TBM Tool Wear Analysis for Cutterhead Configuration and Resource Planning in Glacial Geology

Ulf Gwildis and Jose Aguilar CDM Smith

Kamyar Mosavat The Robbins Company

ABSTRACT: The abrasive nature of glacial geology generally results in Tunnel Boring Machine (TBM) cutting tool inspection and replacement needs that may require hyperbaric interventions and are a cost and risk factor. Correlation analysis of geotechnical conditions, TBM operational parameters, and tool wear measurements is a proven way to gain insight into the wear system behavior. This paper presents findings from various TBM drives in the Seattle and Vancouver, B.C. metropolitan areas on the performance of disc cutters and ripper-type tools in glacial and inter-glacial deposits. The authors provide recommendations for cutterhead configurations, tool management strategies, and the use of monitoring technology.

SUBJECT INTRODUCTION

TBM tool wear is a complex system behavior. The interacting system components include the subsoil characteristics (grain size distribution, coarse components, relative compaction, mineralogy, angularity of grains, etc.), tooling characteristics (tool type, tool materials, cutterhead design, etc.), the excavation process (TBM type using slurry method or earth pressure balance (EPB) method, the latter with variants of soil conditioning approaches), the way the TBM is operated (tool penetration rate, thrust, cutterhead revolution speed, etc.) and ambient conditions (hydrostatic head, temperature, salinity, etc.).

The term glacial geology encompasses a large variety of deposits ranging from fine-grained lacustrine and marine deposits to coarse grained meltwater (outwash) deposits to ice-contact and till deposits with a wide range of grain sizes including cobbles and boulders (Figures 1 and 2). The boundaries of these deposits are typically highly variable and discontinuous. Deposits overridden by glaciers are often very dense or hard. Generally glacial geology is known to be highly abrasive. Several geotechnical laboratory tests exist with the objective of quantifying soil abrasiveness (quartz content by x-ray diffraction, Miller number test for slurry abrasiveness, NTNU/SINTEF Soil Abrasion Test (SATTM), and others.); however, all these tests cover only a limited number of the soil characteristics that are considered causal factors of TBM tool wear. While these tests are valuable for providing contractual baseline descriptions of the subsoil conditions, the test results do not provide a sufficient basis for reliable tool wear prediction.

Another approach to gain insight into the system behavior of TBM tool wear is correlation analysis of the data provided by past TBM projects. In the metropolitan areas of Seattle and Vancouver, B.C. over the past decade numerous pressurized-face TBM drives have been completed in glacial geology (Table 1). This data base covers EPB and Slurry TBMs, cutterhead designs with a wide range of opening ratios, cutterheads equipped with disc cutters and rippertype tools as primary cutting tools, and the full range of various glacial and inter-glacial deposits.

This paper analyses data sets of projects listed in Table 1 correlating tool wear data, subsoil data, cutterhead design, tool selection, and TBM operation. The correlation analysis aims at gaining insight into generally applicable wear mechanisms independent of which specific project has provided the data. The paper concludes with some helpful recommendations for future project planning, design, and execution.

CORRELATION ANALYSES OF GLACIAL GEOLOGY TBM PROJECTS

Plotting the accumulative wear of the various tool positions over the advance length of the TBM—the spread of the graphs reflecting the differences in travel path length as function of the tool position radius on the cutterhead—already shows changes in the graphs' gradients (Figure 3). The selected examples show that the changes in gradient are

135



Figure 1. Excavation exposing glacial deposits in the Seattle area



Figure 2. Core of glacially overconsolidated clay matrix with sharp-edged coarser components

			Year of	TBM	Number of	Length	Diameter
Loc.	Project	Function	Completion	Туре	Drives	(m)	(m)
SEA	Beacon Hill Transit Tunnel	Light Rail	2008	EPBM	2	2 × 1,310	6.5
VAN	Canada Line	Light Rail	2008	EPBM	2	2×~2,500	6.1
SEA	Brightwater East Contract	Wastewater	2008	EPBM	1	4,231	5.9
SEA	Brightwater West Contract	Wastewater	2010	EPBM	1	6,424	4.7
SEA	Brightwater Central Contract	Wastewater	2011	STBM	2	6,651	5.4
SEA	Brightwater BT3C Contract	Wastewater	2011	EPBM	1	3,018	4.9
SEA	U-Link U220	Light Rail	2013	EPBM	2	$2 \times 3,475$	6.6
SEA	U-Link U230	Light Rail	2013	EPBM	2	2 × 1,183	6.6
VAN	Port Mann	Water	2015	EPBM	1	~1,000	3.5
VAN	Evergreen Line	Light Rail	2015	EPBM	1	1,974	9.8
SEA	Alaskan Way Viaduct	Highway	2017	EPBM	1	2,825	17.5
	Replacement Tunnel						
SEA	Northgate Link N125	Light Rail	2017	EPBM	6	5,617	6.5-6.6

