Analysis of Cutting Tool Wearing of Tunnel Boring Machines in Singapore Mixed Face Ground Condition

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Abstract. During shield tunneling in composite stratum, especially in granite stratum with high rock strength and high-water content, the abnormal damage of disc cutter is frequent. This paper analyzes the law of wear of disc cutter and obtains the wear coefficient, and then predicts the number of disc cutters needed for shield machines in tunneling section and reduces the number of disc cutters needed, so as to reduce the extra cost of shield construction.

Keywords: shield machine, disc cutter, wear coefficient, cost control.

1. Introduction
At present, the underground rail transit of Singapore has entered a rapid development stage. As planned by the Singapore government, the subway of Singapore will reach 360 km in 2030, and will enable the pedestrians to reach the subway station in 10 minutes. The shield method is the main construction method of subway construction in Singapore, which is the first choice of tunnel construction due to the strong geological adaptability, safe and reliable, and civilized construction. Although the land area of Singapore is not large, the strata of Singapore are very complex, the rock strength is up to 400 Mpa somewhere, the quartz content is very high, so the tool wear of shield machine is very serious when tunneling in the strata.

In this paper, the statistics and study on the phenomena of disc cutters wearing is mainly carried out by on-site observation the cutter tools wear of shield machine used in the Singapore subway Thomson-East Coast Line construction, and the cause of cutter tool wear and the wear coefficient are analyzed and summarized, providing guidance and cost analysis for tunnel construction in Singapore in the future.

2. Project Profile
The project is the Lentor station (T5) to Mayflower station (T6) section of the Singapore Metro Thomson-East Coast Line. The tunnel is a twin tunnel (south line and north line), and the full length of single line is 1.4 km. The tunnel is lined with prefabricated segments inner diameter of 5.8 m and outer diameter of 6.35 m, and segment length of 1.4 m. Two slurry shield machines manufactured by CREG were used, which have an excavation diameter of 6.67 m, a cutting head opening rate of 32%, and were disassembled with shield left the tunnel.

In the south line, namely the section between the left-line station-to-station tunnel (Changi Bound), Lentor station (T5) and the cut & cover cross over box 5 Xo, the strata tunnelled are all GV (completely weathered granite) and GVI (residual soil) strata. The strata tunnelled in the section between the open excavation tunnel 5XO intermediate station and Mayflower station (T6) section include full face soft soil,
composite strata and full-face rock strata, in which the rock strata and composite strata account for 48.8% (GII- weakly weathered, GIII- moderately weathered).

The tunnel range is covered with fill and residual soil, and underlying by granite as bed rock. The rock and soil in the station-to-station tunnel are residual soil, completely weathered layer and strong weathered layer. The residual soil is mainly distributed in the section between Lentor station (T5) and cut & cover cross over box 5XO. The residual soil, completely and strong weathered layers which easily softened and disintegrated in water, present challenges to the construction.

The physical and mechanical properties of granite residual soil are not uniform, the physical and mechanical test indexes of soil are relatively discrete, and the physical and mechanical properties are very different. In addition, there are "boulders" in the section near the open excavation section 5X0, making the inhomogeneity of the residual soil more prominent.

The geology in the tunnel trace between the open excavation section 5X0 and Mayflower station is complicated and changeable. The tunnel alignment passes through the residual soil, the completely and strong weathered layers and granite. The maximum intensity reaches 400 Mpa, and the full face of most of the sections are mixed rock of weakly to moderately weathered rocks or granite. In part of the sections, the tunnel body passes through the compound strata of residual soil, completely, strong, moderately and weakly weathered strata. The tunnel excavation face may be composite strata that are soft in the upper part and hard in the lower part, boulders wrapped in residual soil and other special strata [1].

In the whole tunnel section of the south line, the full-face soft soil strata account for 74.7% of the whole section, mainly distributed in the first section T5-5XO; the composite section strata accounts for 7.3% of the whole section, mainly distributed in the second section 5 XO-T6; the full-face hard rock strata account for 18% of the whole section, mainly distributed in the second section 5 XO-T6.

The north line, namely the right line tunnel (Woodland Bound) is in excavated by CREC210. The strata tunneled in T5—5X0 section are all GV (completely weathered granite) and GVI (residual soil); The strata tunnelled in 5X0—T6 section include the full-face soft soil, the mixed face, the full-face rock layer, in which the rock strata and composite strata account for 53.5% (GII - weakly weathered, GIII - moderately weathered).

The property of granite residual soil is discrete, the physical and mechanical test indexes of soil are relatively discrete, and the physical and mechanical properties are very different. In addition, there are "boulders" in the section, which makes the inhomogeneity of the residual soil more prominent.

The geology in the tunnel section between 5X0 and Mayflower station is complicated and changeable. The tunnel passes through the residual soil, the completely, strong and weakly weathered layers and granite. The full face of most of the sections are mixed rocks of weakly weathered and moderately weathered rocks or granite. In part of the sections, the tunnel body passes through the compound strata of residual soil, completely, strong, moderately and weakly weathered strata. The tunnel excavation face may be composite strata that are soft in the upper part and hard in the lower part, and boulders wrapped in residual soil and other special strata.

