

TBM prognosis for open-gripper and double-shield machines tunnelling through hard jointed rock with weakness zones

Dr. Nick Barton, NB&A, Oslo, Norway, nickrbarton@hotmail.com

Abstract

A wide-reaching review of TBM tunneling with open-gripper TBM, forms the basis of a prognosis method called Q_{TBM} . Double-shield TBM case records were not used in this initial development as description of the geology and jointed ground is difficult and therefore rather poor. The method of prognosis, using a simple input and calculation model Q_{TBM} has been used on many projects since its development in 2000. The TBM performance data-base numbers some 145 cases representing about 1000 km of TBM tunneling. Since the development of this method, the case record data base has been increased to include double-shield TBM, specifically driving in hard igneous rocks, and of similar abrasiveness to the case to be described in this paper. Open-gripper or double-shield TBM may be used to form a future high-speed rail link from Oslo to Ski in the south, involving 9.6 km and 7.9 km long tunnels. The predicted times for individually driving the two tunnels, using the two TBM options, ranged from about 13 to 41 months.

The shorter tunnel in the south is quite shallow. Data collection to represent likely rock mass conditions, for input to the Q_{TBM} prognoses, was based on Q-histogram classification of more than 300 rock cuttings, during a three weeks field logging campaign. Core logging of the lowest quality sections of seven inclined drillholes, for correlation with local seismic refraction profiling, was utilized as input, when modelling weakness zones. P-wave velocities of 2.2, 2.7 and 3.4 km/s were found to be the mean values for three major groups of weakness zones. Penetration rates and advance rates were estimated for five rock mass classes, with Q-values ranging from 1 to about 200, and for the three weakness zone classes, with a range of widths approximating 18 to 20 m. The most frequent rock type logged was granitic tonalitic gneiss, with lesser frequencies of quartz- and feldspar-rich gneiss, granitic gneiss, and amphibolites. Mostly UCS was equal to or greater than 200 MPa, and the adverse cutter life index CLI values were typically from 5 to 10. Cutter forces modelled were generally from 22 to 32 tnf, but lower in the weakness zones.

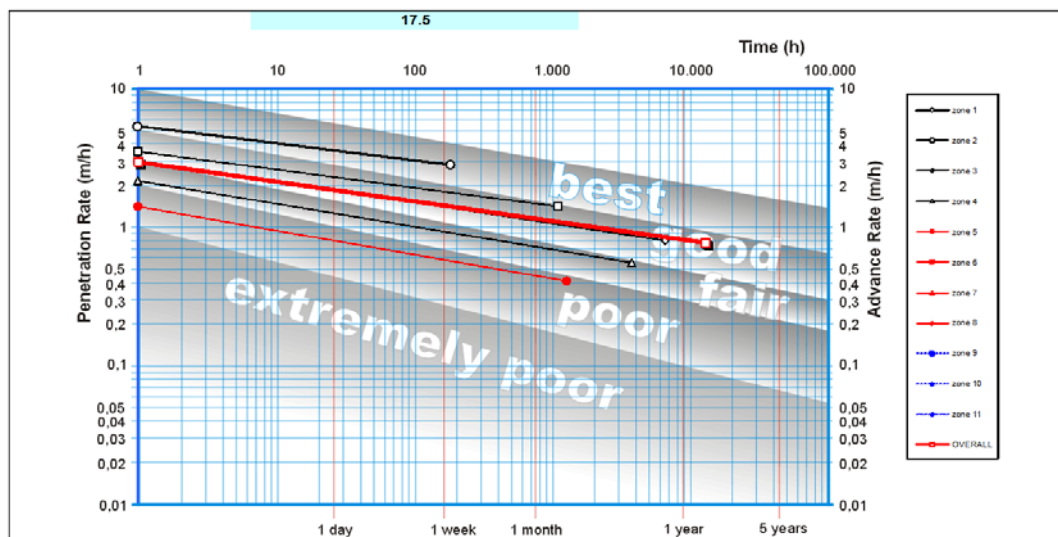


Fig.1 Example of the Q_{TBM} prognosis for the 9.6 km North Tunnel (18 months), assuming double-shield excavation, hence the lesser gradients than for open-gripper TBM (see 'open-gripper' adjectives in figure back-ground). Altogether, some 300 rock cuttings were Q-logged to obtain necessary rock mass quality data for the two tunnels. This was combined with the rock-machine data.

