RELIABILITY OF GEOLOGICAL EXPLORATION METHODS DUring CONSTRUCTION OF THE HSUEHSHAN TUNNEL

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ABSTRACT

The major geological exploratory methods used in the Hsuehshan Tunnel construction include pilot hole drilling, long-distance horizontal drilling, exploratory adit, and advanced geophysical survey techniques, i.e. horizontal seismic profiling (HSP), tunnel seismic prospecting (TSP), and resistivity image profiling (RIP), etc. All the methods were aimed at determining the geological conditions ahead of the TBM tunnel to avoid geological difficulties due to sudden changes in rock mass conditions, i.e. the existence of shear zones or the out-bursting of some isolated underground water aquifer, which might have jeopardized the tunnel safety. With the aid of these exploratory methods, final success was achieved in passing through the highly broken, watery and poor quality quartzite rock mass of the Szeleng Formation at the Eastern end during the construction stage, even though many difficulties had been encountered. This paper summarizes the experiences encountered and the reliability of each of the methods adopted is discussed.

Keyword : pilot hole drilling, long-distance horizontal drilling

INTRODUCTION

Early in the basic design stage, it was decided to use the shield TBM as the excavation tool for Hsuehshan Tunnel because of the time consideration, geologic condition and environmental impact. As specified in the construction contract of the tender documents, various exploratory methods associated with TBM excavation could be applied if necessary during the construction stage. These included pilot hole drilling, long-distance horizontal drilling, bypass tunnel or exploratory adit etc. In addition, supplementary methods were also allowed such as those using geophysical surveying techniques i.e. horizontal seismic profiling (HSP), tunnel seismic prospecting (TSP), and resistivity image profiling (RIP), etc.

Fig. 1 shows the geological profile along the tunnel alignment. The ground conditions were very complex and many major folds and faults were encountered in the tunneling process. This complex geologic condition was pointed out in the tender documents and the risks were self-evident. However, the accuracy of the locations of geologic uncertainties cannot always be specified with high accuracy, and on-going investigations are always necessary to decrease the geological uncertainties. In general, the contractor should be aware of the challenge and be prepared before beginning with the construction.

In the Eastern section of Hsuehshan Tunnel, the TBM drilled through the highly broken, watery and poor quality quartzite rock mass of Szeleng Formation where the occurrence of high angle regional faults was very frequent. During the construction of the Pilot Tunnel in passing through the Eastern fault groups, the Pilot TBM suffered 13 stoppages. A major stoppage happened in February, 1996 which caused a 2 years setback. Fig.2 shows the locations of some of the major incidents that happened in the early years of TBM use. The main factors that impeded the advance of the TBM of the Pilot Tunnel were identified high water inflows accompanied by highly broken rock or high pressure water trapped by a fault zone or some unknown geological barrier.

The experiences gained during the advance of the TBM through the Szeleng Formation were very special and will become invaluable reference material in future tunnel work. This paper summarizes the experiences encountered. The reliabilities of each of the geological exploratory methods adopted is discussed.

PILOT HOLE DRILLING

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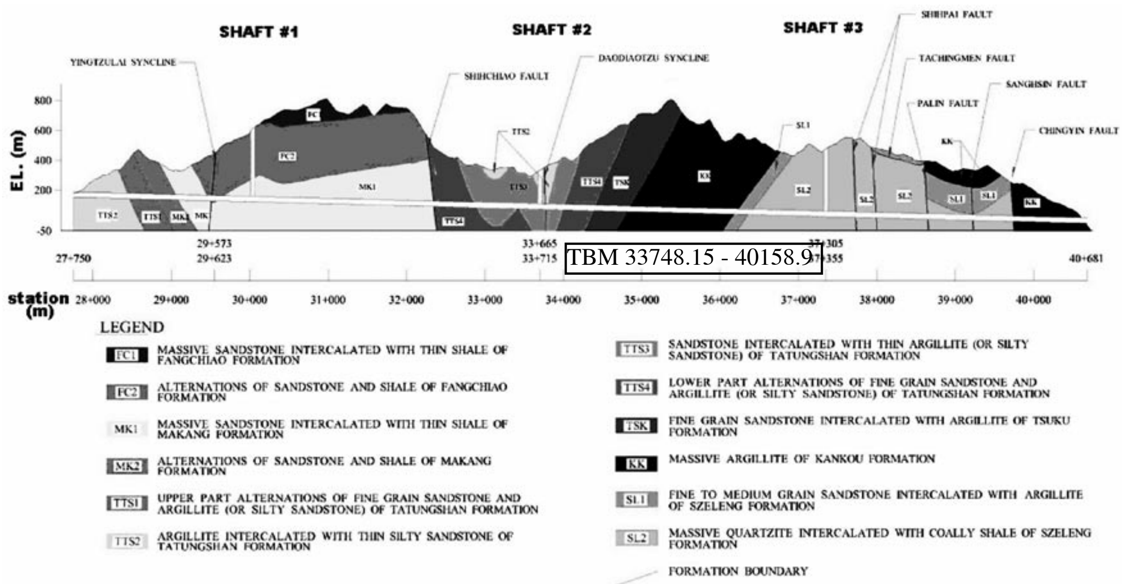