In the whole tunnel section of south line, the full-face soft soil strata account for 74.7% of the whole section, mainly distributed in the first section T5-5XO; the mixed face ground accounts for 9% of the
whole section, mainly distributed in the second section 5 XO-T6; the full-face hard rock strata account for 16.6% of the whole section, mainly distributed in the second section 5 XO-T6. The geological section map is as follows:

![Geological section map of T209 North Line (CREC 210)](image)

**Figure 2.** Geological section map of T209 North Line (CREC 210)

**Table 1.** Geologic Description

| Mark Stratum | Classification | Description                                                                 | Photos |
|--------------|----------------|-----------------------------------------------------------------------------|--------|
| F 1          | Silt           | Silt, sandy silt, Granular sediment of silt                                |        |
| F 2          | Silty clay     | Mixed sediments of silty clay and sandy clay                                |        |
| G II         | Weakly weathered strata | Not easy to be broken by hammer; with the sound of when stuck; fresh rock color is usually retained, but dyed near the seam surface. |        |
| G III        | Moderately weathered strata | Can’t be broken with hands, but it is easy to be broken with hammer, which gives out the sound of dull or slight noise; overall dyeing. |        |
| G IV         | Highly weathered strata | The core can be broken by hand; it is insoluble in water, and completely discolored |        |
| G V          | Completely weathered strata | The original stratum is preserved; the core can be crushed by hands; it is soluble in water, and completely discolored |        |
| G VI         | Residual soil  | The original rock is completely degraded into soil, without residual original texture, and can be crushed by hands |        |
3. Tool Wear Analysis

3.1. Overview of the cutting head plan
The cutting head is designed in a composite structure. The excavation diameter of cutting head is 6,670 mm, and the opening rate is 32%. The cutting head mainly consists of 6 Nos. of twin-disc cutters and 35 Nos. of 19-inch single-disc cutters, including 23 face disc cutters and 12-gauge discs;

3.2. Cutter Tools wear statistics
In the construction of the south-line tunnel, totally 966 rings, i.e., 1352.4 m, were tunneled. A total of 77 Nos. 19-inch single-disc cutters and 4 Nos. 17-inch twin-disc cutters were replaced, of which 52 were normally worn single-disc cutters, 23 were jammed cutters, 2 were oil leakage.

In the construction of north-line tunnel, total 962 rings, i.e., 1346.8 m, were tunneled. A total of 70 Nos. 19-inch single-disc cutters and 11 Nos. 17-inch twin-disc cutters were replaced, of which 23-disc cutters were ground disc cutters caused by geological inadaptability and 1 disc cutter due to broken ring.

3.3. Tool wear analysis
The tool wear data of south line P660-P753 ring in GII/GIII/GIV stratum is analyzed

![Figure 3. Wear Coefficient corresponding to disc cutter (1)](image1)

According to the above data, the maximum wear coefficient of the gauge disc in the strata is 0.07mm/km; the maximum wear coefficient of the face disc cutters in the strata is 0.02mm/km; the average wear coefficient of the disc cutter in the center of the strata is 0.11mm/km. [1]

The disc cutters used in P407 ring (569.8 m), GV, GVI strata in the first section of south line are analyzed

![Figure 4. Wear Coefficient corresponding to disc cutter (2)](image2)
According to the above data, the maximum wear coefficient of the gauge disc in the stratum is 0.03mm/km; In this stratum, the center and front parts are excavated with replaceable ripper without tool replacement. Combined with the tool wear data of GII/GIII/GIV strata, the wear coefficient of positive disc cutters is calculated to be 0.01mm/km, and the wear coefficient of the center tool is 0.05mm/km.

3.4. Estimation of tool wear in north line

According to the wear coefficient calculated above, the tool wear quantity of the north line can be deduced back to verify the accuracy of the above wear coefficient

\[ N = \sum_{i=1}^{n} \frac{\delta_i L_i C_i}{W_R} \]

Where, \( N \) is the number of tools worn, \( \delta \) is the wear coefficient under different strata, \( L \) is the advancement length, \( C \) is the number of tools, and \( W_R \) is the recommended wear limit.

There are 488 rings in the second part of the north line, among which 280 rings are tunneled in GII/GIII/GIV strata, 208 rings are tunneled in GV/GVI strata, with ring length 1.4 m. The number of gauge discs is 12, of positive disc cutters is 23, of central tools is 6; 12 discs can be calculated as 12-disc cutters. The recommended value of \( W_R \) is 12 mm for gauge disc, and 25 mm for the positive disc cutter and center tool;

By calculation, \( N = 57 + 20 = 77 \).

During the tunneling in north line, in the first section, the cutting plan of gauge disc + ripper was adopted, and 5-gauge discs were replaced, so totally 76 tools were consumed in the second section, which can be used as a reference for tool consumption.

4. Conclusions and Recommendations

Through the above statistics and analysis, the following theories are derived.

The ripper and gauge disc cutters can be used when tunneling in GV/GVI strata, which can effectively reduce the consumption of disc cutters;

The above wear coefficient is verified in tunneling of GII/GIII/GIV strata and GV/GVI strata, which can be used as the reference value of tool estimation in the subsequent tunneling of these strata, to reduce the purchasing cost of tools in actual production, and achieve accurate purchasing;

From the above data, it is found that the abnormal damage (grinding wear) to the tools is very common. It is suggested to reduce the rotating torque of the center tool properly, and install the center saw-tooth tool to increase the friction surface of tool rotation.

Acknowledgments

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