MANAGEMENT OF TBM CONSTRUCTION IN HSUEHSHAN MAIN TUNNELS AND PILOT TUNNEL

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ABSTRACT

The construction of Hsuehshan Tunnel is the key to the success of the Taipei-I lan Expressway Project, promoting the economic development of eastern Taiwan. Hsuehshan Tunnel, in length of 12.9Km, the full face TBMs (Tunnel Boring Machines) with an 11.74m boring diameter will be applied for tunnel excavation for both the East Bound and West Bound main tunnels. Between the twin tubes 5 m below, a service pilot tunnel of 4.8m boring diameter is located, and which will also be excavated by TBM ahead of main tunnels for the purpose of water drainage, gathering precise geological information to feed back to the main tunnels construction, ground pretreatment to the main tunnels if necessary, service line for the emergency. Hsuehshan tunnel are among the most difficult TBM projects in the world in terms of adverse geology, water inrushes, tunnel size and tunnel length. Therefore, pre-training of all necessary and available information, technology and technical know-how in connection with TBM operation, normal and correct operate the TBM and all relevant Back-up equipments, maintenance, problematic handling…etc. to all related working crews of the TBM construction team prior to the TBM mining is an great important issue. The most crucial to the increase of economic efficiency of TBM mining operation is including but not be limited to the ground investigation and ground pretreatment, proper planning and management such as optimum manpower and equipment utilization, working cycle control, great coordination and perfect maintenance works to keep high availability rate of TBM. This paper presents our methodology and experience of managing TBM construction in Hsuehshan main and pilot tunnels, with the hope to provide Tunnelling and Underground construction field experts for references for the future.

INTRODUCTION

The 12.9 Km long Hsuehshan Tunnel, "a renowned difficult project in the world" as recorded in the British Encyclopedia, which is composed of 2 main tunnels (westbound and eastbound) and a pilot tunnel (Figure.1). In view of the environment constrain, water drainage during the construction, mucking delivery and portal facilities area…etc. all 3 tunnels were originally planned to be bored by TBMs from the eastern portal and head west. The tunnels are ascending at gradient of 1.254% from Touchang in the east to Pinglin in the west. It pass under the Hsuehshan Ranges in northern Taiwan, in the tunnel horizon, it cut across strong, hard, abrasive and intensely fractured Szeleng Sandstone on the east and indurate sandstone and siltstone on the west. The entire zone heavily affected by tectonically movement is very much faulted and bears a great amount of water. In additional to six identified water-bearing faults, there are many problematic and unanticipated shear zones.

The Client, Taiwan Area National Expressway Engineering Bureau (TANEEB), signed with RSEA Engineering Corporation for the construction of the Hsuehshan pilot tunnel on 15th of July, 1991 as Lot no. 5 of Taipei-I lan expressway, Pinglin-Touchang section. In two years later, signed again for the construction of the Hsuehshan main tunnels and associated structures on 23rd of July, 1993 as Lot no.4 of Taipei-I lan expressway, Pinglin-Toucheng section. Both the

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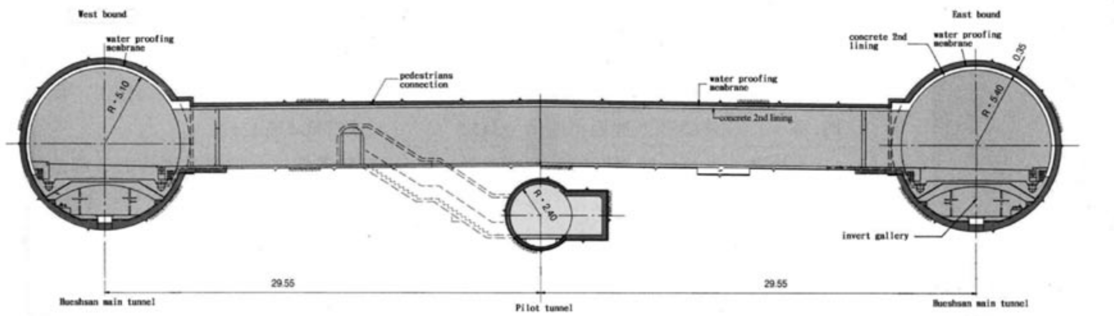


Figure.1 Relevant section drawing of Hueshshan Tunnel.

projects management is held by Sinotech Engineering Consultants Inc.

Owing to the characteristic geological conditions especially in Szeleng Sandstone formation where the TBMs have to start boring, severe cave-ins with high water inflow were encountered, resulting in repeated TBM stuck in Hueshshan main tunnels and pilot tunnel. Pilot tunnel TBM commenced its first boring in December 1992, one month later, it has been stucked. West bound main tunnel TBM was started mining in May 1996, unfortunately, after excavated and advanced 456 meters only, TBM was crushed and buried 100 meters long in the tunnel collapsing on December 15,1997 due to unexpected huge water inrushes with 750~800 l/sec and 18 bar water pressure. As for the east bound TBM, commenced its boring in December 1996, although securely passed the first Chingyin Fault under the protection of Canopy method which was a mixed excavation method together with the conventional D&B and TBM (Figure.2). But, when encountered extremely poor ground stretch of Shanghsin Fault on July 1997, TBM mining operation has been called stop and decided to adopt a long distances of Canopy method in order to secure the safety of the TBM when driving through Shanghsin Fault as well as other identified water-bearing Faults such as Paling, Tachingmen, Shihpai and Shihtsao.