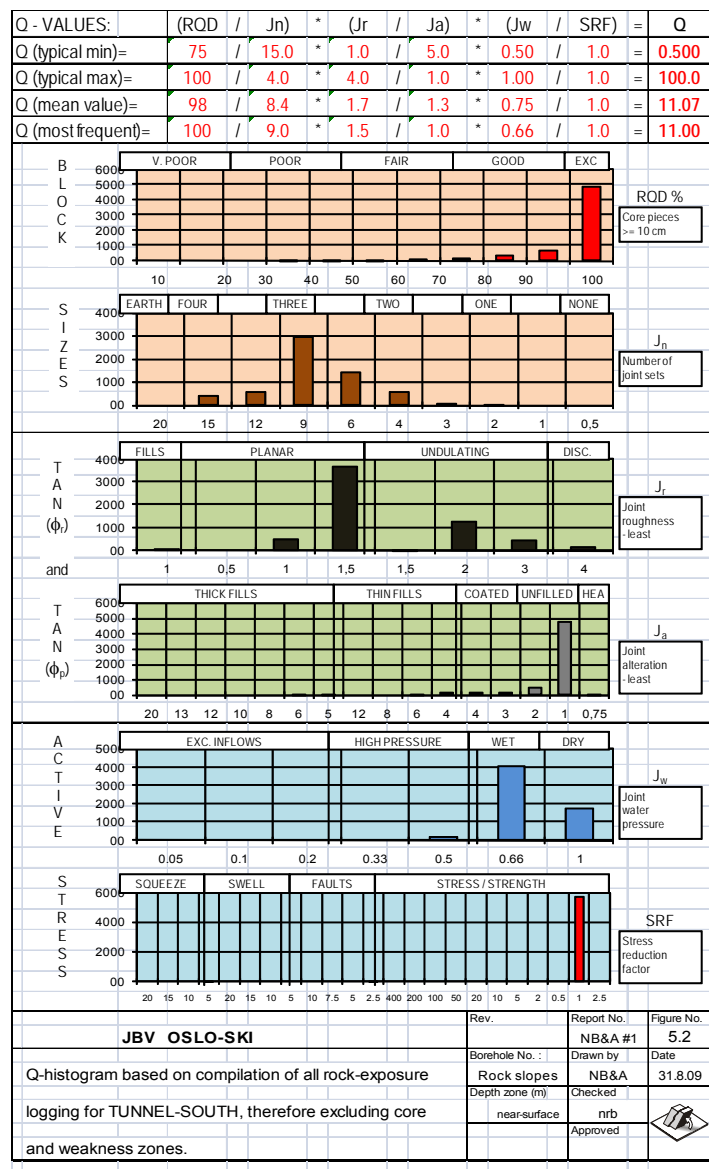


Fig. 2 Q-histogram logging of the five best qualities of rock mass, mostly tonalitic gneiss. The two best rock classes were unfavourable for TBM due to too good rock mass quality (sparse jointing), too high UCS, too low CLI (cutter life index), and too high quartz content.

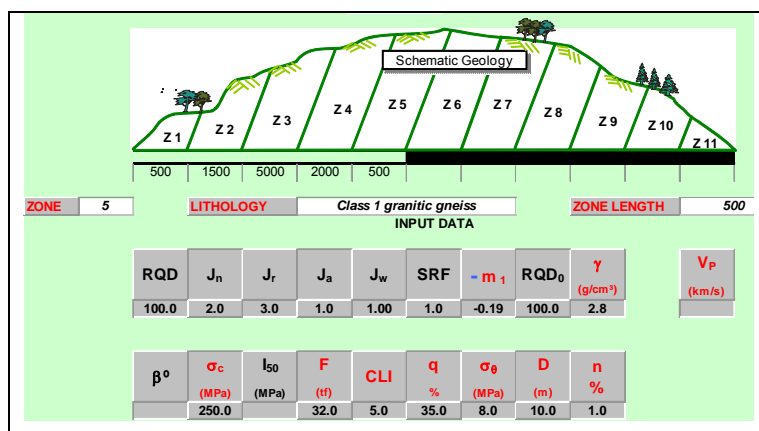


Fig. 3 An example of the input data screen for 500m of the best quality rock mass, which is unfavourable for TBM progress (specifically PR) due to too few joints and too high UCS.

TBM prognosis for open-gripper and double-shield machines tunnelling through hard jointed rock with weakness zones

Dr. Nick Barton, NB&A, Oslo, Norway, nickrbarton@hotmail.com

Summary

A wide-reaching review of TBM tunneling with open-gripper TBM, forms the basis of a prognosis method called Q_{TBM} . Double-shield TBM case records were not used in this initial development as description of the geology and jointed ground is difficult and therefore rather poor. The method of prognosis, using a simple input and calculation model Q_{TBM} has been used on many projects since its development in 2000. The TBM performance data-base numbers some 145 cases representing about 1000 km of TBM tunneling. Since the development of this method, the case record data-base has been increased to include double-shield TBM, specifically driving in hard igneous rocks, and of similar abrasiveness to one of the case to be described in this paper. Open-gripper or double-shield TBM may be used to form a future high-speed rail link from Oslo to Ski in the south, involving 9.6 km and 7.9 km long tunnels. Due to a limited depth of weathering, and relatively shallow tunnels, data collection for input to the Q_{TBM} prognoses, was based on Q-histogram classification of more than 300 rock cuttings, during a three weeks field logging campaign. Weakness zones were modelled using P-wave velocities. Penetration rates and advance rates were estimated for five rock mass classes, (Q1 to Q5), with Q-values ranging from 1 to about 200, and for the three weakness zone classes, with a range of widths approximating 18 to 20 m. The most frequent rock type logged was granitic tonalitic gneiss. Mostly UCS was equal to or greater than 200 MPa. PR and AR and predicted time for construction for the two pairs of tunnels by the two TBM methods were compared, with time required estimated to be from 13 to 41 months.

Keywords: TBM prognosis, open-gripper, double-shield, rail tunnels, Q-logging, rock strength, abrasiveness, penetration rate, advance rate, Q_{TBM} modelling

1. Introduction

The Norwegian rail authority Jernbaneverket are the owners who commissioned this independent study. The planned tunnels in hard igneous rock with weakness zones, were to be tackled either by open-gripper or double-shield TBM. They will form a high-speed Norwegian rail link from Oslo down to Ski in the south. They may be driven either by drill-and-blast from several fronts, or using TBM for the 9.6 km and 7.9 km tunnels. In this study, twin 10 m diameter TBM were assumed. Water ingress must be limited in various localities due to settlement risks.

If TBM excavation is chosen, the two tunnels will be driving north and south from a single adit tunnel, using a common TBM assembly chamber. The tunnels may be driven by twin TBM of about 10 m diameter, as modelled, or by single larger diameter TBM, or by drill-and blast, with its more immediate water-inflow control using systematic pre-injection. Since the Q-logged rock cuttings (e.g. for local roads and a motorway) were up to 15 m height, with depth of weathering mostly limited in the good quality gneisses, it was possible to obtain a valuable source of rock quality data. These data were utilized in TBM prognoses of the mostly 40 to 120 m deep tunnels through the *better classes* of rock mass. In the case of TBM tunnelling, the highest quality rockmass may cause slower progress, and more frequent cutter changes.

