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Hard Rock Tunnel Boring

Vol. 1 of 10

Background and Discussion

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HARD ROCK TUNNEL BORING

Consisting of the following volumes

HARD ROCK TUNNEL BORING VOL. 1 Background and Discussion
HARD ROCK TUNNEL BORING VOL. 2 Design and Construction
HARD ROCK TUNNEL BORING VOL. 3 Advance Rate and Cutter Wear
HARD ROCK TUNNEL BORING VOL. 4 Costs
HARD ROCK TUNNEL BORING VOL. 5 Geology and Site Investigations
HARD ROCK TUNNEL BORING VOL. 6 Performance Data and Back-mapping
HARD ROCK TUNNEL BORING VOL. 7 The Boring Process
HARD ROCK TUNNEL BORING VOL. 8 Drillability - Test Methods
HARD ROCK TUNNEL BORING VOL. 9
Drillability - Catalogue of Drillability Indices
HARD ROCK TUNNEL BORING VOL. 10
Drillability - Statistics of Drillability Test Results

by

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Preface

The thesis is a result of my work at the Department of Building and Construction Engineering at the Norwegian University of Science and Technology in Trondheim.

The aim of the thesis is to provide a toolbox for the design, planning and excavation of hard rock tunnels by tunnel boring machines. The thesis is meant to be a practical tool to be used throughout the planning and construction process.

Parts of the thesis are very much based on previous publications from the department (e.g. the prediction models for advance rate and excavation costs), and should be regarded as updated and improved versions compared to the previous editions. This fact illustrates that my work is part of a long-term commitment by the department in research and development in the tunnel boring field. And, in a few years, the models and data presented here will need to be updated and improved based on new field data obtained through the continuous process of performance data collection.

The department of Building and Construction Engineering started its involvement in tunnel boring in the early 1970s. I have been involved in tunnel boring research and development since 1982, when I started to work for the department. During this time several persons and organisations have been of great importance for my work:

- Professor Odd Johannessen initiated the research on tunnel boring in the 1970s and has been my supervisor par excellence.
- Dr.ing. Arne Lislerud introduced me to hard rock tunnel boring, and many are the hours we have enjoyed together mapping bored tunnels, collecting field data and discussing TBM tunnelling in general.
- Students and colleagues with whom I have co-operated in the field and at the department.
- Persons and organisations in the tunnelling industry that benevolently have contributed to the research activity at the department.

Further acknowledgements are given in Section 3.8 and Appendix 2.

And finally, my warmest thanks to Beate.

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1 Description of the Thesis

The thesis consists of 10 volumes (9 reports and one summary) as specified below.

1A-98	HARD ROCK TUNNEL BORING Design and Construction
1B-98	HARD ROCK TUNNEL BORING Advance Rate and Cutter Wear
1C-98	HARD ROCK TUNNEL BORING Costs
1D-98	HARD ROCK TUNNEL BORING Geology and Site Investigations
1E-98	HARD ROCK TUNNEL BORING Performance Data and Back-mapping
1F-98	HARD ROCK TUNNEL BORING The Boring Process
13A-98	DRILLABILITY Test Methods
13B-98	DRILLABILITY Catalogue of Drillability Indices
13C-98	DRILLABILITY Statistics of Drillability Test Results

And finally, the present volume **HARD ROCK TUNNEL BORING Background and Discussion** with general information about the basis of the above listed reports as well as an overview of the thesis as a whole.

The toolbox of reports is to some extent based on previous editions of the Hard Rock Tunnel Boring Reports [20] - [24] and the Drillability Reports [36] - [41]. All reports are written and finalised by Amund Bruland. Baroline Log has to a large extent prepared the digital database used as background data for the reports 13B-98 and 13C-98. The laboratory technicians Filip Dahl and Torill Sørløkk have also given valuable assistance to the preparation of the digital database. Randi Sæther and Eirik Fyhn have produced most of the numerous illustrations in the reports of the toolbox.

1.1 OBJECTIVE OF THE THESIS

The main purpose of the thesis work has been to improve the existing prediction models and to provide a toolbox for the TBM tunnelling industry (project owners, consultants, contractors, manufacturers, etc.) to be used through all phases of a project:

- Preliminary and feasibility studies
- Project design and optimisation
- Site investigations
- Tendering and contract
- Construction
- Possible disputes or claims.

The various reports of the thesis treat various subjects of TBM tunnelling. Combined with other estimation models published in the Project Report Series from the Department of Building and Construction Engineering, the reports of the thesis provides a reliable and practical tool to be used for:

- Estimating net penetration rate and cutter life
- Estimating construction time and costs, including risk or uncertainty
- Assessing risk with regard to deviation or variation in estimated rock mass boreability, machine parameters and tunnelling performance
- Designing auxiliary systems such as ventilation, muck transport, etc.
- Establishing and managing price regulation in contracts
- Verifying machine performance
- Back-mapping and verification of the geological conditions
- Collecting, normalising and analysing of rock samples, machine performance data and cutter wear data.

The thesis work has not been focused on basic principles, theoretical modelling or laboratory experiments of rock cutting with disc cutters, although observations and results from field studies are presented and analysed in [11]. Several other researchers and institutions have covered those topics. To be mentioned here is the prominent and comprehensive research done at Colorado School of Mines in the USA and at Luleå University of Technology in Sweden. Both institutions have a series of publications ranging over three decades in this area.

1.2 BACKGROUND OF THE ESTIMATION MODELS

The estimation models for penetration rate and cutter life are purely empirical. This means that they are based on field studies and statistics from TBM tunnelling in hard rock conditions, mainly in Norway, but also in some other countries [19].

35 tunnel jobs with more than 250 km of tunnel have been documented in detail. Several other tunnel jobs are represented with cumulated or averaged data or data from shorter sections of the tunnels.

The estimation models in the thesis are not based directly on the total database of performance data and geological back-mapping. The updating of the models is based on the following approach:

- The existing models had already gone through several phases of a continuous process:
  - model development
  - checking and adjusting the models against new data
  - using the models in the planning of new tunnels
  - the same tunnels are then followed closely, providing data and experiences to be incorporated in the models.
- The models published in 1994 [20] and 1988 [21] are based on the cumulated database at that time. Since 1994, only few new data have been provided. Hence, the new data available would not change the models substantially.
- It was therefore decided to base the updating on an analysis of the goodness of the 1994 model against the new data and against selected data acquired after 1985. The selection of data was based on data quality, i.e. tunnel sections with uniform and well-documented geology and machine performance.
- When the "problem areas" had been identified, the models were adjusted to get a better fit to the new and selected data.

1.3 THE HARD ROCK TUNNEL BORING TOOLBOX

The toolbox consists of 9 volumes or reports as listed at the start of this chapter. Some of the reports are basic tools and some are more specialised and in-depth tools. Therefore, some information may be found in more than one of the reports. This has been done to improve the usability of each of the volumes.

The toolbox is not intended to be a tunnel boring encyclopaedia giving all the answers, but rather a representation of the knowledge NTNU has acquired through many years of field studies in the full-scale laboratories of hard rock TBM tunnels.

1.31 Drillability

The three reports about rock drillability [12], [13], [14] are used to assess and evaluate the rock type parameters needed as input to the prediction models. Report [12] describes the laboratory test methods employed to find the drillability indices *DRI* and *CLI*. The test method descriptions are included in the thesis to give the reader a good understanding of the indices, since the test methods are not internationally standardised yet.

The reports [13] and [14] present and analyse laboratory test results of more than 2000 samples tested in our laboratory. The samples are listed with rock name and geographical information of the sample site. The results and indices are analysed statistically to describe the variation within a rock type and between rock types.

The report about geology and site investigations [9] gives information of the system used to collect data and build an adapted engineering geological model of the rock mass. The report also provides information of how to interpret and transform information from other investigation methods such as the Q-system and the RMR System to the NTNU system.

These reports are especially useful during the early phases of a project when little geological information about the rock along the tunnel is available. The reports are meant to improve the interpretations of rock drillability based on the available geological information of a project and to reduce the unavoidable guesswork when little or no information on rock properties is available.

1.32 Planning and Estimating

The prediction models for penetration rate [7] and excavation costs [8] are particularly aimed at the planning and estimating phase of a project, where the models may be used on an aggregated level needing only few input data or on a more detailed level to analyse the influence of selected parameters, e.g. with regard to uncertainty in the geological parameters.

One main purpose of the prediction models is to be able to make estimations of construction time and construction costs as a basis for choice of tunnel route, choice of excavation method (TBM or D&B?) and economic dimensioning of the cross section area.

Transport of the excavated material and fresh air supply to the tunnel are two vital elements of successful tunnel excavation. The systems must be selected and dimensioned before the boring starts, but the performance is not really challenged until the tunnel excavation is nearing completion. The report on tunnel design and construction [6] provides tools and models to dimension the systems according to economical and occupational health requirements.

1.33 Follow-up of the Tunnel Boring

The report describing the practise and tools used when registering and analysing the tunnel boring performance and when back-mapping the tunnel geology [10] is aimed at providing data from the tunnel boring in the best possible agreement with the basis of the prediction models. When performance and geological data of a tunnel are evaluated against the prediction models [7], [8], it is important that the data are collected, normalised and averaged according to the systems used when establishing the models. When it comes to contractual follow-up and even possible claims, it is of vital importance that the collected data are reliable and in accordance with the intentions of the models.

The report describing various aspects of the boring process [11] will also be useful in the follow-up work, since some of the parameters registered in the follow-up are treated more in-depth in that report.

In the geological back-mapping, the report about geology and site investigations [9] is a necessary handbook of classification and measurements of rock mass fracturing.

1.34 Understanding Tunnel Boring

Elements of the rock breaking and cutter wear processes are treated in [11]. The report presents knowledge of the boring process acquired through many years of field studies. The report may not be used directly as a tool in the planning or excavation of a tunnel, but when the interest or need to understand and investigate what is happening in the interaction between the cutters and the rock mass, or to get a better understanding of the various elements of the prediction models, the report provides useful information.

2 Hard Rock Tunnel Boring

The term "hard rock conditions" is not precise and the NTNU prediction model does not cover the total range of rock conditions that may be categorised as hard rock. This chapter will give a rough treatment of hard rock conditions and try to clarify the area of application of the model.

A brief (and incomplete) history and state of the art of hard rock tunnel boring will be given, as well as required developments of the technology in the future.

