

# Rock mass classification for choosing between TBM and drill-and-blast or a hybrid solution

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**ABSTRACT:** The speeds of TBM tunnelling and drill-and-blast tunnelling are compared, using the new  $Q_{TBM}$  model for TBM performance estimation, and the conventional  $Q$ -value for drill-and-blast prognoses. By using these two methods it can be estimated whether a hybrid solution might be the most economic and timely. For instance one would drill-and-blast the most problematic ground, if early access was feasible, while waiting for TBM delivery. A hybrid solution was used at the 18 km long Qinling Tunnel in China, and is also planned in Brazil, where abrasive, massive rocks occur at both ends of the tunnel. Logging methods that can conveniently be used to describe the ground, including the use of seismic, are described in this paper, together with some of the details of the  $Q_{TBM}$  method, including a worked example.

## 1 INTRODUCTION

The pressing need for fast tunnelling solutions for infrastructure development has naturally focussed attention on TBM tunnelling. In hydropower development an even more obvious need for TBM tunnelling is apparent, due to the potentially favourable smooth profile obtained if the rock mass has favourable properties.

Western countries noted with interest the recent introduction of two large TBM into China for a planned 27-month completion of the 18.5 km long Qinling rail tunnel. The hard granites and very hard gneiss reportedly gave best penetration rates of about 4 m/hr but slowed to only 0.3 m/hr in the hardest gneiss. Besides the reportedly massive rock, an overburden as high as 1600 m, and averaging 1000 m, probably played its part in slowing the machines. Utilisation was less than 30% in a 24-hour day on average, and cutter wear was significant (Wallis, 2000).

A political decision to drill-and-blast the central section of the tunnel to bring forward completion deadlines, while the two TBM completed 5.3 and 5.6 km from the N and S portals conveniently focuses attention on our subject "Choosing between TBM and drill-and-blast". A hybrid solution combining the benefits of both methods of tunnelling should always be carefully assessed beforehand, and compared to the single solutions of one (or two) TBM, or drill-and-blasting alone. How best to make this assessment?

Recently, feasibility studies for a 16 km water tunnel in Brazil have focussed on deliberately utilising the hybrid solution, due to the presence of massive, abrasive granites and sandstones at respective ends of the tunnel, and "ideal TBM rock" (phyllites and schists) in the central half of the tunnel. The method used for this assessment was the newly developed  $Q_{TBM}$  concept (Barton, 1998; 2000), which gives detailed prognoses based on rock and rock mass characterisation along planned tunnels.

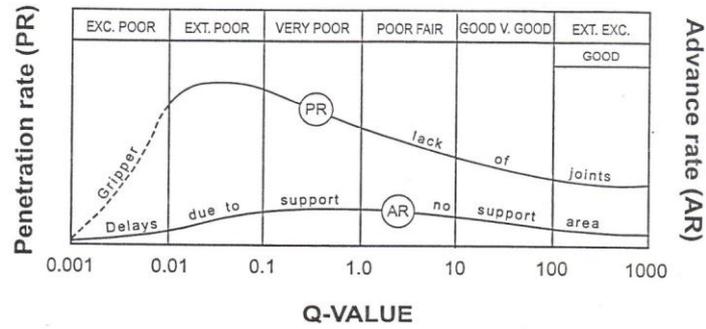


Fig. 1. Conceptual relation between TBM performance and Q-value.

## 2 Q AND $Q_{TBM}$

In Figure 1 the relative magnitudes of TBM penetration rates and actual advance rates are drawn in relation to the Q-value obtained from rock mass classification (Barton et al., 1974). In a later figure we will also see how speeds for drill-and-blast tunnelling are also related with the Q-value but in a significantly different way. In the case of TBM, massive rock is unfavourable for fast penetration, while for drill-and-blast it is obviously favourable due to the lack of tunnel support needs, and can be drilled at reasonable speed despite the lack of jointing.

The new  $Q_{TBM}$  method is built onto the six Q-system parameters that are now widely used around the world. However, there are differences, including the use of  $RQD_o$  — an oriented RQD relevant to the tunnelling direction. Other  $Q_{TBM}$  parameters shown in Figure 2 relate to the ratio of rock mass strength SIGMA and cutter force F, the cutter life index, the quartz content of the rock and the estimated stress level at the tunnel face. Each of these additional parameters are normalised by a typical value, therefore giving higher or lower values of  $Q_{TBM}$ . The most important single parameter by far is cutter force. More details are given later.

## 3 THE LAW OF DECELERATION

A very important fact-of-life for TBM is that there are different *advance rate* curves for each time period (i.e. 24 hours, 1 week, 1 month, etc.). These are shown in Figure 2.

An extensive review of 145 TBM tunnels, totalling more than 1000 km in length (Barton, 2000) has shown that there is a consistent deceleration or decline in the *average* advance rate with time. This is of course known, but hardly quantified or discussed in the literature, where *best weeks* and *best months* make more impressive reading.

The general trends of these numerous cases are drawn in Figure 3, where WR (world record), "good", "fair", "poor" and "extremely poor" lines of performance are drawn. The actual case records are plotted in Figure 4.

