GEOLOGICAL EXPLORATION OF THE HSUEHSHAN TUNNEL － REVIEW AND DISCUSSION

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ABSTRACT

Located in a complex geological setting in the northern section of the Hsuehshan Range, the 12.9 km long Hsuehshan Tunnel was finally broken through in September 2004 after a stringent construction period of 14 years. The TBM got stuck in the pilot tunnel 13 times during the excavation and that led up to intense disputes over many issues, especially the degree of accuracy of the geological model of the area along the tunnel alignment. Geological explorations of the Hsuehshan Tunnel had been conducted since 1984 and had aimed to establish a rational geological model that would define the lithological and tectonic characteristics of the rock along the tunnel alignment and pinpoint the major adverse geological conditions as far as the tunneling was concerned. With the breakthrough of the pilot tunnel, an insight on the geology was obtained and compared to the predicted geological conditions. The comparison indicates that the geological model set up in the planning and design stages was basically correct with an accepted degree of accuracy.

Key words: Hsuehshan Tunnel, pilot tunnel, tectonics, Szeleng Sandstone, water inflow.

INTRODUCTION

Located in northeastern Taiwan, the 12.9 km long, 11.8 m bored diameter twin tube Hsuehshan Tunnel with a typical cross section of 109 m2 is the longest of the five tunnels of the Taipei-Ilan Expressway Project and is the fifth longest highway tunnel in the world. Due to the complicated geology along the tunnel route, a pilot tunnel of 4.8 m in diameter was designed between the twin tubes to provide further geological information for the construction of the main tunnels. The pilot tunnel, bored by the telescopic double shielded TBM from the east portal, commenced its excavation in the autumn of 1991 and was broken through in Oct. 2003. During tunnelling, the TBM in the pilot tunnel was trapped 13 times due to the highly sheared rocks or large water inflows or other nontechnical reasons, resulting in controversial issues regarding the suitability of the geology along the alignment. This paper, referring to the pilot tunnel, first reviews the explorations conducted during the planning and design stages, then follows with a general discussion on the comparison between the measured and predicted geological conditions, and adds some remarks on future explorations of deep-seated long tunnels.

EXPLORATION AND ASSESSMENT REVIEW

The geological explorations of the Hsuehshan Tunnel can be divided into 5 stages, namely the preliminary study, the feasibility study, the route selection stage, the design stage and the construction stage. In each stage, the geological investigation to reconstruct the lithostratigraphy, the tectonic structure and hydrogeology of the area involved continuous core drilling and RQD evaluations of the samples, SPT tests, seismic refractions and piezometric and permeability surveys. It also included remote sensing studies, aerial photograph interpretations, and numerous field investigations. Major issues discussed and findings obtained are summarized as follows：

1. Tectonic Setting

The Hsuehshan Tunnels are located in the northern section of the Hsuehshan Range, which is composed of a folded Tertiary sedimentary rock sequences and belongs to the fold and thrust belt of the Orogenic Belt. During

This Pliocene-Pleistocene orogeny, regional folding

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and thrusting developed running roughly parallel to themountain range and trending in a NEE-SWW direction. Aside from the folding and thrusting, some strike-slip faulting and normal faulting also resulted from the orogenic processes. According to the study, prior to the orogeny in the late Pliocene Period, the Island of Taiwan was situated in a passive continental margin and normal faults occurred during sedimentation. After the orogeny, a back-arc basin was formed in the offshore area of Ilan County in northeastern Taiwan, where the eastern portion of the tunnels is located. The back-arc basin, now called the Okinawa Trench, is still active and can account for the occurrence of the normal faults in this area.

2. Remote Sensing Study

Remote sensing was performed in the early stage of the basic design stage, using the images from the Landsat Thematic Mapper, panchromatic SPOT images and SLAR (Side Looking Airborne Radar) and aerial photos. The remote sensing study was supposed to assist in identifying the adverse geological conditions along the tunnel alignment based on lineaments, drainage systems, landslides etc. Major conclusions from the remote sensing study indicated that there were several prominent lineaments identified in the vicinity of the tunnel alignment. These lineaments are, however, not consistent with any of the known fault zones. Field checks indicated that the lineament at the southeast of the eastern portal of the tunnel, for example, seemed to run along the ridge and parallel to the trend of the Okinawa Trench and did not comply with the general structural trend. Also no known faults seemed to be in line with the identified lineaments and the most prominent lineaments were not consistent with any fault traces.