Table 1. Seattle and Vancouver, B.C., area TBM tunnel construction contracts in glacial geology

Note: SEA = Seattle Metro Area; VAN = Vancouver, B.C. Metro Area; EPBM = Earth Pressure Balance TBM; STBM = Slurry TBM

synchronous and that the tool wear rates of linear sections, when normalizing them for tool travel path length, are quite similar. This indicates that the tool wear is a steady and continuous process although at changing rates over the TBM advance length leading through various soil types. In this scenario, the wear can be interpreted as being caused by variable soil abrasiveness characteristics, by changing TBM operational parameters, or by a combination of both. For normalizing the tool wear W (mm) for travel path length L (mm) a normalized wear parameter NWP is used, which is dimensionless and defined as NWP = $(10^8 \times W)/L$. Putting it in context with the specific energy consumption of the TBM (i.e., the product of cutterhead torque and rotation in relation to the excavated soil volume) as well as the average soil abrasiveness of the soil types excavated between two tool wear measurement locations provides a loose correlation (Figure 4). This correlation seems to confirm the applicability of soil abrasiveness descriptors such as SATTM values for quantifying tool wear (Gwildis et al., 2010). In this specific project example slurry TBMs with high-opening ratio cutterheads and disc cutters as primary cutting tools were utilized. During the two drives boulders were encountered. Observation of rock fragments in the spoils seemed to indicate that the disc cutters excavated the boulders by rock-chipping mechanism as long as they were held in place by the very dense or hard soil matrix of the glacially overconsolidated deposits. In one case the rock chipping reportedly continued till the time when the direction of cutterhead rotation was changed by the TBM operator and the boulder became dislodged, at which point an intervention for manual removal of the remaining boulder became necessary.

The results of Figures 3 and 4 could not be replicated at a TBM drive through glacially overconsolidated interglacial and then glacial deposits, where



Figure 3. Accumulative tool wear over TBM advance length



Figure 4. Normalized wear data (disc cutters) plotted over specific cutterhead energy consumption and soil abrasiveness descriptor (SATTM)

an EPB TBM with a cutterhead equipped with ripper type tools as primary cutting tools was utilized. Applying the same methodology as before does not show harmonious and continuous tool wear, which would have resulted in a symmetrical wear pattern over the face of the cutterhead (under consideration of tool changes) (Figure 5). Nor are there any correlative trends observable in the diagram of normalized wear over average specific cutterhead energy consumption and average soil abrasiveness descriptors (Figure 6) (Shinouda et al., 2011).

It becomes obvious that in this case a different wear mechanism applies and that soil abrasiveness as quantified by the soil abrasiveness descriptors mentioned earlier is not the driving factor. Comparing tool change intervals and average normalized wear rates with the results of tracking coarse component shards in the TBM muck on a per-ring basis indicates



Figure 5. Layout of replaced TBM tools per cutterhead positions



Figure 6. Normalized wear data (ripper-type tools) plotted over specific cutterhead energy consumption and soil abrasiveness descriptor (SATTM)

a correlation while the comparison with specific energy consumption does not (Figures 7 and 8). This finding in conjunction with the non-symmetrical tool wear pattern over the area of the cutterhead points to impact damage sustained by the ripper-type tools when encountering coarse components (boulders, cobbles) as the dominating factor in this specific wear system behavior.

