THE NTNU AND QTBM METHODS OF PROGNOSIS WITH EMPHASIS ON HARD-ROCK MIXED-FACE PROBLEMS

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THE NTNU AND Q_{TBM} METHODS OF PROGNOSIS WITH EMPHASIS ON HARD-ROCK MIXED-FACE PROBLEMS

NTNU- og Q_{TBM}-prognosemodeller med vekt på hard-rock mixed-face problemer

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SUMMARY

The NTNU and Q_{TBM} methods of prognosis are widely used for performance predictions and cost estimates in the planning and risk management of Tunnel Boring Machine (TBM) excavation projects. The methods have been applied for the evaluation of recently completed hard rock TBM projects, both during geological pre-investigations and prognosis and during later tunnel excavation. Not only hard mixed-face conditions (MFC) but also numerous fracture zones have been described and delays predicted, and ultimately some were treated with pre-injection. Hard rock tunnel boring involves great complexity and geological risk which is accentuated with hard-to-very hard rock (i.e., low-to-extremely low boreability/massive hard rock) combined with hard mixed-face conditions. When using prediction~~s~~ models, an appropriate understanding of the model methodology and limitations is of great importance for a reliable application of the models and for consistent assessments to facilitate the control of such risk and to enable delays and budget overruns to be avoided. MFC in TBM tunnelling projects in hard and abrasive rock have a significant impact on performance, tool wear and, consequently, on construction time and excavation costs. The present paper evaluates and discusses the applicability of the NTNU and Q_{TBM} models in hard rock TBM projects with emphasis on hard-rock mixed-face problems.

SAMMENDRAG

NTNU- og QTBM-metodene for prognose er mye brukt for ytelsesforutsigelser og kostnadsestimater i planlegging og risikostyring av utgravingsprosjekter ved tunnelboremaskiner (TBM). Metodene er brukt for evaluering av nylig avsluttede TBM-prosjekter for hardt fjell, både ved geologiske forundersøkelser og prognoser og ved senere tunnelgraving. Ikke bare harde 'mixed-face' (MFC), men også mange bruddsoner er beskrevet med forsinkelser forutsagt, og til slutt ble noen behandlet med pre-injeksjon. Hardbergtunnelboring innebærer stor kompleksitet og geologisk risiko som fremheves med hardt til veldig hardt berg (dvs. lav-til-ekstremt lav borbarhet/massivt hardt berg) kombinert med harde 'mixed-face' forhold. Ved bruk av prediksjonsmodeller er en hensiktsmessig forståelse av modellens metodikk og begrensninger av stor betydning for en pålitelig anvendelse av modellene og for konsistente vurderinger for å lette kontrollen av slik risiko og for å unngå forsinkelser og budsjettoverskridelser. MFC i TBM-tunnelprosjekter i hardt og abrasivt fjell har en betydelig innvirkning på ytelse, kutterslitasje og følgelig på byggetid og utgravingskostnader. Denne artikkelen evaluerer og diskuterer anvendeligheten av NTNU- og Q_{TBM}-modellene i hardrock-TBM-prosjekter med vekt på hard-rock mixed-face problemer.

INTRODUCTION

The tunnel boring machine represents perhaps the ultimate challenge in tunnel prognosis because Tunnel Boring Machine (TBM) performance can range so remarkably widely, especially since the development of TBM technology has made the tunnelling method applicable in an increasingly wider range of rock mass conditions. The writers are aware of penetration rates PR varying from extremes of 1 mm/rev (and even 0.1 m/hr) for continuous boring (with an under-powered machine, extreme rock hardness and very high stress) while 15-20 mm/rev (e.g., 10 m/hr) could be considered as a brief maximum before conveyor-belt overload. Advance rate (AR) which we could term 'actual' rate is even more challenging as it is time or tunnel length dependent. Machine utilization (U), typically expressed in %, varies and must be given for specified intervals such as 1 day, 1 week, 1 month. However, somewhere in the data on progress, and beyond the standard maintenance shift delay to AR_{24} may lie accumulated days of delay for non-systematic pre-injection, and perhaps weeks or months of delay when such pre-treatment was required, but not performed in permeable TBM-trapping fault zones.

An over-riding challenge in hard rock with limited jointing and especially in massive abrasive rock will be cutter consumption. In such conditions, cutter changes and/or cutter inspection will be time consuming and may represent a high percentage of the total machine utilization time. Performance predictions and costs estimates have a major influence on the planning and risk management of TBM excavation projects, especially when there is a lot of hard-to-very hard rock (i.e., low-to-extremely-low boreability). Cutter-ring and bearings performance needs are accentuated, and the geological risk becomes critical. There is an urgent need for reliable prediction to facilitate the control of such risk and to enable delays and budget overruns to be avoided. When using prognosis/prediction models, an appropriate understanding of the model methodology and limitations is of great importance for reliable application and for consistent assessments. The NTNU and Q_{TBM} models have been applied for the evaluation of recently completed hard rock TBM projects, both during geological pre-investigations and prognosis and during later tunnel excavation. Not only hard mixed-face conditions but also numerous fracture zones have been described with Q and V_P. Many such zones were ultimately treated with pre-injection. Here we evaluate and discuss the applicability of the NTNU and Q_{TBM} models in hard rock TBM projects with fracture zones with emphasis in hard-rock mixed-face problems.

The authors will first summarise the two prediction models with which they are intimately familiar, since responsible for the development of one (Q_{TBM}) or significant update of the other (NTNU). Beyond a brief description of the workings of the methods, will be a discussion of the strengths and weaknesses, which leads to a consideration of the advice sometimes given for Q and RMR: 'do both' when characterizing rock masses. Then the potential shortcomings are covered, and the strong points reinforced, such that reliability is improved overall.

For example, cutter wear is described in detail and with great reliability in the NTNU model, but only the CLI (cutter life index) term is used in Q_{TBM}. However, this is such a useful parameter that it is used in two places: to help determine the Q_{TBM} value and to modify the deceleration gradient (-m) which links to a time-dependent utilization U. Fracture zones and faults are not specifically treated in the NTNU model but are a standard part of Q_{TBM} with description using the Q-value or P-wave velocity. Adverse values of each strongly affect deceleration (-m) and therefore utilization, especially when $Q << 1$.

THE NTNU PREDICTION MODEL

The NTNU model is in general focussed on hard-to-very hard rock conditions (i.e., low-to-extremely low boreability) where the excavation cost becomes critical. Standard machine specifications such as number of cutters and operational parameters (i.e., cutterhead velocity, cutter thrust) are given in the NTNU model. Operational parameters are carefully considered since the penetration rate estimation model is based on normalised penetration curves obtained from penetration tests under different rock mass conditions.

The philosophy of the NTNU model is to achieve reliable predictions by combining relevant rock properties and machine parameters. Several steps are involved in the NTNU prediction model, which is used mostly for hard rock TBMs in order to estimate time and costs involved in tunnel excavation using factors such as net penetration rate, cutter life as well as advance rate. The model has been the subject of progressive development since the first version was developed in 1976 by the NTNU (formerly NTH). Table 1 shows the successive editions of the NTNU prediction model to date.

Table 1 History of the NTNU prediction model for hard rock TBMs.

Edition	Year
1st edition	1976
2nd edition	1979 (Published in 1981)
3rd edition	1983
4th edition	1988
5th edition	1994
6th edition	2000
7th edition	2016

The values of net penetration rate and cutter life depend on rock properties and machine parameters. Rock properties consist of intact rock and fracture spacing parameters. These are combined to generate a single rock boreability parameter, called the equivalent fracturing factor (k_{ekv}), while the machine parameters are combined into a single parameter, the equivalent thrust (M_{ekv}).

Figure 1 illustrates the basic penetration rate (mm/rev) as a function of the rock mass equivalent fracturing (k_{ekv}) values for standard machine parameters. The expected penetration rate is given according to recommended gross cutter thrust. This is increased when there is low rock boreability while it is substantially decreased when boreability increases.

Cutter life, measured in hours, is equivalent to the cutter life in rolled distance at a given cutterhead velocity, measured in rpm. Cutter life in hours is combined with the penetration rate (m/h) and the TBM diameter to calculate cutter life in terms of tunnel metres excavated per cutter (m/cutter) and solid cubic metres excavated per cutter (solid rock m^3/cutter). Table 2 lists the machine and rock parameters that influence net penetration rate.

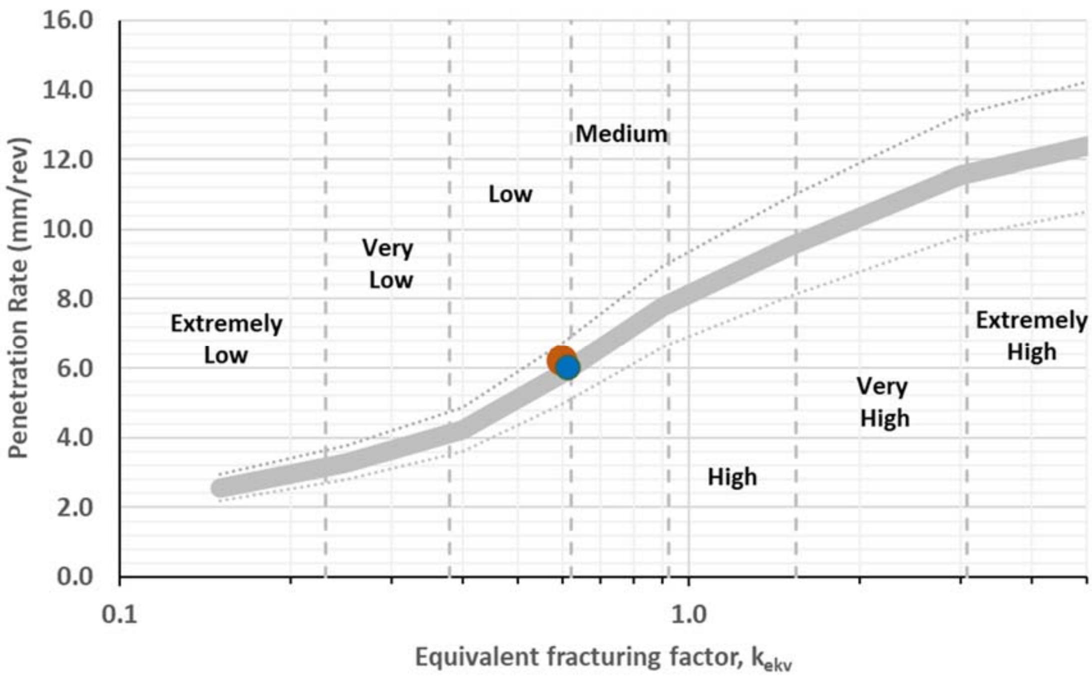


Figure 1 Expected penetration rate (mm/rev) as a function of the rock mass equivalent fracturing (k_{ekv}) values. The categorization refers to rock boreability. The two dots indicate mean rock boreability/penetration rate at Follo Line for TBMs North (orange) and TBMs South (blue).

Table 2 Machine and rock parameters that influence net penetration rate.

Rock properties		**Machine parameters**
Intact Rock	**Rock Mass**	
Drilling Rate Index, DRI	Rock Mass Fracturing Factor (k_s)	TBM diameter
Porosity		Cutter diameter
		Number of cutters
		Gross average cutter thrust
		Average cutter spacing
		Cutterhead rpm

Cutter wear depends on both the rock properties and on machine parameters. These are listed in Table 3.

Table 3. Machine and rock parameters that influence cutter wear.

Rock properties	**Machine parameters**
Cutter Life Index, CLI	TBM diameter
Content of abrasive minerals	Cutter diameter
	Number of cutters
	Cutterhead rpm
	Gross average cutter thrust

The gross advance rate is estimated on the basis of three input parameters:
- Net penetration rate
- Machine utilisation
- Number of working hours in a given period (e.g., a week).

The machine utilisation is in turn based on time consumption for the various operations involved in the tunnel excavation process. Tunnel length exerts an important influence on the time taken to carry out tunnelling activities (learning curve and long-tunnel logistic difficulties). A factor for additional time consumption (hours/km) related to tunnel length is plotted on the vertical axis of Figure 2. Boundary limits have been included for low and high skill levels and tunnel system quality. The term 'skills levels' refers not only to crew members, but also to equipment manufacturers and other relevant factors affecting efficiency.