The most frequent rock type logged was granitic tonalitic gneiss, with lesser frequencies of quartz- and feldspar-rich gneiss, granitic gneiss, and amphibolites. Mostly UCS was equal to or greater than 200 MPa, and the adverse cutter life index CLI values were typically from 5 to 10. For the TBM prognosis modelling, the statistical range of characteristics of all these rock types were effec-

tively represented in the chosen five Q-classes (Q1 to Q5), ranging from $Q > 100$, to $Q = 1$. PR and AR and predicted time for construction for the two pairs of tunnels by the two TBM methods were compared.

2. Rock mass classification of rock cuttings

Almost forty areas with multiple rock exposures were selected, obviously as far as possible near the planned line of the two tunnels. The rock exposures were mostly along rock cuttings for roads, also along cuttings for large buildings, and were selected at various locations along a conveniently oriented motorway. In each of the areas, about nine rock cuttings were Q-histogram logged. Several thousand opinions of conditions for each Q-parameter were thereby collected. Two examples of the rock cuttings are shown in Figure 1a and 1b. The distribution of logging locations and mean Q-values are indicated in Figure 2. An example of the actual distribution of most of the logging locations for the case of the planned 7.9 km long South Tunnel, and more details of the Q-statistics for each area with multiple rock cuttings, are shown in Figure 3.



Fig. 1a and 1b Left: An example of some of the best quality rock along a nearby motorway. Due to its massive nature this would be slower to bore, and is an example of Class 1 rock mass. Right: An example of some of the more jointed rock that would be easier to bore, with reduced cutter change.

Altogether, five rock mass classes and three weakness zone classes were modelled, the latter based on the core logging data and refraction seismic measurements. Table 1 shows the estimated extent and typical depth of the different rock classes. The large amount of 'good quality' rock suggests limited actual tunnel support needs, but progress by TBM will not be fast, and cutter change will likely be frequent, such as 3 m tunnel advance per one-cutter changed. If a double-shield solution is chosen, the tunnel is of course likely to be continuously PC-element lined, although in consistently good quality rock this is actually unnecessary, and indeed has been dispensed with in long stretches in a case known to the writer, with PC elements only in bad zones.

Table 1 Approximate distribution of rock classes in the North and South tunnels. (Representative mean depths are shown in parentheses). Poorer rock classes Q6, Q7 and Q8 were evaluated by means of V_P from refraction seismic profiles in known weakness zones. They were not exposed.

TUNNEL	Q1 Q > 100	Q2 Q 40 - 100	Q3 Q 10 - 40	Q4 Q 10 - 4	Q5 Q 4 - 1
North L \approx 9.6km	500 (160)	2000 (120)	5000 (100)	1500 (80)	500 (70)
South L \approx 7.9 km	200 (130)	1000 (110)	2500 (80)	1750 1750 (60) (30)	500 (30)

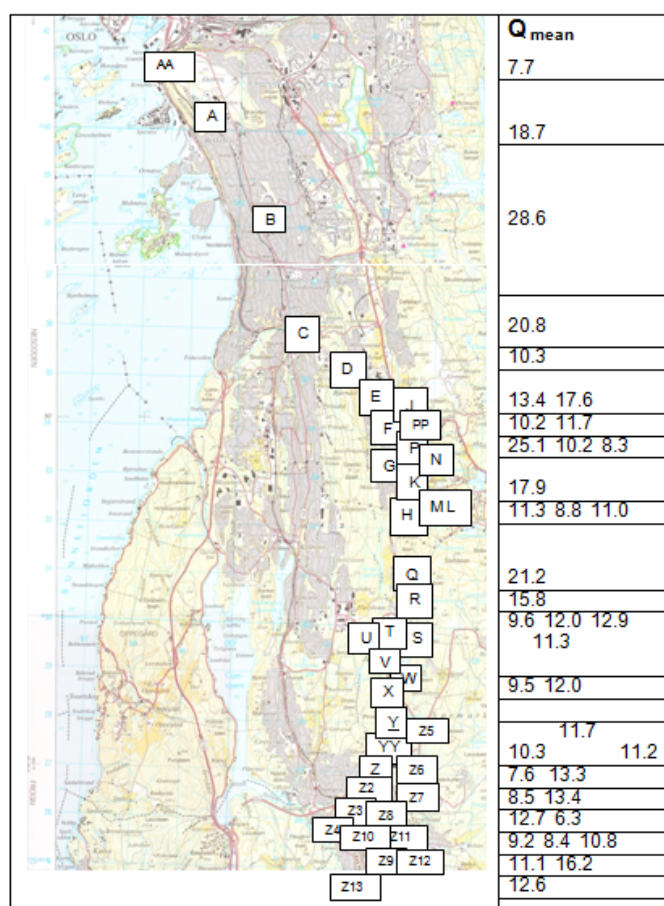


Fig. 2 The 38 areas where Q-histogram logging was performed on mostly nine rock exposures per area. Overall mean Q-values are shown by location, covering some 20 km north to south. Oslo is just beyond the top of the map. Low-quality zones were characterized by seismic V_P and by core.

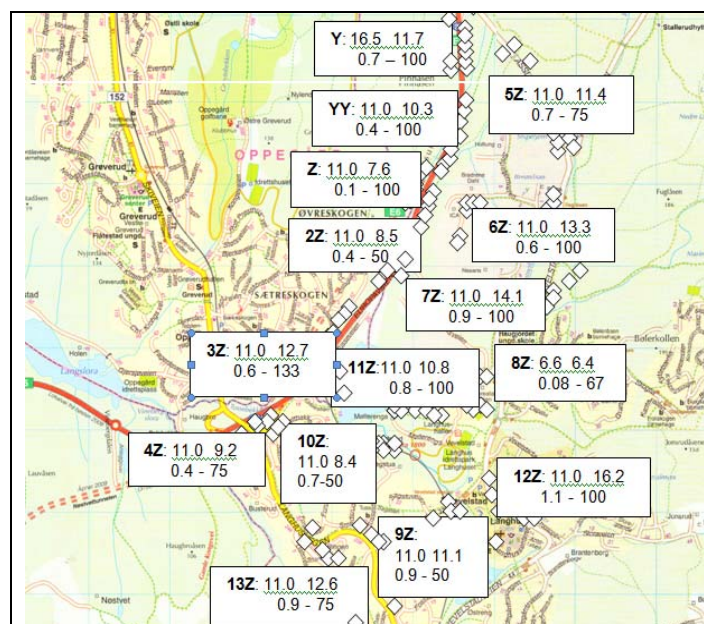


Fig.3 Some of the southern tunnel logging locations (see diamonds). Boxes show mean values for each area logged, each in multiple (8 or 9) locations, with numbers listed in the following order: Q most frequent, Q weighted mean, and Q typical range (not absolute minimum or absolute maximum).