The declining advance with log time can be quantified by the gradient (m), which has units of deceleration ( $LT^{-2}$ ). The importance of this quantification is that the utilisation (U) that links penetration rate (PR) and advance rate (AR):

$$AR = U \times PR \quad (1)$$

must be quantified as a time dependent variable, which is a very necessary step for correct prognoses. We therefore write:

$$U = T^m \quad (2)$$

where T is in hours, and m is always negative. In many typical cases, when neglecting major fault zones:

$$U \approx T^{-1/5} \quad (3)$$

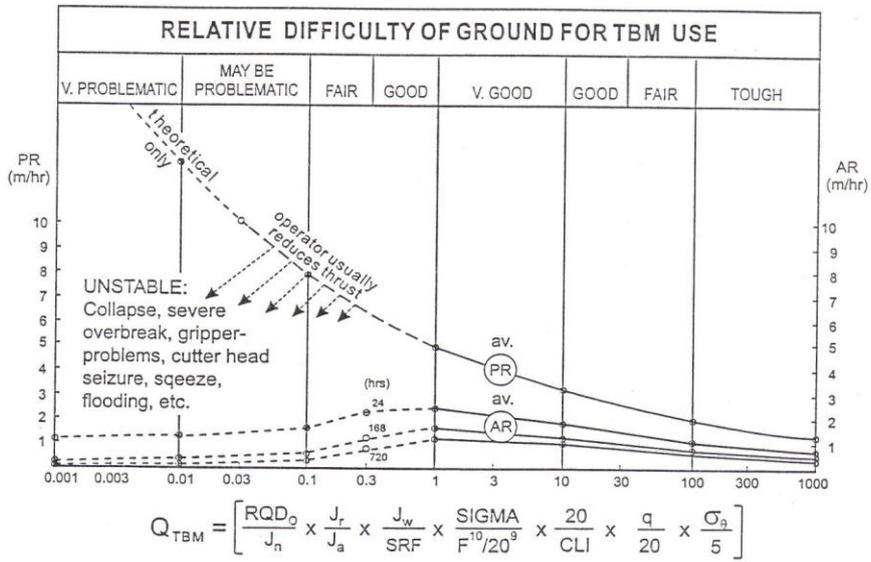


Fig. 2. The  $Q_{TBM}$  method that builds directly onto the  $Q$ -system. (Barton, 1999)

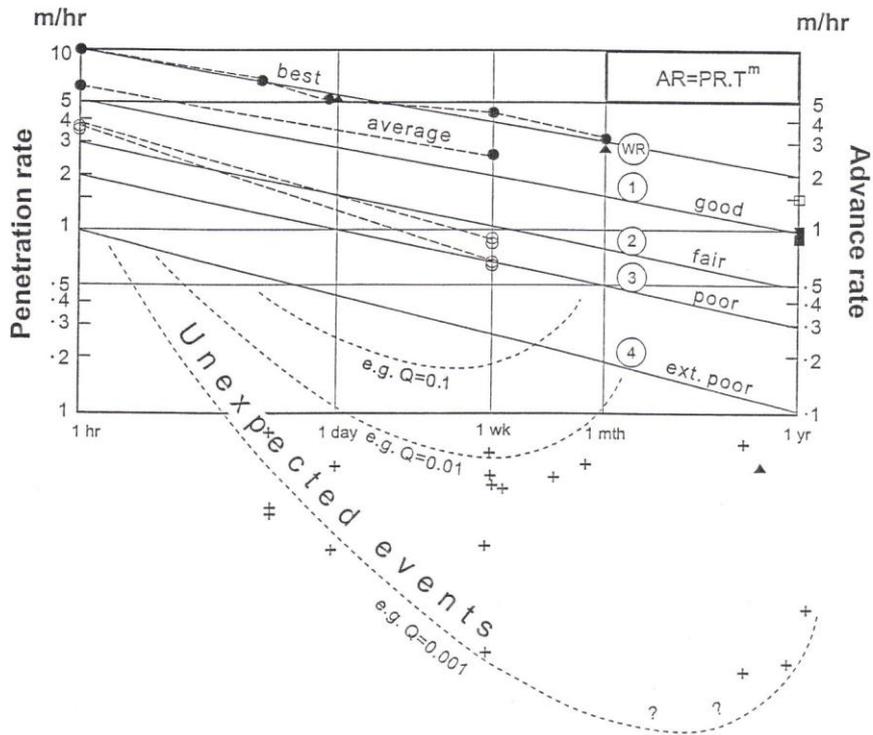


Fig. 3. The decelerating rate of advance in TBM tunnelling. (Barton, 1999)

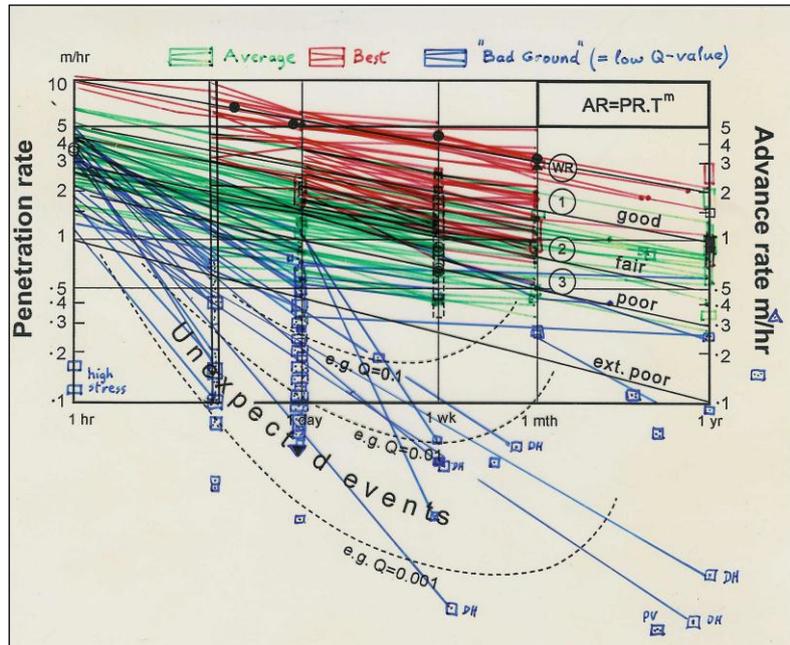


Fig. 4. Case records; 145 tunnels totalling more than 1000 km. (Barton, 2000)