However, the tunnel drives were severely delayed by unexpectedly difficult geology with fractured rock and inflows of water. In order to expedite the construction, additional working face from west portal and the vertical ventilation shaft #2 as well as the interchange station #2 for all 3 tunnels by conventional D&B were adopted. Besides, on-going long distance probing ahead of the TBM, mechanical modification to the pilot TBM, and revision of the construction arrangement were carried out to improve the performance of the excavations of Hsuehshan Tunnel. The varied geological conditions in Taiwan present a stringent challenge to the construction team, regardless of how hard and difficult it was, with our construction team's perseverance and efforts, however, the 12.9 Km long Hsuehshan Tunnel was finally broken through in year of 2004 no matter by TBM, Canopy or D&B methods. Nevertheless, this paper would mainly focus on the management of TBM construction in Hsuehshan Tunnel.

GEOLOGICAL CONDITIONS

Hsuehshan Tunnel, with a maximum overburden of 700 m, is situated within the fold and thrust belt structural region in northern Taiwan. Rock formations based on a few strategically placed bore holes were estimated to be ten expected stratigraphic horizons and twelve structurally homogeneous zones (Figure.3). The identified Faults were Shihtsao (Ⅰ), Northern and Southern Branch of Shiphai (Ⅱ), Tachingmen (Ⅲ), Paling (Ⅳ), Shanghsin (Ⅴ), and Chingyin (Ⅵ), ranging from 10 m to more than 60 m wide. In addition to identified Faults, many problematic lineaments remained in require of further investigation and explanation. Yingtzulai (A) and Taotiaotzu (B) synclines were two major fold structures of regional magnitude. There were other nine or more fold structures of limited extension and magnitude. The following locations were sites of likely higher ground water surge or seepage but there was no indication of the flow quantities and locations were ground water surge was likely to occur:

1. The immediate vicinity of fault zones or where shear gouge was exposed.

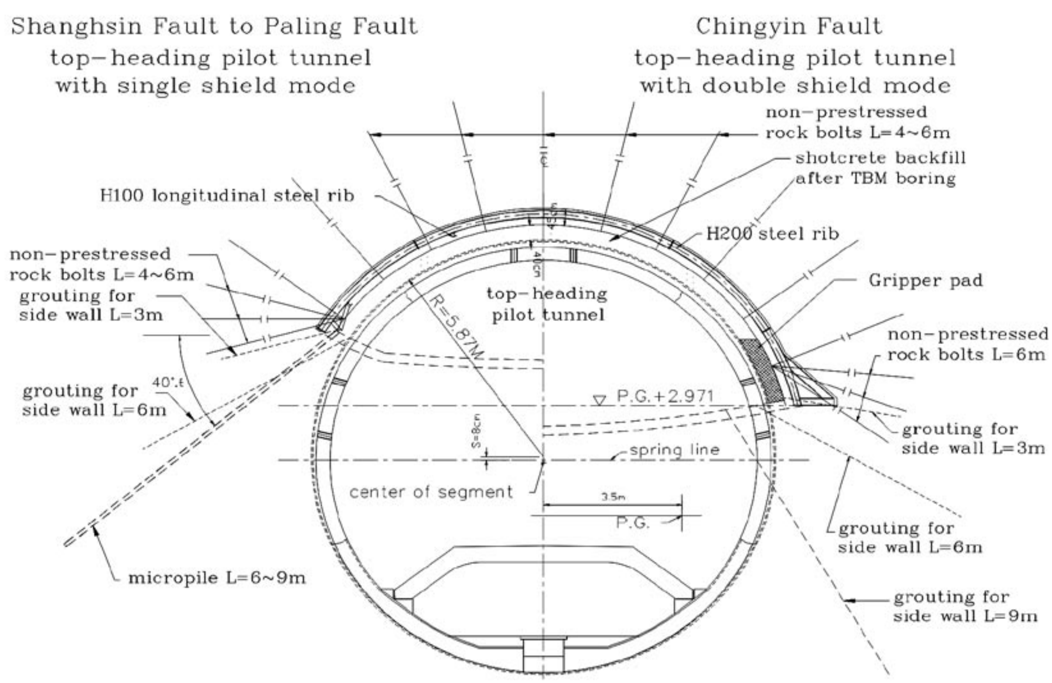
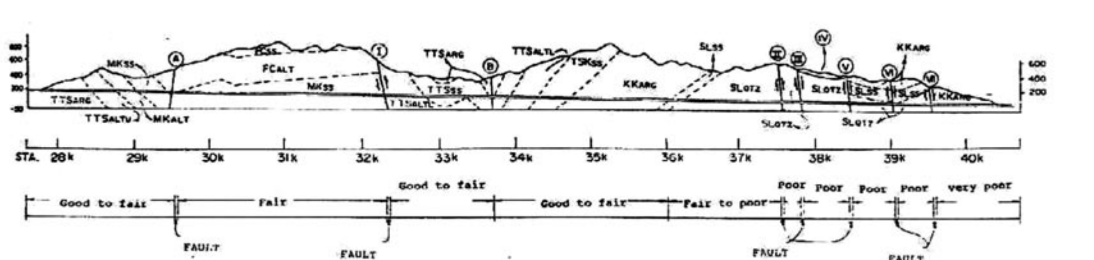


Figure.2 Section drawing of Top-heading pilot tunnel.



