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# Advanced technologies in shield tunneling – A case study in Taiwan

## Technologies avancées dans le tunnel de bouclier – Une étude de cas à Taïwan

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ABSTRACT: TBMs (Tunnel Boring Machine) have been one of the most popular tools used in shield tunneling. With its outstanding efficiency and reliability, shield tunneling with TBMs is always listed as top choices for constructing tunnels particularly in a congested area. Over the past decades, the tunneling and segment installation technologies have been improved to overcome more and more space and time restrictions in the projects. This paper presents an underground cable project in southern Taiwan where advanced technologies of shield tunneling were first introduced to conquer challenges in land acquisition and tight schedule. They included, (1) TBMs docked in the ground; (2) Fast boring; (3) Fast joints; (4) TBM and segment design for sharp curves; and (5) Recycling system for excavated mixture. The paper first briefs the background of the project, including environmental and schedule constraints. It then illustrates how each of the advanced technologies was applied to the project. These technologies led to such accomplishments as tunnel being completed for as long as 5 km without shafts in-between and each ring being built within an hour. Concluding remarks are given at the end of the paper.

RÉSUMÉ : Les tunneliers (Tunnel Boring Machine) ont été l'un des outils les plus populaires utilisés dans le creusement de tunnels de bouclier. Avec son efficacité et sa fiabilité exceptionnelles, le tunnel de blindage avec des tunneliers est toujours répertorié comme les meilleurs choix pour la construction de tunnels, en particulier dans une zone encombrée. Au cours des dernières décennies, les technologies d'installation de tunnels et de segments ont été améliorées pour surmonter de plus en plus de contraintes d'espace et de temps dans les projets. Cet article présente un projet de câble souterrain dans le sud de Taïwan où des technologies avancées de creusement de tunnels de blindage ont été introduites pour la première fois pour relever les défis liés à l'acquisition de terres et à un calendrier serré. Ils comprenaient, (1) des tunneliers amarrés dans le sol ; (2) Alésage rapide ; (3) articulations rapides ; (4) conception de tunneliers et de segments pour les courbes prononcées ; et (5) Système de recyclage du mélange excavé. Le document présente d'abord le contexte du projet, y compris les contraintes environnementales et de calendrier. Il illustre ensuite comment chacune des technologies avancées a été appliquée au projet. Ces technologies ont conduit à des réalisations telles que l'achèvement d'un tunnel sur 5 km sans puits entre les deux et la construction de chaque anneau en une heure. Des remarques de conclusion sont données à la fin de l'article.

KEYWORDS: TBM docking; fast boring; fast joints; sharp curves; recycling system.

## 1 INTRODUCTION

In response to the increasing needs in electricity for the expansion of the Great Kaohsiung Area of southern Taiwan and to enhance the efficiency of power supply system, a 345kV 4-loop cable system was planned to connect two extra-high-voltage substations that were recently built with a total distance of about 12.4 km. To reduce uncertainties encountered in land acquisition, the cable system was distributed mainly under the existing roadways for at least 20 m below ground surface. Only the substations (such as primary, distribution, or secondary) along the route can be used for TBM transfer and major facilities of the system.

Since the project was required to be completed in nearly 3 years, it was divided into two construction districts that were both executed through turnkeys. Advanced shield tunneling technologies were thus introduced for the first time in Taiwan, including (1) TBMs docked in the ground; (2) Fast boring that enables excavation and segment erection operated at the same time; (3) Straight bolts and wedge connectors applied as fast joints for segment installation; (4) TBM and segment design and construction for alignments with radius of curvature (R) as sharp as 30 m; and (5) Recycling system for excavated mixture to minimize the amount of waste muck to be disposed. The paper illustrates these technologies, and improvements are demonstrated for future application.

## 2 PROJECT OVERVIEW

The paper presents the work in the second construction district of the project that is located in Xiaogang and Daliao District of Kaohsiung City, Taiwan. It starts from the Shaft #2 in an existing primary substation (P/S), follows the roadways 2 km eastwards to connect the Shaft #3 at the site for a future distribution substation (D/S), and then goes another 5 km eastwards to end at the Shaft #4 in a newly-built, extra-high voltage substation (E/S) (Figure 1). From the figure, the scope of civil works for the district included construction of the Shafts #3 and #4, the maintenance Shafts E3 and E4 and their connecting passages, the cooling room CS3, and a shield tunnel with inner diameter of 5.7 m and total length of about 7 km.