When we read from the Qinling Tunnel (Wallis, 2000) that "utilisation in a 24 hour day ran at less than 30% on average", this implies an average gradient (m) given by:

$$m = \frac{\log U}{\log T} \quad (4)$$

At Qinling we therefore have:

$$m \leq \frac{(-)0.523}{1.380} \leq (-)0.38$$

This immediately signifies an unfavourably steep gradient of deceleration in Figure 3, presumably due to the hard, abrasive and massive nature of the rock reported at Qinling, and areas of high stress; in fact probably far from ideal for TBM tunnelling.

The great majority of average TBM performances lie between lines (1) and (3) in Figure 3, which makes a lot of TBM tunnelling very successful. However, there are periods with "unexpected events" (i.e. low Q-values in fault zones) that may seriously delay average performance. For entirely different reasons, hard, abrasive, massive conditions and fault zones with clay and maybe water, give unfavourably steep gradients of deceleration. Each are quantified in specific, but different ways, in the  $Q_{TBM}$  approach.

#### 4 COMPARING SPEEDS OF TBM AND DRILL-AND-BLAST

Favourable geology and hydrogeology for the TBM tunnelling option produce dazzling results, which are physically difficult to visualise. For example, 150 m in a day, 500 m in a week, 2 km in a month and 12 km in a year (or even better results) have been achieved in some well-publicised projects. However, these are not typical, nor are they average performances (except perhaps the 12 km in a year).

Before committing to a significant investment, and a significant delivery and assembly time, it is wise to carefully compare TBM and drill-and-blast options, and perhaps find that a hybrid solution is more ideal. If a lot of faulted ground is present, the TBM option should probably be avoided, to help maintain the excellent record of TBM successes. Alternately one may be able to drill-and-blast the most faulted (or most massive) part of the tunnel and use the TBM for the more appropriate conditions, when it arrives at the site sometime later.

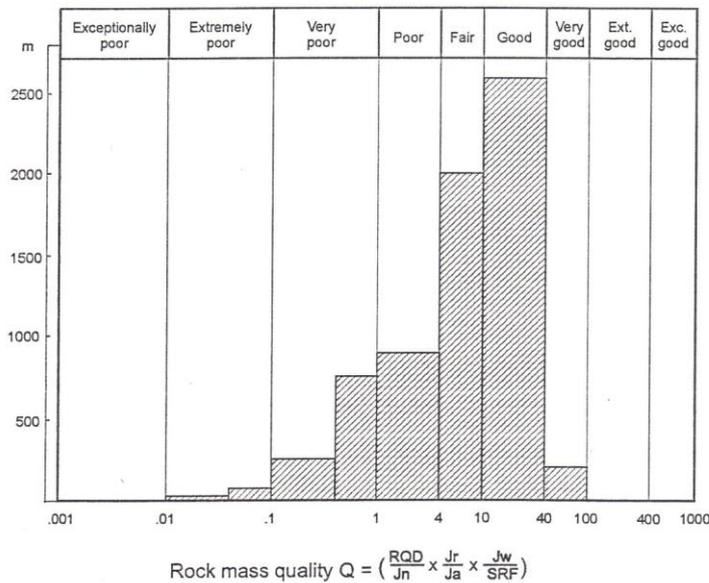


Fig. 5. *Q*-statistics for a planned TBM tunnel. (Løset, 1999)

The *Q*-value statistic along a planned tunnel route (e.g. Figure 5), which may also be used for drill-and-blast support prognoses (e.g. Barton and Grimstad, 1994), can also be used to predict advance rates as indicated in Figure 6. If we first assume that the  $Q_{TBM}$  value may be roughly equal to the *Q*-value, which it may be under "average" conditions, then the TBM option and the drill-and-blast option can be directly compared, first in terms of speed of advance. The comparison shown in Figure 6 uses data obtained from a 50 m<sup>2</sup> drill-and-blast road tunnel (Grimstad, 1999; Barton, 2000) and an equivalent TBM diameter through the same full range of *Q*-values and  $Q_{TBM}$  values.

As one can imagine, if the *daily* TBM advance rate was added to the weekly and monthly performance curves shown in Figure 6, rates of advance perhaps *three to five* times faster might be expected from the TBM option. However, if the tunnel is long, the TBM option will only be attractive if the rock mass quality lies mostly in the central range of *Q* and  $Q_{TBM}$  values.

**Contrary to conventional wisdom, the longer the tunnel the less attractive might be the TBM option.** There are many potential reasons for this, including the greater uncertainty about rock conditions, more extremes of geology and hydrogeology; in fact a large-scale "Weibull flaw" effect, where the "flaws" are now the larger fault zones and major wet zones, which statistically speaking will tend to get more extreme the longer one tunnels. Nevertheless with thorough investigation, and well-jointed conditions, the TBM option may still be very attractive as it could be 1½ to 2 times faster even in a long tunnel, if conditions are close to ideal.

## 5 WHEN *Q* IS NOT EQUAL TO $Q_{TBM}$

The above comparison may of course be unfair to the TBM option because the  $Q_{TBM}$ -value statistics may differ from the *Q*-value statistics, and favour the TBM. Softer rocks, with less quartz content and good tunnel stability would be an obvious case. Furthermore, in many countries the drill-and-blast option will not give as efficient tunnelling as in say Scandinavia, where a high degree of mechanisation is used, such as computer steered drill-jumbos and high capacity, wet process S(fr) robots. It is therefore important to sample local tunnelling experience by drill-and-blast, using a platform such as the *Q*-system, before deciding on the best tunnelling option, or combination of options (i.e. the hybrid solution).

