GEOLOGICAL AND GEOTECHNICAL OVERVIEW OF THE HSUEHSHAN TUNNEL

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ABSTRACT

Various geological investigations in preliminary study, basic design and detail design stages had revealed that there are highly fractured rocks due to intense faulting activities at the eastern part of the Hsuehshan Tunnel and there are favorable rock conditions on the most of its western part of alignment. For the purpose of providing the detail ground conditions on the tunnel horizon, a pilot tunnel that runs between and parallel with the main tunnel was proposed. Comparing the recorded cross geological profile from pilot tunnel with the geological framework in the planning and design stages, the two geological models are found to be very close.

Keyword: Hsuehshan Tunnel, Normal fault, Seismic exploration, Hydrofracturing, Groundwater Water inflow.

INTRODUCTION

The Hsuehshan Tunnel is a twin-tube two-direction expressway tunnel with 12.9 km in length. It cuts through the northern half of the Hsuehshan Range. Besides the two main tunnel tubes a pilot tunnel located a little below the main tunnel tubes is also designed. The main purposes of the pilot tunnel, are to serve as geological investigation in order to understand more geological conditions along the alignment of the tunnel, to provide accesses during tunnel construction, to perform emergent ground treatment or grouting when needed and to pre-drain the ground before excavation. The diameter of the main tunnel tubes is 11.8 m and that of the pilot tunnel is 4.8 m. Except the portal sections that were constructed through conventional drill-and-blast, in both the pilot tunnel and the main tunnel TBM was used. Construction of the pilot tunnel and the main tunnel were commenced in 1991 and 1993 respectively. Since then, due to the adverse geological conditions and the presence of tremendous quantity of groundwater, great difficulty was encountered during tunnel constructions, and the construction schedule lagged far behind.

Situated at the plate collision suture zone, Taiwan is marked with extreme topographic relieves and highly variable geological conditions. A long tunnel running under high overburden like Hsuehshan Tunnel, a vague geological picture at the tunnel alignment is not beyond expectation, even though geological investigation had been performed first. Nevertheless, the information from the geological investigations performed under various scales in various stages were proved to be with crucial importance in the construction of the Hsuehshan Tunnel. The validity of the geological information was verified when the tunnel penetrated through the indicated rock strata. This paper briefly overviews the results and methodologies for the various geological and geotechnical investigations in the design and construction stages.

GEOLOGY OF THE HSUEHSHAN RANGE

The Hsuehshan Tunnel cutting through the Hsuehshan Range geological subprovince, which situated on the western wing of the Central Mountain Range is one of the most complicated geological areas of the island. Rock formations in the Hsuehshan Range comprise folded Tertiary sedimentary sequence, and belong to the fold-and- thrust belt in the active orogenic belt. Most geological structures are regional folds and thrust faults whose strikes are generally in NEE-SWW direction. Normal faults, however, were also formed locally as result of later tectonic activities.

Following the major phase of orogenic movement, back-arc basin spreading occurred in the sea outside of Ilan. This on-going spreading of the back-arc basin

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resulted in normal faulting in areas in the immediate vicinity of Ilan. The Hsuehshan Tunnel is located right in the centre of these geologic complexities.

The earliest available geological information on the northern half of the Hsuehshan Range was contained in the 1:50,000-scale "Geologic Map Sheet and Explanatory Text of the Hsintien Area" by the Japanese geologist Ichikawa, 1932. Names of the major geological features appearing on this map sheet are still in use at present. These names include: the Szeleng Sandstone, the Kankou Formation, the Tsuku Sandstone, the Tatungshan Formation, the Yingtzulai Syncline, the Taotiaotzu Syncline and the Shihtsao Fault. Based on this foundation, later contributions to the geology of the area included topics on structural geology, historical geology, stratigraphy and sedimentology from the Chinese Petroleum Corporation and academic studies. When the Central Geological Survey, Ministry of Economic Affairs, published the 1:50,000 "Geologic map sheet of the Toucheng Area" in 1989, the geologic framework of the project area had been quite well established. In geological investigation for the Hsuehshan Tunnel Project, the geological model and framework of the project area followed these publicly accepted results. Detailed information on geologic structures, distribution of rock formations, the rock mechanical properties as well as hydrogeological behaviours were all recorded and presented during the each study stage for use as reference in engineering design and construction operation.

GEOLOGIC INVESTIGATIONS FOR THE VARIOUS STUDY STAGES

Geological investigations of various scales were conducted during the various stages. Through results of these investigations the basic geologic models along the tunnel alignment were established. Also based on the results, cross section and rock mass quality classifications were established. A brief description on these geological investigations is presented in the following:

1. Geological Evaluation Stage (1982-1984)

Feasibility study on construction of a high-speed highway between Taipei and Ilan commenced in 1982. In 1982 the Taiwan Provincial Bureau of Highways completed a report on "Feasibility Study on Construction of a Tunnel

Table 1 Summary of Geological Exploration Along Hsuehshan Tunnel

Item \ Stage		Preliminary/ Feasibility study (1984~1988)	Route selection stage (1989~1990)	Basic design stage (1990~1991)	Detail design state (1992~1994)	Construction (1991~2004)	Subtotal
Field Mapping		V	V	V	V	V	
Remote Sensing and Airphoto Interpretation			V	V			
Boreholes	hole	16	15	30	15	7	91
	m	1144.5	1036.6	2246.0	859.0	1320.0	6606.1
Refraction 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