The results of Q-histogram logging of all the exposures used to estimate the rock mass quality for Tunnel South of planned 7.9 km length is shown in Figure 4a. For comparison, the result of focused logging of weakness zones sampled in seven inclined boreholes is shown in Figure 4b. As mentioned earlier, the results of several kilometers of seismic refraction profiles was the eventual source of Q_{TBM} modeling of three classes of weakness zones, having successively reducing mean velocities. The focused core-logging of low-quality-zones from seven inclined boreholes was a form of 'quality control' of some of the lowest velocity parts of selected seismic profiles.

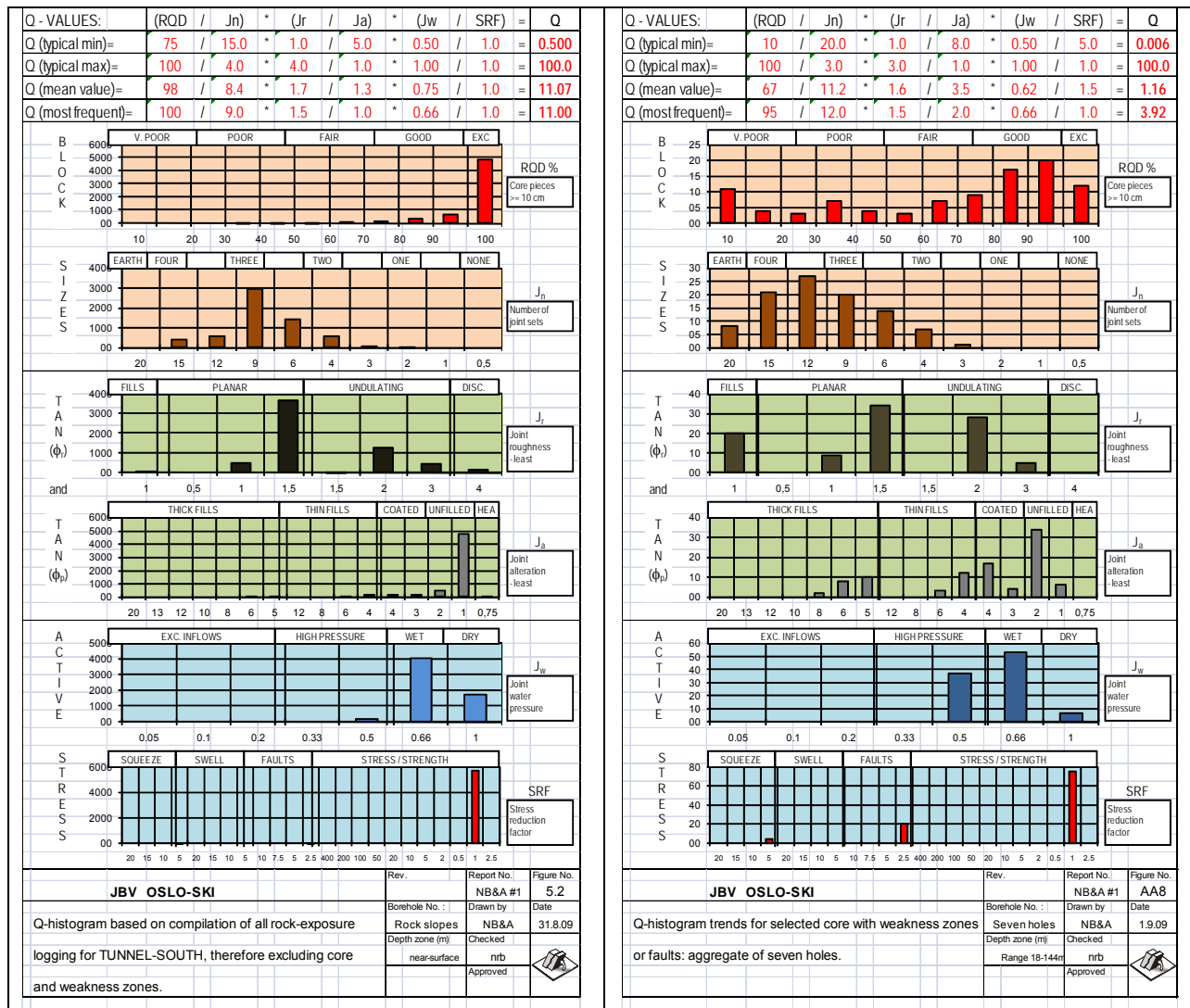


Fig. 4 Q-histogram logging of the Tunnel South rock cuttings (left), and comparison with focused Q-histogram logging of specific weakness zones exposed in seven cored holes.

3. Logging of weakness zones

In addition to the logging of the numerous surface exposures, drill-core logging performed by Jerbaneverket, and two campaigns of seismic refraction measurements performed by GeoPhysix were also utilised. Both the latter were focussed on the reduced rock mass quality experienced when crossing assumed weakness zones and known faults, causing low areas in the terrain. In the Jernbaneverket core-logging, it was found that the most noticeable weakness zones had significant alteration and strength reduction of the rock, but parts had quartz cementation of the crushed zones. There were also traces of faulting and slickensides. Typical Q-values for the weakness zones themselves were *generally* in the range 0.02 to 0.25 [1]. Some of the weakness zones had

several decimeters of clay, and *focussed* Q-logging by the writer suggested that several may have $Q < 0.01$. An example of part of a weakness zone is shown in Figure 5.



