Chapter 52

HARD ROCK TUNNEL BORING PREDICTION AND FIELD PERFORMANCE

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ABSTRACT

The differences and similarities between various performance prediction methods for hard rock TBMs are reviewed and discussed. Main emphasis is placed on the Norwegian and American methods, which are based, in many ways, on quite different principles. Test and prediction results for the same rock types based on methods used at the Colorado School of Mines and the Norwegian Institute of Technology are compared. Despite the basic differences in prediction methodology, the performance estimates were found to be in good agreement. The paper also reviews the design and field performance issues for hard rock TBMs, as well as some important developments based on recent case-histories.

INTRODUCTION

In the last few decades, there have been significant developments in hard rock TBM technology, and technically, TBMs have now reached a stage of development where a tunnel can practically be bored in any rock and ground. Still, however, performance prediction is an important part of any TBM project. This is due to the general need of cost- and schedule-evaluations at the various planning stages of a tunnel project, as well as to develop the information necessary for a reliable comparison between alternative tunnel construction methods (TBM vs. drill & blast).

A wide variety of performance prediction methods and principles are used in different countries and by the various TBM manufacturers. Some of the methods are based mainly on one or two rock parameters (for instance uniaxial compressive strength and a rock abrasion value), while others are based on a combination of comprehensive laboratory, field- and machine-data. This paper will discuss mainly the prediction methods used at the Norwegian Institute of Technology (NTH) and the Colorado School of Mines (CSM) which in many ways are based on quite different principles. As will be discussed later, however, this does not necessarily mean that the prediction results have to be very different.

The paper also will review design and field performance of hard rock TBMs, and based on recent hard rock TBM projects, some key elements of recent developments will be described.

MAIN PRINCIPLES OF PERFORMANCE PREDICTION

In general, methods for TBM performance prediction are based on one or more of the following main principles:

1) Field mapping and/or -testing
2) Small scale laboratory testing ("index testing")
3) Large scale laboratory testing
4) Empirical methods
5) Theoretical models

Contrary to for conventional rock drilling, full scale field testing is not a feasible option for TBM performance prediction. Full scale laboratory testing is carried out only at CSM. In brief, the NTH performance prediction method is a combination of principles Nos. 1, 2 and 4, and the CSM methodology combines aspects of all five principles.

In all TBM performance prediction methods, careful sampling is a key factor. If the test samples are not representative of the actual field conditions, the prediction results, of course, will not be very reliable.

The NTH-method

The NTH hard rock TBM prognosis model is based primarily on empirical correlations between geological/rock mechanical parameters and actual tunnelling performance.

Time- and cost curves for the various tunnelling operations have been established by collecting and analyzing a great amount of data on tunnelling performance and rock mass properties. The prognosis model is continuously revised and improved as new tunnelling data become available. Today's model (Johannessen et al., 1988) is representing version No. 4, and is based on data from about 150 km of bored tunnels.

Geological field mapping, rock sampling and rock testing form the basis for the performance prediction. Originally, the test procedures were developed in the 1960s for evaluating the drillability of rocks by percussive drilling (Selmer-Olsen & Blindheim, 1971). Basically the same tests and much the same parameters also represent the key input in the TBM prognosis model.

Representative, 10 - 15 kg samples of the different rock types along the tunnel are taken to the laboratory, and the following standard tests are carried out:

- Brittleness test
- Siever's J-value test
- Abrasion tests

The basic principles of the actual tests are shown in Fig. 1.

The brittleness test (Fig. 1 a) is basically an aggregate impact test. The actual rock is crushed according to specified procedures in a jaw-crusher, and a defined volume ($V = 189\ cm^3$, corresponding to 500 g of material for density $2.65\ g/cm^3$) of the fraction 11.2-16.0 mm is used as sample material in each test. The brittleness value (S) is defined as the percentage of material that passes the 11.2 mm sieve after 20 drops of the weight.

The Siever's J-value test (Fig. 1 b) is a miniature drill test. The drill is carefully ground for each test to ensure a constant geometry. The Siever's J-value (SJ) is the penetration in 1/10 mm after 200 rotations of the drill.

The so-called Drilling Rate Index (DRI) is compiled from the brittleness- and Siever's J-value as shown in Fig. 2 a.