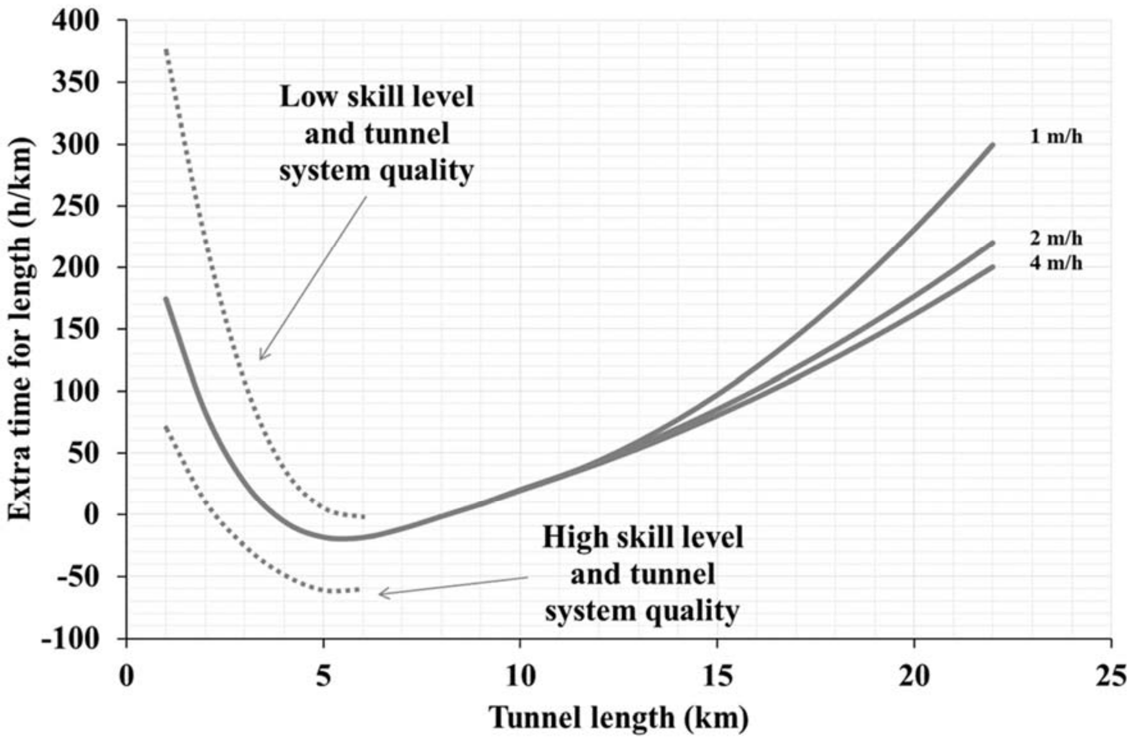


Figure 2 Additional time (hours/km) plotted against tunnel length.

Figure 3 shows a performance prediction flowchart generated by the latest version of the NTNU model.

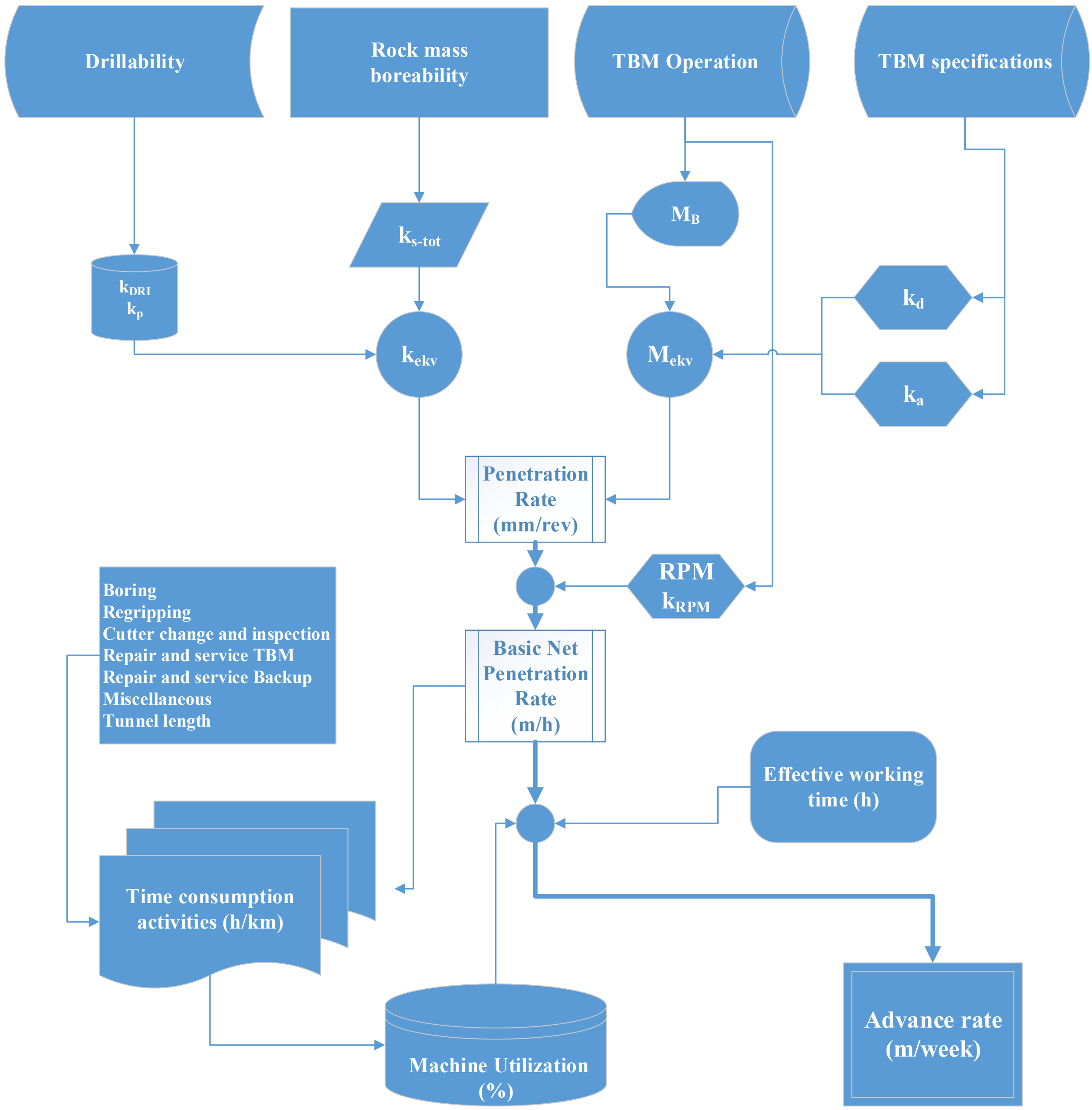


Figure 3. Performance prediction flowchart generated by the latest version of the NTNU model (Macias, 2016).

THE Q_{TBM} MODEL

It may be helpful to start this brief summary of Q_{TBM} with a figure relating the conventional Q-system scale of rock quality and how PR and AR are likely to be distributed, in principle. The six Q-parameters are used directly as 'the first half' of Q_{TBM}. The only specific provision is that RQD should be evaluated in the tunnelling direction when viewing and logging oriented core, or e.g. road-or-rail related rock cuttings and rock exposures, if available. We term it RQDo as a reminder of the orientation. In the case of steeply dipping bedding, the horizontal estimate of RQDo, being significantly lower, is extra important.

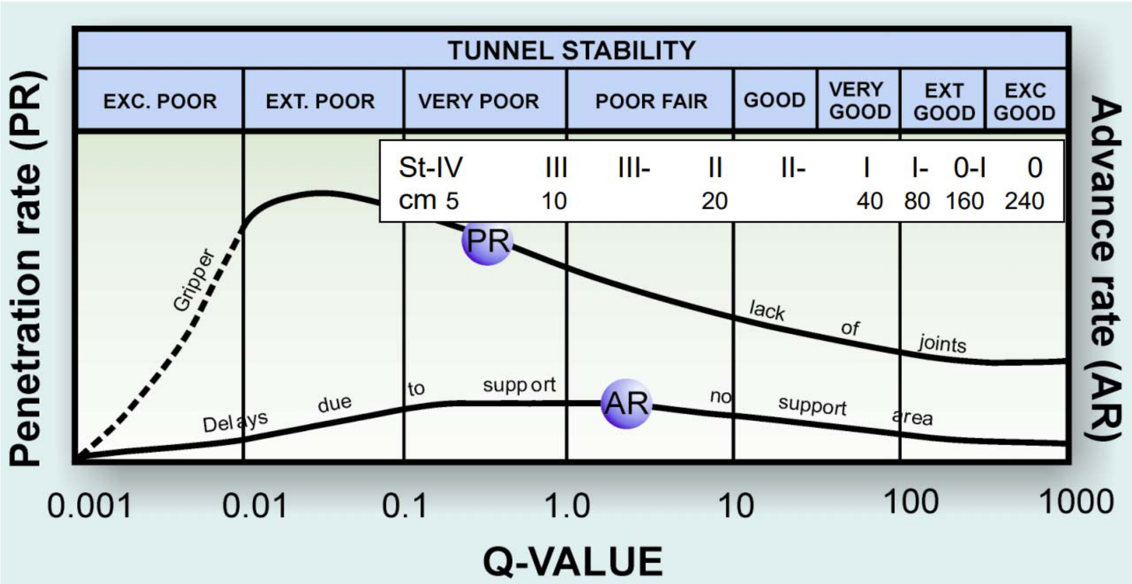


Figure 4 The Q-value scale for describing rock mass quality, with hypothetical PR and AR curves. The inset shows an approximate NTNU fracturing class (and spacing). The normal 'Q-adjectives' good, very good etc. are modified for TBM in the next figure.

In Figure 5 we see the 'addition' of normalized machine-rock interaction parameters. Firstly, 'neutral' values of (net) cutter force F are normalised by 20tnf and compared with an estimate of the compressive strength SIGMA of the rock mass (range approx. 1 to 100MPa). The components F^{10} and 20^{9} were derived by trial and error, and F has been tested successfully against PR predictions over the range of 7tnf to 32tnf using real cases. The ratio 20/CLI is followed by q/20, so the cutter life index and quartz content (%) are each normalized by a neutral value of 20. The final term in the Q_{TBM} equation is $\sigma_\theta/5$ which is an important correction for the tunnel depth, and represents an approximate estimate of biaxial stress in the tunnel face (a stress that resists cutter chipping) of 5MPa per 100m depth.

A particularly reliable part of the Q_{TBM} prognosis model is the deceleration aspect shown in Figure 6, since so strongly supported with case records for open-gripper TBM. However, there is generally reduced deceleration for double-shield TBM, due to their efficiencies of mostly not too delayed final support and the usual semi-continuous push-off-liner progress when boring. Perhaps surprisingly, world record TBM performances also show similar deceleration, as indicated in Figure 7. Figure 5 illustrates the most frequent instability problems in tunnelling caused by faulted rock at the 'left-hand' end of the Q_{TBM} scale.

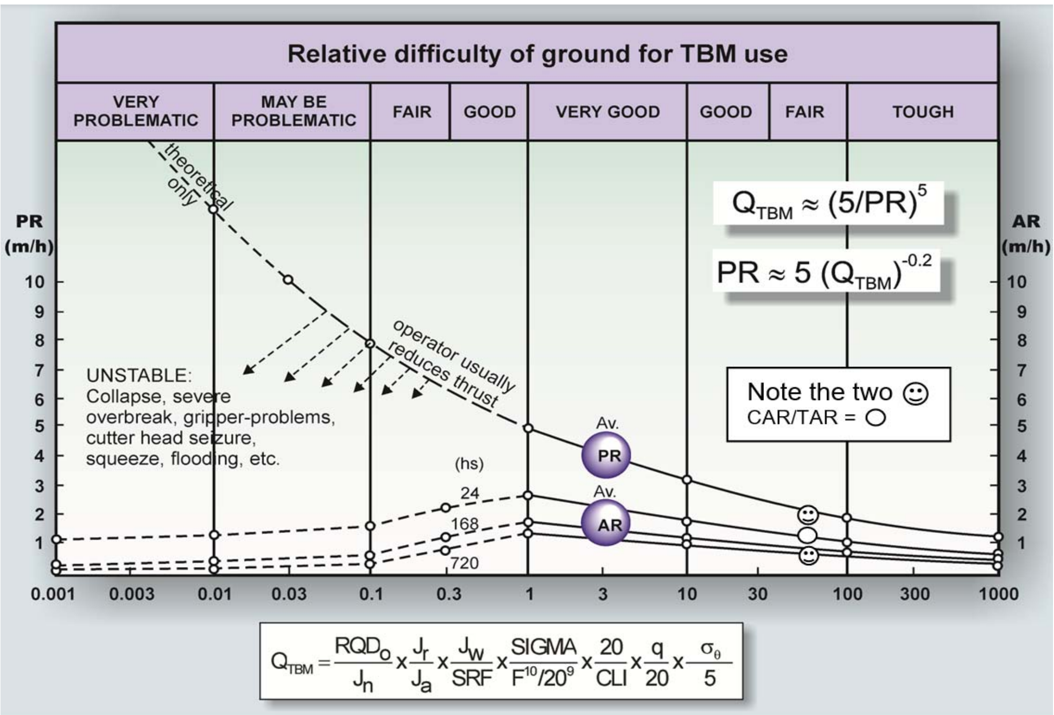


Figure 5 The Q_{TBM} equation was developed by trial and error using approx. 1,000km of TBM case records involving 145 lengths of well-described and mostly open-gripper TBM. Note the three curves for AR for 24hours, 1 week and 1 month. The two 'smiley' symbols drawn at a Q (and approx. Q_{TBM}) value of 60 show approximate PR = 2m/hr and AR = 0.5m/hr, relevant to the mean PR and AR of the 4 x 9km of the double-shield TBM used at the Follobanen twin rail tunnels south east of Oslo, in southern Norway.