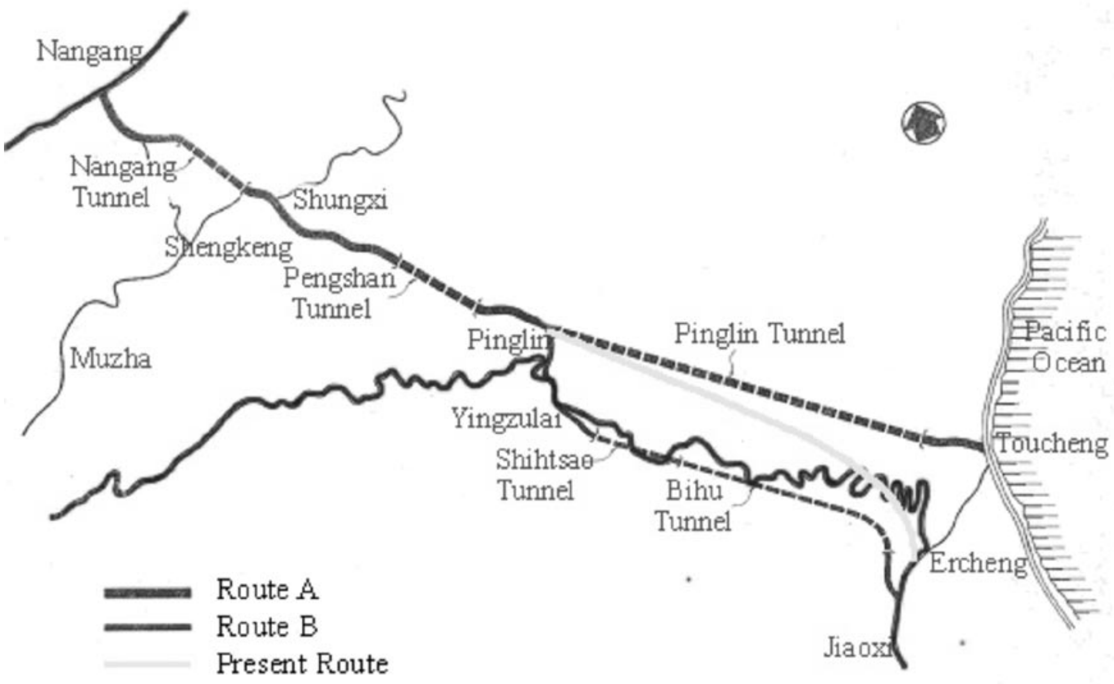

Figure1 The Candidate Route from Nankang-Toucheng in Year of 1984

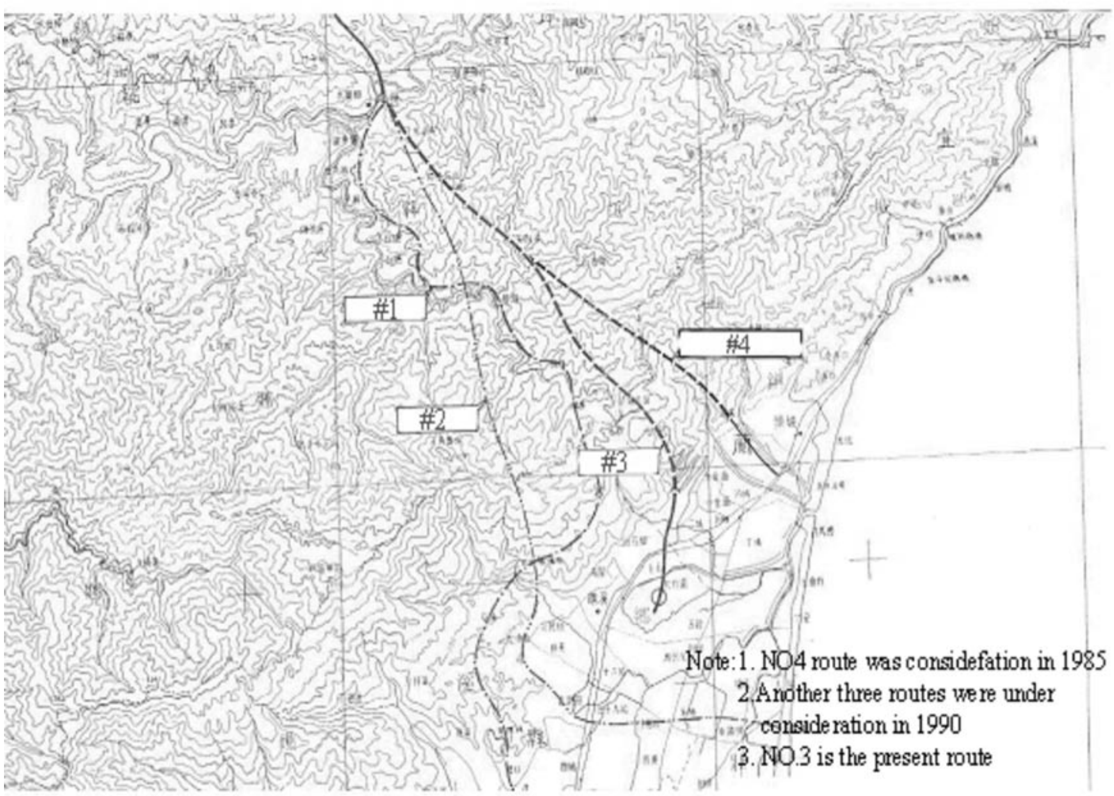

Figure2 Candidate Routes of Hsuehshan Tunnel

Highway between Nankang and Toucheng". In this report two route alignments were proposed (see Figure 1 for details).

To appraise whether the proposed route alignments are feasible, the Taiwan Provincial Bureau of Highways entrusted consulting firms to conduct a geological evaluation of these two routes in 1984. A report entitled "Geological Evaluation Report on a Tunnel Highway between Nankang and Toucheng" was completed. This report presented evaluation on the geological conditions along the proposed routes and proposed initial engineering layouts. Geological investigation works conducted during this stage are presented in Table 1.

At time of preparation of the report this route was designed as an ordinary highway. The alignment of the proposed route managed to avoid the Chinying and the Shanghsin Faults by passing through the northern side of the fractured Szeleng Sandstone. The eastern portal of the Hsuehshan Tunnel was located proximal to the town of Toucheng at a spot some 3 km from the present portal. The proposed route was shelved when the highway was up-graded to an expressway.

2. Feasibility Study Stage (1987-1988)

The Institute of Transportation, Ministry of Transportation and Communications, conducted feasibility study on a highway between Taipei and Ilan. In 1987, the American consulting firm De Leuw Cather was entrusted to conduct the feasibility study, but there was no additional geological investigation except reviewing the existing geomorphologic and geological information. During the feasibility study three route alignments were proposed (Figure 2). All three routes were planned with standards of an expressway. Evaluation performed during this study stage following criteria on engineering technique, environmental impact, and economic effects indicated that route No.2 should be the one to be selected. However, the difference between routes No.1 and No.3 was very insignificant.

3. Route Selection Stage (1989-1990)

In 1989, the Taiwan Area Expressway Engineering Bureau (TANEEB) became the supervisory authority over planning and construction of the Taipei-Ilan Expressway. In this stage, De Leuw Cather was entrusted to conduct route evaluation study and Sinotech Engineering Ltd. to conduct additional geological investigation on various routes of the Hsuehshan Tunnel. Items of geological investigation included urface geological mapping, subsurface exploration through boreholes, geophysical surveys and remote sensing and air photo interpretation. Results of these investigations had furnished information in route selection. Table 1 presents contents of these investigations.

Results of field geological investigations and information from drilling indicated that the geological conditions of the western portal area are good. Rock mass quality for 3/4 length of the western part of the tunnel alignment falls between fair and good; rock mass quality for the remaining 1/4 length of the tunnel on the eastern part is poor. Among these, area of around 1 km in the vicinity of the eastern portal is fractured, loose rock mass. Judging from the regional geological and structural geological models, this fractured, loose rock mass persists in the mountainside area between Chiaochi and Toucheng, none of the routes can avoid traversing this poor rock mass. The geological conditions of the concentrated occurrence of faults on the eastern half of the tunnel alignment as well as the shear and fracture zones could be unravelled in fine details through an exploratory pilot tunnel excavated between the two main tunnels. Information collected from this exploratory pilot tunnel would serve as reference in design and construction of the main tunnels.