Since the tunnel alignment is mainly to follow the existing roadways and the shafts for TBM departure or arrival can only be allocated inside the site for existing or planning substations, there are 12 horizontally curved sections with R value smaller than 120 m. Figure 2 shows the distribution of the curved sections along the alignment. Among these 12 sections, there are

1 section with R of 60 m and 5 with R of 30 m. The maximum vertical slope of the alignment is about 4% in response to the ground surface variation.

From the geomorphologic and geological perspectives, this

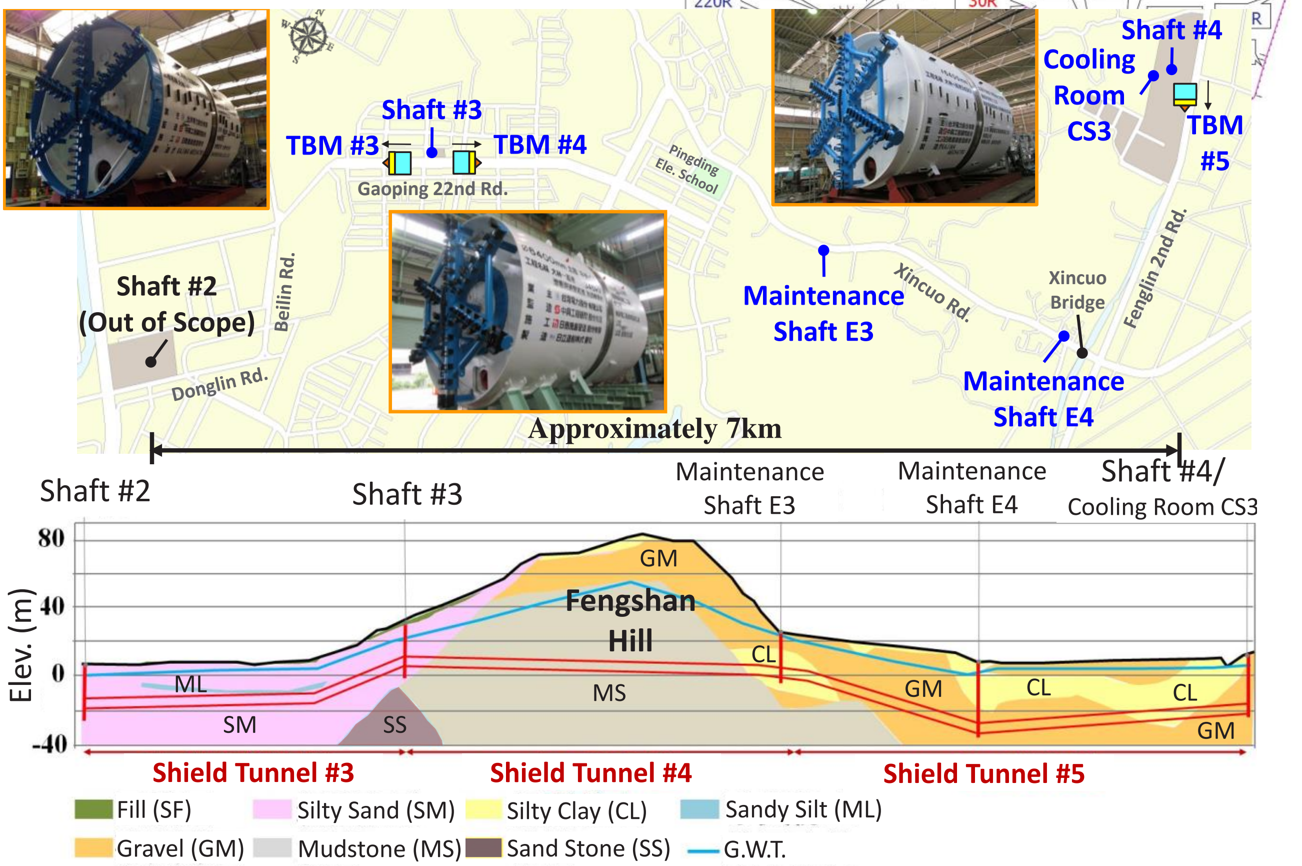


Figure 1. Project plan and geological profile

construction district starts from an alluvium plain, passes eastwards through Fengshan Hills, and ends at terrace deposits, each of which feature silty sands, mudstone, and clays/gravels, respectively, over the depths of tunneling. With surface elevation varying approximately from 8 m to 85 m above MSL (Mean Sea Level), the depths of groundwater level ranges roughly from 3.9 m to 21.0 m with lower bound on the two ends of the district and upper bound in the hilly area. A hydro-static distribution with depth is observed over the range of the scope.

Figure 2. Distribution of curved section along alignment

## 3 ADVANCED TECHNOLOGIES IN SHIELD TUNNELING

To meet the schedule and space constraints and to conquer the challenges in tunnel alignment (i.e., long distance, sharp curves, and complex ground condition), basic setting of tunneling was determined, including

- EPB (Earth Pressure Balanced) type TBMs were chosen with bore diameter of 6.4 m and length of about 11 m.
- Articulation cylinder of spherical type was equipped between the front and rear shield to allow about a maximum of 11 and 1 degrees of adjustment in horizontal and vertical direction, respectively.
