Hard-rock TBM performance prediction

The authors (see separate block), present a paper covering an improved method of predicting penetrating, cutter wear and advance rate by calculation for TBMs in hard rock

Performance predictions form an essential basis for the calculation of costs and the operational planning of construction projects. In tunnelling, the main performance figure is the advance rate. Especially in long tunnels, a prediction of advance rate that is as accurate as possible is of great importance, even in early phases of the project. As realisation is coming closer, the exact planning of the construction operations becomes more and more important. This requires an even more exact prediction of advance rate.

For the contractors, advance rate is a crucial parameter for the calculation of their tenders and for assessing the scheduling risk. For conventional tunnelling, analysing the cycle time has become a proven method to calculate the advance rate. The results are normally within an acceptable bandwidth.

No standard method of calculation has so far established itself for mechanised tunnelling. As has been found in tenders, the advance rates predicted by tenderers are sometimes a long way from reality. This situation, which is criticised by L. Home[1] using the words 'Tolerance of inaccurate estimations is hurting our industry' [Ref 1], is extremely unsatisfactory for all participants of a project. The causes for this situation are investigated below, and a new method of calculation will be presented, which leads to better, i.e., more accurate, results.

Basis

In order to predict advance rates for TBMs in a given geology, the first thing that has to be calculated is the penetration rate, expressed in millimetres advance per revolution of the cutterhead. The next step is the calculation of the net boring speed, which depends on the cutterhead rotation speed, in metres per hour. The following step leads from net boring speed to the advance rate. In this step, the obstacles, malfunctions, and downtimes of boring operations must be taken into account. This happens in many cases by using a general utilisation factor (in percentage terms) or, if the calculation is more exact, by estimating the total downtime in minutes or hours per shift or working day.

Another factor that must be included into the calculation is the excavation time, i.e., the working time available for excavation. This is a maximum of 24 hours per day. If a regular maintenance shift is planned or if the working time model does not provide for 24-hour operation, the time for excavation is accordingly less. In rock formations with a high share of abrasive minerals, cutter wear has to be considered in the calculation. As soon as the time available in the maintenance shift is insufficient to do all necessary cutter changes, the time available for excavation is automatically reduced. The situation becomes even worse if individual cutters must be changed during the excavation time as a result of impact damage. With gripper TBMs, the amount and type of support to be installed immediately behind the cutterhead also have a major influence on advance rate. The installation of shotcrete in this area almost always leads to an interruption of the boring cycle, while anchors, steel mesh, and steel channels can normally be installed simultaneously with the boring progress. In addition, various aspects of machine design, construction operations, logistics, and organisation must be taken into

Authors

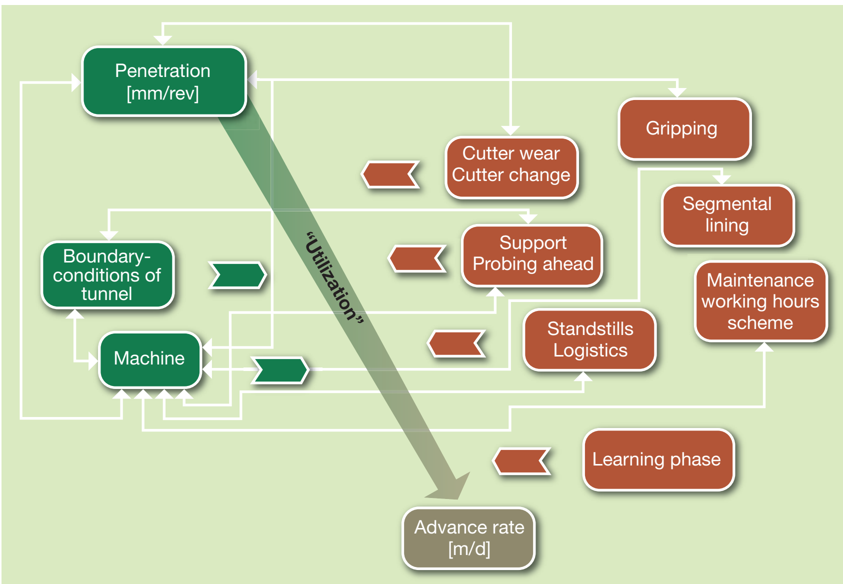
Univ Prof Dipl-Ing E Schneider, Department of Construction Management, University of Innsbruck

