FAILURE MODES OF TBM AND REMEDIAL MEASURES USED IN THE HSUEHSHAN TUNNEL

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ABSTRACT

During the excavation of the Hsuehshan Tunnel, the three TBMs were stopped many times. These stoppages were unavoidable and caused serious delays in the construction schedule. From the 28 major stoppages of the TBMs, 3 types of failure modes were identified, namely (1) the cutter head jammed, (2) the shield body jammed, and (3) the TBM became buried. Remedial measures used for extracting the stalled TBMs according to the failure modes were studied and classified. It is expected that the TBM experiences gained in the Hsuehshan Tunnel can serve as a guide for future tunneling with TBMs in similar geological conditions. This paper discusses those guidelines.

Keywords : TBM stoppages, failure modes, remedial measures

INTRODUCTION

In the construction of the Hsuehshan Tunnel, the three TBMs were launched from the east portal of the Touchen end towards the west portal of the Pinglin end. All the TBMs were designed to be double shielded instead of open types to ensure the safety of the machines during the excavation stage. Table 1 summarizes the major events that the three TBMs encountered. In total, there were 28 major work stoppages had been encountered during their westward journeys. Most of the stoppages happened in the tunnel section where the rock strata stratigraphically belonged to the Szeleng formation which was characterized by hard, brittle quartzite often containing high water inflows. The conditions that caused the major stoppages of the three TBMs are summarized as shown in Table 2. In this paper, the data associated with the TBM stoppages were collected and the failure modes of these incidences studied. The measures to remedy the 3 types of failure modes were classified to give a summary of the experiences gained and this will be helpful for any future tunneling with TBMs in similar geological conditions.

REVIEW OF GEOLOGICAL CONDITIONS

Fig.1 shows the geological profile of the Hsuehshan Tunnel. The rock formations along the tunnel alignment mainly belong to the Hsuehshan Range Geological Sub-province of Tertiary Age which is consisted of several subunits, including from oldest to youngest : the Szeleng (SL), the Kankou (KK), the Tsuku (TSK), the Tatunshan (TTS), the Makang (MK), and the Fangchiao (FC). All the rock mass in the sub-province has suffered low degrees of metamorphism and the rock material has became indurate. Among these subunits, the Szeleng formation which is composed of quartzite or fine quartzose sandstone intercalated with argillite was the most difficult tunnel section and it hindered the normal progress of the tunnel work. The Szeleng formation contained many regional faults because of the opening of Okinawa Trough on the Northeastern Taiwan. These faults were extensional in nature and groundwater activity is apparent there.

During construction, shear zones with thicknesses of more than 50 cm were encountered in 98 different places, The maximum water inflow encountered in these 98 places had a flow rate of 750 liters per second and a maximum water pressure of 18 kg/cm2. Beyond the tunnel section within the Szeleng formation, the rock mass conditions improved significantly.

The concept of structural uniform regimes of rock masses had been introduced in the design stage of the Hsuehshan Project. The structural uniform regimes of rock masses were classified according to lithologies and the natures of discontinuities, i.e. the joint orientation, spacing, and persistence. This concept proved to be very helpful in characterizing the mechanical properties of the rock masses for the tunneling. From evidences

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gleaned during construction, 3 uniform groundwater regimes were identified. The locations of the three regimes can be seen in Fig.1 and their characteristics are summarized as follows.

Regime I : From the portal of the Touchen end heading west toward the Chingyin Fault, the rock mass is composed of argillite of the Kankou Formation. The groundwater encountered there was mainly from isolated water aquifers, and decayed quickly after a few days when truncated by the tunnel heading.

Regime II : From the Chingyin Fault heading west to the boundary of SL/KK, the rock mass is composed of the Szeleng Formation. The bursting out of groundwater along with broken rock masses and large faults occurred very often. These groundwater inflows were observed to be long-lasting had a high potential to be recharged. Drainage facilities were usually required in the tunnel construction.

