Soil Abrasion Effects on TBM Tunneling

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Tool wear (primary wear) and damage to the cutterhead (secondary wear) occur during tunneling with pressurized face tunnel boring machines (TBM) in abrasive soils and impact tunneling operation, schedule, and cost. Yet the wear process and its impacts are not well understood. Recent attempts of describing and quantifying the abrasiveness of soils by laboratory testing have mainly focused on a limited array of soil properties, namely the mineralogy, the angularity of soil grains, and – to some degree – the grain size distribution. Empirical data from past tunnel projects in abrasive soils are limited and the available data do not contain required information on the geological and hydrogeological conditions encountered and recordings of the TBM operational parameters. To study the impact of soil abrasiveness on tunneling machines and tool wear, a data base of several tunneling projects has been developed. This incorporates data from the Brightwater Conveyance System in the Seattle, Washington area, which includes 20 kilometers (13 miles) of tunnels predominantly in overconsolidated glacial and non-glacial deposits. The soil layers along the alignment are considered to be moderately to highly abrasive. The project is divided into four main tunneling sections: two using earth pressure balance (EPB) machines and two using slurry TBMs. Laboratory test data describing soil abrasiveness and field data collected during tunnel construction are compiled in the data base. This paper describes preliminary results of the analysis regarding parameters influencing TBM wear. In addition, this paper outlines research efforts currently underway in a cooperative endeavor by CDM, the Technical University of Darmstadt (TUD), and Penn State University (PSU) to further the understanding of soil abrasion effects on TBM tunneling.

1. Starting Point

For TBM tunneling in abrasive soils under hydrostatic head the task of predicting tool wear is important for developing a realistic cost estimate and bid price. During construction the number and duration of hyperbaric interventions for cutterhead inspections and maintenance is a major factor impacting schedule and thereby cost. In the past, tool wear predictions were based on empirical data bases maintained by machine manufactures and tunnel contractors. The applicability of past project experiences to a specific tunnel alignment was typically not questioned or checked independently. Only recently efforts have been made by the owners’ designers to include descriptors of soil abrasiveness as well as baseline values for the different soil types along the alignment in the bidding and contract documents. These descriptors are either numerical values quantifying certain soil properties considered relevant in causing wear or the results of laboratory procedures emulating TBM tool wear in contact with soil components in a simplified tribological system, i.e. a system of interacting surfaces in relative motion subjected to the principles of friction, lubrication, and wear. Correlating reproducible test results with clearly defined soil types allows use for baseline purposes.

Since wear in a tribological system is driven, among other factors, by the difference in hardness between the two wear bodies, for evaluating TBM mining operations the percentage of minerals with a hardness exceeding cutter steel is important. Via x-ray diffractometry, the content of Quartz and other hard minerals can be determined and the percentage ratio can be used as soil abrasiveness descriptor.
When considering using the results of a simplified wear test as a descriptor, the Soil Abrasion Test (SAT) developed by NTNU from the existing AV/AVS test for rock and first presented in 2006 is an example [1]. The SAT value is determined from the material loss of wear specimens brought in contact under a defined normal force with the test soil being dispersed on a rotating wheel. The test procedure has been modified since to include a maximum grain size of 4 mm instead of 1 mm [2]. Other laboratory procedures of quantifying soil abrasiveness include the LCPC test for which test series have been presented by the Technical University of Munich [3]. The test principle is also determining material loss of a wear specimen, in this case an impeller rotating at high speed within a receptacle filled with the test soil material. Numerous other wear tests involving granular material do exist, often with the objective of determining the wear resistance of the test material. For mechanized tunneling using slurry TBMs, the Miller Number test per ASTM G75-07 for determining slurry abrasivity is of interest [4]. The test principle is determining wear loss of test specimen after a defined motion within a basin filled with the test slurry. The applicability of the Miller Number as a suitable descriptor of soil abrasiveness for predicting tool wear is a matter of opinion even more than for the other test procedures, since the wear mechanism is different.

The current approach for describing soil abrasiveness as a reproducible numerical value focuses on a limited array of soil properties, namely mineralogy, angularity of soil grains, and grain size distribution, the latter being restricted with regard to the maximum allowable grain size due to scaling issues.