- Three layers of steel tail brushes and uneven cutter bits were mounted against anticipated high hydraulic pressure and long-distance boring, respectively.
- The "soft-eye" (i.e., FRP rebars) was installed on both departure and arrival shafts for TBM breaking-through.
- Five equal-size segments (i.e., 2A+2B+K) were fabricated for a ring. Each ring was mounted with 3 grouting holes allocated on the Type B and K segments (Figure 3).

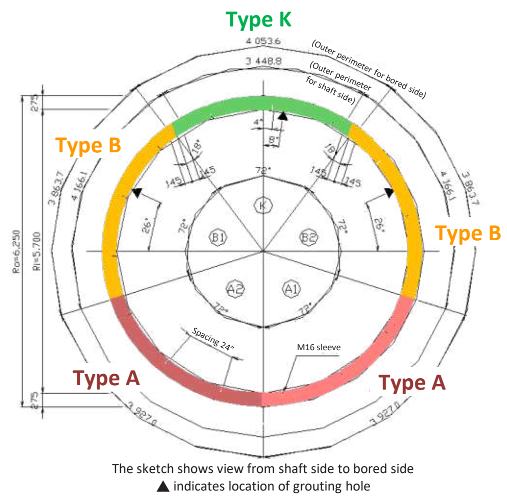


Figure 3. Division of segment in a ring

- The width of the ring varied from 1.5 m to 0.3 m to fit the alignment. Arrangements are outlined in Table 1.

Furthermore, advanced technologies in shield tunneling were introduced, as described in the following sections.

Table 1. Segment arrangement

| Item | *Dimension* | | |
|---|---|---|---|
| Inner Diameter (m) | | 5.7 | |
| Thickness (m) | | 0.275 | |
| Outer Diameter (m) | | 6.25 | |
| Width (m) | 1.5 (R≧220m) | 0.75 (75m≦R < 220m) | 0.3 (R < 75m) |
| Division / ring | | 5 | |
| Type | RC | RC | Steel |

## 3.1 *TBM docking*

Since there was no public land available for TBM transfer between the Shafts #4 and #5 that are 5 km apart, two TBMs (i.e., TBM #4 and #5 in Figure1) were employed and launched from the Shafts to dock with each other in the ground. The district was one of the pioneers in Taiwan to apply this docking technology.

In this district, the modified DKT (Direct Docking Tunnel) method was adopted for the TBM docking. As sketched in Figure 4, the receiver TBM first arrives at the designed docking point waiting for the push-in TBM. When the push-in TBM arrives, the receiver withdraws its cutterhead into the shield and pushes out the cover flange. The push-in TBM then penetrates into the receiver with its cutterhead retreated and shield welded to the cover flange. Water-proof measures are implemented until no leakage is assured at the joint. Figure 5 shows the photo taken when the two TBMs docked with each other.