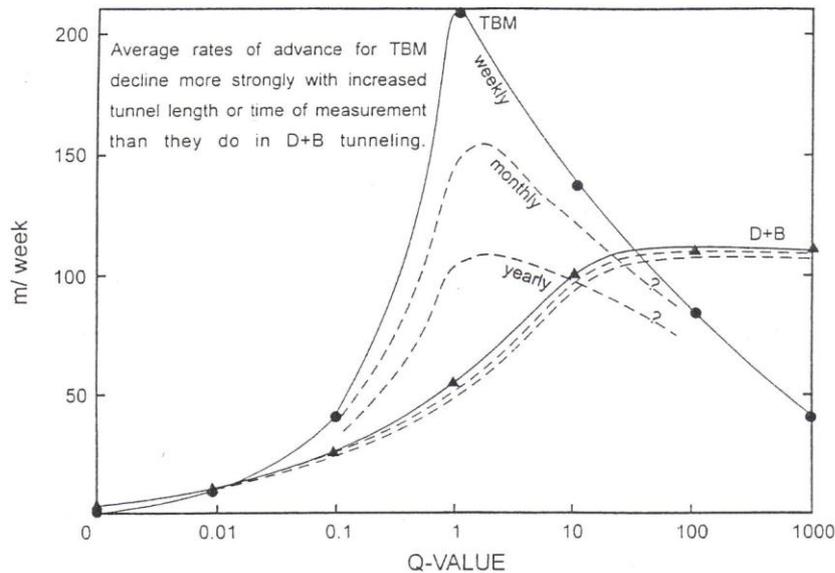


Fig. 6. A comparison of advance rates for TBM and drill-and-blast tunnelling, if we assume  $Q \approx Q_{TBM}$ . (Barton, 2000)

## 6 DIFFERENT SUPPORT NEEDS FAVOUR TBM

One further point that we have so far left out of this brief comparison of tunnelling methods is the level of tunnel support requirements. Figure 7 shows the Grimstad and Barton (1993) tunnel support quantities for drill-and-blast tunnels, which in principle also apply to TBM tunnels. However, there will be a natural tendency to use more (circular) steel sets in the TBM tunnels, especially as temporary support, and of course PC element liners may be attractive if good circular profiles are generally achieved, and if end use is compatible with this choice.

The cross-hatched rectangles shown in Figure 7 represent the threshold zone (on each side of the no-support boundary) where Q-values will be judged to be 2 to 5 times higher in the TBM tunnel (Barton, 2000). There is therefore generally no need for TBM tunnel reinforcement or support in any of these cross-hatched zones. This adds to the favourable nature of the TBM option, and goes some way towards explaining the "peaks" of performance synthesised in the predictions of advance rate shown in Figure 6. We will discuss these aspects further when addressing the details of logging rock quality in TBM tunnels.

## 7 LOGGING OF ROCK QUALITY

We have already seen in Figure 5 what a synthesis of Q-values, and their approximate (expected) distribution may look like in a planned TBM tunnel, in this case one through limestones, shales and sandstones. Here the synthesis was based on geological mapping, drill core logging, and earlier tunnel logging in a smaller TBM tunnel in the same geological area (Løset, 1999).

When collecting Q-parameter data it is obviously necessary to produce (as far as is possible) a prognosis of what the rock mass quality will be in the different geologies and structural domains along the planned tunnel. The following two figures show examples of Q-parameter logging in an existing TBM tunnel (Figure 8), and along 200 m of horizontal drill core prior to tunnelling (Figure 9).

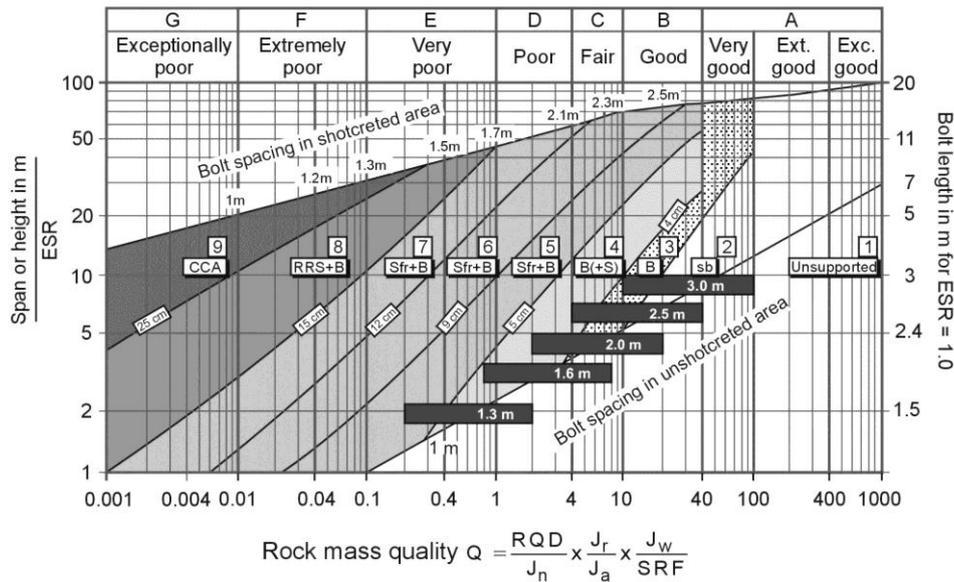


Fig. 7. Support for TBM tunnels is generally not needed in any of the cross-hatched, central threshold areas. (Barton, 2000)