The following sections describe the data bases generated during the design phase and during the construction phase of the four tunnels of the Brightwater Conveyance System Project in the Seattle area, two of the tunnels being advanced by slurry TBMs and two by EPB TBMs. Project data evaluation provides insight regarding the relationship of tool wear data, soil properties, and TBM operational parameters. Based on the conclusions drawn from the project data evaluation, the last section outlines research efforts currently underway by the authors.

2. Design Phase Data Base Development

The Brightwater Conveyance System will connect a third wastewater treatment plant in the growing Seattle metropolitan area – the plant being currently under construction – via 20.4 km of tunnels with design I.D.s between a minimum 4 m and 5.87 m to a marine outfall into the Puget Sound. The system includes a gravity driven effluent pipeline for treated wastewater as well as sections where untreated wastewater is conveyed to the treatment plant by means of a pump station. The hydraulic system requirements resulted for the pronounced topography of the project area in an overburden thickness of up to 150 m and a hydrostatic head of up to 7.3 bars.

The project owner King County commissioned a team of geologists and geotechnical engineers led by CDM to investigate the geological, hydrological, and geotechnical conditions along the alignment, to provide the geotechnical tunnel design, and to coordinate the geotechnical baselines for the different construction contracts with the county and the design team. The subsurface investigation campaign included vertical borings along the alignment with an average spacing of 150 m. The borings were equipped with grouted-in vibrating wire piezometers (VWP) and standpipes equipped with VWPs, constituting a network of groundwater monitoring points that covered the aquifers encountered above, at, and below the tunnel elevation. The subsurface investigation campaign included field testing like pressuremeter tests, geophysical investigations, and pump tests. The campaign also included extensive laboratory testing of soil index properties, strength characteristics, mineralogical composition, geological features, and other data like soil abrasiveness descriptors [5].

The use of different methods of age determination helped identifying the deposits of at least three glacial and inter-glacial sedimentation cycles. Correlation of glacial and non-glacial deposits over horizontal and vertical distances between the borings was an important tool to evaluate the potential for continuity in soil conditions, or lack thereof. Exploration data analysis of the variable geology along the alignment resulted in choosing a geotechnical baseline approach, in which soil types of similar composition, with similar
engineering properties, and partly products of similar geologic forming processes, were combined in Tunnel Soil Groups (TSGs). The TSGs, defined by using a color code, were the basis for the contractual description of typical face conditions, which consist of either single or combinations of more than one TSG. Percentage ranges of the length of each tunnel alignment were then allocated to the different typical face conditions anticipated to be encountered along that alignment during tunneling (Fig. 1). No specifics were identified as to where along the alignment a specific tunnel face condition would be encountered. However, baseline information was provided as to where along the alignment to anticipate an increased probability of encountering disturbed zones or boulder conditions, a prediction that could be made based on tectonic features and after identifying contracts between larger geologic units, for example between glacial and non-glacial deposits of different sedimentation cycles. The baseline information was provided for each tunnel contract by a Geotechnical Baseline Report (GBR). Each GBR was complemented by a Geotechnical Data Report (GDR) which included all data collected during the subsurface investigation phase [6].

![Figure 1: Geotechnical baseline concept](image)

3. Construction Phase Data Base Development

This geotechnical baseline approach lends itself to actual versus baseline tracking of the subsurface conditions encountered during tunneling. CDM in its role of geotechnical consultant to the owner developed a tracking procedure that included all data generated during tunnel construction, the data being archived to ensure verifiability and the interpretation process identifying a typical face condition being documented to ensure reproducibility [7, 8]. Although it was left to the individual contractors to perform tracking with their own personnel, the contractors were contractually required – in addition to standard reporting practice including mining and ring reports – to collect and provide to the owner’s representative TBM spoil samples on a daily basis and a number or specified TBM operational parameters in real-time. Additionally required documentation included information about tools and products used as well as tool changes and tool wear measurements during inspection and maintenance stops.

