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The construction of Pinglin tunnel through adverse geology

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ABSTRACT : Taiwan, on the eastern edge of the Eurasian plate, is being crushed and uplifted as the Philippine Sea plate pushes underneath. The Pinglin tunnel is situated within the fold-and-thrust belt structural region. The construction of Pinglin tunnel through adverse geology was going slowly with a bunch of collapsing disasters no matter whether TBM or DB. This paper presents our experience and methodology through adverse geology.

1 INTRODUCTION

The construction of the Pinglin Tunnel is the key to the success of the Taipei-Ilan Expressway project, which promotes the economic development of eastern Taiwan. Since the west portal within a reserve for Taipei water resource is prohibited to work at the outset, Pinglin tunnels, a pilot tunnel (§ =4.8m) and two main tunnels (§ =11.74m), need the rapid excavation potential and apply TBM technology. The contract stipulates that the Pinglin tunnel shall be excavated by DB (Drill and blast) method while waiting for the TBM delivery, and there after by TBM.

Due to ① potential water surge with high pressure water head and ② the fault gouge and breccia of sheared or fractured zone at the eastern section (about 4.5km or longer) of Pinglin tunnel, which are heavily disturbed by the tectonical movement as shown in Fig. 1, a lot of geological disasters or unusual incidents have been encountered, for instance:

① 60 % of the eastbound main tunnel excavated by DB from the east portal was rebuilt or repaired after extensive deformation, e.g. 5.8 cm / day, substantial cracking and collapsing.

② The pilot tunnel TBM has been stuck ten times, with the standstills to date as shown in Table 1.

③ The long range core drilling in the pilot tunnel as shown in Table 2 demonstrated poor performance even with internationally famous experts.

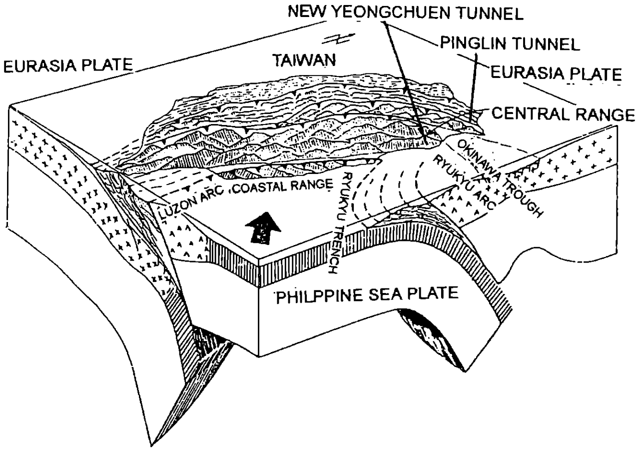


Figure 1. Schematic block diagram showing continent-arc collision and plate tectonic setting of Taiwan.

Table 1 The stuck data of pilot tunnel TBM.

Stuck No.	Stuck Station	Stuck Date	Restarting date	Stuck duration	Notes
1	40^K+138.5	Feb 02,93	Apr 25,93	82	
2	40^K+83	Jun 02,93	Jul 16,93	52	
3	40^K+75	Aug 29,93	Oct 04,93	36	
4	40^K+40.7	Oct 22,93	Dec 21,93	60	
5	39^K+972.4	Feb 22,94	Apr 09,94	45	
6	39^K+841.9	May 25,94	Jul 01,94	37	Chingyin Fault
7	39^K+816	Jul 10,94	Sep 20,94	72	Chingyin Fault
8	39^K+530.4	Nov 10,94	Dec 24,94	47	
9	39^K+168.7	Feb 18,95	Dec 05,95	290	Shanghsin Fault
10	39^K+79	Feb 05,96	Not yet	Unknown	Shanghsin Fault

Table 2 The long core drilling in pilot tunnel.

