EXAMINATION OF THE TBM TYPE SELECTION AND ITS EFFECT IN THE HSUEHSHAN TUNNEL

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ABSTRACT

The 12.9 km long Hsuehshan Tunnel in Taiwan is the longest twin tube, 2-lane vehicle tunnel in Southeast Asia and the fifth longest one in the world. The Hsuehshan Pilot Tunnel is located in-between and slightly below the two Main Tunnels. The aim of the Pilot Tunnel was to obtain geological parameters, pre-treat the weak strata, pre-drain the groundwater, practice TBM operation, and serve as an auxiliary tunnel during and after the construction of the two Main Tunnels. A double shielded TBM (∮ =4.8m) was selected for driving the Pilot Tunnel. This type of TBM was considered suitable for handling the possible spotty adverse ground conditions that might be encountered. The ground support planned for the Pilot Tunnel boring with TBM included the options of rock bolts, shotcrete, steel ribs, and precast segments. Finally, only precast segments were applied to the whole of the Pilot Tunnel. The double shielded TBM (∮ =11.7m) with precast segments for ground support was also used in tunneling of the Main Tunnel. In the plan, the adverse ground would be pretreated from the Pilot Tunnel ahead of the TBM boring in the Main Tunnels. However, the excavation of the Pilot and Main Tunnels by the TBM had to be stopped several times to treat the difficult ground conditions or to repair the machines. The westbound TBM had gotten stuck and then had to be dismantled after excavating only the first 456m. The eastbound and pilot TBMs bored 3,870m and 5,168m, respectively. In this paper, a brief introduction is given concerning the considerations of each TBM type selected. Then, some processes are described such as the TBM operation, the improvement measures, and the techniques for freeing the stuck TBMs. Finally, the examination of the suitability of the types of TBMs for the Hsueshan Tunnel is presented. It is hoped that the experience presented in this paper could be of help to similar projects in the future.

Keywords: Pilot Tunnel, Main Tunnel, double shielded TBM, difficult ground, ground support.

INTRODUCTION

The Taipei-Ilan Expressway goes from the Nangang District of Taipei City to the Toucheng Village in Ilan. Its total length is about 31km. The Hsuehshan Tunnel is part of the Taipei-Ilan Expressway and is 12.9km in length. It is the longest tunnel in Southeast Asia, and the fifth longest twin tube expressway tunnel in the world. There were two TBMs used in excavating the Main Tunnels and both were 11.74m in diameter. They both had started from the Toucheng end. There is also a Pilot Tunnel that's the same length as the Main Tunnels and has a diameter of 4.8m. This Pilot Tunnel was excavated for geological investigation. It was also excavated by a TBM.

According to the geological mapping derived from the excavation, it shows that the rock at the western part mainly consists of sandstone and argillite, and at the eastern part argillite and the Szeleng sandstone, as shown in Figure 1. There are several fault zones about 3km away from the Toucheng end. The thickness of the

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fault gouge is within 6~20m, and the disturbance zone is between 5~40m. Meanwhile it is full of underground water. The Szeleng sandstone is almost 3,671m in length. The maximum uniaxial strength of the Szeleng sandstone is about 3,200kg/cm2. The high hardness and anti-abrasiveness of the Szeleng sandstone combined with the highly fractured zones and abundant groundwater made tunneling more difficult and risky. In the remaining portion of the Tunnels, the rock quality is sound.

THE SELECTION OF THE EXCAVATION METHOD

The 12.9km Hsuehshan Tunnel is the most critical section of the Taipei-Ilan Expressway, and the key issue to breaking the Tunnel through successfully was using the exact excavation method we chose. The optimal excavation method for this project was thoroughly assessed from the initial site investigation, feasibility study, route evaluation and basic design stage. There were many professors, experts and experienced engineers engaged in this assessment job. In the end the AEC (Asian Expressway Consultants) made the comparison between traditional D&B and TBMs method and issued a formal technical report at the basic design stage in 1990. The TBMs method was recommended in the conclusion of this report (AEC 1990), so it was adopted as the guide.

The main reasons for using TBMs were as follows (Chen et al. 2003):

1. The Hsuehshan Tunnel crossed through the water reservation zone of Taipei City. The environmental authority strongly resisted any more increases in the working faces in this area.
2. If D&B were used, an adit about 2km and 8% in slope would have had to be added, and it might have induced some other problems such as environmental pollution due to mucking, drainage, ventilation, etc. Meanwhile, there would have had to have been 6 working faces added in this water reservation zone.
3. If the 12.9 km tunnel were to have been excavated by D&B, it would have taken more than 20 years. This estimate was based on a monthly rate of 50 meters. So the deadline for this project could not have been met.