Logging in TBM tunnels, even behind the back-up rig with good lighting, is not as easy as in a drill-and-blasted tunnel, due to the frequent lack of significant overbreak unless the Q-values are significantly below about 40 in a big tunnel ( $\varnothing$  10 m) or below about 4 in a fairly small tunnel ( $\varnothing \approx 4$  m). There is the added difficulty that an actual Q-value of about 10 in the large tunnel (if the tunnel was drill-and-blasted) may appear to be several times higher in the TBM excavation. In the small tunnel, an actual Q-value of about 1 may appear to be about 4 in the TBM tunnel. This is due to the tendency (actually a correct tendency due to the limited disturbance) for the observer to over-rate RQD and joint spacing and under-rate the number of effective joint sets and joint continuity. There will also be potential errors, such as failing to see clay coated joints if overbreak has not occurred. These "central threshold" biases/errors occur in the cross-hatched areas shown in Figure 7, as discussed earlier.

When comparing Q-logging and RMR logging performed by different parties in the same tunnel, a tendency has been noted for biased RMR observations in the direction of more jointing, because it is easier to record the closer joint spacing and perhaps ignore that much of the tunnel periphery is quite massive. The same could apply to RQD observations, in either the Q-system or RMR method.

A definitive method for avoiding this pitfall is "histogram logging" as illustrated in Figures 8 and 9. This method is actually more representative of actual variability, it can take care of the logger's real uncertainty, and it is faster than the "forced evaluation" of a single value for RQD (or tunnel oriented RQD<sub>0</sub>),  $J_n$ ,  $J_r$ ,  $J_a$ ,  $J_w$  and SRF, which takes significant mental effort in what is often a wet and time-limited environment. The logger may be wet, his paper even wetter and the tunnel invert flowing like a river. The histogram method is the answer here! Later, in the warmth of a site office, with dried logging paper, the engineering geologist can assemble the data, calculate Q-values for individual lengths of the tunnel, and immediately evaluate needs for final support (and more pre-treatment).

The logging turnaround time can, and must, be very short, if selection of correct support class and its implementation are to keep pace with the 10 to 100 metres per day advance rate. For the engineering geologist the 1 m per day advance with "unexpected events" (Figure 3) is the time to log face conditions and supervise "pre-reinforcement" measures such as pre-injection. In maintenance shifts he will need to follow probe drilling, perhaps interpret sonic logging.