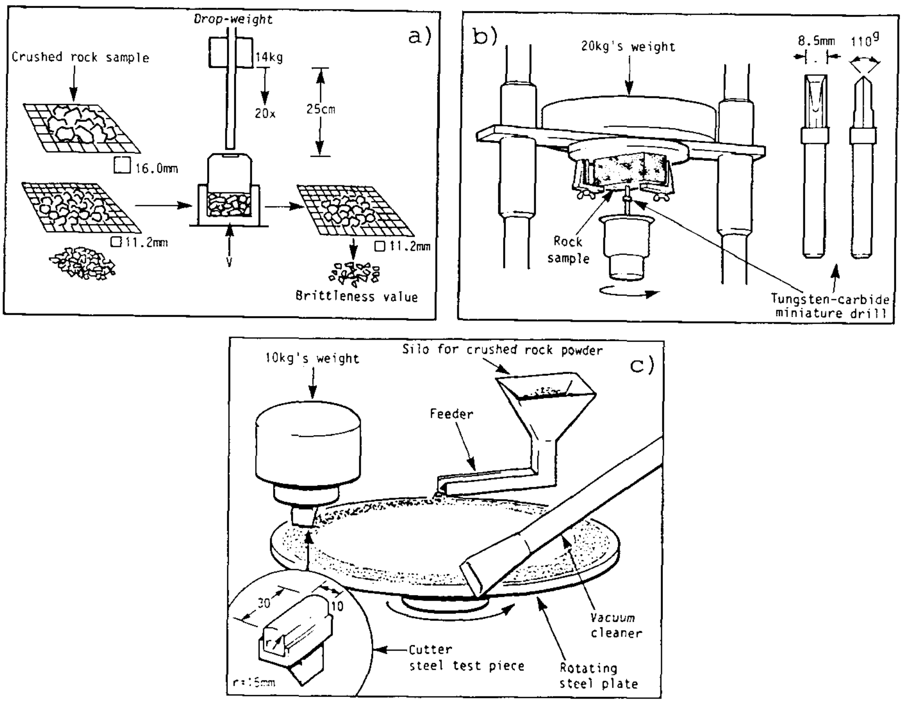

Fig. 1. Basic principles of a) the brittleness test b) the Siever's J-value miniature test and c) the abrasion test.

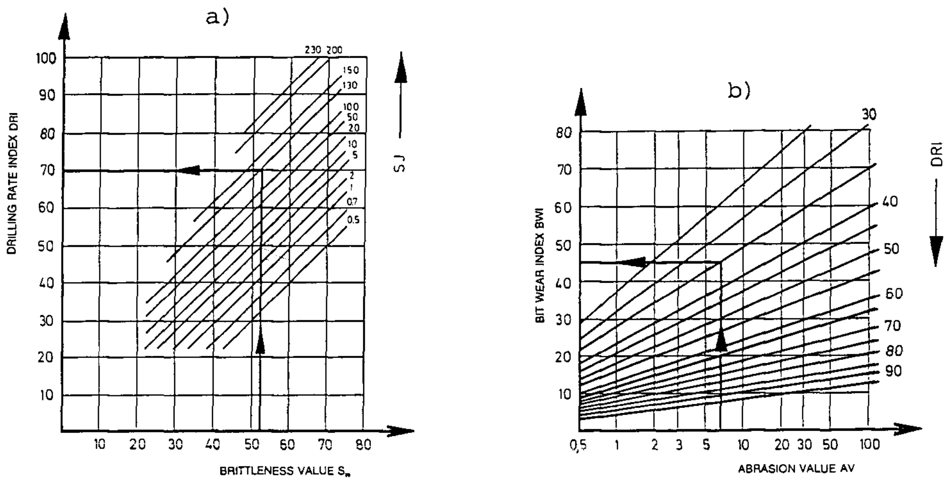

Fig. 2. Diagrams for definition of a) DRI and b) BWI.

In the abrasion test (Fig. 1 c), crushed rock material with grain size smaller than 1 mm is fed on to a rotating steel plate, and the abrasion value (AV) is defined as the weight-loss in mg of a hard-metal test specimen after 100 rotations of the plate (test time 5 minutes). Careful grinding of the test specimen is carried out for every test according to specified procedures.

The so-called Bit Wear Index (BWI) is defined by combining the DRI- and abrasion values, see Fig. 2 b. This index is not used in today's version of the NTH TBM performance prediction model, but is included in the description here because it represents a valuable part of the basis for comparison of mechanical properties (the index is still used for "conventional drilling").

The method for evaluating cutter wear is slightly different from the method for evaluation of percussive drilling bit wear as described above. In the case of cutter wear evaluation, an abrasion value "AVS" is defined by using a test specimen made from cutter steel in the abrasion test (Fig. 1 c) instead of one made from hard metal.