SL	-	Szeleng Sandstone	KK	-	Kankou Formation
TSK	-	Tsuku Sandstone	TTS	-	Tatungshan Formation of Oligocene
MK	-	Miocene Makang	FC	-	Fangchiao Formation
FCss	-	Massive sandstone intercalated with thin shale.	FCalt	-	Alternations of sandstone and shale.
MKss	-	Massive sandstone intercalated with thin shale.	MKalt	-	Alternations of sandstone and shale.
TTSaltl	-	Upper part alternations of fine grain sandstone and argillite (or siltstone) .			
TTSarg	-	Argillite intercalated with thin siltstone.			
TTSss	-	Sandstone intercalated with thin argillite (or siltstone) .			
TTSaltl	-	Lower part alternations of fine grain sandstone and argillite (or siltstone) .			
TSKss	-	Fine grain sandstone intercalated with argillite.			
KKarg	-	Massive argillite.			
SLss	-	Fine to medium grain sandstone intercalated with thin argillite.			
SLqtz	-	Massive quartzite intercalated with coal shale.			

Figure.3 Rock mass classification along the Hsuehshan Tunnel investigation area.

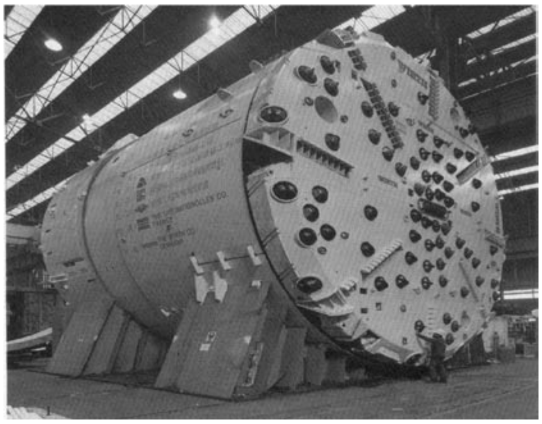


Figure.4 Wirth TBM type TB1172H/TS used for main tunnels.

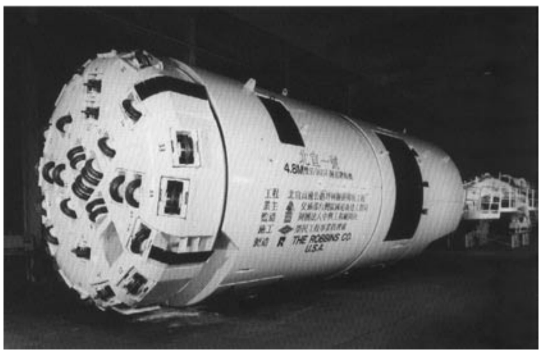


Figure.5 Robbins TBM type 153-269 used for pilot tunnel.

2. Sheared rock mass with weak plants that contained abundant clay, especially the Szeleng Sandstone.

3. The fractured mass at the axial part of syncline structure.

The Szeleng Sandstone, about 3.6 Km long along the tunnel alignment, mainly comprises light gray quartz sandstone with occasional intercalation of dark gray, fine to medium-grained sandstone and carbonaceous shale that vary centimeters to tens of centimeters. Typical Szeleng Sandstone is known as quartzite with quartz content more than 82% (the recorded maximum content was 90%), Mohr's hardness 6~7 and uniaxial compressive strength between 120 to greater than 300 Mpa (the recorded maximum UCS was 310 Mpa). It is coarse to medium-grained, containing feldspar usually turns to clay upon weathering, and the rock became loose. Geotechnical studies indicated that Sandstone is hard and brittle, and when subjected to tectonic compression and faulting, become well fractured with numerous fissures, resulting in a good groundwater reservoir. Investigation also indicated that the groundwater in this area is mainly in the fracture zones or barred behind shear zones. This bountiful groundwater thus became a crucial obstacle to be overcome in TBM excavation in the Szeleng Sandstone section.

