IMPROVING PERFORMANCE OF SHIELD TBM FOR SUBWAY TUNNEL PASSING THROUGH RIVERBED

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Abstract: As a technology of mechanical excavators is developed, an application of Shield TBM becomes variable and wide. As a result, shield TBM can be applied most geological conditions, such as soil condition with high water pressure, hard rock condition, and mixed condition. However, an extensive and detail geological investigation should be conducted to select most suitable equipment and cutting tools for high performance. This paper will focus on an improvement of shield performance in difficult condition by alternative plans and modifications of shield TBM.

Keywords: shield TBM performance, advance rate, cutter consumption, downtime.

1. INTRODUCION

The majority of civil engineering tunnel projects has been carrying out by open cut method (subway tunnel) or drilling and blasting method (mountain tunnel) for economic reason. However, recently, a mechanical excavator is often applied mountain tunnel and subway tunnel because faster development schedules and lower costs can be achieved with mechanical excavators when supported by adequate tunnel planning and detailed performance analysis are supported. Especially, largely increased applications of mechanical excavators for a subway tunnel in urban area are not only economic reason, but also public concern and other environmental reason [4].

Shield tunnels constucted in Korea, larger than 5m diameter, are Gwangju subway tunnel and Busan subway tunnel taking by Doosan Construction & Engineering Co., Ltd. A diameter of shield TBM (Earth pressure balanced Type) of Gwangju subway tunnel is 7.38m, and a diameter of shield TBM (Slurry pressure balanced type) of Busan subway tunnel is 7.28m diameter. In addition, shield TBM in Busan subway tunnel is passing through riverbed, which is very difficult ground condition.

This paper will discuss the status of the site and how improvement of performance has been done.

2. CONSTRUCTION OF BUSAN SUBWAY LINE II, SECTION 230

A construction of Busan Subway Line II, Section 230 is a part of a regional scheme to solve traffic congestion, to provide equivalent development around the city, and to hold 2002 Asian Game successfully in Busan, Korea.

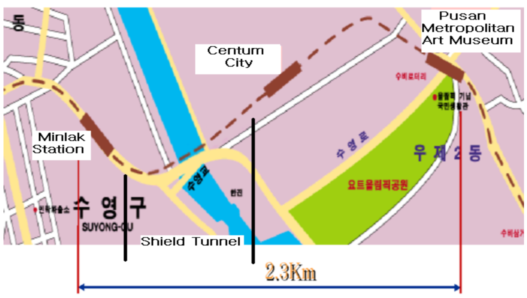


Figure 1. Plane of Busan Subway 230 section

A summery of the construction is shown below.

- Location: Minlak-Dong, Sooyoung-Gu ~ Uoo-Dong, Haeundae-Gu, in Busan
- Length: 2323.4m
  (Include MinLak, Centum City, and Metropolitan Art Museum Station)
- Tunneling Method: Shield TBM, Open cut
- Completion Period: May 19, 1995 ~ May,

31, 2002
□Shield Tunnel :Total 820m (420m+420m), Twin single rail tunnel
□Shield Tunnel Size : 7.1m O.D. (6.5m I.D.)

The shield TBM is passing 9m beneath the river and excavating 420m in length. The shield TBM was planned to start from a departure shaft in Centrum City station to a U-turn shaft in Minlak station. After arriving U-turn shaft, Shield TBM will be repaired and restarted to departure shaft.

This construction was originally planned by open cut method on cofferdam. But because fisher right on downstream and overflow of upstream are caused by reduction of river width during heavy rainfall, a shield tunneling method was selected.

3. GEOLOGICAL INVESTIGATION

A geological investigation is the most important prodedure to design shield TBM and to analyze the performance of it.

The geological investigation was conducted in every 20m along tunnel line and an additional investigation was done during undertaking construction at all times. Figure 2 shows a typical profile of the site.