2.1 HARD ROCK CONDITIONS

The limit between hard and soft rock conditions is not well defined. However, some rough limits of the prediction models presented in this thesis may be given.

- The rock drillability expressed by the Drilling Rate Index *DRI* is in the range of approximately 20 to 80, roughly corresponding to a compressive strength σ_c in the range of approximately 350 MPa to 25 MPa.
- The rock type has medium to low porosity, less than approximately 10 % (volumetric).
- The rock mass degree of fracturing expressed by the average spacing between weakness planes is larger than approximately 50 mm.
- The rock will break as chips (by a brittle failure) between the disc cutters.
- The rock mass has a strength such that the excavated tunnel generally will need only light support in the form of rock bolts or shotcrete (except for weakness zones and other singular phenomena).

From the above one may conclude that the models are applicable for rock conditions where an open TBM with disc cutters would be the normal selection.

High rock stress and water may be present in hard rock conditions. Part of the prediction models may still be used in such conditions, but with caution.

Rock stress may be positive or negative for the penetration rate, depending on the stress level and the magnitude and orientation of the stress anisotropy [9]. There are no indications that high rock stress will influence the cutter life measured in hours. Depending on the need for rock support in rock stress conditions, the machine utilisation and weekly advance rate may be substantially influenced by the necessary time to install the rock support. Hence, the prediction model should not be used directly in such conditions.

Water bearing rock mass may cause serious problems to TBM tunnel excavation. In such conditions, one should use the prediction models with great caution.

2.2 DEVELOPMENT OF HARD ROCK TBMS

It all probably started with Brunel's shield, which was patented in 1818 [1]. The purpose of the shield was to stabilise the soft ground at and near the tunnel face until the permanent brick lining was built. The excavation was performed manually by miners.

The first two tunnel boring machines for rock was built in 1881 and used in Folkestone, England and on the French side of the Channel in 1881 - 1882 to excavate a pilot bore for an early attempt to build the Channel Tunnel [2], [50]. The method of excavation was two rotating arms equipped with ripper teeth [50].

In 1919, a patent for a tunnel boring device was awarded to Mr. I. Bøhn of Norway [3]. The basic working principle of the machine was to hammer out concentric circular tracks in the tunnel face by a rotating "cutterhead", to break the rock between the tracks as chips. This is basically the same rock breaking principle as employed by TBMs with disc cutters of today.

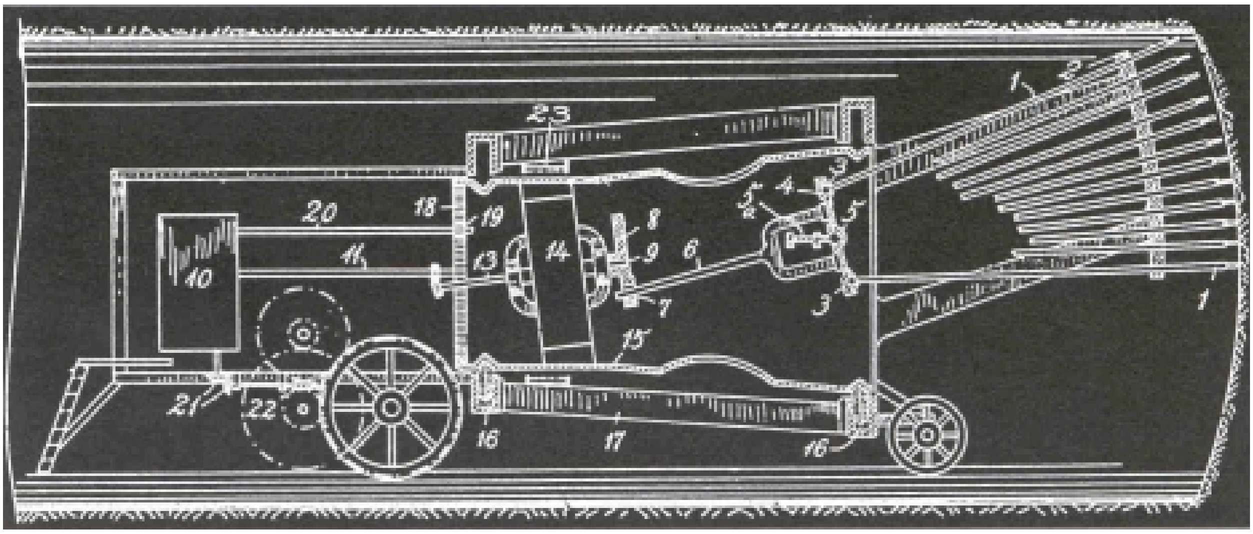

Figure 2.1 *The patented tunnel boring device by Mr. I. Bøhn.*

Year	Cutter diameter mm	Average Cutter Spacing, mm	Applicable Cutter Thrust, kN/cutter	Cutterhead Torque, kW
1956	280 (?)	68	55	250
1970	305	65	100	300
1980	394	67	190	600
1990	483	70	250	1350
2000	483	70	260	1350

Table 2.1 *General machine specifications for a 3.5 m diameter hard rock tunnel boring machine [5].*

From Brunel's shield and forward, several other machine designs were introduced as well, with more or less success. The big step in TBM development came in the 1950s when James S. Robbins introduced the disc cutter. In fact, The Robbins disc cutter was based on ideas by Charles Wilson of the USA from as early as 1850 [4]. The first TBM with disc cutters was used to excavate an 8 m diameter tunnel at Oahe Dam in South Dakota in the USA [5].

Since then, the fundamental machine design has remained the same, but with major changes in machine parameters such as cutter size, cutter thrust, cutterhead *RPM* and cutterhead torque. Table 2.1 gives a rough impression of the machine development since the 1950s.

2.3 STATE OF THE ART

Today, almost all hard rock conditions may be bored by modern TBMs, with tunnel diameter from less than 3 m to more than 12 m. However, the economical result may be less favourable when the technical limits are stretched. Rock types with a compressive strength higher than 300 MPa (*DRI* value less than 20) have been bored. The so-called High Power TBMs of today are designed to bore with a thrust level of up to 330 kN/cutter [15].

The tunnel excavation rates that have been achieved are impressive. A net penetration rate of 6.4 m/h and an advance rate of 253 m/week (100 h) have been achieved as an average for a 10 km long tunnel with a diameter of 3.5 m [16]. In an 18 km long tunnel of 3.4 m diameter, production records show the following [17]:

- Best 8 hours shift 83.0 m
- Best 24 hours day 172.4 m
- Best 136 hours week 703.4 m
- Best 570 hours (?) month 2187 m

The tunnel length feasible to bore from one adit is basically limited by the ventilation requirements. When using a continuous conveyor for muck transport, the feasible length of a 3.5 m diameter tunnel bored in hard rock is approximately 30 km. When the TBM diameter increases, the available space for ventilation ducts increases, and the technically feasible tunnel length is substantially longer. The economically feasible tunnel length is therefore decided by the construction time (e.g. interest during construction) rather than by the direct excavation costs [15].

2.4 LIMITING FACTORS

At the present time, there seems to be a halt in the development of more powerful and productive hard rock TBMs. One important reason for that is that the cutter ring material has reached an applicable cutter load limit [15]. A High Performance TBM is typically designed for an average cutter load of up to 330 kN/cutter, with regard to cutterhead structure, main bearing and thrust system. However, the cutter ring steel quality is limiting the thrust level of 483 mm diameter cutters to 260 - 280 kN/cutter. Figure 2.2 illustrates the effect of the lack in applicable cutter load.

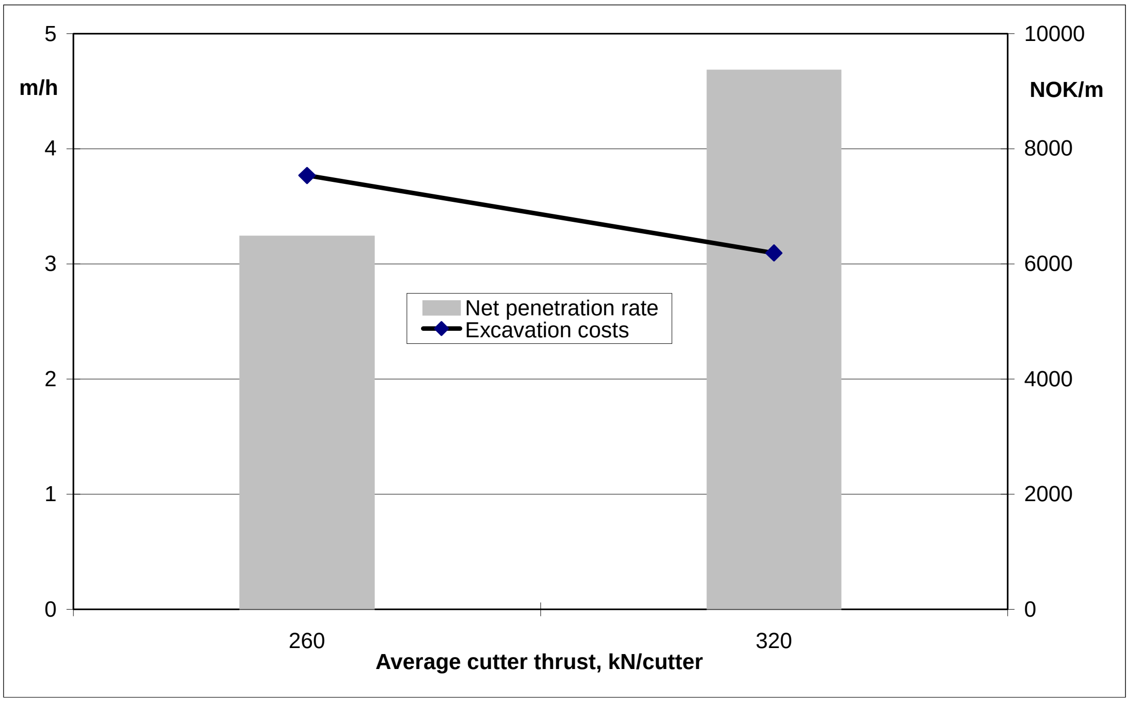

Figure 2.2 *Influence of cutter thrust on net penetration rate and excavation costs for a 5 m diameter and 5000 m long tunnel in rock with DRI = 50, degree of fracturing = St I and α = 30° [7], [8].*

For large diameter TBMs, the relatively slow *RPM* (which is inverse proportional to the TBM diameter) implies that tunnel boring may have difficulties competing with drill and blast tunnelling of equal cross section area. The less decreasing advance rate of drill and blast tunnelling is basically due to the use of the largest possible equipment admitted in the cross section area. Figure 2.3 shows a rough comparison of the decrease in advance rate with increasing cross section area.