3. Field Mapping and Subsurface Exploration

Field mapping was carried out to observe, examine and record the following items:

(1) The attitude of the bedding planes, joint planes and other discontinuities of the outcrops along the tunnel.

(2) The different lithological units

(3) The lithological boundaries and distributions

(4) The area affected, its characteristics, and the extent and attributes of the faults and shear zones.

(5) The major structures such as anticlines, synclines, and faults with different attributes etc.

(6) Water seepage, landslides, or other abnormal symptoms that might give rise to potential geological hazards.

Rock cores from the drilling were carefully examined, photographed and recorded by experienced geologists. In order not to confuse the fault gouge with the material disturbed by the drilling, all the drilling logs were made with the help of detailed operational data. Seismic refractory surveys were performed along almost the whole tunnel alignment. A thorough study and interpretation of the seismic study report by experienced geologists was made to relate the seismic velocity to the geology. Moreover, the identified fault structures were further verified by air photo examination. Some critical locations were selected to perform trench excavations to further confirm the width, attitude, degree of activity and other related attributes. Table 1 shows the geological exploration along the Hsuehshan Tunnel. Together with the surface mapping, borehole drilling and refractory seismic surveys, the geological model was developed.

4. Geological Model

The Hsuehshan tunnel is located in rocks belonging to the Hsuehshan Range which is a sub province of the Central Range Geological Province. These rock formations are slightly metamorphosed Tertiary sedimentary rocks that have been folded and faulted, and belong to the thrust-and-fold belt. The maximum cap rock cover is in excess of 700 m along the tunnel. The rock formations penetrated by the tunnel are in an east to west direction: the Kankou Formation, the Szeleng Sandstone Formation, the Kankou Formation, the Tatungshan Formation, the Makang Formation, and the Fangchiao Formation.

Past studies indicated that these rock formations were folded and thrust faulted during the Pliocene orogeny. The trends of these folded structures and faults mostly strike parallel to the axes of the mountain ranges in a NEE-SWW direction. Besides folds and thrust faults, this orogenic activity also produced the normal faults and the transverse faults that cut across the strikes of these rock formations. The tunnel is located in this zone of active geological configurations, and the geological conditions along the alignment of the tunnel are very complicated. The tunnel is known to pass through six regional faults. In an east to west order of occurrence, they are: the Chingyin

Table 1 GEOLOGICAL EXPLORATION ALONG THE HSUEHSHAN TUNNEL

STAGE ITEM		PRELIMINARY/ FEASIBILITY STUDY (1984~1988)	ROUTE SELECTION STAGE (1989~1990)	BASIC DESIGN STAGE (1990~1991)	DETAILED DESIGN STAGE (1992~1994)	CONSTRUCTION STAGE (1991~2004)	TOTAL
FIELD MAPPING		✓	✓	✓	✓	✓	
REMOTE SENSING AND INTERPRETATION			✓	✓			
BOREHOLES	HOLE	16	15	38	15	7	91
	m	1144.5	1036.6	2607.0	859.0	1320.0	6967.1
REFRACTORY SEISMIC	LINE	4	9	1		2	16
	m	1150.0	12190.0	13110.0		2000.0	28450.0
RIP	LINE					1	1
	m					1500.0	1500.0
TRENCH	SET			7			7
	m3			2099.3			2099.3
ADIT	SET			1			1
	m			150.0			150.0

Fault, the Shanghsin Fault, the Paling Fault, the northern and southern branches of the Shihpai Fault, and the Shihtsao Fault.

About one quarter of the tunnel at the eastern end passes through mainly argillite and quartz sandstone (Szeleng sandstone). In this section, due to the dense occurrence of faults, the rockmasses are intensely fractured. In the western three quarters of the tunnel, the main lithologies comprise sandstone, shale and the alternation of sandstone and shale. The rockmasses in this western section are better in quality.