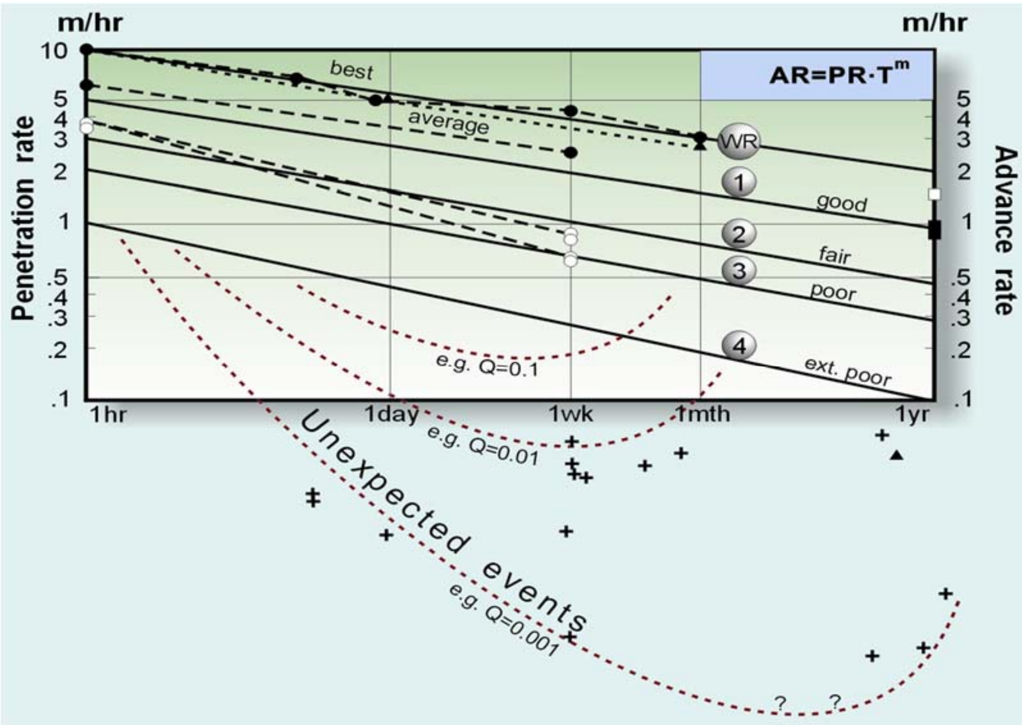


Figure 6 A synthesis of deceleration records for approx. 1,000km of open-gripper TBM. The (+) symbols represent TBM delayed or stuck in fault zones. Double-shield TBM may, at best, have half the deceleration gradients of open-gripper when operated as expected.

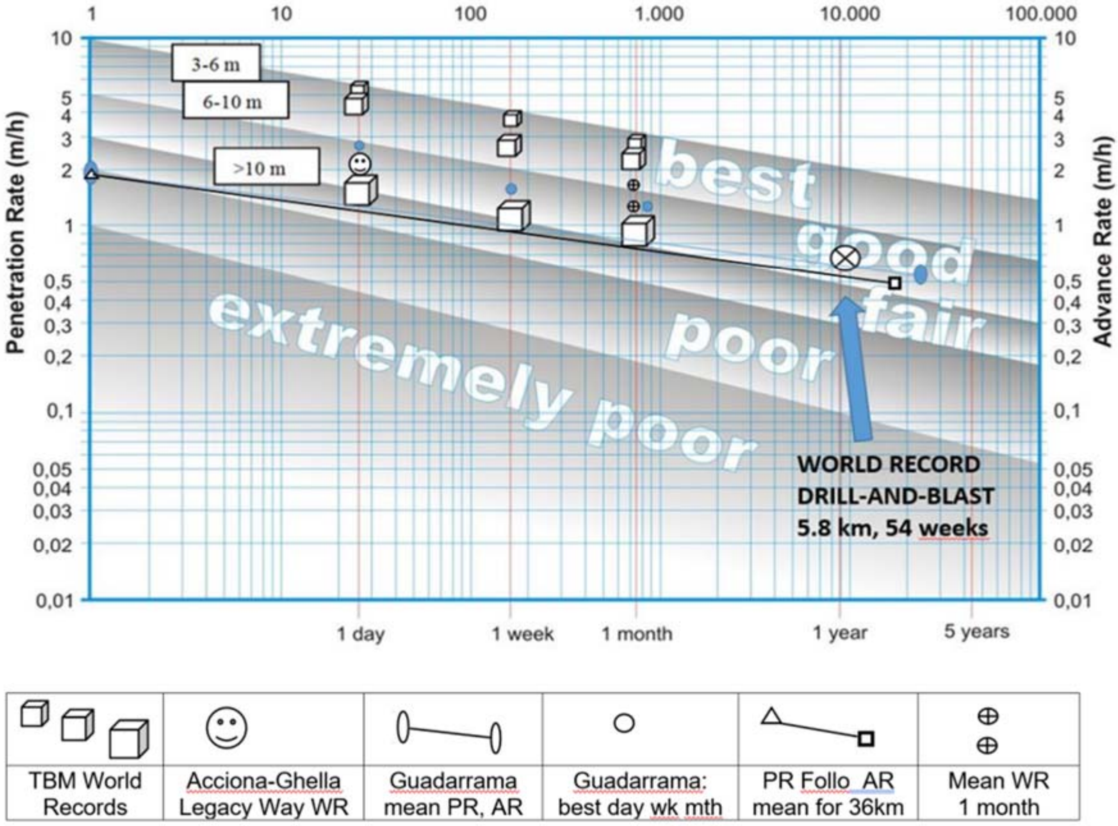


Figure 7 World record performances arranged by size (Barton, 2013) with additional data also explained in the tabulation. The strongly size-related results suggest an additional correction for PR beyond that already included in Q_{TBM}. We should test PR x 5/D, or perhaps a non-linear scale as 'today's' TBM diameters increase beyond the earlier data base.

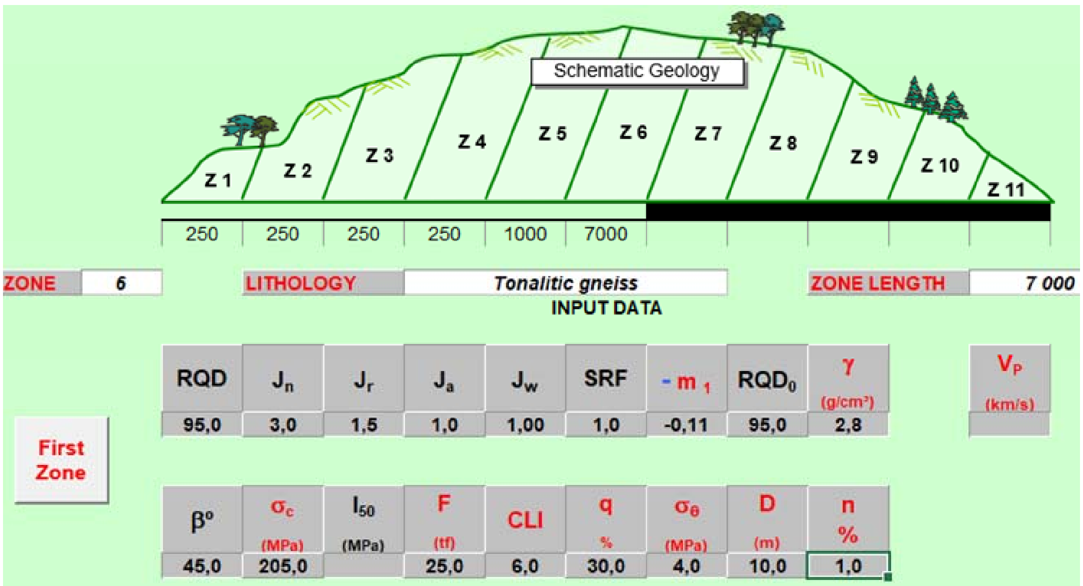


Figure 8 This 'input data' screen of the Q_{TBM} model (Barton and Abrahão, 2003) presents the final 7km of a test fit to Follo Line conditions, with updated (generally higher) Q-values from project logging data and a more complete seismic velocity data base than was available in 2009. The four initial trial 250m lengths included variations of cutter thrust, quartz % and CLI.

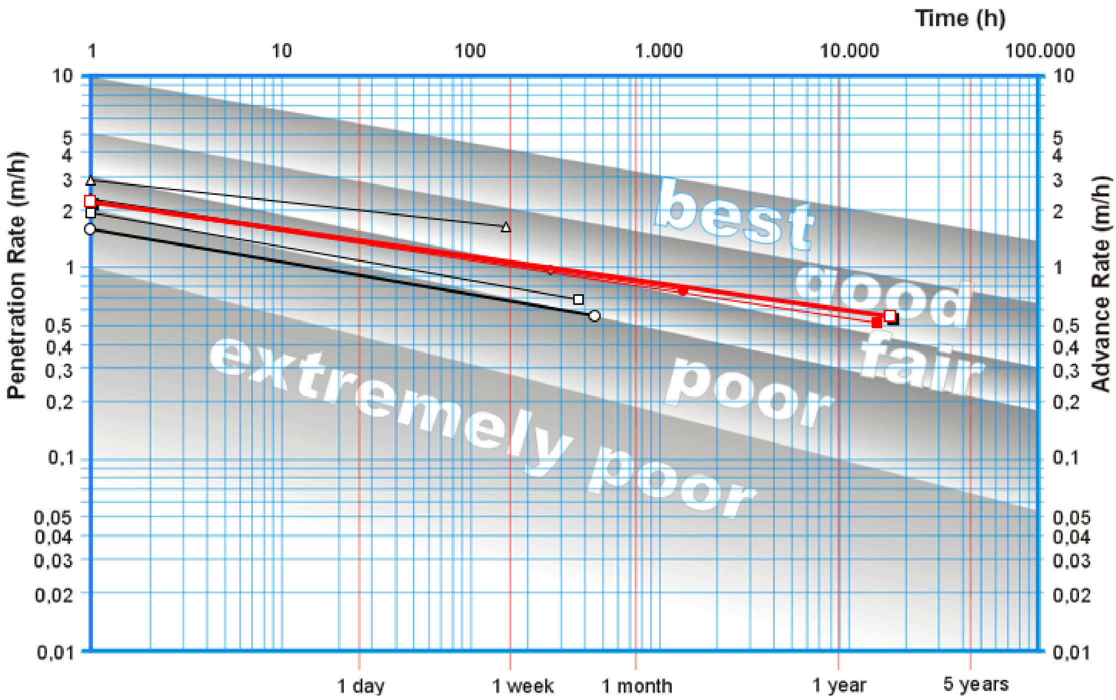


Figure 9 The six modelled lengths (with the dominant 7km) from Figure 8 demonstrate PR mean of approx. 2.3m/hr (slightly high) and AR mean of 0.5m/hr, the latter as experienced on average in the 36km of Follo Line TBM tunnelling.

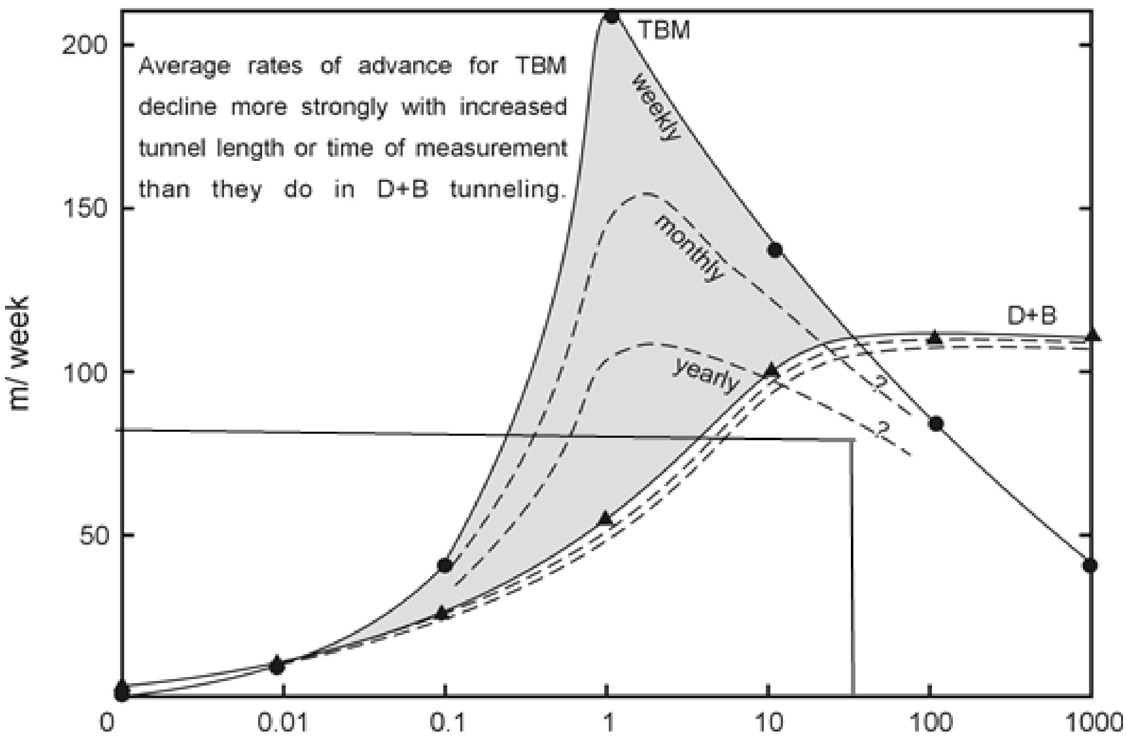


Figure 10 A comparison of TBM and drill-and-blast from Barton, 2000. Note: the added 'rectangle' assumes a Q-value of ≈ 40, intersecting an approx. 2 years result and with mean ≈ 80m/week indicated on the vertical axis. The mean completion time for the four 9km tunnels was 110 weeks. (Note that 80 x110 ≈ 9.0km).