With due consideration on Toucheng as tunnel exiting town, preliminary candidate routes No.3 and No.3 revised, No.3A, and No.3B were proposed. These routes were evaluated based on engineering contents, costs, topography, geologic structures, number of faults crossed, distance to landslide area, thermal spring and geothermal area, traffic safety, and glare at portal etc. Route 3A was selected following evaluation and became the route under construction. Tunnelling with TBM was carefully assessed in this stage in response to the ground condition along the tunnel horizon.

4. Basic Design Stage (1990-1991)

During basic design stage, remote sensing analysis and air photo interpretation was performed, this was aimed at providing topics and issues for field investigation to establish a geological model for the project area. Also, refraction seismic survey was conducted along the entire length of the selected tunnel alignment. For geological investigation, field investigation was supplemented with borehole exploration. The geologic conditions at the portals, along the tunnel alignments as well as the locations and the characteristics of faults were also investigated in detail. Survey was made on abandoned coalmine shafts and waste tips. Exploration through trenching and adits were conducted to pinpoint locations of faults. Through boreholes in-situ stresses and down-hole deformation were measured. Core samples were tested in the laboratory for rock mechanical strengths as well as other relevant tests to get rock mechanical parameters required in designs.

Investigation results indicated that there is a great abundance of groundwater in the project area. Tunnel construction may encounter difficulty of groundwater seepage especially when penetrates through fault gouges and fractured Szeleng Sandstone. Thus, it was warned that precarious groundwater should be paid attention during construction. On the eastern half, tunnel alignment passes through gently dipping rock formations of the Szeleng Sandstone. Gas emission from the carbonaceous argillites and possible failure due to shear gouges in the shear zones should be care. It was recommended that since the geological conditions at eastern half of the tunnel is rather inferior, detailed record on geological features during excavation should be made so as to provide reference in detailed design. On certain sections, overburden is as high as 750 m resulting in load of 200 kg/cm2, that special attention should be rendered to supporting at these locations.

5. Detailed Design Stage (1992-1993)

During detailed design stage a review of the geological information from the previous stages was made, and supplementary geological investigation was conducted where required. The supplementary geological investigation was mainly on realizing the characteristics of the fault zones. In addition, subsurface exploration through boreholes were performed at foundations of important structures and bridge abutments, coalmine pits, known landslides, indistinct fault locations, portals of tunnels, cut-slopes and waste disposal sites. During basic design stage drilling records showed that the site for vertical ventilation shaft No. 3 was not suitable, a new borehole (PH-29-1) was made slightly east of the original site. The new borehole record showed that although the rock formations were locally poor, however, at tunnel level the rock mass was rather good as a vertical shaft location.

6. Supplementary Geological Investigation During Construction (1991-2003)

(1) Investigation during pilot tunnel construction

As safety measures, during construction of the pilot tunnel various advance geological probing investigations were persistently performed, these included HSP and TSP seismic surveys. Initially, horizontal seismic profiling (HSP) was conducted and 5 profiling with total surveyed length of 1065 m were completed. Later, the higher resolution tunnel seismic profiling technique (TSP) was adapted, and 27 surveys totalling 4,115.2 m were completed in the pilot tunnel. In the main tunnel 9 TSP surveys totalling 1037 m were conducted. Horizontal boreholes of reverse circulation coring were 229.95 m and wire line coring were 1330.45 m, thus the total length was 1560.4 m. The length of investigation through boring in TBM and drill-and-blast sections was 5661.6 m.

(2) Investigation for Groundwater Influx Evaluation

Works for this investigation included in-situ field reconnaissance survey and collection of relevant information, data processing and analysis, flow discharge monitoring and analysis, supplementary deep boring for hydrogeological investigation (1 deep hole to 300 m), groundwater table observation monitoring and analysis, radioactive isotopic dating and analysis (C14 and H3), research and study of hydrogeological parameters for fractured rock mass (groundwater influx zone) and estimation of groundwater influx, establishment of a conceptual groundwater model, analysis on hydrogeological conditions during tunnel construction and evaluation on possible effects of tunnel groundwater influx on water resources.

The result of regional hydrological investigation is the regression relation between the mean monthly discharge for each flow monitoring station and the monthly precipitation for the corresponding catchment area. The tunnel alignment was longitudinally divided into three areas; while on the vertical direction it was divided into shallow-seated and deep-seated groundwater, a conceptual term "drawer box" was proposed as hydrogeologic model. The above concept was manifested from groundwater monitoring result, isotopic dating of groundwater and dynamic analysis on groundwater influx. In addition, groundwater influx simulation and hydraulic parameter analysis revealed that permeability coefficient for the fractured Szeleng Sandstone were seemingly steady (ca. 3.0x10-4m/s), and when a fracture zone over several meters in width is encountered in the future, the groundwater influx could be expected to exceed 100 l/s.

(3) Supplementary Geological Investigation Recommended In 6th Consulting Board Meeting

The 6th Consulting Board Meeting recommended that the characteristics of the Shihtsao Fault and the characteristics of the boundary between the hard Szeleng Sandstone and the soft Kankou Formation argillite should be verified through surface geological investigation, seismic refraction survey, ground resistivity imagery profiling and deep borehole drilling.

Two seismic line totalling 2,000 m were surveyed, and 1,710 m of resistivity imagery profiling were performed. The results indicated that the fault fractured zone for the Shihtsao Fault varied from 40 to 70 m with intercalated clay gouge 0.5 to 1.3 m in thickness. Tunnel excavation would encounter fractured rock mass estimated to be 230 m wide. It was also estimated that south of the fault zone was a concentrated fold zone. There were minor folds at the fold axis and minor fault fractures. The boundary between the Szeleng and Kankou Formations inclined at 22o, tunnel excavation would come across longer than expected Szeleng Sandstone rocks, the hard quartzite would extend for an additional 500-529 m toward the west. At the boundary there existed a fracture zone about 20-30 m wide.

(4) Consulting Board Meeting

The Hsuehshan Tunnel can be regarded as the most well-known, most focus-drawing engineering project in Taiwan. During design and planning stages as well as during construction a good number of experts and scholars, domestic and foreign, were invited to participate to contribute and assist through their field of specialization. On record, experts, scholars and consultants came from USA, Japan, South Africa, Italy, Switzerland, Germany, Austria, Korea, Russia and People's Republic of China, their number totalled over 40 man-trips. During construction of the Hsuehshan Tunnel, to ensure proper and timely resolving of difficulties encountered, consulting board meetings were called, the number of such board meeting of tunnelling experts totalled 8.

