Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Tunnel Boring Machine Cutter Maintenance for Constructing Underground Cable Lines from Nuclear Power Plants

Lee Jaehwang, Eric Yee
KEPCO International Nuclear Graduate School, Ulsan, South Korea
Passion9898@gmail.com

1. Introduction

The tunnel boring machine (TBM), a machine used to excavate and construct tunnel-like structures, is being introduced to nuclear power plant (NPP) projects having many underground utilities and structures (i.e. cable tunnels, intake and discharge tunnels, etc.) or any other large project with a considerable underground component located nearby. Figure 1a shows the proposed location of cable tunnels for NPPs. This idea has gained steam after the Fukushima accident that basically forced several NPPs to be decommissioned. In the Fukushima accident, several high-voltage transmission cables were damaged due to intense shaking and it is presumed underground tunnels similar to ones shown in Figure 1b would lessen shaking effects. Additionally, underground waste facilities have also considered using tunneling in their construction, with some of the tunnel elements shown in Figure 2.

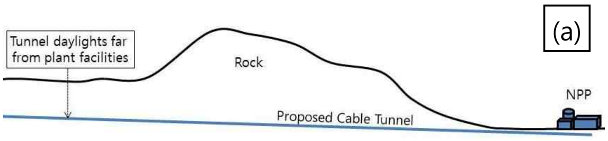


Fig. 1. (a) proposed cable tunnel and (b) example of an underground tunnel for power lines [1].

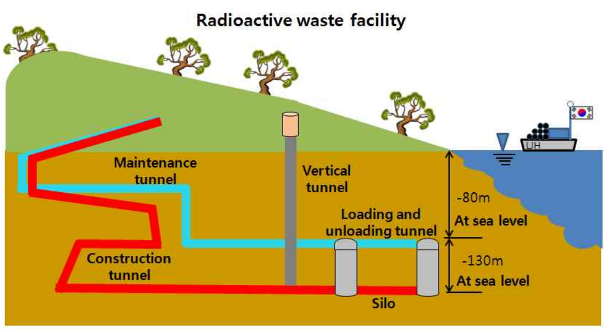


Fig. 2. Concept map of facility.

TBMs can construct an underground tunnel efficiently and without construction noise vibration related problems. Many civil projects, such as NPP construction, set importance on the economics of construction. Thus, advance rate, which is the speed at which the TBM is able to progress along its intended route, is one of the key factors affecting construction period and construction expenses. As the saying goes, “time is money.” In addition, it is important to manage construction permits and civil complaints, even when construction expenses and construction periods are excluded. So, accurate prediction for advance rate is important when designing tunnel project.

Several designers and project owners have tried to improve construction efficiency and tunneling advance rate. There have been several studies on managing the rate of wear, designing an optimum tunnel face, and finding the optimum cutter spacing.

Cutter replacements due to cutter wear and tear are very important because the wear and tear of cutters attached to the cutter head profoundly affect the advance rate. To manage cutter wear and tear is to control parameters related to cutter shape and cutter wear rate. There have been studies on the relationship between rock properties or TBM characteristics, and cutter wear or replacement. However, many of these studies relied on computer simulations or other small scale experiments [2].

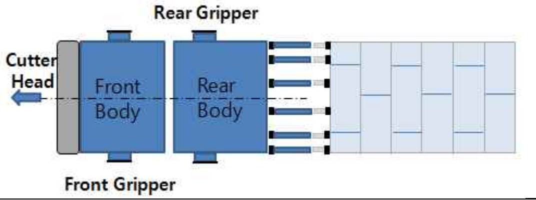
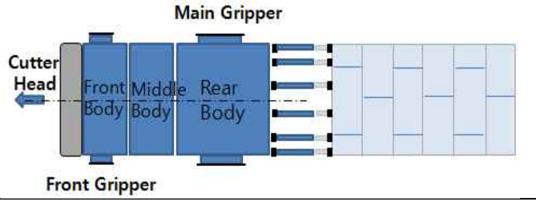
Therefore, this paper attempts to present a correlation between cutter replacement or cutter wear, against various parameters using practical data such as rock quality and TBM shield specifications, from an actual construction site.

