Cutting tool wear prognosis and management of wear-related risks for Mix-Shield TBM in soft ground

Prévision d'usure des outils de coupe et management des risques liés à l'usure pour Mix-Shield TBM en terrain meuble

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ABSTRACT: The wear of cutting tools is a major issue in Mix-Shield tunneling in soft ground, because it is the most common reason for intermission of advance. Thereby the costs for the downtime commonly exceed the costs for the changed cutting tools. However, due to the inaccessibility of the processes involved and the variety of influencing factors, there are no prognosis tools available, that provide reliable information on cutting tool life. With the detailed data analysis of 18 Mix-Shield TBM drives, this paper takes an empirical approach to tool wear in soft ground. The data analysis results in a qualification and quantification of the relevant influencing factors on cutter tool life. This leads to a prognosis model for cutter life in soft ground for Mix-Shield TBM, based on empirical correlations with soil parameters and TBM design and advance parameters. For a realistic approach the model is completed by an engineering process to translate the cutter life into distances for intermission of advance and required amount of cutting tools to be changed.

RÉSUMÉ: L'usure des outils de coupe est un sujet majeur lors de l'excavation en mode Mix-Shield car elle est la raison principale des interventions hyperbares. En effet, les coûts des interventions hyperbares sont souvent supérieurs aux coûts des outils remplacés. A cause de la difficulté d'accés au processus d'excavation et la diversité des facteurs influents, il n'existe pas d'outil de prévision analytique ou empirique permettant d'obtenir des informations fiables sur la durée de vie des outils. Avec une analyse détaillée concernant 18 tunnels forés avec des TBM Mix-Shield, ce document sert de base pour une approche empirique concernant l'usure des outils de coupe en terrain meuble.Les résultats reposent sur l'analyse quantitative et qualitative de tous les facteurs ayant une influence sur la durée de vie des outils. L'exploration de ces résultats mène à un modèle de prévision de la durée de vie des outils de coupe en terrain meuble pour TBM Mix-Shield bàse sur des corrélations empiriques des paramètres géologiques, de forage et du design du TBM. Pour une approche réaliste, le modèle intégrant un process d'ingénierie, permet de convertir la durée de vie de outils en distance pour les interventions hyperbares ainsi que la détermination du nombre d'outils à changer.

KEYWORDS: Mix-Shield TBM, cutting tools, wear, soft ground, wear prognosis, risk management.

1 INTRODUCTION

The changing of cutting tools on Mix-Shield TBMs is either either done at fixed positions with prearranged grout blocks or with hyperbaric works in the excavation chamber. Therefor advance is intermitted and the bentonite suspension is partly replaced by compressed air, which maintains the support of the excavation face while the tools are changed manually. The position for the interventions and the obtainable length of the intervals between the interventions is determined by the wear of the cutting tools. At the same time the boundary conditions in the projects are often critical for hyperbaric interventions, e.g. due to high support pressure, or overlying infrastructure. Consequently careful and foresighted planning of the interventions is necessary in order to avoid such critical areas.

In contrast to this, there are no models available, which allow for a reliable prognosis of the tool life (KÖHLER et al. 2011). Insights on tribological mechanisms on metal surfaces are widely available, but neither analytical models (BERETITSCH 1992), index tests for the abrasivity of soils (NILSEN et al. 2006a,b,c, THURO et al. 2006, THURO & KÄSLING 2009, JAKOBSEN & DAHL 2010, GHARAHBAGH et al. 2011), nor empirical analyses of individual projects (GWILDIS et al. 2011) have resulted in sufficient correlation with the actual wear on Mix-Shield TBMs.

The research presented in this paper therefore focuses on the empirical analysis of tool wear data from reference projects employing Mix-Shield TBMs. The analysis results in the identification and quantification of the relevant influencing factors on tool life and therefore enables a prognosis of the tool life for Mix-Shield TBMs in soft ground. The tool life can then be used in an engineering process to determine the position of the necessary interventions I, the intervals b_I and the necessary amount of tools to be changed n_t.