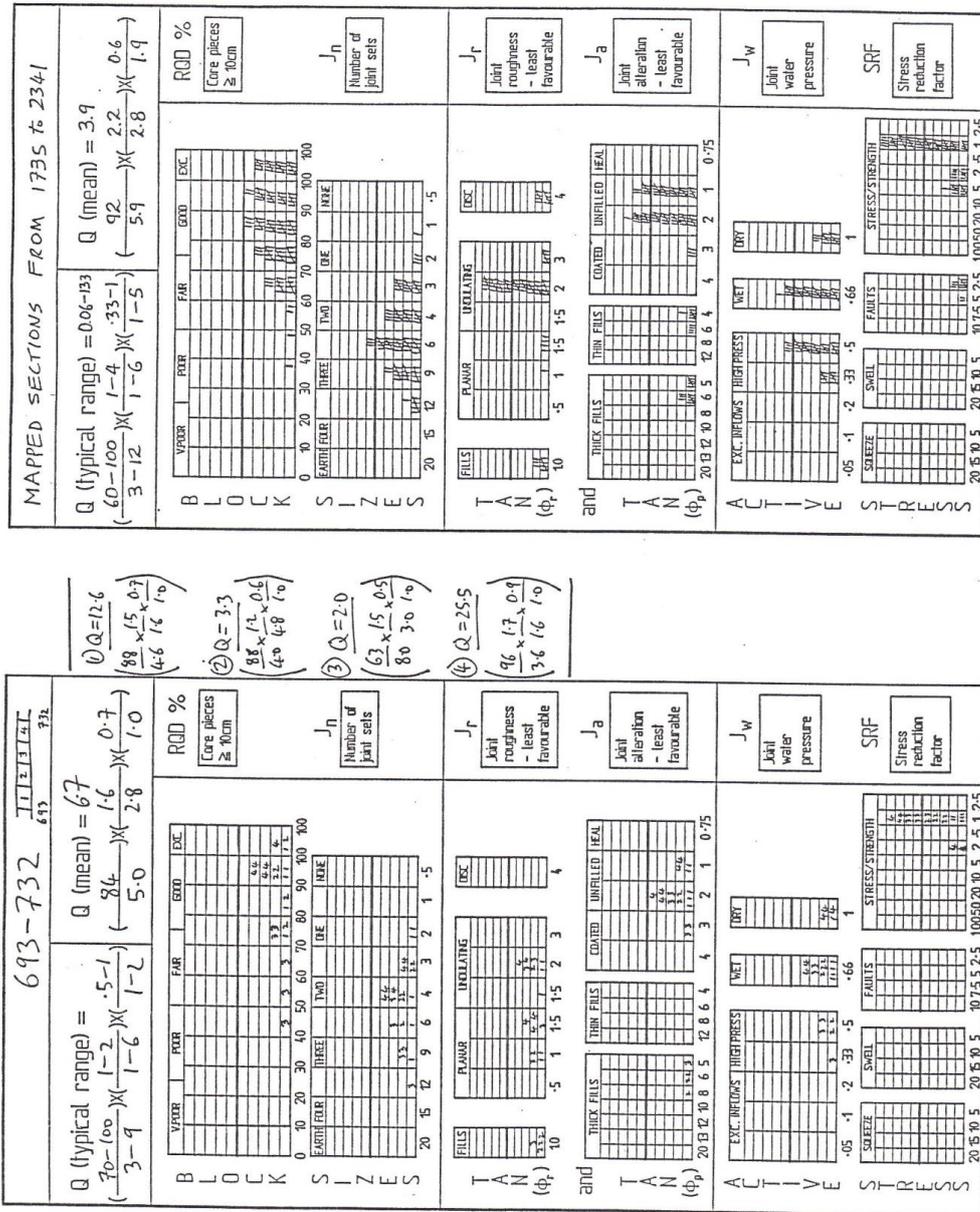


Fig. 8 a) Q-logging of 10 m tunnel lengths (4 observations of each parameter), and b) Assembling of the Q-statistics for 600 m of tunnel. (NGI, 1998)



1 = MASSIVE (M)  
2 = SLIGHTLY JOINTED (S)  
3 = JOINTED (J)  
4 = ZONE (Z) 5 = FAULT (F)

LH 01/A 401.60 - 601.43

Q (typical range) = ( ) X ( ) X ( )      Q (mean) = ( ) X ( ) X ( )

BLOCK SIZES	V. POOR	POOR	FAIR	GOOD	EXC.	RQD %  Core pieces ≥ 10cm												
	0	10	20	30	40	50	60	70	80	90	100	100						
TAN (φ <sub>p</sub> ) and TAN (φ <sub>β</sub> )	EARTH FOUR	THREE	TWO	ONE	NONE	J <sub>n</sub>  Number of joint sets												
	20	15	12	9	6	4	3	2	1	-5								
ACTIVE STRESSES	FILLS	PLANAR	UNDULATING	DISC		J <sub>r</sub>  Joint roughness - least favourable												
	10	-5	1	1.5	1.5	2	3		4									
ACTIVE STRESSES	THICK FILLS	THIN FILLS	COATED	UNFILLED	HEAL	J <sub>a</sub>  Joint alteration - least favourable												
	20	13	12	10	8	6	5	12	8	6	4	4	3	2	1	0.75		
ACTIVE STRESSES	EXC. INFLOWS	HIGH PRESS	WET	DRY	WET (cont.)	J <sub>w</sub>  Joint water pressure												
	-05	-1	-2	-33	-5	-66	1											
ACTIVE STRESSES	SQUEEZE	SWELL	FAULTS	STRESS/STRENGTH			SRF  Stress reduction factor											
	20	15	10	5	20	15	10	5	10	50	20	10	5	2	-5	1	2	-5

Fig. 9 Q-logging of a section of horizontal drill core, ahead of a slowing TBM. (NBA, 2000)

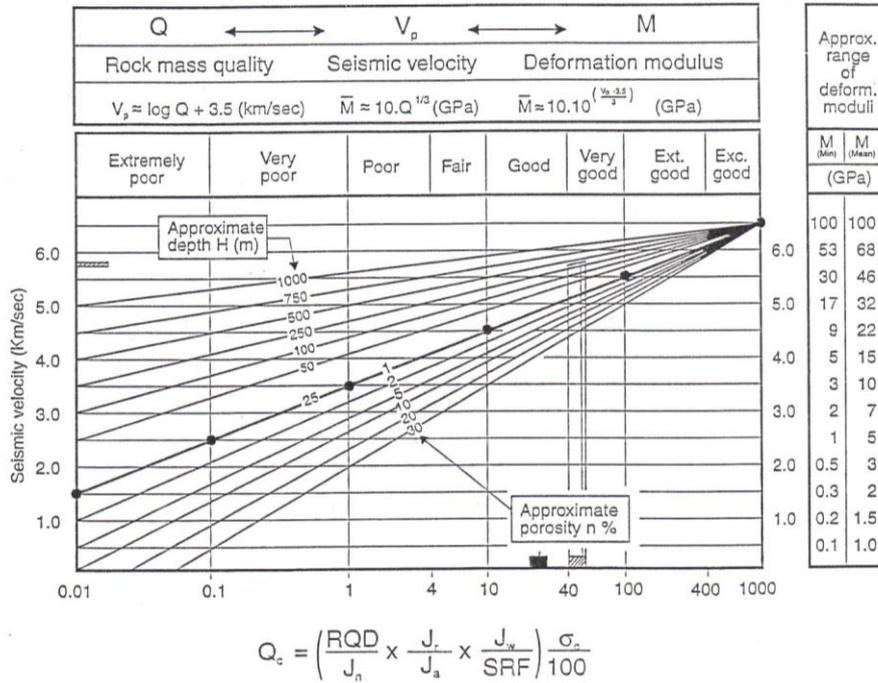


Fig. 10 A method to convert  $V_p$  to a  $Q$ -value, with due regard for the compression strength and porosity of the rock material, and the depth of the seismic measurement. (Barton, 1995)

## 8 USING SEISMIC REFRACTION DATA IN PROGNoses

Unfortunately the practice of long horizontal core drilling is not yet widespread, either before project start or during the tunnelling. There will therefore seldom be such detail as for the 200 m of ground logged in Figure 9. (This was part of a much longer pilot hole.) Much more frequent will be vertical or inclined boreholes, often limited to both ends of the tunnel, due to overburden constraints or perhaps due to a sub-sea location.