Fig. 1 Geologic Profile along the Tunnel Alignment

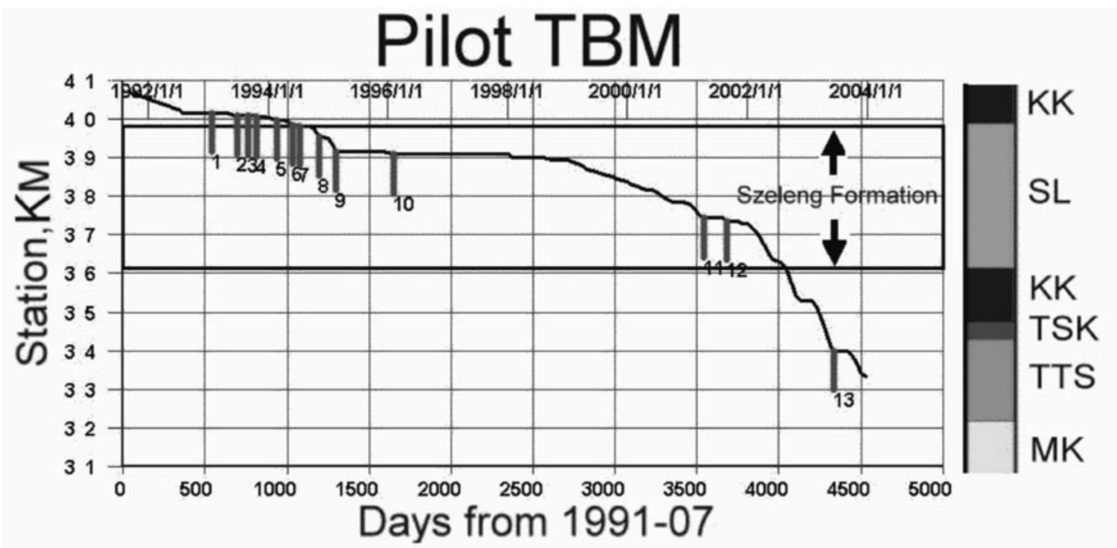


Fig. 2 Major incidents with the Hsuehshan Pilot Tunnel TBM

Fig. 3 shows the setup of Pilot Tunnel TBM's drilling facility. The drilling machine is designed to lie behind the rear end of the shield, a distance of about 10 m away from the cutter head. A drill capacity that could advance a length of 30 meters within two hours was required. With 16 fixed guide hole inlets installed in the perimeter of the drilling machine, either geologic drilling, or drillings for grouting or drainage were possible.

According to the construction specifications, the pilot hole drilling was to use percussion drilling method prior to the TBM launching its new cycle, and geologic data revealed by the pilot drilling should be always a certain distance ahead of the TBM. Percussion drilling uses the repeated impact of a hardened probe to disaggregate rock encountered. Observations made during drilling often provide very important indications that can help evaluate tunnel conditions ahead of the excavation face.

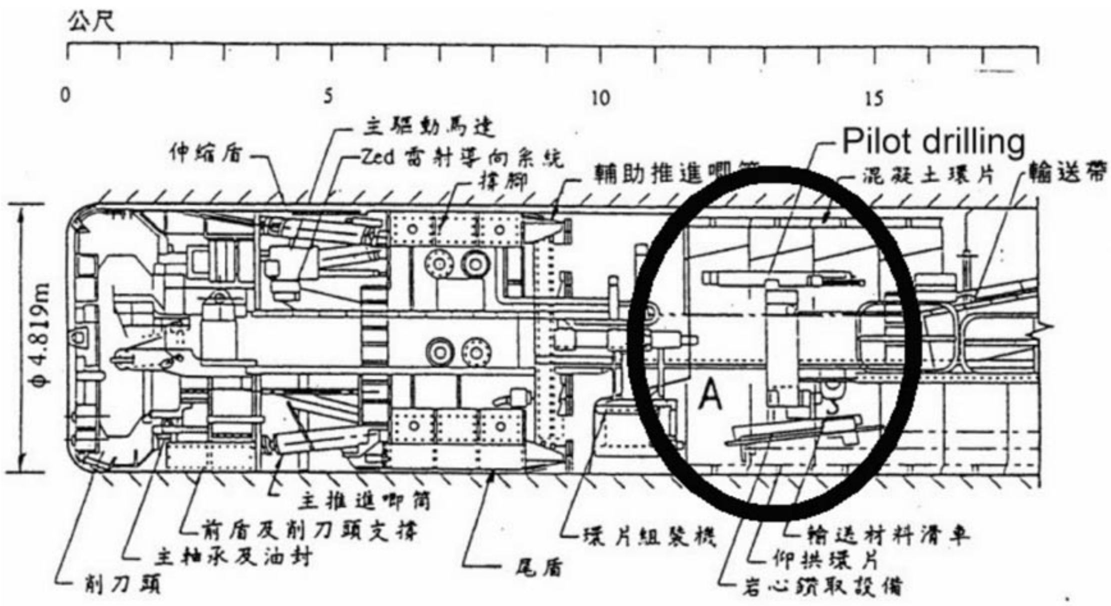


Fig. 3 TBM's Drilling Facility of the Pilot Tunnel

The disadvantage of using percussion drilling is that the geologic data are obtained from the interpretation of the drilling performance such as the penetration rate, stalled condition, water feed back, and sparseness of rock fragments. In such conditions, the geologist is cannot be accurate in the prediction of any meaningful geological conceptual model, especially for those sections with complex drilling data. However, using this method is by all means convenient in a shielded TBM since no available room for geologic data collection is possible.

