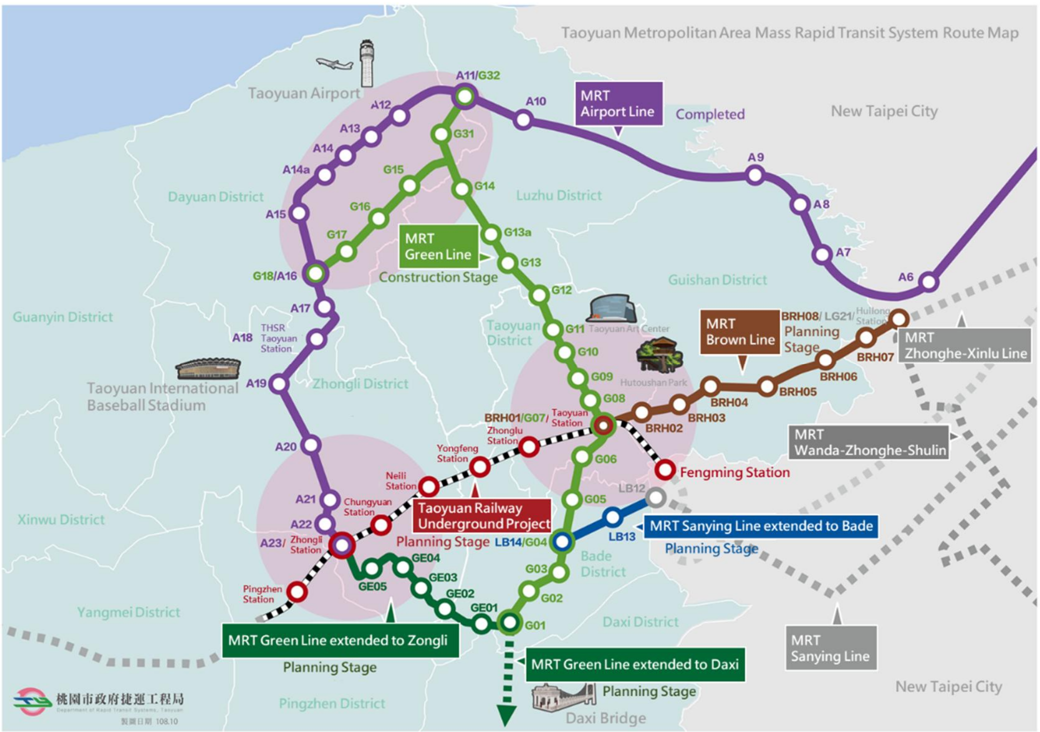

Figure 1. Taoyuan City's Rail Transit Network Plan

Figure 2. Taoyuan Green Line GC03 Project

2. Geology Overview

The Taoyuan Green Line tunnel passes through mainly the Taoyuan formation (桃園層) and Tananwan formation (大南灣層). The Taoyuan formation is mainly composed with 2~4m-thick covering laterite and 11-16m- thick of cobble gravel layer. Cobble gravel layer is mostly metamorphic quartz sandstone filled with silty sand, and partially interbedded with silt and poorly cemented sandstone layer. The panning degree of the cobble gravel layer is poor, and different sizes of boulders, cobbles and gravels are mixed in disorder. The thickness of the Taoyuan layer is about 15-20m, and the gravel content is about 80%, which is a great bearing layer for underground engineering. According to the site investigation results, the maximum particle size of cobble gravels is about 60cm. For now, the maximum particle size of cobble gravels found in the excavation work and the diaphragm wall trench of each station site is also 50cm~60cm.

Below the Taoyuan formation is Tananwan formation, that composed with is Pleistocene sandstone and mudstone, with a depth of at least 60m below the ground surface.

The regional geology distribution of the planned route is shown in Figure 3.

The faults adjacent to the project are the Hukou fault (湖口斷層), the Xinzhuang fault (新莊斷層), the Taipei fault (台北斷層) and the Shanchiao fault (山腳斷層). According to the "Taiwan Active Fault Distribution Map, Central Geological Survey, 2010", only the Hukou fault and the Shanchiao fault are active faults (both are type II). The Shanchiao fault is about 10.7 kilometers away from the project area. Geological surveys show that the last fault activity of Shanchiao fault has been at least 60,000 to 70,000 years ago.

