15 Predicting the Learning Curve in TBM Tunnelling

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15.1 Introduction

With the ongoing development in mechanised tunnelling, driving a tunnel with Tunnel Boring Machines (TBM) has become the state of the art for long tunnels. The advance rate of a TBM in full operation mode can be calculated quite accurately by taking the boundary conditions like geology, diameter, performance data of the TBM, equipment of the TBM, etc. into account (for details see Leitner, 2004 [2]). But especially in the first months of tunnelling, in the so called launching phase the estimation of an average advance rate is a very uncertain task. In this phase different boundary conditions influence the working process; on the one hand the staff gets adjusted to the working processes, local conditions and learn the required skills and on the other hand the equipment gets its final adoption to the project.

Even if there already exist different ways to take this retarded advance into account the effect of low advance rates at the beginning of a tunnelling project does hardly ever find any consideration in the time schedules. In the main part of this article different available approaches for the estimation of the advance rates in the launching phase will be introduced. Finally the authors will describe two approaches for the estimation of the learning curve for shielded TBM with segmental lining.

15.2 TBM Tunnelling

For the excavation of long tunnels or galleries, the application of a Tunnel Boring Machine (TBM) is normally the fastest and most economical method.

In general a TBM provides the maximum possible grade of automation for the excavation as well as for the installation of primary lining and out of that a maximum possible grade of safety for the workers. Tunnelling with a TBM has some remarkable features like:

- High performance out of the mechanisation of the machine
- High performance out of full face excavation
- Possibility of semi automation of production processes (for example the ring building process, or shotcrete robots)
- In case of segmental lining the tunnel is already finished behind the TBM
- Automatic registration of all relevant data
- Automatic control of press forces, torque, amount of mortar etc…

The fact that the number of projects which are excavated by TBM increases shows the overall advantages of this tunnelling method and the enormous development of the machinery equipment (for example possible diameter range for the TBM, etc.).

15.2.1 Machinery and working process

For the evaluation of the learning process it is necessary to evaluate the working cycles of a TBM advance. Regarding the working cycles we can classify the available TBMs into three different categories:

- Open Machines,
- Shield Machines and
- Double Shield Machines.

In solid rock the tunnelling is made with open machines without any shield. Under good conditions a open TBM can operate with a constant advance rate, as the rock support will be installed independent from the excavation from the L2 area on the back up system.

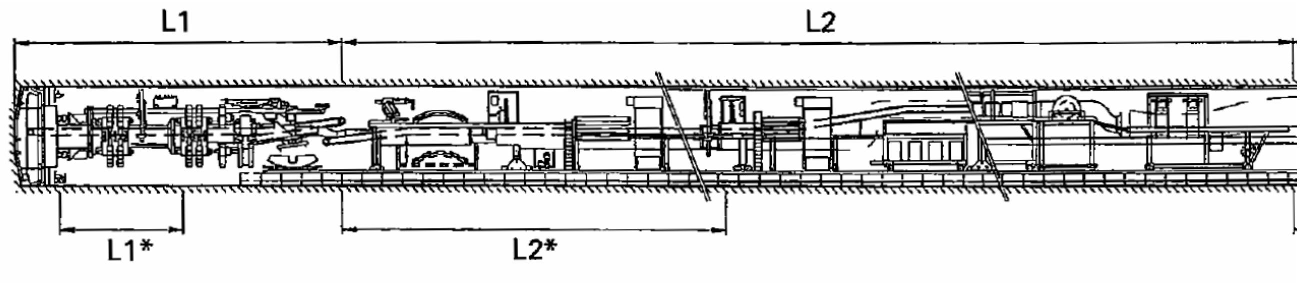

Figure 111: Scheme of an Open TBM, SIA 198 [6]

