

ON THE SHARPLY CURVED SHIELD TUNNELING FOR 345kV POWER CABLES IN TAIWAN

Wen-Chuan Lee¹, Ju-Yu Hung², Keh-Jian Shou³, Peng-Jou Chen⁴, and Tsung-Hai Chen⁵

ABSTRACT

Due to the rapid development of the Taiwanese economy, quality of life is continually improving. Installing extra-high voltage cables in underground tunnels to meet the increased electricity needs of urbanization and modernization is the current trend. In recent years, shield tunneling has become the main underground tunneling method for metropolitan areas because it is safe, avoids the need for ground excavation, does not affect ground transportation, does not hinder the flow of groundwater, and has a low environmental impact.

This paper used the Taiwan Power Company's "Fenglin 2nd Road Shield Tunnel Turn-Key Project of the 345kV Underground Cable Route Connecting Gaogang, Wujia, and Kaohsiung" as a case study site. It has geological properties as high water table, sandy soil, and gravel formations. This paper also introduced the construction experiences of this project, including considering the work safety of launching vertical shaft excavation, designing a divergent shaft to place directly above the shield tunnel, constructing a large-diameter, sharp-curved shield tunnel, revising the project's management items and procedures, and pipejacking a connection adit.

Key words: Power cable tunnel, shield method, shaft, sharp curve.

1. INTRODUCTION

The Taiwan Power Company implemented its Sixth Power Transmission Project to improve power supply capability and electrical power quality of Taiwan's power transmission system. The Project aims to meet the need for new and increased energy resources and electrical load growth, and to address the present situation of a high power transformation equipment utilization ratio and high voltage users without a nuclear power supply. One part of the Sixth Power Transmission Project was the Fenglin 2nd Road shield tunnel and Gaogang engine cooling room turn-key project of the 345kV underground cable connecting Gaogang, Wujia, and Kaohsiung.

Beneath the heavily-trafficked Fenglin 2nd Road in Daliao Township, Kaohsiung County (the parameters of the project) lie pipelines that are important to people's livelihood. The project site also has sand formations and a high water table. Underground construction could potentially be extremely risky. Key issues for this project included:

- (a) Given the geological conditions of the high water table, sand, and gravel formations, tunnel excavation was highly difficult, and shield tunneling would be high-risk.
- (b) Long-distance shield tunneling, changing geological formations, and shield design all needed special consideration.

- (c) The design and construction of the joints connecting the divergent shaft directly above the shield tunnel were extremely complex and difficult, and no actual case related to this transmission project in Taiwan could be referenced.
- (d) The arrival work shaft had already been constructed, limiting the route and line planning, and requiring the construction of a sharp-curve ($R = 50$ m) to connect the shield tunnel with the already completed work shaft.
- (e) Infrastructure protection was tenuous, and emergency exit and divergent shaft construction was difficult. This was because the shield tunnel was to be excavated under a concentration of pipelines important for people's livelihood, across the Zai-lai Large Drainage Zone, and adjacent to Provincial Highway No. 88.

During preparation, the turn-key project team invited bidders to research and analyze design theories and construction methods, collected, integrated, and classified relevant technology, management, environment, and safety projects, and evaluated and implemented a feasible program strategy.

2. PROJECT OVERVIEW

This project had a number of factors to consider, including road management demands, local feeling and transportation in the construction area. Adopting the shield method to construct the cable tunnel could limit the impact on local traffic and environment. The project parameters started from the Gaogang substation adjacent to Vertical Shaft #1, crossed the Zai-lai Large Drainage Zone, and ran north alongside Fenglin 2nd Road up to its intersection with Provincial Highway No. 88. The project material for the combined design and construction contract included a 1.56 kilometer-long shield tunnel with an inner diameter of 5.2 meters, Vertical Shaft #1 (the launch work shaft), an

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¹ General Manager (corresponding author), Wei Mon Industry Co., Ltd. (e-mail: dabeylan@weimon.com.tw).

² Graduate student, Department of Civil Engineering, National Chung-Hsing University, Taichung 402, Taiwan, R.O.C.

³ Professor, Department of Civil Engineering, National Chung-Hsing University, Taichung 402, Taiwan, R.O.C.

⁴ Managing Director, Chien Feng Engineering Co., Ltd.

⁵ Deputy Project Manager, Geotechnical Engineering Department, CECI Engineering Consultants, Inc., Taiwan, R.O.C.

emergency exit 3.5 meters in diameter, a divergent shaft 3.5 meters in diameter, and a cooling room two floors above ground and one floor below ground. It converged with two cable tunnels already constructed by the cut and cover method: A 2.2×2.5 meters single-hole cable tunnel and a 2.8×3.6 meters dual-hole cable tunnel (approximately 53 meters in total length). The location and status of the project is shown in Figs. 1 and 2.

The project was located in Daliao Township, Kaohsiung County. The shield tunnel generally passed through quaternary strata. Holocene alluvium consisting of sand, silt, clay, and gravel formations lie under the Pingtung Plain. The water table was located between approximately GL. -2 and GL. -5 meters. The regional geology is shown in Fig. 3. A longitudinal geological diagram based on test drilling for this project is shown in Fig. 4 (CECI 2007, CTTA 1998). The tunnel overburden was between 12 and 18 meters thick.

