Operational Modelling of Advance Rates for Tunnel Boring Machines

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In tunnelling a reliable prediction of advance rates is the essential basis for the calculation of costs and construction time. The best way to calculate the daily advance rates is by breaking down the cycle of works into significant portions and analyse each step individually. This method is standard practice for conventional tunnelling in Austria and most other countries with a highly developed tunnelling industry.

In TBM-tunnelling, where the processes of excavation and support can be very complex - in particular for gripper TBMs with NATM support – , equivalent/similar methods for calculating the advance rates are not in use. The methods applied to calculate the daily advance rates in TBM tunnelling are rather simple. They are normally based on estimating a net penetration rate and the application of a utilisation factor. The traditional way to calculate the daily advance rates is explained by the following formulas:

[1] $$I_n = \frac{p \times n_B \times 60}{1000}$$

I_n net penetration [m/h]
p penetration [mm/rev]
n_B cutterhead speed [rev/min]

[2] $$Q = u \times I_n \times t_{VS}$$

Q advance rate [m/d]
u utilisation degree [%]
t_{VS} daily working time [h/d]

Though this method is simple to apply and delivers results quickly it has serious disadvantages. When the estimate of the net penetration rate is provided by a TBM manufacturer or a contractor who has based his estimate on the experience from numerous projects worldwide and if it is backed by a theoretical state-of-the-art calculation, the results can be considered as quite reliable. At least they are the best one can get today (1).

With the other important input value– the utilisation factor – things are more difficult. Since this factor summarises many different influences originating from a wide range of sources such as geology, TBM maintenance, tunnel logistics, site organisation and others, it can not be determined with much accuracy. Even when deducted from projects already completed the overall utilisation factor may vary within a wide range (±10 to 20%). The personal experience of the engineers doing the estimate will most likely superimpose the figures derived from similar projects. An input which may improve but could also worsen the

Baubetriebliche Modellierung der Vortriebsgeschwindigkeit für TBM-Vortriebe im Festgestein

Vortriebe mit Tunnelvortriebsmaschinen erfordern eine intensive vorauseilende Planung und Arbeitsvorbereitung. In der Ausführung sind sie daher nicht sehr flexibel. Um die dennoch vorhandenen Optimierungspotenziale nutzen zu können ist es empfehlenswert, den Vortriebsprozess in Teilprozesse zu unterteilen, diese genau zu analysieren und ihre Dauer ebenso genau zu kalkulieren.
Aus dem Vergleich mit einer detaillierten Prognose können während der Ausführung Schwachstellen im Ablauf leichter erkannt, quantifiziert und soweit möglich behoben werden.
Das beschriebene Produktionsmodell stellt einen Algorithmus dar, welcher den Weg von der Ermittlung der Penetration bis hin zur Prognose der Vortriebsgeschwindigkeit transparent und schlüssig beschreibt.
Mit dem vorgestellten Modell ist es möglich, Prognosen über die Vortriebsgeschwindigkeit zu erstellen, Parameterstudien durchzuführen, detaillierte Soll-Ist-Vergleiche zu erstellen und somit gezielt Verbesserungsmaßnahmen durchzuführen sowie die Restbauzeit abzuschätzen.

Tunnel driving with Tunnel Boring Machines requires intensive planning and is not very flexible during construction. For this reason the optimisation potential in the operational phase is limited.
The new method for the calculation of the advance rate proposed in this paper will not only provide more accurate predictions of this rate but will also provide better possibilities for a comparison of the parameters determining TBM performance.
The new method will facilitate parameter studies by varying one or several of these parameters. This feature could be a valuable tool for designers and contractors in planning and bidding TBM-driven Tunnels.
Detailed comparisons between figures estimated and actually found as well as better forecasts of remaining construction time could be another application of the proposed method.

results. In any case the figures delivered by this traditional method of calculation are of a more subjective nature than advisable.

The new method developed by the authors follows the way taken in conventional tunnelling. It looks at the cycles of works respectively strokes of the TBM and breaks them down into significant portions. The duration of each portion or step is estimated by analyzing the activity and the possible downtimes related to it.

Since most tunnels are driven not only through one geological formation but several ones differing from each other by mineralogy, UCS and other properties, it is advisable to do the calculation of the advance rates for each homogenous section separately. This measure should be undertaken for all major tunnels. Even if it does not improve the quality of the prediction for an individual section it will improve the overall result considerably.