2. TBM Selection for Construction

There are many types of Shield TBM and selecting an appropriate TBM typically involves selecting the thrust securing method, the status of the tunnel face opening, and the type of tunnel face, which is shown as a procedure in Figure 3. Project designers and project owners have to select the type of TBM in accordance with the outlined procedure.

An important factor that should be considered when considering TBM for NPP related construction is that there will usually be no feasible way to take the TBM out of the tunnel. Therefore, demountable TBMs should be employed.

Step1. Shield TBM 1st selection (securing method of thrust) [3]

<table>
<tr><th>Contents</th><th>Single type (thrust jack)</th><th>Double type (gripper and thrust jack)</th></tr>
<tr><td rowspan="2">Method introduction</td><td>
</td><td>
</td></tr>
<tr><td>- Excavating with thrust jack supporting from only segments</td><td>- Excavating with repetitive use of thrust jack and gripper</td></tr>
<tr><td>Main characteristics</td><td>- Slow excavation speed
- Easy to reassemble
- Excellent curving performance</td><td>- Fast excavation speed
- Difficulty of reassembling
- Poor curving performance</td></tr>
</table>

Step 2. Shield TBM 2nd selection (the state of opening of tunnel) [3]

Contents	Open mode	Closed mode	Dual mode
Supports for tunnel face	- No support - Tunnel face self-supporting	- Supported by earth pressure balance (EPB) - Supported by excess slurry pressure (ESP)	- No support when applying open mode - Supported by EPB, ESP when applying closed mode
Ground types	- Hard rock ~ Soft rock	- All types of the ground except: - High-strength hard rock - Soil ~ soft rock	- All types of the ground: - Soil ~ hard rock
Response to underground water	- Severely affected by underground water	- Possible to block underground water	- If there is a large amount of underground water, can apply closed mode
Tunneling ability	- Main target is rock - High tunneling ability	- Target is from soil to soft rock - Low tunneling ability	- Target is from soil to hard rock - High tunneling ability
Response to complex ground	- Problems with tunnel face's stability when meeting shattered zone	- Response ability for complex ground (shattered zone) is good	- Optimum for complex ground

Step 3. Shield TBM 3rd selection (open type of tunnel face) [3]

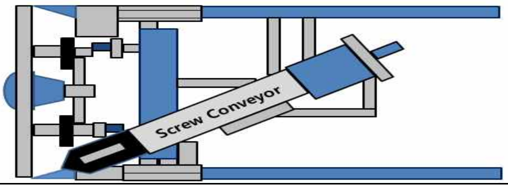
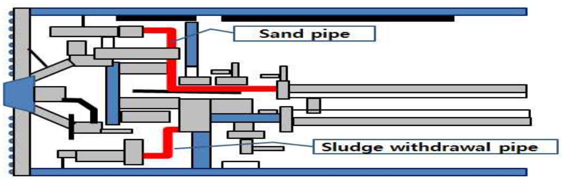
<table>
<tr><th>Contents</th><th>Earth Pressure Balance type (EPB)</th><th>Slurry type</th></tr>
<tr><td rowspan="2">Method introduction</td><td>
</td><td>
</td></tr>
<tr><td>- Feeling with sand at the space between tunnel face and barrier located in the rear of cutterhead to stabilize tunnel face and prevent loosening loads</td><td>- Highly pressurized water in the chamber to support external water and earth pressure</td></tr>
<tr><td>Support facilities</td><td>- Support facilities are simple</td><td>- Need large facilities to reprocess used water</td></tr>
<tr><td>Muck processing performance</td><td>- Possible to get appropriate treatment time and to mix many types of muck processing systems</td><td>- Not fit for rock due to blockage of sludge withdrawal pipe
- Transfer water mixed with muck to sludge withdrawal pipe</td></tr>
</table>

Fig. 3. The three steps in selecting an appropriate TBM.

3. Site Conditions

To explore the relationships between cutter replacement and rock index or engineering properties, data from an actual construction site is needed as well as the results from experiments on rock materials affiliated with the construction site. Therefore, a brief description of the geologic conditions of Gang Nam cable tunnel construction site during design is provided, along with the type of TBM that was selected. This tunnel's route is from Seoul Main Custom intersection to Renaissance hotel in Gang Nam Gu. Figure 4 shows the intended path of the TBM, along with locations of borings used to help evaluate geologic materials as well as marked faults.