3. DESIGN AND ANALYSIS

To ensure safety and meet project requirements the turn-key team meticulously combined design and construction to overcome potential risks posed by the high water table and the deep layer of silty sand in Kaohsiung. Specific efforts included: (1) selection and supervision of safe methods to carry out excavation work from a shaft; (2) use of fiber-reinforced plastic (FRP) machinable method during the shield mirror-face breaking stage; (3) adoption of layout and construction method for installing the divergent shaft directly above the shield tunnel; (4) shield line readjustment; (5) key construction measures for the large-diameter, sharp-curved shield;

(6) building security measures and disaster prevention management.

3.1 Selection and Supervision of a Safe Method to Carry Out Excavation of Shafts

Vertical Shaft #1, the work launching shaft for the shield tunnel, was installed in between Gaogang Power Substation and the Zai-lai Large Drainage Zone. The excavation depth of the shaft was 24 meters. It was designed with a high-strength, well-sealed diaphragm wall (1.2 meters thick and 42 meters deep) as a retaining wall. To meet safety requirements the inner support system comprised eight layers.

Given the geological characteristics of the project site and previous experience in deep excavation projects in the Kaohsiung area, the following measures were taken to ensure the quality and continuous seal of the diaphragm wall:

- When the diaphragm wall trench was excavated, the stability of liquid viscosity and the difference between the liquid level and the water table were both increased to ensure the stability of the trench wall (CTTA 2004).
- PVC pipe was installed in the diaphragm wall (He *et al.* 2005) and ultrasonic tests were conducted after the concrete in the wall reached the required strength to verify the quality of the wall (see Fig. 5).
- The analysis of the ultrasonic test results showed that mud might cause water or sand leaks during the excavation of the work shaft; the outside of the diaphragm wall was reinforced and leaks were plugged before excavating.

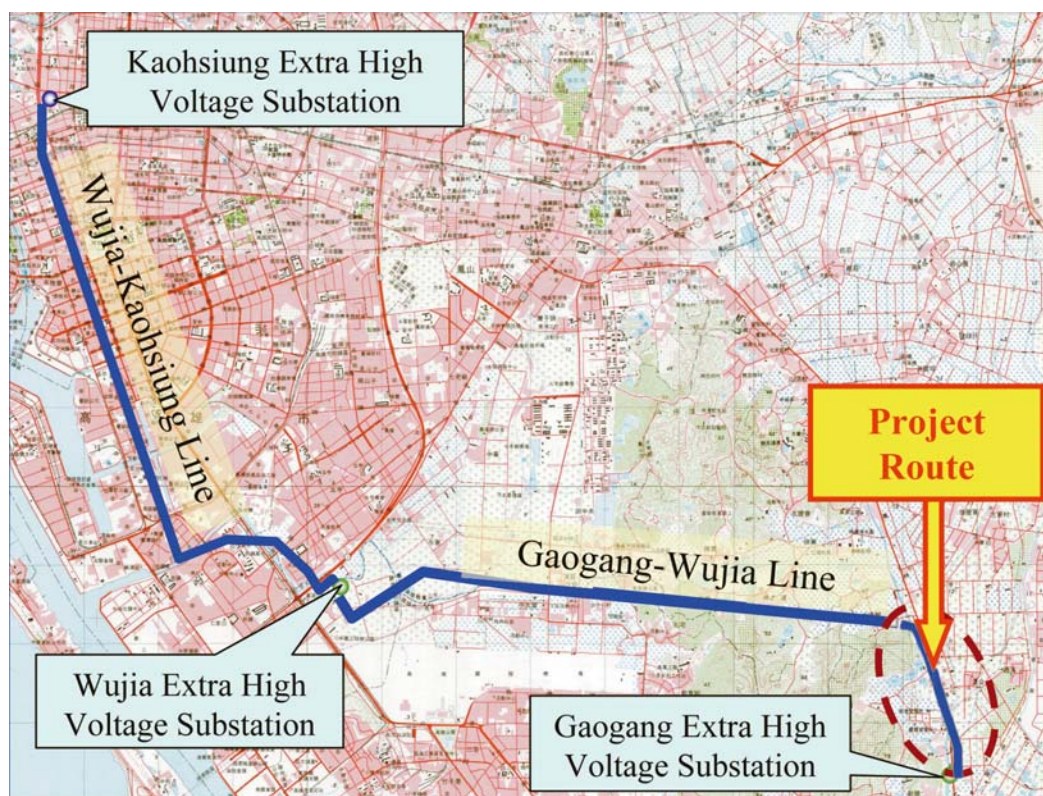


Fig. 1 Position of the Fenglin 2nd road section of the 345kV underground cable connecting Gaogang, Wujia, and Kaohsiung