According to the geotechnical investigation report, the strata are mainly divided into four layers from top to bottom: backfilled layer, silty clay layer, cobble gravel layer and sand/mudstone layer (Tananwan formation), as shown in Figure 4. The strata along the planned route are cobble gravel layer and sand/mudstone layer. The gravel content of cobble gravel layer is about 80%, the Standard Penetration Test value (SPT-N) is higher than 100 and the permeability coefficient K is about $1.01 \times 10^{-3} \sim 3.20 \times 10^{-4}$ cm/s according to the in-situ permeable test.

The thickness of the gravel layer is about 17-25m. The sand/mudstone layer are mainly poorly cemented sandstone, argillaceous sandstone, or sandy mudstone with occasional gravel in it. Even if the SPT-N value is also greater than 100, this layer belongs to the soft rock layer that is easy to soften when exposed to water.

During the investigation period, the data from the water level observation wells installed at each station showed that the groundwater level in the project area is around 3-6m below the surface. The strata, groundwater level, the elevation of each station structure and tunnel of the GC03 project are shown in Figure 4.

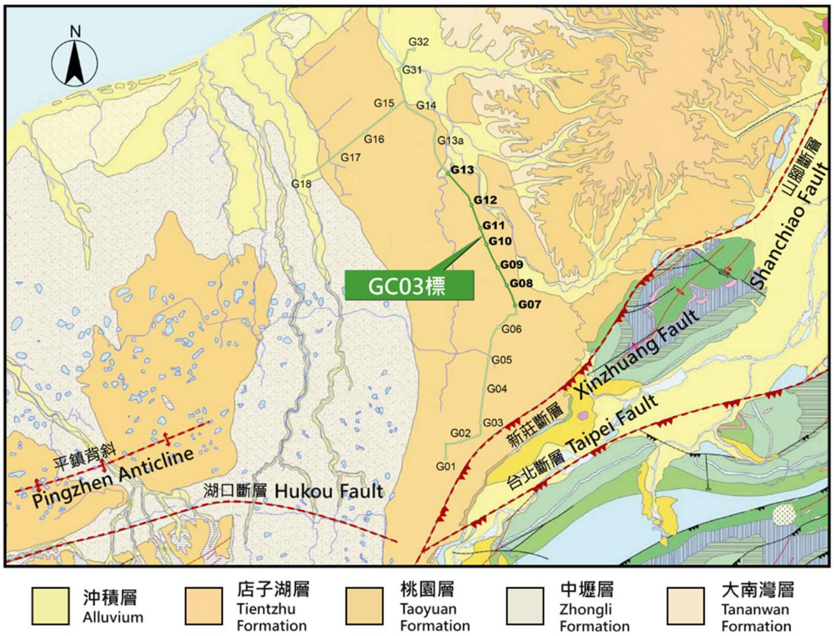

Figure 3. Regional Geology Distribution Around Taoyuan MRT Green Line

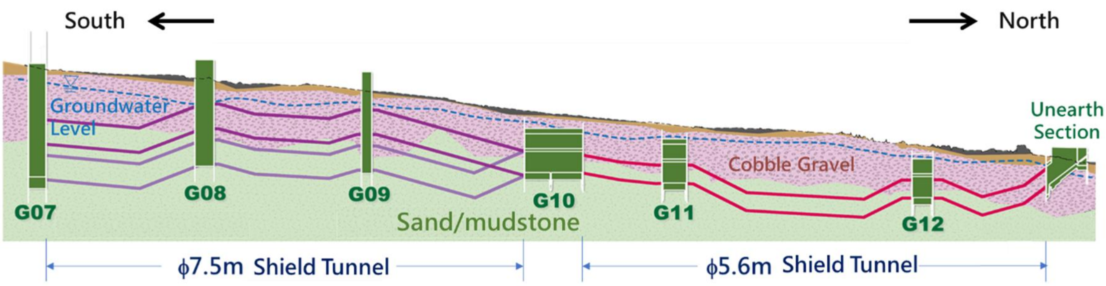

Figure 4. Geology Condition Along the GC03 Project

3. Engineering Challenge

3.1 G07 station, The Deepest Underground MRT Station

The G07 station of Taoyuan MRT Green Line is designed to be integrated with TRA Taoyuan Station. The maximum excavation depth is about 43m, which is currently the deepest excavation for the underground MRT station in Taiwan. The section view of G07 station is shown in Figure 5.
For such a deep station, the diaphragm wall construction, structural buoyancy resistance design, excavation safety, monitoring plan, construction arrangement and contingency plan are all important and challenging issues. In addition, the site is adjacent to the TRA Taoyuan temporary station and FE21' department store, which is crowded area, it's necessary to minimize the impact of the construction on the surrounding area to the minimum.