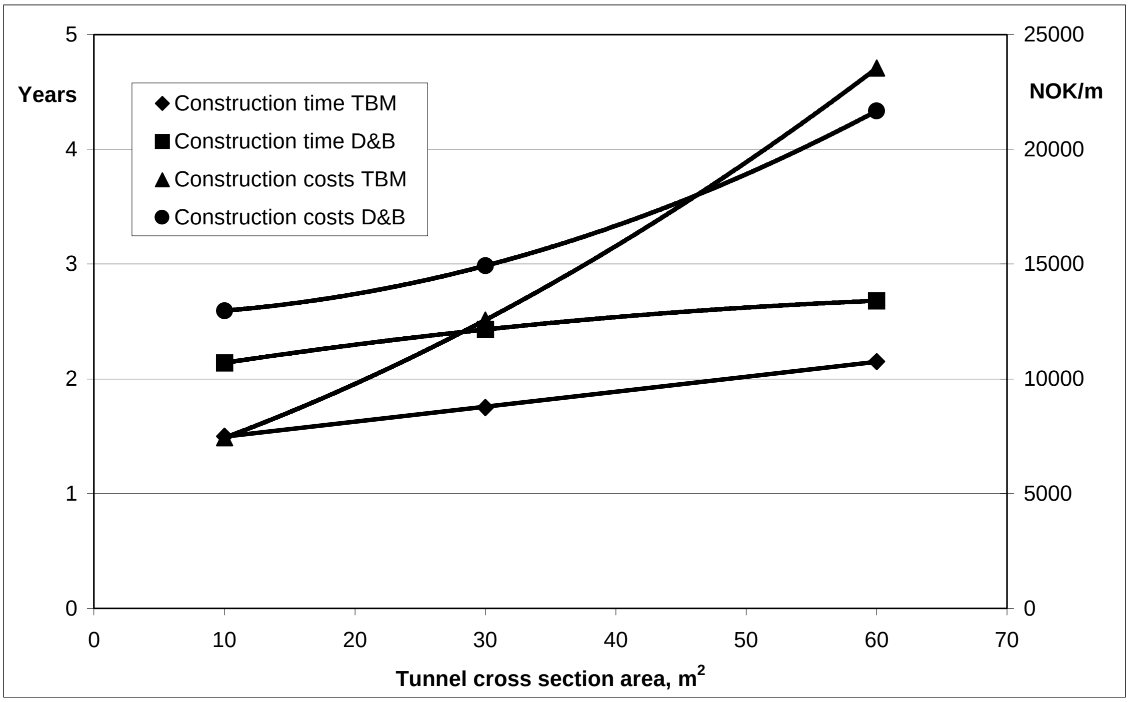

Figure 2.3 *Total construction time and total construction costs (1999 price level) for TBM and drill and blast tunnelling. Tunnel length 6 km. Rock conditions as in Figure 2.2 [18].*

2.5 FUTURE DEVELOPMENT

As we see it, the development of hard rock tunnel boring still has a long way to go. Some areas of the technology have more imminent needs than others, and some of these again are treated below.

<u>Cutter Technology</u>
The cutter technology, and particularly the ring steel quality is limiting the possibilities of efficient boring in hard rock conditions, described above. An increase of 15 % in the applicable thrust may result in as much as 50 % increased penetration rate [15]. Hence, the potential for reduced excavation costs with only small improvements in the ring steel quality is very significant. Increasing the cutter load with 15 % may also require improvements on other parts of the cutter, most probably the bearings. Since the thrust level has been limited by the cutter rings, there is little experience of the long time capacity of the cutter bearings on such high thrust levels. It is our belief that a substantial increase in applicable cutter load must be based on improvements of both ring steel and cutter bearings.

It is important to consider that an improvement of the cutter technology would not only reduce the costs of a given tunnel, but also increase the total market for hard rock TBM tunnels.

Cutterhead *RPM*

Figure 2.3 shows construction time and construction costs for the mid range of hard rock conditions. Since tunnel boring is far more sensitive to the rock conditions than drill and blast [18], TBM tunnelling will lose its advantage when the rock conditions get harder. This is most prominent for the larger tunnel cross-sections and TBM diameters, since the cutterhead *RPM* (and thereby the net penetration rate) is inverse proportional to the TBM diameter. Increased cutterhead *RPM* for large diameter machines may be accomplished through improved cutterhead design with regard to cutter placement, cutter spacing, cutter diameter, double-tracking of gauge cutters, etc.

Cutter Replacement

As the cutter diameter has increased, the cutters have become substantially heavier. The observed unit time to replace one 483 mm diameter cutter is 60 minutes (including time for cutter inspection) [7]. The potential for improvement of the unit time may be realised through dedicated and portable equipment for cutter handling.

Such equipment would also greatly improve the working conditions of the tunnel crew.

Instrumentation and Monitoring

Today, the cutters and the cutterhead are monitored only through the total cutterhead thrust. It would be a great improvement for operation of the machine to have the possibility to instrument representative cutters or cutter positions to register the instantaneous cutter loads or other parameters as indicators of the load situation of an individual cutter. For mix-shield and EPB machines, which will be used more frequently in hard rock conditions in the future, such instrumentation is vital to monitor real cutter loads, since the load situation at the cutterhead of e.g. an EPB machine is very complex and difficult to estimate from the thrust cylinder pressure.

The cutterhead vibration level may be an indicator of the fluctuation in the thrust level of an individual cutter, and might be easier to monitor than the cutter forces.

Manufacturing and Assembly

TBM excavation of short and medium-length tunnels has a disadvantage concerning the time needed from the contract is signed until the boring can start compared to D&B tunnelling. The extra time is needed for manufacturing or refurbishment of the TBM and backup system involved. Transport from the factory to the site is also time consuming. Figure 2.3 does not include TBM manufacturing or refurbishment. Knowing that this may take from four months to one year [15], the advantage of the TBM method is endangered. Possible solutions to this problem are presented in [15]:

- Refurbish or manufacture "at site" or use distributed manufacturing.
- Clients and contractors must consider machine selection as early as possible in the design and bidding phases.
- Use of other contract types, e.g. the client acquires the machine during the design or bidding phase, and hands over the machine to the contractor when the contract is signed [44].

3 The NTNU Model

The NTNU tunnel boring model comprises four interdependent parts to estimate time consumption and costs for tunnel excavation by TBM:

- Net penetration rate in mm/rev and m/h
- Cutter life in h/cutter
- Gross advance rate expressed by time consumption as h/km
- Excavation costs in NOK/m.

This chapter will discuss the model with regard to:

- Input and output parameters
- Strengths and weaknesses
- Successive development (model history)
- Future development.

3.1 NET PENETRATION RATE

3.11 Basic Concept of the Model

The penetration rate model is based on the general progress of the penetration curve as shown in Figure 3.1. Penetration curves are derived from penetration tests with TBMs during boring in various tunnels [5].

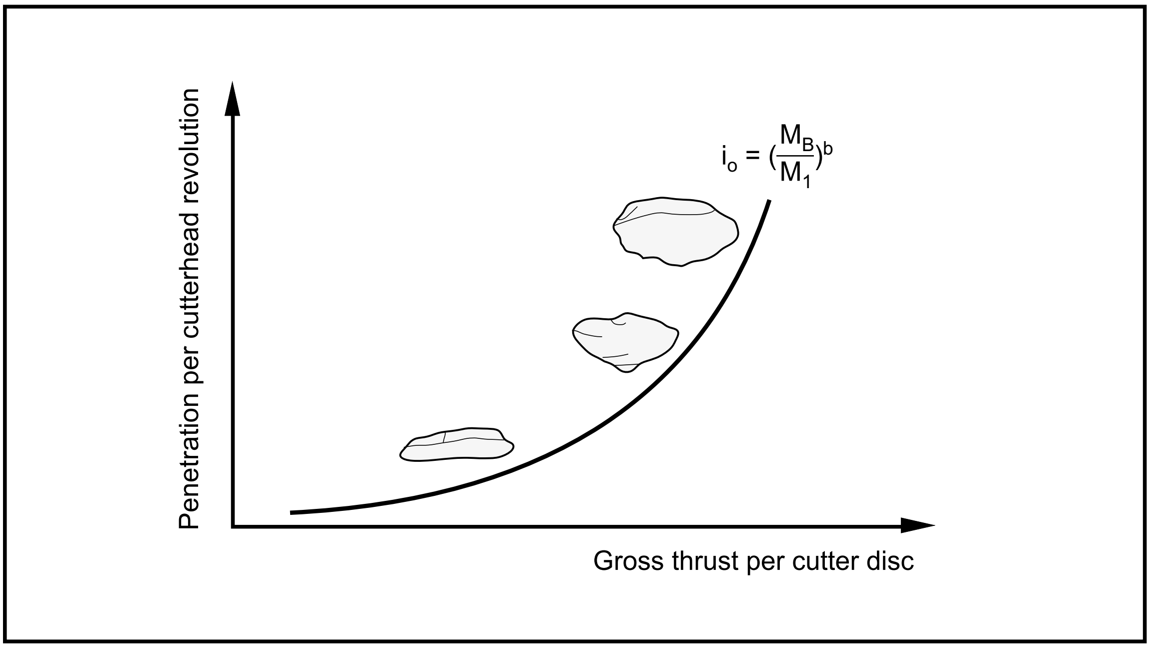

Figure 3.1 *General progress of a penetration test curve.*

The basic features of a penetration curve are the critical or necessary thrust M_1 to achieve a penetration of 1 mm per cutterhead revolution and the penetration coefficient or penetration exponent *b* which describes the effect of a change in the applied cutter thrust.

The selected equation type of the penetration curve gives a very good fit to a wide range of penetration tests with regard to variation in rock mass and machine parameters. When data from a penetration test is plotted in a log-log diagram (see Figure 3.2), it is easy to get a quick evaluation of the test and each point measured, and to get a rough estimate of M_1 and *b*.

The penetration test database contains M_1 and *b* as well as machine parameters and geological parameters. The first step in the development of the model is to perform regression analyses on this database to establish relations between M_1 and *b* and the various geological and TBM parameters.