Fig. 4 Pilot Drilling on TBM (Kruppe HB-40A)

The major difficulties encountered were that the originally designed drilling equipment by Robbins was not suitable for broken quartzite in Szeleng Formation thus it would get stuck easily and in most cases it was incapable of attaining the requirement in time. Table 1

Table 1 The Drilling Performance of the Default Percussion Drilling Machine

NO	LOCATIONS	CORE TAKEN	DRILLING LENGTH (M)	TIME SPENT (HOUR)
1	40k+152	None	14	18
2	40k+105	None	28	16
3	40k+090	None	29	25
4	39k+997	None	36	45
5	39k+868	None	38	8
6	39k+835	None	30	6
7	39k+835	Yes	39	173
8	39k+540	None	30	11
9	39k+198	Yes	38	528

*Szeleng Formation started from Sta.39k+816 (1994/09/20TBM)

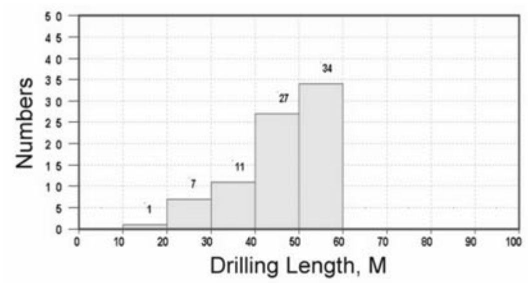


Fig. 5 Histogram of Length of Pilot Drilling (Since December 2000)

shows the performance of the default percussion drilling machine on the Robbins TBM. It can be noted that very embarrassing results were obtained owing to the lack of operational experience, the poor design of the drilling machine, and the poor rock conditions encountered during the early stages of the TBM excavation.

Due to the substandard performance of the drilling machine, most of the required functions could not be fulfilled in hard, broken quartzite which was the typical rock type in the Szeleng Formation. Hence alternative measures had to be considered. The alternative measures were to use locally made drilling machines like the KH-2 or KH-110. These machines showed they had the capacity to drill a maximum length of 77 m without taking cores. In extremely poor geological conditions, numerous machines were introduced into the TBM, including the Board-HD-150, Longyear LM-22, Atlas Copco1238, Diamec 262, Kruppe HB-40A (Fig. 4), etc. But even the most efficient drilling machine could only do 30 meters in 6-7 hours, still far below the original requirement. However, the drilling capacity was significantly improved as shown by the statistical data in Fig. 5. In most cases, drilling a length of 50 to 60 m was very easy to achieve with the modified drilling equipment December 2000 on. In Fig. 6, the smooth progress of the pilot drilling can be identified by the large amount of applications done by the TBM using the modified drilling machine.

LONG DISTANCE HORIZONTAL DRILLING

Geologist were more confident of constructing a precise conceptual geological model when a direct inspection of rock cores was possible. However, the disadvantage of using the core drilling method in the Hsuehshan Tunnel project was the length of time that the tunnel work had to be suspended during the core drilling. Besides that core drilling is more expensive than percussion drilling.

As indicated in the previous section (Fig.2), the Pilot TBM was stalled many times partly because of the poor performance of the pilot drilling facility. In the incident that happened at station 39k+079.4, a large span bypass tunnel was constructed by the drill and blasting (D&B) method to overcome the extremely large amount of water