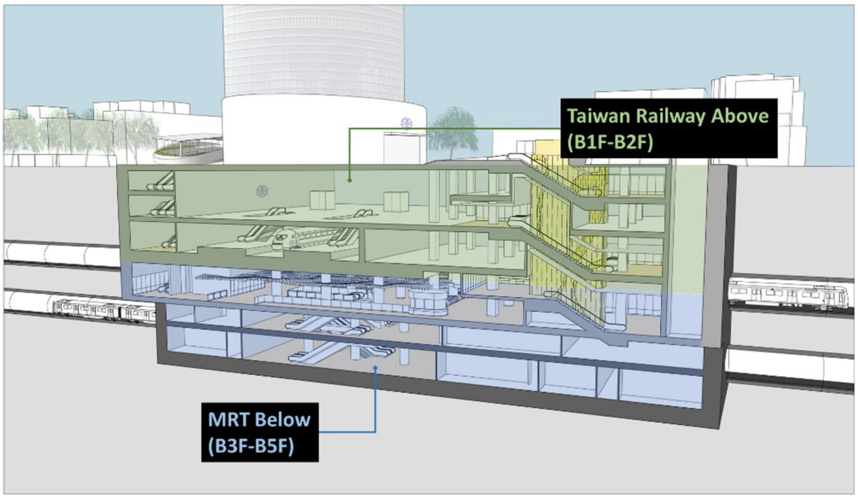

Figure 5. Section View of G07 Station

Considering the good cohesion of the strata (both cobble gravel layer and sand/mudstone layer), the top-down construction method is feasible to adopted for G07 station's excavation and construction. The top-down construction is a construction method that constructs the building structure from top to bottom while excavating downward. As the retaining support's structure, the floor slab has higher stiffness than traditional H-beam steel strut during the excavation stage. The amount of formwork of bottom side and the heavy support frames can also be reduced by using the top-down construction method. The earlier structure completion time can also improve the structural stability, and effectively reduce the construction interface between MRT and TRA. A comparison between traditional bottom-up method and top-down method is summarised in Table 1.

The diaphragm wall of G07 station is 1.2m-thick and 56.3m-deep. The 90-ton MASAGO hydraulic long-bucket and 250-ton large crane were mobilized for construction to ensure the excavation efficiency in gravel and sandstone condition, reduce the aerial laps time of rebar cages, improving efficiency and safety for diaphragm wall construction.

While excavating the diaphragm wall's trench and grouting, the water leakage and trench hole collapsing that often occurred at the range of cobble gravel layer should be avoid, so the double-packer grouting method is carried out on the both inside and outside of the wall trench as the protection measure. In addition to the double-packer grouting, the smaller division of the diaphragm wall units, the thicker end-plates between units, the higher viscosity stabilizing fluid and the slower pouring rate of concrete though the gravel layer, are all to ensure the integrity of the diaphragm wall.

Table 1. Comparison of Top-Down and Bottom-Up Construction Methods

Construction Method	Top-Down	Bottom-Up (traditional)
Pros	1. Slab supporting with higher stiffness 2. Reduce the noise 3. Less affected by weather 4. Less construction interface with TRA 5. Feasible for the great range excavation	1. Structural completeness with fewer seams 2. Flexible working space arrangement 3. Easier to transport the earthwork 4. Low cost
Cons	1. Additional Pile and Column 2. Difficulty in earthwork transporting 3. Higher cost	1. Huge amount of H-beam strut 2. Large displacement of the diaphragm wall, which caused the higher risk of TRA railway impact.

3.2 The Buoyancy Resisting Measure of Underground Station

MRT design regulation is stricter on the buoyancy resistance design of underground stations. Considering the undecided schedule for the follow-up joint development building of the upper part (G07~G09 station), it is necessary to consider the impact of the loading conditions carefully and conservatively at different stages of construction in buoyancy check.

The groundwater level is required to be considered locating on the surface, and the friction of retaining facilities and piles foundation cannot be included in the calculation of buoyancy resistance for long-term stage. The safety factor of buoyancy resisting of short-term and permanent stage should be 1.03 and 1.07, respectively.