3.1. Geologic Conditions.

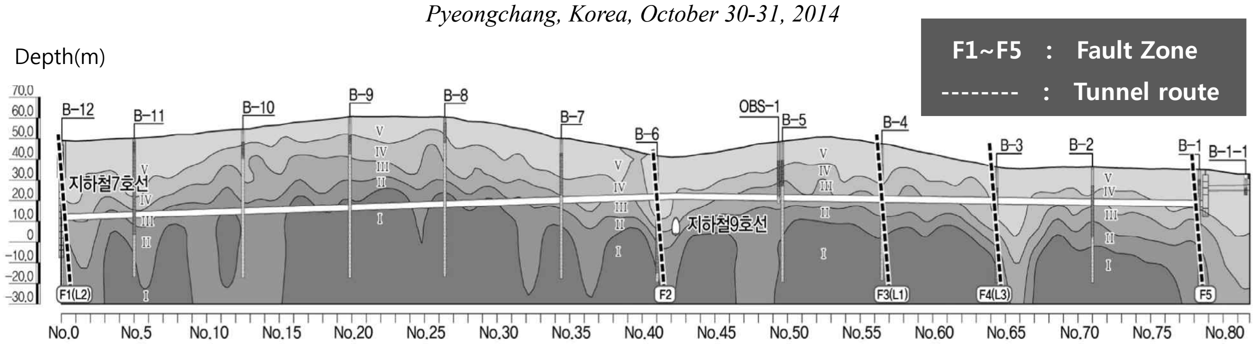


Fig. 4. Rock classification of the construction site path [3].

Weathered soil, weathered rock, soft rock, and hard rock were widely distributed along the construction site, where the tunnel was primarily designed to follow a hard rock route. There are several rock classification schemes that are used to help design tunneling through rock. A common rock classification scheme is the rock mass rating (RMR) system. The RMR of a rock material is dependent on its uniaxial strength, rock quality designation, joint spacing, condition of joints, orientation of the joints, and groundwater. Joints can be considered discontinuities in the rock mass. Another rock classification scheme is the rock quality index (Q). This is a fairly popular classification scheme, from an engineering perspective, and relies on rock quality designation, stress reduction factor, and varying values related to joints such as frequency, roughness, alterations, and water. Both RMR and Q range from 0 to 100, and are not absolute values to describe engineering parameters. For certain construction projects, the contractors will use proprietary rock material classification schemes or more general categorizations for easier communication across different parties. For the site in question, the grade of rock was divided into five grades from one to five and the properties of each grade are described in Table 2 below.

Table 2. Engineering properties related to rock classification [4].

Grade	Evaluation	RMR	Q	Resistivity (Ω-m)	V_p (km/s)
I	Very Good	81~100	>100	>4,960	>5.5
II	Good	61~80	4.0~100	2,720~ 4,960	4.1~5.5
III	Fair	41~60	0.1~4.0	1,490~ 2,720	2.5~4.1
IV	Poor	21~40	0.01~0.1	820~ 1,490	1.5~2.5
V	Very Poor	0~20	<0.01	<820	<1.5

For the tunneling path considered, the distribution of rock materials is approximately 23% grade I, 18% grade II, 32% grade III, 19% grade IV, and 8% grade V. This says that the TBM would have to tunnel through grade III type rock materials 32% of the time.

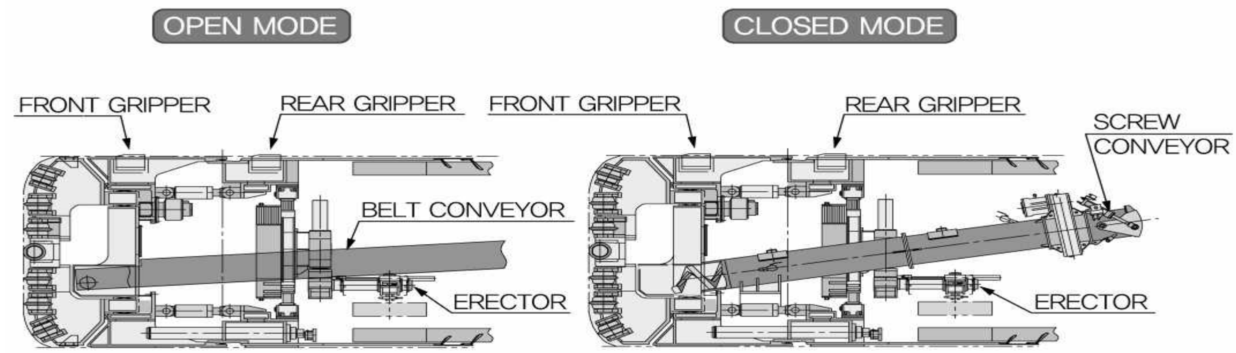


Fig. 4. Dual Mode EPB Single Shield TBM [3].