Based on the geological investigation results (TPC, 2013), the docking point was selected at the place where clayey impermeable layer was anticipated. However, the docking point was eventually moved eastwards to the gravel layer to cover the delayed boring schedule of the receiver TBM #5 as a result of mixed ground of clayey and gravelly soils. The cooling system mounted on the TBMs was first engaged to prevent inflow of high pressure water before the joint was sealed. The double-packer low pressure grouting or TAM (Tube A Manchette) was further conducted from the ground surface to set the final protection. Figure 6 illustrates the sketches of the water-proof measures and photos taken on the site, and Figure 7 shows the photo taken after the connection was completed.

Since the tolerance of docking deviation is only 50 mm, additional locating measure was applied. While the two docking TBMs were still 5 m apart, the traditional traverse survey incorporated into an automatic tracking system was utilized to locate the TBM and segments. While the distance fell into 5 m apart, a horizontal probe with detector equipped on the receiver TBM was applied to double check the location of the push-in TBM. Figure 8 shows the sketch of the additional locating measure and the photo taken on the site. Table 2 summarizes the deviation of location for the two TBMs where both the individual and relative values are within the tolerance of 50 mm.

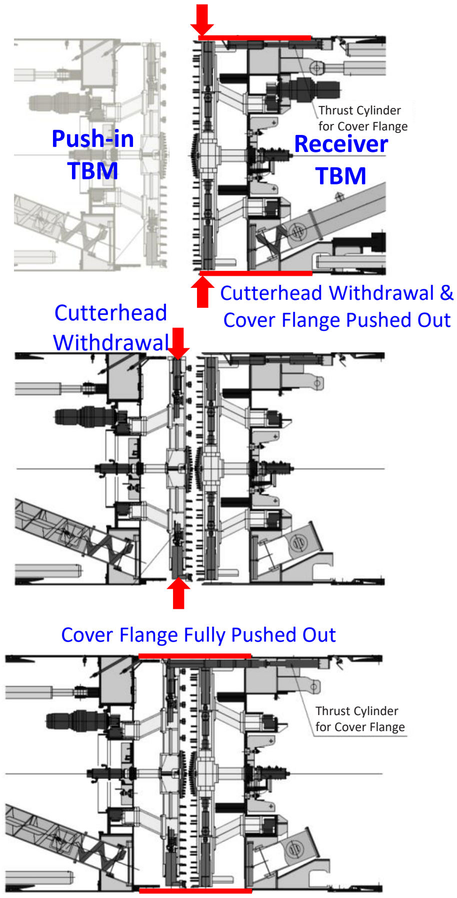


Figure 4. Construction procedure of modified DKT method


Figure 5. Two TBMs docked together

Table 2. Deviation of TBM docking

| TBM | *Design position (m)* | | | *Actual position (m)* | | | *Deviation (mm)* | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N-coor. | E-coor. | Elev. | N-coor. | E-coor. | Elev. | N-coor. | E-coor. | Plan | Elev. |
| #4 | y.372 | x.4499 | 2.300 | y.358 | x.4568 | 2.320 | -14 | +6.9 | 15.6 | 20 |
| #5 | y.382 | x.4702 | 2.300 | y.386 | x.4684 | 2.311 | +4 | -1.8 | 4.4 | 11 |

Note: (i) N-coor. and E-coor. represent longitudinal and horizontal coordinates, respectively; (ii) Elev. represents elevation; (iii) x and y are simplified symbol from actual values.

## 3.2 *Fast boring*

In the shield tunneling, the extension and release of jacks in the TBM play an important role in boring and segment erection. Normally, these two motions are operated independently to simplify the control of the steering. To accelerate the advancing speed, it is crucial if these two motions can be operated simultaneously.