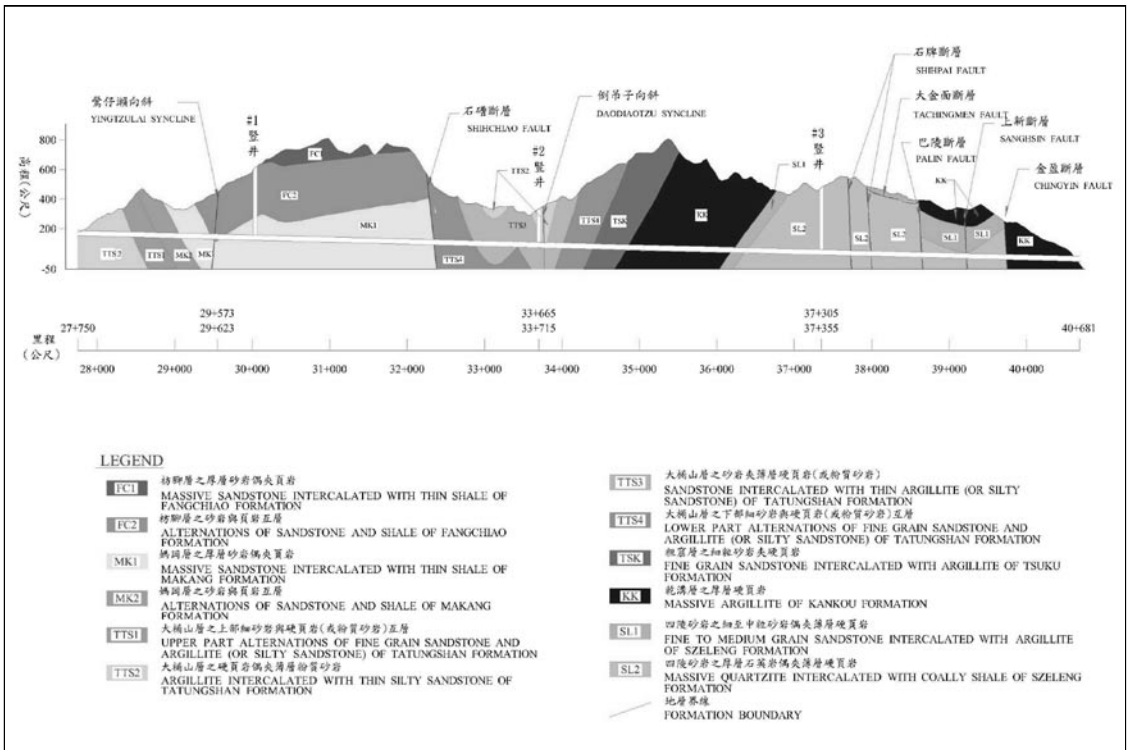

Figure 1 Geological Profile of the Hsuehshan Tunnel

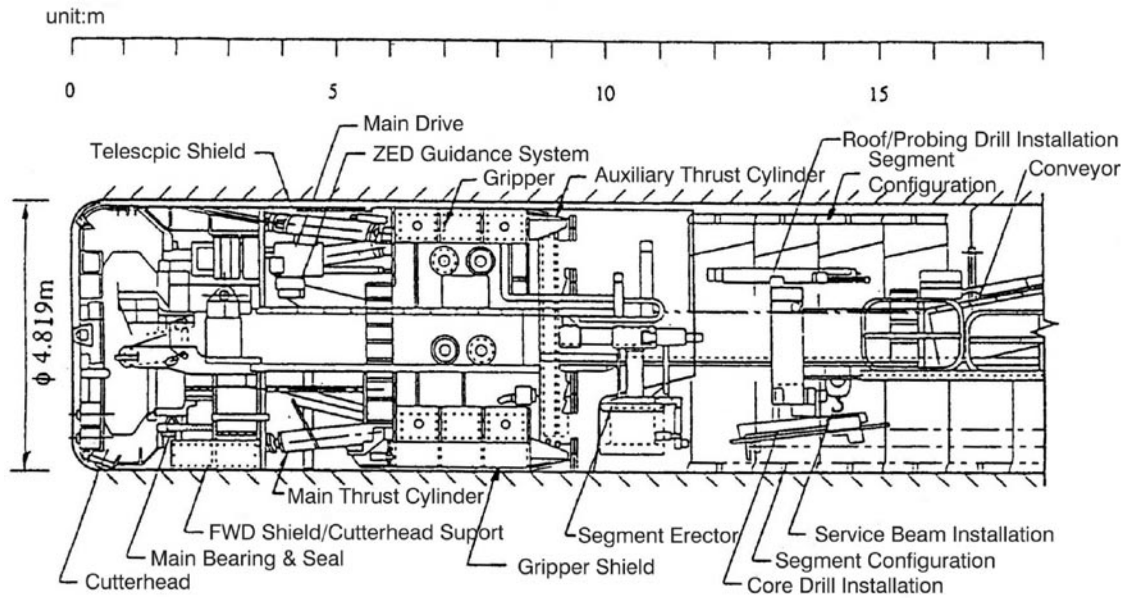

Figure 2 Longitudinal Profile of the Pilot Tunnel TBM of the Hsuehshan Tunnel

4. 10km of the Hsuehshan Tunnel were situated in sound geological conditions. The TBM's daily progress in sound geological conditions is several times that of the progress of the D&B method. The TBMs also require less labor than the D&B method. The remaining 3km situated in poor geological conditions could still be excavated by the TBMs after ground treatment.
5. The advantages of excavating from the east portal with TBMs were mucking and drainage by gravity, less environmental influences, etc. Also the excavated material from the TBM could be used as the backfill for the embankment at the interchange of Toucheng.
6. Throughout the world, the trend is to use TBMs in long tunnels. Especially since the functioning of TBMs has been improved lately. Also, the operation and management of TBMs may be transferred to the local engineers at the same time.
7. After the assessment by many experienced foreign experts, it was the conclusion to adopt the TBMs for use because of the economy, schedule, safety, manpower, and feasibility to excavate.