To meet to the requirement of buoyancy resistance, the structure size of each station in GC03 project are designed to be thickened to increase the structural loading and reduce the height of each floor to reduce the excavation depth. For G07~G09 station, connect the slab to the diaphragm wall, bottom slab and the king post’s pile, so as to facilitate the self-weight of the auxiliary structure to resist buoyancy in the permanent stage. For the unearth section, considering to thicken the parapet and extend the foundation slab to meet the buoyancy resisting requirement.

3.3 G08-G09 station, The Connection Passage Between Station and Tunnel

G08 station is located at the existing Yonghe Market while G09 station is positioned near Taoyuan Night Market. Both stations are located along the 15-meter-wide Zhongzheng Road, which experiences heavy traffic. Typically, underground metro stations are constructed using cut-and-cover methods beneath the road. However, the committee of Environmental Impact Assessment requested that cut-and-cover construction should be prohibited for the sections of Zhongzheng Road. As a result, during the basic design phase, it was determined to position the G08 and G09 stations on the outer side of Zhongzheng Road.

The design and construction of stations are inspired from various sources, including the Hong Kong MTR Island Line, London Underground's Central Line, and Beijing Subway. The approach involves using passageways to connect the platforms and the station. In addition to concerns of structural design, a comprehensive assessment of architectural space, ventilation, fire safety, and pedestrian flow has been performed to meet regulatory requirements. Notably, this project marks the first case in Taiwan of using split-platform station design (also known as Tube station), as illustrated in Figures 6. The numerical analysis is also performed for the scheme, and partial results are shown in Figure 7.

Figure 6. Split-Platform Design for G08/G09 Station

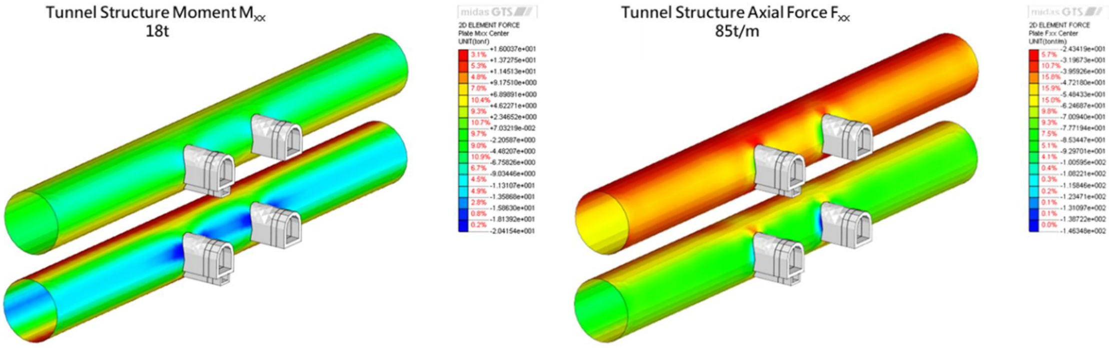

Figure 7. Finite Element Analysis for the Side Connecting Passage

As mentioned above, the tunnel with an inner diameter of 7.5m will be adopted between G07~G10 station, and the escape route will be set in the tunnel. After G10 station, Zhongzheng Road is widened enough to set up the traditional connecting passages between tunnels. Therefore, the traditional 5.6m-diameter tunnel is adopted from G10 station to G12/G13 unearth section.

3.4 Tunnel Drainage Plan for GC03 Project

The connecting passage of the tunnels is planned between G11 and G12 station. In the past, the general plan for tunnel drainage scheme adopts the setting of the sump below the passage (see Figure 8). According to the other MRT's construction experience, the grouting quality in the passage is unstable, and the possibility of water seepage and soil leakage after grouting during the construction of the traditional sump is high, which causes the high construction risk. Serious accidents occurred during the construction of drainage facilities for the Kaohsiung MRT CO2 project's connecting passage. The excavation risk between tunnel must be considered and optimized.

In GC03 project, the configuration of the sump under the connecting passage will not be used. The inverted arch sump will be set at the lowest point of the longitudinal slope of the shield tunnels, which can meet the capacity and design and functional requirements, instead of additional excavation in risky condition. The cross-sectional configuration is illustrated in Figure 8. This optimized tunnel drainage configuration has been used in CG590A of Taipei MRT Songshan Line.