In the years following the publication of these early findings (Gwildis et al. 2010, Shinouda et al., 2011), several additional TBM drives have been completed in similar geotechnical conditions, for which relevant data sets were collected to allow further correlation analysis (Table 1). All these projects include tunnel drives beneath the groundwater table that were excavated in glacially overconsolidated, glacial and interglacial deposits. In all cases the geotechnical conditions were contractually described by a Geotechnical Baseline Report (GBR) grouping the

137



Figure 7. Coarse component tracking



Figure 8. Specific energy consumption vs. tool change intervals and normalized tool wear

highly variable geologic units into soil groups with similar geotechnical characteristics and tunneling behavior and using terms such as Tunnel Soil Group or Engineering Soil Unit. Although defined based on geotechnical criteria, these soil groups nevertheless are a direct reflection of the geologic environment at the time of deposition. Lacustrine and marine sediments were deposited in low-energy environments resulting in mostly fine-grained soil materials. Meltwater (outwash) deposits of high-flow-velocity rivers generally consist of sands and gravels. In comparison, till and ice-contact deposits represent a wide range of grain sizes, often a silty and fine-sandy matrix with large amounts of coarser components that are distributed irregularly and include singular or locally accumulated (nested) cobbles and boulders. Due to the geologic processes related to glacial advances and retreats, boulders tend to accumulate at the boundaries of the till units to overlying or underlying deposits (till contacts). In the following the geotechnical conditions along the tunnel drives are categorized using a simplified terminology into



Figure 9. Tool wear measurements over tool travel distances

clay, sand/gravel, and till, with special mentioning of till contacts.

Case study project 1 includes an EPB TBM with ripper-type tools as primary cutting tools supplemented by disc cutters in gauge positions as well as scrapers. The tunnel alignment was excavated in clay and till. Significant differences in the tool wear rate were recorded during tool inspections at 80%, 93%, and 95% of the drive length. Plotting the wear measurements over the tool travel distance indicates low wear rates at the first inspection stop and significantly increased wear rates thereafter (Figure 9). Plotting the wear normalized for the tool travel distance as an average NWP value over the drive length provides a clearer picture of this wear behavior (Figure 10). Visualizing the advance lengths through the two soil units by the graph of a till-clay distribution factor with "1" indicting a full face of till and "0" indicating a full face of clay provides the geotechnical context and identifies the drive sections through the geologic contact. The relationship between tool wear rates and geologic contact sections does not point to the contact as the main contributor to the significant wear rate increase. This happens mostly in the full face of till near the end of the drive. Reported loss of soil conditioning functionality in this section would indicate lack of the associated mitigating effects (Hedayatzadeh et al., 2017) and therefore should be considered a potential factor.

Case study project 2 also includes an EPB TBM. Over the tunnel alignment section considered in this paper, the TBM cutterhead was almost exclusively equipped with ripper-type tools as primary cutting tools as well as scrapers. The tunnel section was excavated first mostly in clay followed by interfingering layers of sand and till. Plotting specific energy consumption and cutterhead torque over the TBM drive length shows zones with significantly decreased values in the transition between the clay and sand/till sections and within the latter



Figure 10. Relationship of average NWP values and geotechnical conditions

(Figure 11). The graphs show a fluctuating but overall constant specific energy consumption while the torque, fluctuating in sync, shows an upwards sloping trendline. The tool wear measurements normalized for tool travel length indicate generally low tool wear rates in clay and significantly increased tool wear rates in sand/till (Figure 12). The latter show a wide margin of variation, pointing in addition to continuous wear by soil abrasiveness to other wear mechanisms as causal factors. The presence of till contacts in the sections between inspection stops where the highest normalized wear values were determined points to boulder impact damage as a likely explanation. This explanation is also consistent with the observation that the highest normalized wear values were determined at distal tool positions (positions at large cutterhead radii away from the center) on the planar face area of the cutterhead, where the travel speed and impact forces are high in comparison with other tool positions.

Case study project 3 includes an EPB TBM whose cutterhead was dressed using varying tool configurations of disc cutters and ripper type tools as primary cutting tools in addition to scrapers. The tool types at individual tool positions were changed as the TBM advanced through mixed face conditions consisting of interfingering layers of till and sands and later a full face of sand. At the start of the drive exclusively ripper-type tools were used; however, the tool type was soon changed to disc cutters while the TBM advanced in face conditions with frequent till contacts and the resulting increased probability of boulder encounters. The tool type was changed back to ripper-type tools when the TBM was advancing predominantly through a full face of sands (interlayered with silts and gravels) (Figure 13). Plotting the average of all tool wear measurements and observations for each inspection stop over the drive lengthin cases of asymmetric tool wear the maximum extent of material loss on a tool is considered-shows



Figure 11. Cutterhead torque and specific energy over TBM drive length



Figure 13. Dressing of the cutterhead with different tool types over the drive length

generally higher wear in the mixed face sections of sands and tills as compared to the full-face sections in glacial sands. (Figure 14).