It then becomes more important to utilise and interpret shallow refraction seismic measurements, and eventual cross-hole seismic velocities (mean values or tomographic) that may (or should) be available across major fault zones. Conversion to approximate  $Q$ -values, using the  $Q_c$  normalisation method shown in Figure 10, has proved to give useful estimates of quality along the tunnel of interest. (TBM or drill-and-blast.) The continuous seismic velocity log is a form of extrapolation (actually intrapolation) between boreholes, and can be calibrated by the intermittent core-logging. The inter-relationships shown in Figure 10 have been obtained by just such calibrations (Barton, 1998).

In one recent TBM tunnelling problem, with difficult sub-sea conditions and extensive delays due to faulted ground and pre-injection needs, the use of the  $V_p$ - $Q_c$ - $Q$  conversion, and estimation of  $Q_{TBM}$  (Figure 2) proved far more accurate than "conventional" methods of TBM prognosis, which vastly over-predicted the actual progress. The tunnel concerned has significant lengths of low  $Q$ -values, which seriously undermine the expectation of *faster* TBM tunnelling than drill-and-blast tunnelling. In Figure 6 nomenclature, we are too far to the left, and the tunnelling is now taking too long.

## 9 PR ESTIMATED FROM $Q_{TBM}$

The methods used to predict penetration rate (PR) with uninterrupted boring, and average advance rate (AR) for different periods of tunnelling will now be briefly summarised. More details are given by Barton, 2000.

The basic empirical equation for estimating  $Q_{TBM}$  is given in Figure 2 and is as follows:

$$Q_{TBM} = \left( \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right) \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5} \quad (5)$$

In the parentheses is an oriented Q-value,  $Q_o$ , based on oriented RQD ( $RQD_o$  in the tunnelling direction) and  $J_r/J_a$  relevant to the ease (or difficulty) of boring with the most optimally oriented joint set. Rough, discontinuous joints hinder progress (PR) while smooth continuous joints help PR but hinder AR if support needs increase. (We take care of the latter by suitable choice of gradient  $-m$ ).

SIGMA – a measure of the rock mass strength, allows anisotropic behaviour or large ratios of  $\sigma_c/I_{50}$  (due to cleavage or foliation) to influence the penetration rate. SIGMA in its simplest form is given as:

$$SIGMA_{cm} = 5\gamma Q_c^{1/3} \quad \text{MPa} \quad (6)$$

$$\text{where } \gamma = \text{rock density (gm/cc)}, Q_c = Q_o \times \frac{\sigma_c}{100}$$

Cutter force  $F$  (tnf) is calculated from the net thrust/cutter, i.e. minus the cylinder pressure needed to pull the back-up equipment. It has an approximately quadratic effect on PR (i.e. changing  $F$  from 20 to 30 tnf/cutter may increase PR by a factor of about 9/4). However, because  $F$  is compared to SIGMA, the  $Q_{TBM}$  model also allows PR to *reduce* with increased cutter force (as it may in very hard rocks, e.g. Grandori et al., 1995). The case shown in Figure 11 from Nelson et al., 1983, is a graphic example of this possibility, especially when cutter loading is limited.

The term CLI (cutter life index) in equation 5 is an empirical term developed by the University of Trondheim (NTH, 1994). It is obtained from the combined use of a miniature drilling test and a cutter steel abrasion (weight loss) test. Typical values of CLI might be 5 for quartzite, 15 for gneiss, 30 for phyllites, 80 for shale and 100 for limestone. However, quite wide ranges are seen, due partly to quartz content ( $q$ ) which is a separate term in the equation for  $Q_{TBM}$  ( $q$  in %). Finally, we have a rough estimate of the maximum biaxial stress component on the tunnel face, normalised by 5 MPa, an assumed value for 100 m depth.

As will be noted in Figure 2,  $Q_{TBM}$  allows one to estimate the average penetration rate PR, or to back-calculate it from the average performance of this parameter.

$$PR \approx 5 Q_{TBM}^{-1/5} \quad (6)$$

$$\text{or } Q_{TBM} \approx (5/PR)^5 \quad (7)$$

where PR is in m/hr

In Figure 2, only the “central” range of  $Q_{TBM}$  is shown. With very low cutter force in very hard rock,  $Q_{TBM}$  becomes a very large number, while in fault zones, it will become too low, and the operator must reduce thrust to allow time for stabilisation. The table below gives a feel for the sort of magnitudes involved.

Table 1. Estimates of  $Q_{TBM}$  for lines WR, 1, 2, 3 and 4 in Figure 3.

	PR m/hr	$Q_{TBM}$
WR (“world record”)	10	0.03
Line 1 (“good”)	5	1
Line 2 (“fair”)	3	13
Line 3 (“poor”)	2	98
Line 4 (“extr. poor”)	1	3125
Exceptional case	0.1	312,500,000

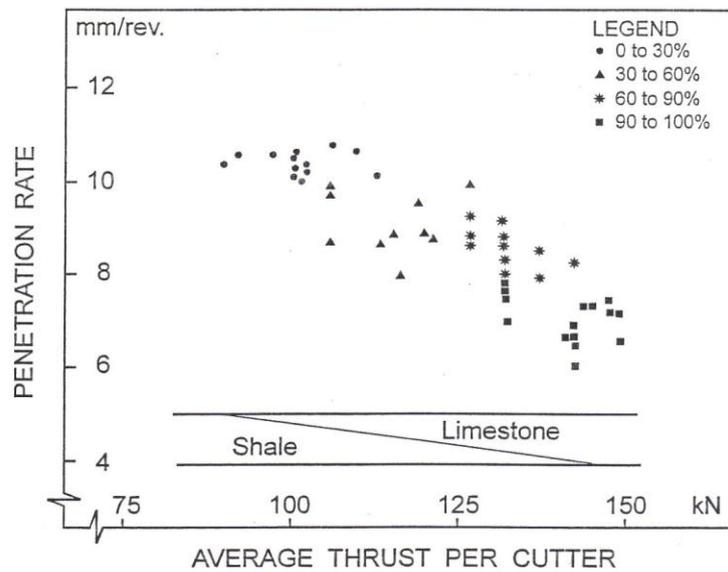


Fig. 11 Penetration rate versus thrust per cutter for specified percentages of limestone. (Nelson et al., 1983)