Fig. 5 Part of a weakness zone as recovered in an inclined borehole. There is a decimeters zone of soft clay in the next core box as well (see easily-penetrating blue pencil).

The P-wave velocities of the weakness zones appeared to be grouped in three main velocity ranges: 2000-2300m/s (6 cases, mean 18 m wide), 2500-2900m/s (9 cases, mean 18 m wide) and 3200-3500m/s (4 cases, mean 20 m wide), so there was no apparent differentiation concerning width and velocity in general. The three following groups of velocities were therefore simulated in the Q_{TBM} prognosis model as a starting point: 2170, 2730 and 3355 m/s, to approximately represent the above ranges. A Q_{TBM} input data option for *shallow* tunnels, is to directly apply the P-wave velocity in place of the Q-parameters. Recorded V_P velocities are automatically converted to Q-values if desired, using the empirical relations [2]: They can be 'over-ridden' by Q if desired.

$$V_P \approx \log Q_c + 3.5 \text{ (km/s)} \quad (1)$$

(where $Q_c = Q \times UCS/100$ with UCS in units of MPa)

$$Q \approx 100/UCS \times 10^{(V_P - 3.5)} \quad (2)$$

(When $V_P=3.5$ km/s, $UCS \approx 100$ MPa, $Q_c = Q \approx 1$. When $V_P = 4.5$ km/s, $UCS \approx 200$ MPa, $Q_c \approx 10$, therefore $Q \approx 5$)

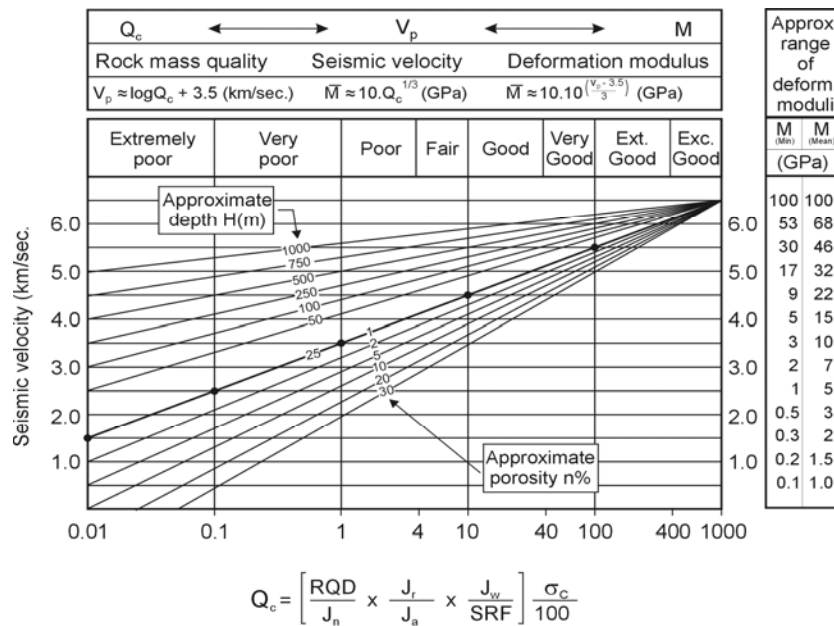


Fig. 6 Approximate empirical conversion of V_P to Q , with corrections for depth and σ_c [2].

Laboratory test data from NTNU/SINTEF of Trondheim, concerning strength and abrasion parameters for the mostly tonalitic and also quartz- and feldspar-rich gneisses, were combined with the above mentioned Q-data statistics to help give estimates of potential TBM tunnelling speeds, using the Q_{TBM} prognosis model [3]. In general UCS (or σ_c) values ranged from about 200 to 260 MPa, and CLI was an unfavourable 6 to 10 in general, meaning heavy cutter wear. Quartz contents varied from 25 to 35%, again unfavourable, meaning typically only 3m advance per cutter change, which of course is performed in multiples, where possible. Because weakness zones generally had wall rock of reduced strength, these higher UCS values (200-260 MPa) were not used when approximately converting V_P to Q.

4. Deceleration trends of TBM tunnels after the learning curve

The trends of declining advance rate with increased time period, derived from an analysis of 145 well-described cases and about 1000 km of mostly open-gripper TBM [4] are shown in Figure 7. This decline is also seen in world record breaking projects, where it can be noted that the mean AR (advance rate) after 1 year is an exceptional 2.0 m/hr, or about 16 km in one year. This of course, by its nature as a record, is very rare. Mean AR of 0.5 m/hr or 1 m/hr after one year of tunneling are more frequent where conditions are less favourable, such as when there is too much rock with high Q-value, combined with high UCS, high quartz content, and correspondingly low cutter life, which sometimes averages < 3m/cutter, despite areas with many times more than this.

Note that the standard *utilization equation* $AR = PR \times U$ (sometimes quoted with unclearly defined time interval in the literature), has been re-cast as $AR = PR \times T^m$ in Figure 7. The component $(-)^m$ is a negative gradient of deceleration, with T as total hours (i.e. 24, 168, 720 hours for daily, weekly, or monthly periods). The three arrows in Fig.7 from top to bottom represent: 1) *Typical delays when pre-injecting*. 2) *Double-shield TBM efficiencies, giving about $0.5 \times (-m)$, to $0.66 \times (-m)$, which can convert a 'poor' PR almost to a 'good' AR*. 3) *Arrow in form of cross indicates where Q-values have strong links to 'unexpected events', which without pre-injection may compromise progress*.