Taking a closer look at the disc cutters reveals in most cases of high wear measurement values that the wear is non-symmetrical due to flat-spotting of the cutter ring or tool damage significant enough that possible flat-spotting in the early stages of damage is not observable anymore. Plotting the disc cutter wear data over the cutterhead radius tool positions, a trend of higher wear at the inner tool positions, a trend that becomes even more pronounced if the wear data are normalized for tool travel path length (Figure 15). Identifying those tool positions where tool damage or flat-spotting has occurred is mirroring the tool wear distribution pattern, as shown exemplarily for one of the inspection stops (Figure 16).

Flat-spotting of disc cutters is a phenomenon where the cutter loses its functionality of rotating



Figure 12. Normalized tool wear (NWP) over cutterhead radius



Figure 14. Tool wear measurements at inspection stops

which results in the ring and subsequently the whole tool to experience material loss only at the side that is in contact with the tunnel face. In the past this phenomenon has been associated mostly with finegrained soils and high adhesive forces (stickiness potential). Observing this phenomenon in predominantly granular soils suggests other causal factors to explain the loss of tool functionality.

The observed phenomenon is interesting especially when compared to the symmetrical tool wear recorded for the slurry TBM operation described earlier (Figures 3 and 4), where flat-spotting and tool damage recordings were rare events despite significant sections of that drive involving fine-grained glacial soils. Further research may be directed at the interaction of EPB TBM operation, soil conditioning, and tool performance. Collecting tool performance data by continuous data logging would likely yield a valuable data basis for this research.

GENERAL TRENDS

The case study projects presented herein generally confirm that fine-grained glacial and interglacial deposits cause significantly less tool wear over the same tool travel path length than coarse grained ones irrespective of the specific energy required to excavate those soil types. This trend applies to slurry TBMs as well as EPB TBMs using either disc cutters or ripper-type tools as primary cutting tools. This general trend is consistent with the results of soil abrasiveness laboratory test procedures such as Miller Number and SATTM, at least qualitatively.

If the distribution of tool wear over the face of the cutterhead is symmetrical, there is an increased probability that some correlations between soil abrasiveness descriptors, TBM operational parameters, and tool wear measurements normalized for tool travel path length can be found (Figure 4). Examples for symmetrical tool wear are provided by Figure 3, where a slurry TBM equipped with disc cutters excavated a variety of glacial soil types including boulder conditions without experiencing significant tool damage, and by Figure 17, where an EPB TBM equipped with ripper-type tools had excavated a tunnel section through face conditions dominated by glaciofluvial sands and gravels.

Where EPB TBMs have been advanced through glacial soils that include till and till contacts, the latter often representing a depositional environment with an increased probability of the accumulation of boulders and cobbles, non-symmetrical tool wear distributions have been observed. Explaining irregular tool wear patterns of ripper-type tools with impact damage by boulders and subsequent accelerated soil abrasion seems likely in many cases (Figures 5, 7, 8, 12).

Where ripper-type tools are used, boulders encountered in the tunnel face are broken into smaller pieces by impact forces. Arguably the applicability of this mechanism is limited by the size of the boulder encountered in the face. When disc cutters are used, the boulder may be excavated by rock chipping similar to the application of disc cutters in hard rock. This requires that the boulder is not dislodged from its soil matrix during the excavation process. In glacially overconsolidated soils, boulders are generally assumed to be embedded in a soil matrix of sufficient strength to offer resistance against being easily dislodged. However, when a non-symmetrical wear and damage distribution of disc cutters on the cutterhead is observed, this suggests a different excavation mechanism than rock chipping. Furthermore, a high number of damaged tools at radius positions close to the center of the cutterhead also points to factors beyond the risk of shock-loading and bearing failure due to boulder encounters (Figure 18).