Advance rates resulting from a calculation performed by the traditional method allow only comparisons of the estimated advance rates with the ones actually achieved. This is not very satisfactory because such a comparison doesn't show where the differences are originating from. One can only guess whether e.g. the number of cutter changes, the excessive downtime of the tunnel conveyor or frequent failures of the power supply are the main reason for the unsatisfactory advance rates. The new approach enables the contractor to compare his assumptions on the various kinds of downtime with the delays and stoppages that actually occurred. The only tools required to achieve this ambitious goal are a detailed calculation of the advance rate done in the proposed way and a monitoring system using the same categories for boring and downtime as applied in the calculation (plus TBM operators and a data logging system which is able to provide the necessary figures).

Operational Modelling

The aim of the new approach is to model the processes of mechanised tunnelling in hard rock in such a way that the path from the calculation of the penetration rate to the daily advance rate can be taken step by step. The starting point for the modelling is - besides machine specifications - the penetration rate. The various models existing for estimating this value are shown in (2). Cutter wear, which is a penetration-related factor, finds its way into the model later.

Depending on the type of TBM the process of an entire cycle is broken down into small portions. For an open type TBM boring and supporting measures have to be looked into in detail. For shielded TBMs boring and segment placing are the processes to be broken down into smaller items. For a gripper type TBM these processes are very complex. Therefore the approach will be explained for a shielded TBM where it can be explained easier.

Calculation of cycle time

The duration of a cycle is defined by two sub processes:

- Boring
- Support

Boring can be broken down as follows:

[3] $$t_V = t_{V,v} + t_{V,l} + t_{V,a}$$

t_V total time consumption for sub process Boring [min/cycle]
$t_{V,v}$ time consumption for preparation [min/cycle]
$t_{V,l}$ time consumption for boring [min/cycle]

[4] $$t_{V,l} = \frac{h \times 1000}{p \times n_B}$$

h stroke length [m/cycle]
p penetration [mm/rev]
n_B cutterhead speed [rev/min]

$t_{V,a}$ time consumption for post processing [min/stroke]

A restricting factor to the theoretically possible advance rates in soft rock can be given by the limited capacity of the conveyor and logistic system. Other constraints like the necessity to construct an invert of in situ cast concrete simultaneously to the excavation may pose additional restrictions. Basic restrictions are given by the maximum possible rotational speed of the cutterhead and the maximum penetration of cutters depending on disc diameter and shape.

As far as shielded TBMs are concerned additional attention has to be paid to the filling of the annular gap between segmental lining and rock with mortar respectively pea gravel.

Support can be broken down as follows:
(for a shielded TBM)

[5] $$t_{S,TBM-S} = t_{S,v} + t_{S,s} + t_{S,ab}$$

$t_{S,\ TBM\text{-}S}$ total time consumption for sub process Support [min/ring]
$t_{S,v}$ time consumption for preparation [min/ring]
$t_{S,s}$ time consumption for segment erection [min/ring]

[6] $$t_{S,s} = t_{S,t} \times a$$

$t_{S,t}$ time consumption for installation of one segment [min/segment]

a number of segments per ring [segments/ring]

$t_{S,ab}$ time consumption for post-processing [min/ring]

Working Cycle

The time needed to complete one cycle with a TBM represents the main process. It is explained by the following equation:

[7] $$t_{Z,TBM-S} = t_V + t_{S,TBM-S}$$

$t_{Z,TBM-S}$ total time consumption for one cycle [min/stroke]

The illustrated approach used for shielded TBM represents the simplest case. For double shield and especially open type TBMs there are several possible combinations of driving and support that influence the duration of a working cycle - detailed in (3).

Factors interfering the main process

Beside the unavoidable downtime related to the main process there are other downtimes originating from the logistic system which have to be looked at. These downtimes interfere with the more or less continuous row of cycles performed by the TBM. They are resulting from the following causes:

- Working time model (shift organisation)
- Cutter control and change
- Exploratory measures
- Extension of tunnel conveyor
- Downtimes of TBM and Backup
- Others

There are two ways to integrate these downtimes in a prediction model.

The first one is a simple linear addition of the downtimes. The so estimated totalised downtime is subtracted from the daily working time. The remaining effective working time combined with time consumption for boring leads to the advance rate.