Fig. 2 Aerial view of the location of the Fenglin road project

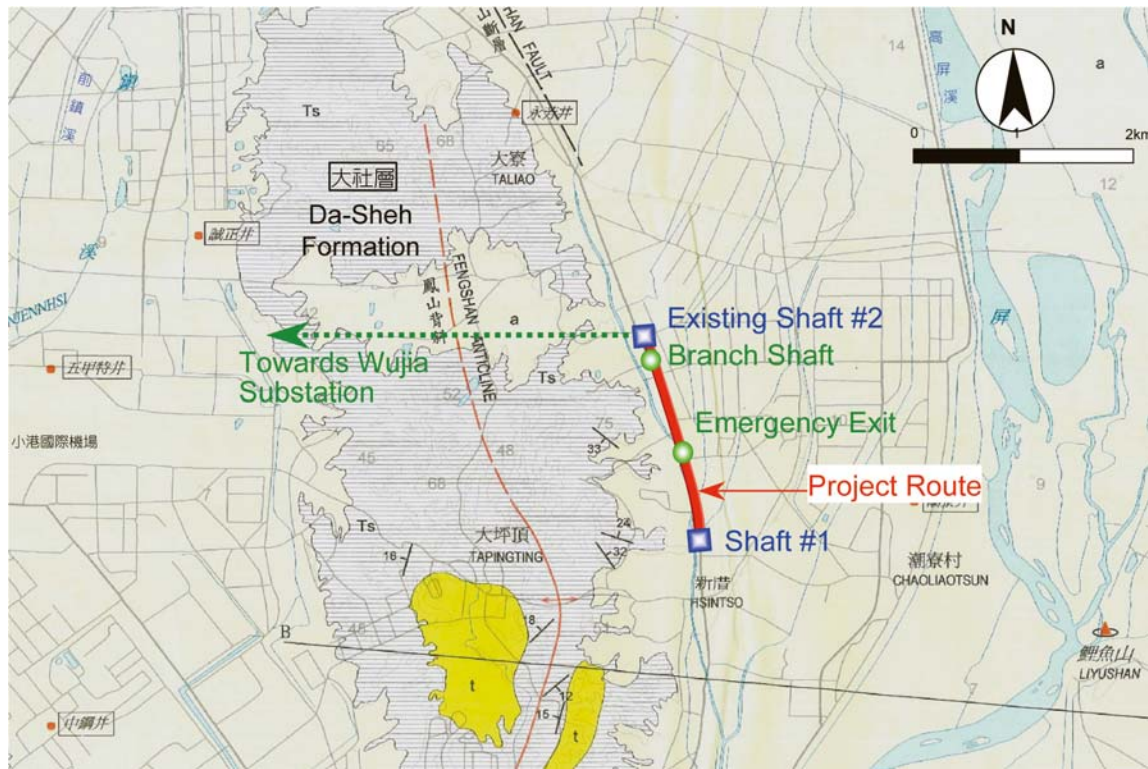


Fig. 3 Regional geological map

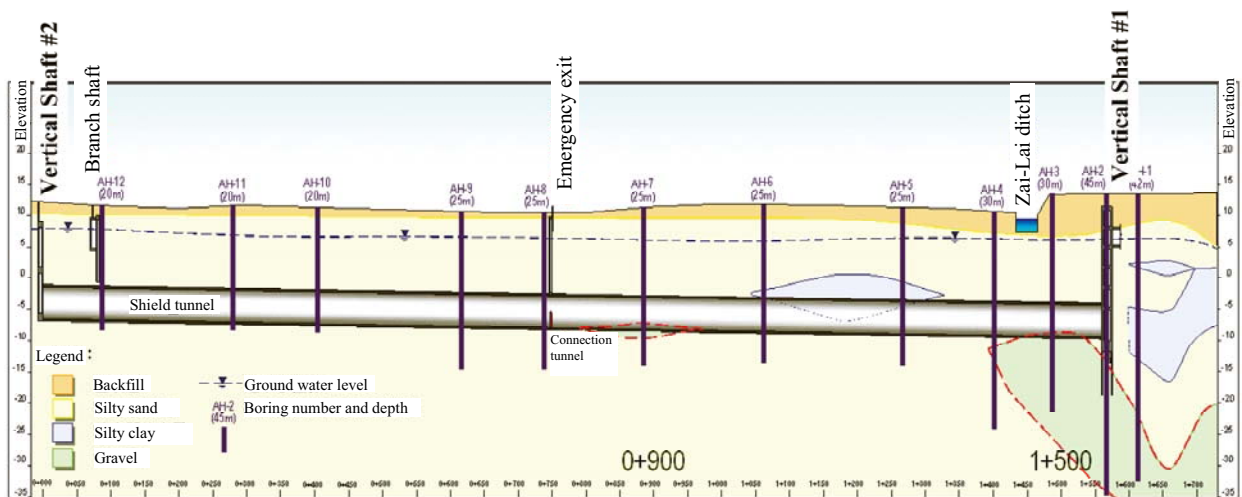


Fig. 4 Longitudinal geological diagram



Fig. 5 PVC test pipe in the diaphragm wall and the ultrasonic test

3.2 Use of the Machinable FRP Method during the Mirror-Face Breaking Phase

Shield break of mirror-face is the most critical task of the shield construction process. It is also one of the most frequent causes of accidents in this type of project. Considering the proximity of the launch work shaft to the Zai-lai Large Drainage Zone, to ensure construction safety and to avoid the gushes of sand often caused by traditional mirror-face breaking methods, the project replaced traditional steel rebar with FRP in the mirror-face breaking parameters (see Fig. 6). Due to the fact that the shield could directly cut FRP and the diaphragm wall during tunneling, use of FRP, in addition to reducing construction time, also significantly improved safety during mirror-face breaking (Kwong 2007).

3.3 Layout and Construction Methods for Installing the Divergent Shaft Directly on Top of the Shield Tunnel

The divergent shaft was installed directly above the shield tunnel and connected to it by a flexible expansion joint with an

internal diameter of 2.4 meters and a height of 1.85 meters (see Fig. 7). This flexible expansion joint ensured the safety of the joint region, improved the shock resistance of the structure, and avoided the need for a traditional divergent well in installation of a tunnel adit (connection pathway). Divergent wells can easily cause sand gushes and uneven collapse.