Based on the laboratory testing, a so-called "cutter Life Index" (CLI) is defined as follows (Johannessen et al., 1988):

$$CLI = 13.84 * (SJ/AVS)^{0.3847}$$

At the NTH rock engineering laboratory, drillability testing acording to the described procedures has been carried out for more than 25 years. In Fig. 3 DRI- and BWI test results for about 200 different rock samples (mainly Norwegian) are presented. As can be seen, the results represent a wide variety in drillability properties. There is, however, very clearly a correlation between DRI/BWI and rock category.

To give an idea of the drillability properties of some American rocks compared to Scandinavian, values from recent boreability tests of Yucca Mountain (Nevada) welded tuff (TsW2), Apache Leap (Arizona) unwelded tuff (AL), and Windy Point (Colorado) Granite (WP), are also plotted in Fig. 3. As can be seen, the TsW2- and AL samples both can be characterized as having medium DRI- and BWI-values compared to the Scandinavian rocks. The WP-sample may be characterized as having a medium to low DRI-value and a high BWI-value.

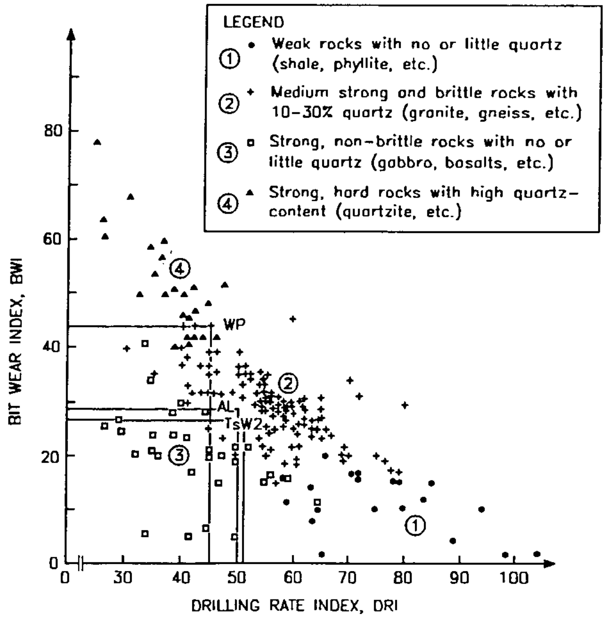

Fig. 3. DRI- and BWI-results for about 200 rock samles tested at NTH (diagram after Lien, 1979).

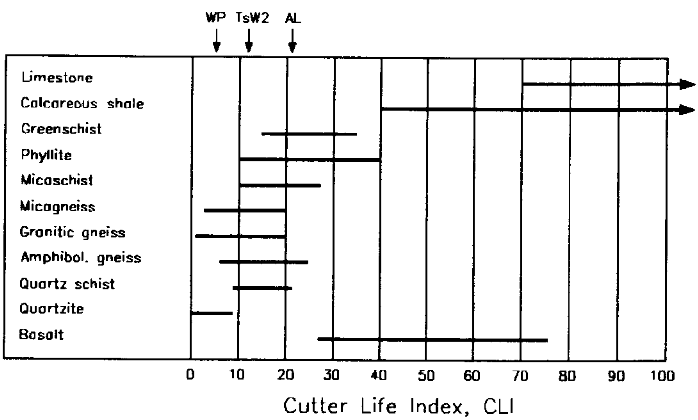

Fig. 4. CLI-values from rock testing at NTH (diagram after Johannessen et al., 1990).