The proposed model follows a different way. It starts with an estimation of the foreseeable downtime like cutter control and –changes, conveyor belt prolongation and similar items. In a second step the presumable duration of unforeseeable interruptions of the boring or support caused by failures of the TBM, the backup equipment, the tunnel transport system, ventilation, electric power supply and other problems has to be evaluated.

At first thought it would seem to be the best way to deduct the downtimes directly from the planned daily working time (24 hours or less).The daily advance rate could then be calculated easily.

The authors propose a different way. In order to enable the utilisation of iterative calculation methods, a fictitious cycle, applicable on a 24 hrs working time will be generated. This is achieved by allocating the durations in proportional quotas to the basic durations of a cycle.

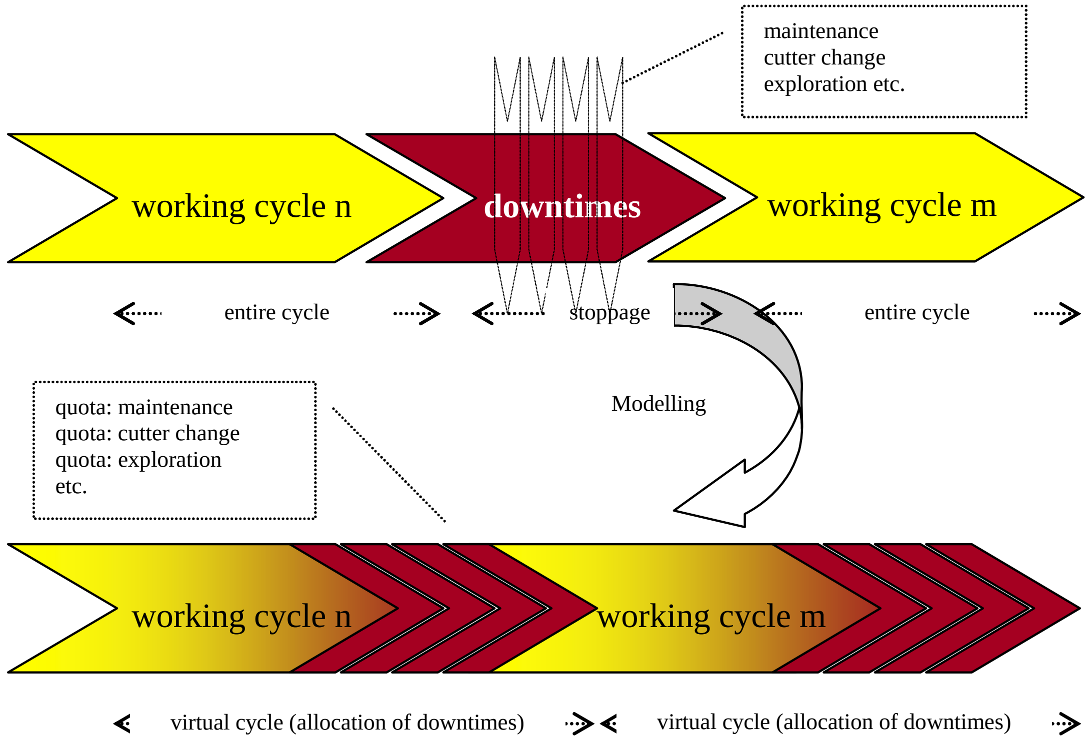

Fig. 1 Allocation of downtimes on the working cycles

Bild 1 Umlage der Stillstandszeiten auf die einzelnen Vor-

This iteration is necessary because all the time quotas depend on the final result, namely the cycles per day and in the end also the advance rate. Another advantage of the proposed method will be that parameter studies can easily be carried out, because the model reacts flexible on varying input parameters.

To explain the procedure, the integration of cutter wear (foreseeable downtime) and downtimes of TBM and backup (unforeseeable downtime) are shown in an example.

Cutter consumption

Usually cutter control is performed at least once every day during the maintenance shift (if there is one). If changes are necessary they will also be done during this time provided for revision work.

As input parameter for the operational model the cutter ring life in metres per cutter (e.g. estimated as shown in (4) or (5)) is utilised. With this value in combination with the advance rate the amount of cutters to be changed can be calculated as follows.