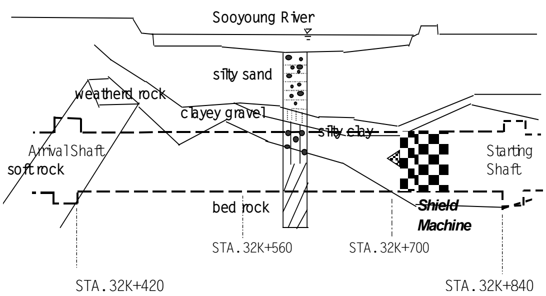


Figure 2. Geological profile of Sooyoung riverbed

The depth of soil layer is about 13 meters on land side and about 9 meters on riverbed side.

The subsurface geology in this area consists of fluvial deposits such as silty sand, sand, clay, silty clay, and colluviums such as clayey gravel and clayey gravel boulders. The rock bed consists of granodiorite and andesite of Cretaceous age.

The subsurface geology of tunneling section is divided into three types ;

- Full face rock section :
  STA. 32K+420 ~ STA. 32K+560
- Mixed face section :
  STA. 32K+560 ~ STA. 32K+700
- Full face soil section :
  STA. 32K+700 ~ STA.32K+840

A strength of the rock mass (unconfined compression strength) is higher than 2400kg/cm^2 around STA. 32K+420 and a strength of it is decreased to lower than 500kg/cm^2 around STA. 32K+560.

A mixed face section is consisted of bedrock and soil. Bedrock is consisted of weathered rock (lower than 500kg/cm^2) and hard rock(higher than 2000kg/cm^2), and RQD is very low (lower than 30%). The mixed face section is composed of clay gravel mainly (the N value is higher than 50) and the rest of it is silty sand (the N value is lower than 15).

The full face soil section is consisted of clay gravel at the lower side and silty sand at the upper side. The N value of clay gravel layer is higher than 50 and silty sand is lower than 15, so the possibility of collapse in silty sand layer is very high during the construction.

4. TECHNICAL SPECIFICATION OF SHIELD TBM

The shield TBM was designed to excavate in both soil and rock condition.

A detail specification of the machine is shown in Table 1.

Table 1. Detail specification of Shield TBM

	Specification
1. Type of Shield	Slurry Pressure Balanced Shield
2. O. D. of Shield	7,280mm
3. O. D. of Segment	7,100mm
4. I. D. of Segment	6,500mm
5. Length of Shield	8330mm
6. Cutter head	Flat cutter head
1) Type	2 way rotation 6 spoke intermediate supporting
2) Electric Motor Power	132kw * 7 EA = 924kw
3) Speed	0 ~ 0.8rpm (high torque) 0 ~ 1.5 rpm (low torque)
4) Opening Ratio	29%
7. Roller Disks	Combination 14” (constant cross section)
1) No. of Roller Disks	Face (37), Gauge(4), Center(4)
8. Shield jack	24 uinits
1) Stroke	1700 mm
2) Max. Thrust	200tf*24=4800tf
9. Weight of Shield	425 ton

5. FACTORS AFFECTING SHIELD TBM PERFORMANCE

The shield TBM performance depends on the advance rate and cutter consumption, and is affected by both ground parameters and machine factors, respectively. Both ground parameters and machine factors affect the advance rate, which are listed below [2] [4].

- Ground Parameters: surface geology type of tunneling section, fracturing, drillability , abrasiveness, hardness, UCS and point load strength
- Machine factors: cutter shape and size, RPM, cutterhead curvature, cutter space, number of disks, thrust

The cutter consumption is directly related to cutter abrasiveness. The same as the advance rate, both ground parameters and machine factors affect cutter abrasiveness. These factors are listed below [2] [4].

- Ground Parameters: cutter life index, mineral content (Quartz, mica, calcite, and amphibole)
- Machine factors: cutter size, RPM, number of disks, cutterhead diameter, cutter rotation

6. EXCAVATION OF SHIELD TUNNELLING PASSING RIVERBED

6.1Operation of Shield Excavation

The change of geological condition during shield excavation affects the operation of shield TBM and the advance rate of machine. Figure 3 shows the significant increase of thrust in mixed condition compared to soil condition. Also, thrust of shield TBM is proportion to UCS on rock. As seen in figure 3, when a shield TBM drives from soil condition to mixed or rock condition, and if shield TBM keeps a high extension speed of shield jack, the roller disks will be damaged by extremely high thrust load and momentary load.