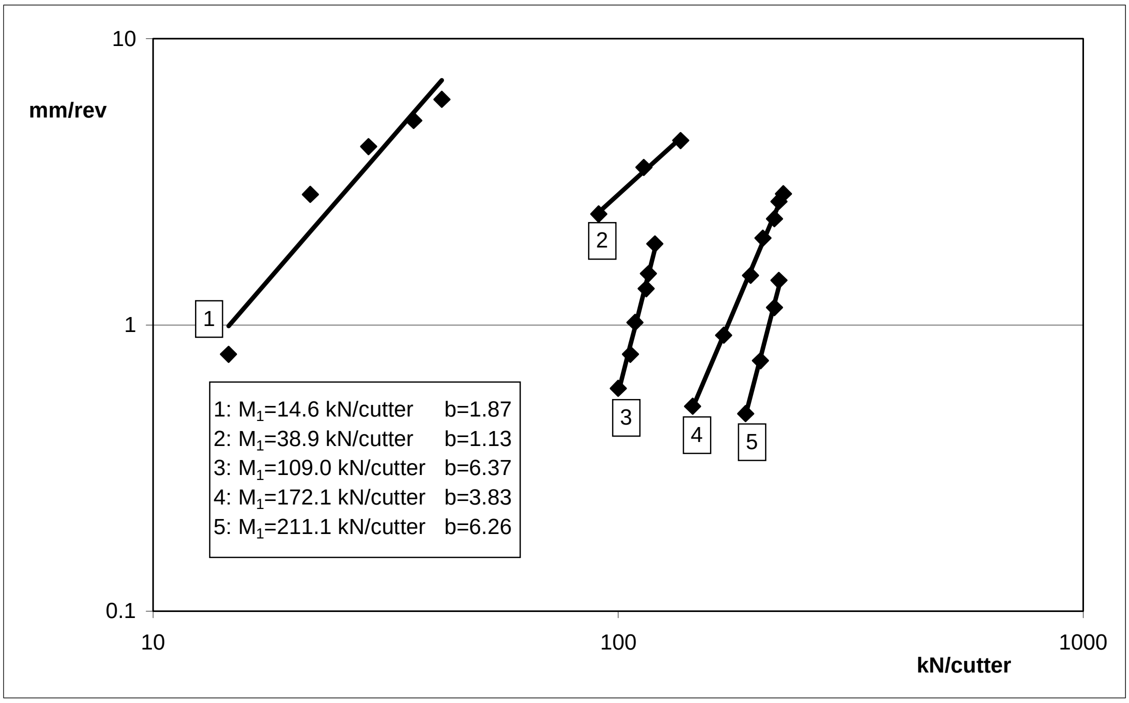

Figure 3.2 *Plot of some penetration tests.*

A second database contains averaged data from follow-up and back-mapping of more than 250 km of tunnel as described in [10]. The next step in the development of the model is to evaluate the regression model against the averaged data and adjust the regression constants and exponents to get a best possible fit to these data. This process generally leads to less distinct influence of each of the parameters.

As the model shows [7], we have chosen to aggregate the influence of the machine parameters in the equivalent thrust M_{ekv}. The penetration coefficient b is not influenced by the cutter diameter or the average cutter spacing. This is of course not completely in accordance with the reality, but more an attempt to limit the number of necessary correction factors.

With regard to the rock mass parameters, their aggregated influence is expressed by the equivalent fracturing factor k_{ekv}. The k_{ekv} again decides the necessary critical thrust M_1 and the penetration coefficient b. The model has a strong interrelation between M_1 and b. When M_1 is reduced, b is also reduced. This is not completely in accordance with the reality, as shown in Figure 3.2, but more a limitation of the number of necessary correction factors.

3.12 Parameters

The input parameters to predict the penetration in mm/rev are separated in geological and machine parameters.

Rock Mass Parameters	Machine Parameters
• Fracturing; frequency and orientation • Drilling Rate Index, *DRI* • Porosity	• Gross average cutter thrust • Average cutter spacing • Cutter diameter

Table 3.1 *Machine and rock parameters of the penetration rate model.*

The *DRI* [12] expresses the drillability of intact rock. The *DRI* should be well suited for the purpose since it is composed by the rock surface hardness measured by the Sievers' J-value and by the rock brittleness value S_{20} or "willingness" to initiate and propagate cracks. The brittleness test may also be seen as a measurement of the necessary or specific energy to crush the rock. Thuro and Spaun [32] has found "destruction work" to be a highly significant parameter for evaluation of percussive drilling rate. The Department of Building and Construction Engineering at NTNU has found close relations between the *DRI* and rock drilling methods such as top hammer and down the hole percussive drilling and roller bit drilling [33], [34].

Furthermore, the brittleness test is very dynamic and believed to break the rock by induced tensile failure. When the chipping under a cutter is efficient, the cutter force situation is very dynamic and the large chips are believed to loosen by induced tensile cracks (predominantly) [11].

The rock mass fracturing is expressed by the k_s factor [11] which is composed by the rock mass degree of fracturing or the average spacing between planes of weakness, and of the angle between the tunnel axis and the planes of weakness. In hard rock conditions, the rock mass fracturing is found to be the geological factor of largest influence on the net penetration rate and thereby on the tunnelling costs.

The great influence of the rock mass degree of fracturing is simply understood as nature's help to tunnel boring. In the concept of specific energy, the rock mass has already been subject to a part of the necessary crushing energy through the geological history. Furthermore, the existing fractures will cause fall-outs in the rock face, which will relieve some cutters of their load and transfer that load to the rest of the cutters. This creates higher average load on the cutters still in contact with the rock surface and a more dynamic load situation for all cutters.

Follow-up and back-mapping of tunnels have shown that even the smallest fissures barely visible and even thin mica layers act as planes of weakness in the boring process.

NTNU has found the effect of rock mass fracturing to be of such importance that one may say that prediction models for penetration rate of tunnel boring must have an input parameter describing the degree of fracturing.

Usually, hard rocks have a porosity of less than 2 % (volumetric). In some few cases in our database the rock porosity is up to 11 %. The exact size of the correction factor for rock porosity is uncertain, but the field data shows a clear influence. The influence of the porosity is explained by the pores acting as crack initiators and amplifiers of the crack propagation. One should expect that this effect should be counted for in the *DRI* testing of the rock. The effect of porosity on the *DRI* is not large enough compared to the effect on the penetration rate. Hence, a separate correction factor of rock porosity is included in the model.

On the machine side, the average cutter load is the main parameter. The reason for this is obvious. With increased load, the cutter edge will penetrate deeper into the rock surface and therefore transmit the energy from the cutterhead to the rock more efficiently. The efficiency increase may be interpreted as the penetration coefficient b of the penetration curve. Penetration tests in hard and non-fractured rock mass have shown penetration coefficients of up to $b = 7$. This shows the decisive influence of even the smallest increase of the cutter thrust in rock mass of low boreability.

The NTNU model uses gross average cutter thrust. This means that the total cutterhead thrust (i.e. the thrust force delivered by the thrust cylinders) is divided by the number of cutters on the cutterhead. The cutter thrust is also averaged over time, implying that calculation of cutter thrust must relate to the average thrust cylinder pressure, and not the maximum deflections of the pressure gauge. No corrections for drag or friction are made. However, the gross average thrust must be corrected if the back-up system is towed during boring. The gross thrust is selected in order to get the most reliable and reproducible thrust measurements in tunnel conditions, which are quite different from laboratory conditions, and to avoid discussions on cutterhead support pressure, cutterhead friction, etc.

The average cutter thrust is a simplification of the thrust distribution over the cutterhead. Still, this is the only practical approach when estimating and back-calculating the cutter thrust. A good simulation of the thrust distribution would probably include around 10 parameters. The significance of such a simulation is doubtful with regard to penetration prediction, and would certainly complicate the prediction models.

The applicable cutter thrust is closely related to the cutter diameter, the cutter ring quality and the rock mass fracturing. The relation between the cutter diameter and the maximum recommended thrust is shown in [7]. The present model does not give a relation between the applicable cutter thrust and the rock mass degree of fracturing. Previous editions of the model in 1979 [23] and 1983 [22] and Büchi [25] show such relations. The background of the relations is somewhat unclear, since it seems they are based on a combination of several factors, such as available torque, cutterhead vibrations and muck removal capacity. If one considers the capacity of the cutters alone, we believe that the reduction in applicable thrust should be less than the publications referenced above indicate (approximately 30 % rather than 50 %). The model considers cutter thrust reduction due to torque limitations separately, and the muck handling capacity should be given as a maximum net penetration rate directly.

In addition to increasing applicable cutter thrust with increasing cutter diameter, the cutter diameter also decides the contact area under the cutter ring edge and therefore the cutter ring indentation for a given cutter load. This is considered in the correction factor for cutter diameter.

The correction factor for cutter diameter contains to some extent a correction for cutter ring edge width, since varying cutter diameter implies varying edge width of the standard rings used. However, one must say that the NTNU model does not consider the cutter edge width as an independent parameter.

The NTNU model includes the average spacing of the cutters on the cutterhead. By average spacing one means the cutterhead radius divided by the number of cutters on the cutterhead. Some cutterheads have more than one cutter per track in the outer gauge tracks. As long as the double-tracking does not exceed 10 % of the total number of cutters, the model can be used, both with regard to average spacing and average cutter thrust. The model is based on cutterheads with cutter spacing varying over the cutterhead radius so that the relative radius to the position of the average cutter is approximately 0.6, see also [11].

The model does not distinguish between flat and domed cutterheads. Usually, a domed cutterhead has more cutters than a flat cutterhead of the same diameter, since the domed cutterhead has a longer perimeter from the centre to the outer gauge position and more space for cutters. The estimated penetration rate will be slightly higher for the domed cutterhead since the average cutter spacing will be less compared to a flat cutterhead.

The cutterhead RPM is known to have substantial influence on the basic penetration (mm/rev), e.g. [35]. On the other hand, the majority of the TBMs in the database have a cutterhead *RPM* according to the same maximum rolling velocity of the outer gauge cutter. Hence, the model presupposes a cutterhead *RPM* approximately in accordance with that rolling velocity. Over the last years, also data from hard rock TBMs with substantially lower cutterhead *RPM* (i.e. shield machines) have indicated that the low *RPM* influences the basic penetration. For the time being, the field data are too few to incorporate the cutterhead *RPM* in the basic penetration prediction, but a first indication is given in [11].