Szeleng Sandstone is mainly comprised of light gray to white quartz sandstone with occasional intercalations of dark gray, fine to medium-grained sandstone and carbonaceous shale that varies in thickness from several centimeters to tens of centimeters. Typical sandstone in the Szeleng Sandstone Formation is known as quartzite, it is coarse to medium-grained, containing feldspar, and well cemented. The feldspar turns to clay upon weathering, and the rock becomes loose. Rocks belonging to the Szeleng Sandstone Formation are mainly distributed on the eastern part of the Hsuehshan Tunnel, from approximately sta. 36k+400 heading east. Quartz sandstone of the Szeleng Sandstone Formation is hard, brittle and abrasive, when subjected to tectonic compression and faulting, the rock became well fractured with numerous fissures, and the rockmass became a good groundwater reservoir. Investigation indicated that the groundwater in this area is mainly in the fracture zones or held behind shear zones. This bountiful groundwater thus became a crucial obstacle to be overcome in the TBM excavation of the Szeleng Sandstone section.

Based on the geological, geomechanical and hydrogeological information and predictions made using simple empirical analyses, the rockmass quality along the tunnel alignment was divided into 6 homogeneous sections, as shown in Fig 1.

5.Geological Concerns During the Design Stage

As stated earlier, the 13 times the TBM got stuck in the pilot tunnel caused arguments over whether the difficult ground conditions were foreseen or not prior to tunnelling. As a matter of fact, the major geologically adverse conditions and related issues were identified early in the route selection stage and had been discussed with famous international TBM experts. The geotechnical conditions of particular concern at the Hsuehshan Tunnel site, as described in the final report of the Geological Investigation for Hsuehshan Tunnel (May 1990), were as follows:

(1) High water inflow

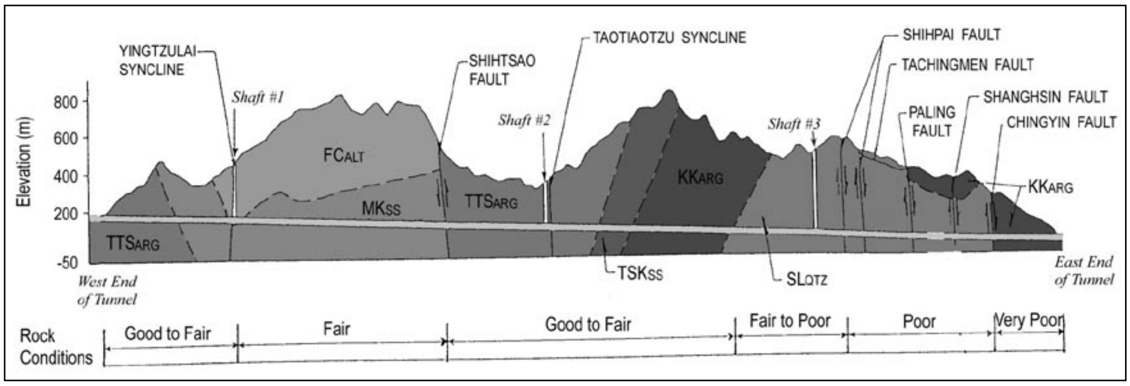

Figure 1 Geological Profile along the Hsuehshan Tunnel (After Basic Design Report, 1991)

(2) Water inflow from behind the fault zone water dams with the potential of large amounts of gouge material inflow.

(3) Hard rock (Szeleng quartzitic sandstone)

(4) Squeezing or swelling material in fault zones

(5) Conditions which would cause the TBM to get stuck

In response to those concerns, the international experts commented as follows:

(1) Water inflows have been successfully negotiated by TBMs when appropriately designed for encountering water. There are numerous case histories to support this.