No.	Station	Expected drilling length	Actual drilling length	Expected drilling days	Actual drilling days	Driller's nationality	Equipment type and torque
1	39K+139	300 m	107.25 m	20	78	South Africa	TONE TEL 7 1200kgm
2	39K+110	300 m	103.55 m	NA	33	Japan	TONE TOP LS12 1400kgm
3	39K+019	300 m	126.40 m	NA	64	Japan	TONE TOP LS12 1400kgm

④ Although the adverse geology was pretreated from the pilot tunnel, the TBM of westbound tunnel was stuck five times as shown in Table 3 and buried in a collapsing calamity on December 16, 1997.

⑤ The excavation of ventilation shaft #3 commenced in April 1996 and sank to date only to a depth of 130m below surface, with the rate of underground water ingress 10 to 20 liters / second.

However, Pinglin tunnels are not alone. The New Yeong-Chuen Tunnel, being located in the Ryukyu Arc of plate tectonic setting, collapsed on October 24, 1998 with the water ingress of 80 m^3 / min and buried more than 500 m of the tunnel length.

The Pinglin pilot tunnel was constructed for the purpose of obtaining geotechnical data and ground behavior, identifying anticipated adverse geology and providing effective pretreatment to the main tunnel construction. Without competent preinvestigation, it became difficult to tailor the design of the machine to potential geological problems and to ascertain what will happen to pilot TBM boring. Consequently, the serious delay due to trapping incidents of the pilot TBM occurred and put the main tunnel construction in a dilemma as well. The TBM of main tunnel might not be able to traverse the zone of the pilot TBM passage without trouble, because of the size effect (ϕ = 4.8 m vs. ϕ = 11.74 m).

If the pure DB method with a slow but steady advance rate were realistically used for the excavation of Pinglin pilot tunnel, most Pinglin pilot tunnel or at least the 4.5km unique geological zone would have been holed through. More haste, less speed. To avoid potential ground hazards in the future, an early finish of Pinglin pilot tunnel is essential and takes the first priority. Additionally, a pilot tunnel through the top heading or central portion of the main tunnel, the long hole directional drilling and use for ground treatment, etc., shall be considered for the unique 4.5km fractured zones as shown in Fig. 2. prior to the commencement of the main TBM tunnelling. "It is suggested to perform the pilot top heading excavation with conventional

Table 3 The stuck data of the westbound TBM.

No.	Stuck Station	Stuck Reason	Stuck Date	Restarting Date	Stuck Duration
1	39K+239.1	Cutter head jam	Oct 22, 96	Jan 08, 97	78
2	39K+236.7	Cutter head jam	Jan 10, 97	Mar 05, 97	54
3	39K+217.0	Cutter head jam	Apr 05, 97	May 06, 97	31
4	39K+208.6	Front shield trap	May 09, 97	May 21, 97	13
5	39K+076.0	Tail shield trap	Jul 13, 97	Jul 24, 97	12