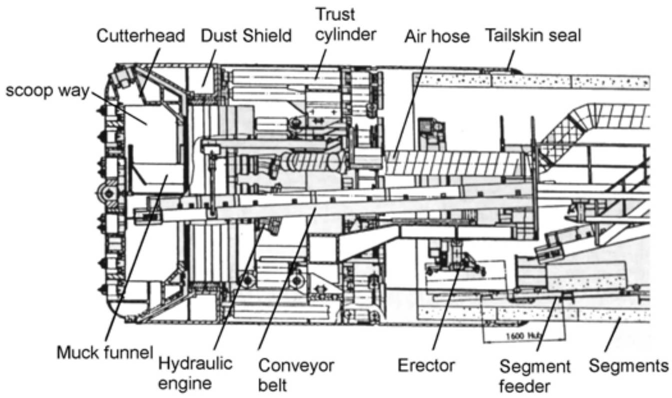

Figure 112: Scheme of a Single Shield TBM (Schneider, Wais 2003 [2])

In soft ground and highly unstable rock where the standing time of the ground is not sufficient enough for the usage of a open TBM a Shield TBM is used. The ground support in the area of the TBM is realized by the steel shield. In the protected area of the tail shield the support measures – normally prefabricated concrete segments - are installed. On the one hand the segments are used as a ground support measure and as the final lining of the tunnel and on the other hand the segments are used for pushing forward the shield machine. For the installation of the segments an erector that is located in the tail shield of the TBM is used. The angular ring gap between the segments and the excavated tunnel surface is grouted with mortar; that ensures the full face contact between the segments and the rock. Tunnelling with any single shield machine follows a cyclic working procedure:

- Excavation
- Installation of the segmental lining

The gripper enables a continuous advance with Double Shield Machines. In good geological conditions where a bracing with grippers is possible, the segments can be installed while a stroke is bored completely, because the thrust forces of the cutterhead have not to be supported by the installed segment ring.

15.3 The Launching Phase

From the beginning of a tunnel project and more important during the tendering of a tunnel project the advance rates of a TBM have to be estimated to achieve an accurate time schedule of the whole project. In this calculation parameters like geology, hydrogeology, performance of the TBM and many more get used to estimate the advance rate in full operation mode of the TBM in detail.

15.3.1 Training and familiarisation effects

Observing the advance rates of a TBM over the production time, an increase in performance can be stated. One explanation for this increase is the effect of familiarisation, provided that there are no other reasons (like geological surroundings, change of technology, etc.).

Psychology, which is regarded as the origin of learning science, has developed models and theories describing and explaining learning processes in a general way. As a result of all this explanations the familiarisation period can be regarded as a phase of creation of knowledge which leads to a modification of company structures and processes.

The most important influence on the advance rate in the launching phase is the training and familiarisation of the staff. This is mainly due to the fact that every project uses a different type of machine and has different conditions and logistics on site. In international projects most of the labourers first have to be trained from experienced expatriate foremen.

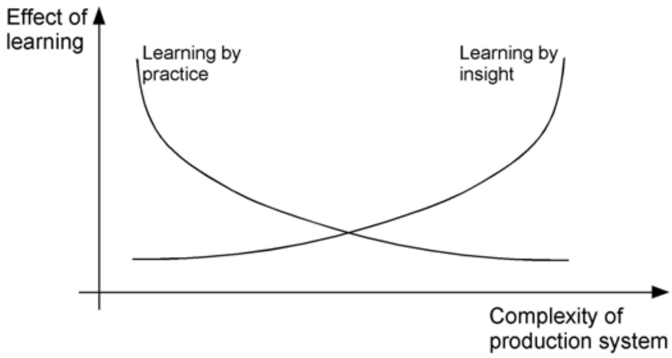

Figure 113: Changes of the effect of learning (Hieber, 1990 [5])

The effect of learning and training in a mechanical tunnelling process with all its cyclic working steps can be compared with the effects of learning in any industrial production system. There are two different ways of learning (Andress, 1994 [6]), the learning by practice during the repetition of simple working processes and the learning by insight in complex working processes. Those different ways of learning occur at different times on different levels of the organisation on site. The simple labourers learn their duties and responsibilities starting with the first day of tunnelling. The foremen, mechanics and machine operators with more complex duties and long term experiences from former projects need some time until they create the proper organisational system on the actual site.