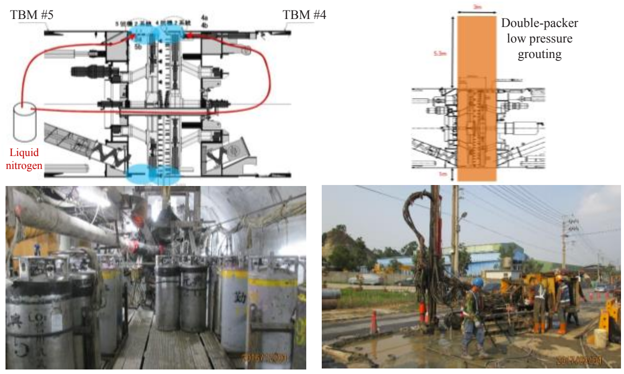


Figure 6. Cooling method and grouting applied as water-proof measures

Figure 7. Completion of tunnel connection

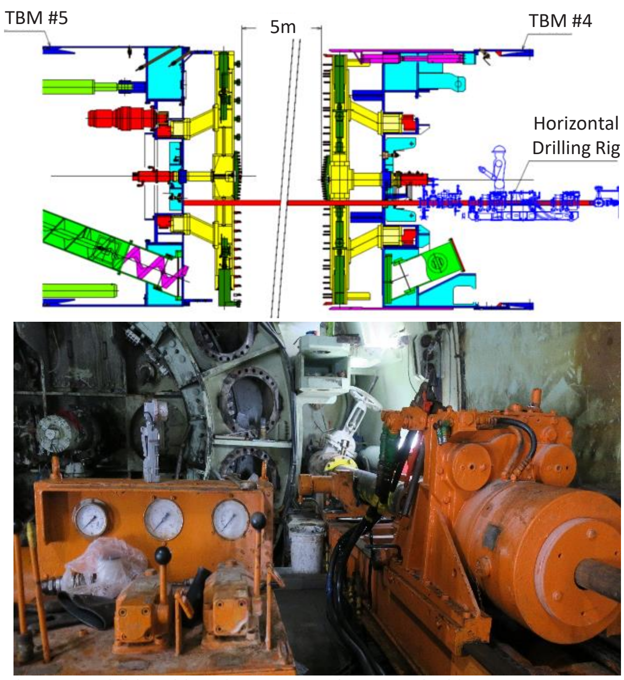


Figure 8. Additional locating measure for TBM docking

This idea was applied to the construction district with an automatic balance system introduced to adjust pressure of each thrust cylinder during tunneling. To prevent difficulties arising from TBM passing through sharp curves in the district, however, the cylinders were designed to have strokes just enough for inserting the K-segment, the last segment erected in a ring. Figure 9 sketches that the first segment is erected when the jacks are extended to 1.5 m. While the TBM keeps advancing to 2.3 m, the erection of second segment is finished. Boring is then paused and restarted until the rest of the segments in a ring is built. Such boring procedure for a ring was estimated to be finished approximately within 40 minutes (Table 3).

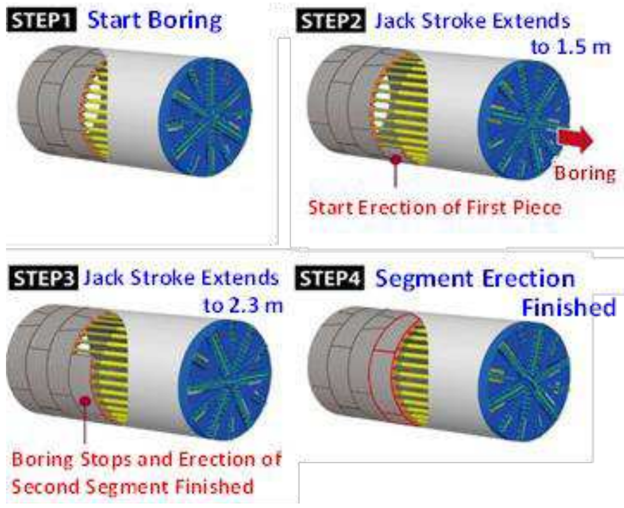


Figure 9. Construction sequence of fast boring

Table 3. TBM advancing rate

| TBM | #3 | #4 | #5 |
|---|---|---|---|
| Advancing Rate Per Day | 19 rings | 18 rings | 21 rings |
| Completion Time Per Ring | 60 min. | 65 min. | 55 min. |
| Excavation Time Per Ring | 38 min. | 43 min. | 33 min. |
| Assembly Time Per Ring | 22 min. | 22 min. | 22 min. |