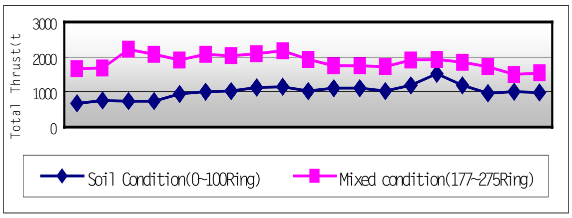


Figure 3. Thrust in soil and mixed condition

Therefore, an operation mode of shield TBM between soil condition and mixed / rock condition should be changed from normal mode (low RPM and high extension speed of shield jack) to rock mode (high RPM and low extension speed of shield jack). It delivers better performance and protects from damaging cutter tools by overload. Other operational information is listed below.

- Earth Pressure of face: 1.5 ~ 2.0 kg/cm^2.
- Feeding Pressure: 1.8~ 2.1 kg/cm^2
- Backfill Grouting Injection Pressure : 1.5 ~ 2.0 kg/cm^2

6.2Down time for changing Cutter Tools

Shield tunneling should be supported by adequate tunnel planning and detailed performance analysis in order to reduce downtime and to achieve high performance.

In this project, a major mechanical source of downtime was the change of the cutter tools among shield TBM repair, maintenance, and back-up systems repair. In addition, a large amount of downtime of cutter change was associated with a ground stabilization, which wasn't pretreated to change cutter tools in soil due to unexpected stop and cutter change.

Since shield TBM started to excavate in November 20, 2000, 125 roller disks have been changed through 5 times until July 16, 2001. High frequency of cutter change takes a considerable part of the tunneling performance in mixed face condition under River. As the result of field data, the percentages of the total shaft time (238days) associated with cutter change and grouting (111 days) is 48.76%. Table 2 summarizes downtime for cutterchange including the ground stabilization.

Table 2 Location and downtime for cutter change

	Location	No. of cutters changed	Downtime (day)
1st change	212.4m (177R)	30	60
2nd change	234m (195R)	26	29
3rd change	250.8m (209R)	15	14
4th change	267.6m (223R)	45	5
5th change	291.6m (243R)	9	3
Total	**291.6m (243R)**	**125 Pieces**	**111 days**

7. IMPROVING OF SHIELD EXCAVATION

7.1 Analyzing cutter abrasion form and distortion

Roller disks were changed every 20m in mix face and full face rock condition. The distance to be driven depends on ground parameters and machine factors, which was explained in chapter 4. Figure 4 shows an increase of torque before cutterhead got stock. There are the reasons that those roller disks are highly worn and flat worn cause high rolling forces.

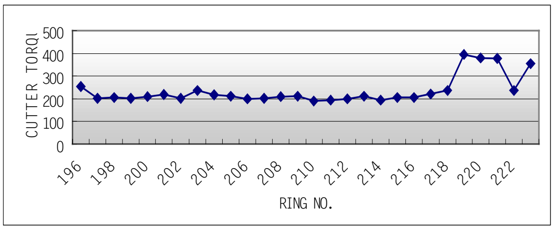


Figure 4. Change of torque associated with abrasion of cutter

A cutter consumption is associated with high disk abrasiveness. And geological condition can be predicted by abrasion form of roller disks. According to the University of Troundheim and the Norwegian Institute of Technology [2], abrasion forms of roller disks are different depending on abrasiveness. The flat edge, a, in Figure 5 occurs when boring in rock with high resistance to indention and high abrasiveness e.g. granitic gneiss. The double-curved edge, b, in Figure 5 occurs when boring in rock with average resistance to indention and high abrasiveness e.g. mica schist with a high quartz content. The heavily abraded disk, c, in Figure 5 occurs for a combination of low resistance to indention and low abrasiveness. The sharp edge, d, occurs when boring in rock with particularly low resistance to indention and low abrasiveness, e.g. lime clay slate.