A PROJECT CASE: THE FOLLO LINE TBM PROJECT

Project overview

The Follo Line is a high-speed rail project that connects the city of Oslo with the town of Ski via twin 19.5 km tunnels, the longest in Scandinavia. A total of four TBM were used (Figure 11 shows one of the Follo Line TBM leaving the common launch chamber). The excavations, carried out by ACCIONA-Ghella Joint Venture (AGJV), started from the centre of the project alignment, with two TBMs excavating towards the North (TBM 1 and TBM 2) and two TBMs towards the South (TBM 3 and TBM 4).

Figure 11 One of the Follo Line TBM leaving the common launch chamber near the remarkable Åsland work site where all PC elements for the four tunnels were fabricated.

Performances at Follo Line TBM project

The rocks of the project area consist predominantly of Precambrian gneisses. A significant number of intrusives from the Permian period, as well as amphibolite dykes/sills occur. The Precambrian gneisses are folded in sharp isoclinal folds, and they expose a clear foliation. The dominant rock structure in the project area strikes N-S to NW-SE. There were numerous sub-vertical fractures zones with low P-wave velocities and low interpreted Q-values. These zones generally had high permeability. They often had clay cores. They were drilled with inclined holes where low velocities were indicated. The generally high Q-values, mostly in the range 10 to 100 were initially deduced from surface logging and from relatively high P-wave velocities. These were eventually measured over many kilometres of the project corridor.

The two TBMs towards North (TBM 1 and 2) reached the outskirts of Oslo on 11th September 2018 and the other two TBMs towards Ski in the South (TBM 3 and 4) completed their work on 26th February 2019. Table 4 summarizes the performance for each TBM at the Follo Line Project.

Table 4. Mean performances at Follo Line Project for TBM 1, 2, 3 and 4.

TBM	Tunnel Length (m)	Penetration rate (mm/rev)	Net Penetration Rate (m/h)	Advance Rate (m/day)*
TBM 1	8,898	6.2	1.9	14.6
TBM 2	8,908	6.2	1.9	15.3
TBM 3	9,142	6.2	2.0	13.5
TBM 4	9,129	6.1	1.9	13.1

*It includes around 21% of pre-grouting and other delays

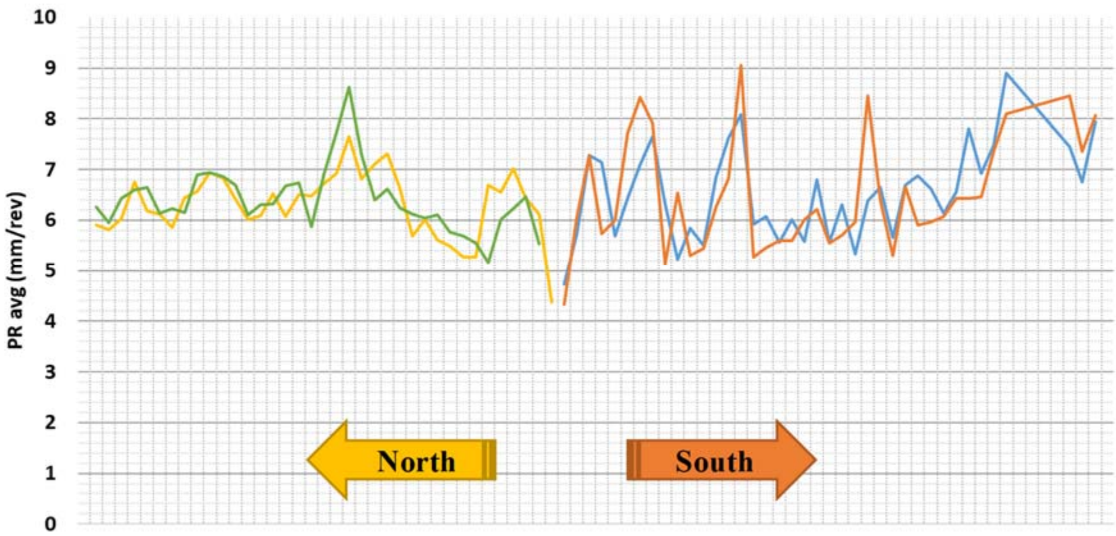


Figure 12 Average penetration rate (mm/rev) for every 250 m section towards North (TBM 1, 2) and towards South (TBM 3, 4)

Table 5 summarizes the laboratory results per lithology. Values of UCS, DRI™, CLI™, and abrasive minerals content are given. A total of 146 rock samples were tested.

Table 5 Laboratory results per lithology for all the TBMs.

Rock type	UCS	DRI™	CLI™	Abrasive minerals content (%)
Gneisses	115	46	8.5	37
Supra crustal Gneiss	167	41	6.7	42
Amphibolite	178	58	17.0	11
Pegmatite	-	37	7.6	36
Porphyry	264	47	11.2	< 1

*Abrasive minerals content includes Quartz, Epidote, Garnet and Pyrite.

Table 6 summarizes the rock mass parameters (k_{s-tot} and Q-values) with mean values and typical ranges.

Table 6.- Rock mass parameters (k_{s-tot} and Q-values).

Tunnel	$\mathbf{k_{s-tot}}$	**Q-values**
TBMs North	0.61 (0.36 – 1.54)	38 (0.01 – 300)
TBMs South	0.68 (0.36 – 2.69)	31 (0.08 – 300)

*ks-tot evaluated (independent assessment by the first author) along the entire length from Optical Televiewer (OTV) and Q-values from face mapping on a daily basis.

Pre-grouting

Systematic probe drilling was performed at Follo Line project. It consisted of 2 holes of 34 m length. Pre-grouting (PG) was performed based on probe hole leakages. The pre-grouting typically consisted of 20 holes of 34 m length with 6 m overlap. In the end, around 21% (7.6 kms) of the tunnel lengths were pre-grouted.

Pre-grouting is a tunnelling activity that typically results in large time consumption within the TBM tunnel cycle, and may influence the critical path if needed systematically as in drill-and-blast projects under settlement-sensitive areas.

Table 7 summarizes the time consumption in hours/km of PG and the Q_{TBM} deceleration parameter m_1 representing time delay. An early PG delay in TBM tunnelling in the Oslo area was plotted in Figure 6 (see PR = 4 m/hr and the two sloping dotted lines: a doubling of -m).

Table 7 Time consumption for pre-grouting (hours/km and m_1).

Tunnel	**hours/km (PG length)**	$\mathbf{m_1}$ **(PG length)**
TBMs North	1,390	-0.14
TBMs South	1,339	-0.14

Engineering geological mapping in D&B vs TBM tunnels

A nearly parallel drill and blast tunnel (The Escape Tunnel) of 2,700 m length is located between the TBM towards the north covering nearly 30% of the TBM tunnels. This provided relevant and valuable information on rock mass quality. Figure 13 shows the Escape tunnel alignment running parallel to the TBM tunnels towards North.

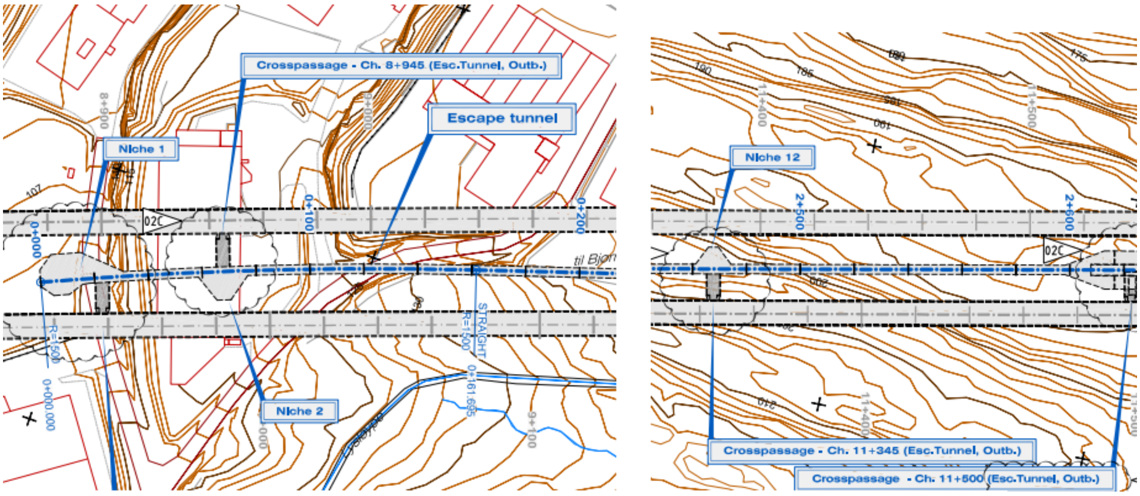


Figure 13 Escape tunnel alignment parallel to the TBM tunnels towards North. (Just the beginning and end are shown).

Continuous geological mapping was performed during the excavation of the Escape Tunnel using the Q-system method. In addition, the geologist teams had the opportunity to become familiar with the NTNU model methodology.

Blasted tunnels will tend to increase fracture continuity and may result in overestimation of the degree of fracturing resulting in an over-exposure of the total rock mass fracturing in comparison with TBM. Since the NTNU – TBM prognosis methodology for rock mass evaluation is solely based on bored tunnels and solely applies for TBM tunnelling, the attempt to apply engineering geological mapping for evaluating the rock mass fracturing in drill and blast tunnels must be considered with special caution.

The Q-method was initially developed for rock mass characterization and for estimation of single-shell (NMT) tunnel and cavern support, and exclusively in drill and blast excavations. Barton (2000) discussed findings from the Svartisen tunnel (Løset, 1992), where Q-values mapped in the TBM tunnel section were 1.5 to 3.0 times higher than those from the subsequently drill-and-blasted road tunnel expansion. The higher Q-values were noted in the middle range (from 4 to 30). Table 8 summarizes the Q-values and $k_{s\text{-}tot}$ in the Escape Tunnel and in the TBM tunnels, respectively.

Table 8 Summary of Q-values and rock mass fracturing factor ($k_{s\text{-}tot}$) in the Escape and TBM tunnels (considering just the TBM length parallel to the Escape tunnel).

Rock mass	**Escape Tunnels**	**TBM tunnels**
Average Q values	15	37
Average $k_{s\text{-}tot}$	0.82	0.58*

*According to the first author's independent evaluation

The mean Q-values in the TBM tunnels are 2.5 times higher than those estimated in the Escape Tunnel (blasted). The results are in good agreement with Løset (1992) and later Barton (2000) as previously discussed. The total ranges of the $k_{s\text{-}tot}$ (0.36 - 4.5) and Q-values (0.001 – 1,000) are clearly different and therefore the Q-variations would be approximate. There are no previous published experiences making the attempt to evaluate $k_{s\text{-}tot}$ in drill and blast tunnels. However, previous experiences have shown that the deviations are analogous to the findings at the Follo Line Project.

Unforeseen groundwater inflow

Due to the hard rock conditions, consistently low average PR were achieved, mostly in the limited range of 1.9 to 2.1 m/hr for the four TBM. Furthermore, the TBMs experienced major interruptions of the usual “fast” learning curve, due to challenging hard-rock MFC towards the North, and specific water-related events towards the South. Figure 14 shows AR performance versus tunnel length for all four TBM, with a clear indication of the reasons for delays. There is a remarkable reduction in tunnel production in the case of TBM 2 close to the 1,000m mark.

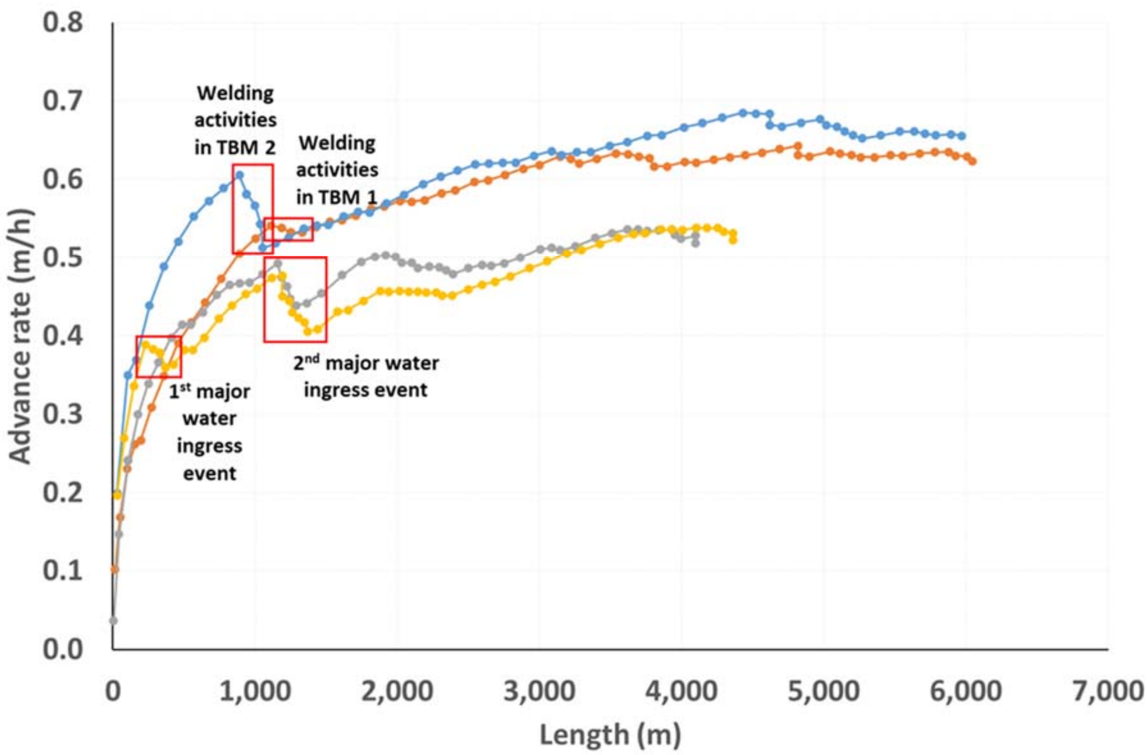


Figure 14 Reduction in tunnel production due to the challenging conditions meant that the four TBM had not managed (by 4 and 6 km) to reach the usual deceleration trend with tunnel length increase.