### 3.3 *Fast joints*

Another measure to accelerate the advancing speed is to shorten the assembly time for segments. As shown in Figures 10 and 11, the DS (disc spring), or straight bolts alike, and cone, or wedge alike, connectors were first introduced to Taiwan as segment and ring joints, respectively (e.g., Mitsui, 2014). These joints are fastened just by simply pushing the neighboring segments together. No nuts are needed as required in the curved bolts, which are the most-frequent type used in Taiwan.

As summarized in Table 3, the introduction of fast joints reduced the assembly time to around 20 minutes for a ring erection. A significant improvement was achieved as compared to 50 minutes taken for the traditional curved bolts in a 6-segment ring. A ring could thus be finished within an hour and a total of about 20 rings could be finished in a day (Table 3), nearly double the advancing rate of TBMs using traditional boring and joints.

### 3.4 *Sharp curves*

It is never an easy job for TBMs passing through sharp curves. Its success relies on close coordination of TBM and segment design and thorough investigation of the effects on the surrounding environments. Table 4 summarizes the check items for this issue.

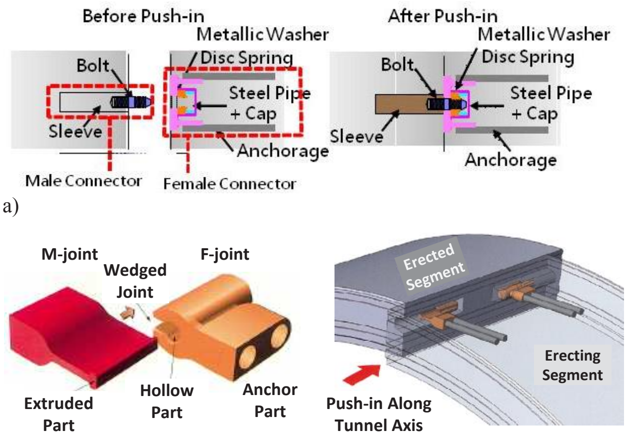


Figure 10. Fast joints: (a) straight bolts and (b) wedge connectors


Figure 11. Fast joints adopted for the district

In this district, TBMs passing through sharp curves was simulated and assessed to obtain optimum combination of over-cut, outer and inner gap, stroke of cylinders, and articulation angle (Figure 12). The TBMs were designed accordingly.

Furthermore, the corresponding segment width was determined as well as the structural design. The ground condition was also evaluated to provide sufficient reaction against the torsion of TBM boring. Effects of over-cut on the surroundings were assessed and supplementary measures such as grouting were adopted as contingency. Figure 13 shows the photo taken for the completed curved sections of the tunnel. According to the monitoring readings (Chen et al., 2017), the resulting surface and in-ground settlements all fell within the alert level (2 cm) of monitoring control.

### 3.5 *Recycling system for excavated mixture*

Though EPB TBMs were adopted in the district, a mud mixture of slurry, bentonite, foam, and polymer additives was injected outside the cutterhead to increase the liquidity of the excavated earth and stability control on the excavation face as well. In the past, the whole mixture was transported to the shaft and dumped out directly without any treatment.

In the district, a recycling system was introduced for the first time to reduce the use of mud mixture and the amount of excavated earth to be disposed. The excavated earth was first mixed with slurry after discharged from the screw conveyor. It was then transported back to the departure shaft and moved out through pumped pipes. If big gravels or cobbles were encountered, they would be crushed down into small pieces before remixed with slurry.