3.5 Improvement Measure for the Risk of the Shield Machine Breakthrough Phase

The shield tunnel in GC03 project is divided in 2 parts, Φ7.5m from G07 to G10 station and Φ5.6m from G10 to G12/G13 unearth section. The depth of the departure and arrival ends of the Φ7.5m shield

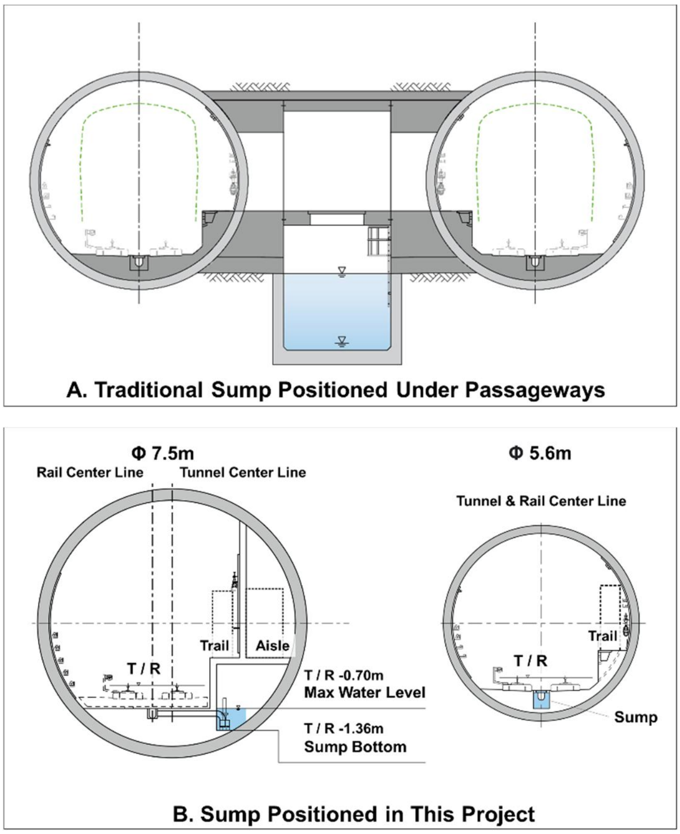

Figure 8. Comparison of Tunnel Drainage Plan

The shield machine cannot directly cut through the rebars of the shaft diaphragm wall. The traditional way is to knock out the concrete part from the inside of the shaft in advance, and cut the rebars manually. Following the traditional construction process, there's only 20cm-thick concrete with the improved soil outside the shaft at this stage, to resist the huge soil pressure, ground water pressure and the drilling impact during breakthrough. The construction risk is high.

In GC03 project, Fiber-Reinforced Plastics (FRP) material is adopted to replace steel rebars in mirror-face range. The FRP bar part of the diaphragm wall can be directly cut by drill bit (As shown in Figure 9) Adopting FRP can make the tunnelling process continuous, that effectively reducing the breakthrough risk. In addition to the FRP bar, the double-packer grouting method is also adopted for the soil improvement method outside of the shaft as water-proofing measure. FRP material has adopted in many construction cases in Taipei MRT, Kaohsiung MRT and Taipower's tunnel construction. The domestic tech is quite mature enough to ensure the effect of reducing the risk of mirror-face breakthrough, and even save the quantity of soil improvement in many cases.

Mirror-face breakthrough is one of the riskiest phases of entire project so that considering the multiple defencing measure in each stage is necessary. The protection measures include water testing, supplementary grouting, shield compartments, filling CLSM to the gap between compartment and the diaphragm wall, mirror-face connecting frame and water-proof sealing, etc. So far, the two shield machine of GC03 project have departed from G12/G13 unearth section and successfully and safely arrived at the working shaft of the G12 station.

