ANALYSIS OF TBM CYCLE TIME IN the HSUEHSHAN TUNNEL

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ABSTRACT

The reasons for poor advance rates of the TBMs used in the Hsuehshan Tunnel Project were identified. Cycle time statistical analysis was carried out for both Pilot Tunnel TBM and Eastbound main tunnel TBM. The possible explanations as to the poor advance rates of the TBMs were discussed with regards to the classifications of the rock mass using RMR. From the analysis, the RMR or rock mass types poorly correlated with the advance rates of TBM. This was true either for quartzite of Szeleng Formation or non-quartzite of other rock Formations. Instead, it was noted that the management policies might have played a more important role. Nevertheless, the boring rates in quartzite of high RMR values were quite low because of the prevailing influences of intact rock material properties. Although the statistics data showed that overall TBM performance was not satisfactory, the best advance rate of the TBMs still reached remarkable levels.

Keyword : cycle time, pilot tunnel TBM, east bound tunnel TBM, penetrating rates

INTRODUCTION

Three TBM were used for to excavate the 12.9 km long Hsuehshan Tunnel northwestward from Touchen end in Ilan County. They were the pilot tunnel TBM (Pilot TBM), the Eastbound main tunnel TBM (EB TBM) and Westbound main tunnel TBM (WB TBM). The center to center distance of the Eastbound and Westbound main tunnel is 60 m and decreases towards both tunnel portals into a distance of 40 m. The tunnel section for the three tunnels is shown in Fig.1.

The Pilot Tunnel runs between the 2 paralleled main tunnel tubes. The Pilot Tunnel has a center elevation 5 m below the main tubes. The WB TBM was launched on 1996/05/02 from sta.39k+358 and stopped on 1997/12/15 at sta.38k+902.5. The WB TBM was abandoned after having only excavated 456 m before disaster struck on 1997/12/14. Both of the Pilot TBM and the EB TBM were struggling with the adverse rock conditions in the Southeastern Section of Hsuehshan Tunnel. These adverse rock conditions were within the Szeleng Formation and included highly fractured quartzite, high groundwater inflow, and major extensional major faults. Fig. 2 shows the locations of major incidents that impeded the northwestward advance of the TBMs. The TBMs were unable to bore even half of the proposed length of the Hsuehshan Tunnel because of the difficulties they encountered.

Table 1 shows the amount of excavation by the TBMs in both tunnels. Despite of the serious delays that caused the embarrassing results, the maximum daily progress

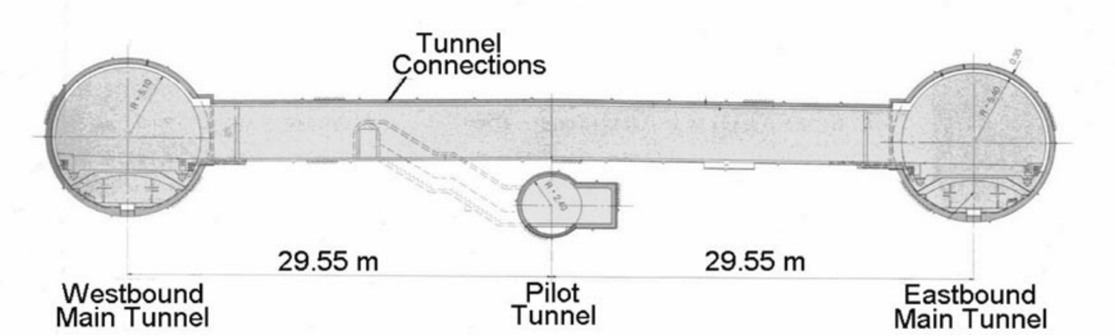

Fig. 1 Layout of Hsuehshan Tunnel

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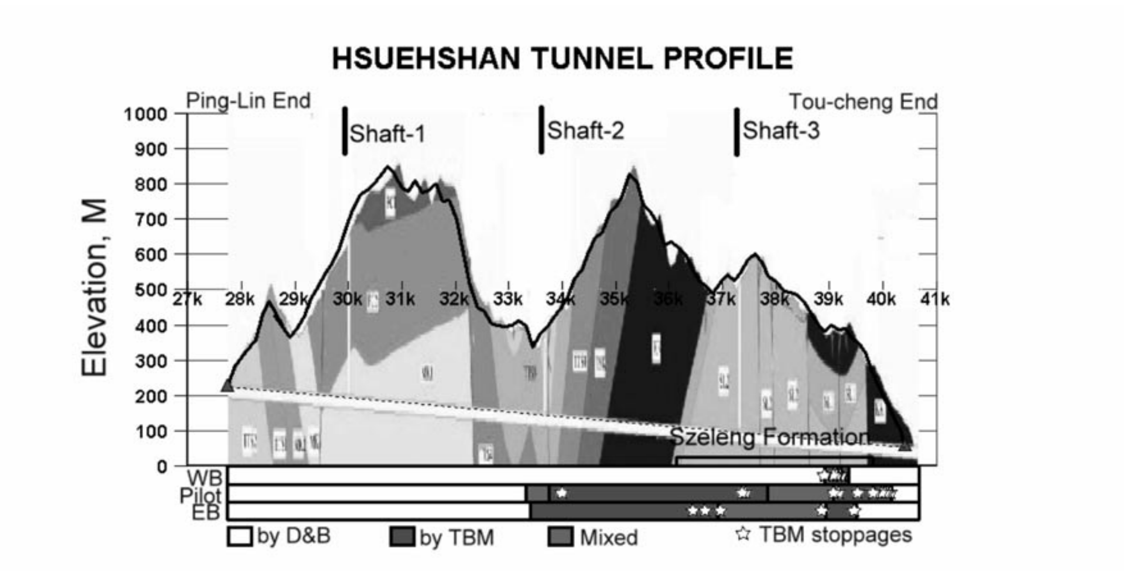