3.2. Equipment condition

Dual mode EPB single TBM was employed to this construction site. The machine could change the state of the tunnel face and needed only a small area to set up the muck processing plant. In addition, there were 12 hydraulic thrust jacks at the rear of the shield head.

There were two different kinds of length segments for the lining and tunnel structure. One was 0.6 m length segment for initial digging and severe curve course sections while the other was 1.2m length. Additionally, there were two different kinds of shape segments. One was the standard shape used in normal, straight routes while the other had a tapered shape for curved sections. This machine could also be dismantled for removal, making it suitable for use at a nuclear power plant related facilities.

The cutter head for this machine contained twenty two roller cutters, five center cutters and G1, G2 cutters which were used to excavate earth materials while simultaneously being in contact with the tunnel face.

The advance rate was also dependent on the replacement of disc cutters thus contributing to construction expenses and construction scheduling. If the replacement of the cutters is less frequent, then the more the efficient the tunneling process would be. The arrangement of each cutter is as shown in Figure 5. The figure shows both a front and rear view of the cutter head, with the G1 and G2 cutters notably aligned at the edge of the cross.

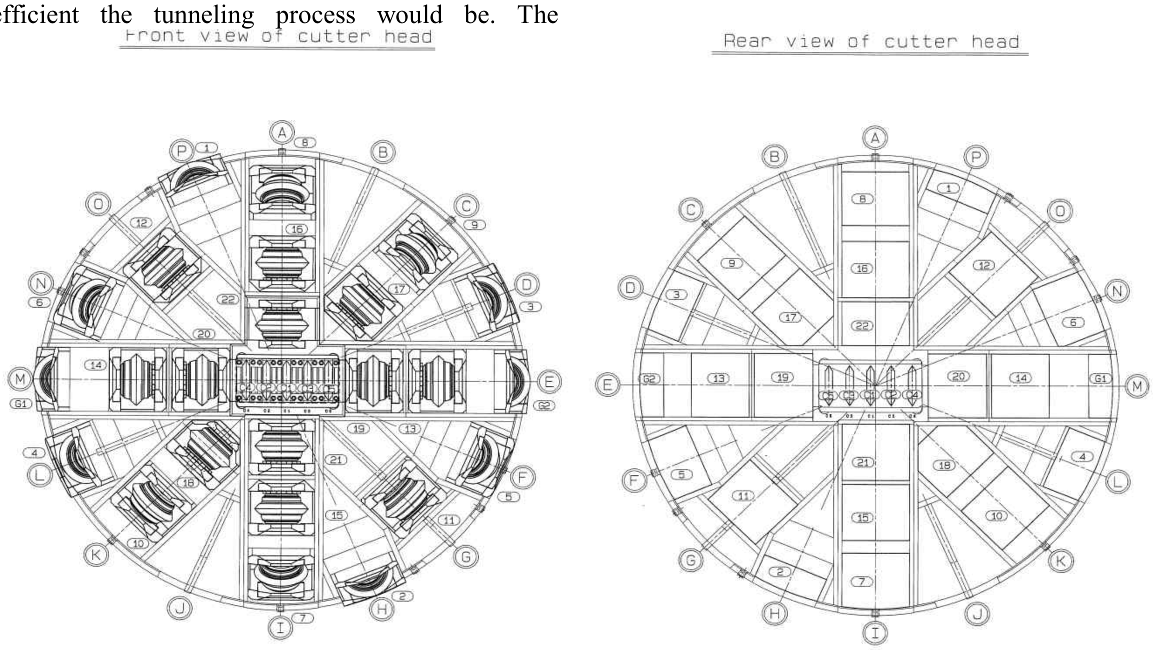


Fig. 5. Arrangement of roller cutters [3].