2 DATA ANALYSIS

2.1 *Basic data*

For the data analysis 10 reference projects employing 13 Mix shield TBMs for 18 drives were researched. The related tool change data are summarized in tab.1.

Table 1. Overview of the raw tool change data researched in the reference projects.

Soil type	Volume	Disc Cutters	Scrapers
DIN EN 14688 T1	[m³]	[pcs.]	[pcs.]
Clay & Silt	2.843.645	212	327
Sand	1.281.604	238	937
Gravel	1.188.783	1.180	1.336
Total:	**5.314.031**	**1.630**	**2.600**

For each of the cutting tools the cutting distance s_c in km describing the tool life was calculated. Given the track radius r_t of the tool in mm or rather the cutting distance of the tool per cutter head revolution $2\pi \cdot r_t$, the penetration rate p in mm/rev and the advance chainage b_a and b_s of the TBM in m, where the cutting tool was assembled on and disassembled from the cutter head, the cutting distance s_c in km can be approximated by (1).

$$s_c = \frac{2\pi \cdot r_t}{1000} \cdot \frac{(b_s - b_a)}{p} \qquad (1)$$

Following that, distinct values for the relevant influencing factors on the tool life were attributed to each tool change. Based on the work of THURO (2002) in general geotechnical parameters and TBM design and advance parameters were considered as influencing factors.

The attribution of distinct values for geotechnical parameters required the formation of geotechnical sections. The criteria applied for the formation of the sections were:

- Constant share of different soil types in the excavation face in % (+/- 10%).
- Constant thickness of the cover above the tunnel axis h_{ta} in m (+/- 10 m).
- Constant water table above the tunnel axis h_{wt} in m (+/-5 m).

The documentation of the tool changes in the reference projects is insufficient for a clear determination of the condition of each tool at the boundary between geotechnical sections. The attribution of distinct values for geotechnical parameters is therefore limited to tools that were assembled and disassembled on the cutter head within one section.

The TBM advance data were taken from the data acquisition system of the TBMs. For each tool change average values between the chainage of the assembly b_a and disassembly b_s of the tool on the cutter head were calculated.

In order to focus the data analysis on the constant wear of the cutting tools caused by the abrasivity of the excavated soil all preventive tool changes as well as damages of tools were eliminated from the data pool, because they usually occur before the wear limit of the cutting tool is reached.

Considering the formation of geotechnical sections and elimination of preventive tool changes and damages, only 23% of all tool changes could be identified as significant for the constant tool wear caused by the abrasivity of the soil. The tool changes utilized in the data analysis are summarized in tab.2.

Table 2. Overview of the tool change data utilized for the data analysis.

Soil type	Volume	Disc cutters	Scrapers
DIN EN 14688 T1	[m³]	[pcs.]	[pcs.]
Clay & Silt	2.787.514	32	119
Sand	620.783	125	106
Gravel	817.076	278	245
Total:	**4.225.373**	**435**	**470**

2.2 *Analysis method*

The process oriented empirical analysis of the tool change data has the target to identify and quantify the relevant influencing factors on tool life. In addition, the following factors given in the reference projects were considered in the analysis method:

- Variance of the documentation quality.
- Range of different data types to be analyzed.
- Unclear definition of statistical properties for the basic data.

Due to these factors e.g. a multivariate analysis of variance for relevant influencing factors is not feasible. Consequently options for the standardization of a variety of the impact factors were developed, in order to enable a selective regression analysis of single factors or combinations of factors. The available options are based on comparison of different advance situations:

- Comparison of the cutting distance s_c in different geotechnical sections excavated by a TBM without changing TBM design and advance parameters.
- Comparison of the cutting distance s_c for different TBM design parameters in a geotechnical section without changing TBM advance parameters.
- Comparison of the cutting distance s_c for different TBM advance parameters between parallel tunnels excavated by identical TBMs.
- Comparisons of the cutting distance s_c for individual impact factors between different projects, in case all other impact factors can be standardized.