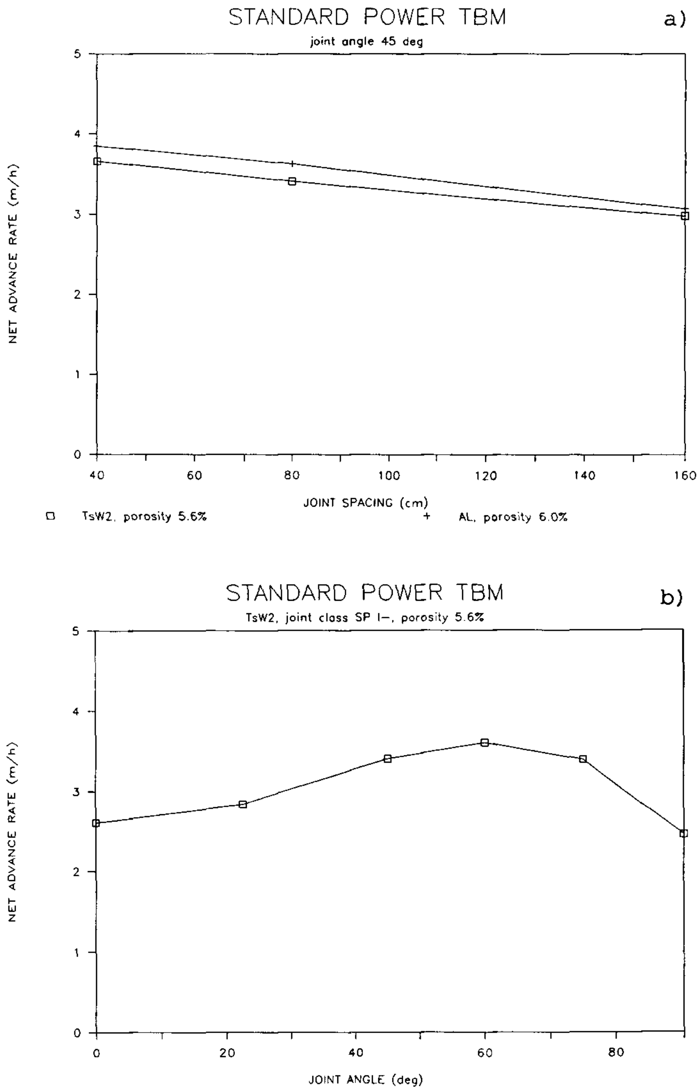

Fig. 5. Estimated TBM advance rates for TsW2- and Al-tuffs as function of joint spacing according to the NTH prognosis model (a), and estimated advance rate for TsW2 as function of joint angle (b) ("Standard Power TBM"; 2400 hp/17" cutters).

The most common ranges of CLI-values for different rock types according to the NTH laboratory test results are shown in Fig. 4. For comparison purposes, the measured CLI-values for the TsW2-, AL- and WP-samples are also displayed. The CLI-values may be characterized as medium for AL, medium to low for TsW2 and low for the WP.

In the NTH performance prediction model, the jointing is of great importance. As an example, estimated net advance rates for the TsW2- and AL-tuffs as functions of joint spacing and joint angle (minimum angle between tunnel axis and joint plane) are shown in Fig. 5. Because of the important role of jointing, great emphasis is placed on joint mapping during field investigations.

For more detailed description of the NTH hard rock TBM prognosis model and the various design- and correlation graphs that are used for performance prediction, reference is made to the comprehensive NTH-report (Johannessen et al., 1988).

The CSM-method

The Earth Mechanics Institute (EMI) of the Colorado School of Mines has also developed a set of TBM performance and cost models from over 20 years of theoretical analysis, laboratory testing and field data evaluations. The performance prediction techniques used by EMI fall under three general categories based on the available geologic data and rock samples representative of the formations to be bored, as discussed briefly below:

1. Theoretical/empirical models

CSM has developed a theoretical/empirical model to predict tunnel boreability. The model is continually upgraded and improved as more field data becomes avail able for comparison to predicted performance. This prediction approach makes use of certain rock properties and geologic information either provided in geotechnical documents from a proposed TBM project or those measured on core samples received from the job site. The properties commonly measued as input into the theoretical/empirical model include the uniaxial compressive strength,the Brazilian tensile strength and the elastic properties together with density. If samples are available, a punch-penetration test is also performed to gain insight into the rock brittleness or the lack thereof.

All this information together with average joint spacing and orientation, if available, are then entered into the computer model to calculate TBM penetration rates as a function of cutter geometry, spacing, layout, head profile, rpm and the available machine thrust, torque and cutterhead power. If foliation or bedding is present, the calculated performance is also adjusted to account for these effects by considering machine direction of advance with respect to foliation/bedding direction. Cutter costs are calculated from the Cerchar abrasivity measurements (Fig. 6). This test provides a Cerchar Abrasivity Index (CAI) which is translated into cutter life in terms of rolling feet before replacement.

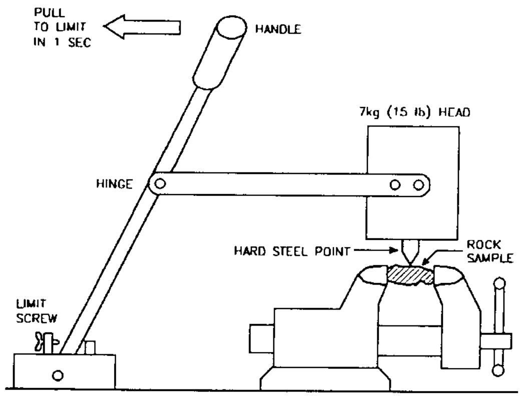

Fig. 6. Main principle of the Cerchar test. The CAI-value is the average diameter of the abraded area of the steel pin in tenths of mm after 1 cm travel across the rock surface (from Ozdemir et al., 1991).