MODIFICATIONS TO THE PILOT TUNNEL AND MAIN TUNNEL TBMS

According to the results of the geological investigations at the basic design stage, there were 6 large known faults, countless small fault zones and an unknown number of fracture zones along the route. There was 3km of fractures and hard Szeleng sandstone that were full of ground water. The highest overburden was about 700m. Falling rocks and cave-ins were unavoidable. To ensure safety, shield protection was needed in these TBMs. Double shielded TBMs would be more efficient than single shielded ones during the simultaneous excavation and installation of the segments. Therefore, after the AEC consultants considered both the safety and schedule demands, the final suggestion was to select the double shielded TBMs. Besides, the purpose of geological investigation, the support system in the Pilot Tunnel was designed to use segments and traditional NATM supports as well.

Pilot Tunnel TBM

The TBM used in the Pilot Tunnel was manufactured by Robbins, USA, It was 4.8m in diameter, had a head length of 10.8m, with a total length of 188m including the backup system. The cutter head was electrically driven. Total weight was 720T including the head and backup system. Its longitudinal profile is shown in Figure 2 and technical data is shown in Table 1. In addition, for geological investigation before the TBM excavation, there are two movable drillers on a ring for probing installed near the tail shield. The probe drilling could be coring or non-coring.

Due to the many difficulties during excavation, the modification of the Pilot Tunnel TBM was necessary for use in poor geological zones. The mainly modified items included as follows (Chang 2003):

1. Welding grill bars on the opening of the mucker of the cutter head to control the quantity of the incoming rock being cut in order to prevent the conveyer from being overloaded or shutdown.
2. Welding plates with inclined angles around the opening of mucker of the cutter head to reduce the friction during cutter head rotation.
3. On the top of the cutter head, there was a protection mask added at 120 degrees to absorb the earth pressure from the upper part of the falling rock. It could also keep the cutter head from being struck by debris and decrease the possibility of TBM getting stuck.
4. Improvement of the capacity of the driller and the stability of the base to upgrade the efficiency of the probe drilling.
5. The roller bits and gears of the cutter head drive motor were changed to lower speeds to increase the rotation torque and improve the ability of release from getting stuck in poor geological conditions.

Main Tunnel TBMs

The TBMs used in the Main Tunnels were manufactured by Wirth, Germany. They were 11.74m in diameter, with a head length of 10.9m, and a total length of 250m including the backup systems. The cutter head is

Table 1 Technical Data for the Pilot Tunnel & Main Tunnel TBMs of the Hsuehshan Tunnel

No.	Item	Pilot Tunnel TBM	Main Tunnel TBM
A.	TBM Head		
1.	Type / Model	Robbins 153-269/Double Shields	Wirth TBM 1172 H TS/Double Shields
2.	Cutter head Diameter / Length of TBM	4.819~4.8m / 10.833m	11.74m / 10.94m
3.	Forward Shield Outer Diameter	4,758mm	11,650mm
4.	Tail Shield Taper / Outer Dia. of Shield at Rear Edge	38mm / 4,720mm	10mm / 11,640mm
5.	No. of Cutter head Motors / Output Power	6 / 160kW (Electrical)	18 / 4,000kW (Hydraulic)
6.	Cutter head Speed, Low Speed / High Speed	4.0~4.9rpm / 8~9.8rpm	0~4 rpm
7.	Cutter head Torque, Low Speed / High Speed	2,030kNm / 1015kNm	7,200kNm~30,000kNm
8.	No. of Primary Thrust Cylinders / Thrust Force	12 / 630kN	18 / 50,600kN
9.	No. of Cutters / Size	34 / 432mm (17in)	80 / 432mm (17in)
10.	Main Bearing Diameter / Weight	3,048mm / 3,452kg	6,800mm
11.	No. of Stabilizer Cylinders / Thrust Force	2 / 2,114kN	2 / 8,500kN
12.	No. of Gripper Cylinders / Thrust Force	2 / 15,728kN	2 / 65,000kN
13.	No. of Auxiliary Thrust Cylinders / Thrust Force	8 / 2,114kN	28 / 78,700kN
14.	Segment Width / Thickness / Outer Diameter	1.2m / 18cm / 4,610mm	1.5m / 35cm / 11,500mm
15.	Minimum Excavating Radius	350m	500m
16.	Total Weight / Total Capacity	360T / 1,122kW	1,400T / 6,400kW
B.	Back-Up System		
17.	Type / Number / Diameter / Depth of Driller	Rotary & Percussion / 2 / 76mm / 80m	Montabert HC80 / 1 / 76mm / 80m
18.	Equipment for Gravel Backfill / Grouting	Aliva 285 / KG-15	Aliva 285
19.	Wet Shotcrete Equipment / Working Rate	Aliva 285 / 4 m^3/hr	Optional
20.	Number of Conveyors / Capacity	3 / 6m^3/min	4 / 1,200 m^3/hr
21.	Muck Car Power / Capacity / Speed	Hydraulic / 10*8m^3 / 15km/hr	Hydraulic / 6*15m^3 / 15km/hr
22.	Total Length / Total Weight / Capacity	177m / 360T / 500kW	250m / 700T / 5,540kW