The step by step tracking procedure (Fig. 2) includes several revision levels allowing re-evaluation of interpreted face conditions as additional data became available. The initial determination is whether the TBM spoil material corresponds to one or more of the Tunnel Soil Groups, consisting of Teal TSG (fine-
grained, plastic soils), Purple TSG (fine-grained, non-plastic soils), Yellow TSG (predominantly fine to medium sand), Red TSG (predominantly coarse sand and gravel), and – locally within a post-glacial valley filling – Tan TSG (plastic, very soft, organic silt). Laboratory index testing of a TBM spoil sample or its different phases – if different phases are distinguishable – can be used for identification or confirmation purposes. In a next step the continuously recorded TBM operational parameters are evaluated regarding changes between sampling locations and correlation of system behavior with interpreted face conditions. In some instances discontinuities such as the abrupt change of cutterhead torque in conjunction with cutterhead rotation speed and changes in the amplitude of chamber pressure fluctuations of slurry TBMs may provide indications of changes in tunnel face conditions near the tunnel station where the discontinuity was recorded. Other instances may indicate a more gradual transition from one tunnel face condition to another. The continuously recorded TBM operational parameters as well as parameters reported on a per-ring basis, for example tail void grout volumes, can be used for further analyses. Statistical analyses used for evaluating correlations between data sets and interpreted face conditions serve as validation tool.

Two of the Brightwater tunnels were mined using Herrenknecht Mix-Shields whose cutterheads were equipped with 14-inch diameter twin disc cutters as primary cutting tools. The wear of those disc cutters was measured using millimeter gauges set on the shoulders of a disc cutter during inspection stops and read by the contractor’s personnel. The other two Brightwater tunnels were mined using Lovat EPB TBMs whose cutterheads were equipped with carbide-tipped picks as primary cutting tools. Wear data of those tools consist primarily of a description of their condition and tool length measurements after they have been replaced during a maintenance stop.

The regular wear measurements of the disc cutters used by the Mix-Shields provide a larger and – despite the possibilities of limited accuracy in conjunction with the described data collection during interventions – a more detailed data base. The wear data evaluation presented in the next section focuses primarily on the Mix-Shields and disc cutters.

![Figure 2: Geotechnical tracking procedure during TBM advance](image-url)
4. Data Evaluation

In order to investigate a complex system behavior like TBM tool wear, the collected data sets need to be identified as representing components of that system, categorized, and reproducibly quantified, i.e. reduced to a numerical value or set of values. Meaningful data reduction is based on analyzing components of the simplified system. In the following, data reduction methods are described for the main components of the tribological system.

4.1 Ground Conditions

The tracking results of categorized face conditions per GBR were sub-divided into their TSG components, for each of which the percentage of the soil volume mined between to wear data collection points (intervention stops where wear data measurements were performed) was determined. Mixed face conditions were equally divided into their constituting TSGs.

Once the percentage distribution between two wear data collection points had been established, soil abrasiveness descriptors (like Quartz content, SAT value, Miller number, etc.) representative for each TSG (for example the average value of available laboratory test data for a specific TSG) could be allocated. Combining percentages and abrasiveness numbers then resulted in a numerical value for the tunnel section between two wear data collection points.

4.2 TBM Operational Parameters

The sets of TBM operational parameters at any given time are a function of ground conditions and variables that are controlled by the TBM operator. Statistical analysis allows identifying trends and/or correlations between certain parameters and tracking results within certain ranges, serving thereby as a validation tool of tracking results.

Among the different TBM operational parameters, cutterhead energy consumption \( E_{CH} \) has limited sensitivity to variables controlled by the TBM operator. This parameter is calculated from the cutterhead power \( P_{CH} \) in [kW], the TBM advance speed \( V \) in [m/sec], and the area of the tunnel face in [m²]:

\[
E_{CH} = \frac{P_{CH}}{(V \times A_F)} \quad [kJ/m^3]
\]

The cutterhead power was calculated from the cutterhead torque and was provided by the data acquisition system of the Mix-Shields and also provided via the TPC data system.

4.3 Tool Wear Measurements

As the Mix-Shields advanced, typically several gauge measurements of the progressing disc cutter wear were taken at subsequent interventions before a disc cutter was replaced. Since the tool wear is dependent on a tool’s travel path length which in turn is a function of the tool’s cutterhead position, some tools were replaced at a given inspection stop while others remained in place to be replaced at later stops. Plotting of accumulative wear measurements over the TBM advance length illustrates the different wear rates of the tool positions as well as dependencies with regard to the tunnel section and thereby the ground conditions (Fig. 3). In order to provide a data set that is the basis for further analysis of dependencies, the tool wear measurements need to be normalized regarding the travel path length of the according tool.

