Analyses of driving performance in mechanized tunnelling
Determination model and actual examples

Rainer Stempkowski
Technical University of Vienna, Austria

ABSTRACT: This paper presents a determination model for estimating the driving performance in mechanized tunnelling. To come to an average driving performance, the penetration has to be calculated first. With the help of the penetration and the rotational speed of cutter head, the net-rate of advance is determined. After calculation the utilization factor, that describes the percentage of drilling time in comparison to the working hours, the action time or commission time, the total rate of advance can be worked out. With the aid of three examples the determination model is tested. Finally sensitivity analyses show the extent of influence of different parameters to the advance rate.

1 INTRODUCTION

Since a main basis of costs in tunnelling is the determination of driving performance, all the main influences to the driving performance and their dependence on each other have to be analysed. Beside all the influences of the machine, various influences of the rock, the minerals, the water, and the training effect have to be taken into consideration.

With the help of the presented model for determining the driving performance, it is possible to estimate the advance rate and the construction time of any tunnel that is driven with TBM.

The new driving-rate model is presented on three different examples, one tunnel with a small diameter, that has already been driven, one tunnel in progress and one tunnel with a big diameter, that is being designed at the moment.

2 DETERMINATION OF THE DRIVING PERFORMANCE

To come to an average driving performance, the penetration has to be calculated first. In the second step the net-rate of advance depending on diameter of the machine and the penetration is determined. The next step is the calculation of the utilization factor that describes the percentage of drilling time in comparison to the working hours, the action time or commission time. The result is an average total rate of advance per working day or per month.

![Figure 1. Four steps to determine the advance rate](image.png)

penetration
[mm/r]

net-rate of advance
[theoretical maximum advance rate in m/h]

utilization factor
[% drilling time / working hours, action or commission time]

total-rate of advance
[average driving performance in m per working day or m per month]

1st step - penetration $p$

The penetration is defined as intrusion depression of the discs into the rock during one revolution of the cutterhead. It depends on the drilling pressure of the TBM, the geology and the rocks.

The higher the drilling pressure of the TBM the weaker the rock, and the smaller the strengths of rock and minerals the higher is the penetration.

One possibility to estimate the penetration was shown in my dissertation [Stempkowski 1996]. With the help of a Drilling Rate Index (DRI) that is determined by the kind of rock and rock strength,
and the rock mass factor \((f_g)\) that is determined by the classification of ground and the angle of tunnel axes and sheeting, the penetration can be found in the following figure.

![Penetration vs. Rock Mass Factor](image)

**Figure 2.** Penetration in dependence of rock factor and Drilling rate index (DRI)

Dr. Gehring from the Tamrock company found a direct connection between penetration and axial compressive strength, that is shown in the next figure.

![Penetration vs. Axial Compressive Strength](image)

**Figure 3.** Penetration in dependence of axial compressive strength [Gehring 1995]

In general the penetration is of the order of 4 to 10 mm/r, with a technical maximum of 15 mm/r. As long as no detailed drillings have been made, the average penetration can never be calculated exactly but has to be estimated.

**2nd step - net-rate of advance \(I_N\)**

The net-rate of advance is the advance during drilling time. It is determined by the penetration \([p]\) and the rotational speed of the cutter head \([n]\).

\[
I_N = \frac{p \times n \times 60}{1000} \quad [\text{m per hour}]
\]

The rotational speed of the cutter head is in inverse proportion to the diameter of the cutter head and it can be calculated with \(n = f_n / d\) [rpm]. The average rotation speed factor \(f_n\) amounts to \(\approx 50\) with a bandwidth of +/- 10%. More detailed datas for the maximum rotation speed of the cutter head can be received by the machine producers.

For calculation it makes sense to reduce the maximum rotation speed to 80%, because a machine can’t dive all time with a full speed.

![Net-rate of Advance](image)

**Figure 4.** Net-rate of advance

**3rd step - Utilization factor \(UF\)**

The measure of utilization describes the real advance rate of the TBM. To determine the utilization factor the different components of the service life time of a TBM have to be analysed. The following figure gives an overview over service life time, commission time, action time and the working hours of the TBM. The drilling time is the only time when the TBM advances. In all other cases the machine stands still. (see figure 5)

Three different kinds of utilization factors can be defined:

1. The Utilization Factor \(UF1\) corresponds to the relation between the drilling time and the working hours and amounts in general to about 40 to 70%.
2. The Utilization Factor \(UF2\) corresponds to the relation between the drilling time and the action time and is of the order of 30 to 50%.
3. The Utilization Factor \(UF3\) corresponds to the relation between the drilling time and the com-
mission time - including the time for transport, installation and dismantling - and amounts in general to about 20 to 35%.