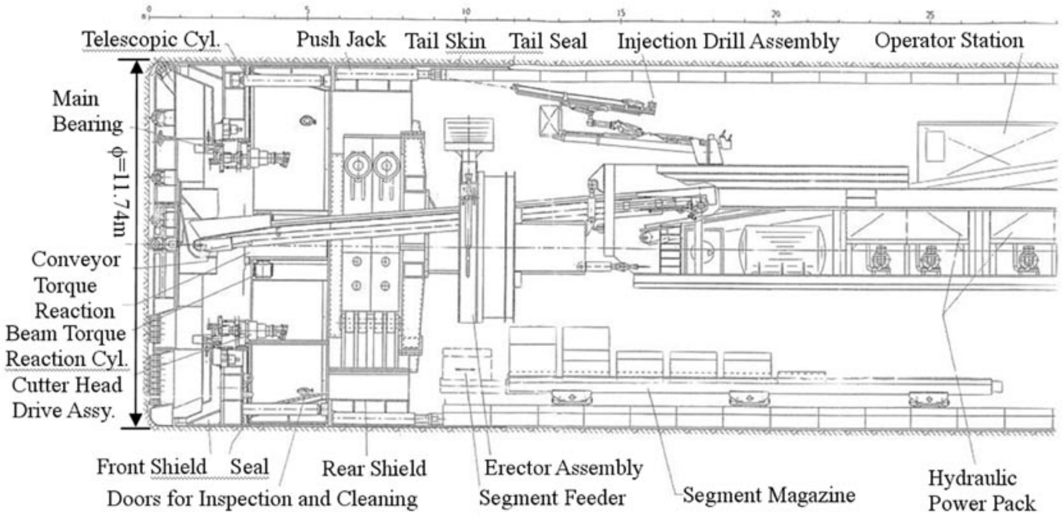

Figure 3 Longitudinal Profile of the Main Tunnel TBM of the Hsuehshan Tunnel

hydraulically driven. Total weight was 2,100T including head and backup system. Its longitudinal profile is shown in Figure 3 and technical data is shown in Table 1.

The experience gained from using the Pilot Tunnel TBM helped us to understand how to modify the Main Tunnel TBM. So there were many modifications that were different from the Pilot Tunnel TBM, and the main items were as follows (Chang 2003):

1. An automatic griller was installed on the opening of the mucker of the cutter head for controlling the quantity of incoming rock.
2. The cutter head protruding rim of the front shield was reduced from the 120cm used in the Pilot Tunnel TBM to 90 cm in the Main Tunnel TBM to decrease the resistance of cutter head rotation.
3. The Driller was installed on a fixed base to increase the stability of the driller itself and improve the efficiency of drilling.
4. The gage cutter on the cutter head was able to adjust to enlarge the profile up to 10cm. Therefore the diameter of excavation could be increased 20cm as required for deformation control in various poor geological conditions. This prevented TBM from getting stuck during excavation.
5. The drive motors in the cutter head were changed from electrical to hydraulic.

PROGESS OF TBM EXCAVATION

Pilot Tunnel TBM

The drill and blast method was adopted at the east portal of the Pilot Tunnel in July 1991 and was used to excavate a length of 522.1m till September 1992. The best monthly progress was 73m/month and the monthly average was 40m/month.

The Pilot Tunnel TBM was launched in Jan. 1993, and the total length excavated in full face was 5,168m ending in Oct. 2003. Although the hardness of the Szeleng sandstone had uniaxial strength of more than 3,200kg/cm2, the average monthly progress (excluding the time for getting unstuck and the extensive maintenance) of the Pilot Tunnel TBM still reached up to 191m/month and the best daily advance was 17.1m/day. It was a big achievement at that time. When the Pilot Tunnel TBM arrived at the argillite of the Kankou and Tatungshan Formations, the rock quality appeared to be very sound. There was no grouting there and the boring went smoothly. The average advance rate in the sedimentary rock sections was 378m/month, and the best was 400m/month and the best daily progress was 24.7m/day. The TBM had reached its expected efficiency rate. But two jacking cylinders were shut down, and that caused the Pilot Tunnel TBM to not be able to drive at full speed. If the TBM management could be improved so there would be fewer breakdowns, even more progress could be made. The monthly progress of the Pilot Tunnel TBM excavating in full face is shown in Figure 4.

Westbound TBM

The east face of the Main Tunnel heading westbound was excavated by the D&B method from August 1993.