The major factors influencing learning can be divided into three groups; however, the amount of influence based on the individual factors on the learning behaviour cannot be determined:

- Man
    - Qualification and motivation
    - Construction site organisation
    - Communication on the construction site
- Machine and support system
    - Machine type
    - Adaptation measures
    - Condition of the driving system
    - Conditions of the back-up system
    - Type of support system
- Geology
    - Geological formation
    - Hydro geological conditions
    - Changes between sections of homogeneous geology
- General conditions
    - Degree of difficulty
    - Intensity of work preparation
    - Local Conditions

As an example for the training effect, the duration of the installation of a segmental ring is observed over the amount of repetitions. As shown in Figure 114 the erector operator and its staff reduce the time needed for the installation of the segment ring drastically during the first 500 m of a Tunnel.

The TBM control software records all the times required for each ring. These times were extracted from the system of a EPB Shield TBM with approximately 5,0 m diameter and are displayed in Figure 114.

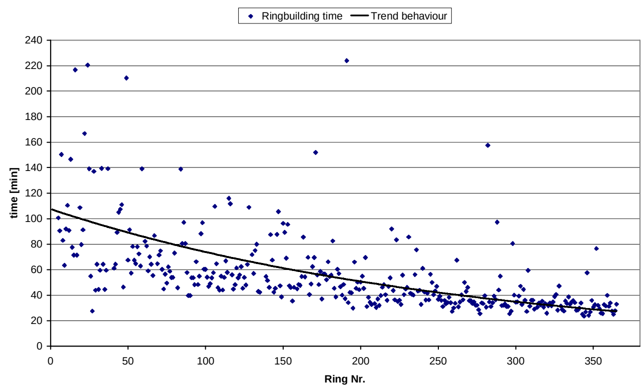

Figure 114: Ringbuilding times in the north tunnel according to the Herrenknecht control system

It has to be taken into account that the ringbuilding times recorded from the TBM control system are not that accurate as we should expect. As the system starts counting as soon as a button “Ringbuild” in the operator cabin is pressed and stops counting as soon as the button is released, it is not always a very accurate method. For example during breakdowns when the erector has to be moved for different reasons, the ringbuild modus is all the time switched on, and so very high ringbuilding times get recorded.

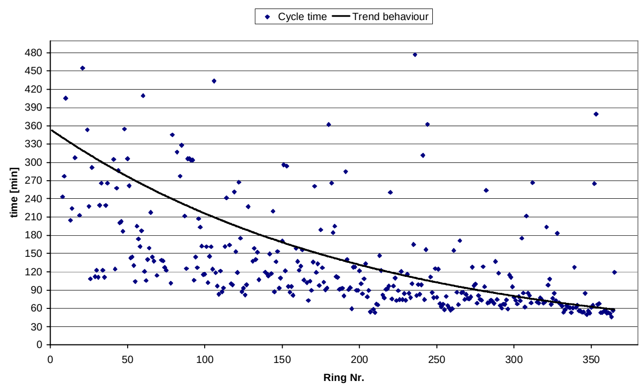

Figure 115: Cycle times (excavation, ringbuilding, delay, breakdown) according to the control system

The automatic data acquisition of the TBM also records the complete cycle time including, excavation, ringbuilding, and delays. It starts counting as soon as the machine is in advance modus for the excavation, and it stops counting as soon as the machine is again in advance modus for the following excavation. Due to this measuring procedure, any interruption like a breakdown leads necessarily to high cycle times. The cycle times with duration of more than eight hours are not shown in the graph, but they still influence the exponential trend behaviour (Figure 115). The reduction of the cycle times is a clear indication for the improvement of the tunnelling process. A faster ringbuild can be achieved by a good erector operator, but the reduction of the whole cycle time is only possible if every labourer is familiarised with its work and knows exactly his position in the team.