The casing construction method was adopted to excavate the divergent shaft and complementary ground improvement grouting was designed (Kwong 2007). An air-tight chamber and a temporary support system were also installed in the shield tunnel, ensuring the stability and safety of the joint area. To ensure the functionality of the flexible expansion pipe, the weight of the side wall of the divergent shaft was transferred to steel casing by anchored steel rebar during the construction process. In this way deformation of the flexible expansion pipe by the weight of the divergent shaft was avoided. In addition, horizontal wings were installed in the top of the side wall of the divergent shaft to support its structural weight, avoiding concentration of divergent shaft weight on the shield tunnel affecting its structural safety.

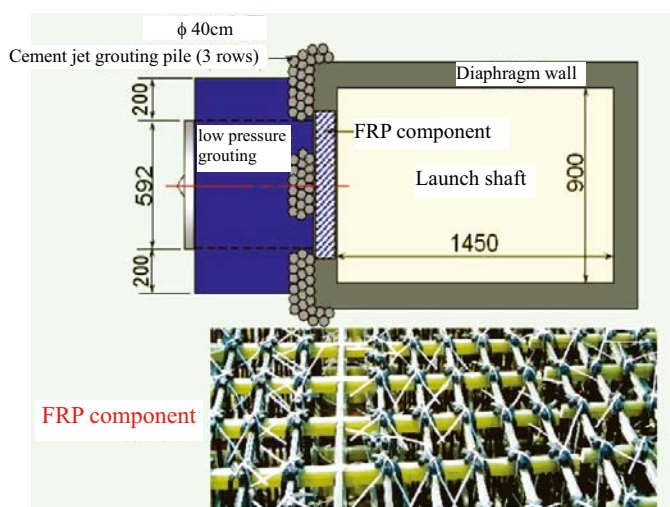


Fig. 6 Machinable FRP method



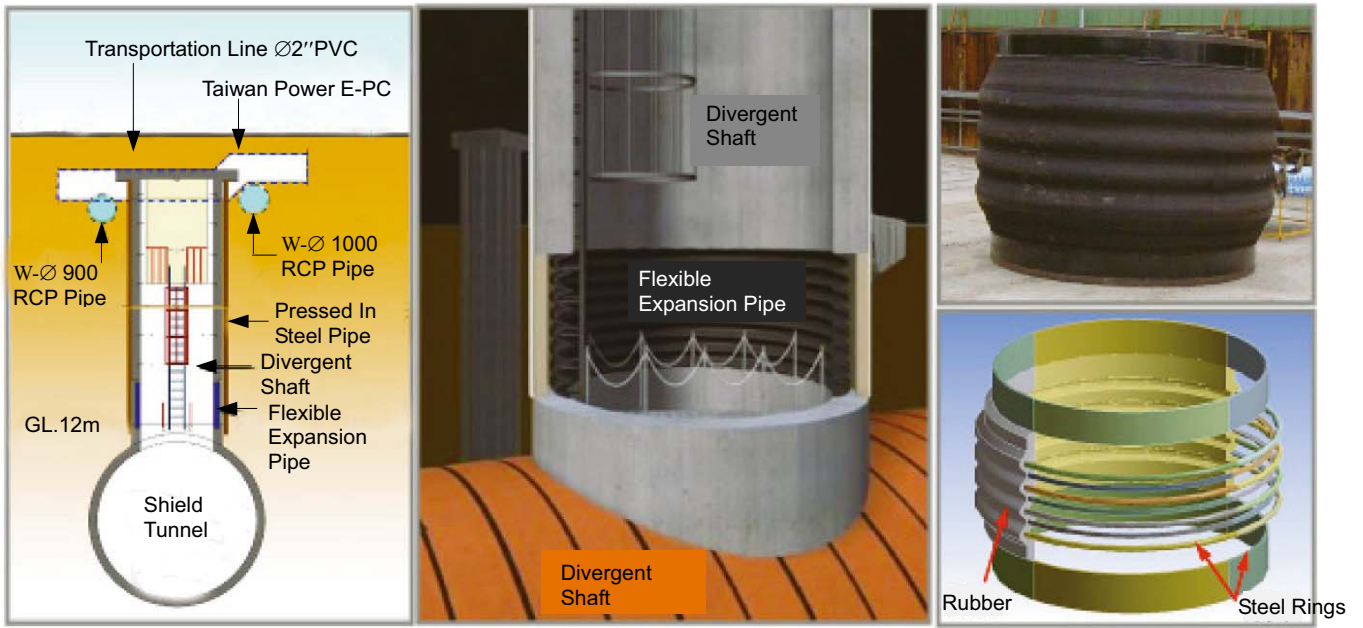


Fig. 7 Diagram of flexible expansion pipe construction

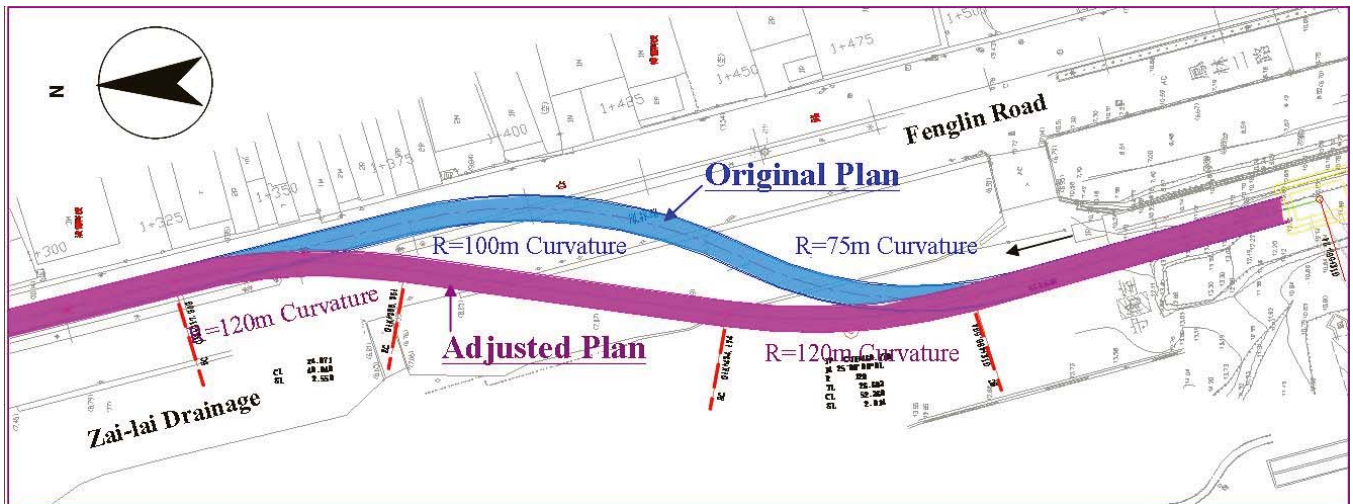


Fig. 8 A comparison of the shield route lines in the zai-lai large drainage zone, before and after adjustment

3.4 Shield Line Readjustment

The original route of the cable tunnel changed direction at the Zai-lai Large Drainage Zone to connect to the Gaogang Power Substation and the Fenglin 2nd Road tunnel. The segments were to be connected by two curves with a turning radius of 75 meters and 100 meters, respectively (see Fig. 8). However, because this plan lacked a buffer zone of at least one body length of the shield machine, excavation had to be expanded during construction. This plan also did not take advantage of the shield tunneling and preserve the Zai-lai Large Drainage Zone. Additionally, a turning radius of only 75 meters required construction of a steel segment lining, extending the construction period and increasing project expenses.

After review, the area line was adjusted to two curves each

with a turning radius of 120 meters, and a connection segment of 68 meters. In addition to reducing the number and variance of curved, shaped segments and speeding up the construction progress, the larger turning radii allowed reinforced concrete lining to be used instead of steel lining. These wider ring segments increased construction speed and reduced costs.