2. Laboratory Cutting tests

If samples of sufficient size are available from the proposed job site, laboratory cutting tests are performed using a Linear Cutting Machine (LCM, see Fig. 7).

In this test, the rock sample (size up to 100 x 50 x 50 cm) is cast in concrete within a heavy steel box to provide the necessary confinement. A servo controlled hydraulic actuator forces the sample under the cutter at preset depth of penetration and width of spacing, and with constant velocity (25 cm/sec). Thus, various promising combinations of cutter spacing and penetration can be tested directly with this equipment. The best combinations are those which produce the largest volume of rock chips using the least amount of specific cutting energy.

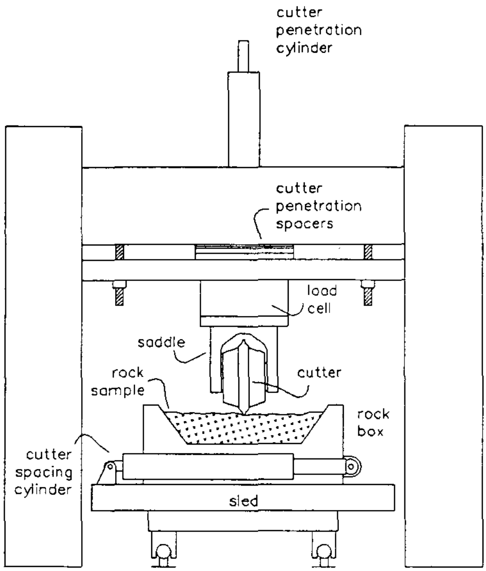

Fig. 7. The EMI Linear Cutting Machine (LCM), from Ozdemir et al. (1991).

The LCM-test uses full size cutters and is capable of generating the full range of cutter loads and penetrations experienced in field boring. As a result, the test results can be directly applied to field performance prediction since no scaling of results is needed.

This test has been used extensively over the last 20 years and has proven highly reliable for accurately predicting field TBM performance. The test can also be used to conduct performance optimization studies in terms of determining the most efficient cut spacing and cutter geometry for obtaining the highest rates of penetration for a proposed tunnelling project. The cuttings generated from linear cutting tests are also collected and sieve analysis performed to determine chip size distributions. This information proves very useful in cases where TBM cuttings are to be evaluated for use as tunnel invert backfill or as road base material.

3. Rotary Cutting Tests

For large tunnel projects or testing new cutterhead designs, full-scale boring tests can be performed on a 2-m diameter, computer-controlled rotary cutting machine available at CSM. This test fixture allows testing and evaluation of different cutter types, spacings, rpms, thrusts and input powers under field simulated conditions.

COMPARISON BETWEEN NTH AND CSM RESULTS

In 1991-92, samples of the TsW2 welded tuff being evaluated for boreability performance at CSM were also sent to the NTH-laboratory in Norway. Standard, Norwegian boreability testing was carried out to develop performance predictions for comparison to CSM results.

Performance prediction was carried out for two different types of TBM; a Standard Power ("StP") and a High Power ("HP") machine. The specifications of each machine are given in Table 1.

TABLE 1. Key data of the Standard Power and High Power TBMs used in the TsW2 performance predictions.

	StP	HP
Cutterhead diameter (m)	7.6	7.6
Rotational speed (rpm)	6.36	7.0
Number of cutters	50	47
Cutter diameter (mm)	432	482
Cutter spacing (mm)	76	81
Max cutter load (kN)	222	267
Cutterhead power (hp)	6 * 400	7 * 450

Some key figures from the CSM-predictions are summarized in Table 2.

As can be seen, the LCM-tests indicate that the TsW2 welded tuff requires more machine torque for excavation than initially estimated. This is attributed to this rock being less brittle than originally estimated. As a result of the higher torque requirement, the estimated penetration rates are reduced by 12-26% compared to the initial prediction, and the average cutter life is reduced by 9-12%.

TABLE 2. Results from the CSM performance prediction for TsW2. "CSM-T" are results based on the theoretical/empirical method, "CSM-L" are results based on LCM-testing.

	StP TBM CSM-T	StP TBM CSM-L	HP TBM CSM-T	HP TBM CSM-L
Operating thrust (kN)	11111	8178	12533	8533
Max operating torque (kNm)	2687	2741	2749	3202
Penetration (mm/rev)	6.09	5.33	8.88	6.55
Penetration rate (m/h)	2.33	2.04	3.73	2.75
Average cutter life (tm/cutter)	3.44	2.77	6.86	4.39

As shown in Fig. 5, the predictions based on the NTH-model to a great extent depend on the degree of jointing and the direction of the jointing relatively to the tunnel axis. In this case average joint spacing 80 cm (joint class "SP I-") is believed most realistically to describe the in-situ rock conditions. Based on field observations, the predominant joint angle (angle between tunnel axis and main joint set) is believed to be about 45 degrees. It is emphasized, however, that detailed fracture mapping has not been carried out in this case.