MAJOR INVESTIGATION WORKS AND RESULTS

Among the various investigations, some of the major works are highlighted as follow：

1. Deep Borehole Drilling

There are three ventilation shafts along the Hsuehshan Tunnel, overburden at these ventilation shafts were as high as 270-460 m. Among them, the shaft No.3 is then the deepest and needed to be explored by deep boring urgently. In Taiwan due to limitations imposed by requirement and equipment, the deep borehole seldom exceeded 200 m. Deep borehole PH-29 for vertical shaft No. 3 encountered poor geological conditions, the underlying rock mass was intensely fractured, hard and abrasive. The local drilling company failed to complete the tough task. This pointed to future difficulty in vertical shaft excavation. A new borehole PH29-1, 490m deep, was then re-sited. The contract was awarded to the Japanese contractor New Dowa Engineering Consultant Co. The borehole was drilled with a 24-hour non-stop schedule. It was finished in 102 days and the depth reached 496 m. The net boring rate amounted to 25-30 m per 24-hour shift (see Table 2&3 for details). urthermore, this operation achieved a recovery rate of 90% as stipulated in the contract criteria. The reasons for the success were mainly due to the Japanese contractor's excellent professionalism and management.

There was very little deep borehole drilling experience in Taiwan. The drilling of deep borehole PH-29-1 was a milestone in deep borehole boring. Relevant issues learned were: how to increase work efficiency, strengthening worksite safety, renewal of old worn-out equipment, training and educating of good working personnel, effective management and conscious attention to environmental topics.

2. Hydrofracturing Tests for In-situ Stresses

Available geologic information indicated that the major geologic structure of Taiwan was formed through a mid-Tertiary orogenic movement. The Philippine sea plate moved in a SE-NW direction causing a series of thrust faults and fold structures. The axis of these thrusts and folds are parallel to the main axis of Taiwan. The

Table 2 Analysis of Bits Consumption

Category	Size(mm)	No	hardness	Result						Situation of boring			Advance rate	
				Drilling period (1992)	Drilling depth(m)	Drilling depth (m)	Core (m)	Core recovering (%)	Drilling time(h)	Loading (t)	Revolution (rpm)	Pumping volume (l/min)	1m (h/m)	1min (cm/min)
Tricone Bits	5.5/8" (142.9mm)	1	MH	5.19-5.19	0-24.3	24.3	0	0	5.0	500	60	80	0.21	8.1
	Subtotal	1p	MH	5.19-5.19	0-24.3	24.3	0	0	5.0	500	60	80	0.21	8.1
Diamond Bits	Bore 101mm (HQ-WL)	2	C25	5.19-5.24	24.3-110.7	86.4	70.9	82.1	46.5	500-1500	80-300	30-70	0.54	3.1
	Subtotal	1p	C25	5.19-5.24	24.3-110.7	86.4	70.9	82.1	46.5	500-1500	80-300	30-70	0.54	3.1
	Reaming 101mm (HQ-WL)	3	E35	6.9-6.11	110.7-267.0	156.3	-	-	52.0	800-1500	200-230	60-80	0.33	5.01
	Reaming Subtotal	1p	E35	6.9-6.11	110.7-267.0	156.3	-	-	52.0	800-1500	200-230	60-80	0.33	5.01
	Bore 76.5mm (NQ-WL)	4	E35	5.27-5.29	110.7-172.8	62.1	57.7	92.9	31.75	500-1500	250-380	40-60	0.51	3.26
		5	E35	5.29-5.31	172.8-243.9	71.1	71.1	100	28.75	1000	300	40	0.4	4.12
		6	E35	5.31-6.02	243.9-270.5	26.6	26.6	100	16.75	1000-1500	150-300	30-40	0.63	2.65
		7	E35	6.13-6.17	270.5-378.5	108.0	108.0	100	60.25	1000-2000	250-300	30-60	0.56	2.99
		8	E35	6.17-6.19	378.5-421.1	42.6	36.9	86.6	25.5	1000-2000	300-350	40-60	0.6	2.78
		9	E35	6.19-6.19	421.1-431.2	10.1	10.1	100	6.2	1500	300	40	0.64	2.59
		10	E35	6.23-6.23	431.2-431.6	0.4	0.4	100	0.5	1500	240	60	1.25	1.33
		11	E35	6.28-6.28	431.6-433.9	2.3	2.3	100	1.75	1500	200	60	0.76	2.19
		12	E35	7.3-7.3	433.9-434.3	0.4	0.4	100	0.75	1000	300	70	1.88	0.89
		13	E35	7.3-7.4	434.3-476.7	42.4	42.4	100	23.75	1000	300	70	0.56	2.98
		14	U10	7.4-7.5	476.7-496.0	19.3	19.3	100	6.5	1500	300	60	0.34	4.95
	Subtotal	11p		5.27-7.5	110.7-496.0	385.3	375.2	97.4	202.75	500-2000	150-380	30-70	0.53	3.17
	Total	12p		5.19-7.5	24.3-496.0	471.7	446.1	94.6	249.25	500-2000	80-380	30-70	0.53	3.15
Bore Total		13p	D45	5.19-7.5	0-496.0	496.0	-	-	254.25	500-2000	60-380	30-80	0.51	3.25
Diamond saw	Bore 101mm (HQ-WL)	1	D45	5.19-5.24	24.3-110.7	86.4	70.9	82.1	46.5	500-1500	80-300	30-70	0.54	3.10
	Reaming 101mm (HQ-WL)	2	D45	6.9-6.11	110.7-267.0	156.3	-	-	52.0	800-1500	200-230	60-80	0.33	5.01
	Bore 76.5mm (NQ-WL)	3	D45	5.27-5.31	110.7-243.9	133.2	128.8	96.7	60.5	500-1500	250-380	40-60	0.45	3.67
		4	D45	5.31-6.2	243.9-270.5	26.6	26.6	100	16.75	1000-1500	150-300	30-40	0.63	2.65
		5	D45	6.13-6.17	270.5-378.5	108.0	108.0	100	60.25	1000-2000	250-300	30-60	0.56	2.99
		6	D45	6.17-6.19	378.5-421.1	42.6	36.9	86.6	25.5	1000-2000	300-350	40-60	0.60	2.78
		7	D45	6.19-6.19	421.1-431.2	10.1	10.1	100	6.5	1500	300	40	0.64	2.59
		8	D45	6.23-6.28	431.2-433.9	2.7	2.7	100	2.25	1500	200-240	60	0.83	2.00
		9	D45	7.3-7.3	433.9-434.3	0.4	0.4	100	0.75	1000	300	70	1.88	0.89
		10	D45	7.3-7.5	434.3-496.0	61.7	61.7	100	30.25	1000-1500	300	60-70	0.49	3.40
	Subtotal	8p		5.27-7.5	110.7-496.0	385.3	375.2	97.4	202.75	500-2000	150-380	30-70	0.53	3.17
	Total	9p		5.19-7.5	24.3-496.0	471.7	446.1	94.6	249.25	500-2000	80-380	30-70	0.53	3.15