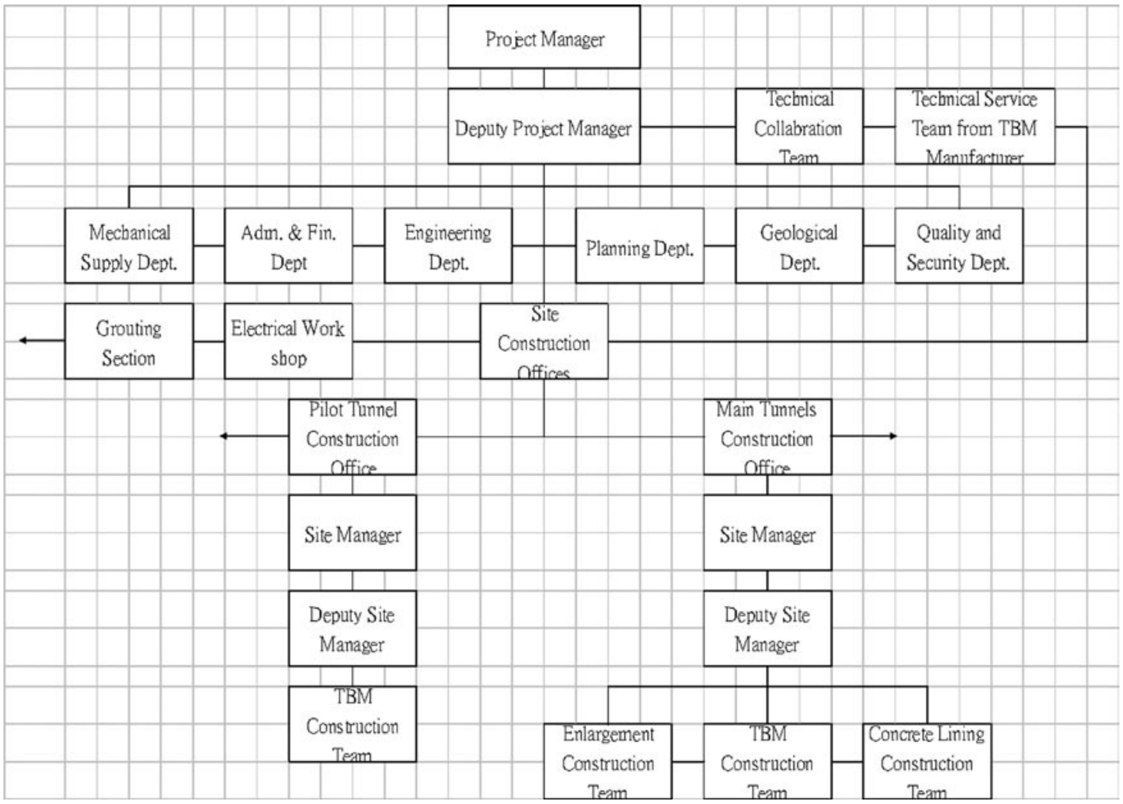
TBM OF MAIN TUNNELS AND PILOT TUNNEL

The TBM that utilized for pilot tunnel is a Double

Table 1. The general specifications of TBMs used in Hsuehshan tunnel.

Item	Description	Unit	Pilot Tunnel	Main Tunnel
1	Bore diameter	m	4.819	11.74
2	Cutter numbers	ea	34	83
3	Cutter Disk diameter	mm	432	432
4	Cutter head speed	rpm	4.5~4.9(low)/ 8.0~9.8(high)	0~4
5	Cutter head torque	KNm	2010 / 4.5rpm 1005 / 9.8rpm	7200 / 4rpm 30000 / 0.95rpm 36000 / 0.25rpm
6	Cutter head drive power	Kw	960	4000
7	Cutter head drive module	set	6 (electric motor)	18 (Hydraulic motor)
8	Thrust	KN	7562 (on cutter head)	50600 / double mode 78700 / single mode
9	Gripper clamping force	KN	31456	65000 (3-point anchoring)
10	Total equipped power	Kw	1760	7550
11	Mining stroke	m	1.2	1.5
12	Machine length (TBM+BU)	m	177	250
13	Machine weight (TBM+BU)	ton	360	2300
14	Manufacturer / Type		Robbins, USA / 153-269	Wirth, West Germany / TB1172H/TS

Table 2. Project management organization chart.



Shielded type designed with a boring diameter of 4.8 m, and was manufactured by Robbins Company. The two identical TBMs with a boring diameter of 11.74 m used in Hsuehshan main tunnels are of full face Telescope / Double Shielded type hard rock designs which were the largest Double Shielded hard rock machines ever built by the TBM manufacturer, Wirth Company (Figure. 4, 5).

A telescope shield machine allows bore and erecting a tunnel support simultaneously, when the rock conditions provide a proper gripping of the tunnel wall. In the telescope type mode of excavation, the front shield including the cutter head is thrust forward with the rear shield locked in the rock using the grippers so that neither thrust forces nor torque are transferred to the tunnel lining. Behind the gripper shield, within the protection of the tail skin, a reinforced precast concrete segmental lining is installed with the help of a segment erector. If gripping of the machine is not possible in unstable ground conditions, the machine is operated like a simple shield machine; i.e. the boring operation has to be interrupted for the installation of the tunnel support. In order to tunnel through difficult formations and squeezing rock conditions, as well as bring the feedback from those serious incidents of pilot TBM, the TBMs of main tunnels were designed with certain features:

1. The bore diameter can be increased by means of enlargement cutters to provide a relief over cut, when driving through possibly squeezing rock formations.
2. The cutter head center can be adjusted vertically relative to the front shield.
3. The cutter head shield is as close to the tunnel face as possible.
4. Cutter head with reversible speed hydraulic drive with high break-out torque.
5. For mixed ground as well as hard rock, the cutter head is fitted with disc cutters and picks. These tools can be replaced from within the protection of the cutter head.
6. Cutter head peripheral bucket openings can partially be closed to limit muck inflow.
7. The muck hopper can be closed with a hydraulically operated gate to prevent water and / or mud from

Table 3. East bound main tunnel TBM construction team organization chart.

TBM Operation Supervisor

- Mechanical Shift Engineer
- Civil Shift Engineer
- Electrical Shift Engineer — TBM Operator

Mechanical Shift Engineer

E	L	1.TBM & B/U Operation
1	6	- Cutter inspection and exchanging
		- Hyd. system maintenance and repair
		- Lub. system and cooling water system maintenance and repair
		- Conveyor system, equipment maintenance and repair
		- Miscellaneous works
E	L	2.Along the Tunnel and Outside Portal area
1	6	- Rails, tracks and shunters maintenance and repair

Civil Shift Engineer

E	L	1.Shield & Equip. Bridges Area
1	2	- Segment erection
		- Muck cleaning
	4	- Pea gravel back filling
		- Mortar grouting
		- Steel ribs installation (if necessary)
	2	- Miscellaneous works
E	L	2 B/U Operation
1	2	- Crane operators
	4	- Arch deck installation
		- Rail installation
	11	- Locomotive drivers
	2	- Coordinator
		- Miscellaneous works

Electrical Shift Engineer

E	L	1.TBM & B/U Operation
1	2	- PLC & electronic system maintenance and repair
	1	- Electrical system maintenance and repair
		- Cable for power and lighting system extension and maintenance
	1	- #4+5 conveyor operator
	2	- Dumping device operator
		- Miscellaneous works

Remarks :

1. Total manpower per shift (8 hour) : 55 people (E : Engineer, L : Labour)
2. Above manpower did not include working crews at outside portal such as rolling stock workshop, precast segment loading and unloading yard, cutter workshop…etc.
3. Above manpower did not consider peoples on leave.

entering the shield.