HARD ROCK TBM TUNNELLING

A process of great complexity is involved when tunnel boring due to the interaction between the rock mass and the machine. The prediction of performances (e.g., Penetration rate) and cutter life are not straightforward issues and involve major risk assessments. When hard-to-very hard rock (i.e. low-to-extremely low boreability) the complexity is accentuated becoming, in many cases, critical for the achievement of the final schedule and reasonable tunnelling cost.

Understanding of tunnel boring and wear processes thus enhances performance prediction and cutter life assessments in hard rock tunnel boring projects. Performance predictions and cost estimates are often decisive in the selection of excavation methods and have a major influence on the planning and risk management of TBM excavation projects.

Predictions of excavation costs for hard rock TBM projects involve the consideration of geological risk. The level of risk increases in importance as the degree of rock mass fracturing decreases. Figure 15 shows relative excavation costs as a function of rock mass fracturing. The reference excavation cost value is set as that corresponding to "medium rock boreability (k_{ekv} = 0.75) for a 7-metre diameter TBM with standard machine specifications in a tunnel exhibiting standard rock properties of medium intact rock boreability. Q-values have been roughly included.

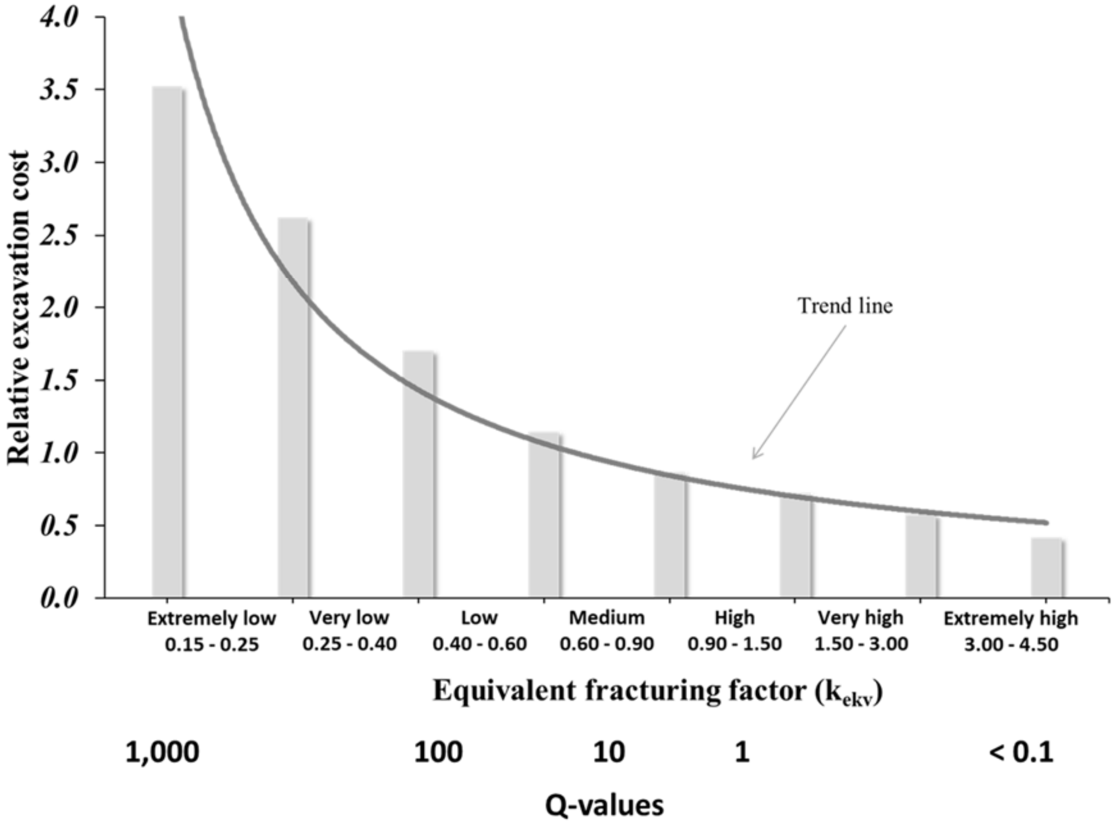


Figure 15 Relative excavation costs as a function of equivalent rock mass fracturing (k_{ekv}) and Q-values. The categories refer to rock boreability. Only tunnel excavation is considered.

The figure shows that low values of fracturing (e.g., k_{ekv} 0.15 - 0.60 or Q-values as high as 100-1,000) result in dramatic increases in excavation costs. However, at high degrees of fracturing (e.g., high k_{ekv} and low Q-values), changes in fracture class have relatively little effect on

excavation costs. Nevertheless, tunnel support costs may increase and there may be (ring-building) problems caused by overbreak. This end of the quality spectrum is tackled by low Q and low Q_{TBM} values and the possibility of reduced utilization, so potentially reduced AR.
The additional time and cost associated with special ground support and/or pre-grouting in highly fractured and faulted zones are not included in Figure 15.

Rock boreability

'Rock boreability' is a comprehensive parameter of rocks under excavation and expresses the result of the interaction between a given rock mass and the TBM. Rock boreability can be defined as the resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass composed of intact rock containing planes of weakness. Therefore, penetration rate and cutter wear are influenced by intact rock and the rock mass properties, so these are of great importance for performance predictions, cost evaluations and selection of excavation method.

Unanticipated situations and/or inappropriate assessments can result in considerable delays and great risk of cost overruns. Reliable predictions are therefore required for prediction of net penetration rate and tool wear, for time consumption and excavation costs, including risk and assessing risk linked to variation in rock mass boreability. Reliable predictions are also needed for establishing and managing contract price regulation. Several test methods are available to assess rock mass boreability (i.e., rock strength, rock surface hardness, rock brittleness, rock abrasivity, rock petrography, degree of fracturing, fracture/joint conditions, number of fracture/joint sets etc.).

The main rock parameters (intact rock and rock mass) that affect boreability assessments in hard rock conditions are listed below. A brief review of the state-of-the-art and discussion of relevant parameters is added at the end of these lists.

Intact rock boreability:

Several methods to assess the influence of intact rock properties are available. The main intact rock properties and commonly used test methods are listed in the following:

- Rock strength: Uniaxial Compressive Strength (UCS), Brazilian Tensile Strength (BTS), Point Load Test (PLT);
- Surface hardness: Sievers' J miniature drill test (SJ), Vickers hardness of the rock (VHR), Punch penetration test;
- Brittleness: Brittleness Value (S20), Toughness Coefficient (TC) based on the ratio of UCS : BTS, and Brittleness Index (BI) via punch penetration test as well as several approaches based on strain and stress-strain relations..
- Abrasivity: Index values based on *model testing setups*; for instance, Cerchar Abrasivity Test (CAI), LCPC test, Abrasion Value Cutter Steel test (AVS). Index values based on *intrinsic rock properties*; for instance, Schimazek Index, Rock Abrasivity Index (RAI), Abrasive mineral content (AMC), Vickers hardness number of rock (VHNR) or Equivalent Quartz Content (EQC)
- Rock Composition / Mineral Content: Rock petrography (Rock texture, mineral composition including measures for relevant minerals, for instance quartz content).

Rock mass boreability:

Relevant rock mass properties include quantitative description of planes of weakness or discontinuities in a given rock mass, number of joint or fracture sets and their orientation, spacing and condition as well as primary and secondary stress conditions and groundwater. Several rock mass descriptive and classification methods to describe rock mass properties to help evaluate rock mass boreability are needed.

- Type of discontinuities
- Spacing
- Orientation
- Number of fracture/joint sets
- Fracture/joint characteristics (aperture, filling, persistence…)
- Fabric anisotropy (e.g., schistosity)
- Classification methods (RQD, RMR, Q…)
- Stress conditions (depth and lateral conditions)
- Mixed face conditions MFC

Understanding rock mass boreability

An evaluation of the influence of the rock mass on the TBM tunnelling process is not always easy or straightforward. Nevertheless, it is important to get a comprehensive understanding of rock mass boreability. Figure 16 shows a schematic outlining different approaches to the understanding of rock mass boreability in connection with hard rock TBM tunnelling according to Macias (2016).

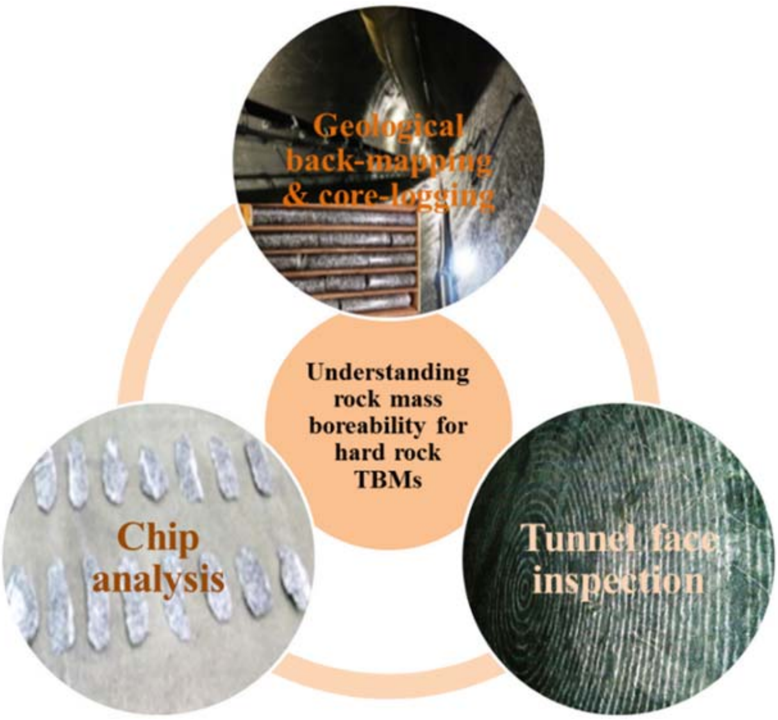


Figure 16 Schematic outlining different approaches to the understanding of rock mass boreability in connection with hard rock TBM tunnelling (Macias, 2016).

Tunnel face inspection enables the identification of fractures that influence the rock breaking process, and the voids formed following the breaking process as determined by the presence of fractures. Continuous (during each maintenance shift) tunnel face inspection is a part of the geological back-mapping methodology.
The presence of voids implies that a few cutters have lost contact with the face during tunnelling, transferring the load to other cutters. This will result in a dynamic effect during the breaking process and therefore in an increase of the penetration rate. Moreover, the relative orientations of the fractures in relation to the tunnel direction result in different void sizes.

Figure 17 is a photograph taken during a tunnel face inspection showing two fractures that have different levels of influence on the rock breaking process due to their respective orientations (Macias, 2016). The fracture on the left exhibits a relatively high angle with the tunnel orientation (a strike of 50° and a dip of 70°). This results in a relative angle (α) of 62° that in turn results in a larger void area and thus a greater influence on the penetration rate.
The fracture on the right of the photograph exhibits an angle of 10° with the tunnel orientation and a dip of 50°, resulting in a relative angle (α-parameter) of 9°. This fracture has only a minimal influence on the rock breaking process, and only small areas of voids are observed.

It is important to note the small veins shown in Figure 17 that do not influence the rock breaking process of the rock mass. These veins, together with other small fractures, may have been considered during the geological pre-investigation (of blasted cuttings) and/or back-mapping process, leading to overestimates of rock mass boreability and misleading performance predictions.

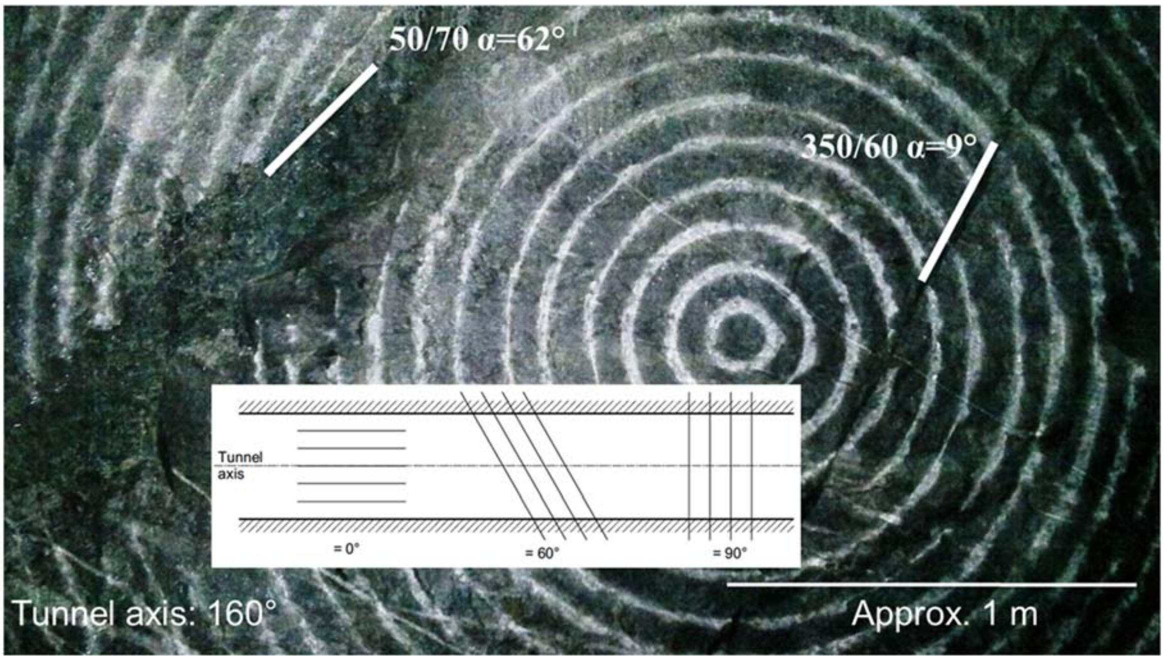


Figure 17 A photograph taken during a tunnel face inspection showing void areas generated after tunnelling in a fractured rock mass. The tunnel axis orientation is 160 degrees. (Modified from Macias, 2016).