Table3 Drilling Rate of PH-29-1 in Selected Rocks

A. HQ-WL borehole

Rock formation	Section (m)	Length Bored (m)	Spent (hour)	Drilling Rate (m/h)
Weathered、fractured、coarse to medium grained quartzitic sandstone	30.0-36.5	4.5	2.75	1.75
Fractured、coarse to medium grained quartzitic sandstone	47.3-61.3	14.0	4.67	3.00
Alternation of medium grained quartzitic sandstone and black shale	61.3-72.2	10.9	4.92	2.22
Greenish-gray medium to coarse grained quartzitic sandstone	734.-110.7	37.0	17.42	2.14
B. NQ-WL borehole				
Alternation of muddy sandstone, black shale and coarse grained quartzitic sandstone	123.5-153.3	29.8	15.17	1.96
Coarse grained quartzitic sandstone	218.3-231.5	13.2	5.00	2.64
Alternation of greenish-gray fine grained quartzitic sandstone and dark gray siltstone	286.4-297.4	14.0	8.63	1.62
Coarse grained quartzitic sandstone	300.4-312.5	12.1	8.17	1.48
Gray, medium to fine grained quartzitic sandstone	331.3-347.0	15.7	7.00	2.24
Medium to coarse grained quartzitic sandstone	433.9-453.3	19.4	9.00	2.16
Greenish-gray fine grained quartzitic sandstone	483.6-496.0	12.4	4.83	2.57

northern part of Taiwan including the location of the present project is located within the compressive zone. The major stress axis should coincide with the compressional direction and ran parallel to the strike of the tunnel alignment. This stress axis gradually rotated consequent to opening and spreading of the Okinawa Trench, and normal faults were formed. Some stylolite shown in the vertical drill cores of Szeleng sandstone was observed during deep hole drilling, which implied that parts of the rocks in the northern Hsuehshan ranges was once subjected to higher vertical stress (Figure. 3). The strike of this spreading was NW-SE.

Hence it could be concluded that the stress conditions along the tunnel alignment are highly complicated. Furthermore, overburden along the tunnel alignment varied in thickness from place to place, thus parts of the tunnel alignment might encounter very high in-situ stresses. To evaluate the regional tectonic stresses in the vicinity of the tunnel alignment, hydraulic fracturing test for in-situ stresses measurements were performed in deep boreholes PH-19 and PH-20, both of which were bored to tunnel invert elevation. In borehole PH-19 tests were at depths 155.9 m – 258.9 m. In this test, hydraulic fracturing were conducted 12 times, fracture patterns duplicated 8 times. In borehole PH-20 tests were at depths 134.1-246.9 m. In this test, hydraulic fracturing were conducted 20 times, fracture patterns duplicated 12 times.

The results of measurements indicated that the vertical stress (SV) for overburden fell between the maximum horizontal stress (SH) and minimum stress (Sh) (Figure 4), the maximum stress ratio(KH=SH/SV) was 0.8-1.3, the minimum stress ratio (Kh=Sh/Sv) was 0.5-1.7 (Figure 5); the direction of maximum stress was NE-SW, approximately normal to the strike of the tunnel alignment. The measured results agreed well with current researches on geotectonics.

3. Geomechanical Characteristics

The rock formations along the tunnel alignment comprised sandstone, quartz sandstone, siltstone and argillite. The

Figure 3 Stylolite in the Vertical Drill Core of Szeleng Sandatone

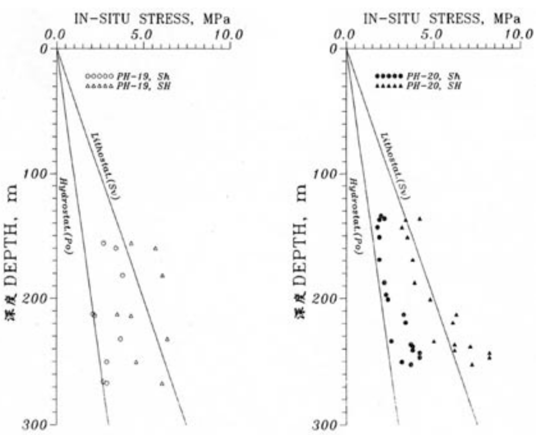

Figure4 Correlation between in-situ Stress Magnitude and Depth

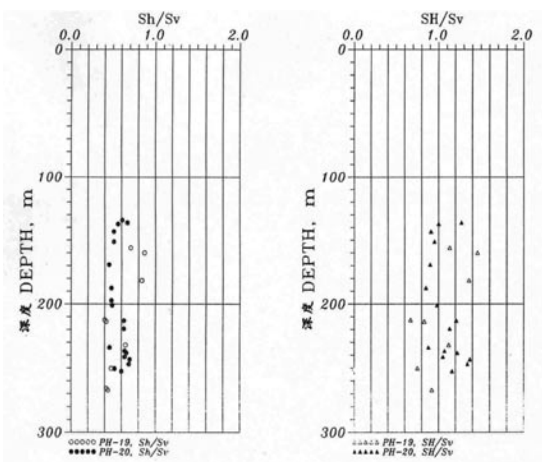

Figure 5 Correlation between Stress Ratio and Depth

Table 4 Index Properties of Rock Materials

Rock Materials	Stratum	Unit Weight r_t(t/m^3)	Water content Wn(%)	Special Gravity	Void Ration (10^{-2})	Absorption Abs (%)
Argillaceous Rocks (ST)	FC	2.70	1.4	2.75	3.2	2.21
	MK	2.68	1.3	2.7	3.0	1.9
	TTS	2.68	1.2-1.7	2.72-2.75	3.0-4.1	2.0-2.9
	KK	2.70	1.3	2.74-2.75	3.0-3.4	1.8-1.91
	SL	2.55-2.69	1.6-3.1	2.68-2.73	4.0-8.4	1.7-6.74
Arenaceous Rocks (SS)	FC	2.64	1.1	2.71	3.0	1.85
	MK	2.68	-			
	TTS	2.68	1.4	2.73	3.7	2.84
	SL	2.57-2.68	0.6-3.7	2.71-2.75	1.0-11.2	1.10-6.17
Quartzitic Rocks(QTZ)	SL	2.55-2.67	0.3-0.7	2.64-2.68	1.0-5.6	0.5-2.20