Dipl-Ing. Dr. echn. M Spiegl, Managing director of SSP BauConsult GmbH, Innsbruck

Dipl-In. M Turtscher, Department of Construction Management, University of Innsbruck

Dipl-Ing Dr techn. W Leitner, G Hinteregger & Sohne, BaugmbH, Salzburg

Below: **Figure 1 – Interdependencies from penetration to advance rate**



account in calculating the advance rate. The quantitative inclusion of all these parameters, interdependencies, and influences is all but simple and—since several iterations for the calculations are necessary—is only possible in a complex calculation model. Figure 1 shows the main interdependencies.

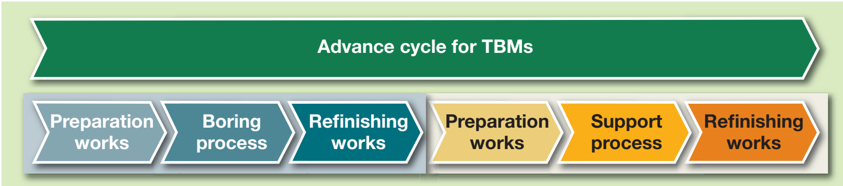
In practice most calculation models use simplified algorithms, which only take the major relations into account. Also, there are many projects in which not all necessary data for an accurate calculation of the advance rate is available. Experienced users, in particular the construction contractors working in mechanised tunneling, are often able to compensate these deficiencies by their own experience. In view of the essential influence of the advance rate on excavation prices, on time-dependent site overheads and the fact that advance rate must be guaranteed by contractors in many cases (or is at least penalised through deadlines) there is a high risk to take for contractors. Motivated by the analysis of a large number of tunnels excavated by TBM and by the wish to find a better solution to a problem that has so far been solved unsatisfactorily, the authors have developed a new model to calculate advance rate with a software that takes the complex interdependencies into account simplifying the complicated calculation work for the user.

State of the art

There are a number of models to predict the penetration rate. They are based on different concepts and on different experiences. The best-known models are the CSM[2] model (1993[3]), the model by Gehring[4] (1995) and the NTNU[5] model (1998). They are used individually, but sometimes also in combination with each other[6]. TheTBM manufacturers and some experts also use their own or modified standard methods for calculation.

Since the models have been developed mainly to predict penetration, none of them contains a method for calculating advance rate that meets the requirements outlined above. In most cases, they are limited to determining the penetration rate; several models also include methods to calculate cutter wear. However, various authors, among them N Barton [ref 3], have established a correlation between net boring speed and advance rate on the basis of empirical data.

A. Bruland, who in his thesis [ref 4] developed the current version of the NTNU model, has shown a way how advance rate can be derived from net boring speed by employing a general ‘utilisation factor’. Another kind of information on the amount of utilisation rates can be found with M Alber [ref 5], who places utilisation rates in relation to the stability of the rock mass. The knowledge of contractors who are the real experts on utilisation rates is normally kept as a business secret and is rarely published.



Above: **Figure 2 – Advance cycle for single shield TBM**

Proposals for improvement

The current practice of modelling TBM advances as semi-continuous processes and to calculate advance speed on the basis of penetration rate, cutterhead speed and daily working hours in combination with utilisation rates, possibly detailed by specific calculations for gripper setting, ring installation and other downtimes, provides only an incomplete model of reality. In calculating advance rate, it is much more fitting to take into account that TBM advance is not a continuous process but always (i.e., regardless of the machine type) an intermittent (i.e., cyclical) one. This is made evident from Figure 2, which shows one stroke with a single shield TBM, where support is provided by segments.