4. Analysis of Site Conditions

4.1. Advance rate

Several prediction models for penetration rate in soft rock and hard rock have been developed all around the world, such as the CSM model (Colorado School of Mines, USA), NTNU model (Trondheim University, Norway), Austria model, Swiss model, and Robbins model. Robbins is a company that manufactures TBMs and TBM equipment. The aforementioned models use fracture theory and empirical statistics in predicting an advance rate and machine excavation. Parameters such as Q_{tbm} and RMi_{tbm} are widely used in empirical rock classification as well. The advance rate as estimated by Q_{tbm} is presented along with the TBM manufacturer's model. To calculate the advance rate using Q_{tbm}, Q_{tbm} must first be calculated by:

$$\mathbf{Q_{tbm}} = Q_0 \left(\frac{SIGMA}{F_T^{10}/20^9}\right)\left(\frac{20}{CLI}\right)\left(\frac{q}{20}\right)\left(\frac{\sigma_\theta}{5}\right) \qquad (1)$$

where:

$\mathbf{Q_0}$ = Q value by $RQD_0 = \left(\frac{RQD_0}{J_n}\right)\left(\frac{J_r}{J_a}\right)\left(\frac{J_w}{SRF}\right)$
$\mathbf{F_T}$ (tonf) = thrust
$\mathbf{RQD_0}$ = axial RQD of tunnel
CLI = Cutter Life Index
SIGMA = rock mass strength
$\mathbf{q}$(%) = quartz content
$\boldsymbol{\sigma_\theta}$(MPa) = strain acting on the tunnel face

and

$$SIGMA = 5\gamma(Q_c)^{1/3} \text{ or } SIGMA = 5\gamma(Q_t)^{1/3}$$

$$Q_c = Q_{10}\left(\frac{\sigma_c}{100}\right), Q_t = Q_0\left(\frac{I_{50}}{4}\right)$$

σ_c(MPa) = **Unconfined compression strength**
I_{50}(MPa) = **Point load strength**,
$\gamma\left(\frac{g}{cm^3}\right)$ = **Unit weight**

Using Q_{tbm}, an advance rate, PR, can be estimated using:

$$\mathbf{PR = 5(Q_{tbm})^{-1.5} \quad [m/h]}$$

The advance rate at each distance can be calculated using equation (1) across this project and plotted as below in figure 6. For the tunneling project, Figure 6 shows the maximum advance rate was 3.56 m/hr and the minimum advance rate was 0.69 m/hr, with an average advance rate of 2.48 m/hr.

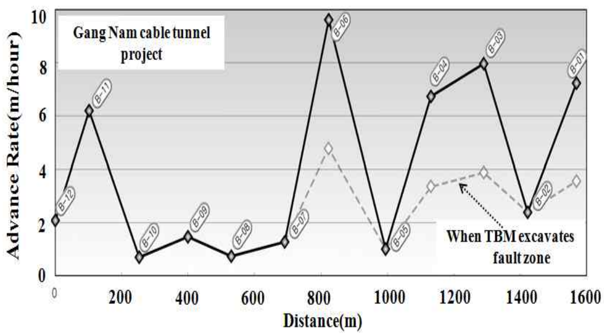


Fig. 6. Advance rate for each distance using Eq (1) [3].

Alternatively, the TBM manufacturer's relationship for TBM advance rate is given by:

$$PR = K \cdot (Wd - Wo)^{\alpha} \cdot N^{\beta} \quad [cm/min] \quad (2)$$

where:

K = *drillability constant*
Wd = *unit bore load [kgf/cm]*
Wo = *threshold load [kgf/cm]*
N = *rotational speed [min^{-1}]*
α, β= *specified constants*

The result of using Eq. (2) is shown in Figure 7.

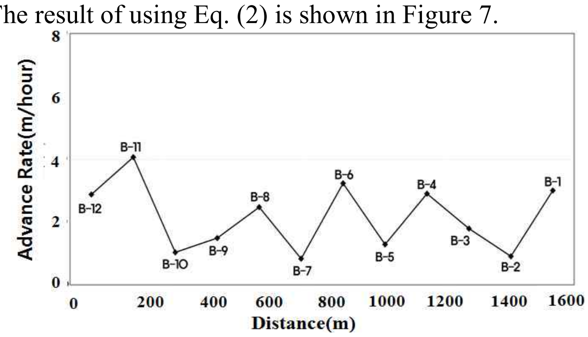


Fig. 7. Advance rate using Eq. (2) [3].