3.5 Key Construction Measures for the Large-Diameter, Sharp-Curved Shield

Because pre-existing pipelines are concentrated under the project site, a turning work shaft could not be installed. Confined by the width of the road and the pre-constructed arrival work shaft, a sharp-curved shield was needed. The conditions of the

project site can be seen in Fig. 9. This project involved the first ever domestic construction of a 5.93 meter large-diameter, sharp-curved shield tunnel ($R = 50$ m). The following measures were adopted to achieve the requirements of the line (Kwong 2007):

- (a) The shield was designed with a spherical folding structure and configured with an overbreak cutter; in this way a fold angle of more than 4.7° could be reached.
- (b) The tunnel structure was designed with steel ring segments. Standard steel segments were 50 centimeters wide. Width of shaped steel segments were a maximum of 50 centimeters and a minimum of 39 centimeters; a difference of 11 centimeters, according to linear requirements.
- (c) Tunneling operations control data management of the test center (Fig. 10) was used to correct and control shield movement during construction.

4. CONSTRUCTION MANAGEMENT AND PERFORMANCE

This project began construction on March 23, 2006. Excavation of the shield tunnel was successfully completed on June 24, 2008, with the arrival of the shield at the empty ground improvement shaft, its disassembly, and its transportation through Vertical Shaft #1. This chapter describes the following instances of specific construction management and implementation performance: (1) special engineering methods for the diaphragm wall around the launch working shaft; (2) casing excavation method for the divergent shaft and the emergency exit; (3) shield tunneling construction management; (4) shield unit and sharp curve construction; (5) connection adit jacking construction.

4.1 Special Engineering Methods for Construction of the Diaphragm Wall around the Launch Working Shaft

Construction of the diaphragm wall around the working shaft comprised 12 construction units. During the construction