Fig. 2 Geological Profile along the Tunnel Alignment

of the Pilot TBM still reached 24.73 m. This happened on 2003/04/25. The best monthly progress was 400.82 m achieved in May of 2003. The EB TBM had a maximum daily progress of 17.9 m on 2002/12/05. The best monthly progress for the EB TBM was 360.1 m happened in March of 2004. Table 2 shows the percentages of excavation length for the two tunnels per rock stratigraphic units. The tunnels ran through the Szeleng Formation for 3.6 to 3.7 km. This was about 36 % of the total tunnel length. Almost all the major TBM stoppages occurred in this formation where quartzite was the typical rock material (Fig.2). Due to the serious delays, the tunnels then had to be excavated by drilling and blasting methods starting from the northwest portal at the Pinglin end and additional excavation faces were created inside ventilation shaft no.2.

This paper focuses on the statistical analysis of the performance of the TBMs under different ground conditions. Rock materials are classified into either quartzite (the Szeleng Formation) or non-quartzite (mainly argillite or find sandstone of the Kankou, the Tsuku, and the Tatungshan Formations). Table 3 summarizes the major mechanical properties of these two rock groups. A rock mass rating system proposed by Bieniawski has been used to classify the integrity of the rock masses encountered and served as a guide for support selection. This method of rock mass classification is shown in Table 4.

In the analysis, one cycle time was defined as the total time in minutes spent on the construction in one TBM cycle (shift or the advance of one pre-cast concrete segment). Cycle time was comprised of several activities, including (A) boring, (B) invert cleaning, (C) segment installation, (D) back filling, (E) maintenance, (F) drilling, (G) malfunction, (H) utility extension, and (I) others. TBM downtime caused by non-equipment delays such as the machine operation being suspended to recover from geological hazards was excluded. In the EB TBM, because the time for "invert cleaning" was not significant and hence it was included into the cycle time activity of "others". Performances of TBMs were evaluated using the (1) average monthly progress, (2) penetration rate in meter per hour (m/hr) or boring rate in minimeter per revolution (mm/rev), (3) utilization ratio in %, and (4) advance rate in meter per hour. Since the WB TBM had drilled only a short distance prior to its dismantling, the analysis did not included WB TBM.

BASIC TBM DATA

The double-shielded parts of the Pilot TBM and EB TBM are illustrated in Fig. 3. Their functional specifications are also shown in Table 5 and Table 6.

Advance of TBM

The Pilot TBM completed excavation of a length of 5,168 m

Table 1 Statistics of TBM Excavation Length

EXCAVATION	USING TBM (M)	USING D&B (M)	USING TBM WITH D&B (M)	TOTAL LENGTH (M)
Pilot Tunnel	5,168	6,112	1,662	12,942
EB main Tunnel	3,870	5,603	3,444	12,917

Table 2 Statistics of Excavation Length in Various Rock Units

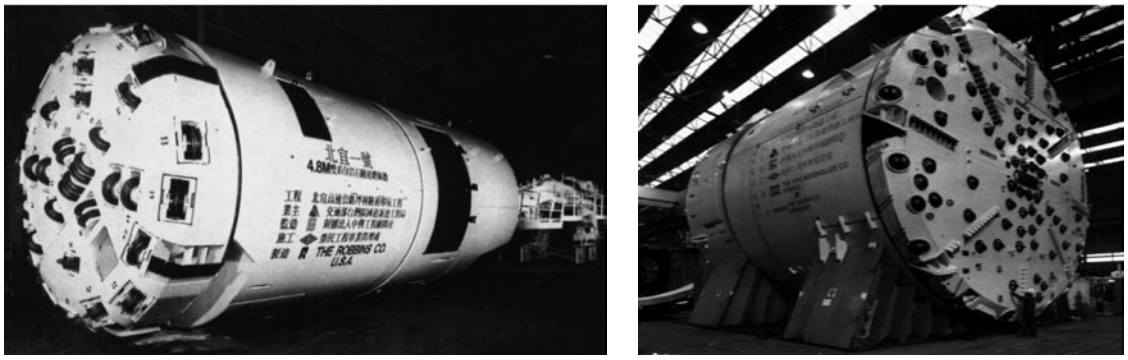
ROCK STRATIGRAPHIC UNIT	LITHOLOGY	PILOT TUNNEL	EB MAIN TUNNEL
Szeleng Formation (SL)	Massive quartzite intercalated with coaly shale Fine to medium grain meta-sandstone intercalated with argillite	3,671 (28%)	3,685 (29%)
Kankou Formation (KK)	Massive argillite	2,161 (17%)	2,129 (16%)
Tsuku Formation (TSK)	Fine grain sandstone and argillite	416 (3%)	448 (3%)
Tatungshan Formation (TTS)	Alternations of fine grain sandstone and argillite (or silty sandstone) Sandstone intercalated with thin argillite (or silty sandstone) Argillite intercalated with thin silty sandstone Alternations of fine grain sandstone argillite (or silty sandstone)	3,018 (23%)	3,170 (25%)
Makang Formation (MK)	Alternations of sandstone and shale Massive sandstone intercalated with thin shale	3,295 (26%)	3,108 (24%)
Fangchiao Formation (FC)	Alternations of sandstone and shale Massive sandstone intercalated with thin shale	381 (3%)	377 (3%)