3.2 CUTTER WEAR

3.21 Basic Concept of The Model

The cutter wear, or more correct, the cutter life model is based on time dependent abrasion of the cutter rings. The model is entirely based on field data in the form of cutter change logs and corresponding rock samples tested in the laboratory. The collection and treatment of data are described in [10]. Cutter life in h/cutter is equivalent to cutter life in rolled distance (km/cutter) for a given cutterhead *RPM*.

The cutter life in hours is combined with the net penetration rate (m/h) and the TBM diameter to calculate the cutter life in m/cutter and sm^3/cutter, which both are better comprehensible units of measurement.

3.22 Parameters

The input parameters to predict the cutter life in h/cutter are separated in geological and machine parameters.

Rock Mass Parameters	Machine Parameters
• Cutter Life Index, *CLI* • Rock quartz content (%)	• Number of cutters on the cutterhead • Cutter diameter • TBM diameter • Cutterhead RPM

Table 3.2 *Machine and rock parameters of the cutter life model.*

The *CLI* expresses the abrasion properties of crushed rock powder and the rock face of the tunnel. The *CLI* is considered as representative for the abrasion process of the cutter ring. The CLI is composed by the abrasion value *AVS* of crushed rock powder and by the rock surface hardness measured by the Sievers' J-value. The *AVS* expresses how fast the crushed rock and rock chips will abrade the ring and the *SJ* expresses where on the ring the abrasion will occur.

Time dependent abrasion tests are widely used to characterise wear resistance of steel or other metals, and some of these tests are standardised, e.g. [42].

Neither of the two laboratory tests constituting the *CLI* are dynamic, this may be a lack of the index.

The quartz content of the rock has been necessary to include as a correction factor to the cutter life derived from the *CLI*. This has become necessary since different rock types with the same quartz content show different relations between the *CLI* and the experienced cutter life. The cause of this is most likely found in a difference in how the other minerals of the crushed rock powder acts against the cutter ring and the laboratory test piece. The conditions under a cutter ring are characterised as much more dynamic and having a higher stress level than the conditions under the test piece in the laboratory.

The model does not incorporate the rock mass fracturing. Field experience shows that especially Marked Single Joints are demanding with regard to cutter wear [11]. However, since the model is based entirely on field data, the actual rock mass fracturing is incorporated in the registered cutter life, but not possible to relate to a separate parameter.

On the machine side, the cutter diameter is the main parameter. This is obviously because an increased cutter diameter means more ring steel to abrade before the cutter has to be replaced. We have found a more or less proportional relation between the cutter diameter and the cutter life [7]. The contact stress between the cutter edge and the rock surface decreases with increased cutter diameter for given rock conditions at maximum applicable cutter thrust, while the load rate of the same contact area is fairly equal for the various cutter diameters (according to [7]). The increasing cutter diameter implies that the ring edge is less stiff against side forces that will occur during indentation. This is compensated through the increased edge width. The above-mentioned factors, and probably others, may explain the proportionality between cutter life and cutter diameter.

The correction for number of cutters is also obvious. For a given penetration rate, the amount of crushed rock per second flowing past one cutter is less for the machine with the highest number of cutters. In the same rock conditions, the model estimates a higher penetration rate for the machine with the highest number of cutters, which will increase the cutter life in sm^3/cutter even more than the cutter life in h/cutter.

Increased TBM diameter gives higher cutter life. The effect is explained by two reasons:

- The ratio of face cutters to centre and gauge cutters increases with increasing TBM diameter. The face cutters have more favourable working conditions compared to the centre and gauge cutters.
- The average cutter on the cutterhead has a less curved rolling track as the TBM diameter increases. Most likely this results in lower side forces on the cutter ring.

The correction factor for cutterhead *RPM* is explained by the rolling velocity of the cutter, or the length of track covered per second. The increasing length of track per second with increasing cutterhead *RPM* is supposed to have an inverse proportional effect on the cutter life in h/cutter. A secondary effect of increased rolling velocity is higher peak loads on the cutter edge. This effect is not incorporated in the correction factor.

One important machine factor is not included in the cutter life model: the cutter thrust. Experience shows that at a certain cutter thrust level, the cutter rings start to show destructive wear instead of abrasive wear. The model presupposes that the TBM is operated below that thrust level to avoid the destructive wear.

One should expect that when boring with low cutter thrust in favourable rock conditions, the wear rate of the cutters would decrease due to lower stress in the contact area between the cutter and the rock surface. We do not have any data confirming the assumption. More likely, the effect is included in the basic cutter life as a function of *CLI*, since the database shows a quite significant relation between good rock mass boreability and high *CLI* values.

3.3 ADVANCE RATE

3.31 Basic Concept of The Model

Advance rate is measured as m/day, m/week or similar. The advance rate is estimated by the machine utilisation in % and the net penetration rate in m/h. The model is based on averaged data over the complete tunnel length.

The estimation of machine utilisation is based on estimating the time consumption in h/km for various operations necessary for the tunnel excavation. It is the time determining operational time or the time that requires stop in the boring that is included in the model. This means that the system for registering the time consumption of the various operations must be seen from the TBM and not for the tunnel as a whole.

3.32 Parameters

Geological and machine parameters are indirectly included in the model through the net penetration rate and the cutter life. The influence of each parameter is difficult to identify, but in general one can say that increased penetration rate reduces the machine utilisation, as does reduced cutter life. It is only through such estimations that one is able to say something about the possible influence of single parameters, but this should be used by caution, since the background data are aggregated values.

The unit time per replaced cutter is decisive for the time consumption of cutter changes. In our model the unit time is 45 - 60 minutes per replaced cutter, depending on the cutter diameter. The unit time is a quite rough number and does not consider parameters such as TBM diameter and cutter life.

In practise, a cutter change should include several cutters. The more cutters replaced during one stop, the less influence the fixed time for rigging and similar will have on the unit time. Replacing a high number of cutters at each stop for cutter change is most likely to achieve for large diameter TBMs.

When the cutter life increases, the time used for routine inspections of the cutter state at the cutterhead increases, and one should expect that the unit time would increase. We have no data supporting this assumption.

In the background data of the model, the averaged time consumption of the various operations is taken from the shift logs, mostly representing 100 working hours per week. It has been common that unforeseen time consumption outside the ordinary working hours has not been registered in the logs. When the weekly working hours are increased, less spare time is available to handle unforeseen incidents and more of such time consumption will be registered in the logs. The effective working hours per week is meant to cover this situation.

3.4 EXCAVATION COSTS

3.41 Basic Concept of The Model

The cost model is based on detailed estimations of all costs included in the excavation costs. By excavation costs one means only the costs directly related to excavation of the tunnel, excluding rock support. This may differ quite a lot from contract prices, since the contract prices may cover more or less of the tunnelling operations.

The detailed estimations are based on consumption of input resources (e.g. depreciation, spare parts, consumables) and pricing of the resources. As an example, the cutter costs are estimated based on the following:

- Life of cutter rings, bearings and hubs as a function of *CLI*
- Unit price of each of the above components
- Consumptions of other materials
- Cutter shop
- Wages of the cutter repairman.

In the printed edition of the cost model [8], the user will not be able to see all the background details, but in the PC program FULLPROF containing the same model and developed at the Department of Building and Construction Engineering at NTNU, all these data are shown and the user has the opportunity to give his own basic input data.

The model for cost estimation of capital equipment such as TBM, backup system and transport equipment is described in [43]. The model is based on estimations according to economical useful life, with some modifications.

The cost model is directly based on and linked to the models for penetration rate, cutter life and advance rate.

3.42 Parameters

The number of input parameters in the cost model is quite large, as can be seen in FULLPROF, and all these parameters will not be discussed here.

The influence of the geological and machine parameters may be generalised to the following: When the penetration rate or cutter life is increased, the excavation costs are decreased, and vice versa.

3.5 FIELD DATA ACQUISITION

In general, the complete database has been acquired through field performance studies and engineering geological back-mapping performed by the Department of Building and Construction Engineering at NTNU directly or in co-operation with an external partner (tunnel owner or contractor).

Collection of field data is a time and cost consuming process. At present, the NTNU database represents 40 man-years roughly estimated. The main part of this work has been financed by our external partners. Without this beneficial support and the openness and co-operating spirit of the partners, the NTNU model would most likely not have existed in its current form. As a rather small, but important, exchange for the external support and openness, NTNU has promised not to disclose any information from the field data acquisition. Hence, our database is not available outside NTNU.

The close co-operation with external partners has lead the NTNU model in a practical rather than theoretical direction, since our partners have asked for tools to be used directly in their activity.

3.6 MODEL HISTORY

The development of the model started in the mid '70, and the first version was published in 1976 [24]. Through the preceding five stages and with the current edition, the model has become more comprehensive (and maybe too complex) with regard to modelling approach and input and output possibilities. The following will give a brief description of the model development and give some comparison of prediction results.

<u>1976</u>
The 1976 model predicts net penetration rate (m/h), cutter costs (NOK/sm^3), weekly advance rate (m/week) and excavation costs (NOK/m). The *DRI* is used to describe the intact rock with regard to penetration rate. The degree of fracturing is given as three categories: spacing ≥ 20 cm, ≈ 10 cm and ≤ 5 cm. Type and orientation of the fracturing are not considered. *DRI* and the degree of fracturing give the net penetration rate, while machine parameters are not considered, but rather assumed to be optimal for the rock conditions. The cutter costs (and therefore the cutter life) is based on the Bit Wear Index *BWI* [12]. Rock content of quartz or other minerals is not considered.

Even the first edition in 1976 is a complete tool for estimating time consumption and costs, and an interesting comparison between tunnel boring and drill and blast tunnelling with regard to excavation costs is given. The conclusion of the comparison is that tunnel boring is only economically applicable in cross section areas ≤ 12 m^2 and then in the most favourable rock conditions with high *DRI* and fracture spacing ≤ 5 cm.

<u>1979</u>
The 1979 edition (published in 1981) [23] predicts the same four output items as the 1976 edition. On the input data side, several changes have been done. Cutter thrust level is used in

the net penetration rate and cutter costs estimation model. The applicable cutter thrust is related to rock mass degree of fracturing. The cutter coefficient is introduced to be able to check if the machine will be torque limited.