(2) Fault zones containing clay often act as aquicludes and behave as water dams, which when penetrated release large amounts of water in combination with rock altered to soil. Such sudden releases can cause local failure and collapse of the tunnel. Tunnels have been excavated successfully through this type of condition in several tunnels with TBMs. Examples of such tunnels are the Tunel de los Rosales in Colmbia excavated by a shielded TBM using pre-cast segments, the Nast Tunnel by an unshielded TBM, and several other tunnels with similar inflows of water and unconsolidated material.

(3) When known fault zones are anticipated, drilling probes can locate and pre-drain them. For the more, the full face and shielded support of a TBM can effectively minimize the impact of such adverse conditions and allow safe and stable traversing of these fault zones.

(4) The Szeleng sandstone may be one of the hardest rocks in Taiwan, however, in comparison to hard rock (3000-4000kg/cm2) that has been bored successfully elsewhere in the world, it cannot be considered too difficult for mechanical boring. Since it is hard and compact, abrasion of the cutting disks is of no concern.

Many of the reports mentioned that the best way to overcome all of the concerns, considerations and skepticism, was to do probing drilling ahead of the tunnel face and to drive a small diameter pilot tunnel prior to excavation of the main tunnels.

DISCUSSION

With the breakthrough of the Hsuehshan pilot tunnel, an insight on the geological conditions along the tunnel was obtained, and a rough comparison between the actual and predicted ground conditions could be made in terms of lithology, structure, rock class and water inflow. Fig 2 is the actual geological condition recorded during tunnelling.

1. Lithology

With the surface and subsurface exploration during the planning and design stages, it was fully understood that the tunnel was going to penetrate the abrasive Szeleng quartz sandstone and the indurated Kankou argillite in the eastern part, the Oligocene Tatungshan Formation in the middle and the Miocene sedimentary rocks of the Makang and the Fangchiao Formations in the west. According to the excavation records, the distribution of the lithological units along the tunnel is roughly similar to that predicted. It is worthwhile to mention there was a dispute over the extent of the Szeleng sandstone and the contact behavior of the quarzitic sandstone/argillite along the tunnel