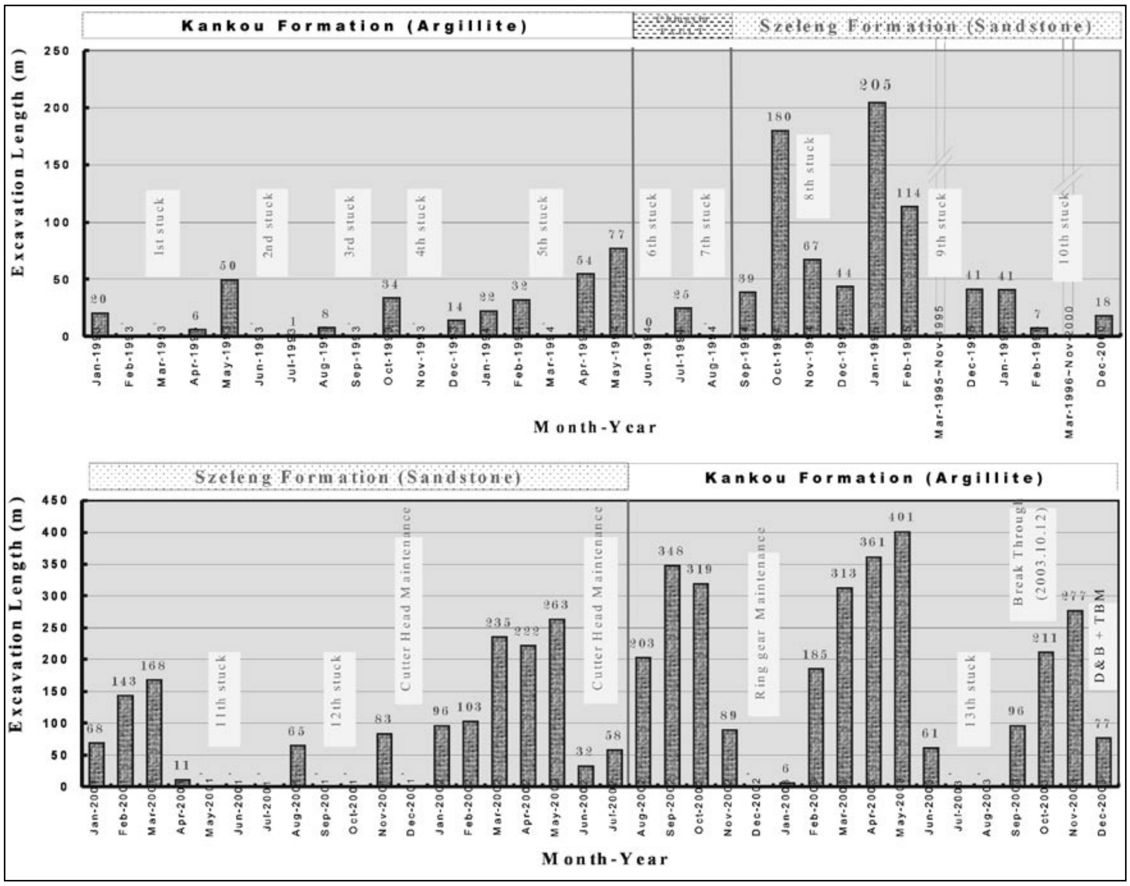

Figure 4 Monthly Progress of the Pilot Tunnel TBM Excavating in Full Face

Until April 1995 the total excavated length was 893m within 21 months. The average monthly progress of the top heading part was about 42m/month. The best progress of the top heading part was 85m/month.

The Westbound TBM was pushed into the tunnel on the sliding cradle in Jan. 1996 and began to cut in full face in May 1996. There was a huge disaster in Dec. 1997, and the progress was 455m within 20 months and that was an average of 23m/month. But in this period, the TBM also made the best daily record of 14.7m/day. The statistical monthly progress in full face is shown in Figure 5. The main reasons why the Westbound TBM couldn't be faster were the fractures and the hardness of the rock, the failure to penetrate into the rock with the cutter, and the vibration of the cutter making the rock loosen and fall. Owing to the overbreak, the production of debris was not stable so overloading and shutdowns of the conveyer happened frequently. The cutter head met too much resistance and it was hard to backfill grouting into the segments, etc. Moreover, these tough situations were encountered at the learning stage for the operator. The difficulties were due to a lack of experience in using TBMs, and the hard to control timing of the ground treatment, so the progress of the Westbound TBM seemed too slow.

In September 1997, the Westbound TBM reached the front of the Shanghsin Fault, and this fault had already been encountered by the Pilot Tunnel TBM and the Eastbound TBM. Aware of this geological condition beforehand, the necessary stop and treatment had been done in advance. First there was a top heading gallery excavated about 3m above the shield. After restarting the TBM there was a cave in with a large quantity of water ingress. The water was unexpected because there was no indication of it during the initial probing. About 90m of the existing tunnel was buried, and the volume of debris was about 7,000m3 with a water quantity of 750 l/sec. Thus the segments yielded down and the Westbound TBM was destroyed. After examination and assessment by the TBM experts, the recommendation was that the repair fee could be higher than buying a new one, and if repaired, it would take at least 3 years. So the contractor suggested disassembling the Westbound TBM and changing to D&B method for the rest of the length of the Westbound Tunnel.

Eastbound TBM

The east face of the Main Tunnel heading eastbound was excavated by D&B method from August 1993. Until April 1995 the total excavated length was 732m within 20 months. The average monthly progress was about 36m/month. The best progress of the top heading was 3.5m/day and 60.7m/month.

The French contractor S.B. began to construct the sliding cradle for the Eastbound TBM in May 1996. The Eastbound TBM drove in full face from September 1996. Concerned about the Eastbound TBM surpassing the Pilot Tunnel TBM, the contractor claimed that there was no responsibility for him to take the unexpected geological risks existing in front of the Eastbound TBM. So the Contractor asked for compensation, otherwise the Eastbound TBM would stop. From that time on, RSEA thought this behavior had violated the contract. Therefore RSEA terminated this contract with S.B. and continued this work itself. Up to August 2004, 3870m had been excavated in full face by the Eastbound TBM. The best monthly and daily progresses were 360.1m/month and 17.9m/day, respectively. The statistical monthly progress in full face is shown in Figure 6. Within this period, the TBM got stuck five times and the situation was similar to that of the Westbound TBM's.

The Pilot Tunnel TBM encountered the Shanghsin Fault prior to the Eastbound TBM, thus pretreatments were done in advance of the Eastbound TBM. The countermeasure was a bypass tunnel about 110m in length excavated from the hillside behind the shield to reach the cutter head. Afterwards, the top heading gallery was excavated and supported at first as shown in Figure 7. It helped the Eastbound TBM drive the lower half safely through the poor geological zone without rocks falling. So it passed this Shanghsin Fault zone smoothly and safely. Though these measures were costly and time consuming, they were quite safe and continued to be used afterwards.