Table 3 Classification of Rock Types for Analysis

ROCK GROUP	UNIAXIAL COMPRESSIVE STRENGTH (MPA)	QUARTZ CONTENT (%)	TOTAL HARDNESS
Quartzite (SL Formation)	100-320	71-82	100-160
Non-quartzite (Other Formation)	20-90	20-64	18-50

Table 4 Rock Mass Classification used in Hsuehshan Tunnel

RMR RANGE	ROCK MASS CLASSIFICATION	SUPPORT TYPE
80-100	Very good rock mass	I
60-80	Good rock mass	II
40-60	Fair rock mass	III
20-40	Poor rock mass	IV
10-20	Very poor rock mass	V
<10	Extremely poor rock mass	VI



(a) Pilot TBM (ϕ=4.8 m)

(b) EB and WB TBM (ϕ=11.74 m)

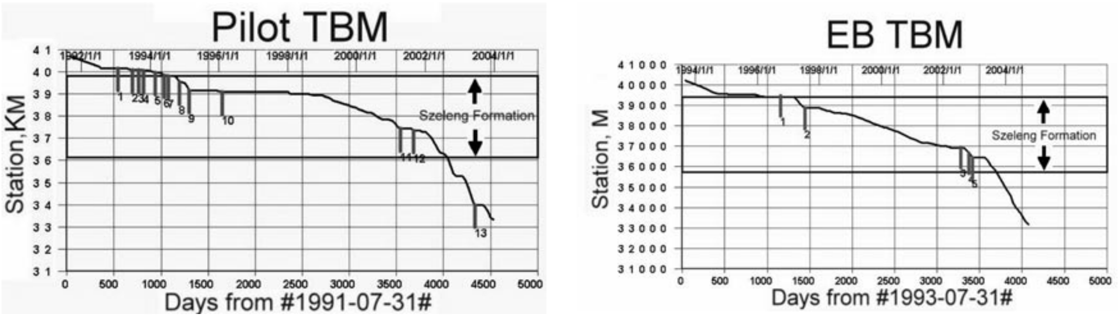
Fig. 3 TBM used in the Hsuehshan Tunnel

Table 5 Functional Specifications of Pilot TBM

1. Machine Type (NT$ 320,000,000)	ROBBINS 153-269 double shielded
2. Diameter of Cutter Head	4.8 M
3. Length of Double Shield	11.33 M (Cutter head to the rear shield)
4. Motor Type	Eletronic-driven, water cooled type (160KW)
5. Motor Number Used	6
6. Cutter Used	Face cutter *19, perimeter cutter * 7, center cutter * 8
7. Cutter Size	432 MM (17 IN.)
8. Rotation Rate, RPM	9.12(H)-4.56(L), modified to 7.0(H)-3.5(L)
9. Rotation Torque, kNM	1005(H)-2010(L), modified to 1306(H)-2612(L)
10. Gripper Number / Thrust	2 / 15,728 KN
11. Weight of Machine Head	305T
12. Boring Capacity	1,122KW
13. Pilot Drilling Machine/Hole Size/Length	HB-40A / 76MM / 80M
14. Capacity of Debris Output	360 M^3 / Hour
15. BU Length / Weight / Power Capacity	177 M / 360 T / 500 KW

Table 6 Functional Specifications of EB TBM

1. Machine type (NT$ 1,000,000,000)	WIRTH(German) / 1172 H / TS, double shielded
2. Cutter Head Diameter / Length	11.74 M / 11.7 M (cutter head to rear shield)
3. Outer Diameter of Front Shield	11.67 M
4. Outer Diameter of Rear Shield	11.655 M
5. Motor Type / No. / Capacity	Hydraulic-driven / 18 / 4,000 KW
6. Rotation Speed (Low-High)	0 ~ 4 RPM
7. Torque	7,200 KNM ~ 30,000 KNM
8. Thrust Piston No. / Thrust	18 / 50,670 KN
9. Rotation Rate, RPM	0-4
10. Rotation Torque, kNM	7200-30000
11. Cutter Used	Face * 71, perimeter * 3, central * 6, overcut * 3
12. Cutter Size / Weight	432 MM (17 IN.) / 181-186 KG
13. Size of Main Bearing	6,800 MM
14. Gripper No. / Thrust	2 / 6,920 KN
15. Gripper Seat No./ Thrust	2 x 4 / 65,000 KN
16. Auxiliary Thrust Piston No./ Thrust	28 / 78,820 KN
17.Segment Width / Thickness	1.5 M / 0.35 M
18.Segment Outer Diameter	11.5 M
19. Weight of Machine Head	1400 T
20. Boring Capacity	6400 KW
21. Pilot Drilling Machine	Montabert HC 80I /max. torque 800NM /35 KW hydraulic pump
22. Pilot Hole Size / Drilling Length	100MM max∮/depth 40 M
23. Capacity of Debris Output	1200 T/Hr.
24. BU Length / Weight / Power capacity	239 m / 700 T/ 5540 KW (shield excluded)