In addition to tunnel face inspection, chip analysis provides information relevant to boring efficiency. It may also be a valuable tool that can contribute towards the understanding of the rock boreability of a given rock mass. Inspection of rock chips may enable us to identify and/or measure the variation in shear strength properties along a given plane of weakness and the possible influence of intact rock and the rock mass resistance as a whole. Figure 18 shows an analysis of crack propagation in a rock chip sample.

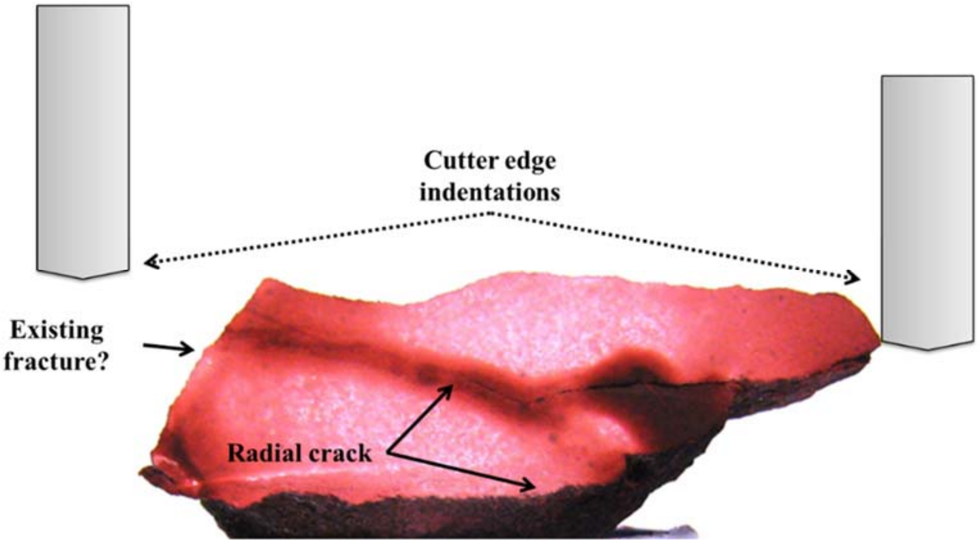


Figure 18 Crack analysis of a rock chip sample (Macias, 2016).

Figure 19 shows examples of rock mass conditions from TBM tunnel face and core drilling, related to approximated Q-values and D&B/TBM overall expected performances on the basis of the Q_{TBM} model.

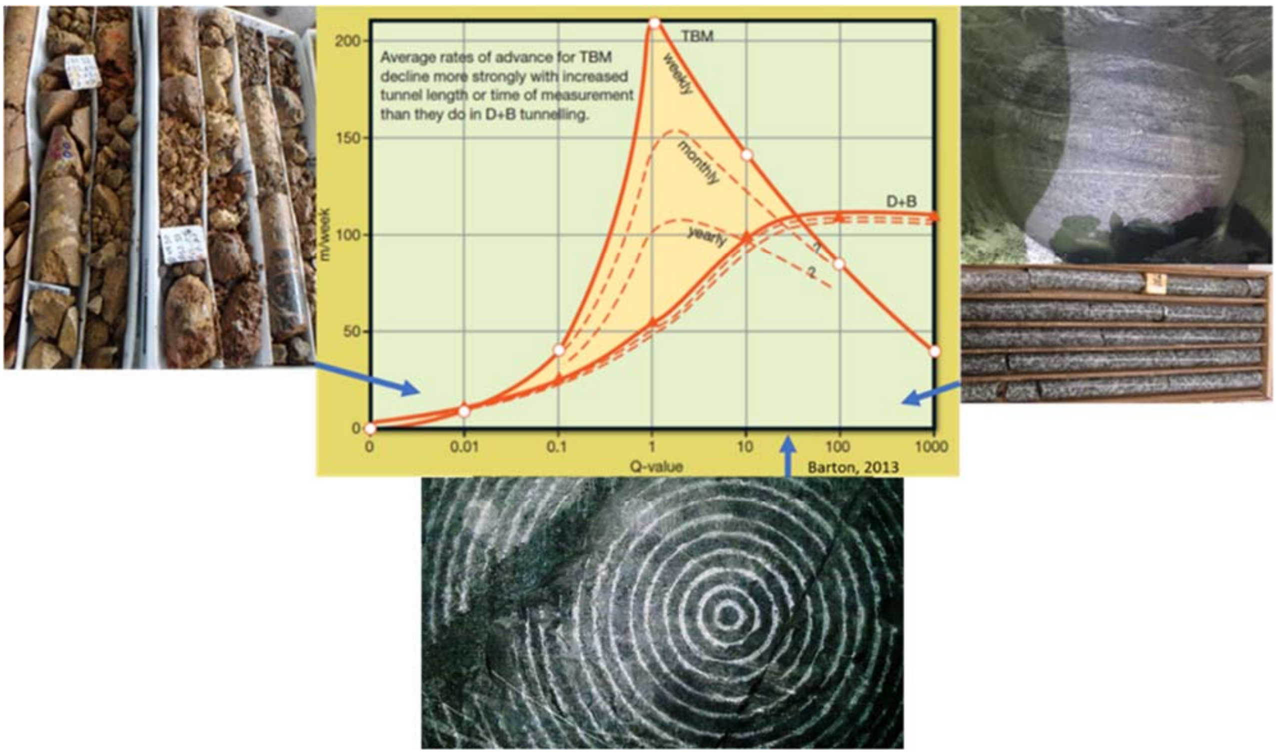


Figure 19 Illustration of rock mass conditions related to approximated Q-values and D&B/TBM overall expected performances on the basis of the Q_{TBM} model.

MIXED FACE CONDITIONS IN HARD ROCK

Mixed Face Conditions (MFC) in TBM tunnelling projects in hard and abrasive rock have a significant impact on performance, tool wear and, consequently, on construction time and excavation costs.

The general understanding of MFC is a situation, where two or more rock mass bodies with significantly different boreability are encountered at the same tunnel face. It is commonly assumed that all cutters on the cutterhead have to achieve the same penetration rate per one revolution whether cutting through hard or soft rock, or through massive or closely fractured rock masses. On the other hand, there may be no cutting work at all due to local overbreak at the tunnel face. In the case of the latter, overloading of cutters and high peak loads might occur. This does not stop a typical hard rock TBM with today's state of the art design, but might cause significant negative effects to TBM performance (i.e., slowing m/day), and cause wear and increased cutter consumption and excavation cost due to adverse effects on the critical number of cutters/m³ of excavated rock.

According to Macias et al. (2020), the definition of Mixed Face Conditions (MFC) in hard rock TBM tunnelling is the following: *"MFC in hard rock tunnelling occurs in case of the existence of two or more rock mass bodies with significantly different boreability parameters encountered at the tunnel face and occurs at the interaction of the cutterhead and rock mass while cutting the rock. MFC is a handicap for TBM tunnelling which affects the operational parameters, penetration rate and/or affects the cutter consumption and/or affects the TBM cutterhead or main body"*. However, the estimation models of cutter consumption such as in the NTNU model are generally developed for "usual" conditions where operational parameters (e.g., thrust level) result mainly in abrasive wear to the cutter rings.

Entacher (2013) carried out remote monitoring of individual cutter forces during tunnel boring and showed that with remote cutter monitoring it is possible to detect many different features that are of great importance for TBM operations. Figure 20 shows a generic sketch of cutting force distribution of just three of many cutters where the tunnel face consists of a hard and soft rock layer.

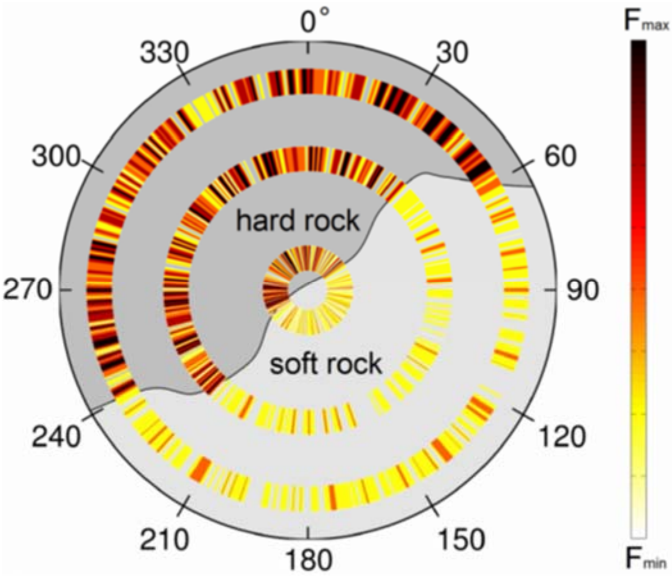


Figure 20 Generic sketch of cutting force distribution of three cutters where the tunnel face consists of a hard and soft rock layer (Entacher, 2013).

Boring in low rock boreability hard-to-very-hard rock masses is difficult and demanding for the cutter discs and bearings and for the machine structure. The applied cutter thrust will need to be high enough to achieve penetration when challenged by hard-to-very-hard rock masses. Figure 21 shows the disc utilization concept envisaged by Alber et al. (2018) caused by MFC.

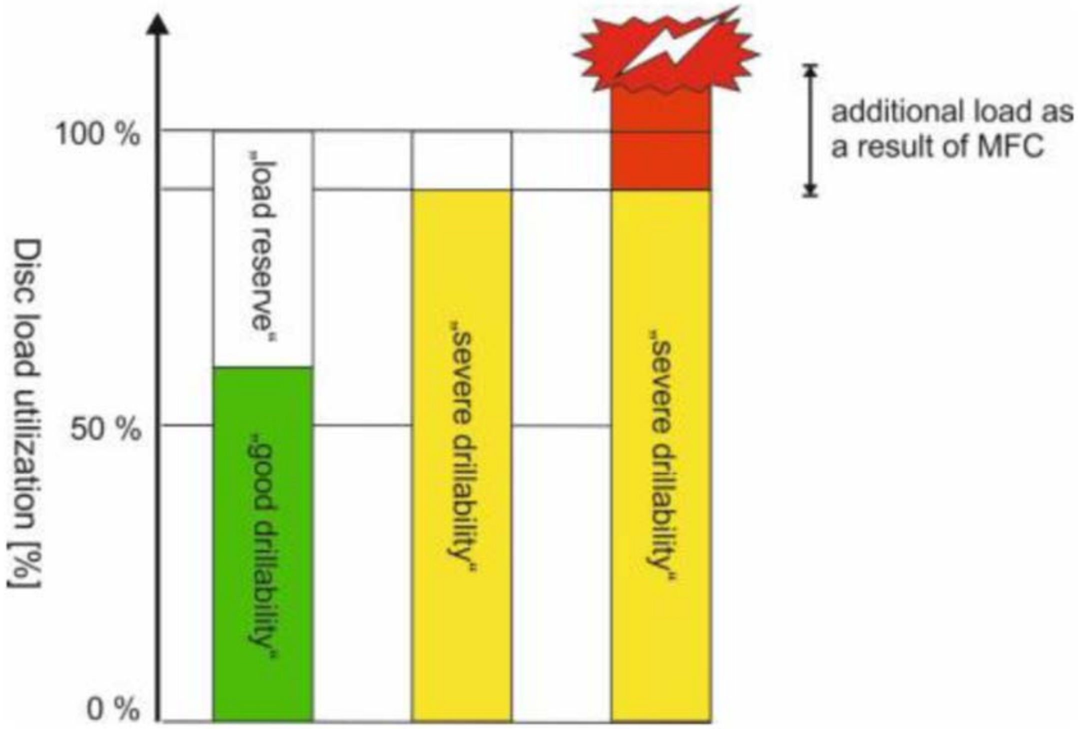


Figure 21 Concept of disc utilization where MFC may occur (Alber et al., 2018).

When boring through tunnel stretches with MFC in hard-to-very-hard rock masses, the cutter discs will experience high peak loads and hammering when rolling from a massive/non-fractured to a more fractured rock of different boreability caused for instance by a significant 1:2 jump of intact rock UCS (e.g., 100 MPa suddenly changing to 200 MPa).

In addition, when cutters are rolling in MFC due to a combination of-hard-to-very-hard massive rock mass adjacent to partial void areas caused by overbreak or weaker rock areas, the strength ratio will be virtually infinite and the impact on some of the cutters will be more severe.