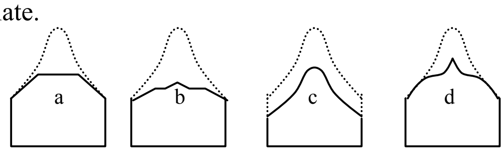
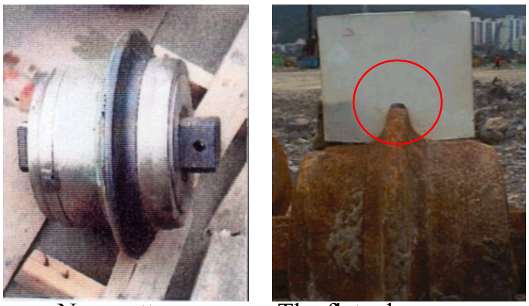


Figure 5. Abrasion forms

Picture 1 is shown new cutter and the cutter worn down to type a. It can be concluded that the property of rock mass on tunnel face is high abrasive and hard based on the observation of cutter worn and rock sample.



New cutter The flat edge

Picture 1. New cutter and the cutter normally worn down

Also, it is concluded that the rock on the site is hard and based on size of chipping rock discharged from chamber. Because thin and long chips means high surface hardness, and thick or rectangular chips means low surface hardness. Picture 2 shows a size and shape of chips, which are less than 3 cm long and 1 cm thick, obtained from the tunnel.

Picture 2. Chipping rocks discharged from chamber

There are several unusual abrasion forms of roller disk found from cutter change. Firstly, picture 3 shows the cutter worn down to a flat shape in 1st cutter change by impact. This shape of wear reduces seriously cutter life. The main reasons of cutter worn down to a flat shape are the damage of bearings of hub from joints or boundary between soil and rock by large thrust and momentary load.

Picture 3. The cutter worn down to a flat shape

According to Hard Rock Tunnel Boring from the University of Troundheim and the Norwegian Institute of Technology [2], the constantly varying surface of the rock face (fractures or mixed face) will result in an uneven distribution of the total thrust on the cutters. The momentary load on a single cutter may be up 10 times the average load. And weakness planes in the rock mass and mixed faces produce heavy blows on the cutterhead and vibration in the machine. It may produce “Frozen bearing” and cause the stop of rotation.

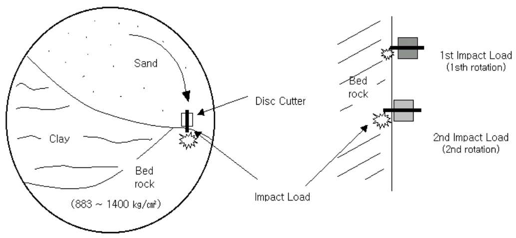


Figure 6 Cutter damage in mixed face condition

Secondly, picture 4 shows the distortion of cutter mount (T-bar), which supports the load of roller disk. It was damaged by the large thrust and the momentary load, interrupted a normal rotation of roller disks, and caused the roller disks worn down to a flat shape.

Picture 4. The distorted cutter mount

Thirdly, picture 5 shows the distorted cutter ring. Low hardness of cutter rings against high UCS rock face caused the distortion of cutter rings.

Picture 5. The distorted cutter ring

Those three unusual abrasion forms of roller disk produced the cutter life shorter and consumption of disk higher.

7.2Making alternative plan

The planned advance rate was 4.8m/day. But, from the data, shield tunneling has been achieved low performance, which an average advance rate including down time was 1.22 m/day and a cutter consumption was 2.33 m/cutter. The major reasons of low advance rate and high cutter consumption are concluded below.

- The investigation of geological condition on the site was inaccurate and inadequate. Higher UCS rock consists on site than what investigated.
- The usage of smaller Roller disks (14”) with low load capacities, which was far less than what was required for efficient cutting of the rock formations encountered.
- The large momentary load on cutters damages the bearing of roller disk and cause unusual abrasion more than soil and full face rock condition.