EXAMINATION OF THE EFFECT OF THE TBM

Driller Function of the Pilot Tunnel TBM

In both the Pilot Tunnel and the Main Tunnel, the TBM got stuck was mainly because of no grouting done in advance as requested in the design. Taking cores while probing the Pilot Tunnel was requested in this

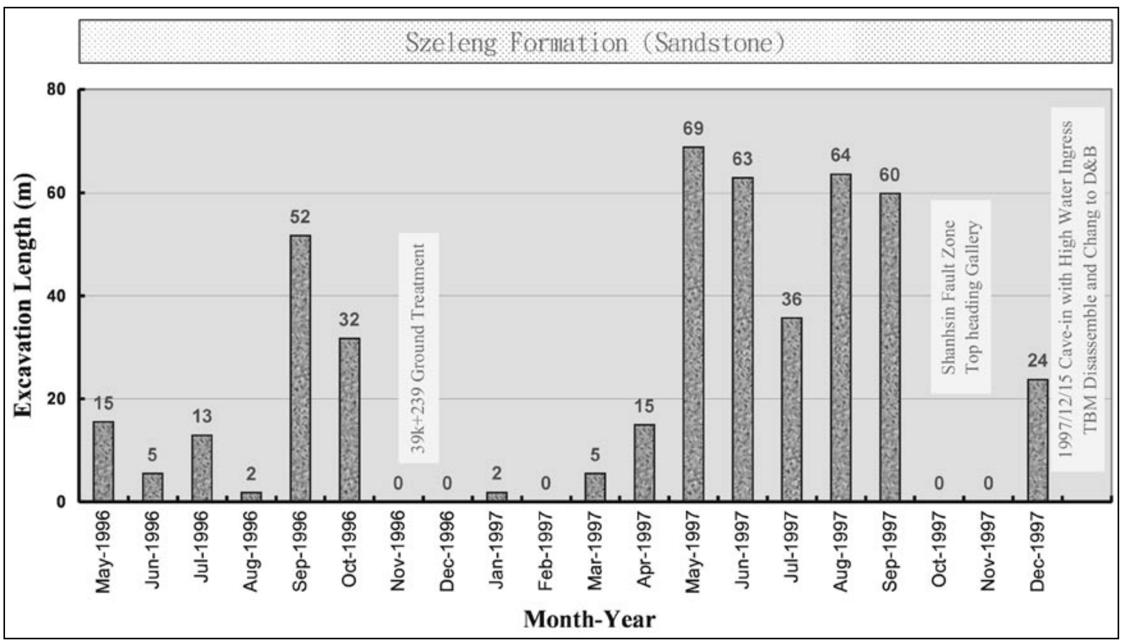

Figure 5 Monthly Progress of the Westbound TBM Excavating in Full Face

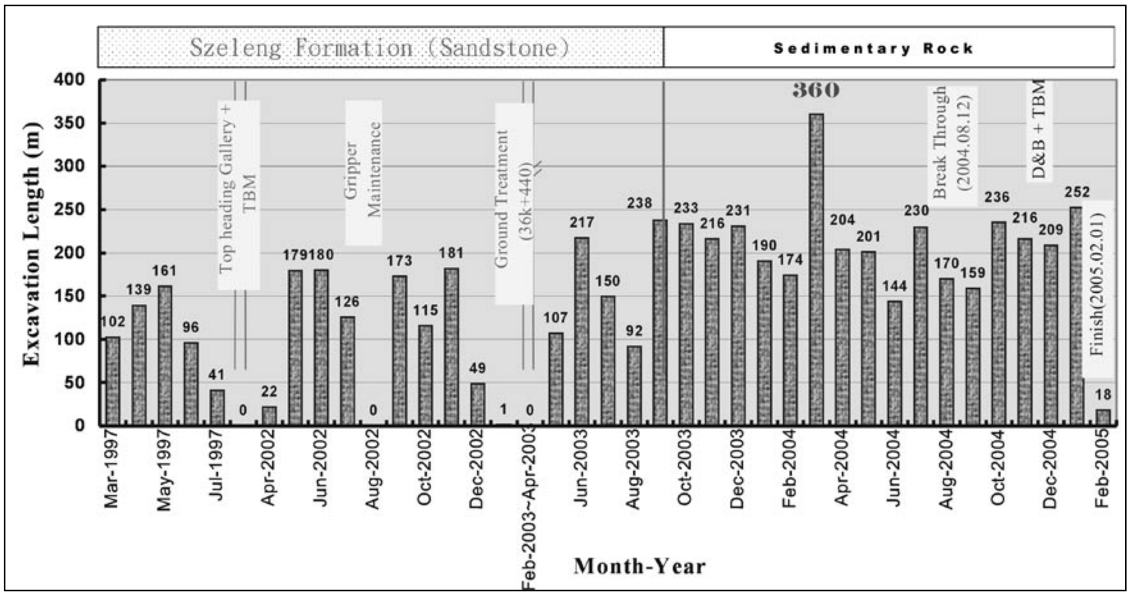

Figure 6 Monthly Progress of the Eastbound TBM Excavating in Full Face

contract to help predict poor geological conditions in advance. This helped the engineers to determine when to advance or stop to grout.