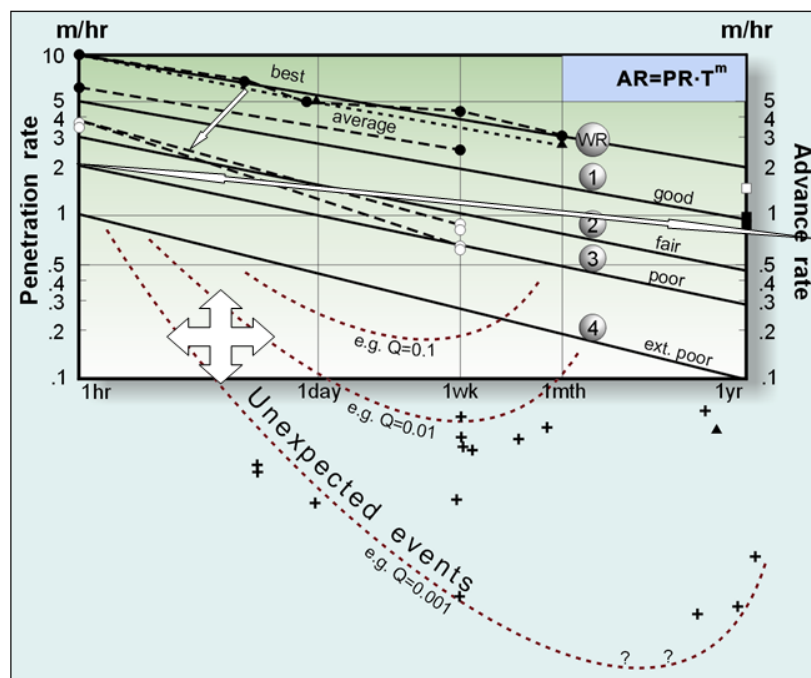


Fig. 7 Even record-breaking TBM projects, also double-shield TBM, show a general deceleration. In the beginning of a 'learning curve' period, lower PR (left axis) and a reduced AR are typical, giving a temporarily steeper gradient or more negative $(-)^m$, meaning lower utilization as all TBM crews, especially maintenance, cutter change, train operations, and shift-changes get up to speed.

5. Why serious fault zones tend to delay TBM

There are unfortunately very good ‘theo-empirical’ reasons why marked fault zones are so difficult for TBM (with or without double-shields). *Theo-empirical* means that lack of belief is often penalized. Of course less serious weakness zones are perfectly tackled by double-shield, with the option for push-off-liner thrust when grippers cannot be used. We need three basic equations. The first is $AR = PR \times U$, where $U = T^m$ (see Figure 7). Due to the reducing utilization with time increase, advance rate decelerates, but does so to a lesser *general* extent with double-shield TBM with their push-off liner possibilities in weakness zones. Modern double-shield TBM, that are well operated, may show roughly halved $-m$ in relation to Fig. 7, (i.e. a very efficient high utilization). Poorly operated and underpowered TBM in hard abrasive rock may be similar to open-gripper results (as Figure 7).

Since the time needed to advance length L for all tunnels and all TBM is $T = L/AR$, then $T = L / (PR \times T^m)$. This must be re-arranged so that T only appears once:

$$T = (L / PR)^{1/(1+m)} \quad (3)$$

This is a very important equation for TBM, assuming one accepts that the deceleration gradient ($-m$) is often strongly related to low Q -values in *fault zones*, as shown by the empirical data in Figure 8. Equation 3 is important because negative ($-$) m values reducing towards ($-$)1.0 (i.e. steeper gradients) make the component $^{1/(1+m)}$ *too large*.

If the fault zone is wide (significantly large L) and PR is low, due to gripper problems, collapses, delayed support, etc.) then L/PR gets too big to tolerate a big component $^{1/(1+m)}$ in equation 3. It is easy (in fact all too easy) to calculate an almost ‘infinite’ time for passing through a fault zone using this ‘theo-empirical’ equation. This also agrees with reality, in numerous, little-reported cases. So far this equation seems to be absent from other literature, as the inevitability of deceleration ($-m$) does not yet seem to have been accepted as a useful method of quantifying reduced utilization with increased time. There is a common and perhaps unfortunate trend to quote utilization for a fixed time period, like one week.

TBM *must follow* a negative m -value, even when breaking world records, like 16 km in one year, or 2.5 km in one month, even 120 m in 24 hours, since even here, PR is sure to be greater than the implied and remarkable mean AR of about 5 m/hr for the record 24 hours period. The uppermost line of world record performances seen in Figure 7 is therefore also showing deceleration, but with a less steep gradient ($-m$). Note that ‘average’ and ‘best’ are differentiated at the top of Figure 7.

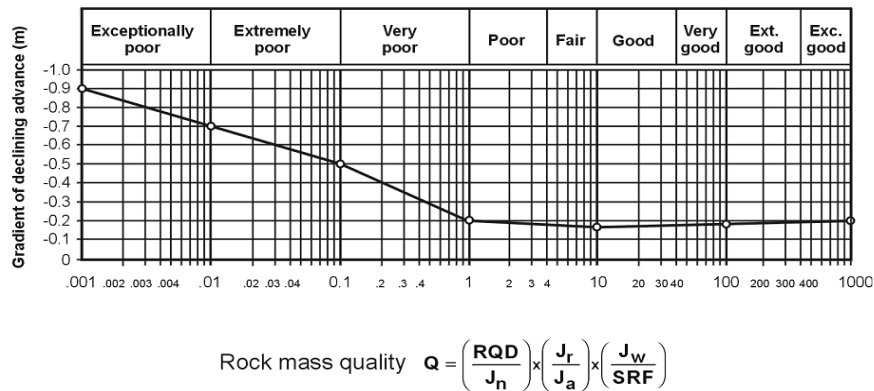


Fig. 8 The gradient of deceleration (with relevant units of m/hr/hr) derived from mostly open-gripper TBM case records that were analysed in [4], is strongly linked to the Q -values in the case of poor (faulted-rock) rock conditions.

Note that poor rock conditions are marked by the arrow-in-the-form-of-a-cross in Figure 7 (so-called 'unexpected events'). Pre-injection, capable of improving the effective Q-value, due to potential improvements of all six Q-parameters [5], will also effectively reduce the initial estimate of the negative gradient (-m). Other machine-rock interaction parameters, including CLI (cutter life index), quartz content, and rock material porosity, modify or 'fine-tune' this initial Q-based gradient, to slightly steeper or to shallower gradients.