On the geological side, the rock mass fracturing is described by four fracturing classes (corresponding to the Classes I to IV used today) and the angle between the tunnel axis and the planes of weakness. Fractures with an average spacing of 40 cm (Class I) or less are believed to influence the penetration rate. The effect of the rock mass fracturing is increases for low *DRI* values and decreases for high *DRI* values. In the classification of fracturing, a distinction between Joints and fissures are made, but it is unclear how fissures are treated since the model is applicable for continuous fractures (joints). For the cutter costs, the TBM diameter is used as a correction factor.

The excavation cost model is more detailed, but basically the same. A comparison of excavation costs is given and the conclusion is much the same as in 1976.

<u>1983</u>
In the 1983 edition [22], a distinction between fissure and joint classes was made, and Fracture Class 0 (non-fractured rock mass) was included. The principal form of the effect of rock mass fracturing on the penetration rate was changed so that for fracture spacing of 10 cm or more, the optimum angle is around 60°, and not 90° as previously. The cutter diameter (305 mm to 432 mm) was included in the penetration rate model.

Marked Single Joints was included in the classification of rock mass fracturing, and a model for penetration rate addition due to such joints was presented.

For the first time, the cutter life in h/cutter was estimated for 356 mm and 394 mm cutters, based on the new index *CLI*. The rock quartz content in % was used as a correction factor. The cutter life estimate also included correction factors for cutterhead RPM and cutterhead diameter.

A new model for machine utilisation consisting of six sub-operations in the tunnelling process was presented. The excavation cost model was still more detailed.

<u>1988</u>
On the geology side, the 1988 edition [21] was almost equal to the 1983 edition, with the inclusion of mica and amphibole in addition to quartz in the rock mineral content correction of the cutter life. The influence of Marked Single Joints was included in the Fracturing Classes again. The influence of rock porosity was acknowledged, but only as a tentative correction factor.

The modelling approach of the penetration rate was now based on the penetration curve, in principle the same approach as currently used. The influence of the average cutter spacing was acknowledged and included in the model. The model covered cutter diameters from 356 mm to 483 mm.

The cutter constant was introduced to help estimate the cutter coefficient and the necessary torque or installed cutterhead power.

The estimation model for cutter life now separated the correction factor for cutterhead diameter in two: one for domed cutterheads and one for flat cutterheads.

The machine utilisation model consisted of the same sub-operations as before, but was now based on estimating the time consumption in h/km for each sub-operation and then estimate the machine utilisation from the time for boring.

The cost model remained unchanged.

<u>1994</u>
The 1994 edition [20] brought some practical changes in the penetration estimation process, but the basis was still the penetration curve. The cutter size covered by the model was increased to 500 mm. The rock mass influence on the penetration rate was aggregated in the equivalent fracturing factor and the influence of the machine parameters was aggregated in the equivalent thrust. The Marked Single Joints were introduced again with a separate penetration rate addition. For rocks with porosity larger than 2 %, the influence was included in the equivalent fracturing factor.

The cutter life estimation was now based on quartz content as the only rock mineral of influence besides the *CLI*.

For the machine utilisation, the time consumption for TBM and Backup repair and maintenance, and the aggregated sub-operation Miscellaneous, were found to be a function of the net penetration rate.

There were no significant changes to the excavation cost model.

<u>1998</u>
The 1998 edition [7] brought some practical changes in the penetration estimation process, but no significant changes in the modelling approach.

The advance rate model introduced the possibility to estimate the weekly penetration rate for other working hours than 100 h/week.

The cost model [8] brought only minor changes.

Prediction Results over Time

The following gives a rough comparison of advance rate and excavation costs for the prediction models from 1976 to 1998.

The geological parameters used are shown below.

Parameter Set	Gneiss	Phyllite
DRI	40	60
CLI	8	25
Quartz Content	20 %	25 %
Fracture Class	St 0-I	St III
Angle	20°	20°

Table 3.3 *Geological parameters for comparison of prediction models.*

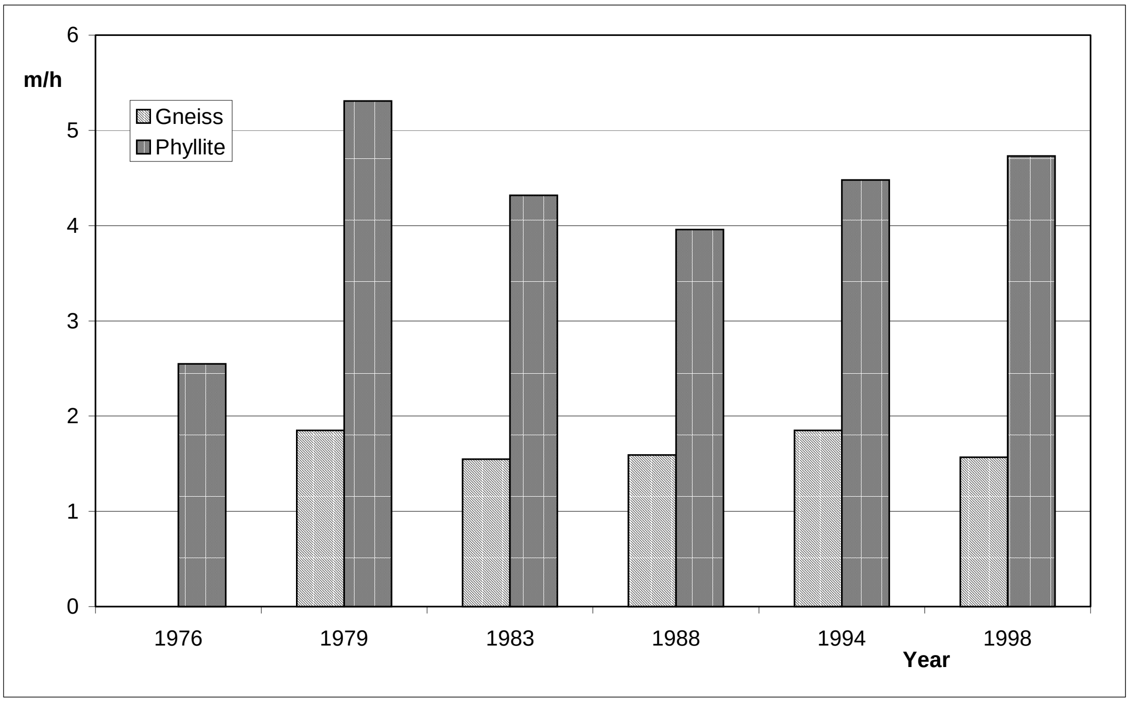

Figure 3.3 *Predicted net penetration rate for a 3.5 m diameter TBM with 394 mm cutters [18].*

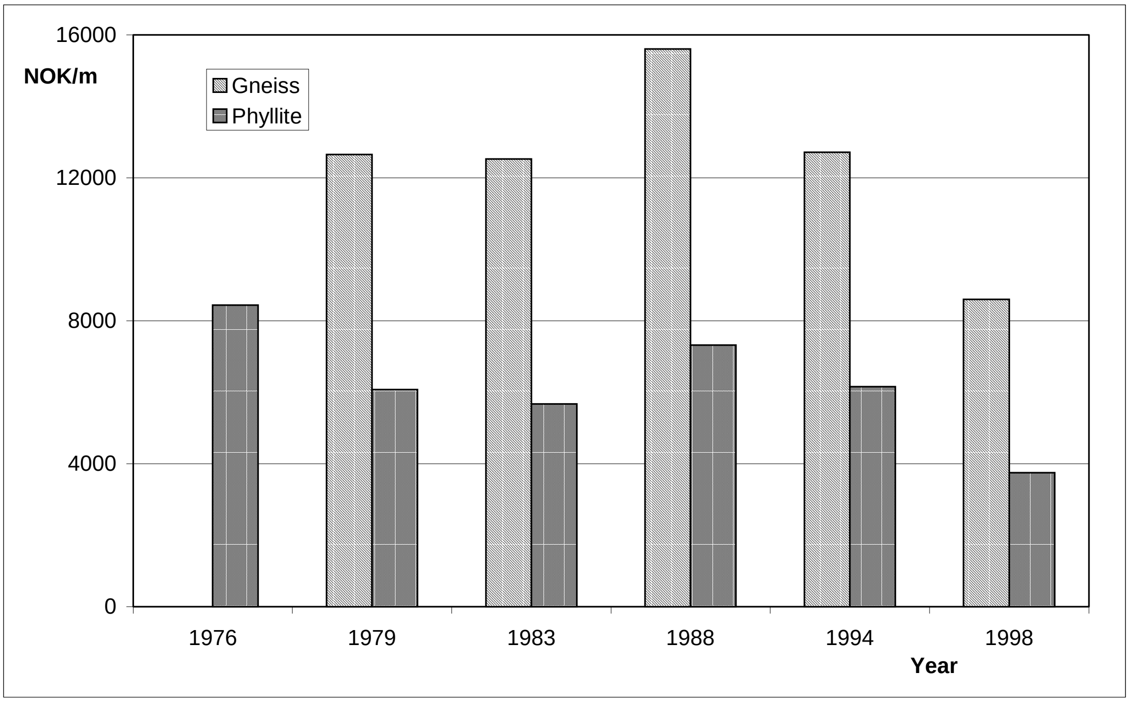

Figure 3.4 *Predicted excavation costs for a 3.5 m diameter TBM with 394 mm cutters. Price level of January 1999 [18].*

The development of the penetration rate estimates is fairly consistent, with the exception of the two first editions.

The very high costs predicted by the 1988 edition cannot be explained satisfactorily, except from the possibility of generally conservative assumptions of the basic input parameters, all summing up in one direction.

3.7 FUTURE DEVELOPMENT

As can be seen from Figures 3.3 and 3.4 there has been some variation in the prediction results between the consecutive editions of the model, and there is still room for improvement.

Evaluating the various sub-models, we believe that the estimation of the cutter life in h/cutter is the one with most uncertainty attached. Improving the quality of the cutter life estimates should have priority for the next edition.

The basic penetration model (mm/rev) must be supplemented with a correction factor for cutterhead *RPM*. This is of special importance when the model is to be used for mix-shield or EPB machines, since these machines have low cutterhead *RPM*.

The mapping of the rock mass fracturing is a subjective matter, as it is in other rock mass classification systems. Improvement in the mapping practise, especially during the site investigations, is desirable. Development of more objective methods, e.g. use of seismics, has long been asked for [45]. An instrument measuring the degree of fracturing may be found in the future, but for the near future one must improve the existing methods and develop routines for quality control of the mapping results.