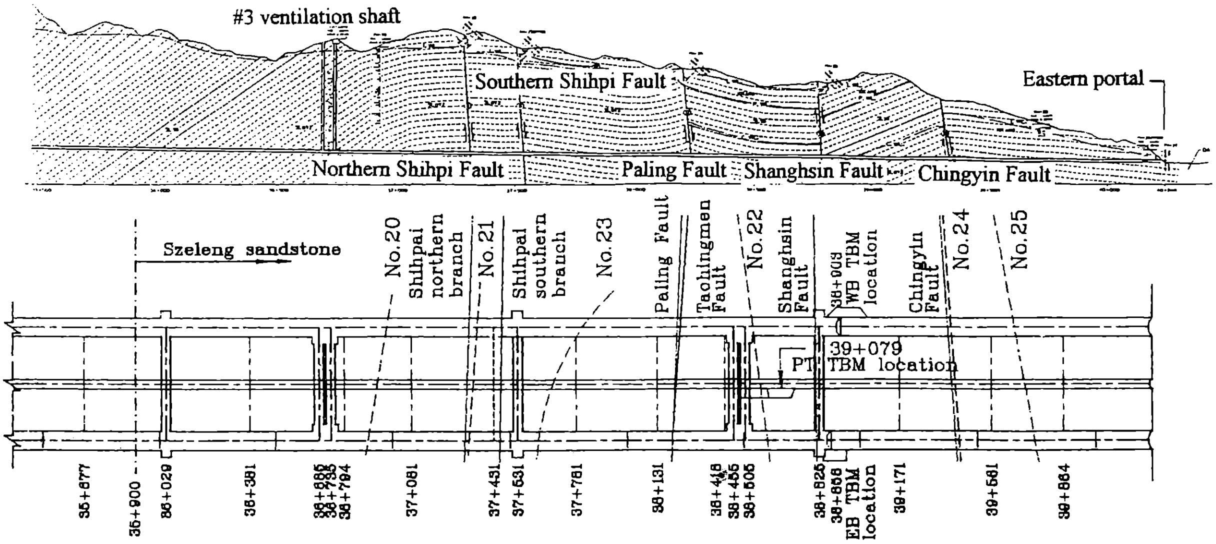


Figure 2. Geological profile at the eastern section of Pinglin tunnel including No.20, 21, 22, 23, 24 and 25 problematic lineaments.

system until the two next major faults being encounted and mined through. After the sandstone, the excavation of main tunnel will continue with full face (FF) TBM. "(The Advisory Board meeting No.5 of TANEEB (March 7, 1998))

2 GEOLOGY

Rock formation at the eastern section of Pinglin tunnel, based on a few strategically placed boreholes, are estimated as shown in Fig. 2. The Szeleng Sandstone, identified faults, and groundwater conditions are described according to the preinvestigation report as follows:

(1) Szeleng Sandstone is a fine to medium grain sandstone intercalated with thin argillite. The total thickness of quartzite and quartz sandstone is estimated to comprise 88% of the whole Szeleng Sandstone. Szeleng Sandstone formations are composed of sediments representing three depositional cycles. There are very thin coal seams in the depositional cycles. All these indicated that the Szeleng formation was a near shore deltaic-swamp depositional product. Several sets of well-developed pressure solution stylolites are indications that the Szeleng Formation had been subjected to intense lithostatic loading pressure following its diagnosis. Some of the stylolites are open as weak planes. The Szeleng Sandstone is the hardest rock in Taiwan. However, due to the faults, joint sets, close fractures, and soft infilling, etc., alternated irregularly, the rock mass as a whole is very loose and very weak.

(2) The faults are mainly composed of fault gouge, mud-rock, and breccia from the fragmentary argillite of the Kankou Formation and some Szeleng Sandstone. The water permeability of fault gouge and mud-rock is not high. Some of the quartzite breccia fissures are glued and the quartz sandstone fractures are heavily rested. Therefore, this rock mass is highly permeable to water and is very weak.

(3) The mountainous area of the Pinglin Tunnels is blessed with abundant rainfall. Consequently, the groundwater level is very high. It has been estimated that the water head could vary from 100 meters up to 480 meters. So far, the maximum water inrush at the Pinglin Tunnel has been 750 liters per second with 18-bar pressure. There is no indication of the precise locations and flow quantities where groundwater surges are likely to occur. However, the following locations are sites of likely higher groundwater surges or seepage:

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

② Sheared rock masses with weak planes that contain abundant clay, especially the Szeleng Sandstone.

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

Recently, the record from Advisory Board Meeting No. 5 of TANEEB (March 7, 1998) provides a definite picture about how the ground is going to react to or behave towards the TBM boring at depth: "The highly fractured and loose rock mass subjected to high water pressure behaves like loose sand submerged in water, considering the scale of the ground influenced by the excavation of the three tunnel tubes".

3 TBM TORQUE

The TBM of Pinglin main tunnel as shown in Table 4 has by far the highest available torque in the world. Its breakout torque is approximately 1.65 times higher than the one derived from actual torque provided on the Mount Russelin and Bozberg tunnel TBM in Switzerland (machines of very similar diameter). However, the value of breakout torque obtained for the extremely fractured sandstone or running sand (ϕ=36° and c=0) either by Atkinson (i.e. 38,787KNm) or by Murayama formula (i.e. 69,924KNm) is higher than 30,000KNm of Pinglin main tunnel TBM. That is perhaps why the TBM was stuck so easily, even though the adverse geology was pretreated from the pilot tunnel. Comparison with other EPB machines of large diameters shows that the breakout torque capacity of Pinglin main TBM will be in the low middle range for that type of machine. Therefore, the Pinglin main TBM can be used to stabilize the excavation face if necessary.