Deceleration is a phenomenon that is seen in general since the TBM may be getting a beating and its rail system and muck conveyor belt is getting longer. There is also a mechanical-logistics statistic going hand-in-hand with the rock mass statistic, meaning variable performance in variable rock conditions. The increased chance of mixed face conditions, and for both softer and harder rock as the tunnel length increases, adds to potential for problems with vibration levels, and gives adverse loading of cutter bearings, and may reduce the life of main bearings [4].

6. Prognoses using the Q_{TBM} model

For each part of the planned Oslo-Ski tunnel, prognoses were compared using hard rock open-gripper TBM and double-shield TBM, where robust PC element liner construction concurrent with thrust from the grippers gives a very fast method of tunnelling. This more expensive method has the possible advantage of converting a possibly 'poor' PR (due to rock hardness and short cutter life) almost into a 'good' AR, if the tunnel is long, due to the high utilization, despite frequent cutter changes. With suitable design of gaskets it can also give a water-tight and fully supported tunnel (after possible initial leakage in the first 10 to 15 m from the face). Double-shield TBM have been used with notable success in high-speed rail projects through hard rock masses, e.g. Guadarrama's 4 x 14 km, with two Wirth and two Herrenknecht TBM taking just 30 to 33 months [6].

Figure 9 illustrates the input data screen for the last of five rock mass classes used to define the likely quality ranges of Jernbaneverket's planned Tunnel North running south from Oslo. As may be noted, the first six parameters are the (almost) conventional Q-parameters, but with a specific requirement to consider RQD_0 oriented in the horizontal (visual scan-line) direction, and preferably/obviously in the planned tunneling direction. Anisotropically distributed RQD logged conventionally in vertical holes represents a potential source of error if used to predict PR.

Schematic Geology												
Z1 Z2 Z3 Z4 Z5 Z6 Z7 Z8 Z9 Z10 Z11												
500 1500 5000 2000 500												
ZONE	5										ZONE LENGTH	500
LITHOLOGY	Class 1 granitic gneiss											
INPUT DATA												
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ	V_p			
100.0	2.0	3.0	1.0	1.00	1.0	-0.19	100.0	(g/cm ³) 2.8	(km/s)			
β_0	σ_c	I_{50}	F	CLI	q	σ_θ	D	n				
	(MPa)	(MPa)	(tf)	%	(MPa)	(m)	%					
	250.0		32.0	5.0	35.0	8.0	10.0	1.0				

Fig. 9 An example of the input data screen for 500m of the best quality rock mass. Successive zones (or combined lengths) of the same assumed rock classes 5 (poorest), 4, 3, 2 and 1 (best, as in the figure), plus the various weakness zone classes, gradually complete the modelled tunnel.

The cumulative time for the nine simulated weakness zones, shown modelled in Figure 10, is nearly three months. In these simulations, no pre-treatment has been modelled: neither the delay caused by pre-injection (doubled $-m$, approx: see shortest arrow in Figure 7), nor the tougher bor-

ing through improved rock on either side of a weakness zone, nor the faster boring through the 'Q-improved-by-grouting' weakness zone itself. For a discussion of the possibility of effectively improving Q-parameters, and therefore the effective Q-value itself, by high pressure particulate pre-grouting, using for instance micro-cements with micro-silica, see [5].

Figure 11 a and b show a comparison of open-gripper and double-shield prognoses, for the case of the longer North Tunnel of 9.6 km, with significantly deeper sections of the tunnel than found in the South Tunnel (Refer to Table 1 for these differences)

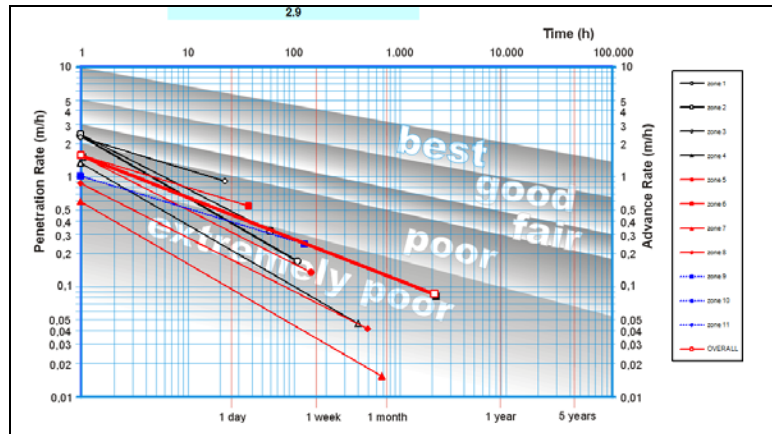


Fig. 10 The modeling of nine potential weakness zones, with some variation in cutter force F , and three sets of geotechnical input data, suggest a potential 3 months delay. This is preliminary data. Note the consistently steep (-) m gradients, due to the low V_p and correspondingly low Q (Fig. 8).