The *DRI* and *CLI* need to be tested in the laboratory and need quite large sample volume per test. A portable test as supplement to the *DRI* and *CLI*, to be used in the field, both for site investigations and back-mapping are needed. The point load test [46] [47] is portable and widely used, but needs to be correlated to the *DRI* on a wide range of rock types.

The Schmidt Hammer [48] and the Equotip Hardness Tester [49] should also be investigated with regard to be used for preliminary testing of the rock drillability in the field. Correlation to the *DRI* and *CLI* needs to be tested on rock samples from TBM tunnels.

Our rock sample archive of the laboratory testing of *DRI* and *CLI* should be utilised to characterise grain size, texture, mineral content, colour, precise rock name etc. to enhance the quality of the drillability database and to try to correlate e.g. *DRI* with grain size.

The samples in the rock sample archive may be tested for the Cerchar Abrasivity Index, since the CAI test needs only small sample specimens. CAI is used by several laboratories already to characterise the rock abrasivity.

3.8 RESEARCHERS AND RESEARCH PARTNERS

The history of the NTNU model indicates that many people and external research partners have been involved in the work, which is more than true. In Appendix 2 I have tried to make a complete list of the persons involved at NTNU, with a great risk of unintentionally leaving somebody out. To those, I ask their forgiveness.

However, the persons mentioned below have been a part of the hard rock tunnel boring team at NTNU for quite long periods of time and have contributed substantially to the NTNU model and to the understanding of hard rock tunnel boring.

- Professor Odd Johannessen
- O. Torgeir Blindheim
- Erik Dahl Johannessen
- Arne Lislerud
- Steinar Johannessen
- Amund Bruland
- Tore Movinkel
- Bjørn-Erik Johannessen
- Bård Sandberg

Of our external research partners, we have had especially longstanding and good relations to the following:

- The Norwegian State Power Board
- Statkraft Anlegg as (contractor)
- The Norwegian Public Roads Administration
- The Research Council of Norway
- The Robbins Company (machine manufacturer)
- Atlas Copco (machine manufacturer)
- Mr. Arnulf Hansen, a tunnel boring institution by himself.

4 Other Prediction Models

Several researchers and institutions have published models on:

- Rock breaking
- Penetration rate
- Cutter wear
- Excavation costs

related to hard rock tunnel boring. Some of these models are presented and commented briefly in this chapter.

It is difficult to compare the various models with regard to prediction results, since the input parameters are varying, especially the parameters used to describe the rock mass properties. However, while the modelling approach may be quite different, the results of the various models may be fairly close.

4.1 ERNST BÜCHI

In his doctor dissertation about "the influence of geological parameters on the advance rate of a TBM" [25], Ernst Büchi presents a prediction model for net penetration rate. The model uses the cutter force model of Colorado school of Mines (see below) as a starting point, based on [26], [27], and then makes correction for rock anisotropy and rock mass fracturing.

The background data of the model are from several tunnelling sites, covering approximately 38 km of bored tunnels.

The penetration rate is estimated stepwise as outlined below.

- Use the Colorado School of Mines predictor formula to estimate the net penetration (mm/rev) in isotropic and non-fractured rock mass. This is used as a minimum or basic net penetration rate. Important input parameters are cutter diameter, cutter load, nominal spacing between cutters, rock compressive strength, rock shear strength, rock tensile strength and cutter edge angle.
- Correct for rock anisotropy to obtain the net penetration rate of anisotropic and non-fractured rock mass. One should note that schistosity ("Schieferung") is included in the rock anisotropy. The maximum correction is 33 % increased penetration rate for an angle of 90° between the tunnel axis and the orientation of the anisotropy. For an angle of 0°, the correction is 0 %. This step is skipped for isotropic rock types like granite.
- Correct for rock mass fracturing to obtain the penetration rate for fractured rock mass. A fracture must at least be identifiable for 2/3 of the tunnel perimeter. The distance between fractures is measured as observed along the tunnel axis, and not perpendicular to the fracture planes. The maximum correction is 100 % increased penetration rate for a spacing of 50 mm between the fractures. For a spacing of 2 m and larger, the correction is 0 %.

From the above, one can see that the Büchi model incorporates the most important factors used in the current NTNU model. These are:

- Rock strength parameters as an expression of the rock boreability
- Spacing between and orientation of rock mass fractures
- Cutter thrust
- Cutter diameter
- Cutter spacing.

The Büchi model is quite similar to the first models published by the Department of Building and Construction Engineering at NTNU [24], [23], [22] (see Chapter 3), where a basic penetration estimated from the rock drillability DRI (instead of compressive, tensile and shear strength) and then corrected for rock mass fracturing (spacing and orientation) and cutter geometry (average cutter spacing and cutter diameter). As for the NTNU model, the rock mass degree of fracturing is the most important factor.

Another important feature of the model, which is similar to the NTNU models, is that it is based on field performance data and geological back-mapping of tunnels.

The Büchi model also estimates the advance rate as m/day.

4.2 COLORADO SCHOOL OF MINES

The Excavation Engineering and Earth Mechanics Institute at the Colorado School of Mines (CSM) has published prediction models to estimate net penetration rate (and cutter wear and costs) since 1977 [26]. The current model of penetration rate was published in 1993 [28] and updated in 1996 [29]. An important part of the CSM models has been the machine design (i.e. the cutter and cutterhead design, including the cutterhead drive system).

The CSM modelling approach is to estimate the necessary cutter forces for a given penetration (mm/rev). The cutter force equations may be solved with regard to penetration or one may use iteration to find the maximum obtainable penetration for a given set of machine specifications in a given rock.

The background data of the model is a large database of linear cutting tests performed on non-fractured rock samples in the CSM laboratory.

The penetration rate is estimated stepwise as summarised below.

- Find the base pressure under the cutter edge, based on one (compressive strength) or all of the following parameters: Uniaxial compressive strength of the rock, Brazilian tensile strength of the rock, spacing between cuts, cutter tip thickness, cutter radius, penetration. Each of the input parameters are listed with a range of application, e.g. 0.25 - 3 cm/rev for depth of penetration.
- Decide the pressure distribution function under the indented part of cutter edge according to recommendations for constant cross section cutters and wedge shaped cutters. (The 1996 update [29] gives one pressure formula applicable in all cases.)
- Estimate the normal (cutter thrust) and rolling (cutterhead torque) cutting forces.
- Increase or decrease the depth of penetration until the necessary cutter thrust or the necessary cutterhead torque is in accordance with the machine specifications.

The CSM model incorporates the most important factors used in the current NTNU model to estimate the basic penetration. These are:

- Rock strength parameters as an expression of the rock boreability
- Cutter thrust
- Cutter diameter
- Cutter spacing.

The most important objection to the model is that it does not systematically incorporate rock mass fracturing in the prediction model. Furthermore, the complete model has, to my knowledge, not been published. Hence, it is difficult to give the CSM model a complete and satisfactory comparison to the NTNU model with regard to the modelling approach.

However, a comparison of the prediction results of the CSM and NTNU models has been published [29]. The conclusion of this study is that the models gives "fairly close estimates on machine performance".

The CSM model also predicts:

- Cutter life in m^3/cutter
- Cutter costs in USD/m^3
- Advance rate in m/day.

The models used for these purposes are not published.

4.3 LULEÅ UNIVERSITY OF TECHNOLOGY

The Luleå University of Technology has several publications on prediction of hard rock tunnel boring performance. The current model was published in 1991 [30].

The background of the model is an experimental model based on laboratory indentation tests adjusted for field data from 19 km of bored tunnels.

The penetration rate is estimated stepwise as summarised below.

- Find the penetration index (mm/kN) of the rock based on indentation tests in the laboratory.

- The boreability index (mm/kN) is found by correcting the penetration index for rock type and rock mass fracturing. The correction factor for rock mass fracturing is identical to the NTNU factor k_s.
- The net penetration (mm/rev) is found by multiplying the boreability index with the applicable cutter thrust.

The Luleå model incorporates the most important rock mass factors used in the current NTNU model to estimate the basic penetration. These are:

- Rock indentation corrected for rock type as an expression of the rock boreability
- Rock mass degree of fracturing
- Orientation of rock mass fractures

With regard to machine factors, only the cutter thrust is considered. Cutter diameter and cutter spacing is not included. Hence, the model is not applicable when e.g. analysing the machine selection for a tunnel.

The Luleå model also provides estimates of advance rate expressed as total number of shifts needed to bore the tunnel or the geological zone. Furthermore, an excavation cost prediction model is given, based on the NTNU model from 1983 [22], but several changes have been made by the Luleå University of Technology.

4.4 THE NELSON MODEL

The model is named after Pricilla P. Nelson who has been active in tunnel boring research for many years. The first version of the model was published in 1994 [30]. The prediction model is based on a large database with information from 630 projects (1994). The data base is organised in 4 levels of detail, with level 1 containing large-scale and averaged project data, and level 4 being the most detailed with data from tunnel maps and shift reports.

The model is available as PC software combined with the four-level database. The modelling or simulation approach is made possible by modern computer technology. In principle, the prediction model functions as follows:

- Set up a table of available input data of the new tunnel according to the requirements of the analysis method to be used. There are six analysis methods with different level of detail, depending on which level of the database one will run the simulation against.

- Match and select data from similar projects, geological zones, etc. in the database level selected.
- Run the retrieved data through various statistical treatments available to get estimations of e.g. penetration rate, construction time, construction costs and cutter wear. The estimated parameters are presented as distributions, of which mean values and standard deviation can be calculated.

From the above, it is clear that the predicted performance is highly dependent on the user selections in addition to the "facts" of the database, especially with regard to which probability density functions one selects to run the retrieved data through.

The modelling (or more precise: the simulation) approach is very different from the three models presented above and from the NTNU model. However, the Nelson model may use the same input data as the other four models, but whether each of the input parameters will have any influence on the prediction results depends on the available information in the database. The Nelson model may give an estimate of e.g. cutter costs and excavation costs as long as the database contains such information.

4.5 THE DELFT UNIVERSITY OF TECHNOLOGY

The Delft model is in preparation and will be published in the near future [31]. The modelling technique used is hybrid neuro-fuzzy models, combining fuzzy logic and artificial neural networks. In their modelling work, the Delft University has used levels 1 and 2 of the database produced by Nelson et al. [30].