Regime III : From the boundary of SL/KK heading west to the portal in the Pinglin end, the rock materials were quite strong and the rock mass conditions were moderate to good based on the rock mass classification system. The degree of water conductivity was between that of Regime I and Regime II. The sudden out-bursting of groundwater was rare but constant, moderate pressure inflows were often observed.

Fig.2 shows a conceptual groundwater model in which the groundwater conditions within the rock mass can be blocked by the sheared zones which can be rich in clay seams or fault zones to form a checker-like flow pattern. Adjacent to some major fault zones, high water concentration zones were formed in the rock mass due to the dense jointing with clayey shear zones. This formed a typical situation where the TBM would be seriously affected when passing through such a kind of rock mass. In most cases, when the TBM struck through the water aquifers which were confined by sheared zones or fault zones, large amounts of water rushed out all of a sudden and resulted in cave-ins adjacent to the cutter head of the TBM and jammed the machine thereby preventing it from free rotating. Photo 1 shows a local groundwater condition in the tunnel where pressurized groundwater was gushing out of the drilled holes.

IDENTIFICATION OF FAILURE MODES

Failure Modes of Stalled TBMs

The total time spent on restoring the TBMs after work stoppages amounted to 2563 days. The average time spent on restoration was 3 months and the longest time spent on a restoration was more then 10 months. Most of the stoppages happened in the excavation of the first 3-km of the tunnel and mainly in the rock mass of the Szeleng Formation. There were 13 work stoppages in the excavation of the Pilot Tunnel and the 10th incident was the most severe. After the 10th incident, a mixed excavation method was adopted to ensure safety. This method used a top drift precedent to the full face TBM excavation. In the Westbound main tunnel, the TBM had a mishap within the Shangshin Fault and was dismantled

Photo. 1 Groundwater Condition in the Hsueshan Tunnel

TABLE 1 Main Progress of Hsuehshan Tunnel TBM

FAILURE TYPE	PILOT TUNNEL	EASTBOUND MAIN TUNNEL	WESTBOUND MAIN TUNNEL
Station of first blast	40k+684	40k+244.1	40k+251.16
Date of first blast	1991.08.20	1993.07.23	1993.08.07
Date of TBM on site	1992.09.06	1995.05.11	1995.05.11
Date of TBM push on	1992.12.01	1996.05.14	1996.01.24
Date of TBM launching	1993.01.06	1996.08.21	1996.05.02
Station of TBM launching	40k+158.9	39k+512	39k+358
Date of TBM shutdown	2003.10.20	2004.08.12	1997.12.15
Station of TBM shutdown	33k+748.15	33k+410.4	38k+902.5
Date of last blast	2003.12.10	2004.02.01	1997.12.15
Station of last blast	33k+328.77	32k+195.47	38k+902.5
Date of TBM dismantled	2003.12.20	2004.02.02	1999.11.12
Maximum advance per day	24.73 m	17.9 m	14.69 m
Maximum advance per month	400.82 m	360.1 m	68.79 m
Start of Szeleng formation	39K+816	39K+410	39K+370

TABLE 2 Time and Location of the Main Stoppages of the Three TBMs

Tunnel	Station	Time
Pilot Tunnel	40K+138	1993.01.2-1993.04.24, 92 days
	40K+083	1993.05.25-1993.07.15, 52 days
	40K+075	1993.08.29-1993.10.04, 37 days
	40K+040	1993.10.22-1993.12.21, 61 days
	39K+972	1994.02.23-1994.04.07, 44 days
	39K+842	1994.05.25-1994.07.01, 37 days
	39K+816	1994.07.10-1994.09.19, 72 days
	39K+530	1994.11.07-1994.12.23, 46 days
	39K+168	1995.02.18-1995.12.04,290 days
	39K+079	1996.02.05-1996.09.13, 221 days
	37K+431	2001.04.10-2001.08.15, 128 days
	37K+366	2001.08.25-2001.11.17, 76 days
	33K+990	2003.06.10-2003.09.17, 72 days
Total		13 times, 1,228 days