The advance rates shown in Figure 7 are under 4 m/hr, which is very different from the advance rates shown in Figure 6, which was calculated by using Q_{tbm}. Moreover, the average advance rate is lower using Eq. (2) than when using Eq. (1) across the tunnel route. It should be noted that the lower advance rates are similar in magnitude for both approaches. However, one approach would suggest the construction schedule would be faster than the other, and interestingly, neither approach considers the maintenance or replacement of cutters.

4.2. Rock quality

Rock classification schemes (RQD, RMR, Q-system) applied to the tunnel and its surrounding areas was carried out through boring investigations. The investigations focused on the tunnel line, or route, and the upper two diameters of the route, which is labeled as 2D. This is common practice as engineers understand that earth materials rely on the surrounding environment in its behavior to some extent. Table 3 shows the values of the different rock classification schemes and as well as the locations of these parameters along the tunnel line.

Table 3. Rock qualities from boring investigation [4].

Bore Hole	Station Number	Classification	Section(m)	RQD (%)	RMR	q_u (MPa)	Joint Spacing (cm)	Rock Mass Rating	Q	Rock Classification
B-1	NO.78 + 7.2	Upper 2 D	8.6~15.8	11	26	199	60~90	IV	0.074	EXT.POOR
		Scheduled Tunnel location	15.8~19.4	16	29		50~90	IV	0.079	EXT.POOR
B-2	NO.71 + 0.0	Upper 2 D	9.1~16.3	6	31	152.1	40~60	IV	0.05	EXT.POOR
		Scheduled Tunnel location	16.3~19.9	36	46		40~140	III	2.783	POOR
B-3	NO.64 + 8.0	Upper 2 D	8.3~15.5	0	28	77.6	10~20	IV	0.003	EXT.POOR
		Scheduled Tunnel location	15.5~19.1	4	30		10~50	IV	0.037	EXT.POOR
B-4	NO.56 + 9.2	Upper 2 D	18.8~26.0	20	38	50.9	50~70	IV	0.2	VERY POOR
		Scheduled Tunnel location	26.0~29.6	8	29		20~70	IV	0.059	EXT.POOR
B-5	NO.49 + 13.0	Upper 2 D	19.3~26.5	88	75	105.6	250~290	II	74.322	VERY GOOD
		Scheduled Tunnel location	26.5~30.1	90	74		290~340	II	57.884	VERY GOOD
B-6	NO.41 + 0.0	Upper 2 D	12.1~19.3	0	28	46.4	10~25	IV	0.019	EXT.POOR
		Scheduled Tunnel location	19.3~22.9	0	27		20~25	IV	0.019	EXT.POOR
B-7	NO.34 + 8.5	Upper 2 D	23.2~30.4	19	38	162.4	20~110	IV	0.237	VERY POOR
		Scheduled Tunnel location	30.4~34.0	76	72		110~240	II	18.419	GOOD
B-8	NO.26 + 8.1	Upper 2 D	36.6~43.8	99	85	58.3	310~1,500	I	174.793	EXT.GOOD
		Scheduled Tunnel location	43.8~47.4	93	81		420~450	I	164.334	EXT.GOOD
B-9	NO.19 + 17.3	Upper 2 D	39.4~46.6	60	62	92	170~220	II	6.242	FAIR
		Scheduled Tunnel location	46.6~50.2	65	64		220~230	II	10.023	GOOD
B-10	NO.12 + 9.9	Upper 2 D	36.4~43.6	95	83	130.3	300~1,500	I	110.814	EXT.GOOD
		Scheduled Tunnel location	43.6~47.2	99	84		600~1,000	I	153.338	EXT.GOOD
B-11	NO. 5 + 0.0	Upper 2 D	35.0~42.2	32	39	38.5	70~120	IV	0.527	VERY POOR
		Scheduled Tunnel location	42.2~45.8	18	36		60~80	IV	0.062	EXT.POOR
B-12	NO. 0 + 1.2	Upper 2 D	35.9~43.1	54	57	51.3	70~200	III	6.484	FAIR
		Scheduled Tunnel location	43.1~46.7	71	74		200~210	II	1.823	POOR

5. Analysis of Practical Data

This tunnel project installed underground segments almost 1.6 km in length. The TBM had installed almost 1,500 rings of segments with the operator recording all the necessary information. This information, which was presented in the previous sections, will be used to analyze the effect of cutter maintenance to advance rate.