There were two Boart HD 150L (mounted on the main beam), non coring drillers, and one replaceable Longyear LM-22, coring driller. Near the grippers, 16 pilot holes of 80mm in diameter with lookout angles of 6 degrees in radial served as probing and grouting holes. The driller was often stuck due to the hardness and abrasiveness of the rock, the smaller lookout angle, and the lack of stability and capacity,. Meanwhile a percussion driller can't take cores, and it can only be judged from the advance rate, water color and material that washes out. So the drilling work was very difficult. If cores were taken, it usually took more than 24 hours for a 30m drilling and this deeply influenced the progress of the excavation. Though better drillers had been installed afterwards, two piece Atlas Copcos AC-1238 and one piece Diamec 262, the improvement was still limited. During this period, The HSP and TSP methods were used to assist in exploring the geological conditions in front of the Pilot Tunnel TBM.

Geological Investigative Function of the Pilot Tunnel TBM

To ascertain the safety of the Hsuehshan Main Tunnel TBM during construction, the Pilot Tunnel was excavated between the two Main Tunnels. In view of geology, the major functions of the Pilot Tunnel are as follows:

1. To provide detailed data about geological and groundwater conditions before the Main Tunnel TBMs were used.
2. To improve the ground by grouting and removing the gouge in fault zones to help increase the advance rate of the Main Tunnel TBMs and decrease the geological risks during excavation.

A double shielded TBM with a total shield length of 11.5m was adopted in the Pilot Tunnel. If a geologist wanted to inspect the geological conditions, he needed to

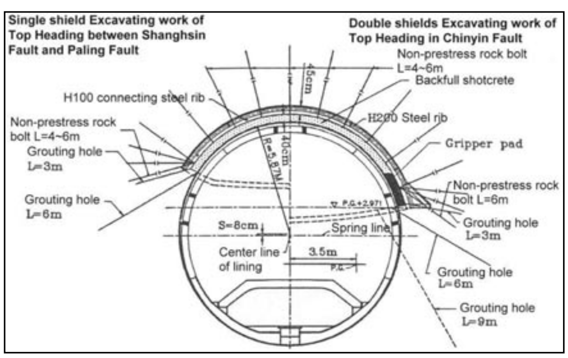

Figure 7 Excavation and Support of Top Heading Gallery

wait until the appearance of the outcrop behind the tail shield of the Pilot Tunnel TBM. But in poor conditions the segments had to be installed immediately and the condition of the face couldn't be observed. Besides, the rock bolt driller, steel rib erector, and shotcreting space were all behind the tail shield. Though the support system of NATM could be applied in good geological conditions, it would be far away from the excavation face. Therefore the effectiveness of the support couldn't be achieved immediately after excavation. So segments were used in the Pilot Tunnel TBM in whole length. The double shielded TBM couldn't reach the function of the Pilot Tunnel as design.

Extensive Maintenance in the Pilot Tunnel TBM

Because of the long time spent boring in the hard Szeleng quartz sandstone, the plates of the cutter head and the neck of the Pilot Tunnel TBM were penetrated. So the TBM was stopped in June 2002 for extensive maintenance, which took 47days. The Pilot Tunnel TBM stopped in an area of coarse and mass quartz sandstone. The geological condition was too sound to bore without any support in one and half months. Certainly the consumption of the cutter head was very serious. 323 pieces of roller discs were replaced within 8 months. The maximum record was 109 pieces in a month and 13 pieces in a day. Due to the hard boring in the Szeleng quartz sandstone, the ring gears and smaller gears had been worn and had seams on them. If the ring couldn't be replaced immediately, they could cause a bigger damage to the main bearing. This was a big issue. So the Pilot Tunnel TBM was stopped on November 8, 2002. The Pilot Tunnel was enlarged in order to remove the cutter head from the TBM by anchoring it on the rock and installing a temporary crane on the crown. Then those worn parts were replaced. This replacement work was a very complicated, difficult, high tech and precise job. It took 83 days total. It was a great learning experience.

Cycle Time of TBMs

The cycle times of the Pilot Tunnel TBM and the Eastbound TBM in the Szeleng sandstone and sedimentary rock in full face excavation are shown in Figure 8 and Figure 9, respectively, excluding the time for getting unstuck and the extensive maintenance. The utilization rates of the Pilot Tunnel TBM and the Eastbound TBM are only 21.85% and 20.58%, respectively. Compared to the European's and the USA's records of 30% to 50%, there's a large gap there. The breakdowns of the Pilot Tunnel TBM and the Eastbound TBM are 17.47%, and 26.61%, respectively. This indicates that the maintenance and management has to be improved. The work items in a cycle time include installation of segments, backfill grouting, and mucking. This doesn't happen simultaneously, so it can't match the design concept of the double shielded TBM.