Tunnel	Station	Time
EB	39K+458	1996.10.03-1996.10.17, 15 days
	38K+858	1997.07.10-1997.11.17, 131 days
	36K+958	2002.07.24-2002.09.03, 41 days
	36K+670	2002.10.24-2002.11.07, 14 days
	36K+440	2002.12.07-2003.05.11, 173 days
Total		5 times, 374 days
WB	39K+239	1996.12.24-1997.01.08, 17 days
	39K+235	1997.03.07-1997.03.24, 18 days
	39K+217	1997.04.04-1997.05.05, 32 days
	39K+209	1997.05.08-1997.05.20, 13 days
	39K+148	1997.06.02-1997.06.10, 9 days
	39K+130	1997.06.16-1997.06.20, 5 days
	39K+077	1997.07.04-1997.07.24, 21 days
	38K+929	1997.09.05-1997.12.11, 98 days
	38K+919	1997.12.13-1997.12.14, 2 days
	38K+902	1997.12.15-1999.12.30, 746 days
Total		10 times, 961 days

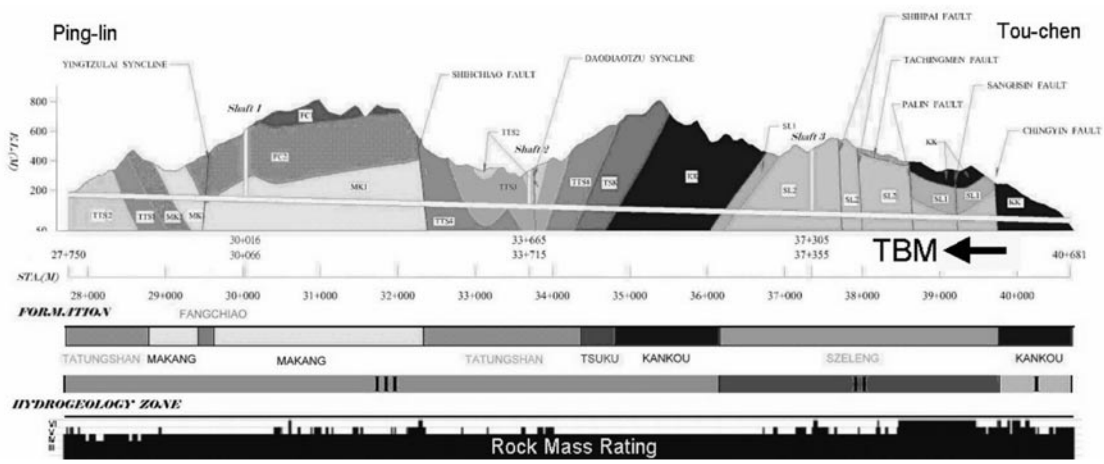

Fig. 1 Geologic Profile along The Hsueshan Tunnel

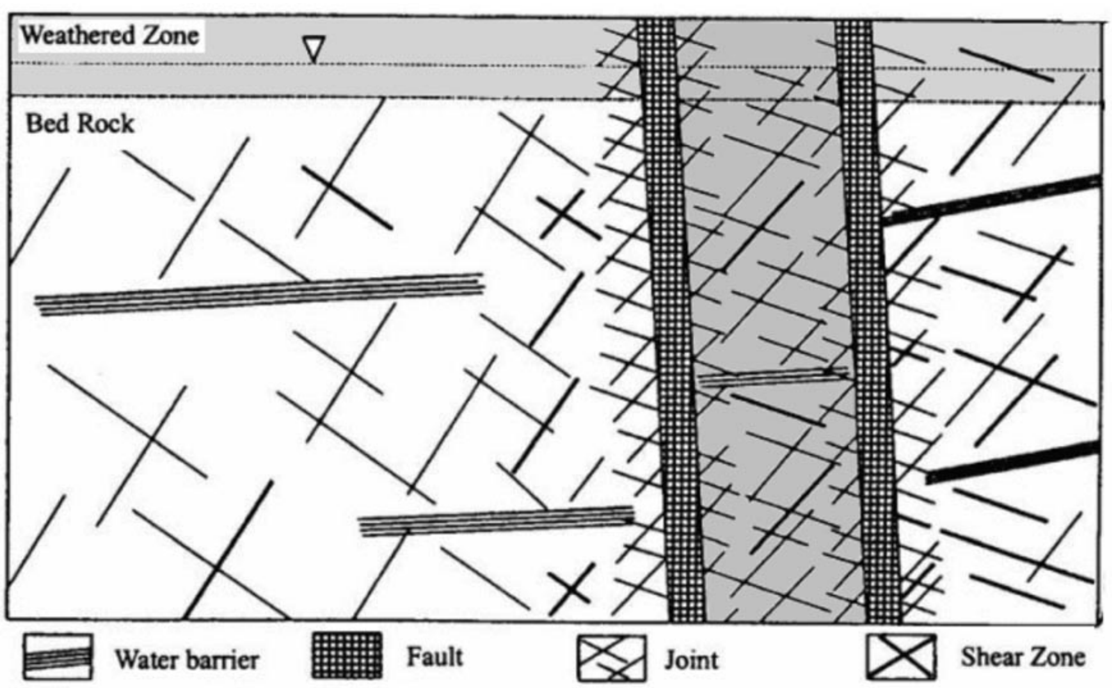

Fig.2 Schematic Illustration of Checker-like Groundwater Model

after 10 stoppages. In the Eastbound main tunnel there were only 5 work stoppages through the whole project. The drop in the number of work stoppages was due to extensive pretreating of the ground and the drilling and blasting of a pilot top heading before the use of the TBM. According to the construction experiences gained from the frequent TBM stoppages in Hsuehshan Tunnel, three major types of failure modes were identified, namely: (1) the cutter head jammed, (2) the shield body jammed, and (3) the TBM became buried. These are illustrated below and summarized in Table 3.