2.3 *Results*

In the first step the data analysis enables the qualification of the influencing factors on tool life in the TBM design and advance parameters given in tab. 3. However, the impact of these factors could not be quantified based on the available data, mainly due to very limited fluctuation range of the factors in the reference projects.

Table 3. Overview of the influencing factors qualified in the data analysis and the according fluctuation range in the reference projects.

TBM design parameters:	**Range:**
Cutter head opening ratio OR_{TBM} [%]	28,4 – 31,0 %
Disc cutters:	
Diameter [inch]	17”
Hardness of the cutter rings [HRC]	57 +/-1
Height above cutter head steel structure h_{dc} [mm]	175 mm
Scrapers:	
Width t_{sc} [mm]:	100 mm
Wear protection of the cutting edge:	Tungsten carbide
Tungsten carb. coverage of the tool surface [%]:	30 - 85%
Height above cutter head steel structure h_{sc} [mm]	140 mm
TBM advance parameters:	**Range:**
Cutter head rotation speed *rpm* [1/min]	0,9 – 2,2 1/min
Density of the bentonite suspension ρ_{SF} [g/cm³]	1,15 – 1,37 g/cm³
Support pressure P_{SF} [bar]	0,9 – 3,7 bar

Exceptions to tab. 3 are given by the following three influencing factors that could be quantified in the data analysis.

For disc cutters the impact of the tip width t_{dc} [mm] of the cutter ring can be quantified. The actual cutting distance s_c increases proportionately with the tip width t_{dc}. Based on the most common value of 19 mm for t_{dc} in the reference projects, the according impact factor f_t on the cutting distance s_c for the prognosis model is described by:

$$f_t = \frac{t_{dc}}{19} \qquad (2)$$

For scrapers the analysis allows for the quantification of the influence of the penetration rate p [mm/rev] and the number of identical scrapers per cutting track and direction of cutter head rotation k_{sc}.

The penetration rate p influences on the cutting forces (BERETITSCH 1992), thereby increasing penetration rate results in increasing cutting forces and wear. Based on the average value of 16 mm/rev for p in the reference projects, the impact of the penetration rate on the cutting distance s_c can be described for the prognosis model by the impact factor f_p :

$$f_p = \frac{1}{1{,}4^{log_{0,5}\left(\frac{16}{p}\right)}} \qquad (3)$$

The number of scrapers per cutting track k_{sc} influences the actual penetration rate p_{sc} of each scraper on the cutting track, since the penetration rate p is shared between all scrapers on the track depending on the angular distance between the scrapers. Inversely to the penetration rate p, the impact of the number of scrapers per cutting track on the cutting distance s_c can be described for the prognosis model by the impact factor f_k:

$$f_k = 1{,}4^{log_2(k_{sc})-1} \qquad (4)$$

For the impact of geotechnical parameters the analysis shows that the correlation of individual parameters with the actual cutting distance s_c does not lead to reasonable results. Therefore a new index value considering the three main influencing factors on abrasive wear was developed. These factors are:

- Abrasivity of the soil components
- Stress at the contact surface between soil and cutting tool
- Shape parameters of the soil components

For the description of the abrasivity of the soil components the Equivalent Quartz Content (*EQC*) in % was selected because of the wide applicability of the test on different soil types and the high availability in the reference projects. The contact stress τ_{act} [kN/m²] was approximated by the shear strength of the soil in the excavation face τ_c using the MOHR-COULOMB criterion. As shape parameter for the soil components the grain size D_{60} in mm was selected, describing the size where 60% of all grains in the soil are smaller than the given value.

The three parameters are weighted and combined in the new Soil Abrasivity Index (*SAI*) (5). Theoretically the dimension of the index is N/m, however the index should be regarded as dimensionless, because of its entirely empirical character.

$$\mathrm{SAI} = \left(\frac{\mathrm{EQC}}{100}\right)^2 \cdot \tau_c \cdot D_{60} \qquad (5)$$

For the analysis of the correlation of the *SAI* with the actual cutting distance s_c achieved by disc cutters in the reference projects the tip width t_{dc} of the disc cutters was standardized at 19.0 mm. The according correlation is shown in fig. 1.