Table 5 Average Uniaxial Compressive Strength of Rock

Rock Materials	Stratum	Monotonic Uniaxial Compressive Strength Uc kg/cm^2	Cyclic Uniaxial Compressive Strength Uc Cyclic kg/cm^2	Estimated from Point Load Test Uc =22Is(50)kg/cm^2
Argillaceous Rocks (ST)	FC	464	551	342
	MK	750	550	618
	TTS	210-410	477-778	393-634
	KK	340-463	538-561	385-394
	SL	137-650	93-660	715-748
Arenaceous Rocks (SS)	FC	1556	1617	1226
	TTS	452-620	766-855	818
	KK	800		
	SL	53	101	
Quartzitic Rocks(QTZ)	SL	986-1670	1264-1775	1287-2394

Tables6 Average Modulus of Elasticity of Rock

Rock Materials		Static Elastic Modulus Es $*10^4 kg/cm^2$	Static Elastic Modulus Ed $*10^4 kg/cm^2$	Es/Ed
	Stratum			
Argillaceous Rocks (ST)	FC	17.6	27.8	0.63
	MK	14.4	-	-
	TTS	6.2-11.2	23.9	0.36
	KK	8.5-32.7	34.6	0.6
	SL	4.2	12.95	0.32
Arenaceous Rocks (SS)	FC	34.5	29.9	1.15
	TTS	8.2-21.0	20.3	0.72
	SL	1.5	9.37	0.16
Quartzitic Rocks(QTZ)	SL	22-30.8	-	

rock mechanical tests included general rock physical properties, uniaxial compressive strength tests, triaxial compressive strength tests, static elasticity tests for rock cores, dynamic elasticity tests for rocks, point load tests, Talber abrasive tests, petrographic analysis, X-ray analysis tests, general physical property tests for clay seams, Schmidt hardness tests, swelling tests, slaking tests and creep tests. These test results will be used in synthetic study to derive the geomechanical properties along the tunnel alignment that included general properties of rocks, strengths of rocks, and rock deformability.

The characteristics of rock formations occurring along the tunnel alignment are as follows: Relevant to siltstone-type of rocks quartzitic rocks and sandstone-type of rocks are generalized in having higher specific gravity, lower porosity and lower water absorption (Table 4). Attention was especially paid to the average quartz content of 82% in the Szeleng sandstone. Some samples of the quartz sandstones showed that the quartz content can be high up to 99%. The total hardness for the Szeleng sandstone, among others, is ranging between 99 and 157, which is statistically close to the total hardness value for similar rocks. All rock materials are mostly medium to high durable materials with high resistance to corrosion but little expansion when water is encountered. Long term cumulative creep deformation is generally smaller than stress failure under load.

Statistical uniaxial compressive strengths for rocks is listed in Table 5. Quartzite in the project area reached strength of 2400 kg/cm2. Other well-cemented sandstones such as sandstones of the Fangchiao Formation may also be as high as 1600 kg/cm2. For siltstones, the strength averaged 400-600 kg/cm2.

Synthesis of laboratory results from elasticity tests and in-situ down-hole deformation tests gave the mean elasticity moduli for rocks along the tunnel alignment as shown in Table 6. According to material classification by Deere and Miller (1996), materials along the tunnel alignment belonged to low to high strength with medium to low modular ratios. Some argillite showed high modular ratios with low strength characteristics. The quartzite and sandstone from the Fangchiao Formation generally showed low to medium modular ratios.

4. Establishing Geological Model

The investigation results were subjected to evaluation and estimation for establishing a geological model for the area along the tunnel alignment. Plan geologic map and profile cross sections of tunnel alignment were prepared (Figures 6, 7). The Hsuehshan Tunnel passed through a series of slightly metamorphosed folded and faulted Tertiary sedimentary rocks. Regional folds thrust faults, strike slip faults and normal faults constituted complicated geologic structures. The geologic characteristics are summarized as follows:

In an old to young ascending order of Hsuehshan Tunnel rock formations are: the Eocene Szeleng Sandstone (SL), the Oligocene Kankou Formation (KK), Tsuku Sandstone (TSK), Tatungshan Formation (TTS), and the Miocene Makang (MK) and Fangchiao Formations (FC), all belonging to the Hsuehshan Range geologic subprovince. These rock formations had been subjected to vigorous orogenic movements, and were deformed by folding and cut by faults. These rock formations thus are not continuous and the thickness of the formations are not complete. The Szeleng Sandstone is a coarse to fine-grained quartzitic sandstone with a uniaxial compressive strength over 3,000 kg/cm2. It distributes 4 km length on the eastern half of the tunnel. For the remainder of the rock formations their uniaxial compressive strengths were mostly between 500 and 800 kg/cm2

Major geologic structures along the tunnel alignment included two regional fold structures and 7 local fold structures. As for faults, in an east to west direction, they are: the Chinying, Shanghsin, Palin, Tachinmian, South Branch of the Shihpai Fault, Northern Branch of the Shihpai Fault and the Shihtsao Fault. All geologic structures had been verified through borehole drilling during design stage, and their spatial relationship with the tunnel had been clarified using available data. Except the Shihtsao Fault, being a thrust fault, all of the faults are normal faults and occur within a 4 km area on the eastern half of the tunnel alignment.

Basing on the lineament patterns, density of faults and rock mass quality from boreholes, it was estimated that for the 3/4 length of the western half of the tunnel alignment the geological conditions are similar: the rock mass quality fall between fair and good with a westward trend of improving; for the remaining 1/4 length on the eastern half the rock mass quality is poor. Especially within 1 km on the eastern side of the tunnel alignment, the rock mass is loose and fractured with very poor rock mass quality.

The pilot tunnel was designed for purpose of draining the groundwater during construction of the main tunnel. The possible total groundwater seepage from the pilot tunnel had been estimated an accumulated of 3.5 cms. The fact that along the tunnel alignment about 7500m long with overburden more than 300 m renders it highly difficult to estimate the groundwater flow in the main tunnel. In the 3 km of the eastern tunnel alignment the groundwater flow varied greatly, and the main points of groundwater outlet were faults and shear zones. The instantaneous influx could not be estimated due to presence of too many control factors.

5. Actual Geological Conditions Compared

The pilot tunnel was designed for purpose of geological exploration. Detailed information concerning lithology of rock formations along the tunnel alignment, the location, extent and characteristics of geologic structures and shear fracture zones were unravelled through the completion of pilot tunnel. Furthermore, the pilot tunnel would provide pre-treatment for adverse ground conditions during construction of the main tunnel. For the first purpose, the actual geology was recorded in detail as cross section profiles (Figure 8). Compare the geologic profile with the geological framework in the planning and design stages, that possess a close match. Lithologies and Geotechnical characteristics of rock formations along the tunnel alignment are very coincident with those estimating in the planning and design stages. Locations of major faults coincided well also (Table 7). The poor rock mass quality predicting for the eastern portal section is also correct designations, and the locations of groundwater emission were correctly plotted during the planning and design stages geologic investigations.