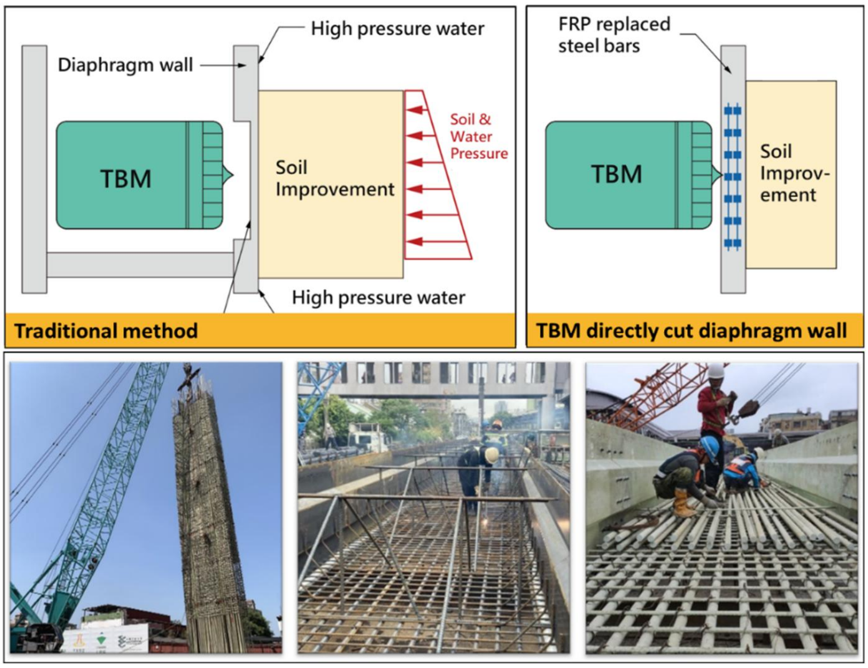

Figure 9. The Diaphragm Wall and FRP/Rebar Cages

3.6 Monitoring and Protection Measure for the Shield Tunnel Construction

The shield tunnel route passes through the various areas with different appearances. The distance between adjacent buildings, structure and foundation type and age are also different. From the south, the tunnel passes through the narrow section of Zhongzheng Road, the adjacent structures are mainly old apartment less than 4 floors. The building survey result shows that some of the building's inclination before the construction stage is already greater than 1/300. And in next section between Ciwen Road (慈文路) and Zhuangjing Road (莊敬路), the Zhongzheng Road is wider and the surrounded by high-rise new building on both sides. In the last part around the National Highway No.1 to G12/G13 unearth section is a relatively empty block, and the adjacent building are mainly tin-sheeted houses.

Among the buildings passing along the shield tunnel, the third-level historic site Jinfu temple (景福宮) and the National Highway No.1 have the highest importance and requirements, and will be analysed in detail separately. The residences will be evaluated based on the standard sections of each type of shield tunnel diameter and depth.
The settlement analysis considering the two-dimensional finite element analysis method by the program PLAXIS.
Based on the monitoring data from the previous case, the Airport MRT CM01 project, which has the similar geology condition to GC03 project. We can sort out the ground settlement caused by the tunnelling work from each section in the cobble gravel and rock formation, compare it with the PLAXIS program analysis result, do the parameter sensitivity test on the ring shrinkage rate, and finally carry out the shrinkage rate and sinkhole type for GC03 project according to the feedback analysis. The PLAXIS model for the Jinfu temple and the Highway foundation impact analysis are shown in Figure 10.