(a) Pilot TBM (b) EB TBM

Fig. 4 Progress and Stoppages of TBM Excavation

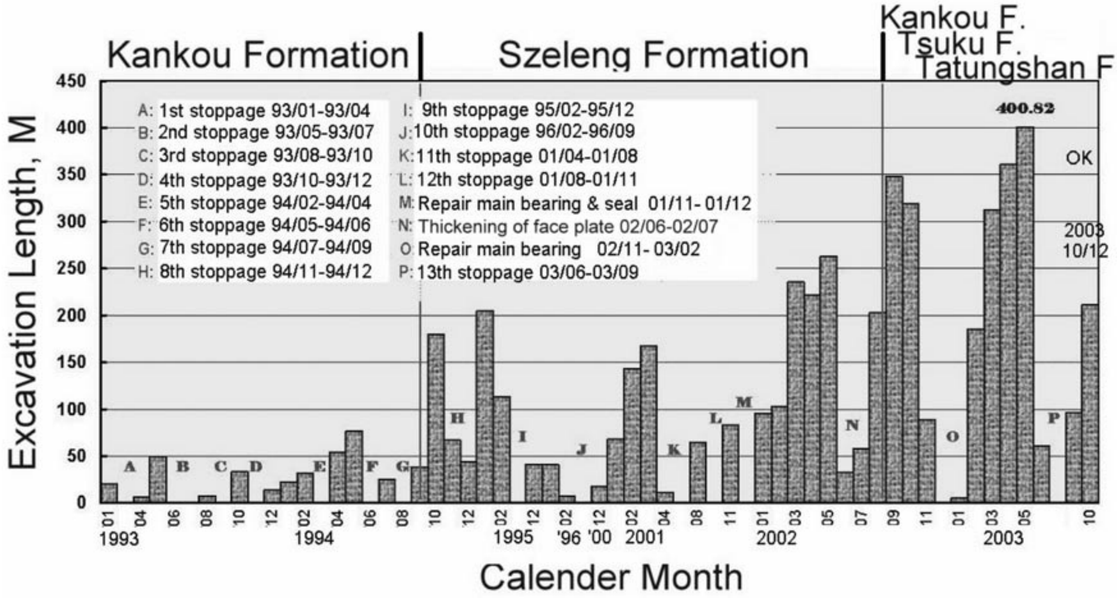


Fig. 5 Database of Cycle Time Analysis of Pilot TBM

and the EB TBM completed 3,870 m. The Pilot TBM was stopped a total of 13 times since its northwestward launch from 40k+158.9 on 1993/01/06. The longest rescue action for the Pilot TBM was 290 days. The EB TBM was only stopped a total of 5 times since it was launched northwestward from 39k+512 on 1995/08/21. Fig. 3 shows the major incidents for both Hsuehshan Tunnel TBMs. These stoppages caused serious delays and it was necessary then to adopt the drill and blast (D&B) excavation method to improve the excavation progress. In some sections mixed methods were introduced in which the top heading was applied using the D&B method prior to the use of the TBM These mixed methods were used in adverse ground conditions in order to facilitate excavation.

Cycle Time Analysis of TBM

The data used in the cycle time analysis comprises that in which the TBM progress was regarded as stable, as shown in Fig. 4 for Pilot TBM and Fig. 5 for EB TBM. The types of rock strata encountered were mainly the Szeleng Formation (Quartzite) and the Kankou, Tsuku, and Tatungshan Formations (Non-quartzite). The mean monthly construction progress of both TBM are also shown in these figures. For Pilot TBM, the cycle numbers in the analysis are 1049 (1139.59 m) within the Szeleng Formation (SL) and 1993 (2395.72 m) within the Kankou , the Tsuku, and the Tatungshan Formations. For the EB TBM, the cycle numbers in statistics are 799 (1198.26 m) within the Szeleng Formation and 1427

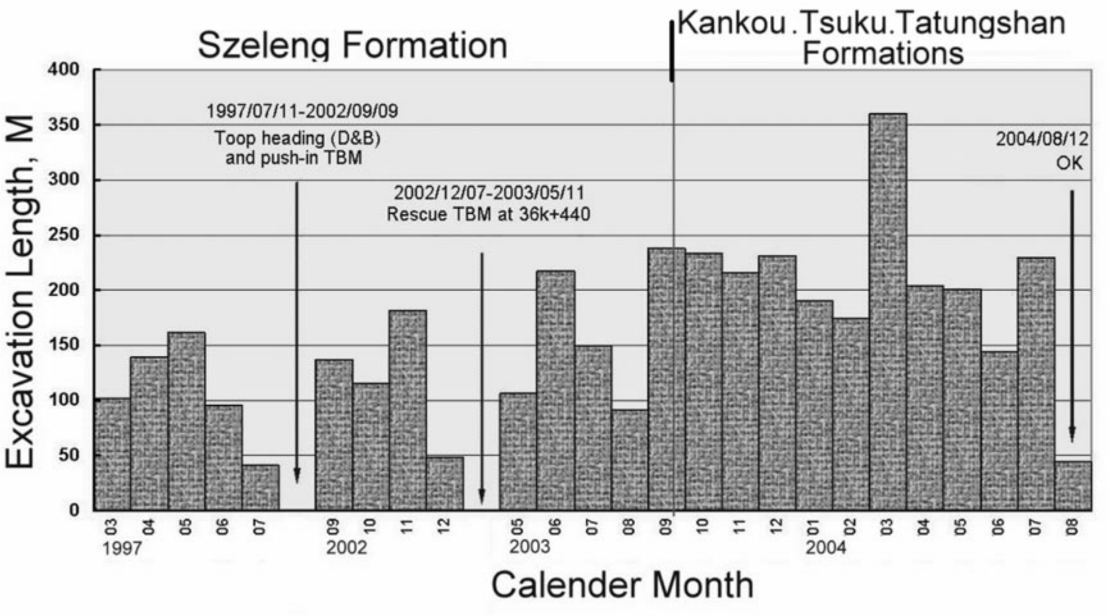


Fig. 6 Database of Cycle Time Analysis of the EB TBM

(2140.01 m) within the Kankou , the Tsuku, and the Tatungshan Formations.