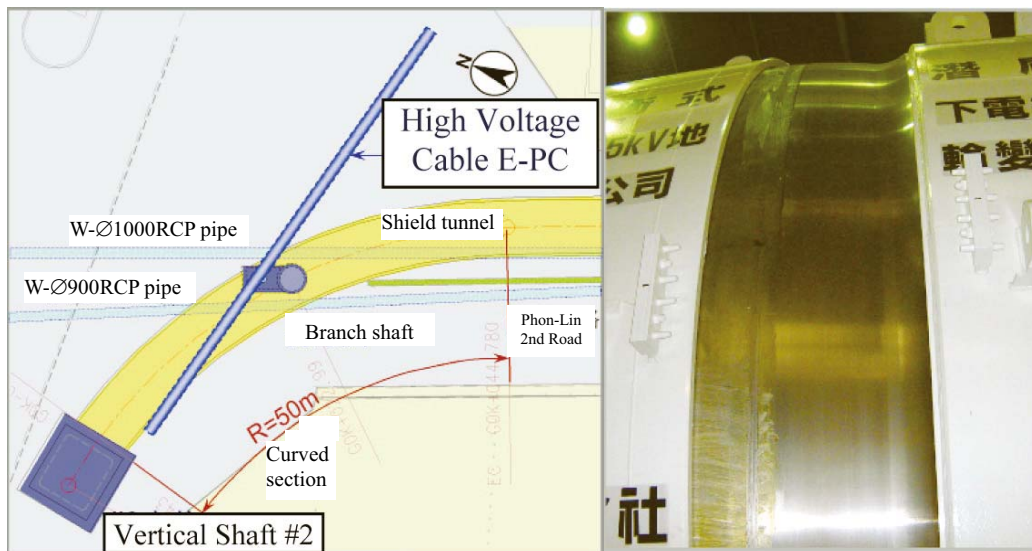


Fig. 9 Distribution of underground pipelines and the folding shield

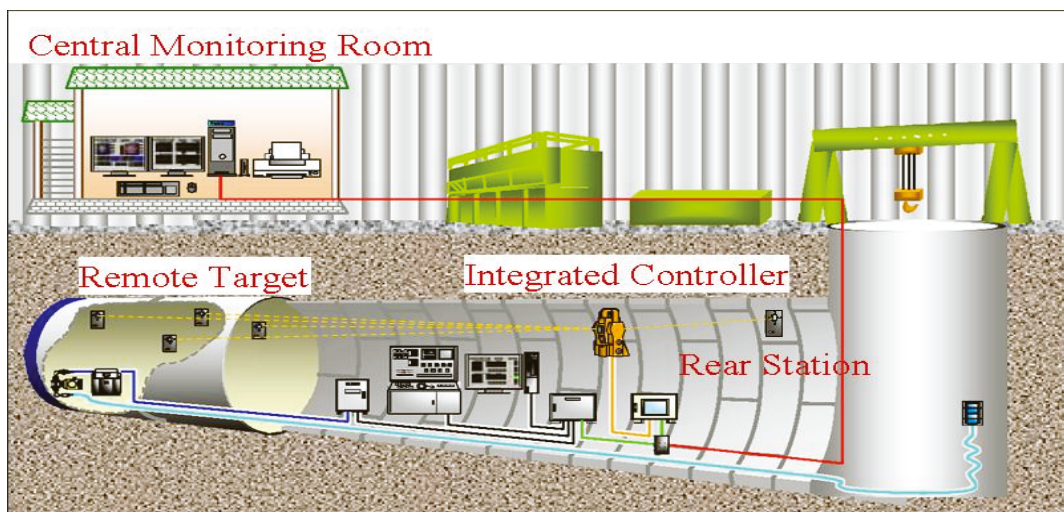


Fig. 10 Test center tunneling operations control management

process, in addition to ensuring a stable liquid differentiation, PVC pipe was embedded in a steel rebar cage. Ultrasonic testing was conducted seven days after the concrete was poured, which verified that the diaphragm wall was of good quality and the wall was free of mud. The excavation process confirmed that there were no leaks in the wall (Taiwan 2006).

FRP is a high strength, low resilience material which reduces wear and tear on shield cutters when the shield is directly cutting tunneling. The project added 38 FRP specialized cutters, which were 2.5 centimeters more convex than average cutters. This achieved the initial purpose of excavating the FRP diaphragm wall.

4.2 Casing Excavation Method for the Divergent Shaft and the Emergency Exit

An emergency exit was installed in the shield tunnel at Fenglin 2nd Road for use by service personnel. The emergency exit had a diameter of 3.5 meters, a depth of 21.4 meters, and was only separated from the shield tunnel by a distance of approximately 60 centimeters. In addition, at the intersection of Fenglin 2nd Road and the Provincial Highway No. 88, a divergent shaft was installed in the shield tunnel to meet the future needs of electric cable. The divergent shaft was 3 meters in diameter, 12 meters deep, and connected with the shield tunnel. Because Fenglin 2nd Road has heavy traffic, and because there is a concentration of large-diameter pipelines necessary for people's live-

lihoods under the road, the emergency exit and the divergent shaft needed to be constructed within a limited space. To ensure construction precision construction and safety of water pipes along both sides of the shaft (water pipe diameters were 900 mm and 1000 mm DIP), a casing shake in and settle method was used to retain and excavate. Measures such as using steel segments in the ground improvement of the connection site and around the tunnel opening, a temporary support system, and an air-tight chamber, ensured construction safety. The construction situation is displayed in Fig. 11.

4.3 Shield Tunneling Construction Management

The total length of cable tunnel in this project was approximately 1.56 kilometers and was located below busy Fenglin 2nd Road. To avoid surface disruption shield tunneling construction methods were adopted. The proximity of the cable tunnel to buildings, important pipelines, the Zai-lai Large Drainage Zone, and a Provincial Highway No. 88 overpass meant that appropriate construction management was required during the shield construction process. In addition to ensuring the safety of the shield tunnel, the volume of displaced soil caused by the construction needed to be as minimal as possible to protect these nearby structures. The related management projects, objectives, and methods are provided in Table 1.



Fig. 11 Steel pipe construction of the emergency exit

Table 1 List of projects, objectives, and methods for managing the shield tunneling construction