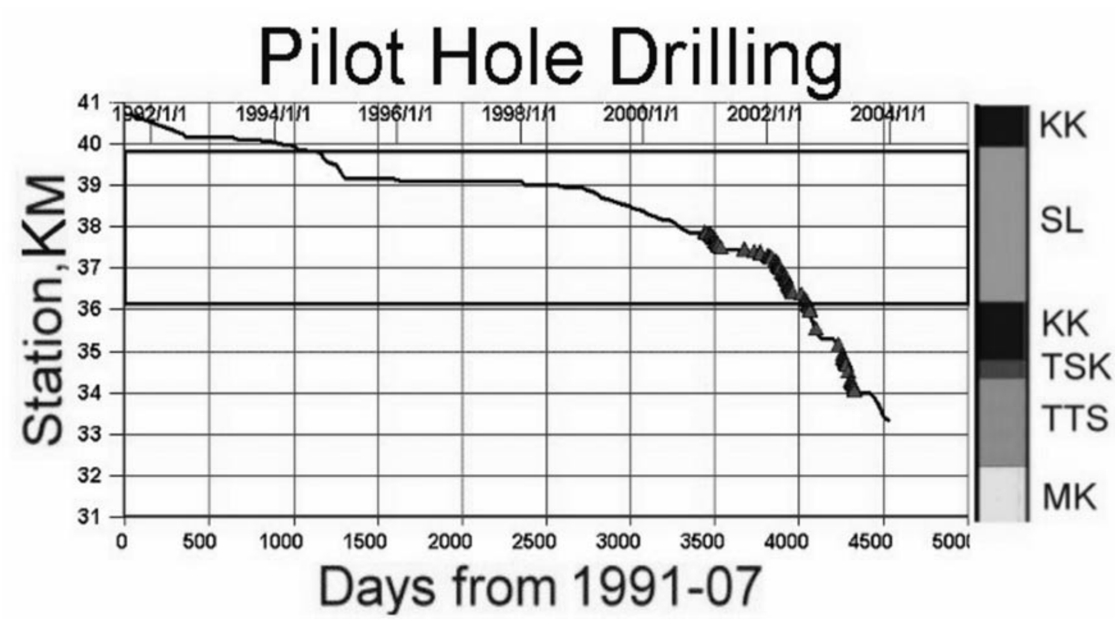
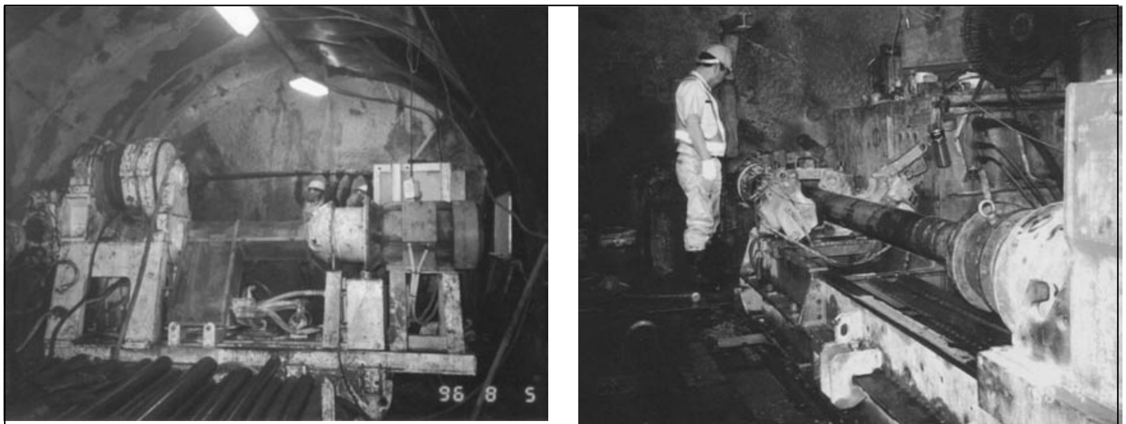


Fig. 6 Locations of TBM pilot drilling after Modification of Drilling Machine



(a) Wire Line Type (LH-1) (b) Double Shielded Reverse Process Type (LHC-3)

Fig. 7 Long Distance Horizontal Drilling (LDHD)