8. Torque support beams transmit the torque reaction forces via the telescopic shield to the gripper shield during the entire boring stroke.
9. Following the tail shield, a multi-purpose drilling system is installed for secondary probe and injection drilling.

The general specifications of TBMs are shown in table 1.

PROJECT MANAGEMENT ORGANIZATION

Project management organization chart for Hsuehshan Tunnel is shown in table 2.

Since, it is the first time contract specification broached the hard rock TBM method to the domestic tunneling project especially in such difficult conditions expected, therefore, the Client (TANEEB) stipulated in the Contract that, the Contractor as RSEA have to select and sign a sub-contract with an renowned and experienced international TBM hard rock tunneling construction company as technical collaboration in order to transfer the TBM technique and know-how to the domestic contractors for the future. Besides, an 8 years experiences in TBM tunneling works related tunneling engineer and equipment superintendent as well as operators with 5 years experiences should be employed for the first 3 Km TBM mining operation. However, RSEA's TBM construction team approved the success of the technical transference and deleted the Clause of technical collaboration in year

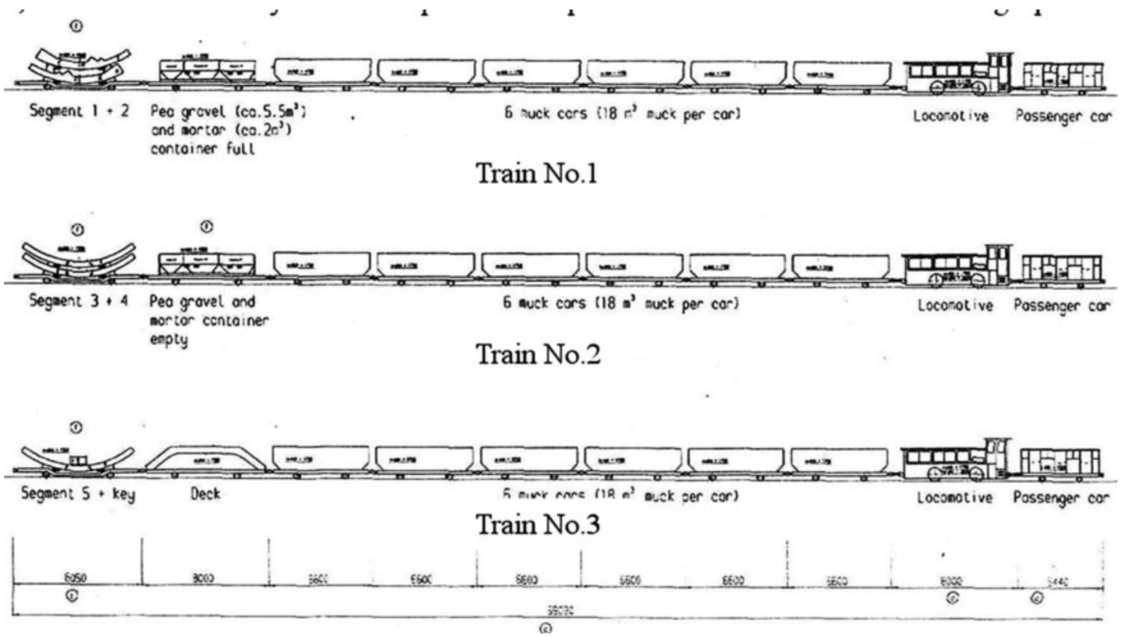


Figure.6 Train system for one stroke of 1.5 m.