It should be noted that wear measurement data from tools other than standard 14-inch diameter discs, for example discs with hardfacing, discs with carbide bits, or experimental cutter tools, were evaluated separately and their data are not included in the subsequent presentation.
4.4 Data Synthesis

Data synthesis aims at showing relationships between the ground conditions represented by an average soil abrasiveness descriptor value, the average TBM energy consumption per excavated soil volume – which is dependant of the strength characteristics of the in-situ soil – and the normalized tool wear. This was done for the Mix-Shield disc cutter wear data. A similar approach may be attempted for the EPB TBM pick wear data once a sufficiently large data base has been generated.

For the Mix-Shield disc cutters, the wear data collected between two subsequent intervention stops were summarized and expressed in terms of an average Normalized Wear Parameter (NWP), calculated from the incremental wear \( W \) in [mm] and the travel length \( L \) in [mm] of each tool by the following equation:

\[
NWP = \frac{10^8 \times W}{L} \quad [-]
\]

The average NWP was then categorized as follows:

<table>
<thead>
<tr>
<th>NWP</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>Negligible wear</td>
</tr>
<tr>
<td>2</td>
<td>Low wear</td>
</tr>
<tr>
<td>5</td>
<td>Moderate wear</td>
</tr>
<tr>
<td>≥ 8</td>
<td>High wear</td>
</tr>
</tbody>
</table>

Each tunnel section between two subsequent intervention stops was analyzed regarding the percentage of TSGs encountered per tracking results and a weighted average soil abrasiveness descriptor was
determined. The following parameters - GBR baseline values as well as the average laboratory test results from the subsurface exploration phase - were used as soil abrasiveness descriptors:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVS/SAT value</td>
<td>per NTNU (original test procedure with max. grain size 1 mm)</td>
</tr>
<tr>
<td>Miller Number</td>
<td>per ASTM G75-07</td>
</tr>
<tr>
<td>Quartz content</td>
<td>per x-ray diffractometry</td>
</tr>
</tbody>
</table>

In addition, the average cutterhead energy consumption per excavated soil volume was determined for the according tunnel section as recorded by the CAP system of the Mix-Shields.

Presenting the categorized NWP values in x-y diagrams with the soil abrasiveness descriptors plotted against the x-axis (linear scale) and the cutterhead energy consumption plotted against the y-axis (logarithmic scale) provides visualization of data correlation trends (Fig. 4).

Figure 4: Synthesis of design phase and construction phase data bases

In all diagrams two areas can be distinguished, one exclusively consisting of data points representing moderate or high tool wear and the other exclusively consisting of data points representing negligible or low tool wear, those two areas being separated by a relatively narrow transition zone.

This distribution indicates that the driving factor for tool wear is a combination of high values of soil abrasiveness descriptors and cutterhead energy consumption, i.e. soil strength. Neither of these
components alone necessarily leads to increased tool wear. All three parameters used in the GBR as soil abrasiveness descriptors show the same trend and can be considered useful for baseline purposes. However, the diagrams illustrate that it requires considering the system components in context in order to be able to predict quantifiably system behavior, i.e. tool wear rates.

5. Research Outlook

Further research of soil abrasion effects on mechanized soft ground tunneling with focus on tool wear and the causal factors related to the geotechnical conditions requires building suitable data bases. This can be achieved for tunnel projects even in cases of highly variable ground as demonstrated in this paper. Another approach is generating a simplified tribological system at the laboratory scale, which can be used for parameter studies. Other than existing tests which take into account only some of the components attributed to soil abrasiveness, the system must include a suitable representation of soil strength. The presenting author has developed the conceptual design of a new laboratory tool wear test apparatus. This new test is intended to replicate tool wear and generate a set of parameters similar to the set used in the project data evaluation presented in this paper. Comparison of laboratory test results and trends observed by project data evaluation can then further the understanding of TBM tool wear processes and assist in tool wear prognoses based on geotechnical data.

6. Acknowledgements

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7. References


[4] ASTM G75-07 Standard test method for determination of slurry abrasivity (Miller number) and slurry abrasion response of materials (SAR number) (October 2007)