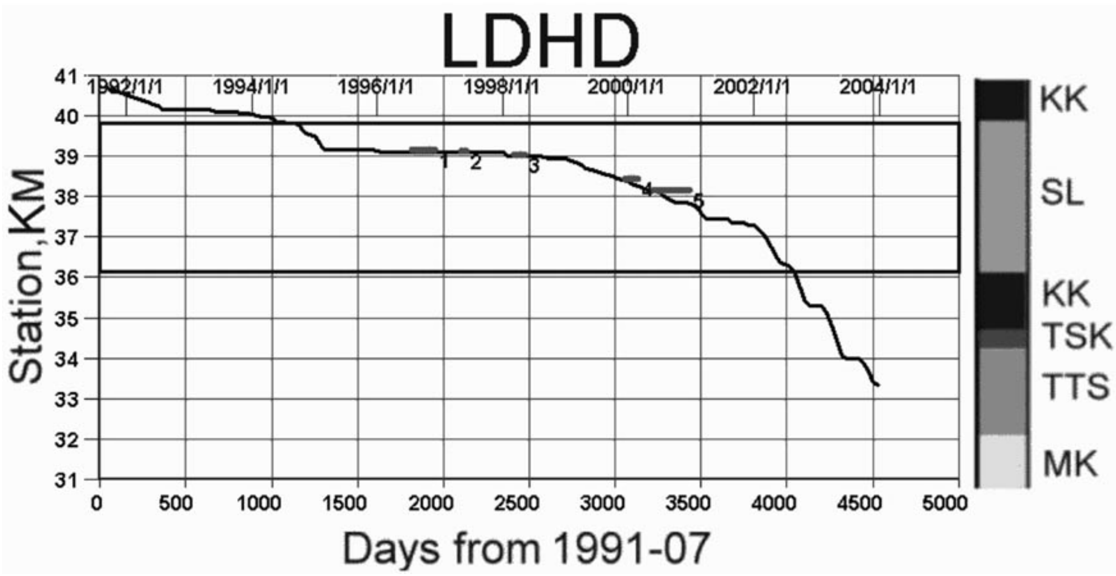


Fig. 8 Locations Long Distance Horizontal Drilling

TABLE 2. Long Distance Horizontal Drilling (LDHD) Used in Pilot Tunnel

HOLE NO	LOCATION	DATE	TYPE OF CORE RECOVERY	MAIN ROCK TYPE	MAXIMUM LENGTH (M)	MAIN CONTRACTOR
LH-1	Sta. 39k+139	1996.07.25 1996.11.30	wire line	Sze-leng	107.25	South Africa (CEMENTATION)
LH-2	Sta. 39k+119	1997.05.05 1997.06.02	double shield reverse process	Sze-leng	103.55	Japan (TONE)
LHC-3	Sta. 39k+019	1998.03.05 1998.05.05	double shield reverse process	Sze-leng	126.4	Japan (TONE)
LHD-4	Sta. 38k+437.8	1999.12.13 2000.02.25	wire line	Sze-leng	262.7	Canada (EDCO)
LHD-5	Sta. 38k+169.5	2000.05.30 2000.12.22	wire line	Sze-leng	480.5	Taiwan (Kuan-Mei)

and broken rock mass that caused the stoppage of the TBM. A series of remedial works was applied to rescue the TBM and the long distance horizontal drilling (LDHD) method was adopted to survey the geologic conditions, and release the pressure within the water aquifer inside rock masses ahead of the TBM.

LDHD was carried out many times from 1996 and 2000, with a total length of 1,080.4 m. The drilling methods can be divided into two types, the wire line type and the double shielded reverse process type as shown in Fig. 7a and Fig. 7b. The drilling locations and the results are outlined in Table 2 and Fig. 8. The first three (LH-1, LH-2, LHC-3) drillings were conducted by international drilling crew entrusted by the main contractor (RSEA), and scheduled to be drilled a length of 300 m. Due to the severe geological conditions of the quartzite, none of them were successful and exploratory works had to be abandoned.

The borehole at LH-1 was conducted by a drilling team from South Africa at a working adit near Sta.39k+139. The purpose of the drilling was to investigate the geologic condition of the 10th stoppage of the TBM. The drilling crews had done an excellent job in a hydropower project in Central Taiwan and were invited to the site to carry out the wire line type LDHD in the Pilot Tunnel. The drilling was finally stopped at a depth of 107.25 m, only 30% of the target length. The crew made almost 20 efforts to grout the borehole walls and increase the stability, but the crews finally had to recognize the difficulties and gave up.

The borehole at LHC-2 was proposed by a Japanese expert who is a member of the technical consulting board. A double shielded reverse process type LDHD was used to replace the wire line type LDHD. This hole was conducted by a drilling crew from Japan at a working adit excavated at the wall of the bypass tunnel near 39k+119, about 20 meters away from the previous hole. Unfortunately, the drilling had to be stopped at a depth of 103.55 m due to a very severe ground water problem encountered, which had 18 kg/cm2 of water pressure and an maximum inflow of 144.7 liters per second. Fig. 9 shows the pressure-flow relationships of the drilling at the depth from 33.5 m to 103.55m.

The borehole at LH-3 was conducted by another drilling crew who also came from Japan. LH-3 was drilled at a working adit excavated at the wall of the bypass tunnel near 39k+019.2, about 100 meters away from the previous hole. This new drilling crew adopted another type of machine still using the double shielded reverse process type LDHD. After failures in two trial locations, the third trial was drilled at a much more satisfactory condition. However, the drilling had to be stopped again at a depth of 126.4 m due to a severe ground water problem encountered in which 16 kg/cm2 of water pressure and an maximum inflow of 100 liter per second were found. The drilling had to be abandoned because the twist force born (500 kg/m) was already close to the maximum capacity (512 kg/m) of the drilling rod.

The borehole at LHD-4 was conducted by a Canadian team at a large working adit (10 m x 5 m x 3.5 m) near 38k+437.8. The wire line type LDHD was re-introduced since there was not much progress using a double shielded reverse process. Mr. Claude from Canada was invited to be the technical advisor throughout the drilling work. The length of the hole drilled reached 262.7 m. The reason for stopping the drilling was no longer the geological factors, but the bias of the drilling direction was too great.

The borehole at LHD-5 was operated by a local contractor at a working adit near 38k+169.5. A breakthrough drilling length of 480.5 m was reached. The purpose was to investigate the geological conditions of Shipai Fault. Mr. J. Demera from Canada was invited to be the technical advisor throughout the drilling work. Mr James from the Philippines took charge of the operation.