[8] $$M = \frac{Q}{H_m}$$

M	number of cutters to be changed per day [c/d]
Q	advance rate (Iteration!) [m/d]
H_m	cutter ring life [m/c]

The number of cutters to be changed each day and an estimate of changing time gives the total time consumption for cutter changing.

[9] $$t_M = M \times t_{M,m}$$

t_M	total time consumption for daily cutter changes [min/d]
$t_{M,m}$	time consumption for one cutter change [min/c]

If the estimated cutter changes per day take longer than the maintenance shift, the extra time has to be added to the maintenance shift. This difference has to be applied on the entire cycle. If the cutter changes can be done within the maintenance shift, this process is not critical and therefore will not influence the advance rate.

Table 1 Influence of downtimes on boring and support (3)

Tabelle 1 Einfluss der Stillstände auf die Prozesse Vortrieb und Sicherung (Ausbau) (3)

Downtime \ Type of TBM	TBM-O	TBM-S	TBM-DS
	Influence on process		
TBM	Driving	Driving	Driving
Backup	Driving	Driving and Support	Driving and Support
Transport (to TBM)		Support	Support
Transport (from TBM)	Driving	Driving	Driving
Others	Driving	Driving and Support	Driving and Support

[10] $$z_M = \frac{(t_M - t_P)}{n}$$

z_M	time quota opened on the entire cycle due to cutter wear [min/cycle]
t_p	time consumption for maintenance [min/d]
n	number of cycles per day (Iteration!) [cycles/d]

The working cycle can now be calculated as follows.

[11] $$t_{Zyklus(m)} = t_Z + z_M \quad \text{für} \quad t_M - t_P > 0$$

[12] $$t_{Zyklus(m)} = t_z \quad \text{für} \quad t_M - t_P \leq 0$$

$t_{Zyklus\,(m)}$	time consumption for one virtual cycle (24 hours per day), cutter wear integrated [min/cycle]
t_Z	time construction for one cycle (boring, support) [min/cycle]

The formulas given refer to a shift model with constant times for maintenance (only as long as the maintenance time has not to be extended due to excessive cutter changes). In order to optimize advance rates in low cutter wear areas the maintenance shifts should be reduced to the time required for cutter changes iteratively.

Downtimes

Beside the foreseeable interruptions there are numerous unforeseeable downtimes that may be caused by failures of the TBM and backup system. They can be summed up in the following categories:

- TBM
- Backup System
- Tunnel Transport
- Others

The daily time consumption for standstills is allocated to the four categories in [min/day]. The method of integrating these stoppages into the model is similar to the integration of cutter changes.

The number of cycles calculated so far (without unforeseeable standstills) will allow better estimates of downtimes. It should be taken into account that the four groups of downtimes will have an influence on different processes (see table 1).

Advance Rate

Tunnel driving with TBM under regular circumstances can be described quite accurately using the proposed model. The calculated time for one cycle represents the time consumption for a virtual cycle that includes all the influences on the two main processes driving and support. The model transfers the actual cyclic process into a virtual continuous one. The integration of the several time quotas which reduce the theoretical advance rate to the realistic one requires several iteration steps.

After the duration of a virtual cycle is calculated, it can be repeated for 24 hours a day. This leads to the number of cycles that can be carried out each day.

[13] $$n = \frac{24 \times 60}{t_{Zyklus(fiktiv)}}$$

$t_{\text{Zyklus (fiktiv)}}$ duration of one virtual cycle (24 hours per day), all influences integrated [min/cycle]

After having calculated the number of cycles per day the advance rate Q [m/d] is calculated by multiplying them with the stroke length h [m/stroke]:

[14] Q = n x h

Conclusion

The model which is briefly presented here puts forward the way from the calculation of penetration and cutter wear to the prediction of the daily advance rate.

It is applicable to open, shielded and double shielded TBM. The number of parameters integrated in the model is variable.

However for practical application the number of parameters to be integrated into the model should be kept reasonable.

The formulas presented in this paper can not show the full scope but only the most important aspects of the entire model. The whole procedure is shown in figure 2. One can see that a large part of the input parameters can be estimated quite accurately, especially as far as foreseeable standstills are concerned. Experienced engineers are aware of the fact that the logistic system of a TBM drive plays a very important role. Therefore the calculation of advance rates should always consider the logistic system besides penetration and cutter wear.