15.4 Modelling the Training Effect

Before being able to discuss the modelling of the training effect, it is necessary to define a suitable measurable variable. In any case it has to be taken into account that it is only possible to measure the effect of learning, not the learning itself. Suitable variables are:

- Effort spent per units produced
- Units produced, effort amount being constant
- Cost

Effort spent includes the following variables:

- Working hours
- Machine hours
- Standstill hours
- Repair hours
- Man hours

The models discussed in the following parts use all together the daily advance rates as the most suitable variable for measuring the training effect. Basically we can differentiate two methods for modelling the training effect:

- Adjustment of learning curves
- Analysis of the familiarisation period on the basis of the advance data.

The concept of learning curves originates from the 1930s and was originally used in production planning and control in the aeronautical industry. As a result of various applications of the learning curve concept a number of learning curve approaches have been developed and adjusted to the special behaviour of the respective case of application. A comparison of different applications shows that there are two dominating types of functions; first, the classic power function approach and second, an exponential function approach. In applications for the construction industry the exponential function approach is dominating.

15.5 Approaches for the effect of familiarisation and training

In order to include the effect of familiarisation and training in the schedule of a TBM project, different researches have been made. They use various approaches with different parameters to estimate the advance rate (m/d) of a TBM in the launching phase.

The main steps for calculating the training effect are:

- Evaluation of already finished projects (adoption of models for the training effect)
- Evaluation of the boundary conditions of the project
- Correlation between boundary conditions and model parameter
- Model for the prognosis of the training effect

Most of the models for the training effect neglect the boundary conditions of the evaluated projects and therefore the evaluated parameters have to be treated with care.

In order to get an overview of the possible ways to estimate the effect of familiarisation in TBM tunnelling, the most common models are explained briefly in the following chapters.

15.5.1 Approach from Gehring

The approach from Gehring includes the experience and knowledge from different projects all around the world. In the approach of Gehring the advance rate develops over the first five months and starts with 30 % of the full advance rate in the first, 60 % in the second, 80 % in the third month, 90 % in the forth and 95 % in the fifth month.

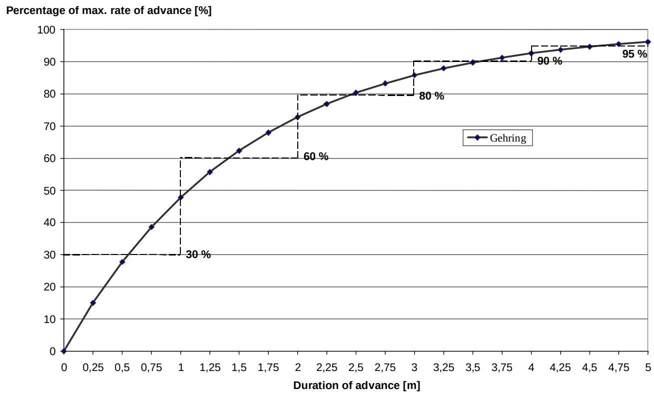

Figure 116: Approach from Gehring, (Wais, 2002 [1]) for the effect of training and familiarisation of a TBM

To convert this approach into an exponential formula an additional reduction parameter of 0,65 is necessary. This parameter was derived by the author with a best fit iteration scheme.

$$f_{famil.} \approx 1 - e^{-d*0,65}$$

with: f_{famil} = Percentage of the maximum rate of advance
d = Duration of advance in months

15.5.2 Approach from Wachter

Wachter [3] separates different types of approaches:

- Classical Learning curve approach with an exponential function
- Analysis of the behaviour in the familiarisation period
- Estimation of the advance rates before the start of the construction
- Estimation of the advance rates when the tunnelling is already in progress (short term prognosis)

In this article only the classical learning curve approach (before the start of the construction) will be presented. The proposed learning curve is adjusted to the data of different projects with Open TBM and Double Shield TBM.

$$L(t) = a*\left(1 - e^{-c*t}\right)* f_1$$

with t = duration of tunnelling in days [d]
L(t) = Advance rate per day [m/wd]
c = Learning curve parameter [-]

The proposed learning curve was also modified to fit to the total progress.