When driving through possibly squeezing rock formation, the bore diameter of Pinglin main tunnel TBM can be increased by means of enlargement cutter to provide a relief overcut and to prevent shields from being trapped. With the projected extent of the convergence and its progress in squeezing rock formation, the cutter head center of Pinglin main tunnel TBM can also be adjusted vertically relative to the front shield. Because of the vertical adjustment, the cutterhead leaves the 60 cm of its periphery open and not being protected by the front shield. Since the fractured formations with nil stand-up time being actually excavated in Pinglin tunnel, the overcutting system seldom functions. However the torque of Pinglin main tunnel TBM must be able to overcome two kinds of resisting moments due to:

① vertical loads (pv) applied on the 60 cm periphery of the cutter head.

② horizontal earth pressure (ph) applied on the surface of the cutter head.

The theoretical torque requirement T is equal to the sum of Tv and Th:

$$Tv = Pv \cdot [\pi Ds \cdot (0.6\ m)] \cdot (Ds/2) \cdot u$$

$$Th = Ph \cdot A \cdot rm \cdot u = Ph \cdot (\pi Ds^2/4) \cdot (Ds/3) \cdot u$$

Table 4 Specification of WIRTH TB 1172 H/TS

Bore diameter	11,740 ㎜
Cutterhead	
-power	4,000 kw
-speed	0-4.0 rpm
-torque at 4.0 rpm and 75% efficiency	7,200 kNm
-breakout torque, at 0.95 rpm	30,000 kNm
-thrust of 18 telescope cylinders	50,600 kN
-thrust of 28 push jacks	78,700 kN
-stroke	1.5 m
-motors	18
Gripper clamping force	65,000 kN
Gripper configuration	T (3-point anchoring)
Hydraulic system pressure(bar)	max.405
Total machine power	7,550 kw
Muck handling capacity	1150 m^3/m
Machine length	250 m
Estimated weight (TBM+BU)	3000 t
Diameter of cutter disc	432 ㎜
Number of cutting discs	
-face	71
-gauge	3
-center	6
-over cutter	3
Transformers installed	2x 3150 kva(690v) 1x 1250 kva(440v)

The hypotheses for the extremely fractured sandstone/quartzite or running ground are:

① internal friction angle $\phi = 35°$

② cohesion c = 0

③ unit weight of loose and fractured rock $\gamma = 2.4\ t/m^3$

3.1 Murayama formula

The calculation as shown in Fig. 3 is based on a head of loose material equal to three times the nominal diameter Ds. The horizontal pressure Ph calculated using Murayama formula will be considered as maximum values, because actual conditions are not those of an EPB machine in superficial ground. As such, the vertical pressure exerted is actually reduced by the silo effect. Without water inflows, the load of collapsed ground is generally limited by the friction of the material against the walls of the fault. For the determination of Pv, Terzaghi formula for average overburden tunnel is applied. With K = 1.1 for completely crushed rock (B = Ht = Ds), the height of decompressed ground is Hp = K (B + Ht) = 2.2 Ds. The torque requirement calculated using Murayama formula is

$$T = Tv + Th = 240\ tm + 3000\ tm = 3240\ tm$$
$$= 69{,}924\ KNm.$$

3.2 Atkinson formula

In collapsed tunnel applications, the Atkinson formulas are generally applied for the calculation of upper and lower limits of the pressure of confinement Pv.