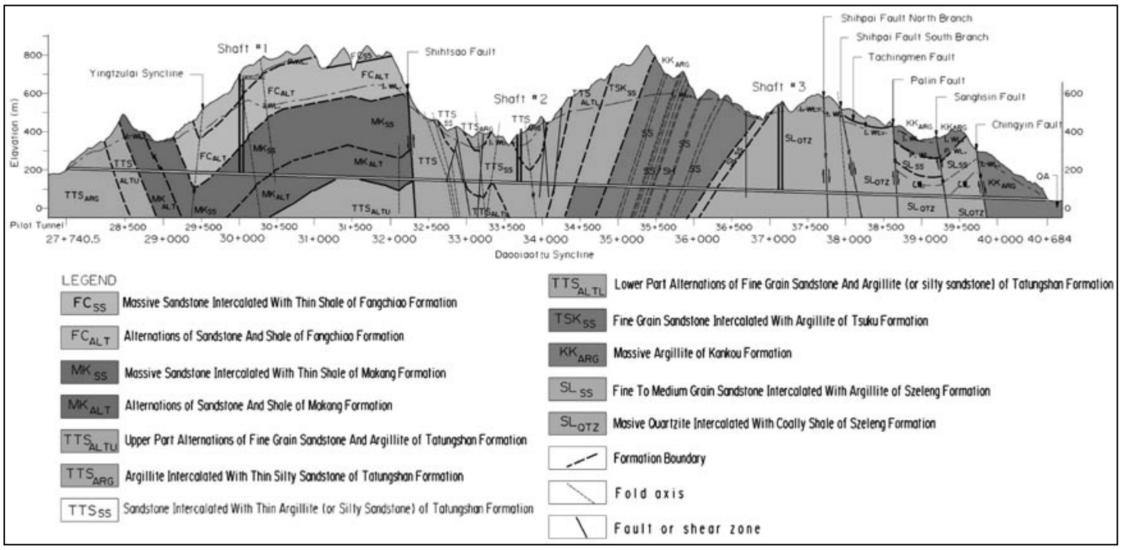

Figure 2 Measured Geological Profile along the Hsuehshan Tunnel

Table 2 COMPARISON OF THE MEASURED AND THE PREDICTED LOCATIONS OF MAJOR FAULT SYSTEMS ALONG THE PILOT TUNNEL

MAJOR STURCTURE		LOCATIOIN	FAULT WIDTH (m)	WIDTH OF DISTURBANCE ZONE (m)	ATTITUDE
SHIHTSAO FAULT	PREDICTED	33+250	10		N90E/80S
	MEASURED	33+260	20	40	N74E/80S
SHIHPAI FLULT	PREDICTED	37+750	20- 30		N75E/80S
	MEASURED	37+756	16	28	N80W/80S
SHIHPAI FAULT-SOUTH BRANCH	PREDICTED	37+900	10- 20		N47E/80S
	MEASURED	38+150	8	14	N25E/77S
PALING FAULT	PREDICTED	38+650	30		N40-70E/80S
	MEASURED	38+680	6	20	N85E/78S
SHANGHSIN FLULT	PREDICTED	39+250	10		N60E/80S
	MEASURED	39+316	6	5	N50E/50S
CHINGYIN FAULT	PREDICTED	39+700	20		N30E/70S
	MEASURED	39+816	7	11	N20E/70S
EXTENT OF SZELENG SANDSTONE	PREDICTED	36+400 ~ 39+650			
	MEASURED	36+145 ~ 39+816			

alignment at a depth of 250 m. It was one of the major concerns for the tunnelling advance rate due to its high strength and abrasiveness. The Szeleng sandstone was originally estimated to be 3250 m long along the alignment. In 1999 when the 6th board meeting was held, questions about the contact between the Szeleng sandstone and the Kankou argillite being a tremendous sheared zone were raised. It was feared that the poor and highly sheared rockmass in the contact zone might cause serious tunnelling problems. Additional explorations with deep drilling and seismic studies were then carried out in 1999 to confirm the quality of the contact and the extent of the Szeleng sandstone at the tunnel horizon. From the additional explorations, it was confirmed that the Kankou argillite was conformably overlying the Szeleng sandstone with a very minor sheared clay