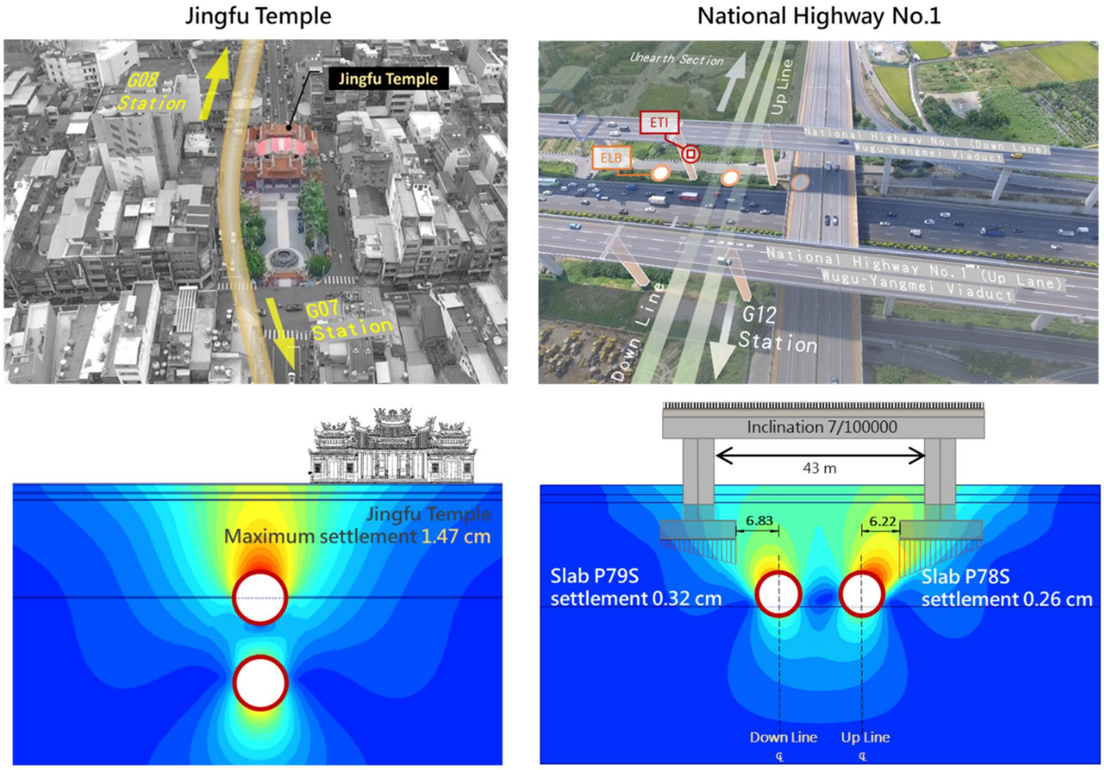

Figure 10. Finite Element Analysis for Jinfu Temple And National Highway No.1

In addition, even if the analysis results show that the tunnelling has a slight impact on the upper structure and does not affect its normal use, automatic monitoring is still carefully planned, and relevant construction and management countermeasures are formulated to reduce the construction risks. For now, the two tunnel through the National Highway No.1 have been crossed successively from November to December 2022, and the protection measures and monitoring plan are as follows.

- The protection measures for National Highway No.1

In order to reduce the influence of the shield tunnel construction crossing the highway, 3 monitoring sections equipped with electronic rod settlement gauges, settlement observation pins and 2 sets of inclinometer casing are set up before the 100m-distance before crossing.
And according to the monitoring results, adjust the applicability of construction management soil pressure and backfill grouting pressure, and cooperate with the following protection measures to ensure that the impact on the structure and stratum is minimized when passing beneath the highway:

1. Before the tunnel passes through, cut-off piles on the both sides are adopted for grouting improvement to block the soil loss and other possible impact of tunnel construction on the pier foundation.
2. On-machine grouting is also used when crossing. At the same time, plastic clay is injected into the outer periphery of the shield shell to reduce the friction, to fill up the over-excavate gap between the shield shell and earth for early resistance before the rings assembling.
3. Reinforced backfill grouting during drilling. Filling the gaps between the ring pieces, soil, and the shield tail, providing the supporting capability of surrounding soil before the leakage occurs, that can

effectively shorten the soil self-supporting phase, reduce the tunnelling risk and the ground surface settlement.

- The monitoring plan and results for National Highway No.1

In order to maintain the structure stability and traffic safety of the National Highway No.1, automatic monitoring instruments including a set of total station and 8 electronic tiltmeters are arranged on the bridge piers. And traditional monitoring instruments including settlement reference point, structure tiltmeter and shallow subsurface settlement point are arranged and monitored manually. The results from automatic and manual monitoring are compared to verify the correctness and reliability of the monitoring data. The on-site monitoring instruments' arrangement are shown in Figure 11.

In the analysis result from PLAXIS model, the maximum settlement on pier is 3.7mm and the surface settlement for the embankments is 2.0-3.0mm during the shield tunnel passing through.
According to the monitoring results of the automatic instrument, the maximum settlement of the pier was about 7mm and the embankments settlement is around 2-4mm, which are similar to the analysis result and both controlled within the management warning value of 13mm. The maximum value measured by the electronic inclinometer is about 113sec, which is controlled within the warning value of 1/700 (294sec). The monitoring data during the tunnelling period are shown in Figure 11.

The above monitoring results show that the construction of the shield tunnel across the National Highway No.1 has no significant impact on the viaduct structure, embankment and the surrounding surface environment.