Management project		Management objective	Management method
Control of shield machine tunneling		Control the torque of the auger conveyor, the force of the hoisting jack, the earth pressure, the angle of the shield machine rotation, and the elevation display meter when operating the shield machine.	Adjust the tunneling and dumping speed to the geological conditions, and control the operand of the shield machine to within the permitted range. Cutting torque = 400A - 600A Jacking force = 5000 kPa - 8000 kPa .
Management of earth pressure		(1) Earth pressure must not exceed the designed safety value for the shield machine (2) Earth pressure within the cabin must not exceed by too much or be less than by too much the natural combination of water pressure and earth pressure, to avoid possible ground subsidence or swelling.	Calculate the natural water pressure and earth pressure for the area of excavation as basis for earth pressure management. Soil cabin pressure: 260 kPa - 280 kPa.
Management of mud pouring		Reduce the torque of the auger conveyor and the blade, prevent soil solidification in the cabin, and increase the plastic flow and water impermeability of soil excavation to prevent spouts of groundwater.	Pour highly concentrated mud, appropriately adjusting the volume according to the dumping conditions.
Management of excavated soil		The amount of soil excavated and the amount of soil dumped during shield tunneling should be roughly equivalent to avoid ground subsidence or swelling.	Manage by comparing the soil load capacity of the bucket in the soil-transport trolley and the section excavated by the shield machine multiplied by the amount of soil produced by the length of the tunnel (including forested areas (松方) and mud). Each segment (m) excavated /0) $27 \text{ m}^3 \sim 28 \text{ m}^3$ of soil.
Management of backfill grouting		Prevent tunnel segment joints from leaking or the ground from subsiding.	After the assembled tunnel segments have been pushed away from the tail of the shield machine, backfill grouting was immediately implemented from the grouting holes in the segments. The backfill grouting pressure was $2.5 \text{ kg/cm}^2 \sim 3 \text{ kg/cm}^2$. The volume of grouting was approximately 2200 liters \sim 2600 liters. When necessary, a second grouting was implemented to prevent leaking.
Management of pouring oil into the back of the shield		To prevent the back of the shield from leaking.	Adopted a three-layered steel brush on the back of shield and installed an automatic oil injection pump to refill the back of the shield at any time.
Management of construction measurements	Wire route and ordnance benchmark measurements	Wire Route Measurement: the datum for the designed central route of the shield tunnel. Ordnance Benchmark Measurement: the datum for the elevation measurement of the shield tunnel.	Set wire coordinate points along the shield tunnel route using a light wave theodolite and recorded measurements. Tested the shield tunnel route according to the ordnance benchmark provided by Party A, set the ordnance benchmark, and recorded measurements.
	Tunneling measurements	(1) Provide a reference for elevation and direction correction during shield tunneling. (2) Provide a reference for the assembly and selection of standard and repaired tunnel segments.	(1) Installed the coordinates and elevation fiducial points for the work shaft as a reference for direction and elevation correction during shield machine tunneling. (2) One coordinate was installed every 50 meters within the shield tunnel. (3) After each segment was assembled, the gap between the segment boundaries and the back of the shield and the true roundness of the segments were measured.
	Shield tunnel connection measurements	Provide a basis for adjusting the elevation of the bottom of the tunnel and provide a walkway used to adjust the thickness of the upward arch.	After the tunnel is connected, measured and recorded the elevation of the bottom of the segments.

Shield tunnel construction will cause the top surface to settle, increasing in severity the closer the soil is to the center of the tunnel. The ratio of the surface area of the settled ground to the surface area of the tunnel is called the ground loss rate, and it is an important indicator to assess the impact of shield construction on surface settlement and on adjacent structures. Before construction, monitoring instruments were laid along the path of the project, and a monitoring section was adopted to provide a reference for construction workers to adjust the shield tunneling parameters.

The project monitored and managed construction according to pre-construction predictions, during-construction monitoring and management, and post-construction feedback analysis. According to feedback analysis on monitoring results, ground loss rate resulting from the construction of the project was approximately 0.5 ~ 0.8%, 0.5 ~ 2.0% lower than the normal rapid-transit construction ground loss rate (average 1.3%). This shows that the shield construction for this project was rigorous and indeed executed according to a management formula.

4.4 Shield Unit and Sharp Curve Construction

Due to the fact that the shield machine would pass through sand, clay, gravel, and other geological strata, an approximately 65% open earth pressure balanced shield with a six-spoke cutter was used to quickly and simultaneously extract and retain the soil. Because shield construction directly cut into the diaphragm wall over a long distance, the number and strength of the cutters were increased from E3 to E5. This meant delays and risks associated with replacing the cutter halfway were avoided. In addition, screw conveyors and throttle valves were custom made without central axes in the front end to help remove gravel and obstacles easily while in the gravel strata.

The shield for this project had an outer diameter of 5.93 meters, a body length of 8.84 meters, and was comprised of three parts: The soil chamber, the ring beam, and the shield tail. To meet the requirement for an $R = 50$ meters acute-curved turn at the end of the tunnel the shield had a spherical, folding structure and was equipped with an overbreak cutter. A detailed drawing of the shield structure is provided in Fig. 12.

The following summarizes the steps taken to address the acute-curve construction:

1. Designed the steel segment measurements according to the radius of the acute curvature.
2. Drew the segment layout on the pre-construction plans, calculated the coordinates of each segment, and recorded the coordinate data in the test center monitor tunneling management system.
3. Corrected the shield positioning and adjusted the shield fold angle, the amount of overbreak, and the overbreak parameters according to deviation reports sent by the central test monitor tunneling management system to the shield operator during excavation.
4. Measured the gap between the orientation of each segment and the shell of the shield after each segment had been installed, and repaired segments and strengthened backfill grouting as needed.
5. Retested the route manually at each shift change.

A picture of the completed steel segments for the acute-curved section of the project can be seen in Fig. 13. The statistical results of the construction deviation are: Average horizontal deviation 1.4 centimeters, average vertical deviation 5 centimeters and the greatest deviation 8.9 centimeters, still less than the allowable deviation 10 centimeters. The vertical and horizontal deviations at the end of the tunnel were 3.2 centimeters and 1 centimeter, meaning the tunnel successfully linked to Vertical Shaft #2.