To come to the utilization factor every part of the service life time has to be analysed in detail. It would go beyond the scope to analyse all these parts within this paper, more details therefor can be found in the dissertation [Stempkowski 1996].

On the example of the Wienerwald-Tunnel the Utilisation Factors UF1 and UF3 are shown in the following figures.

**Figure 5. Service life time of a TBM**

**Figure 6 and 7. Utilization factor UF1 and UF3 (example Wienerwaldtunnel)**

4th step - total advance rate \( I_T \)

The total advance rate is the real average driving performance of the TBM. Within the total advance rate not only the drilling time (= base for net-rate of advance) is considered, but also all kinds of standstill, repairs and maintenances, that are all considered for calculation in the utilization factor.

In dependence on the three different utilization factors, three different total advance rates can be defined, too.

\[
\begin{align*}
I_T^1 &= I_N \times (UF1 / 100) \times 24 \quad \text{[m per day]} \\
I_T^2 &= I_N \times (UF2 / 100) \times 24 \quad \text{[m per day]} \\
I_T^3 &= I_N \times (UF3 / 100) \times 24 \quad \text{[m per day]}
\end{align*}
\]

In the following figure 8 the three different total advance rates are shown in a time-advance-diagramm. The more flat the curve, the higher is the advance rate.

\( I_T^1 \) describes the advance rate of the working time, without considering bigger geological problems or bigger repairs. All bigger standstills like standstills due to mush areas or machine breakdowns can be figured out in the diagramm shown above.

The second total rate of advance \( I_T^2 \) shows the average driving performance from the beginning of the driving work till the end of the driving. This is the most usual comparative figure for the advance rate.

The third total rate of advance \( I_T^3 \) is the average advance rate of the period the TBM is on the site. In this rate the time for installation and dismantling of the TBM is also taken into account.
3 EXAMPLES

The determination model was tested on three examples, the Austrian Sondierstollen Zell am See, a tunnel with a small diameter (3.5m), a part of the Vereina tunnel (diameter 7.6m) in Switzerland and finally the Wienerwaldtunnel, a tunnel for high speed railway near Vienna with a lenght of 13 km and a diameter of 9.5m that should be build within the next years.

For different kinds of rock classes (classification ÖNORM B 2203,1994) the total rate of advance was calculated. The following figures show in a simplified way the results.

As the total advance rate depends on the net rate of advance an the Utilization factor, the total rate of advance can be found with the help of the following figure. The curves are calculated on the base of 24 hours per day and 30.4 days per month. All standstills (for example due to working hours or site breaks) were already taken into consideration with the Utilization Faktor.
Due to the very low utilization factor in the bad rock classes (C) the total rate of advance decreases with worse rock class. The smaller the tunnel, the more difference is between good and bad geology.

The results of a study made by P.P. Nelson show the average total rate of advance for a big number of tunnels. Most of the tunnels had an average total rate of advance between 200 and 400 meters per month.

4 SENSITIVITY ANALYSES

The base for the calculation of the advance rates are special boundary conditions. To relativate possible changes in these boundary conditions, sensitivity analyses of the calculation of the advance rate have to be made. Therefor the basic influences of the advance rate - the machine, the rock and the rock formation - have to be taken into consideration.

On the one hand there is a continuous development in the technology of machines and discs. An increase of the drilling pressure and of the rotational speed leads to a high increase of the advance rate. (see figure 13)

On the other hand the big question is always the geology of the rock. A variation of the axial compressive strength of the rock leads to a slightly less than inverse proportional variation of the advance rate. A reduction of the compressive strength for example of 45% increases the advance rate to nearly 30%, an increase of the compressive strength of the rock of 45% reduces the advance rate just a little bit more than 20%.
5 CONCLUSION

The aim of these analyses of possible scenarios which are based on mathematical models and other case studies is to work out the estimation of costs, advance rates and construction time of a tunnel as realistic as possible.

The base for every estimation of construction time and in further way of costs is the advance rate. The paper figures out how important the definition of advance rate and utilization factor is. As there are big differences between for example the total rate of advance IT1 and IT3 a comparison between different kinds of tunnels would make not much sense without defining the conditions of the frame that is looked at.

6 REFERENCES

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