5.1. Number of Cutter Replacements

In the 1.5 km tunnel section, operators replaced each cutter from 0 to up to 10 times. Cutter wear occurred depending on the position of cutter face based and is summarized in Table 4.

Table 4. Cutter replacement frequency and location.

Number of cutter replacement & repair					
Cutter No.	Replace-ment	repair	Cutter No.	Replace-ment	repair
1	8	9	16	1	2
2	9	5	17	4	9
3	9	12	18	3	2
4	8	11	19	2	10
5	7	16	20	2	4
6	6	10	21	0	5
7	6	14	22	0	4
8	5	10	C1	5	1
9	5	6	C2	4	2
10	3	6	C3	8	2
11	2	7	C4	7	1
12	1	10	C5	7	1
13	1	2	G1	10	4
14	3	10	G2	10	3
15	2	3			

Table 5 reveals cutters located in positions 1, 2, 3, 4, G1, and G2 (which are highlighted in red) had been replaced quite frequently relative to the other positions. Figure 8 highlights in red circles the locations of the most frequently replaced cutters.

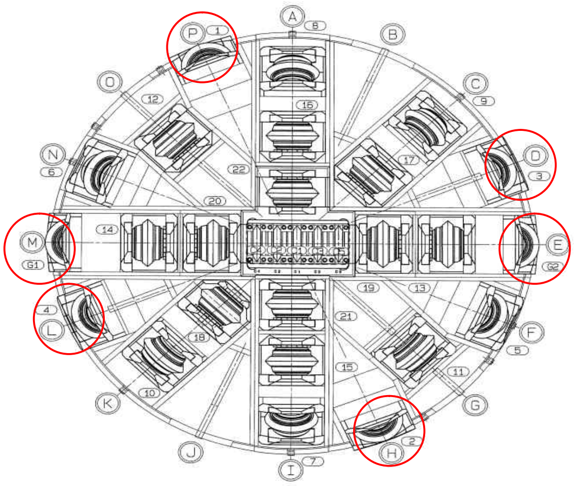


Fig. 8. Locations of frequent cutter replacement.

Table 5 and Figure 8 suggest the exterior cutters have a higher potential for replacement and thus maintenance issues.

5.2. Cutter Replacement and Rock Type

Regardless of the length of the tunnel section, a TBM excavates through the variety of rocks. Table 5 shows the 6 types of rock that the TBM experienced along its stations. These 6 types include banded gneiss, banded gneiss in the alteration zone, augen gneiss, augen gneiss in the alteration zone, alteration zone, and quartz superior, with banded gneiss being the most common rock material excavated along the tunnel line.

Table 5. Type of rock and its section [4].

No.	Type of rock	Section	Length
1	**Banded gneiss**	Sta. No. 0+0 ~ Sta. No. 20+19.4	419.4
		Sta. No. 30+19.9 ~ Sta. No. 37+19	139.1
		Sta. No. 49+19.1 ~ Sta. No. 65+19.4	320.3
2	**Augen gneiss + Zone of alternation**	Sta. No.20+19.1 ~ Sta. No. 30+19.8	200.7
3	**Zone of alternation**	Sta. No. 37+19.1 ~ Sta. No. 43+19	119.9
4	**Augen gneiss**	Sta. No. 43+19.1 ~ Sta. No. 49+19	119.9
5	**Quartz superior Zone**	Sta. No. 65+19.5 ~ Sta. No. 69+19.8	80.3
6	**Banded gneiss + Zone of alternation**	Sta. No. 69+19.9 ~ Sta. No. 78+17.4	177.5

Figure 9 shows cutter repair and replacement separated by the rock material the TBM was excavating. The figure shows a majority of the repairs and replacements occurred in the quartz superior followed by the banded gneiss in the alteration zone.