Neuro-fuzzy modelling is used as an alternative to statistical and regression analyses, and produces a set of rules corresponding to the equations produced by regression analyses. The rules have a general form as shown below:

"**If** CFF is $A_{i,1}$ and UCS is $A_{i,2}$ and RPM is $A_{i,3}$ and Thrust per cutter is $A_{i,4}$ and cutter diameter is $A_{i,n}$ Then penetration rate = f(CFF, UCS, RPM, thrust per cutter, cutter diameter)" [31].

CFF = core fracture frequency
$A_{i,j}$ = fuzzy set or membership function (e.g. **If** CFF is *low*)

In Delft model, each rule leads to a linear function in the.

[31] claims that when comparing the neuro-fuzzy models to traditional statistical methods (regression analyses) and empirical relationships by using data from [30], the neuro-fuzzy models perform better than the two other model types.

4.6 CONCLUSIVE REMARKS

Several other models than those mentioned above have been published, especially penetration rate models. To a great extent, these models do not consider the rock mass fracturing as an input parameter. In some cases the rock mass fracturing may be included through correction factors or similar for the rock type. According to the NTNU, Büchi and Luleå models, the rock mass degree of fracturing and orientation of fracture planes constitutes the most important factor for the net penetration rate.

Development of a prediction model for TBM tunnelling is a more ore less continuous task since new field data and machine specifications are constantly available. Due to the relative rapid development of the TBM technology, a prediction model should not be more than 8 - 10 years old before it is revised based on the new information available.

As shown above, the new modelling approaches may well prove to be a right direction to pursue as an alternative to more traditional approaches. In any case, the international tunnelling industry should have more than one prediction model available when planning and excavating tunnels.

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Appendices

1 LIST OF TBM TUNNELS IN THE DATABASE

The following tunnels are represented with geology and performance data in the NTNU database of TBM tunnelling. Several other tunnel projects are also in the database, but with less detailed data for shorter tunnel sections.

Year	Tunnel	Diameter, m	Length, m
1972-1974	Trondheim, Høvringen	2.3	4300
1974-1976	Oslo, Lysaker - Majorstua	3.15	4300
1977	Fosdalen	3.15	670
1977-1978	Kjøpsvik	3.32	1120
1977-1978	Aurland	3.5	6200
1977-1981	Oslo, Sandvika - Lysaker	3.35	7580
1977-1982	Oslo, Majorstua - Bryn	3.0	7500
1978	Eidfjord, Floskefonn	3.25	350
1978-1981	Oslo, Sandvika - Slemmestad	3.5	14260
1979	Lier	3.5	1200
1979-1980	Eidfjord, Floskefonn	2.53	2807
1979-1982	Oslo, Majorstua - Ruseløkka	3.0	3300
1980	Sildvik shaft	2.53	760
1980-1982	Sørfjord	3.5	5840
1980-1982	Brattset, Skamfer	4.5	8150
1980-1982	Brattset, Næverdal	4.5	7000
1981-1984	Glommedal	3.5	8022
1982-1983	Mosvik	3.5	5390
1982-1983	Sørfjord. extension	3.5	3010
1982-1984	Ulset, Yset	4.5	7300
1983-1984	Ulset	4.5	4960
1983-1984	Tjodan shaft	3.2	1250
1983-1984	Tjodan - Låtervikvatn	3.5	4865
1983-1986	Kobbelv headrace	6.25	9332
1984-1985	Holandsfjord	6.25	4333
1984-1987	Kobbelv transfer	3.5	9206
1984-1986	Fløyfjell	7.8	6850
1985	Nyset-Steggje shaft	3.2	1370
1985-1986	Heimdal	2.7	2800
1986-1989	Jostedal, Stegagjerdet	4.5	9001
1986-1989	Jostedal, Fagredal	4.5	5550
1987	Eidsvåg	8.5	850
1987-1988	Nedre Vinstra	4.75	16562

Year	Tunnel	Diameter, m	Length, m
1988-1989	Stavanger, Bjergsted	3.25	3850
1988-1990	Svartisen headrace	8.5	7308
1989-1990	Svartisen, Storjord	3.5	9277
1989-1990	Stavanger, I.V.A.R.	3.5	8070
1989-1991	Svartisen, Trollberget	4.3	17882
1990	Haugesund	3.25	2500
1990-1992	Svartisen, Trollberget	3.5	8219
1991-1992	Svartisen, Trollberget	5.0	7816
1991-1992	Svartisen, Trollberget	3.5	6162
1991-1992	Meråker	3.5	9647
1991-1992	Klippen tailrace	6.5	3400
1992-1994	Klippen headrace	6.5	6920
1994-1995	Pipeline Tunnel West	4.23	4243
1995-1996	Midmar	3.5	6424

2 PERSONS INVOLVED SINCE 1976

The Hard Rock Tunnel Boring Report

For the previous editions of the Hard Rock Tunnel Boring Report, the following persons were involved at NTNU:

1-76 Norwegian edition
Bengt Drageset, Roy-Egil Hovde, Erik Dahl Johansen, Roar Sandnes, O. Torgeir Blindheim, Odd Johannessen

1-79 Norwegian edition
Knut Gakkestad, Jan Helgebostad, Svein Paulsen, Oddbjørn Aasen, Erik Dahl Johansen, O. Torgeir Blindheim, Odd Johannessen

1-83 Norwegian and English edition
Arne Lislerud, Steinar Johannessen, Amund Bruland, Tore Movinkel, Odd Johannessen

1-88 Norwegian and English edition
Arne Lislerud, Amund Bruland, Bjørn-Erik Johannessen, Tore Movinkel, Karsten Myrvold, Odd Johannessen

1-94 Norwegian and English edition
Bård Sandberg, Amund Bruland, Jan Lima, Odd Johannessen

Drillability Report

For the previous editions of the Drillability Report, the following persons were involved at NTNU:

6-75 Norwegian edition
Bjørn Kielland, Halvdan Ousdal, O. Torgeir Blindheim, Odd Johannessen

8-79 Norwegian and English edition
O. Torgeir Blindheim, Erik Dahl Johansen, Arne Lislerud, Odd Johannessen

4-88 Norwegian edition
Amund Bruland, Sigurd Eriksen, Astrid M. Myran, Rune Rake, Odd Johannessen

13-90 Norwegian and English editions
Amund Bruland, Sigurd Eriksen, Astrid M. Myran, Odd Johannessen

M.Sc. Theses

Over the years, the following students have made their M.Sc. Thesis with field studies of TBM tunnelling or analysis and evaluation of tunnel projects with regard to the possible use of TBM tunnelling as main topics:

Erik Dahl Johansen (1976): Hard Rock Tunnel Boring

Sjur Åge Ekkje & Hjalmar Steinnes (1977): TBM Tunnelling at Aurland

Jan Idar Kollstrøm (1977): Tunnel Boring at Svartisen Hydropower Project

Svein Solum (1977): Tunnel Excavation at the Storeng Hydropower Project

Oddvar Birkeland (1978): TBM Tunnelling at VEAS, Oslo and at Aurland, 4 TBMs

Kjell Garberg (1978): TBM Tunnelling at Svartisen Hydropower Project

Ronald Hardersen (1978): TBM Tunnelling at VEAS, Oslo, 2 TBMs

Jan Hernæs & Odd Opedal (1978): The Fløyfjell Tunnel

Bård Simonsen & Pål Keyser Frølich (1980): TBM Tunnelling at Brattset, 2 TBMs

Kjell Bjønnes (1981): Evaluation of Excavation Methods at the Storeng Hydropower Project

Bjørn Ivar Harsjøen (1982): TBM Tunnelling at Glommedal

Steinar Johannessen (1982): Hard Rock Tunnel Boring

Tormod Søland (1982): Transfer Tunnel Beiarn - Storglomvatn, Svartisen Hydropower Project

Jon Steinar Baadstø (1983): Tunnel Boring of Road Tunnels

Finn Hvoslef & Eivind Opedal (1985): TBM Tunnelling at Kobbelv, 3 TBMs

Bjørn-Erik Johannessen (1985): TBM tunnelling at Fløyfjellet, Bergen

Rune Rake (1985): TBM Tunnelling - A Computer Model

Steinar Grimsmo (1986): TBM Tunnelling at Fløyfjellet, Bergen and at Jostedalen, 2 volumes, 3 TBMs

Tarjei Draugedal (1987): TBM tunnelling at Nedre Vinstra, 2 TBMs

Bård Sandberg & Hans Olav Storkås (1989): TBM Tunnelling at Svartisen, 2 TBMs

Victor Isaksen & Erlend Solberg (1990): TBM Tunnelling at Trollberget, 3 volumes, 3 TBMs

Bergljot Øyvor Skonnord (1990): Tunnel Boring at the Meråker Hydropower Project

Arne Holt (1991): Database for TBM Performance Data

Trond Stang & Torbjørn Aadal (1991): TBM Tunnelling at Trollberget, 3 volumes, 3 TBMs

Bao Hai Viet Nguyen (1993): Drillability

Arne Holt & Stein Are Sande (1996): Mohale Tunnel, South Africa - Production Field Studies, 4 volumes

Randi Hermann (1996): Hard Rock Tunnel Boring - Simplified Prediction Model

Truls Jøstensen & Amund Moen (1998): Cheves Hydropower Project - Evaluation of Excavation Methods

Christian Hågensen & Vegard Kristiansen (2000): TBM Tunnelling at Mohale Outlet

Kai-Morten Høyem & Guttorm Dyrland (2000): TBM Tunnelling at CERN

Researchers at the Department of Building and Construction Engineering

Several researchers employed at the Department have contributed to the results achieved in hard rock tunnel boring. The list is semi-chronological.

Odd Johannessen
Karsten Myrvold
Erik Dahl Johansen
Arne Lislerud
Amund Bruland
Steinar Johannessen
Tore Movinkel
Jon Steinar Baadstø
Bjørn Erik Johannessen
Roar Bardal
Svein Eirik Aune
Rune Rake
Bård Sandberg
Viktor Isaksen
Ole Christian Eidhammer
Jan Lima
Jørgen Moger
Rahim Atabakhsh
Bjørn Velken
Randi Hermann
Elin Hermanstad
Baroline Log

The Laboratory of Engineering Geology at NTNU and SINTEF

The rock laboratory of the Department of Geology and Mineral Resources Engineering and SINTEF Rock and Mineral Engineering has done the rock testing related to the hard rock tunnel boring work at NTNU. Persons involved are:

Rolf Selmer-Olsen
O. Torgeir Blindheim
Arne Hov
Dagfinn Johnsen
Torill Sørløkk
Filip Dahl
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Tore S. Dahlø

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