As a main feature of the proposed model the different boundary conditions were filtered out and correlated to the evaluated parameters of the learning curve. The different geological conditions are filtered out of the daily advance rates by means of filter functions.

All boundary conditions of the site that influence the process of learning are rated in a scale from 1 to 5 (1=poor; 3=standard; 5; good). All the achieved points from one project get summed up to a value LRH (see table below).

Group	Factors	Standard	Good	Poor	Points
Human	Personal	permanent staff 40-50 %, familar with tunnelling, enough auxiliary staff avail. flexible working hours, small fluctuation	100 % permanent staff, very flexible working hours, following an earlier site (from former sites)	low amount of permanent staff, labours from third world countries, high fluctuation rigid working hours rules	
	Organisation	Clear allocation of Function and responsibility, to expierenced staff	Organisation allready in practice (from former sites)	Unclear Functions and Responsibility	
	Communication	good ability to communicate in one common language for the key positions	Communication allready in practice (from former sites)	no or only minor ability to communicate in one language	
Machine	Diameter	Working space and power of the machine match with diameter	Lower planned diameter (performance reserve)	Diameter does not match with machine and trailer concept (too big, too small)	
	TBM type and trailersystem	tested and familarised to the key personal, suitable for soil conditions, suitable trailer, good logistics	System allready in practice (from former sites)	System and ist components do not fit together	
	Condition	TBM and trailer in a good refurbished condition, standard prone to break down	New system , low prone to break down	TBM and trailer used, high prone to break down	
	Support	tested and familarised to the key personal, suitable for TBM type	System allready in practice (from former sites)	unaccustomed, unpractical support system	
Surrounding	Infrastructure	Good accesibility, sufficient area, electric power and water	Good accessibility, sufficient area, electric power and water. Already developed site from former construction	poor accessible, poor conditions of area insufficient water and electric power	
	Supply	competitive suppliers, enough area for storage, suitable spare stock	allready known suppliers from former sites, no time pressure	new or unsuitable suppliers, lack of storage area, insufficient spare stock	
	Starting situation	Filling of key positions allready known minor obstacles by temporary measures low weatherd soil and water at the start, secured start position (Abutment Frame, Starting trestle, Start Ring)	complete personal available, no obstacles temporary meassures, no weathered soil and no water at the starting position secured start position (Abutment Frame, Starting trestle, Start Ring)	insufficient staff available, many obstacles by temporary meassures, insufficient start position, completely weatherd soil with water during start, high time pressure	
Rock	Formation	No gas, loose rocks, drilling possible low water inflow	No gas, stable, good to very good drillable (not too hard), no water inflow	Gas, unstable soil, Water inflow, many changes in soil conditions	
				Summ LRH:	

Table 9: Evaluation of the project influences on the familiarization and training (Wachter, 2001 [3])

The total sum LRH gets used for to classify the learning situation of the construction site. The system of classification is displayed in the Table 10.

Good		Standard		Poor	
55	44	43	23	22	11

Table 10: System of classification for LRH (Wachter, 2001 [59])

With this classification of each project, the parameter c for the learning curve can be estimated separately for all types of TBM (Gripper or Double Shield) with the help of Table 11.

TBM Type	Assesment	Learning Parameter	
		from	to
Double Shield TBM	good	0,02	<
	standard	0,01	0,02
	poor	<	0,01
Open TBM (Gripper)	good	0,05	0,25
	standard	0,01	0,05
	poor	<	0,01

Table 11: Learning curve parameter c for both types of TBM (Wachter, 2001 [3])

With the given parameters and the known geological boundary conditions like penetration and maximum speed (m/h), the calculations as shown in the following example for a tunnel with 1.000 m length have to be made.