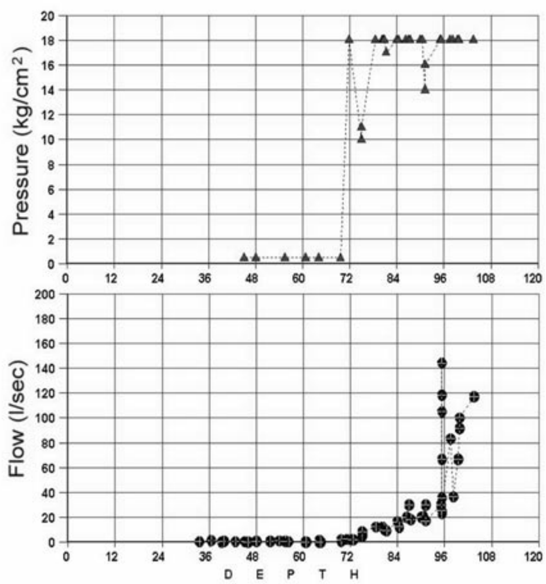
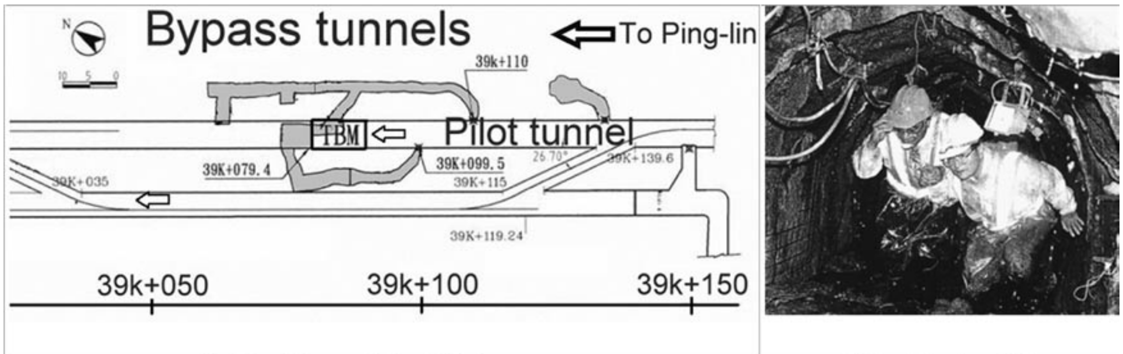
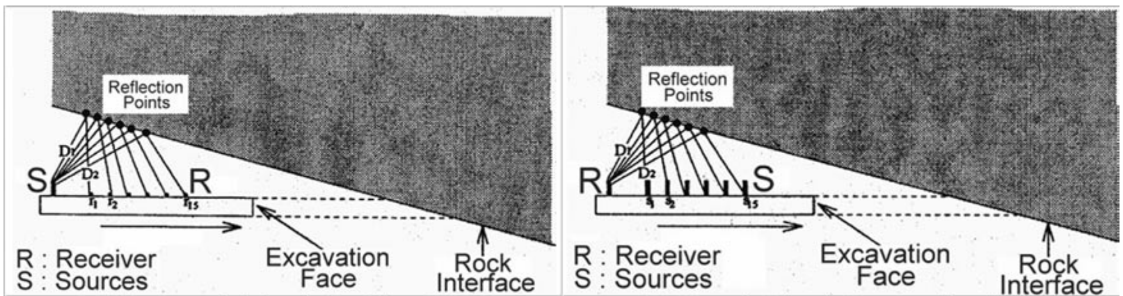


Fig. 9 Plot of Flow vs. Pressure in LH-2



(a) Plan View of the 10th Stoppage | (b) Inside the Adits

Fig. 10 Geological Exploration by Exploratory Adit



(a) Horizontal Seismic Profiling (HSP) | (b) Tunnel Seismic Prospecting (TSP)

Fig. 11 Seismic Reflection Techniques in Tunnel

EXPLORATORY ADIT

To rescue the stalled TBMs from serious hazards, many effective measures were carried out. The most general approach was the introduction of the exploratory adit or bypass tunnel, and the approach is summarized as follows:

∗ Improve the surrounding poor rock mass around the stalled TBM,

∗ Excavate a bypass tunnel (adit) to reach the cutter head portion in the front of the stalled TBM,

∗ Excavate a top drift or adit backwards up to the rear shied to release the stalled TBM,

∗ Excavate a top drift or exploratory adit forwards to improve the adverse rock mass condition prior to recommencing the TBM excavation,

∗ Backfill the cavities created by rescuing the stalled TBM after safety protection measures were made for the freed TBM.

Fig. 10 shows the locations of the bypass tunnels excavated for rescuing the stalled TBM from the 10Th stoppage located at 39k+079. These tunnels not only provided the first aid to the TBM, but supplied the access for grouting and drainage works. As can be seen in Fig 10b, the effective drainage by the bypass tunnel was tremendous. However, this method was expensive and very time-consuming.