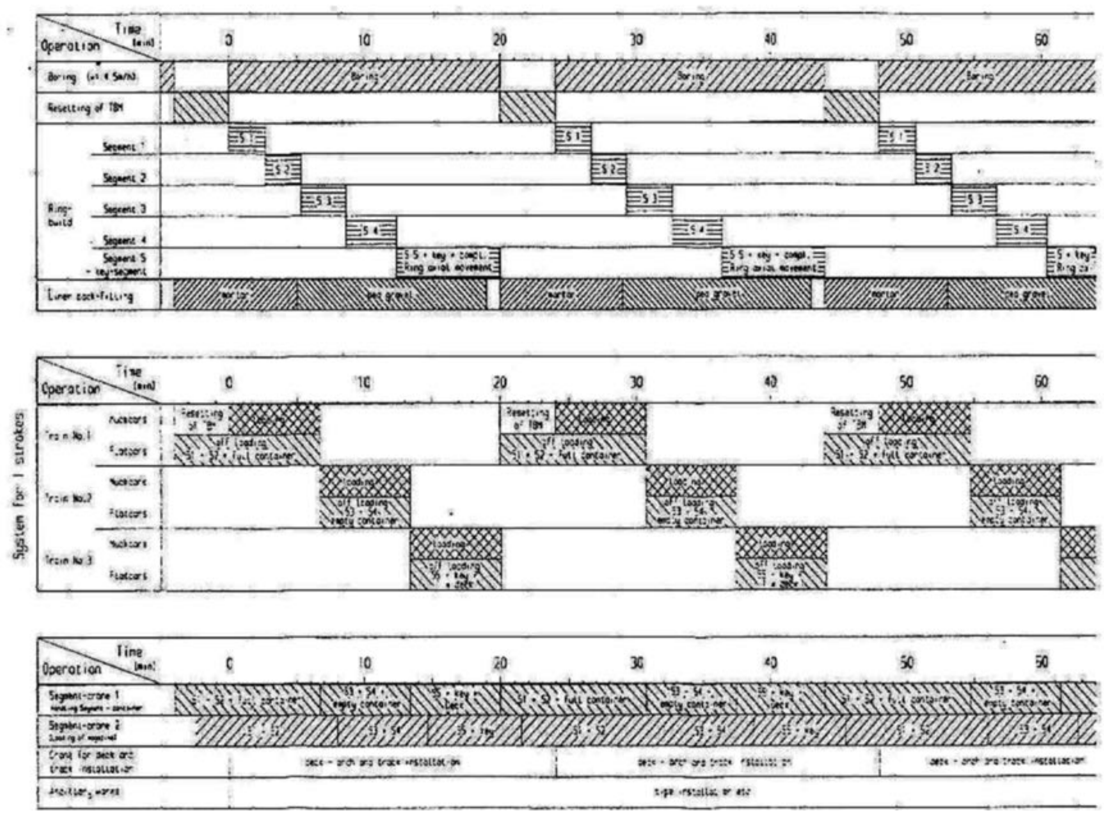


Figure. 7 Operational Sequence of TBM and Back-up System.

of 2003.

As for the organization and manpower either pilot tunnel or main tunnel of the TBM construction teams was adapted in accordance with site progress and requirements. Table 3 shows the maximum manpower of east bound TBM mining operation per shift (8 hour) at the last stage while TBM was drove deep into the mountain for about 7 Km.

CONSTRUCTION EQUIPMENT

Construction equipment described in this chapter is only focus on TBM mining operation, and not included other work items such as enlargement, concrete 2nd lining, ventilation shafts boring, conventional D&B …etc. The list of equipment will be split in two parts as outside equipment and equipment associated with TBM. At the planning period, a justification of the choices has been made in respect of equipment items associated to the TBMs. The justifications have a dual purpose:

1. Check that the size, capacity, engine power or other characteristics of the equipment items provided are adequate.
2. Determine the total number of equipment items to be provided in order to match the program requirements, and establish the delivery schedule on site for each type of equipment.

We hereunder introduce the justification of Mucking cars for main tunnel as an example:

＊ Volume of mucking material for one TBM stroke:

πR^2 x stroke x loosening factor for rock = 3.1416 x $(5.87)^2$ x 1.5 x 1.9 ≒ 310 m^3

＊ Capacity of one mucking car : 18 m^3

＊ Number of mucking cars required for one TBM stroke :

310 m^3 18 m^3 ≒ 18 cars

＊ Number of cars per mucking train : 6 cars

＊ Number of train required for one TBM stroke :

18 cars 6 cars ≒ 3 trains

Figure 6, 7 shows the train system and operation sequence of main tunnel TBM mining operation.

Table 4 shows the maximum main construction equipment utilized in pilot tunnel and east bound main tunnel TBM mining operation at the last stage.

SITE INSTALLATIONS

The size of site installations required for the execution of Hsuehshan Tunnel must be based on the peak daily output envisaged for the TBMs. Therefore, the mucking equipment / muck disposal arrangement, and the precast segment facilities (unloading, storage, loading and transportation) have been designed to match this requirement. The rest of installation, in particular the supply and distribution of electricity, compressed air, batching plant, waste water treatment plant, the offices, workshops, stores and other work areas will be consistent with the above requirements and other site constraints. However, site installations for Hsuehshan Tunnel have been well planned to limit the interferences between the pilot, east bound and west bound tunnel works. The layout of eastern portal for Hsuehshan Tunnel execution is shown in Figure. 8.

REVIEW AND EVALUATION OF THE TBM PERFORMANCES IN HSUEHSHAN TUNNEL

In the original construction arrangement, the excavation of the pilot tunnel by TBM from east portal would commence 2 years ahead of the main tunnel. It was expected that before tunneling of the main tunnel, the pilot tunnel would have been completed, and could provide sufficient lead time in observing underground, identifying potential problems and providing solutions to the main tunnel construction.

Unfortunately, just as the CIRIA publication, "the predominant reason for TBM poor advance rate is in variable ground, with few exceptions", because of the adverse geology with large water inflow, pilot TBM got stuck 10 times from its commencement of boring in December 1992 up to February of 1996, and TBM was advanced only 1080 meters. The severely fractured ground needed to be pretreated before TBM driving through, but the ground investigation either by percussion drilling or core drilling and grouting facilities for ground treatment under such geological condition was very difficult and time consuming to achieve an effective ground improvement, especially at the section where many gouge clays were encountered. As shown in Table 5 of the long range core drilling in the pilot tunnel, it has spent 140 days to achieve a length of 107.25m.

Since the No.10 stoppage, pilot tunnel TBM stood at sta.39k+079, and spent years on freeing the cutter head and continuously progressing through many detour tunnels

Table 4. List of main equipment utilized in Hsuehshan Tunnel TBM mining operation.

Item	Description	Unit	Pilot Tunnel		East Bound Main Tunnel	
			Q'ty	Specification	Q'ty	Specification
	Outside equipment :					
1	Segment storage gantry	U	1	220V/10T	2	Kone XL512 440V/20T
2	Muck dumping device	U	1		1	Rotary tipper for 3 no. cars
3	Cutter workshop	U	1	Robbins	1	Wirth
4	Wheel loader	U	1	CAT 950B	1	Komatsu W250
5	Forklift	U	1	Hyster H6000	1	Yale GDP50F
6	Ventilator	U	8	440V/50HP	2	AEC 90m3/s
	Associated equipment for TBMs :					
7	Diesel locomotive	U	7	25T	16	35T/CFL-200
8	Mucking car	U	33	8m3	48	18m3
9	Segment transport wagon	U	16		12	
10	Wagon for transport of pea gravel and Arch deck	U	-		9	
11	Wagon for transport of personal	U	3		6	
12	Rails	Lot	1	30kg/lm	1	37kg/lm
13	Shunters	Lot	1		1	