CONCLUSIONS

1. The TBM has superior performance indeed and the trend in the world is to use it in long tunnel excavations. There are many other projects using TBMs with good performance. In the world there are no tunnels being bored in perfect geological conditions. The key issue is how to predict and handle problems successfully. The TBM method compares favorably to other methods when considering expense and time. Nevertheless, if the TBM got stuck, it was more difficult to handle than when using the D&B method.
2. It is definitely necessary to have an experienced and skillful pilot with a good maintenance system to backup and drive through the poor zones safely. If any mistakes occurred, they caused serious disasters. So the assessment of unavoidable geological risks, the ability of the contractor, and management should be checked carefully in advance.
3. The main reasons for the difficulties during the excavation of the Hsuehshan Tunnel were the lack of experience in using a TBM, the poor geological conditions situated along the East portion, the hard to excavate quartz sandstone, the failure in probing, etc. Under such situations, the grouting to improve the rock seemed very helpful in gaining more self-standing time in the fractured zones. From experiences of the Pilot Tunnel TBM driving through after three treatments with grouting, it was proved that limiting the amount of falling rocks could help prevent the Pilot Tunnel TBM from getting stuck. Therefore grouting cannot be omitted at all, especially in the weak zones.
4. If there were any new projects with long pilot tunnels, we would have suggested that an open type TBM might be a better choice for speedy excavation, because it could inspect the geological conditions and treat the difficult ground in advance easily.

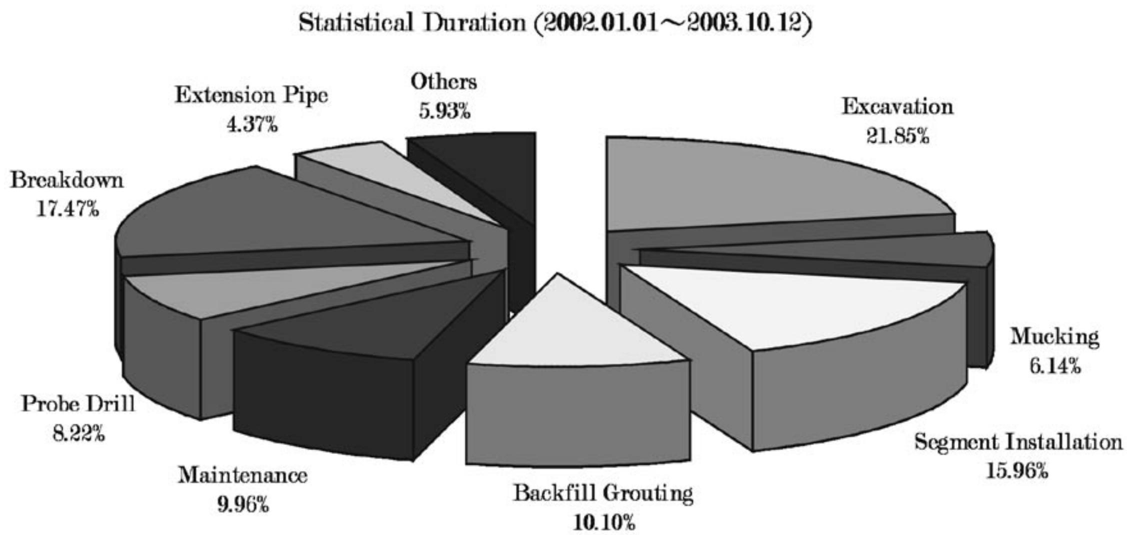

Figure 8 Cycle Time of the Pilot Tunnel TBM Excavating in Full Face

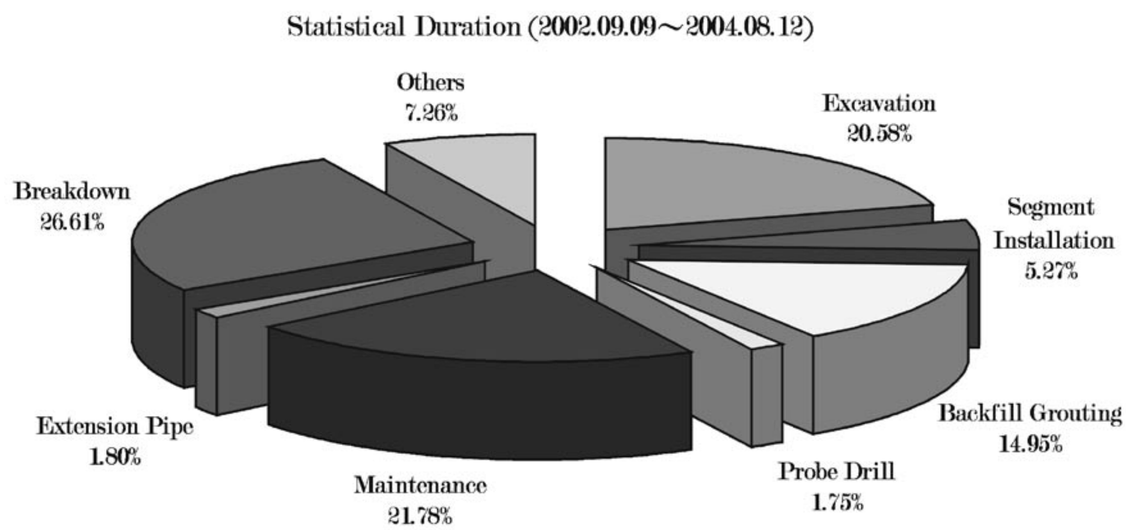

Figure 9 Cycle Time of the Eastbound TBM Excavating in Full Face

5. Many important experiences were gained from excavating the Hsuehshan Tunnel such as how to modify the TBM to cut in quartz sandstone, how to improve the durability of the cutter head, how to select cutting discs, how to replace equipment, how to do standard grouting patterns in fracture and/or high water ingress zones, how to treat the TBM after it had gotten stuck, and how to optimize the TBM pilot. We hope these experiences can be internalized and the knowledge maintained in Taiwan.

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