Upper bound $Pv = \gamma \cdot Ds \cdot [Kp / (Kp^2-1)] = 8.3\ t / m^2$

with $Kp = (1+\sin\phi) / (1 - \sin\phi) = 3.7$

Lower bound $Pv = \gamma \cdot Ds \cdot (1/4 \cdot con\,\phi) \cdot (\cot\phi + \phi - \pi / 2) = 4\ t / m^2$

$Ph = K \cdot (Pv + \gamma \cdot Ds / 2) - 2 \cdot c \cdot Sq(K)$

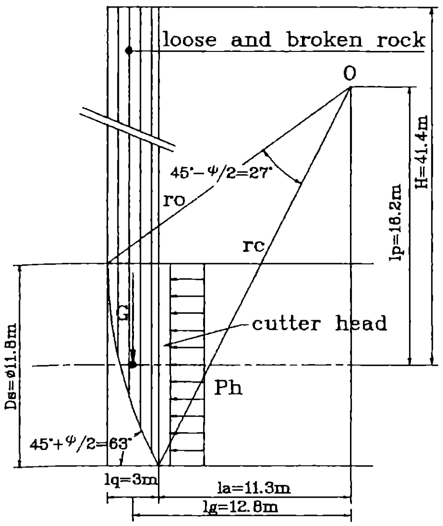
with Ko at rest $= 1 - \sin\phi = 0.43$

Ka active $= \tan^2 (\pi / 4 - \phi / 2) = 0.03$

Atkinson considers a noncohensive soil without water inflow. The ground is supposed to be isotropic. The silo effect, which limits the height effect is taken into consideration. Torque requirement calculated using Atkinson formula are listed as follows:

Ko=0.43	
upper bound Pv=8.3 t / m^2	lower bound Pv=4 t / m^2
upper bound Ph=9.6 t / m^2	lower bound Pv=7.7 t / m^2
T=Tv+Th=376 tm+1421 tm =1,797 tm =38,787 KNm	T=Tv+Th=183 tm+1144 tm =1,327 tm =28,637 KNm
Ka=0.03	
upper bound Pv=8.3 t / m^2	lower bound Pv=4 t / m^2
upper bound Pv=0.7 t / m^2	lower bound Pv=0.5 t / m^2
T=Tv+Th= 376 tm +99 tm = 475 tm = 10,251 KNm	T=Tv+Th= 183 tm+79 tm = 262 tm = 5,654 KNm

Therefore, the adverse geology shall be pretreated; otherwise the cutter head may be stuck. It must be stressed that the breakout torque shall not be used for TBM penetration in collapsing ground without pretreatment, because it may worsen the caving-in chimney and affect the whole tunnel stability.



According to simplified Murayama empirical formula:

$$Ds/ro=\sin(45^\circ+\varphi/2)\times e^{(45^\circ-\varphi/2)\times\tan\varphi}-\sin\{\varphi\}$$

$$lq=ro\times\cos\varphi-rc\times\cos(45^\circ+\varphi/2)$$

$$rc=ro\times e^{(45^\circ-\varphi/2)\times\tan\varphi}$$

$$ph\times Ds\times lp=G\times lg-c(rc^2-ro^2/2\times\tan\varphi)$$

$$\underline{Ph=G\times lg/(Ds\times lp)} \qquad \underline{Th=ph\times A\times rm\times\mu}$$

$$G=41.4m\times2.4t/m^2\times3m=298t/m$$

$$ph=\frac{298t/m\times12.8m}{11.8m\times16.2m}=20t/m^2$$

$$Th=20t/m^2\times110m^2\times3.9m\times0.35=2{,}000mt=64{,}741kNm$$

$lg=12.8m$; as shown

$Ds=11.8m$; as shown

$lp=16.2m$; as shown

$A=110m^2$; area

$rm=0.33\times Ds=3.9m$; couple

$\mu=0.35$; resistance fricition coefficient

$H=3\times Ds$; head of loose and brocken rock

$T_{muck}=2.4t/m^2$; unit weight

$\varphi=36^\circ$; internal fricition angle

$c=0$; cohesion

Figure 3. The calculation of break-out torque using Murayama formula.