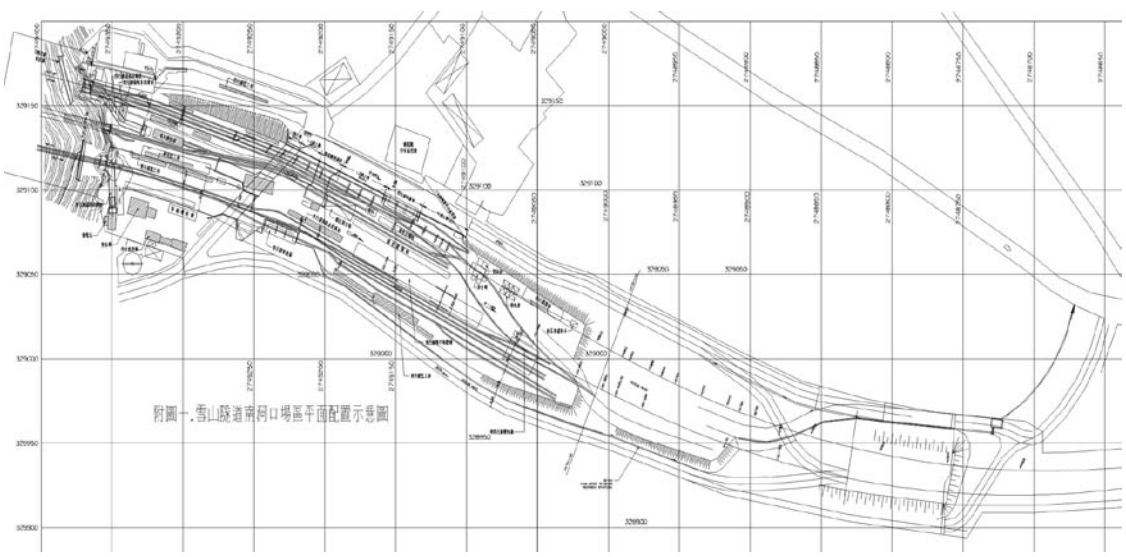


Figure. 8 Layout of eastern portal for Hsuehshan Tunnel excavation.

towards the west portal by means of D&B method. In order to catch up the serious delay, it is compulsory to find possible alternative solution. The Advisory Board Meeting No.5 of the Client TANEEB (March 7, 1998) recommends scenarios of the pilot tunnel to be evaluated in terms of cost and time:

1. Pure D&B method.
2. New TBM pilot bore from the west portal till the quartz sandstone formation.
3. New pilot bore included in the west bound tube face.
4. Two new working faces provided in a short time by the sunken ventilation shaft #2.

However, after many times of experiences in failure

Table 5. The long range core drilling in the pilot tunnel

No.	Station	Expected drilling length	Actual drilling length	Duration of drilling	Actual Drilling days	Driller's nationality	Equipment type and torque
1	39k+139	300 m	107.25 m	July 15,96 ~Dec 1,96	140	South Africa	TONE TEL 7 (1200Nm)
2	39k+120	300 m	103.55 m	April 28,97 ~June 5,97	39	Japan	TONE TOP LS12 (13734Nm)
3	39k+019	300 m	126.40 m	Mar 3,98 ~May 5,98	64	Japan	TONE TOP LS12 (13734Nm)
4	38k+436	600 m	262.70 m	Dec 8,99 ~Feb 2,00	80	Canada	CS-1000 (4382Nm)
5	38k+170	600 m	480.50 m	May 22,00 ~Oct 30,00	162	Taiwan	Long year-44 (2842Nm)

Table 6. The stuck data of pilot tunnel TBM

Stuck No.	Stuck Station	Stuck Date	Restarting date	Stuck duration	Notes	Stuck No.	Stuck Station	Stuck Date	Restarting date	Stuck duration	Notes
1	40^{K}+138	Feb 02,93	Apr25,93	82		8	39^{K}+530	Nov 10,94	Dec 24,94	47	
2	40^{K}+083	Jun 02,93	Jul16,93	52		9	39^{K}+168	Feb 18,95	Dec 05,95	290	Shanghsin Fault
3	40^{K}+075	Aug 29,93	Oct04,93	36		10	39^{K}+079	Feb 05,96	Mar 08,97	397	Shanghsin Fault
4	40^{K}+040	Oct 22,93	Dec21,93	60		11	37k+431	April 10,01	Aug 15,01	128	
5	39^{K}+972	Feb 22,94	Apr09,94	45		12	37k+366	Aug 25,01	Nov 19,01	87	
6	39^{K}+841	May 25,94	Jul01,94	37	Chingyin Fault	13	33k+990	June 08,03	Sept 17,03	101	Shihpai Fault
7	39^{K}+816	Jul 10,94	Sep20,94	72	Chingyin Fault						

of detour tunnels due to collapsing with large water inrushes, finally, the excavation of pilot tunnel by D&B has been achieved to favorable ground sta.37k+836 on the September 2000. As for TBM, it was advanced gradually with invert cutting according to the progress of all activities in the front such as conventional D&B excavation through many detour tunnels, the long range core drillings and gripper pad construction…etc. By end of the year 2000, pilot tunnel TBM was restored full face mining from sta.37k+836. With the joint effort of the construction team and the technical assistance from the international expertise, although, it has been gone through another 3 times stuck as shown in Table 6, pilot tunnel TBM was broken through in October 2003 at sta.33k+748 where the tunnel had been excavated by D&B from west portal.