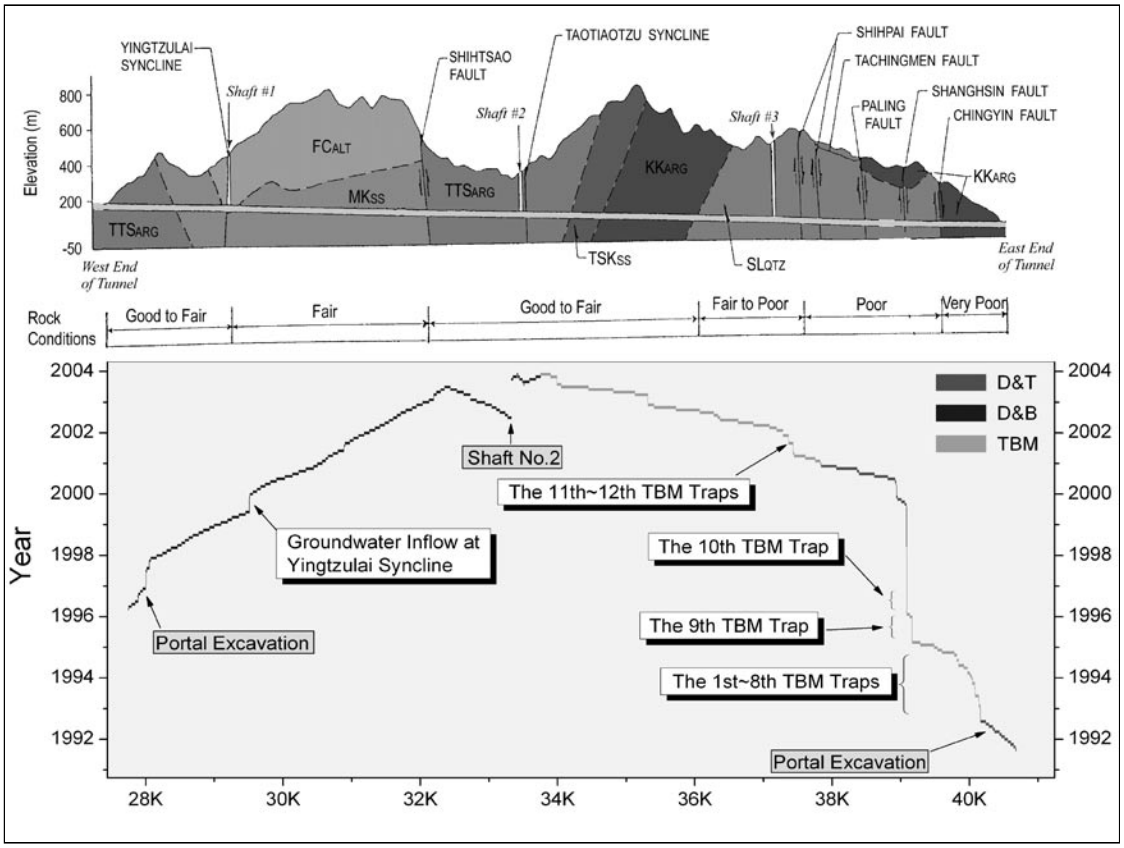

Figure 3 Pilot Tunnel Progress v.s. Predicted Rock Quality

material along the contact. The rock in the vicinity of the contact was intact as predicted. The additional exploration further revealed the extent of the Szeleng sandstone to be 3836m. The actual recorded in the pilot tunnel regarding the contact zone indicated that the rocks were sound and intact as predicted and the length of the Szeleng sandstone is 3671 m. The variation was mainly due to the change of the attitude of the contact. It was considered that supplementary exploration during construction, either from the surface or from the excavation face, is sometimes inevitably needed to clarify some geological skepticism, especially for those conditions that might highly affect the tunnelling advancement or safety.

2. Structure

During the design stage, it was indicated that there were six major faults and two regional fold structures expected to be encountered along the tunnel, aside from numerous small scale shear zones. Of the seven major faults, six are congested within the eastern 3 km of the entrance of the tunnel, resulting in extremely poor rock conditions, especially in the Szeleng Sandstone. Actual excavation data indicated that the major structures along the tunnel alignment were similar to what had been estimated during design stage. Table 2 shows the comparison of the locations of the actual and predicted major structures along the tunnel alignment. It must be pointed out, however, that there were still some blind spots, which were hardly detectable from the surface beforehand. The blind spots like those that exist between the major fault zones can only be precisely defined by probing during construction. Probing, either with long horizontal drilling or geological pilot tunnelling, is a must for a long and deep seated tunnel projects in an area with such a complicated tectonic environment as Taiwan.

3. Rock Class

In the geological exploration of the design stage, the rock along the tunnel was divided into 6 geologically homogeneous sections based on surface and subsurface exploration as shown in Fig 1. The rock east of the Chingyin Fault is mainly highly sheared argillite with perched water stored in the rock, as revealed from the 150 m long exploration adit on the portal area. The rock was classified as extremely poor as far as tunnelling was concerned. From the Chingyin Fault to the contact point of the Szeleng sandstone / Kankou argillite, the rock is mainly fragmented Szeleng sandstone, which is hard, brittle and abrasive, as revealed by many boreholes and lab tests. The rock quality is rated as poor, but when approaching the contact point with the Kankou argillite (36k+400), the rock gradually became fair. From there up to the west portal, the rock quality became better and better, and was classified as fair to good. Fig 3 shows the progress of the pilot tunnel as compared to the predicted rock quality. The rock quality became better and better heading west, as estimated, and provided the basis to expedite the excavation rate after the tunnel passed through the Szeleng sandstone.