For scrapers a very similar correlation between the *SAI* and the actual cutting distance s_c was found. Here the number of identical scrapers per cutting track and direction of rotation k_{sc} was standardized at 2.0. The according correlation is shown in fig. 2.

For both tool types the analysis results in a significant exponential correlation between the Soil Abrasivity Index and the cutting distance s_c. This type of correlation reflects the generally expected relation of soil abrasivity and tool life. An increase in the Soil Abrasivity Index (*SAI*) leads to an according decrease in the cutting distance s_c and vice versa. The correlations comply with the finding that such correlations are in general continuous and nonlinear (FRENZEL 2010). A similar but weaker correlation was found between NTNU soil abrasion tests and the excavation volume v_c in m³ of cutting tools for EBP machines (JAKOBSEN & DAHL 2011).

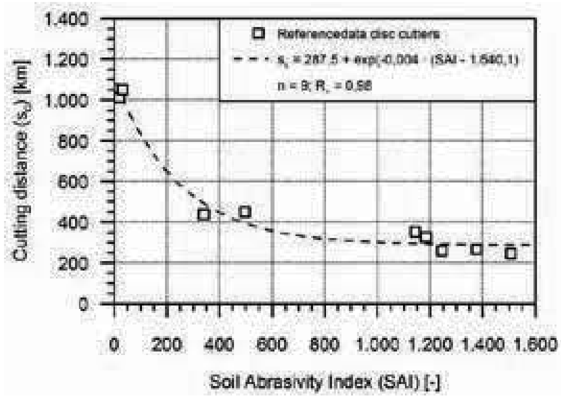

Figure 1. Correlation of the Soil Abrasivity Index (*SAI*) and the cutting distance s_c of disc cutters in different geotechnical conditions.

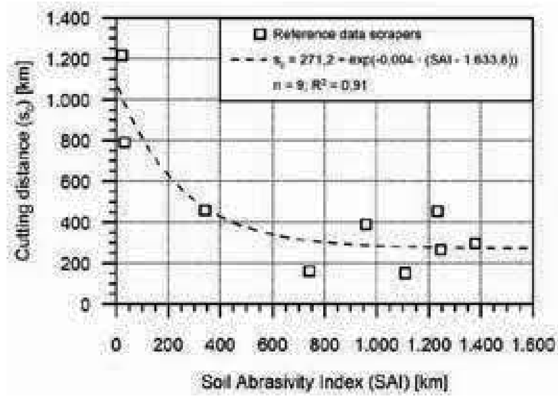

Figure 2: Correlation of the Soil Abrasivity Index (SAI) and the cutting distance s_c of scrapers in different geotechnical conditions.

3 PROGNOSIS MODEL

The results of the data analysis allow for the invers application as an empirical prognosis model for the basic tool life. Based on the tool life an engineering process for the estimation of the resulting demand for hyperbaric interventions I and the intervals b_I between the interventions can be derived.

3.1 *Basic tool life prognosis*

The basic value for the cutting distance s_{cb} in km results from the Soil Abrasivity Index *SAI* (5), entered in the correlations given in fig. 1 and fig. 2 for disc cutters and scrapers. In addition the accuracy of the prognosis has to be considered. For a conservative approach, a reduction of the value of s_{cb} derived from the correlations in fig. 1 and fig. 2 by 40-50% is recommended.

3.2 *Correction of TBM design and advance parameters*

The basic value for the cutting distance s_{cb} needs to be corrected according to the actual TBM design and advance parameters. The correction results in the expected value for the cutting distance s_{ce} in km for disc cutters (6) and scrapers (7).

$$s_{ce} = s_{cb} \cdot f_t \qquad (6)$$

$$s_{ce} = s_{cb} \cdot f_p \cdot f_k \qquad (7)$$

The resulting prognosis values are only valid for projects and TBMs that also comply with the standardized ranges for the other influencing factors on the tool life given in tab. 3.