The cyclical approach makes it possible to consider interruptions and downtimes directly, and according to the cause in calculating the duration of cycle times. Since the durations of individual working procedures can be entered in minutes, a detailed target/actual comparison of downtimes is possible during execution. This is much more meaningful than a target/actual comparison of total times or total utilization rates, which does not provide information on the reasons for different standstills. It was W. Leitner who first described and modelled in detail the processes of construction operations in mechanised tunnelling using this approach. In his dissertation [ref 6], he developed algorithms to this effect for all machine types used in hard rock (gripper TBM, single- and double-shield TBM). These algorithms formed the basis for programming the software presented below.

Penetration rate calculation

As shown in Figure 3, the penetration rate depends on three main factors: the machine, the rock, the rock mass and their interactions.

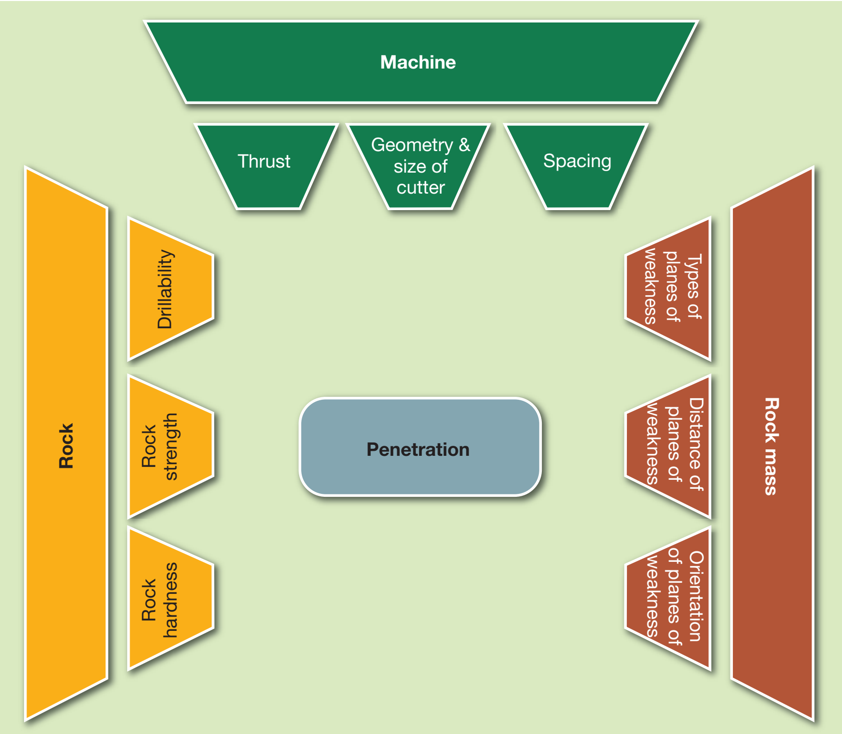
Standard models

Discussing the advantages and disadvantages of the different models for predicting penetration rate, let alone describing the models not explicitly mentioned, would be beyond the scope of this paper. What all models have in common is that they rely substantially on the evaluation of data of completed projects. Thus, the database used is of crucial importance.

In the CSM model, these are mainly data of TBM tunnels in Northern America; with Gehring, they are figures from publications together with data of TBM-bored tunnels in South Africa and South Korea. The NTNU model uses data from tunnels in Scandinavia and abroad. It was when the mechanised excavations in the Alptransit projects in Switzerland were started that a new chapter was opened in hard rock tunnelling by TBM. Therefore it was obvious to use data of these and other

Table 1: Members of the Abrock research group

Name	Institute	University
Prof E Schneider	Institute of Construction Management (co-ordinator)	UIBK University of Innsbruck
Prof K Thuro	Dept of Engineering Geology	TUM University of Technology, Munich
Prof R Galler	Institute for Subsurface Engineering	MU Leoben
Prof G Anagnostou	Institute for Geotechnical Engineering	ETH Zurich
Prof J Zhao	Laboratoire de Mechanique des Roches	EPF Lausanne



Above: **Figure 3 – Major parameters influencing penetration rate**

large traffic tunnels that have been excavated since 1990, or are going to be excavated in the next few years, to either improve an existing model or to develop a completely new model. A major factor for the decision to start this endeavour was the fact that most of the tunnels completed before 1990 had diameters < 7.0m, while modern road and railway tunnels normally require a diameter >9.0 m.