The used parameters are defined in the following way:

I_N = The net advance rate during boring due to penetration and rotation speed [m/h]
I_B = Reference net advance rate [m/h]
f_1 = Parameter of the filter function [-]
a_i = Daily advance rate due to penetration, rotation speed and efficiency [m/wd]
a = Learning curve parameter selected from I_B [m/wd]

Chainage [m]	Percentage [%]	boring speed [m/h] I_N	daily advance [m/wd] a_i	f_1 [-]
0.00 - 100	10%	2,1	15,54	0,778
100 - 400	30%	2,7	19,98	1
400 - 1000	60%	3	22,22	1,11
		2,82	**20,87**	

a =	20,0 m/wd	chosen
I_B =	2,7 m/h	calculated
a_i =	20 h * I_N * 37 %	calculated
$f_1 = \frac{I_N}{I_B}$		calculated

Table 12: Calculation of the different values required for the approach by Wachter, 2001 [3]

To calculate the daily advance rates due to the learning curve, geology and all the above mentioned parameters, the following formula has to be used.

$$L(t) = a * \left(1 - e^{-c*t}\right) * f_1$$

with
t = duration of tunnelling in days [d]
L(t) = Advance rate per day [m/wd]
c = Learning curve parameter [-]

The assumed TBM is a Double Shield TBM with a learning curve parameter of c=0.015, see also (Table 11). The parameter f_1 for the filter function gets adjusted with the changing geology during advance.

In this example it is visible that due to the exponential approach from Wachter, the learning period lasts for the whole length of the tunnel. At the last day with an advance rate of 17.25 m/d, the maximum possible advance rate is not yet reached. Changing to higher or lower values (m/wd) does not change significant the calculated values due to the filter function.

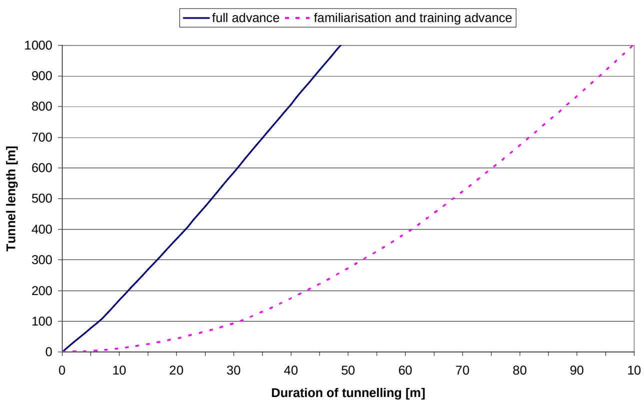

Figure 117: Full advance and reduced advance due to the effect of training and familiarisation

The approach of Wachter seems to be a possibility to assume an advance in the launching phase. But due to the fact that the model parameters were evaluated with the data of Double Shield TBMs and Gripper TBMs with different working cycles than a single shield TBM the model parameters cannot be transferred to a model for a single shield TBM.

15.5.3 Sophisticated approach for single shielded TBM suggested from Wais

For the case of a single shield TBM the parameters of the above explained model have to be modified. The model can then be used for any kind of Single Shield TBM (Slurry, Hydro, EPB) with segmental lining.

The evaluation of the project influences on the familiarisation and training is done in the same way than in the approach of Wachter. In the next step the learning conditions are evaluated with an extended version of the Table 11 (see Table 13).

TBM Type	Assesment	Learning Parameter from	Learning Parameter to	
Double Shield TBM	good	0,02	<	Wachter
	standard	0,01	0,02	
	poor	<	0,01	
Open TBM (Gripper)	good	0,05	0,25	
	standard	0,01	0,05	
	poor	<	0,01	
Single Shield TBM	good	0,025	<	Wais
	standard	0,015	0,025	
	poor	<	0,015	

Table 13: Extension of the evaluation of the learning conditions on site based on (learning curve parameter c) (Wachter. 2001 [3])

The learning parameter c is chosen close to the learning parameters of the Double Shield TBM because both of them use segmental lining support with manual installation. The learning parameter c for the single shield machine was not statistically evaluated and is only based on the experience of four shield machine driven tunnels.