4.5 Connection Adit Construction

The shield tunnel connected a connection adit with the emergency exit. The connection adit passage was a sharp, U-shaped steel segment used to enable construction. To ally with ground improvement grouting, an air-tight compartment and a temporary support system were installed in the shield tunnel to ensure safety and stability during the joint construction. Additionally, a security door was added to the edge of the steel

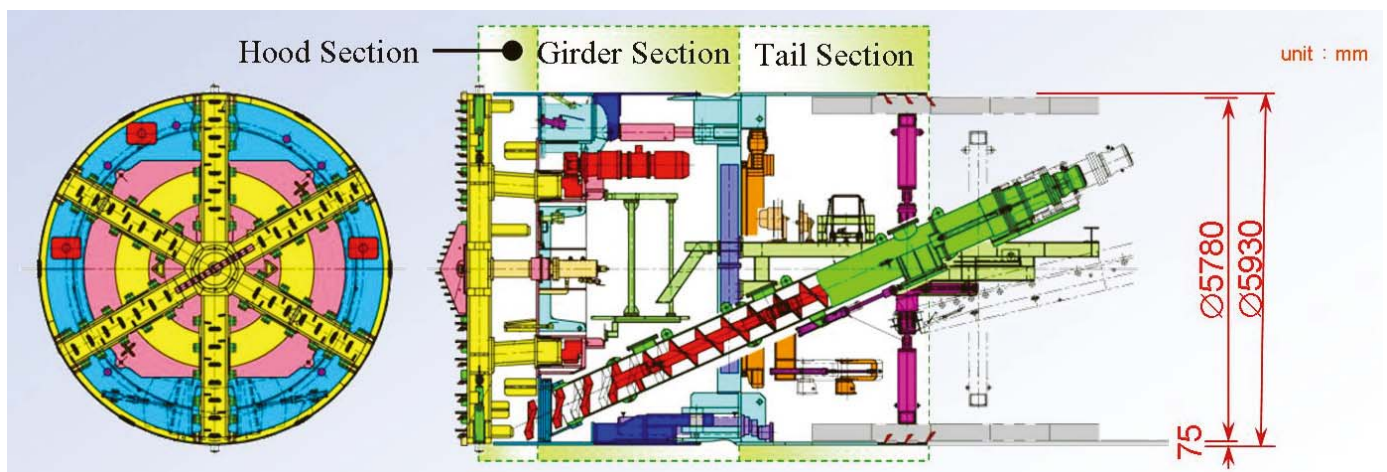


Fig. 12 Schematic of the shield structure



Fig. 13 Steel segments in the sharp-curved section of the tunnel

segments. In the event of the excavation face leaking, the security door would immediately be shut and construction personnel would be evacuated. After additional grouting was completed and the tunnel was confirmed sealed, personnel could resume steel segment construction. After the segments were completed, the edge and the tunnel were welded together, sealing the adit. After the connection adit was temporarily erected in the tunnel and the steel tunnel segments were reinforced, the steel tunnel segments were re-sectioned and the mirror-face was broken.

5. CASE ANALYSIS AND APPLICATION OF RESULTS

1. To ensure the stability of the diaphragm wall trench, the project increased stable liquid viscosity and the difference in the liquid level and the water table. To ensure the safety of subsequent excavations, PVC pipe was laid in the diaphragm wall and ultrasonic tests were conducted to verify the quality of the wall after the concrete reached the required intensity.
2. To increase safety during the shield mirror-face breaking stage, FRP replaced traditional steel rebar and both deep excavation and shield launch were successfully completed. Although this method increased the shield equipment and FRP material costs, it reduced the amount of ground improvement needed at the launch end and substantially increased safety during the mirror-face breaking stage. There were also no gushes of water or sand during this stage. The construction experiences of this project can be a reference for projects with similar geological conditions or operations with similar risks.
3. This is the first project in Taiwan involving a 5.93 meter large-diameter shield sharp-curve construction ($R = 50$ meters). Project design includes a spherical, folding shield configured with an overbreak cutter, a horizontal fold that reached 6.5° , and a vertical fold of 0.5° , and complementary steel segment lining. During construction, it used the test center's tunneling operations control data management system, and the project has already arrived precisely at vertical shaft #2. Due to the fact that vertical shaft #2 was already completed according to its own standards, the structural dimensions and orientation of vertical shaft #2 not only affected the shield construction arrival method for this project; it also restricted the line of the shield as the shield could not be perpendicular to the work shaft and could not arrive in a straight line. This not only increased the difficulty of construction, it also increased project risk. With already limited excavation face parameters, sealed steel sheets were reinforced and concentrated to strengthen the line measurements. Construction of the sharp curve was completed smoothly.
4. The emergency exit and the divergent shaft were constructed by the casing construction method. Complementary ground improvement grouting for the joints was designed and an airtight chamber and temporary support system were installed in the shield tunnel to ensure safety during joint construction. Ground improvement for the shield tunneling and the mirror-face breaking stage required initial construction before the shield passed through. This created issues with the subsequent steel casing installation for the emergency exit and divergent shaft. The task was finally completed with the assistance of drill prep-holes. This case suggests that similar projects subsequently should review the construction process or separate the ground improvement work in to stages to facilitate installation of steel casing.
5. The connection adit used a U-shaped steel pipe jacking method with the necessary ground improvements. The work tunnel already had limited operating room, and adding the arc-shape to the emergency exit, the connection adit, and the shield tunnel increased the difficulty of steel pipe jacking. Through the persistent efforts of the construction team, the challenge was finally overcome and the work was successfully completed.

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