The further development of machine technology (diameter and material of discs, cutterhead geometry and cutter bearings, continuously adjustable rotation speed and the like) let some prediction models appear rather old. Essentially, the only model with continuous further development is the NTNU model, but even there the data forming the basis of the 1998 version is already older than 15 years.

New model development

In order to remedy this shortcoming, in 2006 the research project 'Abrock Analysis and Prediction of Penetration and Cutter Wear' was initiated by E. Schneider. Five renowned university institutes from the Alpine region have banded together to form a research group (see Table 1).

With the support of associated partners from the industry (clients, consulting engineers, contractors, and TBM experts) the teams of the involved institutes work in part projects, which ultimately shall be put together to create a new or improved prediction model.

Using laboratory tests with rock samples, which are mainly carried out at the University of Technology, Munich, and cutting tests using a linear cutting machine that is available to the University of Leoben, known correlations will be reviewed and new correlations—such as between penetration rate and destruction work—shall be investigated in detail. Fundamental research on fracturing under dynamic load shall be carried out using a new testing machine developed at EPF Lausanne. All test series shall be accompanied and supported by numerical modelling and simulations.

The influence of tension in the rock mass and the influence of cutterhead shape on the cutting process is investigated at ETH Zurich. At the University of Innsbruck, geological-geotechnical data and operating data of completed TBM tunnels are fed into the model of Gehring [ref 7]. It is then examined if the consistency between theoretical (calculated) and measured penetration rate can be improved by varying the approaches used in the model or by introducing additional influencing factors. The geological-geotechnical input values for the new model will mainly be found by internationally common and largely standardised physical testing procedures (UCS, BTS and destruction work). The only index test that the Abrock research group considers to be indispensable is the Cerchar abrasivity (CAI) test. In the opinion of the Abrock, other index tests, such as those necessary for the NTNU model, are not sufficiently common and are also not really representative for the cutting process performed by disc cutters[7].

Cutter wear

As already mentioned, the standard models to predict penetration rate also include modules to predict cutter wear. The algorithms contained in these models were deduced from regression analyses based on old data material. Therefore the demand for improvement in this field is also urgent. First findings, which will be published shortly [ref 8], has already been made by a member of the Abrock research group by evaluating recently excavated tunnels.

Advance rate calculation

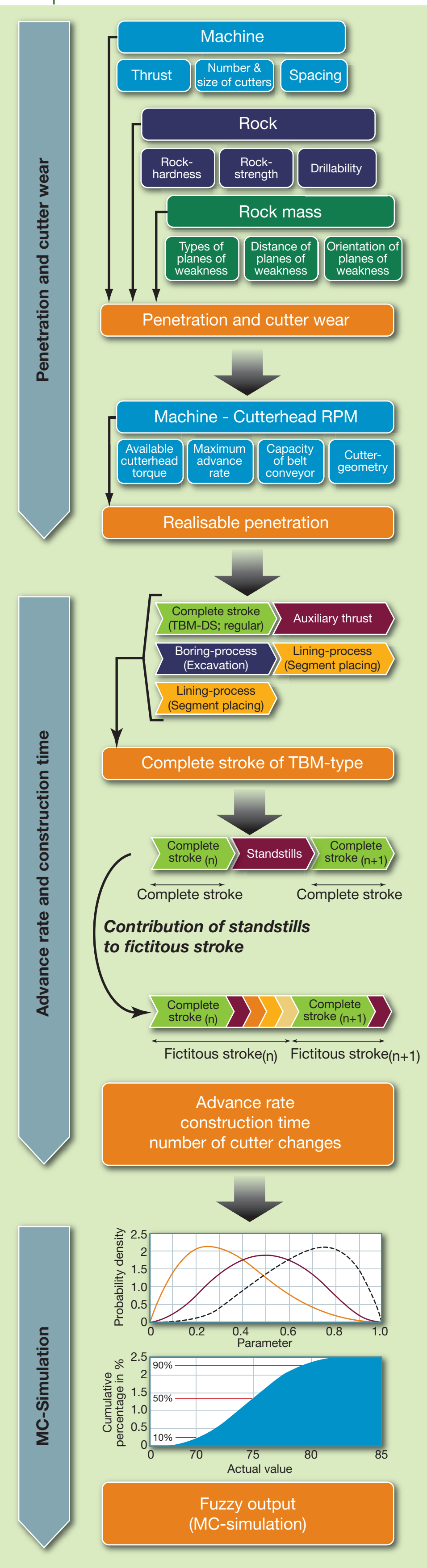
In this step in the calculation, which leads from penetration rate to advance rate, not only aspects of construction operations, organisation, and logistics should be considered, but also those parameters and conditions of machine design that have not been included into the calculation of penetration rate. Relevant parameters are:

- Cutter head rotation speed.
- Available cutterhead torque (depending on cutterhead speed).
- Maximum speed of extension for thrust cylinders.
- Maximum penetration depth of disks (depending on cutter geometry).
- Maximum cutter wear.
- Maximum thrust at cutterhead.
- Maximum thrust per cutter.
- Necessary minimum thrust per cutter.

In addition to the direct influence of the rock and the rock mass in calculating penetration rate, the indirect influence of the rock mass resulting from the installation of support measures must be considered in calculating advance rate. With gripper TBMs, it is the time demand for the support measures and, with shielded machines, the time for the installation of segmental lining that have a major influence on advance rate.

Another factor that can have major influence on the advance rate in abrasive rocks is cutter wear. If more cutters must be replaced than is possible in the time provided for this (i.e., the maintenance shift), the time available for boring is reduced. Unscheduled cutter changes also lead to a reduction in advance rate. Other parameters determining performance to be taken into account are:

- Capacity of the mucking system.
- Capacity of the logistics system.



Left: Figure 4 – Flow chart and functions of Simtunnel Pro 2.0

From the organisational sector:

- planned/available excavation time per working day.
- working days per month/year.
- loss of performance due to the learning phase.

This list, which is not claimed to be complete, may suffice to show that the calculation of advance rate by means of a simple spreadsheet is hardly sufficient. For this reason the first version of 'Simtunnel' using the algorithms of W. Leitner [ref 5], which was developed in 2005 by a student of the University of Innsbruck, was programmed in Java. The software was at the time distributed as freeware together with a (not free of charge) standard calculation for the costs of TBM advances, which was developed in cooperation with a renowned software house[8] at the same time.

Simtunnel Pro 2.0 new programming

Since the first version did not meet the wishes of users in all aspects and also did not take all basic conditions into account, the program was re-developed from scratch in 2009. This time, Simtunnel Pro 2.0 was programmed much more professionally in a programming language (Matlab) that was more appropriate to implement the necessary algorithms and interdependencies (see Figure 4).

The software includes the following new features[9]:

- Default settings for all values (can but need not be changed by user)
- Option to do the calculation with fuzzy input parameters (rock properties, operational parameters, etc.)
- Integration of a module to calculate penetration rate and cutter wear. Selection of Gehring, NTNU, or CSM model; also with individual modifiers[10].
- Works with any working time and shift model
- Takes the learning phase into account (modelling according to Wachter [ref 9])
- Central input table for all values (rock, rock mass, TBM, operation, etc.)
- Result displayed in the form of:
  a) a standardised report
  b) a construction time schedule in various graphics and vector formats
  c) an AutoCAD script file

The tunnel can be divided into any number of homogeneous or advance sections for calculation. These can be calculated individually, with the copy function of the program being especially useful here.

A further subdivision by excavation class, which might be possible in tunnelling with gripper TBMs, is optional. Parameters are entered and calculations are made by sections.

Results are displayed by section and in total; mean values are generated and displayed automatically. With deterministic calculation, discrete values are shown for advance rate, advance time, and number of cutter changes. With probabilistic calculation, distribution functions for advance rate advance time, number of cutter changes, etc., are shown together with mode, fractals, etc.

A standardised technical report in MS Word is output as the calculation result, together with a construction time schedule as an image file or in vector format (distance-time diagram) as well as pie charts for the various activities. Display is from portal A to portal B in total, broken down by advance sections or homogeneous areas.