Figure 22 shows averaged normal forces after three consecutive cutterhead revolutions compared with the corresponding geological mapping (Entacher, 2013). The geological mapping at the tunnel face shows areas with different degrees of fracturing and therefore different boreability. Within this area of cutter force analysis, Entacher (2013) found that for the outer cutter the maximum force was almost 10 times higher than its average loading compared with about 3.5 times higher than previously experienced in other areas. Peak forces seemed to be in the same range for all three cutters while average forces differed significantly (Entacher, 2013).

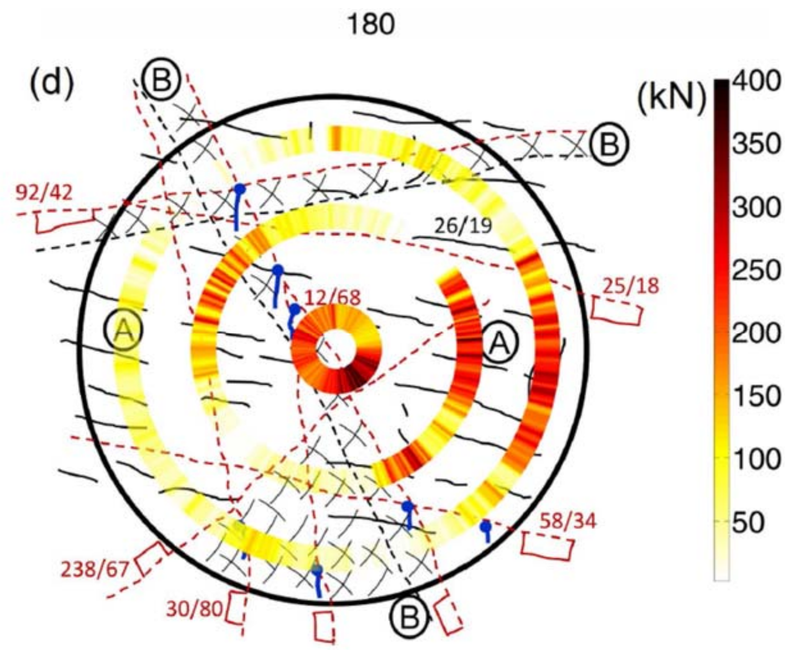


Figure 22 Averaged normal forces after three consecutive cutterhead revolutions compared with the corresponding geological mapping (Entacher, 2013).

The experiences and conclusions from the remote monitoring of individual cutter forces during tunnel boring carried out by Entacher (2013) provides convincing evidence of the severe cutter loading conditions (i.e., peak forces 10 times higher than average loading) when boring through a tunnel face with some significantly different degrees of fracturing and therefore substantially different boreability. Macias et al. (2020) include local over-breaks (e.g., rock face instability, blocky ground) at the tunnel face in the term MFC: representing an extreme situation if the rock is generally hard or very hard as the contrast from e.g., zero across voids to potential 400 kN (or higher) dynamic cutter loads is so extreme.

Illustrative examples of MFCs

The most dominant type of MFC identified at Follo Line was the combination of a massive/non-fractured gneiss (UCS = 111-162 MPa) and void areas in the face due the easily fractured (but actually higher UCS) amphibolite and other intrusives.

Their 'breaking-into-small-blocks' voiding mechanism caused a virtual UCS ≈ 0 MPa contrast to the hard tonalitic gneiss, and, according to the authors' findings and as an independent opinion this is likely to have caused serious consequences for the cutters, as indeed observed.

In the following, several examples from face mapping and camera logging are presented to illustrate the encountered MFC during boring in hard-to-very-hard rock masses. The examples give evidence of the encountered MFC with non-continuous cutter tracks and overbreak combined with massive rock (e.g., gneiss). Figure 23 shows an example of interspersed Amphibolite dykes in massive Gneiss encountered during face mapping.

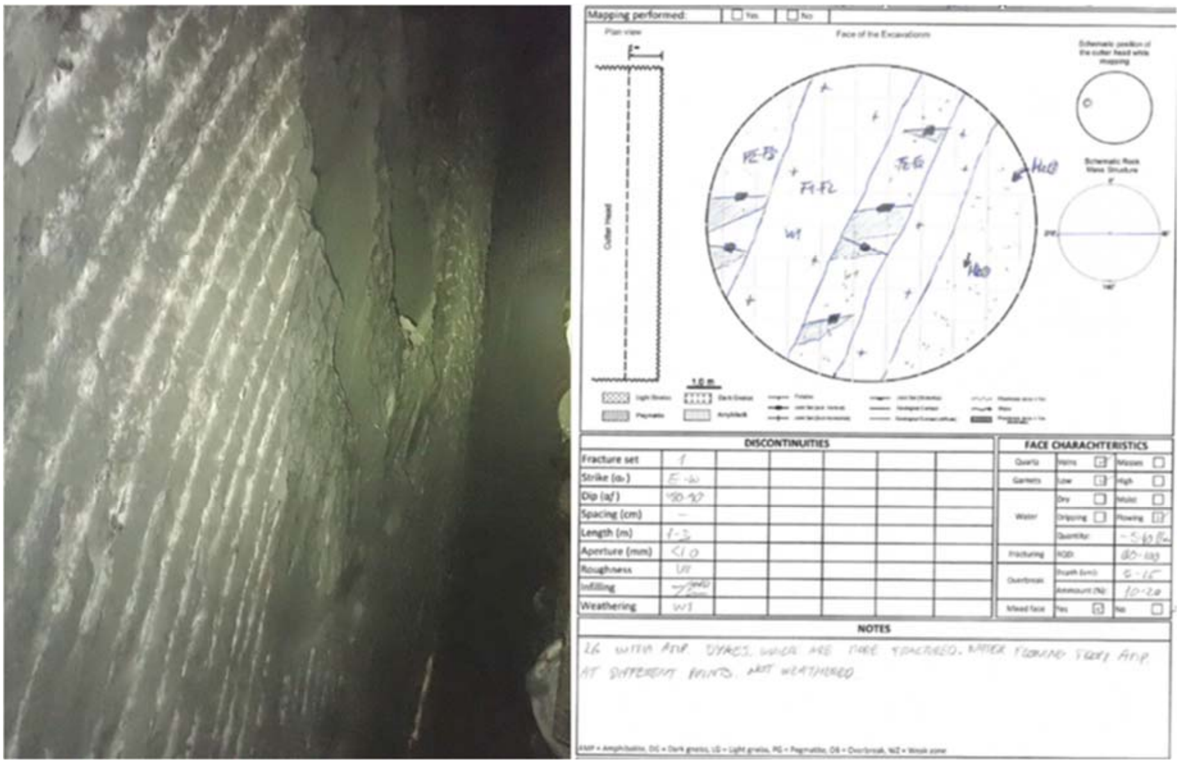


Figure 23 Example of interspersed Amphibolite dykes in massive Gneiss encountered during face mapping. Non-continuous cutter tracks (overbreak) due to Amphibolite dykes are seen.

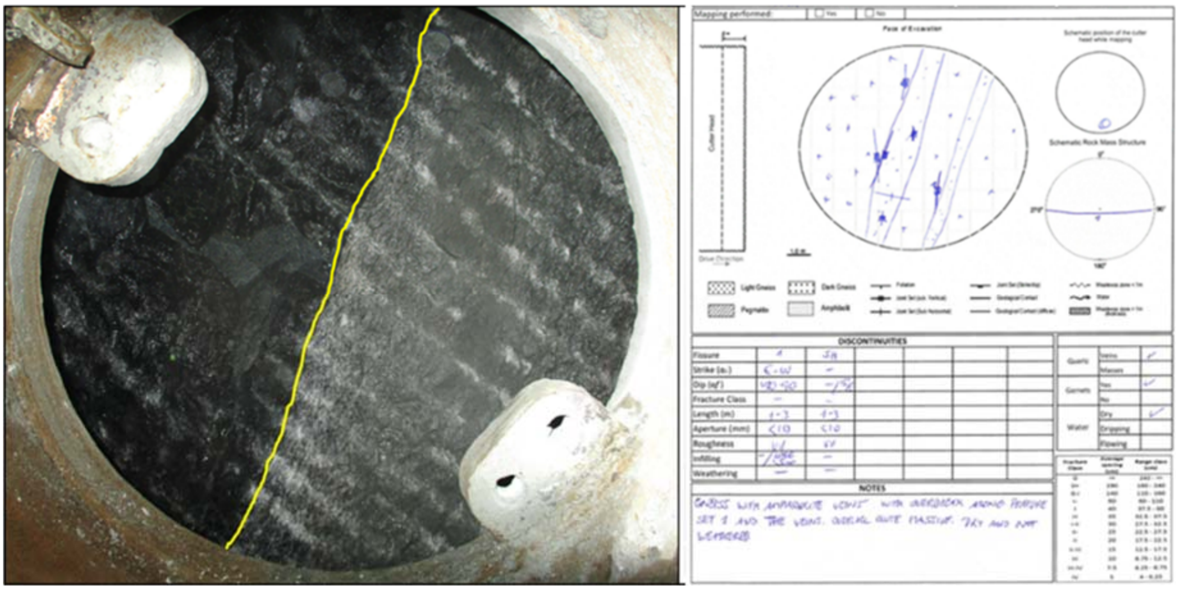


Figure 24 Example of gneiss with amphibolite veins with multiple overbreaks encountered during face mapping. Non-continuous cutter tracks (overbreak) are seen in the locations of the Amphibolite dykes.

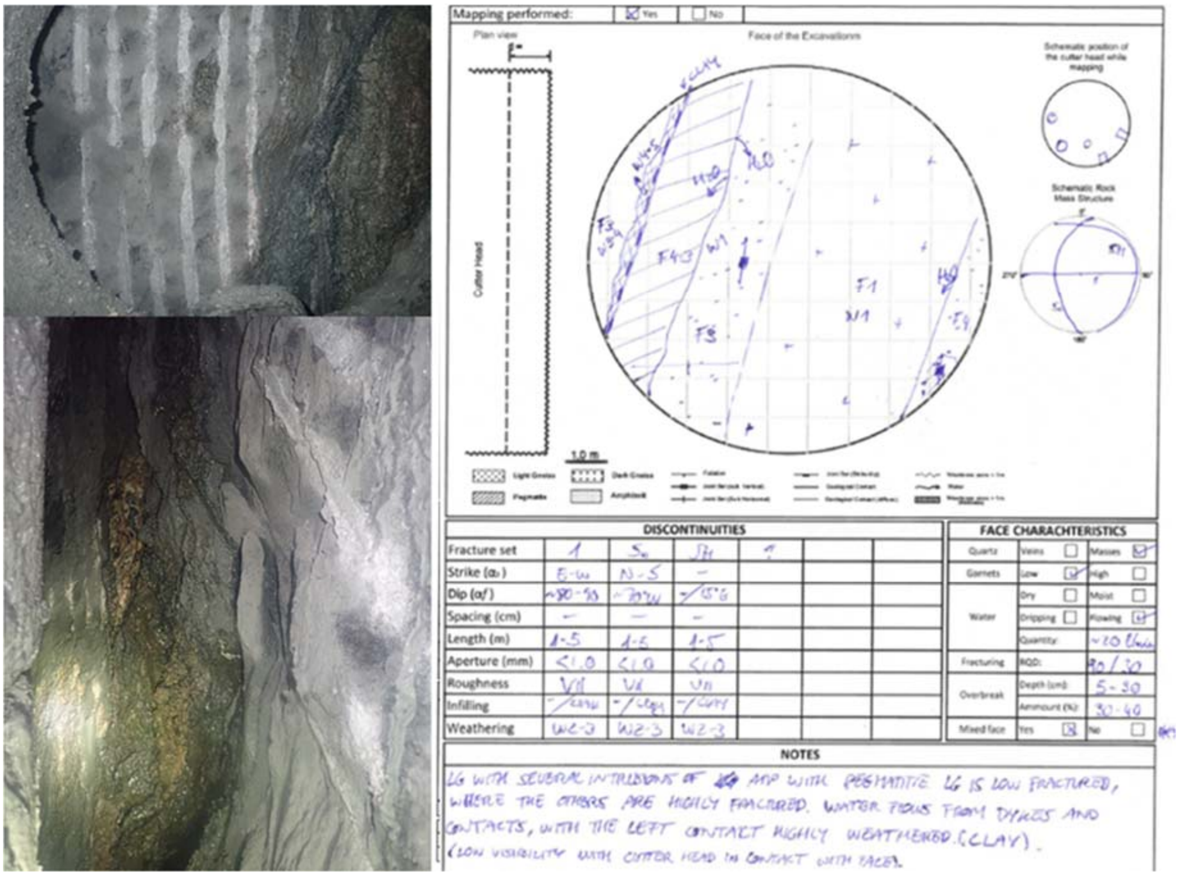


Figure 25 Example of interspersed highly fractured Amphibolite/Pegmatite dykes in sparsely fractured Gneiss encountered during face mapping. Non-continuous cutter tracks (overbreak) across the Amphibolite/Pegmatite dyke are seen.