CONSIDERATIONS FOR CUTTERHEAD DESIGN AND TOOL MANAGEMENT PLANNING

Cutterhead design and tool selection by the tunneling contractor need to consider the requirements of the project specifications and the Geotechnical Baseline Report (GBR). The GBR contractually defines the subsoil conditions by providing geotechnical baselines. In addition to the distribution and engineering characteristics of the geotechnical and geologic units, baselines of specific relevance include soil abrasiveness descriptors, soil stickiness, boulder numbers, size, strength, and distribution, unit boundaries such as till contacts, matrix strength as it relates to the ease of dislodging boulders, as well as baselines for cobbles. The latter, although of lesser significance for cutterhead design, seem to be difficult to quantify. One approach in doing so is by using a Cobble Volume Ratio (CVR) for which empirical relationships to boulder distributions exist (Hunt 2017).



Figure 15. Normalized tool wear distribution of disc cutters by tool position



Figure 16. Example of distribution of disc cutter tool damage and flat-spotting on the cutterhead area



Figure 17. Cutterhead with symmetrical tool wear pattern (ripper-type tools)

For determining the opening ratio as a major parameter for cutterhead design, boulder baselines are a focus. Deciding between high-opening ratio vs. more closed-style cutterheads balances vulnerability regarding boulder impact vs. reduced muck flow and increased torque (Nishimura and Konda 2016). In glacially overconsolidated ground, scrapers are used for conveying the excavated material toward the openings but not as primary cutting tools. Primary cutting tools are either disc cutters or rippertype tools or a combination of both, the tools being dressed at specific radii and spacing, with or without overlapping travel paths. Both of these primary tool types excavate the ground and deal with boulders differently. The mechanism for excavating boulders is impact crushing for ripper type tools and rockchipping (as in a full face of rock) for disc cutters, at least theoretically. As presented in this paper, both tool types have shown effective excavation performance in glacial geology but seem to have limitations under certain operating conditions, which result in high wear rates and non-symmetric tool wear distribution over the cutterhead area.

Maintaining tool functionality as the tools wear down is crucial for an effective and ultimately successful TBM advance. This requires regular inspection and replacement stops due to the current lack of reliable tool wear prediction models. While large-diameter TBMs may have primary tools with individual tool locks and atmospheric access via the cutterhead spokes, for common excavation diameters of 5 to 8 m (15 to 25 ft) hyperbaric interventions or safe havens may be required for conducting tool inspections beneath the groundwater table and in unstable face conditions. The presented case study of high disc cutter damage rates in an EPB application in granular soils leads to the question of how to supplement the inspection schedule beyond common tracking procedures of face conditions and TBM operational parameters.



Figure 18. Cutterhead with non-symmetrical tool wear pattern (disc cutters)



Figure 19. 3-D rendition of disc cutter housing with instrument box



Figure 20. Disc cutter housing with instrument box (rotation speed and temperature)

The authors of this paper suggest considering continuous monitoring of disc cutter functionality by technology that has been used in hard rock applications (Mosavat 2017) (Figures 19 to 21). RPM



Figure 21. Example of disc cutter performance monitoring graph

recordings provide indications of flat-spotting while temperature readings may indicate the risk of tool blocking or particle cementation and baking, which inhibit effective excavation and material flow into the TBM excavation chamber. Response options could include changes in soil conditioning or adjustments of how the TBM is driven.

REFERENCES

- Gwildis, U.G., Sass, I., Rostami, J., Gilbert, M.B., 2010. Soil Abrasion Effects on TBM Tunneling. *ITA-AITES World Tunnel Congress Proceedings*. Vancouver, B.C., June 2010.
- Hedayatzadeh, M., Rostami, J., Peila, D., 2017. Impact of Conditioned Soil Parameters on Tool Wear in Soft Ground Tunneling. *RETC Proceedings*. San Diego, California, June 2017.

- Hunt, S., 2017. Tunneling in Cobbles and Boulders. 10th Annual Breakthroughs in Tunneling Short Course, Chicago, Illinois, August 2017.
- Mosavat, K., 2017. A Smart Disc Cutter Monitoring System Using Cutter Instrumentation Technology. *RETC Proceedings*. San Diego, California, June 2017.
- Nishimura, G., Konda, S., 2016. Lessons Learned from EPB and Slurry Tunneling in Glacially Deposited Soils in Seattle, Washington, USA. *ITA-AITES World Tunnel Congress Proceedings*. San Francisco, California, April 2016.
- Shinouda, M.M., Gwildis, U.G., Wang, P., Hodder, W., 2011. Cutterhead Maintenance for EPB Tunnel Boring Machines. *RETC Proceedings*. San Francisco, California, June 2011.

143