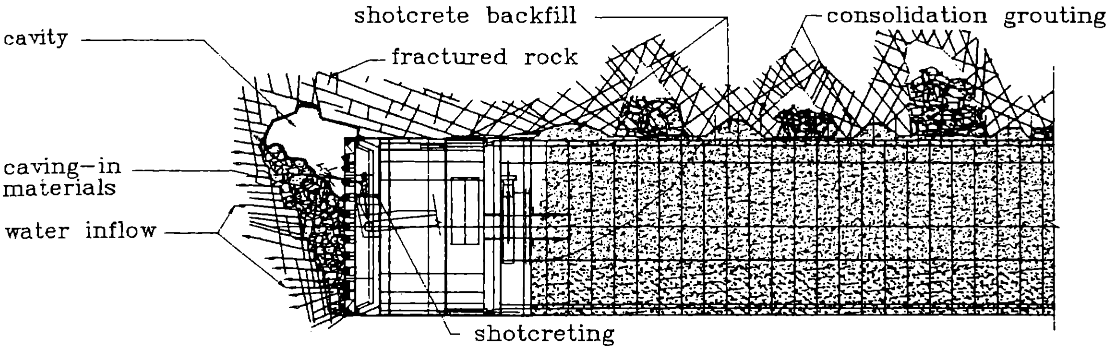


Figure 4. Shotcreting against rock loosening.

Since fractured formations have to be excavated, the cutter head shall be push on the unstable excavation face just like an EPB machine. This has the advantage that large pieces of broken rocks dislodging from the face cannot block the cutter head and damage the cutting tools. The impact damage to cutting tools, i.e. cutters, picks, scrapers, etc. if the TBM is only shoveling is 3.4 times the amount of normal wear.

The loosening zones may precipitate a disaster due to load upraise or high thrust imbalance on rings. The shotcrete shall be applied on the unstable crown, face and side wall as early as possible to protect against rock loosening and caving-in, as shown in Fig.4. It acts as a passive support against the deformation of rock arch and creates quasi-three dimensional stress states. The temporary support of steel arch ribs shall be used to hold unbolted rings for the purpose of sufficient backfill/consolidation grout. All those are crucial and shall be motivated with the reasonable compensation.

4 Remedial measures

The chalk of Channel Tunnel, which is the most favorable geology, shall not be compared with the Pinglin adverse geology in the boundary of plate collision for the TBM boring rate. An undue comparison may impel the last of Pinglin TBMs to ruins. The success of Pinglin mechanized tunnelling shall not depend too much on unrealistically anticipated conditions. The project has lost the westbound main tunnel TBM and suffered from extensive delay and cost overruns for many years, gambling with the unique adverse geology. A reliable and auxiliary method, which is congenial with the TBM and the geology, is introduced. The top heading pilot tunnel has been successfully applied and helped the eastbound main tunnel TBM to bore across the 122m long Chingyin Fault as shown in Fig. 5. The strong roof support acts as a three dimension structural bridge and also a part of permanent structure. The similar top heading pilot incorporating Advisory Board comments into consideration as shown in Fig.5.

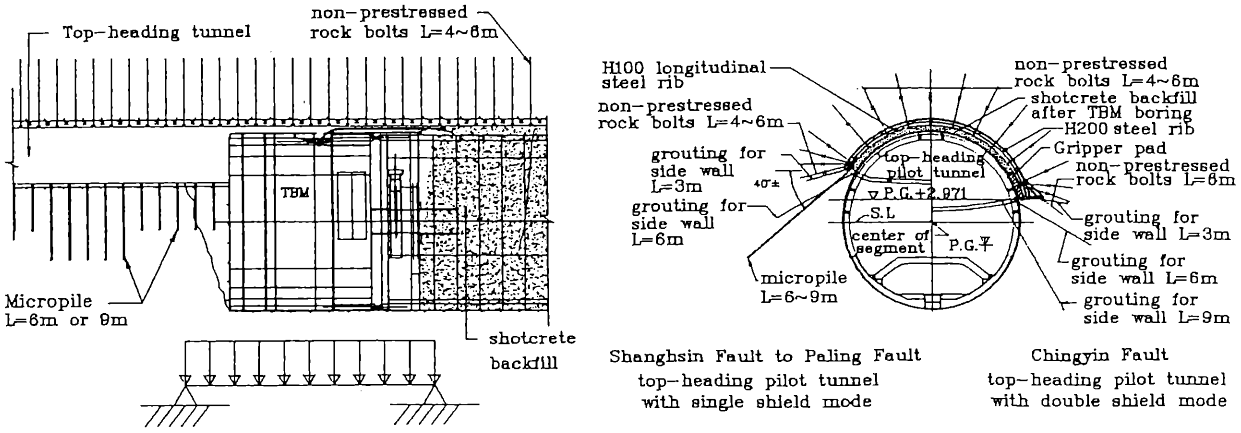


Figure 5. The top heading pilot tunnel.