According to the NTH-model, also the rock porosity has a considerable influence on the TBM performance. The experience with high-porosity rocks is, however, rather limited.

To allow comparison of NTH and CSM results, some key figures from the respective performance predictions are summarized in Tables 3 and 4. For the NTH-analyses all figures are based on a porosity of 5.6%, joint class "SP I-" and a joint angle of 45 degrees. In Table 3, the operating thrust and the maximum operating torque for the NTH-evaluation are identical to the respective figures for the CSM theoretical/empirical evaluation, in Table 4 they are identical to the figures for the CSM linear cutter test (see Table 2).

TABLE 3. Comparison between performance prediction for TsW2 based on the CSM theoretical/empirical method ("CSM-T") and the NTH empirical method.

	StP TBM		HP TBM	
	CSM-T	NTH	CSM-T	NTH
Penetration (mm/rev)	6.09	8.94	8.88	8.48
Penetration rate (m/h)	2.33	3.41	3.73	3.56
Average cutter life (tm/cutter)	3.44	9.56	6.86	13.39

TABLE 4. Comparison between performance predictions for TsW2 based on the CSM Linear Cutter Test ("CSM-L") and the NTH empirical method.

	StP TBM		HP TBM	
	CSM-L	NTH	CSM-L	NTH
Penetration (mm/rev)	5.33	5.39	6.55	4.45
Penetration rate (m/h)	2.04	2.06	2.75	1.87
Average cutter life (tm/cutter)	2.77	5.76	4.39	7.02

From the tables it can be seen that for the Standard Power TBM, there is very close agreement between the NTH penetration prediction and the prediction based on the linear cutter test, while the agreement with the CSM theoretical/empirical prediction is considerably poorer. For the High Power TBM the result is opposite: the best agreement is definitely between the NTH penetration prediction and the CSM theoretical/empirical prediction.

Concerning cutter life, the CSM-figures are in all cases much lower than the figures based on the NTH-model. Considerably closer agreement is obtained if the CSM average cutter life figures are compared with the NTH figures for non-fractured rock.

The apparently odd differences in prediction results between HP- and StP-machines for the NTH-method can be explained by a very low operating thrust for the former and a very high one for the latter according to Norwegian practice, which forms the main empirical basis of the

NTH-method. The high porosity of the TsW2-tuff (5.6%), and the limited experience with high-porosity rocks, may also be a part of the explanation.

FIELD PERFORMANCE

As a result of the continuous improvements in technology, tunnel boring is becoming a more efficient and cost-effective alternative to the conventional drill and blast techniques. This is especially evident in the typical hard rock provinces, such as Scandinavia.

Today, tunnel boring is successfully carried out in rocks with uniaxial compressive strengths exceeding 300 MPa, and with tunnel diameters of 10 m and larger. This section will discuss some key elements of the developments in hard rock TBM-tunnelling based on recent projects completed in Norway.

Norwegian experience

Traditionally, in the hard rocks of Scandinavia, the drill and blast method has held a very strong position. In Norway, drilling and blasting still accounts for more than 80% of the annual tunnel construction. Since the introduction of tunnel boring in the early 1970s, the TBM alternative has, however, become more and more popular, even in hard rocks like gneiss and granite.

TBMs have so far been used for excavation of about 250 km of tunnels in Norway. During high activity periods, up to 9 TBMs operated simultaneously at different sites. Fig. 8 illustrates the fluctuating trends in TBM tunnelling in Norway.

The great majority of the Norwegian TBM tunnels are hydropower tunnels with diameters of 3.5 - 4.5 m. Thus, the major peaks in the histogram shown in Fig. 8 correspond to the high activity periods in hydropower development. Compared to conventional drill and blast tunnelling, the main reasons for the popularity of the TBM alternative for hydropower tunnelling can be summarized as follows:

- For long transfer- and headrace tunnels, the excavation time is often considerably shorter, and the cost considerably lower due to the higher advance rate combined with a reduced requirement for rock support and ventilation.

- The smoother contour of the TBM driven tunnel represents a significant reduction of head-loss in the waterway.