6. Geologic Logging During Tunnel Construction

The pilot tunnel was designed for geologic information collecting. Data collected from the pilot tunnel was analyzed and processed, then constituted the main basis for deriving the geologic conditions of the main tunnel. These geologic informations were used in construction of the main tunnel. They included the location, occurrence, attitude and extent of incompetent zones likely to be encountered in main tunnel construction. These were then plotted and formed geologic plan maps and cross section profiles of the main tunnel. The primary aim of the pilot tunnel geologic investigation was features of significant scale. Joints, beddings, small shears or fractures, and minor quantity of groundwater seepage were omitted since these were common occurrences in any TBM excavated tunnel. Large-scale or extensive shear or fracture zones, faults and structural weak zones that might affect construction operation were investigated. Their location, extent and attitude were identified for future reference in construction operation.

The TBM selected to excavate the Hsuehshan Tunnel was a double-shield type. This was highly inconvenient from the point of view of geological investigation despite the fact that the choice of the TBM was culmination of expertise in this aspect. A double shield TBM only allowed geologic observation from a limited space at the wall and at a very short time before supportive segment installation, hence it was not possible to record in detail the features revealed by TBM excavation. Although the collected data was less than desired, it contributed in certain limited manner towards TBM tunnel construction. The final actual excavation revealed that the pilot tunnel had achieved a preview on the geological conditions, and when large quantity of groundwater was encountered, the pilot tunnel allowed in time draining and lowering of the groundwater.