Cutter Head Jammed

The cutter head may have jammed because of cave-ins or unstable rock wedged falling into it. Water inflow often caused the jams to become worse. The jamming of the cutter head was characterized by either the stalled feed-

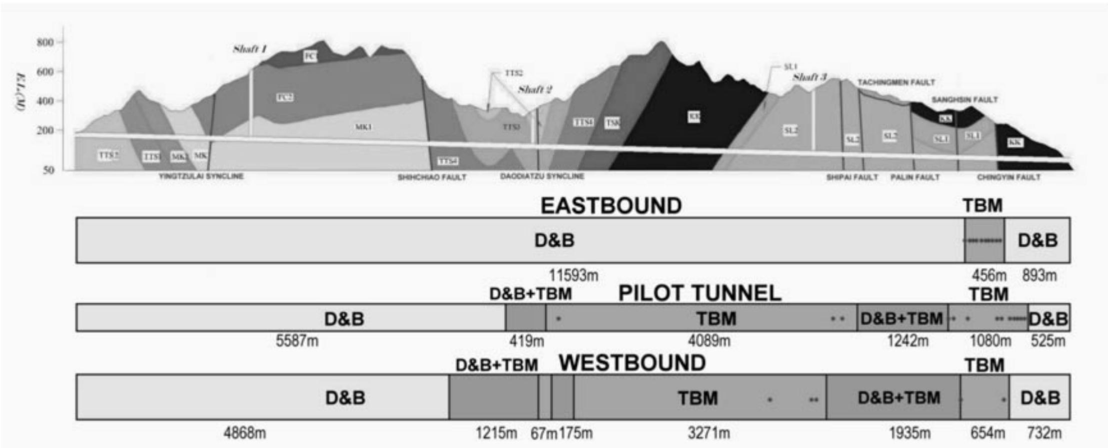

Fig. 3 Profile Showing the Locations TBM Construction

in cabin or the overloading of the output conveyor due to rock fragment from cave-ins preventing the rotation of the cutter head. In some cases the drive motors were inundated with inflowing water and that caused the stoppage.

Shield Body Jammed

Due to the design of the TBM shielding, the area from the excavating face to the rear shield was basically unsupported. Hence, there was a high potential of for loose, unstable rock wedges to fall down and induced a shield body jam. In addition, in tunnel sections where rock masses with low strength were encountered, large deformations would occur because of the large unsupported span from the excavating face to the rear shield and resulted in the inward squeezing of the rock mass that would also jam the shield body unless the TBM could pass through it in time. Two kinds of jamming conditions could be observed: (1) Jamming between the telescopic shield and the cutter head, (2) Jamming at rear shield.