As the result, all options and parts were reviewed and the following alternatives were made:

1) Modifications and mode changes were made during $1^{st} \sim 3^{rd}$ change of roller disk

1 Mount strengthening - T-bar was weld to strength and to support the load.

2 Only high hardness of roller disks was installed.

3 Changing operation mode from normal mode to rock mode – A rotation speed of cutter head was increased from 0.8rpm to 1.8rpm. And the speed of shield jack extension was reduced. It reduced to damaging roller disks and mounts.

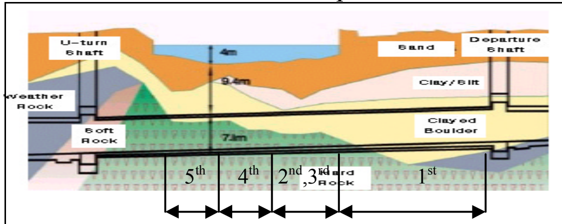
2) Modifications were made after 4^{th} change of Roller disk

1 Using chip insert roller disks - In abrasive rock with high hardness such as this site condition, the cutters must be replaced very frequently. The cutter edge will be easily worn down to a flat shape and not to the normal rounded shape. This result shows lower advance rates than the expected. In order to improve advance rate, roller disks with chip (carbide) insert were used from 4^{th} change of roller disk for alternative plan. In view of the results so far achieved, the cutter (the carbide chip) preserved their shape and high penetration over the cutter’s life. But, some

chip insert disks caused the steel around the carbide inserts were worn out quickly and then the inserts were crushed or removed in ground condition of low RQD and UCS.

2 A change of all roller disks at once – If all the cutters are new, the disc life will be higher due to an even ring wear before the cutter changes begin. Because an additional loads and high abrasion act on the protruding cutters, if the difference between adjacent cutter is occurred.

Table 3. Summaries of shield performance.



	5th change	4th change	2nd, 3rd change	1st change
Traveling Distant	24m (20R)	16.8m (14R)	38.4m (32R)	212.4m (177R)
Average Daily Advance	3.0 m/day	2.1 m/day	1.536 m/day	5.24 m/day
Roller disks Changed	9 cutters	45 cutters (All)	41 cutters (26+15)	30 cutters
Cutter Consumption	2.66 m/ cutter	0.37 m/ cutter	0.93 m/ cutter	7.08 m/ cutter
Ground Condition	Full Face Rock	Soil(1/2) Rock(1/2)	Soil(2/3) Rock(1/3)	Mostly Soil
Type	High abrasiveness rock	High abrasiveness rock	High abrasiveness rock	Sand, Silt, Boulder Clay
UCS (kg/ cm^2)	400~ 2400	600~ 1100	300~ 2000	-
RQD	0 ~ 70 %			
Torque (tf•m)	221	230	198	248
Thrust (kg/ cm^2)	1469	1850	1739	1400

8. CONCLUSION

This project is the first subway tunnel excavation under riverbed in Korea from November 20, 2000 to December 31, 2001 and planned 4.8m/day advance rate. However, the performance of shield TBM suddenly reduced from mixed face section. Therefore, the causes and alternative plans about low performance in mixed face condition have been studied.

The main reasons of low performance are;

1) Geotechnical Causes – Roller cutters were damaged by large momentary load on cutters in mixed face condition more than in soil and fully rock face condition.
2) Mechanical Causes – Flat type cutter head, low hardness of roller disks, 14” of roller cutter, and distortion of mount caused low cutter lifetime and performance.
3) Inaccurate plan by failure of detail performance analysis – More than 10 days for grouting was needed each time by unexpected stop.

In order to improve the performance of shield TBM, several alternative plans were applied, strengthening the mount, and installing high hardness roller disks and chip insert roller disks.

And, consequently, new cutter head, which is a dome type with 55 piece of 17” roller disk, and the mount supported by cutter head, will be installed on shield TBM to increase the performance after shield TBM completes only down tunnel.

Therefore, the authors expect that the advance rate of shield TBM will be achieved over 4.8 m/day with new cutterhead in mixed condition or rock condition. And the authors expect to complete this project on time successfully.

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