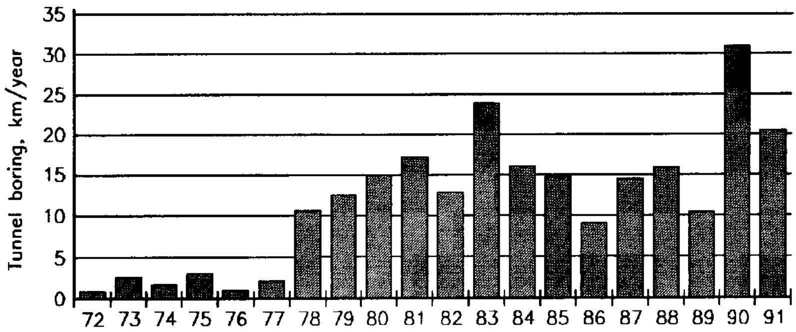

Fig. 8. TBM tunnelling in Norway 1972-91 (satistics from the Norwegian Tunnelling Society, NFF).

The rest of the Norwegian TBM tunnels are mainly sewer tunnels, and a few are road tunnels. Most of these are located in urban areas, and a main reason for choosing the TBM alternative has been to eliminate or reduce the potential problems with blast vibrations.

Since the first Norwegian TBM project in 1972-74 (2.3 m diameter sewer tunnel in Trondheim), with a cutter-ring load of 40 - 53 kN, there has been a gradual development to 17" cutters with maximum load of 200 kN and to modern, High Performance (HP) machines with 19" cutters and maximum load of 320 kN. Consequently, there has been a development in performance from a few tens of meters per week in the early years to several hundred meters per week with the modern HP-machines. New design, HP TBMs have recently been used at the Svartisen and Meråker hydropower projects, which are primarily responsible for the 1990- and 1991-peaks in the histogram shown in Fig. 8.

The following sections will briefly describe the recent TBM tunnelling at Meråker. For a more detailed review of the major Norwegian TBM-projects, see Borg (1988) or Nilsen & Ozdemir (1992).

The Meråker hydropower scheme includes 2 underground hydropower stations (Meråker and Tevla), two large rockfill dams and 39.5 km of tunnels and shafts, see Fig. 9. Tunnel No. 1 on the plan has a length of 10.4 km, and is definitely the longest (the others have lengths between 4.8 and 6.8 km). The diameters planned for the bored alternative varied between 3.2 and 4.9 m.

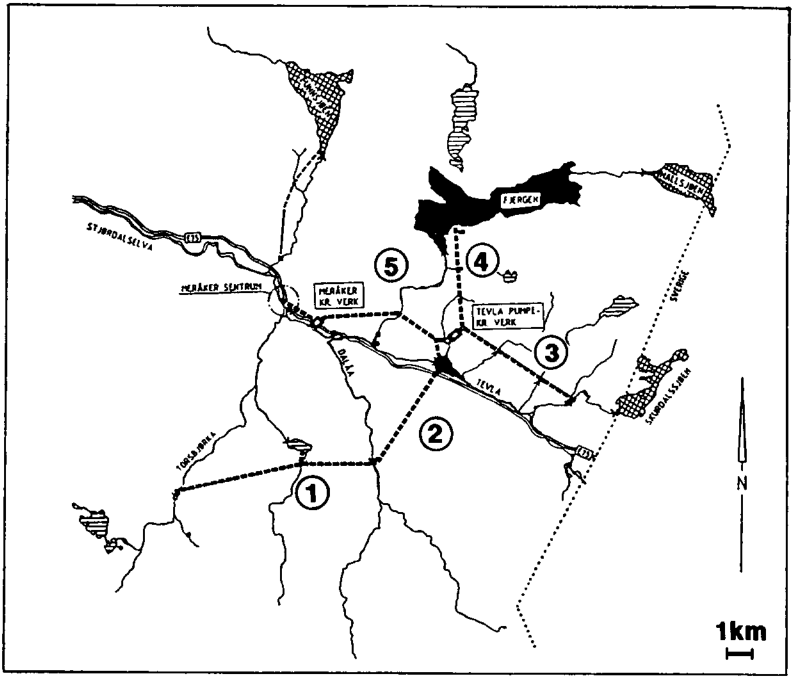

Fig. 9. Plan of the Meråker Hydropower Scheme. Dotted lines are tunnels, rectangles power stations and shaded areas lakes.

The bedrock at Meråker is of lower Paleozoic age, and mainly consists of phyllite, meta-sandstone, meta-gabbro and greenstone. The rock layers generally strike NNE-SSW and dip mainly moderately towards W (i.e. moderately favourable for TBM excavation of tunnel No. 1, cfr. Fig. 5). Data from joint mapping and laboratory testing carried out in 1987-90 are shown in Table 5.