3.3 *Prognosis of interventions and tool changes*

Based on the expected value for the cutting distance s_{ce} the maximum obtainable length $b_{I,max}$ in m of the intervals between interventions for tool changes can be estimated for each geotechnical section using the estimated penetration rate p_e in mm and the diameter of the TBM D_{TBM} in m (8).

$$b_{I,max} = \frac{s_{ce} \cdot p_e}{2 \cdot \pi \cdot D_{TBM}} \tag{8}$$

While $b_{I,max}$ is calculated for both, disc cutters and scrapers, only the lower value of both is considered for the determination of the position of the interventions for tool changes *I*. Consequently the positions can be determined by consecutive addition of the intervals $b_{I,max}$. More detailed calculations for the determination of $b_{I,max}$ considering the factor of utilization of the individual tools are necessary, in case $b_{I,max}$ covers the boundary between different geotechnical sections where different values for s_{ce} and p_e are estimated. In addition the positions of the interventions also need to be adapted to the boundary conditions for hyperbaric works along the tunnel axis. Therefore the actual length of the intervals $b_{I,act}$ can also be selected lower than $b_{I,max}$ (9) in order to shift the position of the interventions *I* and avoid critical areas.

$$b_{I,act} \leq b_{I,max} \tag{9}$$

The relation between $b_{I,act}$ and $b_{I,max}$ influences on the amount of tools that need to be changed during each intervention in order to allow for the intended length of the interval to the next intervention. The lower $b_{I,act}$ is selected compared to $b_{I,max}$, the less tools have to be changed during each intervention, but in return the number of interventions increases.

The number of tools $n_{t,I}$ to be changed during each intervention can be calculated in detail from the factor of utilization of each individual tool. However, this process is often not feasible during early planning stages of a project. Therefore an estimator for the relation of $n_{t,I}$ and the total number of cutting tools on the cutter head n_{tbm} shown in fig. 3 was developed from a detailed simulation of several TBMs in different ground conditions. In the estimator in fig. 3 disc cutters and scrapers can be considered separately, based on the maximum obtainable length of the intervals $b_{I,max}$ (9).

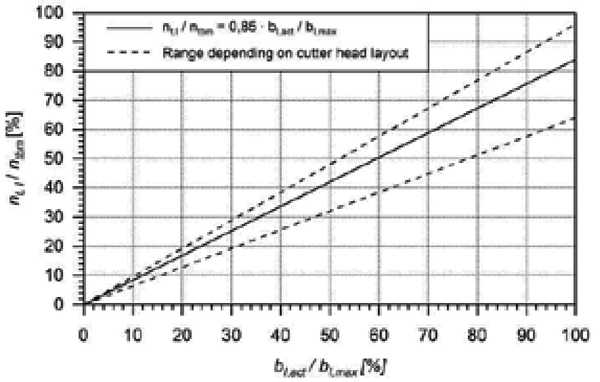

Figure 1. Estimator for the amount of cutting tools $n_{t,I}$ to be changed during an intervention *I*.

Aside the planned interventions for tool changes also short interventions for validation of the geological conditions and the estimated values for the cutting distance s_{ce} have to be considered. A common strategy is to validate s_{ce} in each new geotechnical section once the actual cutting distance $s_{c,act}$ of the tools reaches a value equal to 30-50% of s_{ce} in the new geotechnical section. Again the factor of utilization of the individual tools at the boundary between the geotechnical sections has to be considered.

Additional interventions have to be taken into account if risks for damages of the cutting tools due to clogging in fine grained cohesive soils, in soils containing boulders or manmade obstacles like steel reinforced concrete piles are indicated.

4 CONCLUSIONS

The results presented in this paper provide a new approach to the empirical prognosis of tool wear and the related demand for interventions for Mix-Shield TBMs in soft ground. However, the model still needs to be validated in practical use and an even wider data base is necessary to quantify further influencing factors. For both tasks a followup of the prognosis during advance is mandatory. Consequently the methods for the acquisition of geological data (WENDL 2012) and tool wear data in the advance phase need to be improved. The improvement of the prognosis model and its application in a more detailed version additionally depend on development of according software tools in order to organize the amount of various data types and follow up the exact condition of each individual tool on the cutter head.

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