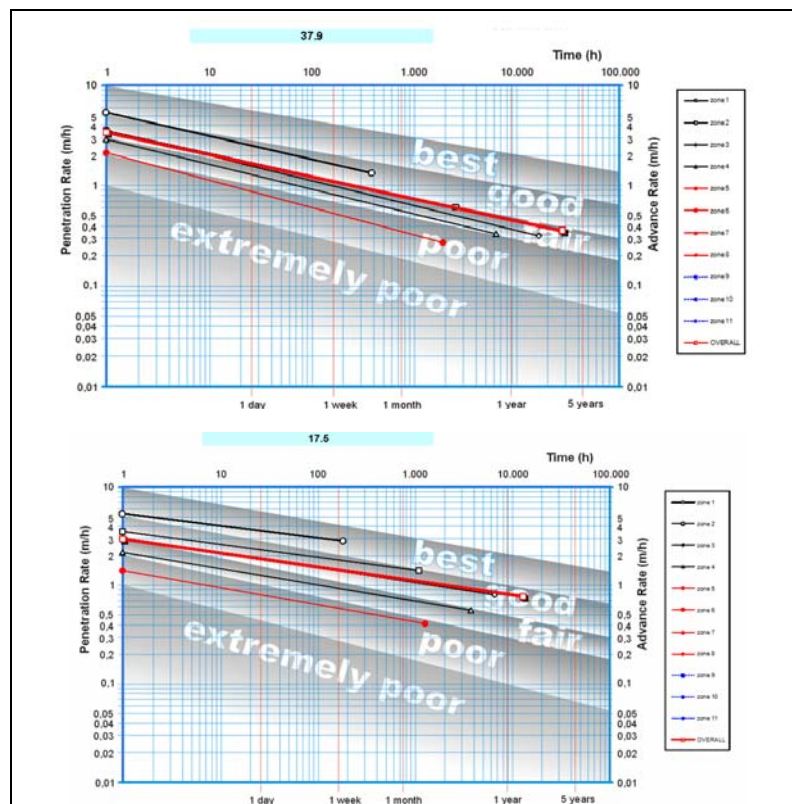


Fig. 11 Examples of Q_{TBM} open-gripper and double-shield simulations for the planned 9.6 km long Tunnel North.

Note the modelled contrast of open-gripper (about 3 years) and double-shield (about 1.5 years), with weakness zone modelling needing to be added to either solution. The latter part of the prognosis is incomplete as investigations are on-going. The initial Q-based deceleration gradients (from Figure 8) ranged from -0.17 to -0.19 (for the open-gripper TBM) and from -0.10 to -0.12 (for the double-shield TBM), becoming respectively -0.23 to -0.27 and -0.12 to -0.17 after 'fine-tuning'. This is due to the adverse rock-cutter interaction in the case of hard granites and gneisses. Improved efficiencies in modern open-gripper TBM might reduce the above open-gripper gradients.

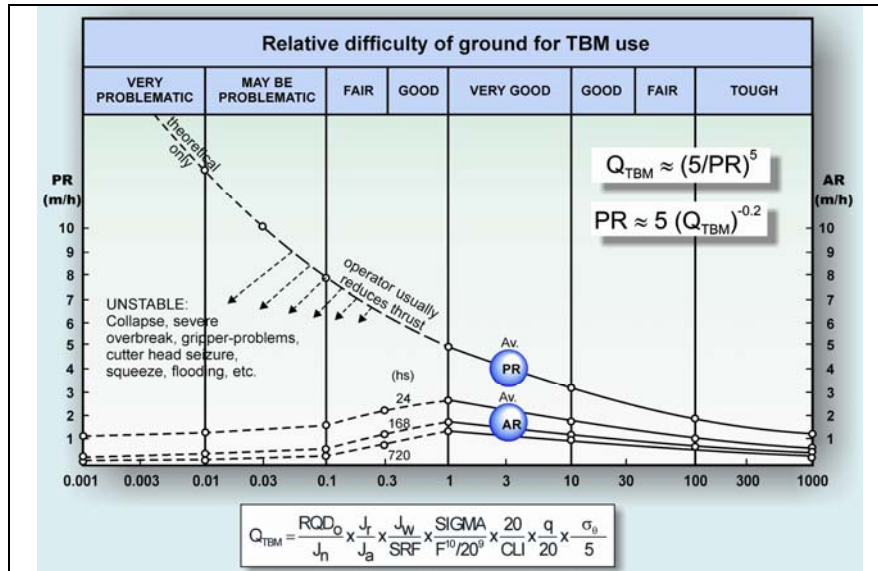


Fig. 12 The underlying Q_{TBM} empiricism and key parameters. The Q_{TBM} equation shows the combination of the Q-classification to describe the rock mass, and various rock material and machine/rock interaction parameters to describe how the cutters will react with the rock material (CLI = cutter-life index from NTNU-Trondheim, q = quartz content, σ_0 = assumed biaxial stress acting on the tunnel face ≈ 5 MPa per 100 m depth). These parameters act in addition to the effects of variable jointing frequency as reflected in the Q-value.

The empirically derived equation shown under the above figure, indicates the importance of mean cutter force (F : normalised by 20 tnf.) in relation to the estimated strength $SIGMA$ of the rock mass. The latter is derived from the following empirically *estimated* equation [4], (where γ = rock density):

$$SIGMA \approx 5 \gamma Q_C^{1/3} \quad (4)$$

It is very important to match machine capacity to expected rock strength, especially in granites and gneisses, as the typically assumed *increased PR with increased mean cutter force (F)* may in fact be reversed with under-powered machines: increasing the cutter force due to the appearance of high-strength rock, may nevertheless show reduced PR, despite a logical intention to maintain PR.

References

1. BARTON, N. & B. GAMMELSÆTER., Application of the Q-system and Q_{TBM} prognosis to predict TBM tunnelling potential for the planned Oslo-Ski rail tunnels. *Nordic Rock Mechanics Conf.*, Kongsberg, Norway, 2010.
2. BARTON, N. *Rock Quality, Seismic Velocity, Attenuation and Anisotropy*. 729 p, Taylor & Francis, UK & Netherlands, 2006.
3. BARTON, N. and ABRAHÃO, R. Employing the Q_{TBM} prognosis model. *Tunnels and Tunnelling International*, 20-23, December, 2003.
4. BARTON, N. *TBM Tunnelling in Jointed and Faulted Rock*. 173p. Balkema, Rotterdam, 2000.
5. BARTON, N. Some new Q-value correlations to assist in site characterization and tunnel design. *Int. J. Rock Mech. & Min. Sci.* Vol. 39/2:185-216, 2002.
6. ADIF, 2005. *Guadarrama Base Tunnel*. Ministerio de Fomento, Madrid, Spain.