TBM Became Buried

In some situations, severe cave-ins accompanied by water inundation and debris flow resulted in the breakdown of the TBM and the TBM was completely buried. A lot of effort was necessary to restore the TBM under such conditions.

By collecting the data associated with the 28 stoppages, the types of failure modes for the three TBMs used in the Hsuehshan Tunnel can be identified and listed in Table 3. The results are shown in Table 4, Table 5, and Table 6 respectively for the three TBMs.

REMEDIAL MEASURES

Remedial Measures for Jammed Cutter Head

In case of the cutter head jamming, the typical remedial measures were comprised of the pulling the TBM back a short distance and cleaning up the debris. This was followed by refilling the cavities with shotcrete or cement mortar from the feed-in cabin on the cutter head. After the TBM was again able to move forward, extensive ground treatments such as consolidation grouting were carried out behind the TBM to improve the inferior rock mass. This was normally done to ensure the safety of the other forthcoming TBM.

Remedial Measures for a Jammed Shield Body

(1) Jamming between the telescopic shield and the cutter head :

* **Bypass tunnel excavation:** Excavating a bypass tunnel starting from a point on the side wall of the main tunnel was about 3 to 5 m behind the rear shield, where better geologic conditions could be encountered. The main alignment of the bypass ran parallel to the main tunnel with a side to side distance about one diameter of the main tunnel.
* **Relief of the telescopic shield:** Excavating a bypass tunnel from the side wall of the main tunnel up to the front of the cutter head, and extending the over-mining along the shield body until a clearance of

TABLE 3 Failure Modes of TBM

FAILURE TYPE	MODE	DESCRIPTIONS
Cutter Head Jammed	A	Rotation disabled, TBM stalled
Shield Body Jammed	B	Jamming between telescopic shield and cutter head, TBM stalled
		Jamming at rear shield, TBM stalled
TBM Buried	C	High water inflow, Water inundation and debris flow, TBM Buried

TABLE 4 Failure Modes of Pilot Tunnel TBM

STATION	FAILURE TYPE	ROCK TYPE	WATER INFLOW (L/SEC)	DESCRIPTIONS
40k+138.50	A	Argillite/KK	11-32	3 bypass tunnels
40k+083	A	Argillite/KK	20-40	1 bypass tunnel
40k+075	A	Argillite/KK	-	1 bypass tunnel with 1 top drift
40k+040.7	A	Argillite/KK	-	1 bypass tunnel with 1 top drift
39k+972.4	A	Argillite/KK	-	1 bypass tunnel with 1 top drift
39k+841.9	A	Argillite/KK*	-	2 bypass tunnels with 1 top drift
39k+816	A	Argillite/KK Fine SS/SL*	25-30	2 bypass tunnels with 1 top drift
39k+530.44	C	Quartzite/SL	185	1 bypass tunnel with 1 top drift, 1 drainage gallery
39k+168.7	C	Quartzite /SL	150	6 bypass tunnels with 1 top drift
39k+079.4	B	Quartzite /SL	150	6 bypass tunnels with 1 top drift
37k+431	A	Quartzite /SL Argillite/KK	20	1 bypass tunnel with 1 top drift
37k+366	A	Argillite/KK Coarse SS/KK	5	1 bypass tunnel with 1 top drift
33k+989.5	A	Fine SS/TTS** ST/TTS	-	1 bypass tunnel with 1 top drift

TABLE 5 Failure Modes of Eastbound Tunnel TBM

STATION	FAILURE TYPE	ROCK TYPE	WATER INFLOW L/SEC	DESCRIPTIONS
39k+458	A	Quartzite/SL	-	
38k+857.76	A+B	Quartzite/SL	-	Use bypass tunnel + top heading
36K+958	B	Quartzite/SL	-	
36K+670	B	Quartzite/SL	-	
36k+440	A	Quartzite/SL	40	Use top drift

one meter at the roof and haunch were obtained. The dimension of the clearance could be modified depending on the severeness of the jam.