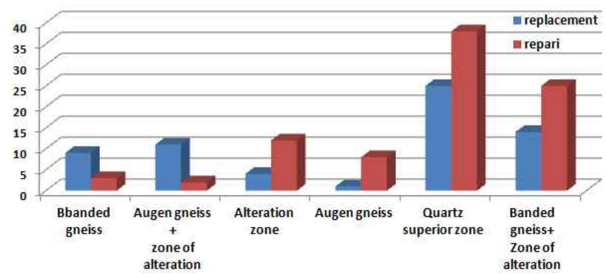


Fig. 9. A number of cutter repair and replacement while excavating each zones

5.3. Mechanical Performance

Advance rate is influenced by not only rock conditions but also mechanical performance. Figure 10 below shows the difference between predicted advance rate in the previous section and actual advance rate as recorded from operators' records from the tunnel project. As can be seen in the figure, the actual advance rate is much lower than the predicted advanced rate for an overwhelming majority of the tunnel route.

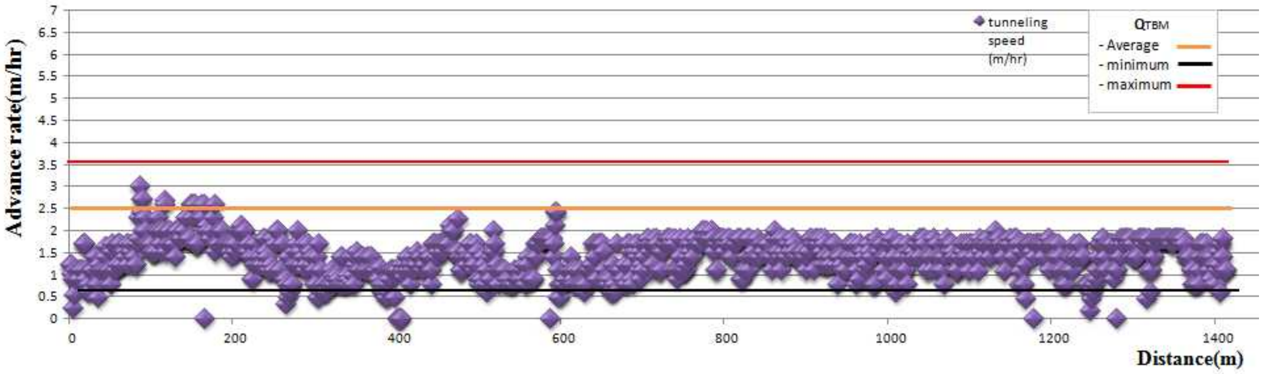


Fig. 10. The difference between predicted advance rate and actual advance rate.

6. Conclusions

This study was conducted to suggest directions in the improvement of TBM cutters by analyzing relationships between rock conditions and cutter maintenance as well as TBM advance rates. Actual field data was collected and compared to actual design values in evaluating the effectiveness of traditional approaches.

An analysis of the frequency of cutter replacements revealed cutters located at the exterior of the cutterhead had relatively high replacement rates than cutters located in the interior of cutterhead surface, especially cutters in the G1 and G2 positions. This would suggest more durable cutters should be installed in the exterior portions of the cutterhead to help save on construction expenses. An alternative would be to redesign the cutterhead or TBM such that the wear and tear on the exterior portions is lessened.

When the records were viewed from the perspective of rock type, analysis showed the frequency of cutter replacement and repair was much higher in the quartz superior rock, basically 2 to 10 times more. It is well known rocks containing high amounts of quartz have high rock strengths, which would suggest more work was needed from the cutters to break down the rock. Thus, designers may need to design a more favorable cutterhead, or in some extreme cases modify the tunnel route. Alternatively, construction personnel can be prepared for frequent and multiple cutter replacements or repairs when the TBM has reached a quartz-like rock formation.

Interestingly, the advance rate as calculated from the Q_{tbm} and manufacturers suggested approach generally over predicted the actual advance rate data. This leads to better advance rate models and implies the management of cutter replacement and repair is very important when considering advance rate.

Based on the results shown above, studying the relationships between rock conditions and equipment characteristics against cutter replacement and maintenance can lead to better performance. Moreover, the evidence suggests better advance rate models are needed to improve process controls and budgetary controls at tunnel construction sites.

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