GEOPHYSICAL METHOD

Reflection Method

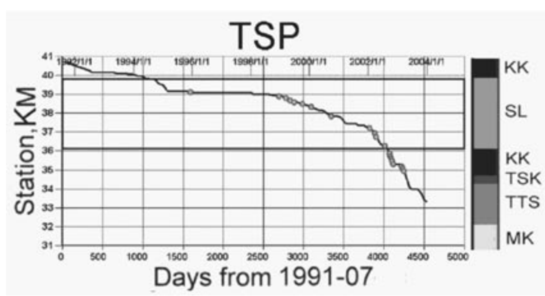


Fig. 12 Locations of Application of TSP

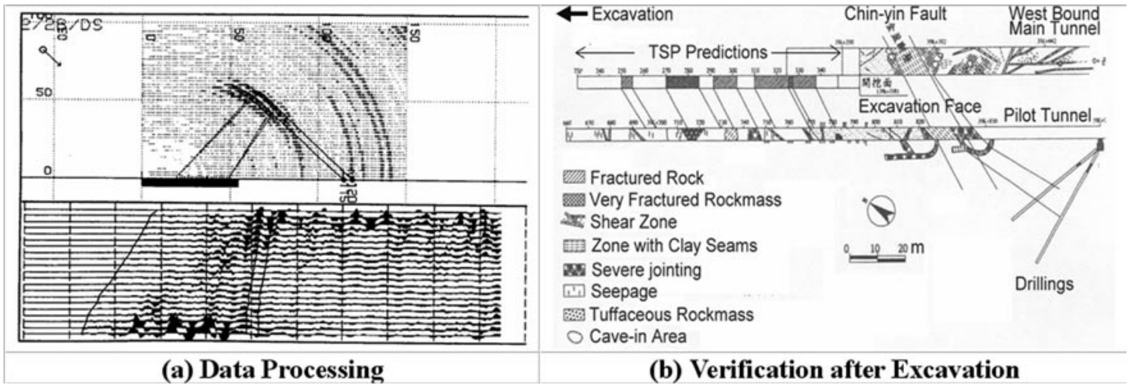


Fig. 13 Correlation of results of TSP after excavation

Other methods that can be considered in a TBM operation are the application of geophysical survey methods based on seismic reflection principles. These methods can serve as auxiliary methods when pilot drilling can not work efficiently. Two reflection methods for prospecting tunnel geological conditions were adopted, including the use of horizontal seismic profiling (HSP), and tunnel seismic prospecting (TSP). The layouts of the surveys are shown in Fig. 11a and Fig. 11b respectively.

By using data processing and seismic reflection principles, both HSP and TSP can locate tunnel sections where transitions of rock mass condition go from poor to good, or vise versa. Normally, major fault events can be predicted with a high level of accuracy by both methods despite the inaccuracy of their predicted locations to meet the engineering requirements needed in the TBM excavation.

The HSP methods were conducted five times for trial purposes at the beginning of the Pilot Tunnel excavation. But no persuasive results were obtained. The last application happened to be applied only three days prior to the 10th stoppage of the TBM. It was obvious that the HSP failed to predict the geologic hazards ahead of tunnel. The results of the TSP usually showed higher accuracy than those of HSP, but the operation took more time and was more expensive. The TSP measurements were conducted in the later stage when the modification of Pilot TBM was done. Fig. 12 shows the locations of the TSP surveys along with the TBM excavation.

Fig. 13 shows an example of the data processing and interpretation involved in the TSP survey. The received amplitudes and travel times of the reflective waves were transformed from the time domain to the space domain, and the events were predicted in terms of the distance ahead of tunnel. Normally the predictive length may be up to 100 m or 150 m depending on the rock mass conditions. In Fig.13b, the predicted locations of the rock interfaces by TSP were compared with those revealed after excavation, and satisfactory results can be noted. In general, the reliability must always be examined carefully and it is also necessary to have enough experience to make significant interpretations.

RIP Measurement

Unfortunately, neither the HSP nor the TSP was sensitive to the existence of ground water. Instead, resistivity image profiling (RIP) is one of the geophysical survey methods suitable for predicting the groundwater conditions by recognizing the resistivities of varied stratum. The RIP measurements in the Hsuehshan Tunnel are summarized in Table 3. Three measurements were carried out at the locations in between shaft no.1 and shaft no.2. Surveyed depth can be down to 700 m below the ground surface. Fig. 14 shows the results of RIP measurements in the surveyed area.

A few of the tunnel sections with extremely low resistivity values were identified in which ground water concentration regimes under different warning levels of excavation dangers were predicted as indicated with star symbols in Fig.14. One of the major purposes was to evaluate the water-bearing condition of Shi-tsao Fault. As shown in Fig.15 from 31k+500 to 32k+500, there were speculation of a high potential of ground water since the low resistivity values had been noted. However, later excavation proved that this was a false warning. It should be noted that low resistivity can not be directly correlated

TABLE 3. RIP Measurement

NO	LOCATION	DATE	DEPTH (M)	LENGTH (M)	SUB CONTRACTOR
RIP-1	EB Sta. 29k+200 EB Sta. 31k+200	1996.07.25 1996.11.30	775	2000	RSEA/ITRI
RIP-2	EB Sta. 32k+700 EB Sta. 34k+200	1997.05.05 1997.06.02	775	1500	RSEA/ITRI
RIP-3	EB Sta. 31k+095 EB Sta. 32k+850	1998.03.05 1998.05.05	700	1755	SINOTECH/UG