Table 7 and Table 8 show the statistics of cycle time analysis in quartzite rocks and non-quartzite rocks respectively for the Pilot TBM. The major rock mass types encountered were type II, III, IV and V in which the type III and IV were the dominant ones. Some of the data of type VI rock mass was withdrawn due to the fact that only limited cycles were collected. It has to be pointed out that because rock mass classification can not be carried out accurately inside a shielded machine, the rock type statistics shown here were not considered to be highly accurate. Table 8 and Table 9 show the statistics of cycle time analysis of the EB TBM for the rock groups mentioned above. No type II rock masses were found, and type III and IV were again more dominant than type V and VI.

Cycle time analysis of the two types of rock groups for both TBMs was conducted. The average results of the Pilot TBM are shown in Fig. 7. The mean shift time for quartzite was 321.25 min/shift, for non-quartzite was 209.75 min/shift. The results of the Pilot TBM indicate that the time used for each item was significantly different between quartzite and non-quartzite. The time spent for items C (segment installation), E (maintenance mainly for changing disk cutter) and F (Drilling) in particular was much greater for quartzite than that for non-quartzite. In general, cycle time for Pilot TBM excavation in quartzite is significantly higher than that for non-quartzite.

The results for the EB TBM are shown in Fig. 8. The mean shift time for quartzite was 360 min/shift, for non-quartzite was 484.67 min/shift. It is noted that the cycle time for EB TBM excavation per shift in quartzite is less than that for non-quartzite, contrary to that found for the Pilot TBM. Basically, the results show that there was not much difference in each item for both rock groups but the time spent for item D (maintenance) was much greater for quartzite than that for non-quartzite. The major activity of the item "maintenance" was mainly the time spent for replacing the disk cutter. In contrast, the time spent for item F (malfunction) was much less for quartzite than that for non-quartzite, especially in Type IV rock

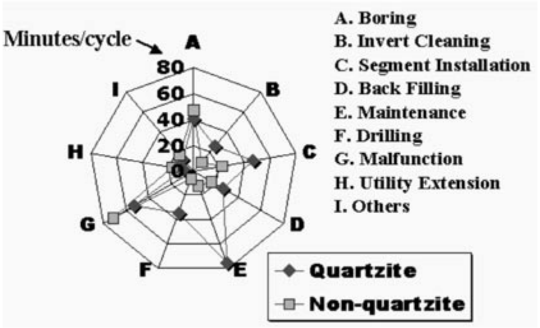


Fig. 7 Cycle Time Analysis of Pilot TBM

Table 7 Statistics of Cycle Time Analysis in Quartzite Rocks for the Pilot TBM (unit in min/ cycle)

ROCK MASS CLASSIFICATION	II	III	IV	V	AVERAGE
Shifts (Cycles) in Statistics	20	487	405	37	1049
Length of Excavation (M)	24	583.03	488.16	44.4	1139.59
A. Boring	58	37	33	34	40.50
B. Invert Cleaning	9	15	17	60	25.25
C. Segment Installation	32	34	47	73	46.50
D. Back Filling	28	20	20	38	26.5
E. Maintenance	68	164	29	40	75.25
F. Drilling	56	20	36	25	34.25
G. Malfunction	71	58	43	39	52.75
H. Utility Extension	6	9	6	9	7.5
I. Others	9	16	9	17	12.75
SUM=A+B+C+D+E+F+G+H+I	337	373	240	335	321.25

Table 8 Statistics of Cycle Time Analysis in Non-quartzite Rocks for the Pilot TBM (unit in min/ cycle)

ROCK MASS CLASSIFICATION	II	III	IV	V	AVERAGE
Shifts (Cycles) in Statistics	45	1475	401	72	1993
Length of Excavation (M)	54	1774.12	481.2	86.4	2395.72
A. Boring	38	44	43	54	47.25
B. Cleaning	8	7	12	10	9.25
C. Segment Installation	19	23	26	23	22.75
D. Back Filling	20	18	17	7	15.50
E. Maintenance	9	16	12	11	12.00
F. Drilling	2	11	4	8	6.25
G. Malfunction	53	102	32	97	71.00
H. Utility Extension	11	8	6	23	16.22
I. Others	14	14	7	30	16.25
SUM=A+B+C+D+E+F+G+H+I	174	243	159	263	209.75

Table 9 Statistics of Cycle Time Analysis in Quartzite rocks for the EB TBM (unit in min/ cycle)

ROCK MASS CLASSIFICATION	III	IV	V	VI	AVERAGE
Shifts (Cycles) in statistics	313	320	139	27	799
Length of Excavation (M)	470	480	208.26	40	1198.26
A. Boring	66	77	60	54	64.25
B. Segment Installation	15	20	23	19	19.25
C. Back filling	31	24	62	93	52.50
D. Maintenance	135	142	80	73	107.50
E. Drilling	12	8	0	0	5.00
F. Malfunction	65	87	66	23	60.25
G. Utility extension	2	1	8	0	2.25
H. Others	19	29	133	13	48.50
SUM=A+B+C+D+E+F+G+H	345	388	432	275	360.00

Table 10 Statistics of Cycle Time Analysis in Non-quartzite rocks for the EB TBM (unit in min/ cycle)

ROCK MASS CLASSIFICATION	III	IV	V	AVERAGE
Shifts (Cycles) in statistics	715	699	13	1427
Length of Excavation (M)	1071.5	1048.91	19.6	2140.01
A. Boring	67	71	52	63.33
B. Segment Installation	15	17	25	19.00
C. Back filling	46	62	70	59.33
D. Maintenance	34	49	142	75.00
E. Drilling	3	6	0	3.00
F. Malfunction	64	109	298	157.00
G. Utility extension	6	8	77	30.00

mass. This is interesting and the reason may be due to the management policies rather than the geological factors.