4. Groundwater

From the deep bore drilling along the tunnel, it was observed that some groundwater tables might fluctuate drastically indicating a pressurized water body was impeded behind the clay material. Due to this phenomenon, it was believed and concluded in the exploration report that high water inflow might be expected when tunnelling. With the pack test data obtained during drilling, the groundwater inflow was estimated using the empirical formula developed by Goodman et al (1965). Based on the analysis, the total amount of groundwater inflow into the 12.9 km long tunnel would be about 180,000 l/min or 3 cms (TANEEB, 2000). It was considered in the design report that when a water bearing zone was be encountered, the inflow could increase significantly for a few days before gradually decreasing until the flow reached a new stable condition.

During construction, high pressure groundwater impeded by the sheared zones was encountered so frequently that supplementary investigations were performed from 1997 to 2000 to further understand the nature of the groundwater inflow along the Hsuehshan Tunnel. The studies established a correlation between the monthly average water flow of selected survey points and the precipitation of the corresponding catchment areas. The studies also divided the tunnel into three different hydrogeological conceptual models with different water inflow potentials. Based on the excavation records of the pilot tunnel and the water inflows encountered, the groundwater impeded behind the high-angle impervious faults and the sheared materials formed groundwater reservoirs of various scales in the fragmented zones. Furthermore, the bedding seams developed along the low angle bedding planes constituted horizontal impervious boundaries, while the high angle sheared zones constituted vertical impervious boundaries, and together, both formed a lattice type of groundwater storage. An Isotope study of the groundwater indicated the water inflow of the Hsuehshan Tunnel might have some impact on the deep-seated groundwater, but seemed to have less impact on the shallow groundwater, based on the fluctuation of the water tables in the deep and shallow boreholes along the tunnel alignment.

CONCLUDING REMARKS

1. Due to topographic inaccessibility and exploration technique constraints, the geological exploration of deep seated long tunnels can only be limited to certain areas and with the data thus obtained it is possible to develop a rational model of the tunnel alignment. In an area with geological conditions so complicated as Taiwan, it is extremely difficult to have the predicted geological conditions be a perfect match with the actual conditions encountered. For the Hsuehshan Tunnel, the comparison between the actual ground conditions and the predicted conditions indicated that there was a high degree of accuracy in terms of lithology, tectonics, rockmass quality and areas where potentially difficult geology might be encountered. This implies that the engineering geological assessment proposed in the planning and design stages of the Hsuehshan Tunnel was acceptable in terms of alleviating the possibilities of encountering geological surprises during tunnelling.
2. There are many factors that account for a successful tunnelling work. Among them, the accuracy of the geological assessment, the adequacy of the equipment, the methodology adopted for tunnelling, and the experience and the capability of the crew to cope with geological and mechanical surprises are the key factors. Cases around the world indicate that construction delays are mainly due to tunnelling in difficult ground. But this is definitely not related to the accuracy of the geological assessment. In anticipated but difficult ground conditions, successful tunnelling mainly relies on construction management, adequacy of the equipment adopted,

and the flexibility of the method adopted to cope with the adverse ground conditions.

3. Though the degree of accuracy of the geological model is proven to be acceptable based on the actual ground conditions during excavation, there were still some blind spots, which were not able to be detected from the surface beforehand. The blind spots, like those existing between the major fault zones, could only have been precisely defined by probing during construction. Probing, either with long horizontal drilling or geological pilot tunnel heading, is a must for a long and deep seated tunnel project in an area with such a complicated tectonic environment as Taiwan.
4. The purpose of a pilot tunnel is to record the detailed geology along the excavated section of the tunnel, including many of the previously unknown shear zones. However, limited by the TBM shield and the erecting of segments, geological observation in Hsuehshan Tunnel could only be conducted in a constrained space either behind the shield end or where segment erection allowed. Geological evaluation, consequently, suffered in precision in this instance. For this reason, advance probing by any means was a key issue in this engineering project.
5. Since geological conditions are not the only factors to be considered in tunnel planning, unfavorable geological conditions cannot always be avoided. However, we still have to say that route selection is a key task in the beginning for any long tunnel project and should be a geologically-oriented work. In addition, when following the mechanized tunnelling trend, we need more versatile measures to get geological information ahead of TBM along the alignment, more knowledge on rock TBMs, more experience on TBM construction, and more flexibility on contracts in future TBM projects in Taiwan.

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