The proposed model provides a good tool for generating transparent estimates of advance rates, on which parameter studies and target/actual comparisons can be carried out. It can be set up in such a way that the values estimated for the calculation can be compared with the values actually found (machine performance as well as geology), furthermore it is possible to estimate the actual, the predicted and contractual construction times and to forecast the presumable remaining construction time.

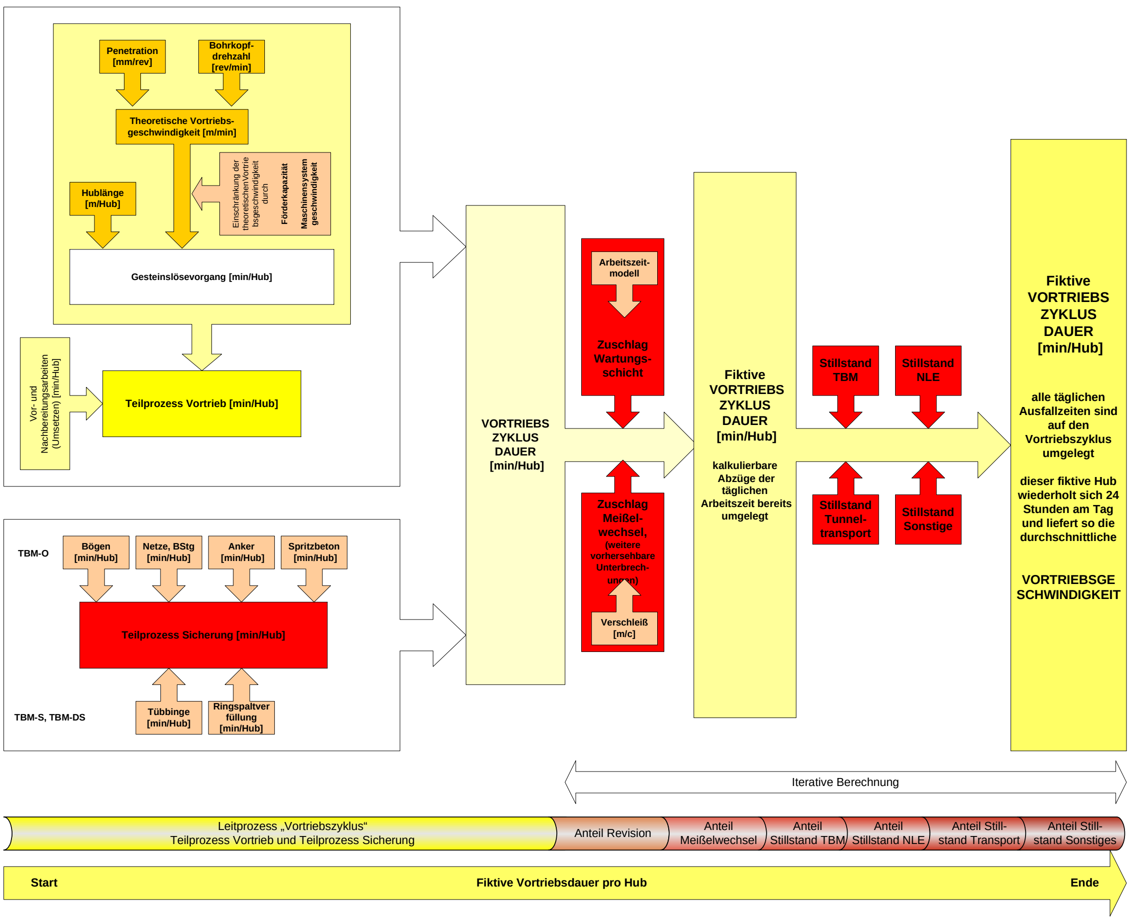

Fig 2 Flow chart Operational Modelling (3)

Bild 2 Vorgangsweise der baubetrieblichen Modellierung (3)

The authors regret that the application of the given formulas within a spreadsheet is quite extensive. But this shortcoming will soon be overcome, because the department of construction management - in collaboration with the Institute of Computer Science - is on the way to develop the software for an expert system to make the application of the presented model much easier for the user. This development is part of the EUREKA! research project *TISROCK* – TBM Tunnelling in Squeezing Rock.

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