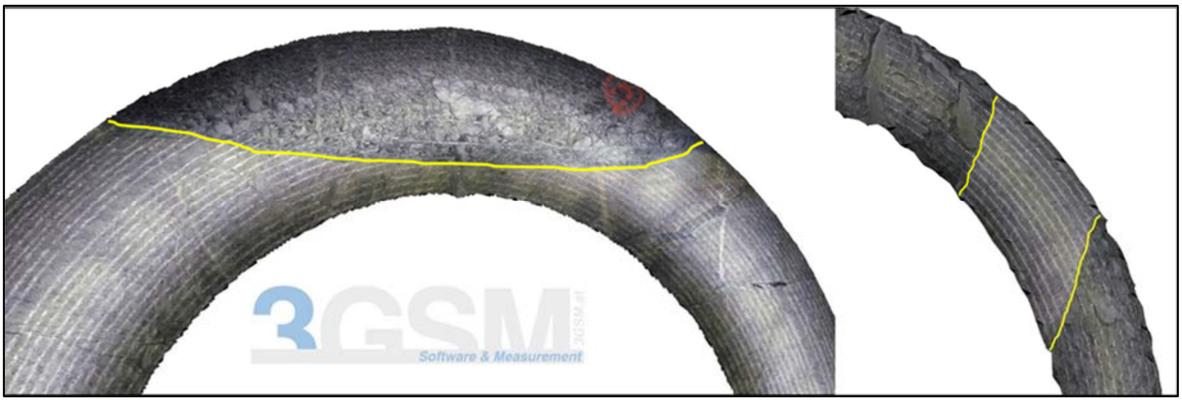
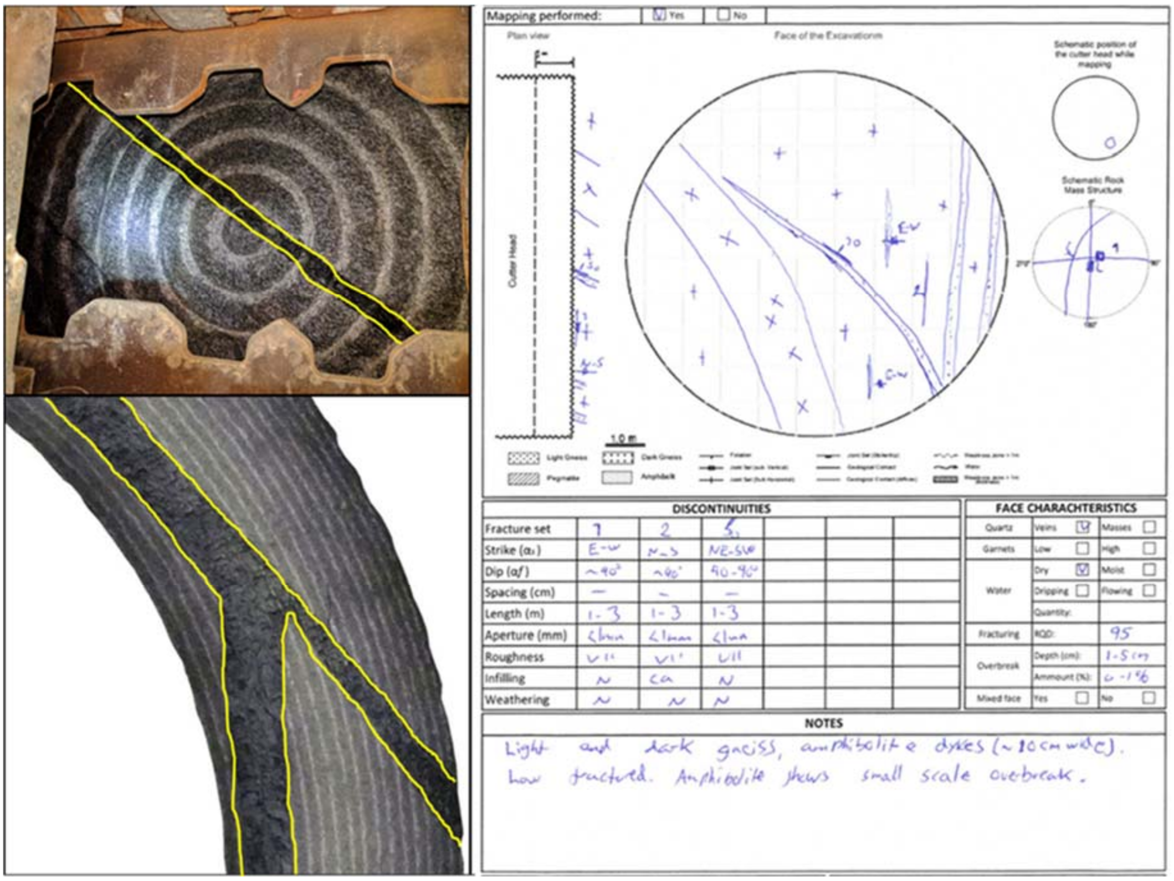


Figure 26 Example of 3D camera logging (by 3GSM) for identification and evaluation of MFC. Such camera logging allows a detailed evaluation of the continuity of the cutter disc tracks and therefore of the different boreability in the same tunnel face during tunnel boring.

Figure 27 Example of light coloured gneiss, and dark amphibolite dykes with small scale overbreak encountered during face mapping. Non-continuous cutter tracks occur across the Amphibolite dykes due to the overbreak.



The Amphibolite showed an unexpectedly different boreability with a “breaking mechanism” resulting in larger than expected cubic shaped ‘chips’ when occurring adjacent to the more frequent massive Gneiss during rock breaking by the TBM cutter discs. Figure 28 illustrates the characteristic differences in chip type and size.

Figure 28 Example of chips of Gneiss (left) and Amphibolite from the same chipping analysis (i.e., from the same tunnel face). (Photo: Javier Macias).

The unforeseen “breaking mechanism” of the Amphibolite during tunnel boring, resulted in an uneven tunnel face with a combination of overbreaks causing loss of continuity of the cutter tracks so clearly seen in the massive Gneiss. The result is tunnel boring conditions with a combination of a massive/sparsely fractured rock and large void/overbreaks when ‘in’ the Amphibolite (actually mostly non-contact/UCS = 0 MPa). This behaviour at the tunnel face will principally result in high peak loads on the cutters combined with high vibrations.

The above examples of encountered MFC are demonstrated by non-continuous cutter tracks due to overbreak and occur when there is a predominance of massive rock (e.g., gneiss). Macias et al. (2020) recently introduced a new methodology to identify and categorize MFC in hard rock TBM tunnelling based on general geological and geotechnical investigations, considering the main aspects creating MFC. These are: significant difference in rock strength, significant difference in rock mass fracturing and occurrence of blockiness at the tunnel face. An MFC rating system was developed which is adjusted according to the TBM diameter. The larger the MFC rating, the more probable will be the occurrence of MFC and its serious consequences.

Figure 29 shows examples of identification of potential MFC (local over-breaks: rock face instability, blocky ground at tunnel face.

Figure 29 Examples of identification of potential MFC left photo: core drilling indicating contact between sandstone (UCS ~ 100 MPa; low degree of fracturing) and lutite (UCS ~ 15 MPa; highly fractured), right photo: field mapping indicating potential MFC due to blockiness (Macias et al. 2020).

Cutter damage in MFCs

The reasons for urgent cutter change following damage are listed below and illustrated in Figure 30 and Figure 31.

- **'Abrasive/Normal wear (W/N)'** – cutter replaced due to maximum cutter ring wear;
- **'Blocked (B)'** – cutter replaced due to blocked bearing;
- **'Chipping (C)'** – cutter replaced due to chipping in the cutter ring;
- **'Mushrooming (M)'** – cutter replaced due to excessive mushrooming in the cutter ring;
- **'Oil leakage (OL)'** – cutter replaced due to oil leakage in the bearing;
- **'Ring crack (Cr)'** – cutter replaced due to crack(s) in the cutter ring;
- **'Others (X)'** – cutter replaced for reasons other than the above.

Figure 30 Illustration of the reasons for replacement of cutter rings a) Abrasive wear, b) Mushrooming, c) Chipping and d) Ring crack.

Figure 31 Illustration of the reasons for replacement of cutter bearings a) Oil leakage, b) Oil leakage with indication of blockage, c) Blocked cutter and d) Other reasons (including cracking).

Figure 32 shows cutter life data (m^3/c) and wear patterns taken from several tunnel sections (hard rock TBM tunnelling) exhibiting a variety of rock mass conditions. Several different boring conditions, from non-fractured hard rock to fractured rock and rock type contacts (i.e. transitions) are illustrated. The rock type transition produces large instantaneous loads on the cutters resulting in a high rate of cutter replacement due to bearing set problems such as blockage.

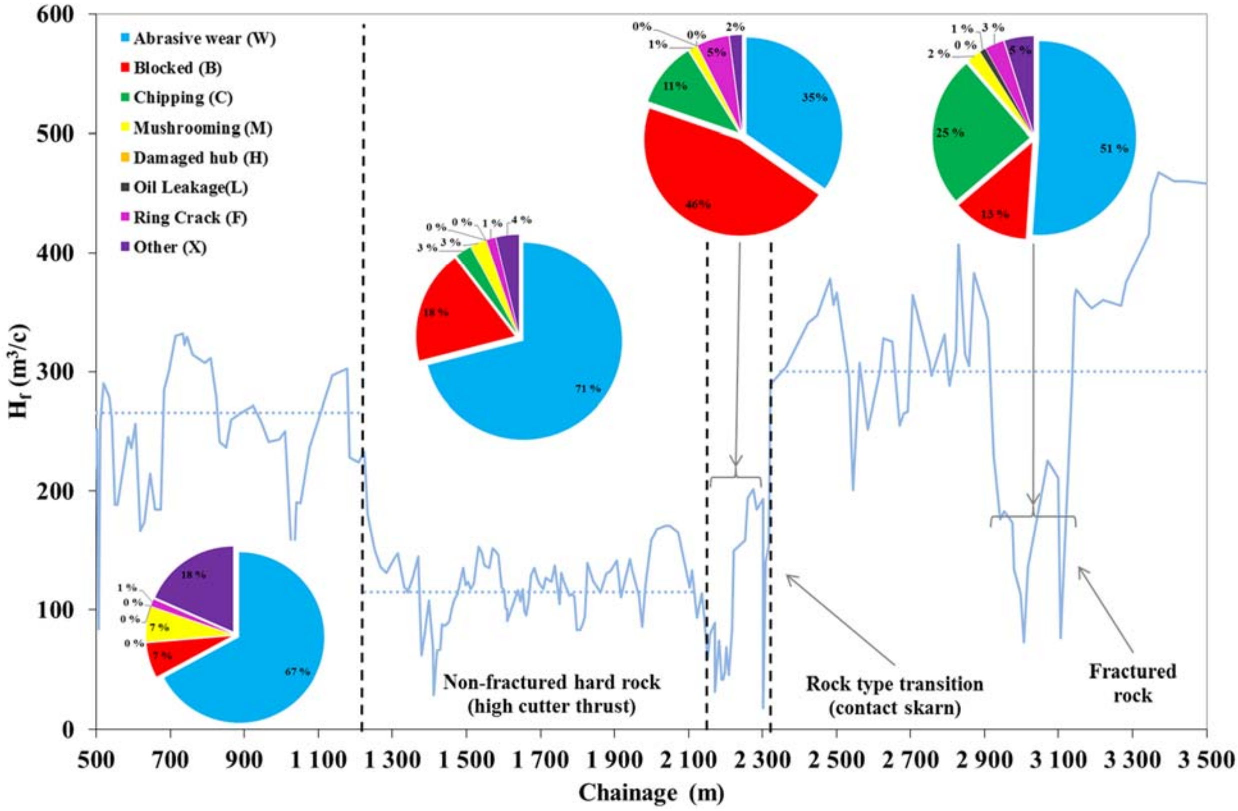


Figure 32 Cutter life data and wear patterns from several tunnel sections (Macias, 2016).

A higher amount of chipping is often related to hard fractured rock while blocked cutters often occur in rock type transition with different rock boreability (i.e., MFC) and in sections of non-fractured rock mass where high cutter thrust is demanded.

CONCLUSIONS

The NTNU and Q_{TBM} models have been applied to the Follo Line project. Both of them at design stage and in addition, the NTNU model as a basis for the contractual risk sharing and compensation system.

From the experience gained by the authors in international hard rock TBM projects in which they are directly involved, including the Follo Line project, the following main conclusions are emphasised:

1. TBM performance can be accurately estimated when using the estimation models. There should however be extensive knowledge regarding the functional structure of the models, to ensure that their strengths and limitations are well understood by the users.

2. When characterizing rock boreability (e.g. at project planning stage) it is important to always bear in mind that during the site investigations one must rely on interpretation and extrapolation of information from selected and available spots along the tunnel route. The site investigations for TBM projects, especially in hard rock, should put more emphasis on the (lack of) rock mass fracturing outside highly fractured and/or fault zones and also evaluate what might be the most challenging tunnel boring conditions (i.e., low penetration rate, high cutter consumption) if this is the relevant case.

3. The potential impact of hard-rock mixed-face (MFC) which may not be included in the models, or only indirectly, should be additionally considered. MFC in TBM tunnelling projects in hard and abrasive rock have a significant impact on performance, tool wear and, consequently, on construction time and excavation costs. That means MFC affect the tunnelling in a negative way and therefore it is important to make an assessment of the potential occurrence of MFC along the tunnel.

4. Expectations of pre-grouting quantities together with the risk to be affected by "unforeseen" events should be evaluated and included in the excavation time prognosis (e.g., currently NTNU model does not include those).

5. Findings from blasted and or exposed rock areas (e.g., D&B tunnels, surface cuttings) must be considered with caution when extrapolating and using the values for rock boreability evaluations.

6. Consideration of the same advice sometimes given for Q and RMR: 'do both' when characterizing rock masses, suggests the use of several prediction models. Then the potential shortcomings are covered, and the strong points reinforced, such that reliability is improved overall.

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