DISCUSSIONS

TBM performance can be associated with many controlling factors. According to Parkes (1988), The influences on TBM performance can be summarized as follows:

∗ The ground condition

∗ Tunnel design

∗ Local practices

∗ Management policies

∗ Machine capability

Among these factors, the ground condition and, in particular, the existence of rock discontinuities and the presence of groundwater were regarded as the most important factors which could influence the advance rate of the TBM. However, other factors may also play very important roles and they all contribute to affecting the overall performance of the TBM. In addition, the maintenance and general operation may have significant influence if the operators of the TBM don't have enough experience, as was the case in Taiwan. In this section, emphasis was put on the advance rate with respect to the rock mass classification.

Rock Mass Classification vs. Advance Rate

In Fig. 9 and Fig. 10, the cycle times of different types of rock masses were analyzed for Pilot TBM and the EB TBM. For the Pilot TBM (Fig. 9), the cycle times for each corresponding item were widely scattered and did not follow any significant trend with respect to the rock mass types. However, it is noted that for rock type II, the boring time (item A) and drilling time (item F) of quartzite rock per shift are significantly higher than that of the non-quartzite rock. Rock classes were determined from the RMR (score 0-100) in which not only the rock material strength but the rock joint conditions played an important role. The significantly higher boring time of the quartzite rock can reflect the fact that when joints are rare in the rock mass, the boring time of the TBM would be controlled by the strength of the rock materials.

In contrast, when there were frequent joints in the rock mass, i.e. for type III or worse, the boring time will be independent of the rock mass class. It may be interesting to note that the maintenance times (item E) were also significantly higher in quartzite for all types of rock mass in the statistics, especially type III. This is believed to be due to the management policies in which timely replacements of worn disk cutters were done within the tunnel sections of type III rock mass for safety reason.

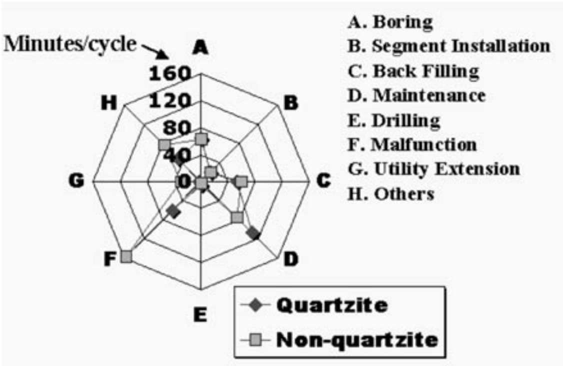
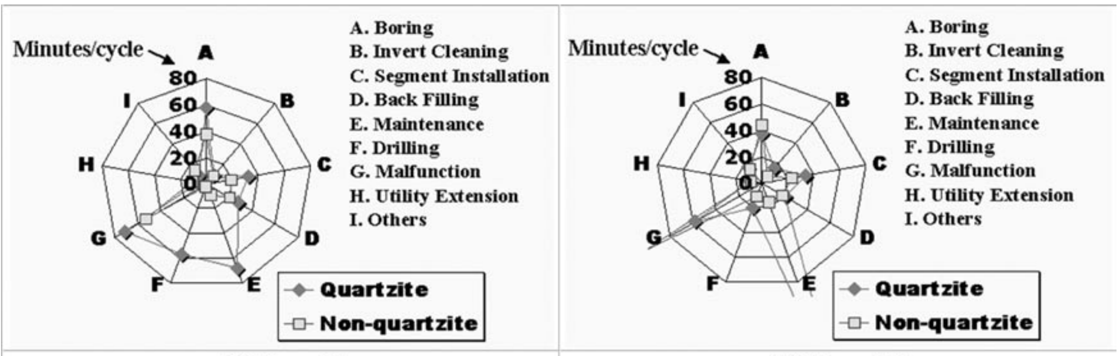
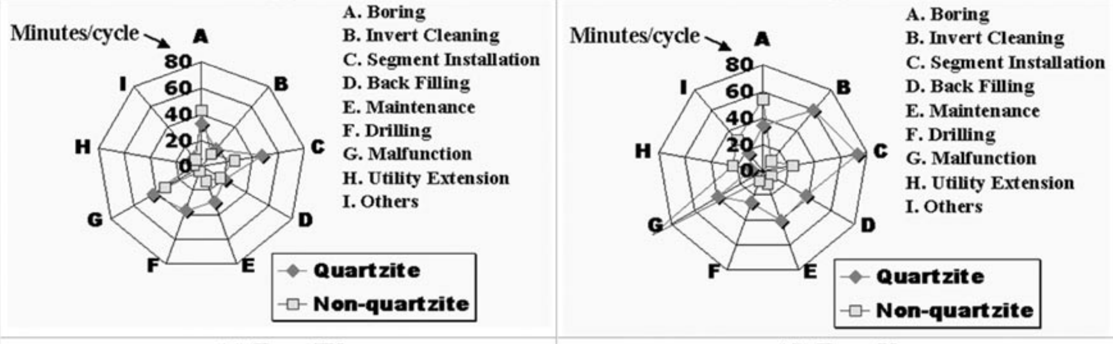