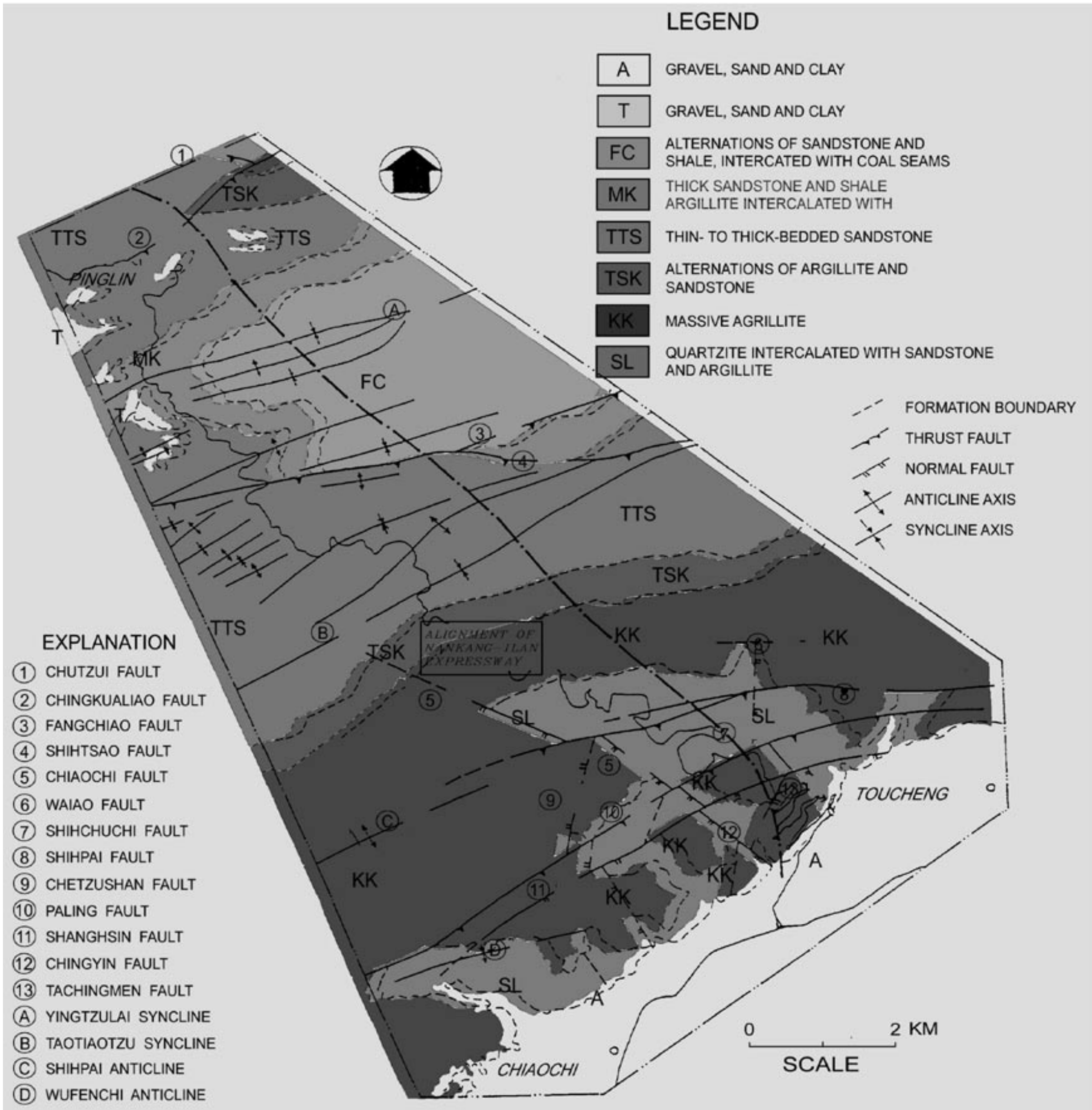

Figure 6 Geological Plan Map of Hsuehshan Tunnel Area

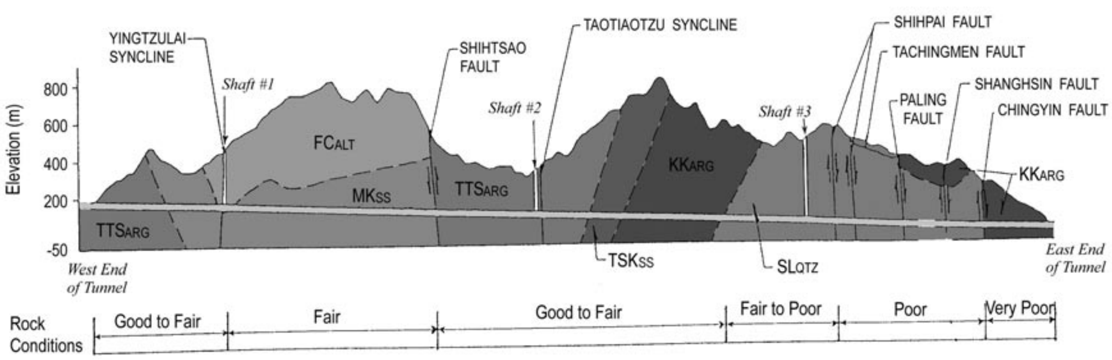

Figure 7 Geological Profile along the Hsuehshan Tunnel

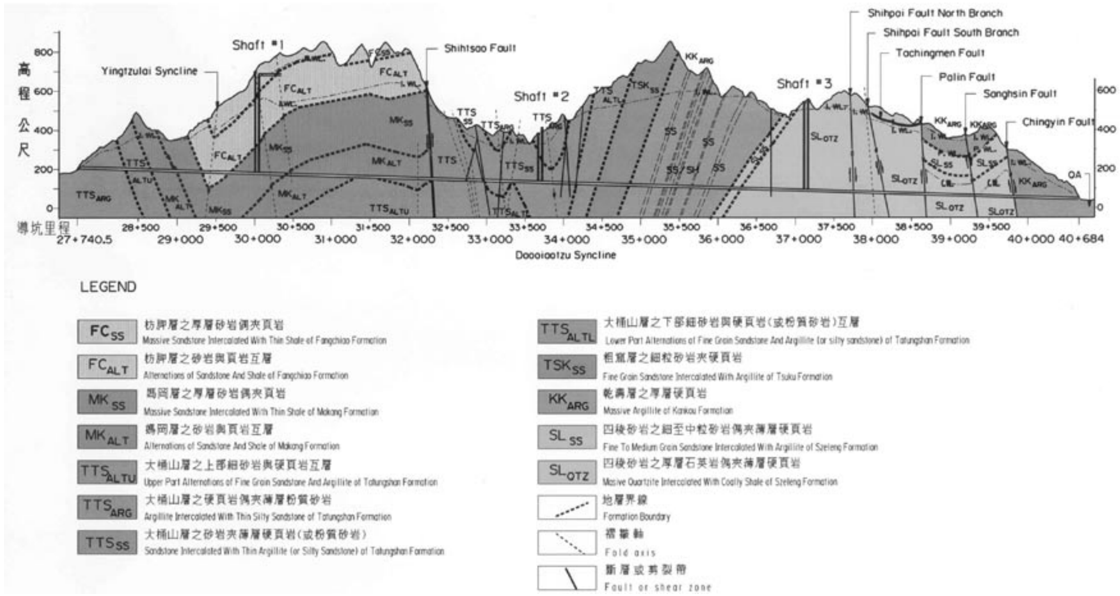

Figure 8 The Actual Geological Profile along Hsuehshan Tunnel

Table 7 Comparison of the Measured and Predicted Fault System along Pilot Tunnel

Major structure		Location	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 Fault-north branch	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 Fault	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			

* Mileage of pilot tunnel

7. Groundwater Dating and Analysis

During tunnel construction groundwater from influx was analyzed that was also dated using radioactive isotopes to clarify the source of this large quantity of groundwater. Radioactive dating using hydrogen isotopes deuterium and tritium would reveal the age of the groundwater. This age of the groundwater was the time from the date the groundwater entered into the saturate zone in the groundwater column. It would also reflect the rate of groundwater circulation and its relationship with meteoric water and surface water. Isotopes C14 and H3 were used in dating and deriving the age of the groundwater that would in turn reveal the origin of the groundwater. The older the age of the groundwater the poorer the groundwater circulation was. Dating through H3 would reveal whether young, recent water had been mixed into the groundwater. If tritium was detected in the groundwater, it would indicate that the groundwater was a mixture of older groundwater and younger groundwater.

Twenty groundwater samples collected from various points of groundwater influx at the eastern end of the tunnel were used in the analysis. Except four samples showing analytical values smaller than 1TU, the concentration of tritium for the remainder of the samples was between 1-3.2TU, a value very close to tritium concentration in rainwater in northern Taiwan for recent years. This analytical result showed that the groundwater possessed atomic explosion signature, and thus it contained recharge water after 1953. The H3 signal TU>1 on groundwater at the eastern portal and a groundwater age of <6000 years revealed that surface water had seeped into the tunnel by ways of fracture zones. At the west portal, groundwater influx did not show signal of recent surface water influx.

Domestic and foreign cases indicated that once the tunnel was completed that would form one of the conduits for groundwater flow. Long-term groundwater drawing would effect the overall behaviour of the groundwater. The Hsuehshan Tunnel is a long tunnel inclined towards the east in a single direction. Its completion and long-term groundwater drawing would surely impose certain effects on the groundwater system. Hence, mitigating impact from a long tunnel on the groundwater system would be an important issue of consideration in planning and design of any long tunnel.

ENGINNEERING RESPONSE

Geologic investigations revealed that geological condition of the Hsuehshan Tunnel was very complicated. Engineering difficulties included encountering six major faults and a bulk of fractured, hard quartzite and large quantity of groundwater. Most of the tunnel alignment is under overburden more than 300 m. It was not possible to explore fully geologic conditions at tunnel elevation through deep boreholes. To solve this problem, construction of an advance pilot tunnel before the main tunnel is preferable.

The major drawback for a pilot tunnel is the increased engineering cost. On the other hand, through information provided by the pilot tunnel certain pre-treatments could be taken and thus reduce engineering risks that would ultimately result in actual saving in engineering costs. In the Hsuehshan Tunnel project the final decision was to excavate a 5-m diameter pilot tunnel between the two tubes of the main tunnel with an elevation slightly lower than that of the main tunnel.

In Hsuehshan Tunnel project, TBM was adopted as the major tunnelling method. However, due to the extremely poor ground condition at the eastern part of tunnel, engineering response to this was to adopt the traditional D&B method for the first 1 km, at least exceed the Chinyin Fault.

CONCLUSION

For a long, deep-buried tunnel difficulty is unavoidable. When the uncertainty of geological conditions combined with these difficulties, the problem seemed to become insurmountable. Taiwan locates on the collision zone of two plates, that the geologic conditions are highly variable and complicated. Long tunnel construction in mountainous areas is especially difficult.

High precipitation results in voluminous groundwater. Torrential rain finds its way through crevices in fault zones and shear fractures to seep into the ground where they accumulated into huge bodies of groundwater. In the Hsuehshan Tunnel project area faults and shear fractures are mostly inclined at high-angles and conceals under vegetation and soil covers. These discontinuous structures could not be precisely represented in attitudes of their discontinuities and their distributions. Geophysical exploration ould only reveal potential weak zones that usually could not be successfully detected through shallow boreholes or deep vertical boreholes. Horizontal long boreholes then became the only useful means to identify incipient fractures and the large volume of groundwater stored behind thee clayey fracture zones. Horizontal long boreholes would also drain groundwater body ahead of excavation thus improving the ground ahead. Recognizing the advantages of horizontal long boreholes, it should be integrated into the plan of geological investigation for long tunnel with deep burial.

Investigation through excavation of a pilot tunnel promises advance knowledge on the geological conditions of the grounds of the main tunnel. The pilot tunnel also serves the purposes of pre-draining groundwater and pre-treating grounds in the main tunnel, thus making it an important tool for long, deep-buried tunnels with difficult geologic conditions like Hsuehshan Tunnel.

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