The calculation of the advance rate is done with respect to the ringbuilding time and the boring time; in this article it is only displayed in a very plain way. For detailed information see Leitner, 2004 [2]. First of all the cycle time for one cycle has to be calculated.

$$t_{cyl} = 60\left[\frac{\min}{h}\right] * \frac{L_S[m]}{I_N\left[m/h\right]} + t_{RB}[\min]$$

with:
- t_{cyl} = Duration of one advance cycle (advance and ringbuilding) under well trained conditions [min]
- L_S = Length of the segment [m]
- I_N = Net advance rate with respect to penetration and rotation of the cutterhead [m/h]
- t_{RB} = Time required for the ringbuilding under normal conditions with well trained staff

With the cycle time, the absolute advance rate I_{Abs} can be calculated with:

$$I_{Abs} = \frac{L_S[m]}{t_{cycl}[\min]} * 60 \left[\min/h\right]$$

With the absolute advance rate I_{Abs} the formulas from Wachter can be used the following way. The whole process of calculation will be demonstrated at the example of a shield tunnelling project from a German contractor in Singapore. The penetration rates for the project were given for each type of soil encountered on the alignment of the tunnel.

The sum of LRH was 27 and so the situation on site was classified by the author as a standard learning situation. As 27 lies in the lower range of standard, the learning parameter c was set to 0.017 for both tunnels. The total availability has been set to 37%.

Chain. [m]	Percent. [%]	Boring speed [mm/min]	Netto adv. I_N[m/h]	absolut adv. [m/h] I_{abs}	daily adv. [m/wd] a_i	f_1 [-]
0.00 - 95	1,69%	35	2	1,365	10,101	0,72
95 - 3345	57,83%	80	5	2,152	15,923	1,14
3345 - 5620	40,48%	50	3	1,696	12,548	0,90
				1,954	14,458	

a =	14	m/wd	chosen
I_B =	1,892	m/h	calculated
a_i =	20 h * I_{Abs} * 37 %	m/wd	calculated
$f_1 = \frac{I_{Abs}}{I_B}$			calculated
0,37 %		availability	

Figure 118: Calculation of the different values required for the approach suggested from the author

When all those parameters are calculated the advance rate with respect to the learning behaviour can be derived with the following formula.

$$L(t) = a*\left(1-e^{-c*t}\right)* f_1$$

with:
t = Duration of tunnelling in days [d]
L(t) = Advance rate per day [m/wd]
c = Learning curve parameter [-]

The effect of training and familiarisation causes a delay of 57 days compared with the full advance rate calculated from the geological data available.

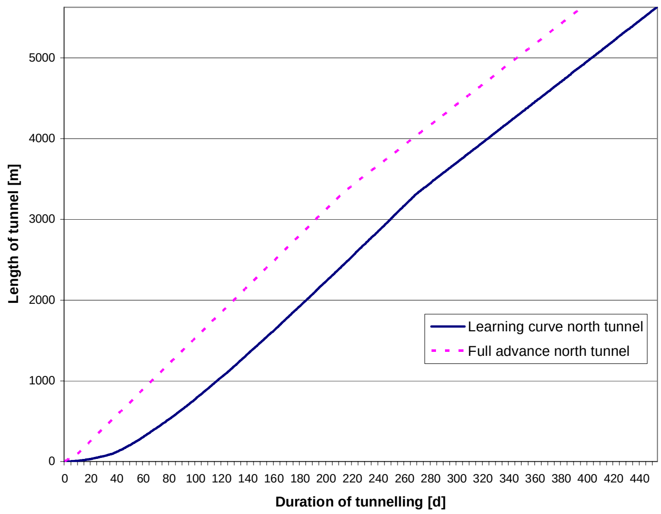

Figure 119: The full advance rate of a the TBM and the advance rate with respect to the learning curve for a single shield TBM proposed by the author

15.5.4 Simple approach for single shielded TBM suggested from Wais

A TBM producer was so kind to hand over some data of nine different tunnelling projects worldwide. The machines were all Shield TBMs (EPB, Hydroshield) with segmental lining support. In this paper the first 500 m of the tunnels got examined, as in this phase the familiarisation and training have the biggest influence. As the data is not very detailed, it is not possible to compare it with the before mentioned approaches from Wachter, Wais and Gehring. Due to the imperfect data the following assumption and commitments have been made by the authors:

- The machines had different advance rates during the 500 m of tunnel, the highest weekly advance rate was set to 100 % and the others were expressed in percentage of the maximum.
- Influence due to the geology and hydrogeology have been neglected as in the first 500 m they play only a minor role with respect to the advance rate.
- The advance rates handed over were all given in meters per week. So it is not possible to sort out breakdowns or holidays with duration smaller than one week.
- Weeks with a total tunnelling performance smaller than 10 % of the maximum were neglected and had no influence on the curve as such a small weekly advance rate due to interruptions has nothing to do with familiarisation and training of the staff.
- The percentage of max. advance from all the projects in every week got averaged to achieve the values of the graph.

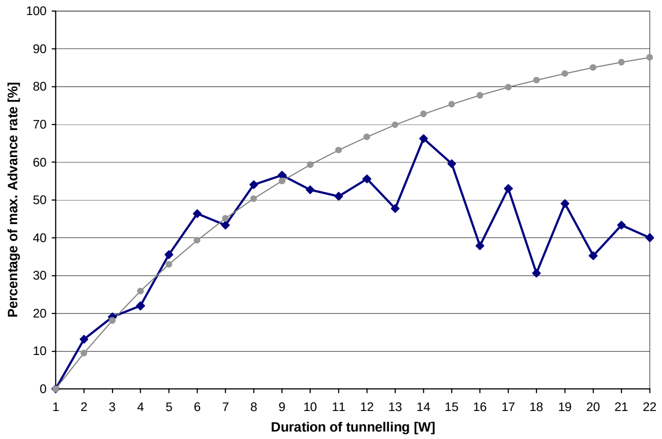

Figure 120: Average performance rates of various shield machines

In the first 11 weeks (Figure 120) a very steady increase of the curve is recognizable. After 12 weeks the curve is strong influenced by single values as the total amount of remaining projects is already reduced due to the fact that the first projects have tunnelled 500 m after 11 weeks. This fact is especially important in the last observed weeks (Week 17-22). There the curve is very unsteady and strong influenced by the single values. If only the first 14 weeks of tunnelling with the steady curve get examined the following approach can be derived:

$$f_{famil} \approx 1 - e^{-d*0.1}$$

with: d : Duration of advance in weeks

f_{famil} : Percentage of the maximum rate of advance

This would be an approach that would be even more conservative than the approach from Gehring. It cannot be called generally valid, as more detailed information about the projects are not available. The biggest problem is that the advance rates were given in m/w. Interruptions over one or two days due to breakdowns, installation of trailers or other reasons lead to a reduced advance rate per week. This reduced advance rate has nothing to do with learning and familiarisation and has to be taken into account for the schedule separately.

This simple approach with one parameter can be a very useful model for tendering. Especially during tendering the time available for the calculation of a time-way program is quite small and an easy applicable approach has great advantages.

15.6 Conclusions

Tunnelling with a TBM is one of the most sophisticated working processes in the construction business. Various details have to be taken into account during the process of planning and construction. But nevertheless it has developed to the state of the art in many tunnel constructions.

The effect of familiarisation is clearly visible in almost all tunnelling project. The measured cycle times proved that the whole process of tunnelling and its organisation improve during construction. Even if there are various approaches, the prediction of the effect of familiarisation and training in the schedule of a tunnelling project is still a difficult and uncertain task. In case of a well estimated advance rate in full operation mode, the approaches from Gehring and the simple approach by the author can to be quite reliable and able to estimate the effect of familiarisation and training. They are easy to use and can be included in any project even without informations in all details. One of the greatest advantages of those approaches is the simple and fast application, which is especially important during the time of tendering. The more sophisticated approaches of Wachter and Wais should be used for the time after the tender when more detailed information are available and the pressure of time is not so strong.

As extending the date of completion of contract is always combined with high fines it is recommended to calculate the timetable as realistic as possible. A realistic schedule for a tunnelling project can only be done with respect to the effect of familiarisation and training.

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