Table 4. Check item for TBM passing through sharp curves

| Check item | *Detail* | *Response* |
|---|---|---|
| TBM | Earth resistance against TBM torsion<br>Lateral subgrade reaction against TBM eccentric force<br>Boring under high hydraulic pressure | Select proper TBM for certain specifications and capabilities |
| | Clearance for segment erection on tail shield | Assure enough space at tail shield |
| Segment | Excessive deformation and movement resulted from thrust and torque of TBM boring | Proper segment dimension and division<br>Space check for tunneling on sharp-curve sections |
| Effects on surroundings | Over-excavation during sharp-curve boring leading to effects on surrounding ground and existing structures | Conduct back grouting firmly<br>Supplementary measures adopted |

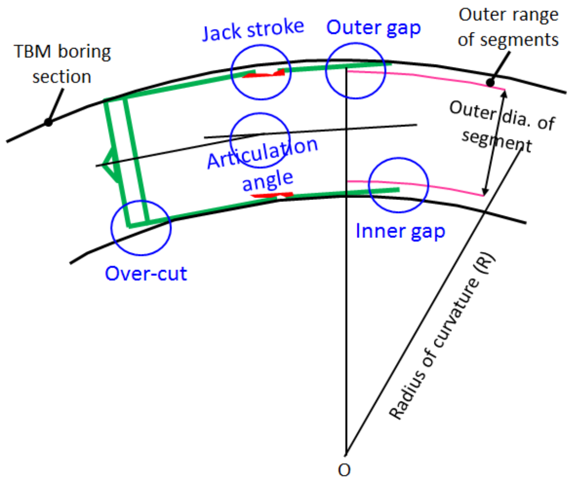


Figure 12. Schematic of TBMs passing through curves


Figure 13. Completion of tunnel on curved sections

Figure 14 sketches the layout of the recycling system on the departure shaft. The system was principally composed of one pre-processor and three earth separators. Once the mixed earths and slurry was pumped out of the shaft, they were sent to the pre-processor for preliminary separation. They then were split in the earth separator into earths and slurry through shaking sieves and centrifuge. The earths were stored in the disposal pit whereas the slurry was sent to the recycle pit to mix with high density slurry before transported back to the shaft for reuse. Figure 15 shows the recycling facilities taken on the site.

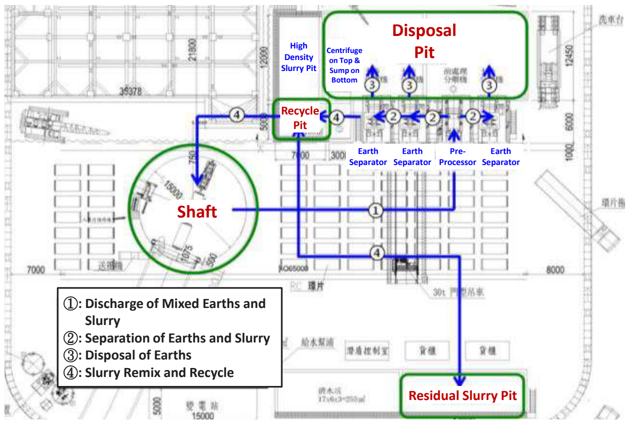

Figure 14. Plan layout of recycling system

Figure 15. Recycling facilities on site

## 4 CONCLUDING REMARKS

Advanced technologies in shield tunneling were introduced to accelerate the advancing speed and to conquer challenges in long-distance boring. They were adjusted to accommodate the complex ground condition and sharply curved alignment. The shield tunneling design and construction illustrated in the paper were based on the close collaboration and were derived from integration of concerns among consultants, contractors, manufacturers, and suppliers. Significant improvements were demonstrated through monitoring results.

## 5 ACKNOWLEDGEMENTS


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## 6 REFERENCES


Chen, D.J., Mitsui, T. and Kao, F.M. 2017. Brief of sharp curve design and construction for Taipower Dalin-Gaogang shield tunnels. *Journal of Professional Geotechnical Engineers* 14, 14-23.

Mitsui, T. 2014. Recent trend and issues of shield tunneling technology in Japan. *Professional Engineer Journal* 66, 34-41.

Taiwan Power Company (TPC) 2013. *Supplementary geological investigation report for shield tunnel and Gaogang cooling room turnkey of the second construction district of Dalin-Gaogang 345 kV cable project*.