Owing to serious delay in pilot tunnel excavation, it puts the TBM boring of main tunnels in a dilemma.

West bound main tunnel TBM has been gone through 5 times stuck since its commencement of boring in May 1996, and still can not avert a disaster from tunnel

Figure.9 Interferences of TBM mining.

Figure.10 Water pipe lines, tracks…damaged

collapsing accompanies unexpected huge water inrushes with 750~800 l/sec and 18 bar water pressure on December 15,1997. As a result, the TBM was aborted and conventional D&B method was then employed in September 1999 for the rest of west bound tunnel excavation. However, west bound main tunnel was broken through in 17th of March 2004 at sta.34k+754 by D&B from both the eastern and western portals as well as additional working faces from vertical ventilation shaft #2 and the interchange station #2.

East bound main tunnel TBM was commenced its boring in December 1996, although successfully bored across the first Chingyin Fault under the protection of Top-heading pilot tunnel which provided a strong roof support together with reinforced concrete gripper pad (noted as Canopy Method), but when encountered extremely poor ground stretch of Shanghsin Fault at sta.38k+858 on July 1997, TBM mining operation has been called stop and decided to adopt a long distances of Canopy method in order to secure the safety of the TBM when driving through Shanghsin Fault as well as other identified water-bearing Faults such as Paling, Tachingmen, Shihpai and Shihtsao. The said decision was supported as well by the Advisory Board Meeting No.5 of TANEEB (March 7, 1998). Since then, east bound TBM was stopped for 2 year and 9 months, until 1st of April 2000, TBM re-started advancing gradually with bench cutting according to the progress of Top-heading excavation in the front till drove across the Northern Branch of Shihpai Fault at the sta.36k+923. By 9th of September 2002, east bound TBM restored full face mining operation from sta.36k+923 after cutter head has been repaired and reinforced by wear plates. Nevertheless, TBM still has gone through one time tail shield trapped because of rock burst and one time with cutter head jammed due to running type ground mixed with clay, blocky mud and water. In September 2003, east bound TBM finally broke away from the Szeleng Sandstone formation and drove into Kankou formation at sta.35k+640 with the best monthly record of 239 m/month that we had ever made.

When RSEA's TBM construction team keen to expect to have better daily production, but they were totally disappointed. In order to catch up the whole program of Hsuehshan tunnel from the serious delay in tunneling , all the activities for associated structures such as breakage and removal of arch segments at enlargement sections, excavation of enlargement and niches, construction of concrete sub drains, 2nd concrete lining, construction of ventilation stations, interchange stations …etc were started progressing at the same time during TBM mining in one single tube. All these activities caused not only the huge interferences but also damaged the rails, tracks, water pipe lines and HV power cables for the back up of TBM mining operation (Figure.9, 10).

With the understanding from the Client, RSEA waived some of the activities as aforesaid and concentrated in TBM mining operation in March of 2003. As a result, RSEA's TBM construction team approved their ability and achieved the best monthly advance rate of 360.10 m/month. In this particular project, generally, east bound TBM mining operation was only executing 2 shifts (8hour/shift) in a day in case no any signs of abnormal or risky conditions for the tunnel. Night shift was stopped for back filling and consolidating of the tunnel behind the pre cast segments which were built on the previous 2 shifts. In the mean time, cutters

Table 7. Data and Average performance of TBMs

Item	Description	Unit	TBM of Pilot tunnel (Boring dia.4.819m)	TBM of East Bound main tunnel (Boring dia.11.74m)
1	Total excavation length in full face	m	5168	3882.836
2	Total excavation length in Canopy method	m	1663	3433.697
3	Total excavation length (full face + Canopy)	m	6831	7316.533
4	Total cutter consumption	ea	520	1636
5	Average cutter usage for the whole length	Cutter/m	0.076	0.224
6	Average cutter usage in Szeleng Sandstone section	Cutter/m	-	0.387
7	Average cutter usage in other section (ARG,SS)	Cutter/m	-	0.059
8	The best monthly advance rate	m	400.800	360.100
9	The best daily advance rate	m	24.700	19.528
10	Average monthly advance rate in the year of 2004	m	-	207.571

inspection, exchanging, maintenances and repair works on mechanical, hydraulic and electric systems, cleaning and preparing works for next mining operation…etc. were carried out. Furthermore, tunnel at night shift was also considered as the access for the usage of all other associated structures construction. However, with the joint effort of the TBM construction team and the assistance from the Client TANEEB as well as from project management Sinotech, east bound main tunnel TBM was broken through on 8th of August 2004 at sta.33k+414 where the tunnel had been excavated the Top heading by D&B from the western portal.

Table 7 shows the data and average performance of TBM mining operation in Hsuehshan Tunnel.

CONCLUSION

The 1st time use of TBM of this size for tunnel excavation in Taiwan was indeed a new venture especially in such difficult conditions encountered. It was inevitable that too many responsibilities, pressures, challenges fell on the shoulder of TBM construction team and had been suffered from many failures and difficulties with full of blood, sweat and tears. Even though, we had never dejected to progress towards. An article, in the name of "Pinglin Perseverance in Taiwan" written by Dr. Shani Wallis which published in the T&T (Tunnels & Tunnelling International) Magazine on October of 1998, noted that: "This is the tunnel that just can not be built, but the Taiwanese are not giving up". Even so, there are still remains that we need to gain more experiences in managing and operating a modern mechanized tunneling system, to enhance our ability to cope with those difficult ground conditions that might be frequently encountered in the future tunneling projects. However, we would like to share our passed experiences and welcome your valuable critiques.

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International. Note: Pinglin Tunnel was re-named as Hsuehshan Tunnel.