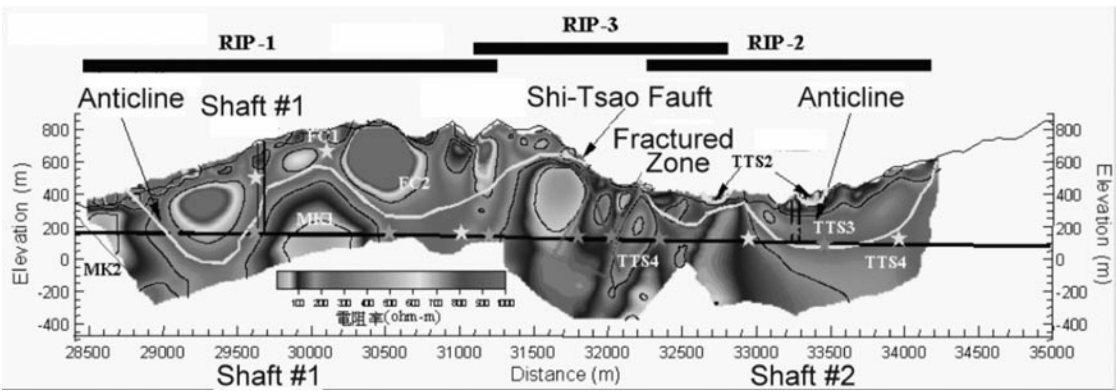


Fig. 14 RIP Measurements in Hsuehshan Tunnel

with the existence of ground water in rock masses.

CONCLUSIONS & RECOMMENDATIONS

Geological investigation during the Pilot Tunnel excavation was implemented inside the TBM shield and very limited geologic information could be obtained. This might have been one of the major reasons that caused the machine to stall several times. Also the major inferior geologic conditions, not only caused the TBM to stall for a significant time but also jeopardized the remedial efforts. The inferior geological conditions of the Pilot Tunnel were characterized by numerous water inflows and the highly broken rock mass of Szeleng Formation at the Eastern end. In general, during the construction stage, the existence of faults and sudden out-bursts of groundwater were the two major causes of the TBM stalling in the Pilot Tunnel excavation.

The advantage of using percussion drilling in the Pilot TBM was it helped to quickly identify inferior geologic conditions so that necessary actions to ensure the safety of the Pilot TBM could be taken. Experience showed that the performance of the drilling machine of the Pilot TBM, designed by Robbins, was not satisfactory in hard, broken rock like quartzite. In mixed ground condition, other exploratory geologic survey method must be adopted as a supplementary tool.

The geological interpretations, which were derived from the core-taking were much more reliable than those from percussion type drilling. The long distance horizontal drilling (LDHD) technique had been used

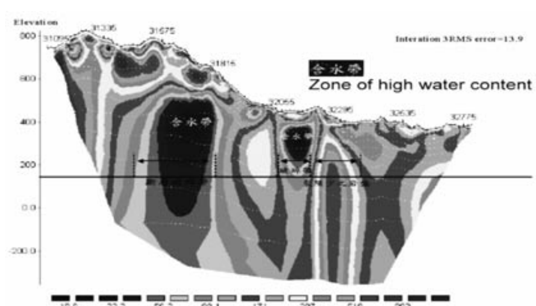


Fig. 15 RIP Measurement Near Shitsao Fault (RIP-3)

very often in recently years. It proved to be a very effective method when tunneling was suspended due to high water inflow or when adverse rock mass conditions were encountered. In a hydropower project in Central Taiwan, a pilot LDHD with a length of 901 m was bored and that became the new record for drilling distance. With the same crew and same machine, no comparable output could be obtained due to the ground condition in the Hsuehshan Tunnel being so different. The quartzite or quartzose sandstone in the Szeleng Formation contained a high percentage of quartz mineral and the intact rock material has an unconfined compressive strength higher than 300 MPa in some cases. Since the rock mass was so blocky the effective advance in rotary drilling was hindered. The high water inflow further deteriorated the situation and hence a lot of international drilling teams had to recognize their failure and abandon their operations. Nevertheless, this drilling technique was very good for constructing a geological scenario, evaluating high-pressure ground water conditions and effectively draining the ground water because of its large-size drilled holes.

Geophysical survey methods were introduced to the sections where drilling works were not applicable and geologic prediction ahead of tunnel was necessary. Like most geophysical survey methods, the domain of prediction is rather large but the reliability of the results is relatively low. Using the HSP or TSP, only large events in which major fault zones happen to be located ahead of the TBM can be identified with confidence. Resistivity image profiling (RIP) is regarded as a very effective tool in locating subsurface water concentration regimes. From the experiences in Hsuehshan Tunnel, it did not offer very accurate predictions, especially for the measurements near the Shi-tsao Fault. The reason is not clear but it shows that this survey technique still has its limitations especially in deep tunnels with complex lithologies. It has to be recognized that using geophysical survey methods in tunnels is still in an experimental stage at the moment and they should be adopted with caution. It is expected that more accurate and more efficient hardware and/or software survey methods will emerge in the future.

REFERENCES

* Sinotech Engineering Consultants, Inc. (1991), "Basic design phase evaluation report of geo-mechanical test and investigation, Pinglin-Touchen section, Taipei-Ilan Expressway."
* Sinotech Engineering Consultants, Ltd. (2004), "Final evaluation report of geologic investigations of Pilot Tunnel, Hsuehshan Tunnel."
* Chang, W.C. and Chang, L.C. (2004), "Case study : Syue-Shan tunnel construction under special geological conditions," Proceeding 2004 Cross-Strait Seminar on Ground Engineering, papers contributed from Taiwan, Taipei.