Fig. 8 Cycle Time Analysis of the EB TBM



(a) Type II (b) Type III



(c) Type IV (d) Type V

Fig. 9 Cycle Time Analysis by Types of Rock Mass for the Pilot TBM

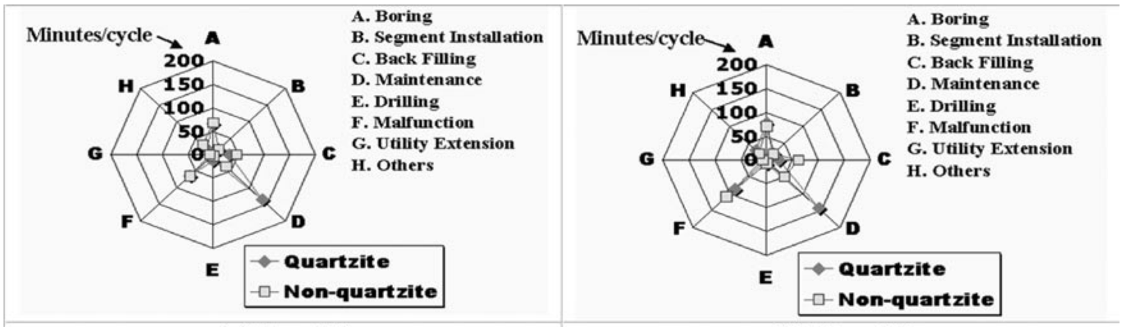
Similar to that of Fig. 9, the cycle times for each corresponding item were also widely scattered on the EB TBM (Fig. 10), and did not follow any significant trend with respect to the rock mass types. The boring time of quartzite rock per shift is not much different than that of non-quartzite rock. The significant higher maintenance time (D) of quartzite rock can be noted for type III and type IV rock masses. It was noted that the malfunction time (F) was significantly higher in quartzite for type V rock mass and the management policies of the contractor may be responsible. No type VI rock masses were found for non-quartzite rock groups.

As shown in Fig. 11 and Fig. 12, the times for boring and maintenance in quartzite and non-quartzite rocks under different rock mass types were compared. For the Pilot TBM (Fig. 11), there was no significant difference in the boring time among all the types of rock masses except for those of type II as mentioned above. On the other hand, the maintenance time for type III rock masses was significantly higher than other types. This may be due to the fact that changing the disk cutter took so much time. The frequent replacement of the disk cutter was due to the high abrasiveness of the rock encountered or the intentionally delayed maintenance in the more stable type III rock mass.

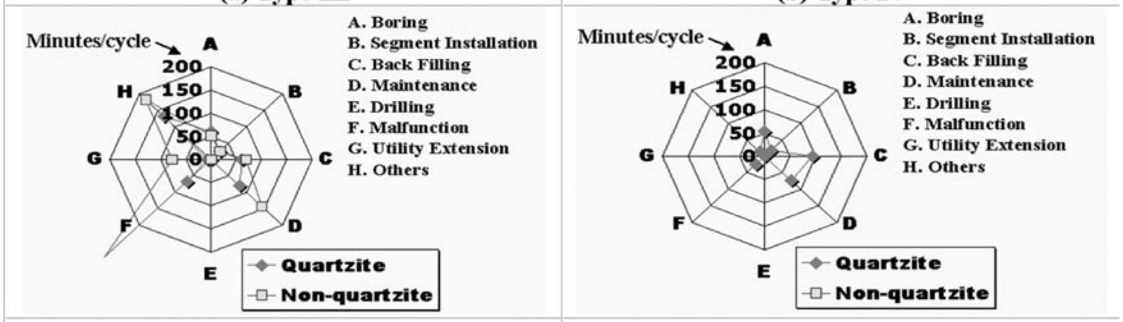
For the EB TBM in Fig. 12, there was no significant difference in the boring time among all the types of rock masses. On the other hand, the maintenance time for type III and VI rock masses was significant higher than other types. However, no general trend of correlation between boring time or maintenance time and rock mass type can be observed from the analysis.

Performance of TBM

Table 11 summarizes the statistics of the mean TBM performance in the Hsuehshan Tunnel. The statistical data comprises the TBM excavation from 2002/01 to 2003/10 for the Pilot TBM, and 2002/09 to 2004/08 for the EB TBM. During these times the TBM excavations were regarded as being in normal and stable conditions. From the data shown, the mean monthly progress of the Pilot TBM is about twice as much in non-quartzite rock as that in quartzite rocks. For the EB TBM, the progress in quartzite rock was also slower although the difference is much smaller. The slow progresses in the quartzite rocks reflect the fact that there were severe difficulties in passing through the abundant quartzite within the