* **Pilot geological exploratory:** Periodic geological exploration by pilot hole drilling was applied in order to understand the stability of the rock mass. Consolidation grouting could be done to improve the inferior rock mass where required.

Jamming at rear shield :

* If the jamming happen at both the cutter head and the

TABLE 6 Failure Modes of Westbound Tunnel TBM

STATION	FAILURE TYPE	ROCK TYPE	WATER INFLOW L/SEC	DESCRIPTIONS
39k+239	A	Quartzite/SL	-	
39k+234.6	A	Quartzite/SL	-	
39k+217	A	Quartzite/SL	-	
39k+208.63	A	Quartzite/SL	-	
39k+148.05	B	Quartzite/SL	-	
39k+129.96	B	Quartzite/SL	-	
39k+077	B	Quartzite/SL	-	1 top heading tunnel from segment A
38k+929	C	Quartzite/SL	130	1 top heading tunnel from segment A
38k+919	C	Quartzite /SL*	143	1 top heading tunnel from segment A
38k+902.5	C	Quartzite /SL#	750	TBM dismantled

rear shield due to the squeezing of the surrounding rock mass, the remedial measures were same as (1). The relief excavation at the rear shield was done by the over-mining from the excavation face along the shield body backwards and relief holes were drilled if necessary. Restoration checks on the rear shield function were performed in adequate time to minimize excavation work and to reduce the total restoration time of the stalled TBM.

* If only the rear shield jammed due to the squeezing of the surrounding rock mass, the remedial measures comprised partly cutting off the front edge of the rear shield and extending the over-mining outwards and upwards along the shield body up to the rear shield. The other portion of the treatment was selected according to the jamming conditions and equipment availability. To relieve the rear shield, a minimum amount of dynamite or hand trimming was applied to remove the squeezing rock. Restoration checks on the function of the rear shield function could be performed in adequate time until the stalled TBM was completely restored.

Remedial Measures for TBM buried

In cases where severe cave-ins were accompanied by water inundation and debris flow and this resulted in the breakdown of the TBM, excavating bypass tunnels from the side walls of the main tunnel behind the stalled machine were necessary in order to rescue the buried TBM. These bypass tunnels were excavated mainly to the front of the cutter head, and extended the over-mining until working clearances were obtained. A top drift to explore the geologic conditions or to perform ground improvement ahead of the TBM could have been excavated. The decision of whether to use the bypass tunnel in this situation depended on the following factors:

* The severeness of stalled conditions and dimensions of the affected areas
* The locations and dimensions of the areas to be treated
* The geological and groundwater conditions of the areas to be treated
* The types and dimensions of the excavation tools and drilling equipment to be used
* The presumed time and budget.

Determining the location of the entrance for the bypass tunnel was dependent on many factors, including the total length of the bypass tunnel, the processing time and the construction plan. In general, the distance from the entrance of the bypass tunnel to the cutter head should be as short as possible. Once the location was decided, further plans could be made based on information associated with the strategies mentioned above. However, due to the design of the shield machine, the available locations were often limited and the only locations that could be used were as follows:

* The side wall near the rear shield, as shown in Fig. 4.
* The side wall behind the rear shield, as shown in Fig. 5.
* The tunnel roof behind the rear shield, as shown in Fig. 6.