Summary

There are proven models for calculating penetration rate. Since the underlying data is relatively old and mostly from tunnels with diameters <6.0-7.0 m, this material is no longer up to date. Also, there has been considerable progress since 1990 in TBM technology, in particular as far as cutters are concerned (material, shape, and diameter of disks).

The changed situation has motivated a research group consisting of five university institutes from the Alpine region to pick up the topic of the prediction of penetration rate and cutter wear, with the objective of developing a completely new or improved prediction model. However, penetration rate is only one—although the first and major—parameter to calculate advance rate.

The prediction of advance rate is essentially a task of construction planning, in which aspects of machine technology, operation, organisation and logistics must be taken into account. A simple straightforward calculation is insufficient for doing this: calculation must happen in iterative steps.

On the basis of a doctoral thesis accepted in 2004 at the University of Innsbruck, an engineering firm specialising in construction planning and economics[11] has developed the software Simtunnel Pro 2.0 making it possible to calculate advance rate in a comprehensible way, taking all conceivable influences and basic conditions into account.

A more accurate method of hard-rock TBM performance prediction is required, as suggested by the paper, for better project estimation. [Photo: The Robbins Company]

Endnotes

1 President of The Robbins Company, USA
2 Colorado School of Mines
3 Listed by year of last publication
4 Former Head of F&E, Voest-Alpine Montantechnik, Zeltweg, Austria
5 Norges teknisk-naturvitenskapelige universitet I Trondheim, Norway
6 eg E Buchi, who takes the CSM model as a basis and combines it with parts of the NTNU model in order to take ointo account rock anisotropy and fracture joints (see refs. 2 and 4).
7 However, this does not reduce the popularity of the Norwegian model. One of the reasons may be the fact that the diagrams in the publications of the NTNU permit an estimation of the values DRI and CLI , which are necessary to calculate penetration rate, without having to carry out the corresponding tests
8 AUER – Die Bausoftware GmbH; www.bausoftware.at
9 www.simtunnel.com
10 In addition, it is of course also possible to enter penetration and wear data directly, which have either been estimated, given by TBM manufacturers, or calculated by external experts.
11 SSP BauConsult GmbH, Innsbruck, www.sspbauconsult.at Literature/References

References

[1] Home, Lok (2005). 'Penetration rate baseline dilemma', T&T North America, June 2005 pp 4-5
[2] Buchi, Ernst (1984). 'Einfluss geologischer Parameter auf die Vortriebsleistung einer Tunnelbohrmaschine (mit besonderer Berücksichtigung der Gesteinsanisotropie)', Dissertation, University of Berne, 1984
[3] Barton, Nick (2000). 'TBM Tunnelling in jointed and faulted rock' pp 51-56, AA Balkema, Rotterdam 2000.
[4] Bruland, Amund (1998). 'Hard rock tunnel boring – Advance rate and cutter wear', Project report 1B-98, NTNU Trondheim, 1998; pp 33-40.
[5] Alaber, Michael (2008). 'An Integrated Approach to Penetration, Advance Rates and Disc Cutter Wear for Hard Rock TBM Drives', Geomechanik und Tunnelbau 1/2008, pp 29-37, Ernst u Sohn, Berlin.
[6] Leitmner, Wolfgang (2004). 'Baubetriebliche Modellierung der Prozesse maschineller Tunnelvortriebe im Festgestein', Dissertation, University of Innsbruck. Books on Demand, Norderstedt 2004 ISBN 3-8334-1844-3
[7] Gehring, Karl-Heinz (1995). 'Leistungs- und Verschleißprognosen im maschinellen Tunnelbau', Felsbau Nr. 6/1995; pp 439-448.
[8] Frenzel, Christian (2010). 'Kostenprognose für Schneidrollen bei maschinellen Tunnelvortrieben im Festgestein', Dissertation, University of Technology, Munich. Pfeil Verlag, Munich, 2010.
[9] Wachter, Robert (2001). 'Der Einarbeitungseffekt bei mechanischen Tunnelvortrieben', Dissertation, University of Innsbruck. Innsbruck University Press 2001 ISBN 3-901249-60-5