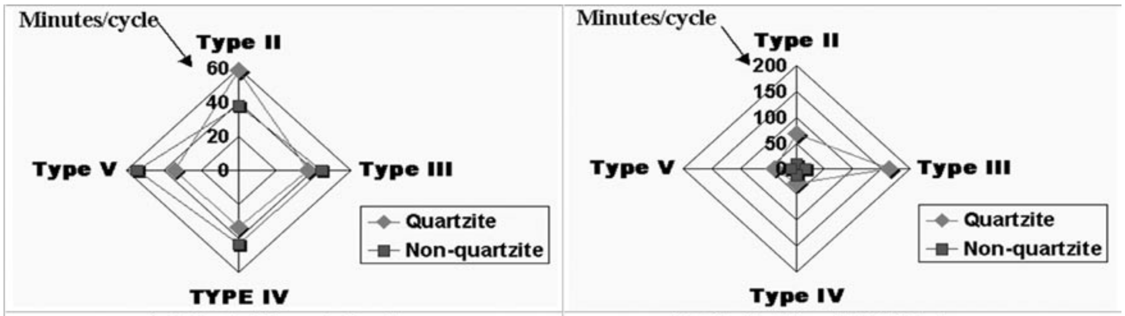


(a) Type III　(b) Type IV



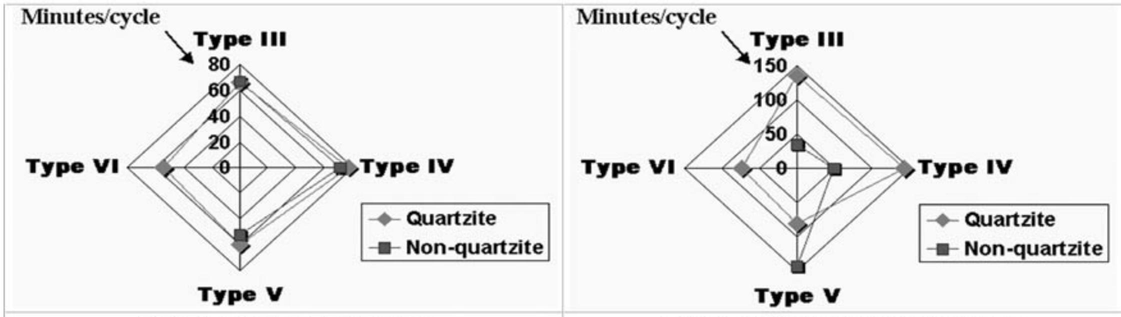
(c) Type V　(d) Type VI

Fig. 10 Cycle Time Analysis by Types of Rock Mass for the EB TBM



(a) Cycle Time A:Boring　(b) Cycle Time E: Maintenance

Fig. 11 TBM cycle time analysis by items for the Pilot TBM



(a) Cycle Time A:Boring　(b) Cycle Time D: Maintenance

Fig. 12 TBM Cycle Time Analysis by Items for the EB TBM

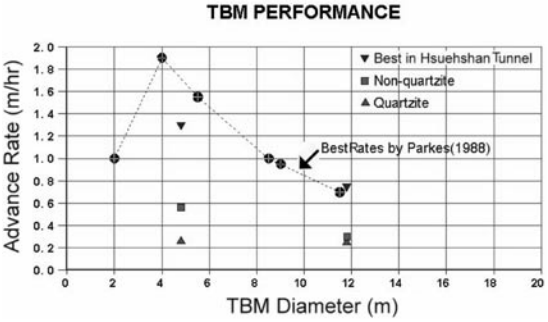


Fig. 13 Comparison of Advance Rate with the Diameter of Hard Rock TBM

Szeleng Formation.

From case studies covering 65 tunnels in many different tunnel projects, Parkes (1988) pointed out the best advance rate (m/hr) that a TBM could achieve and this is shown in Fig. 13. As the figure shows for a diameter of 5.5 m the estimated rate is 1.55 m/hr while for a TBM with a diameter of 11.5 m it is 0.7 m/hr. The average advance rates shown in Table 11 were plotted against the TBM diameter and are shown in the figure. The average data shows that unsatisfactory advance rates were obtained. Nevertheless, the plotting of the best advance rates for both the TBMs used in Hsuehshan Tunnel shows that the TBM performances were approaching the ideal rate in spite of their poor average performances.

CONCLUSIONS

The performance of the TBM used in the Hsuehshan Tunnel was studied in a statistical manner in this paper. Cycle time analysis for the Pilot TBM and the EB TBM showed that there were no general trends of correlation between the boring time or the maintenance time and rock mass type could be observed.

The reasons for rock mass class not playing an important role in affecting the cycle time may be due to the low level of accuracy in making the rock mass ratings in a shielded machine. Instead, the management policies instead were the major controlling factors that related to the advance rates in the Hsuehshan Tunnel Project. The influences of geologic factors would only become important for those rock mass classes where rock discontinuities are rare (Type II) and the strength of the rock material becomes dominant.

It is believed that overall performance is a function of many factors, including the TBM capability, excavated diameter, nature of the ground conditions and the presence of groundwater, etc. Since the rock tunnel TBM applied in the Hsuehshan Project was also the first applied in Taiwan, lack of experience was responsible for the poor progress in passing through the quartzite rock mass in the Szeleng Formation. Nevertheless, both the best performances of the Pilot TBM and the EB TBM were excellent in the later stages of the excavation under moderate geological conditions.

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Table 11 Statistics of TBM Performance in Hsuehshan Tunnel

TBM PERFORMANCE	UNIT	PILOT TBM QUARTZITE	PILOT TBM NON-QUARTZITE	EB TBM QUARTZITE	EB TBM NON-QUARTZITE
Monthly Progress	M	151.79	318.08	176.72	211.88
Penetration Rate	M/Hr	2.43	1.95	1.51	1.47
Utilization Ratio	%	11	29	16	20
Advance Rate	M/Hr	0.26	0.56	0.25	0.30

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