TABLE 5. Summary of drillability properties (mean values with standard deviations in parenthesis where applicable) and degrees of jointing for the Meråker rocks.

Rock type	DRI	CLI	Jointing
Phyllite	58(5)	57(16)	Intense (thin fissures)
Meta-sandstone	46(10	31(28)	Moderate to intense
Meta-gabbro	35(11)	22(3)	Very moderate
Greenstone	27	18	Moderate

Based on the results of field investigations and laboratory testing, there was little doubt that the meta-gabbro and the greenstone would be difficult to bore. On the other hand, phyllite, the predominant rocktype in the area, had to be characterized as very favourable for tunnel-boring.

For various reasons, among which the high capital costs of TBMs was the main one (see Nilsen & Ozdemir), the TBM-alternative was chosen for only the longest tunnel at Meråker (tunnel No. 1). Fig. 10 shows the geology along this tunnel.

Tunnel boring from adit Dalåa started in October 1991 with a 3.5 m diameter Robbins HP-TBM (1800 hp/19" cutters with maximum load of 320 kN). The boring operation was completed in august 1992. Remarkable results were achieved from the very beginning. Assambling of the machine, from the day of arrival to the actual start of boring, took only 3.5 weeks. In the very first month of tunnelling, more than 1000 m of tunnel was bored.

As a result of the geological conditions (see Fig. 10) the best results were achieved the last four kilometers, with net advance rates around 9 m/h. Some other key figures for the Meråker project (Johannessen, 1992) are as follows:

Average weekly advance	:	253 m (100 h/week)
Best day	:	100 "
Best week	:	426 "
Best month	:	1358 "
Average TBM-utilization	:	40%

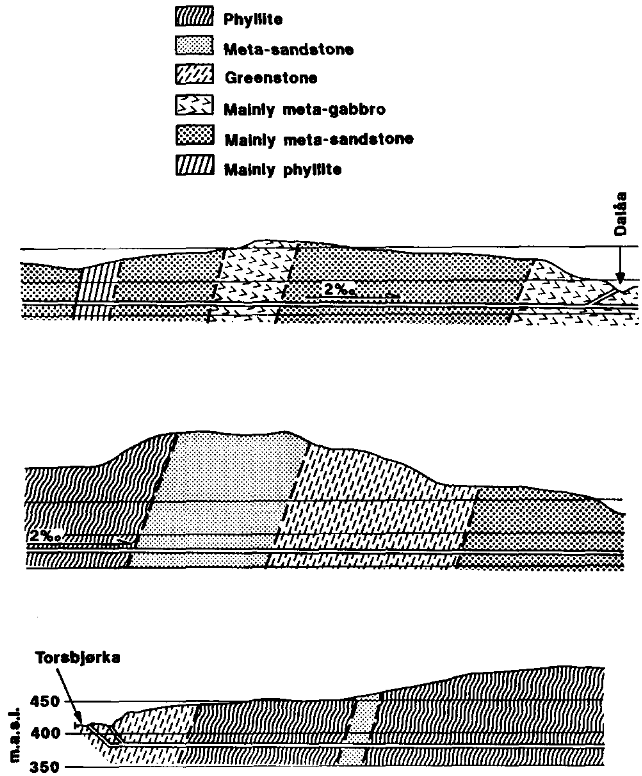

Fig. 10. Longitudinal section of the 10.4 km long TBM-tunnel at Meråker.

CONCLUSIONS

The basic principles of the various hard rock TBM performance prediction methods are often quite different. Between the NTH- and the CSM-methods the main difference is that while the former is focusing on field mapping, and in particular joint mapping, the latter is more putting emphasis on full-scale testing of the rock in the laboratory complemented by theoretically developed relationships.

A great advantage of the CSM-method is that new and "unexpected" rock conditions may be taken easily into account, and machine design optimization can easily be accomplished. The main advantages of the NTH-method are the generally very comprehensive empirical data-basis, where the important influence of rock jointing can be easily taken into account. The two methods, however, supplement each other, and future plans call for combining the different principles into an accurate, universal TBM prediction method. In most cases, as has already been demonstrated by the TsW2-example, the prediction results correlate very closely.

Hard rock no longer presents a limitation for the economic use of TBMs (Ozdemir, 1992). As shown by the Meråker-case and several other projects, very high performances can be achieved even in the hardest rocks. Perhaps even more important, the Meråker project demonstrates that new-design High Performance TBMs have provided additional improvements in tunnel boring technology in geologies consisting of alternating very hard and relatively soft rocks.

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