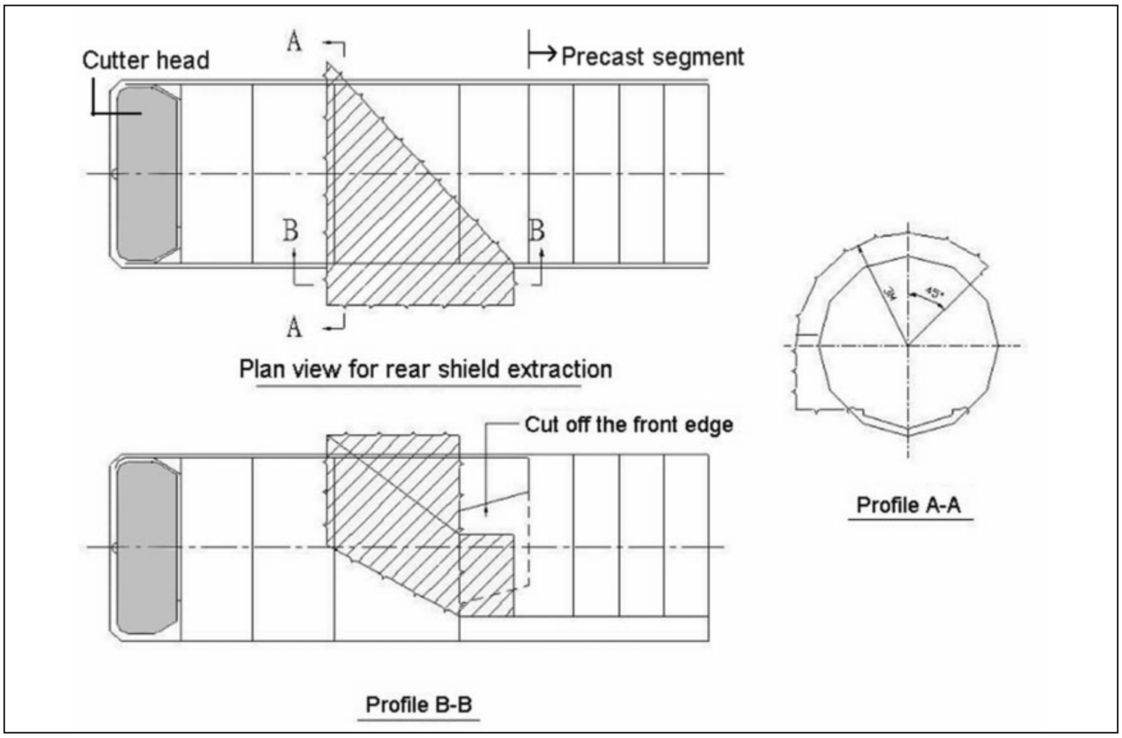

Fig. 4 Entrance at Side Wall near the Rear Shield

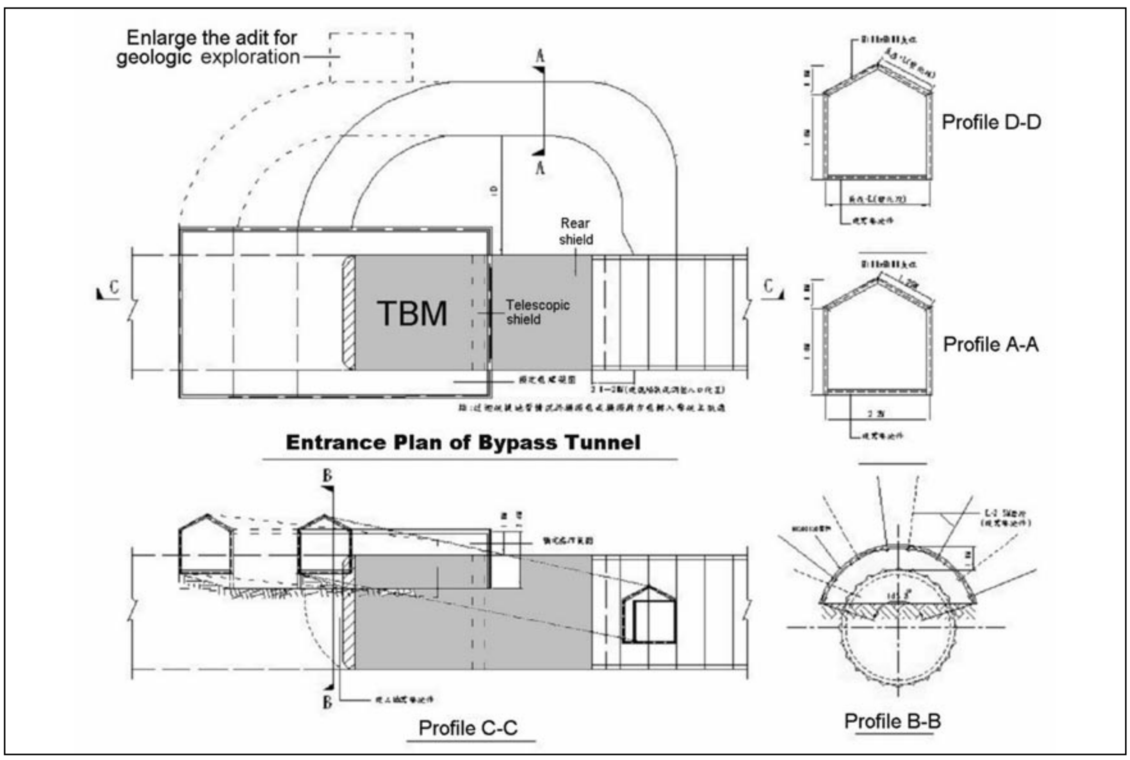

Fig. 5 Entrance at Side Wall behind the Rear Shield

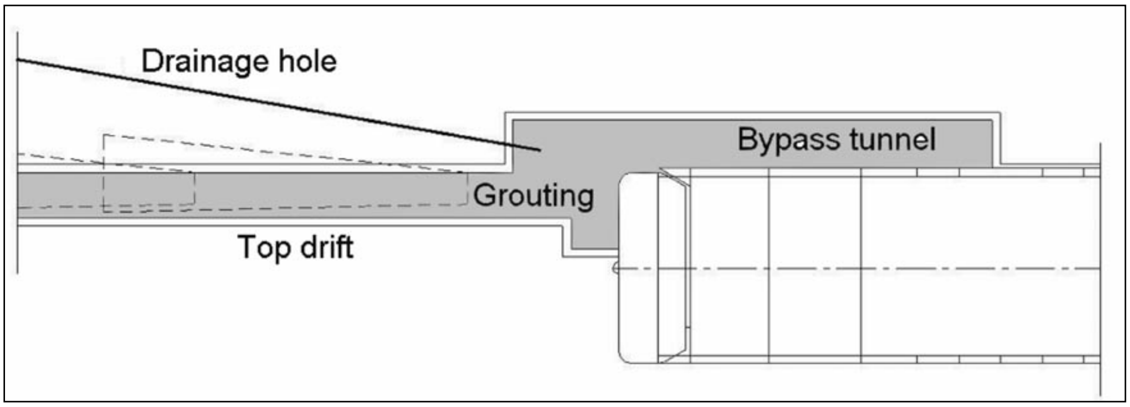

Fig. 6 Entrance at Tunnel Roof near the Rear Shield

CONCLUSIONS & RECOMMENDATIONS

Among the 28 major stoppages, three major types of failure modes for the stalled TBMs were identified, namely: (1) the cutter head jammed, (2) the shield body jammed, and (3) the TBM became buried. In this paper, the remedial measures use to extract the stalled TBM under different failure modes were studied and classified.

In the case of the cutter head jamming, the typical remedial measures comprised pulling the TBM back a short distance and cleaning the debris. This was followed by refilling the cavities with shotcrete or cement mortar from the feed-in cabin on the cutter head. If the jamming occurred between the telescopic shield and the cutter head, the remedial measures included excavating a bypass tunnel, relief excavation of the telescopic shield, and pilot geological exploration. If jamming occurred at the rear shield, relief excavation at the rear shield and extension of the over-mining backwards and drilling relief holes was required. Worst of all, if severe cave-ins were accompanied by water inundation and debris flow and this resulted in the breakdown of the TBM, excavating bypass tunnels from the side wall of the main tunnel behind the stalled machine was necessary in order to rescue the buried TBM.

There were a lot of lessons learned through the excavation of the Hsuehshan Tunnel using the TBM, in particular the experiences gained within the difficult Szeleng Formation. It is expected that the TBM experiences gained in Hsuehshan Tunnel can serve as a guide for future tunneling with TBMs in similar geological conditions.

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