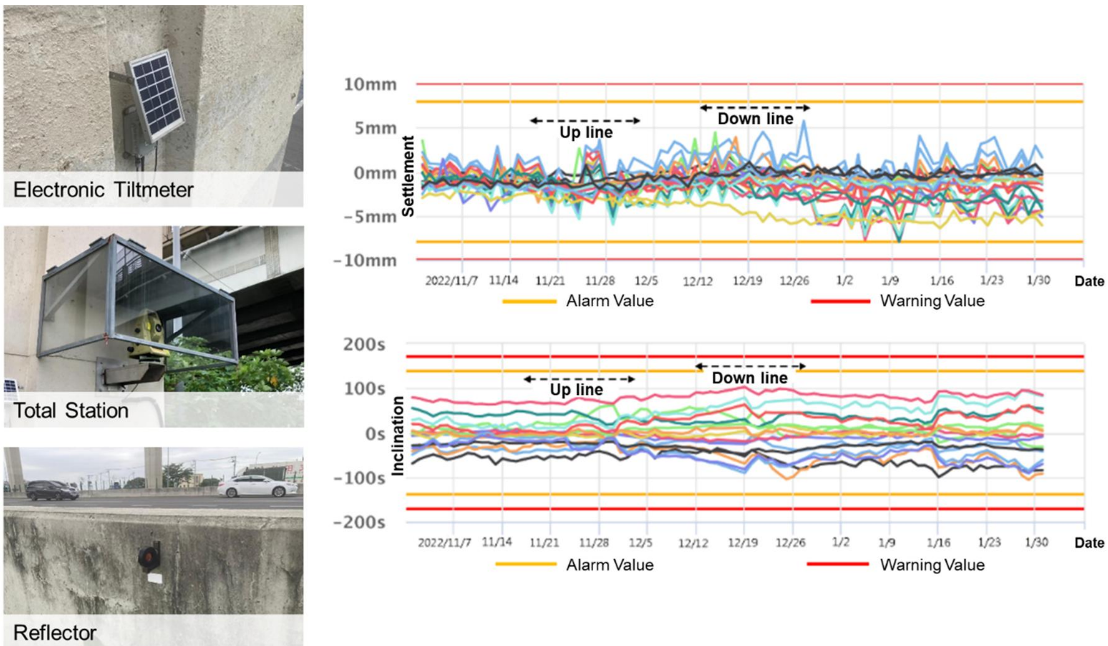

Figure 11. Monitoring Instruments and Results for National Highway No.1

4. Summary

1. The G07 station adopts the top-down construction method, which is evaluated to be feasible in the Taoyuan geology condition. The beam and slab with higher stiffness as the retaining support, which greatly improves the structural stability in the excavation stage and effectively reduces the impact on the adjacent buildings and TRA rails.

2. G08 and G09 station are designed in the way of connecting platforms and stations by connecting passages, comprehensive assessment of architectural space, ventilation, fire safety, and pedestrian flow has been performed to meet regulatory requirements. Notably, this project marks the first case in Taiwan of using split-platform station design.
   For the configuration, the MRT shield tunnel with the largest inner diameter of 7.5m in Taiwan has been adopted, and the tunnel drainage system has also been reviewed to reduce construction risks.

3. For adjacent structures with high importance, proper protection measures and the establishment of an automatic monitoring and warning system can effectively grasp the changes in the construction situation, so that appropriate contingency measures can be taken in time to ensure construction safety;

4. At present, the shield tunnels have passed through beneath the National Highway and has been successfully breakthrough the G12 station northern working shaft. The feasibility of FRP bar, soil improvement and Highway pier's protection measures has been confirmed in cobble gravel strata. The monitoring data collected will be used for feedback analysis, reference for future cases.

5. The monitoring results during the crossing period showed that the settlement and inclination of the bridge piers and embankments were controlled within the management values that can meet the requirement of the Highway Bureau. The construction had no significant impact on the embankment, viaduct structure and the surrounding surface environment.

References

Department of Rapid Transit Systems, Taoyuan, MRT Green Line webpage (https://dorts.tycg.gov.tw/business/mrt-green-line), Taipei, visit date: 2023/08/11

CTCI Resources Engineering Inc., Taoyuan MRT Green Line GC03 Underground Section Between G07 Station~North Daylighting Civil Construction Turnkey Project Internal Design Documents, Taipei, 2023

Chinese Taipei Tunnelling Association, The Design and Construction Guidelines for Shield Tunnelling, Taipei, 2009

CTCI Resources Engineering Inc., Geotechnical Investigation and the In-situ Test Report of Taoyuan MRT Green Line GC03 Project, Taipei, 2019