will be tried again to overcome the fractured Szeleng Sandstone, Paling Fault and Shihpi Fault further into the mountain. Without gripper pad, the TBM will then cut out bench with single shield mode. It includes:

① H200 x 200 (double if necessary) steel arch supports at 1.0 m to 1.5 m spacing.
② three layers of mesh-reinforced shotcrete.
③ 4 m to 6 m long pattern rockbolts at a spacing of 1.5 m each direction.
④ two layers of geogrid reinforced shotcrete for invert closing.
⑤ three 4 m to 6 m long rockbolts, 6 m to 9 m micro piles and cement grouting at the foot of the steel rib for sidewall reinforcement.
⑥ four longitudinal H100 x 100 steel ribs or anchor bolts with mesh-reinforced shotcrete sidewall to bridge steel arch ribs together.

By way of the top heading pilot tunnel, the faults, and problematic areas associated with potential hazards will be detected. The clay gouge material in the fault zone, very thin and closed joint can not be grouted effectively, none the less the faulted/fractured zones and running ground shall be grouted in advance including the crown, side walls and bench underneath. The top heading pilot shall be able to eliminate the principal problem of crown stability. Then the face and side wall stability relevant to the TBM bench cutting will be kept up by means of ground treatment.

The TBM and its backup play an inopportune role in interference and delay of logistics, mucking and immediate remedy. All pedestrian cross connections, vehicular cross connections, ventilation stations and interchange stations shall be mined through and used to facilitate inter-tunnel communication and operation. The rockbolts / anchors, steel ribs and consolidation grouting are proposed for rock reinforcement in zones of weak pillars and enlargements.

Shall the westbound main tunnel TBM be rebuilt and risked again through the unique geology due to tectonical movement? Shall the newly TBM be redesigned, considering the progressive failure above the shield, ground limitations of drilling and grouting as well as the time delay of tunnel support? Flooding was probably the cause of more tunnel catastrophes in Taiwan. Even after the unique 4.5km fractured zones, no one can assure the viability of the Pinglin TBM yet. Still a lot of puzzles continuously challenge the Pinglin Project.

REFERENCE

HO, C.S. 1988. *An introduction to the geology of Taiwan explanatory text of the geologic map of Taiwan.* Central Geological Survey/The Ministry of Economic Affairs/Taiwan ROC.

National Expressway Engineering Bureau 1998. *Record on advisory board meeting No. 5 of Taipei-Ilan Expressway project.*

Sinotech Engineering Consultants Inc. 1993. *Taiwan Area National Expressway Engineering Bureau Ministry of Communications final report on geological exploration for detail design of Taipei-Ilan Expressway project.*

Tseng, Y.Y., H.C. Tsai, C.T. Tseng & Bennie Chu 1997. The Pinglin EB TBM penetration through Chingyin Fault. *Ninth International Conference on Computer Methods and Advances in Geomechanics.*

Tseng, Y.Y., H.C. Tsai, C.T. Tseng & Bennie Chu 1998. The Pinglin east bound mechanized tunnelling, *World Tunnel Congress '98- Tunnels and Metropolises.*

Tseng, Y.Y., S.L. Wong, Bennie Chu & C.H. Wong 1998. The Pinglin mechanized tunnelling in difficult ground. *15th Canadian Tunnelling Conference. Engineering Geology-A Global View from the Pacific Rim.*

Tseng, Y.Y., H.C. Tsai, C.T. Tseng, & Bennie Chu 1998. Operational characteristics of EB TBM in broken rocks. *Regional Symposium on Sedimentary Rock Engineering.*

Wallis, S. 1998. Pinglin perseverance in Taiwan. *T&T International.*

Wirth & Spie Batignolles 1993. *Torque determination and torque calculation for Pinglin east bound TBM of Taipei-Ilan Expressway.*