#### 10 AR ESTIMATED FROM PR

As we have seen earlier when discussing gradients of deceleration, the simple relation between PR and AR:

$$AR = PR \times U$$

is too simple, because the time period (shift, day, week, month, etc.) needs to be specified since  $U = T^m$

A constant gradient (i.e.  $m = -0.20$ ) as seen in central areas of Figure 3 (midway between lines 2 and 3) would give utilisation percentages that fall, naturally, with increasing time periods as in Table 2.

Table 2. Typical PR, U and AR data for one year of TBM tunnelling (when  $m = 0.20$ )

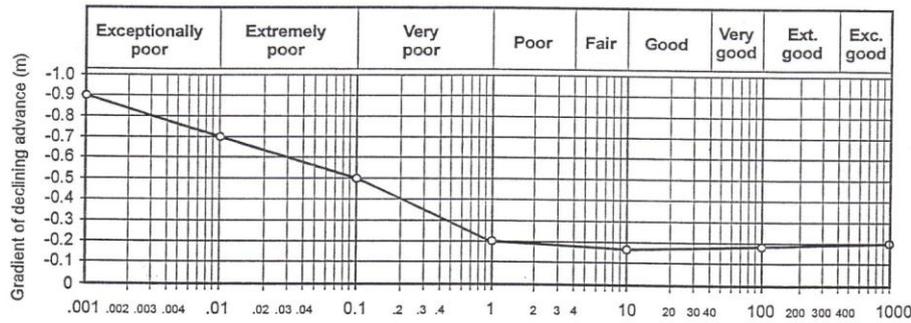
PR	1 shift	1 day	1 week	1 month	3 months	1 year	
1 hr	8 hrs	24 hrs	168 hrs	720 hrs	2160 hrs	8760 hrs	
U =	100%	66%	53%	36%	27%	16%	
AR =	3.0	2.0	1.6	1.1	0.8	0.5	m/hr

This is the reason why specifying utilisation as "53%" must be qualified by the relevant time period. In the above case – the mean utilization per 24-hour day.

The table below shows how gradient ( $m$ ) is estimated. As seen in both the table and in Figure 12, there is a strong dependence on the conventional Q-value when stability is poor ( $Q = 0.1, 0.01$  and  $0.001$ ), but most dependence on abrasion factors when the rock is stable and perhaps massive.

Table 3. Gradient  $m$  and utilisation as a function of Q-values for average 1-month periods.

Q-value	0.001	0.01	0.1	1.0	10	100	1000
$m$	-0.9	-0.7	-0.5	-0.22	-0.17	-0.19	-0.21
$U_{720}$	0.003	0.01	0.04	0.24	0.33	0.29	0.25



$$\text{Rock mass quality } Q = \left( \frac{RQD}{J_n} \right) \times \left( \frac{J_r}{J_a} \right) \times \left( \frac{J_w}{SRF} \right)$$

Fig. 12 Preliminary estimate of declining advance rate gradient (-m), as a function of Q-value.

Utilisation percentages are enormously dependent on the relevant range of Q-values, especially when longer time periods are involved. Table 3 tells us that when penetrating a fault zone that takes 1 month (720 hrs) only 1% of the time would be spend in advancing the tunnel if the Q-value was as low as 0.01.

Because abrasion terms are so important when the rock is of "good" quality for stability (i.e.  $Q = 100$  or even 1000) empirically derived "fine tuning" has been necessary in estimating the final gradient m. The following equation is used:

$$m \approx m_1 \left( \frac{D}{5} \right)^{0.20} \left( \frac{20}{CLI} \right)^{0.15} \left( \frac{q}{20} \right)^{0.10} \left( \frac{n}{2} \right)^{0.05} \quad (8)$$

where D = tunnel diameter in metres, and n = porosity of rock matrix (in %).

To avoid zero problems, yet retain simplicity, both (q) and (n) should be set to  $\geq 0.5\%$ , as also applies to (q) in equation 5.

The preliminary gradient (now termed  $-m_1$ ) obtained from Table 3 or Figure 12) may or may not be modified by equation 8, since all terms are normalized by typical, "central trending" values.

We are now in a position to estimate the mean advance rate (AR) from  $Q_{TBM}$  and  $-m$ , using equations 1, 2 and 6:

$$AR = PR \times U \quad U = T^m \quad PR \approx 5 Q_{TBM}^{-1/5}$$

which give:

$$AR \approx 5 Q_{TBM}^{-1/5} \times T^m \quad (9)$$

## 11 WORKED EXAMPLE

On the final pages of this keynote lecture, a worked example is shown. It is a hypothetical example but is based on a real case) and consists of equal lengths (4 km) of massive abrasive sandstone, then phyllites, then mica schists and finally massive, high strength granite. Readers will note from the estimation of time (T) to advance through each geological domain, where:

$$T = \left( \frac{L}{PR} \right)^{\frac{1}{1+m}} \quad (10)$$

that the far "too tough to bore" sandstone and granite ( $T = 22,070$  hours,  $T = 18,933$  hours – each more than 2 years) will need drill-and-blasting. This, fortunately, can be done from either



#### F) PENETRATION RATE

$$PR \approx 5(Q_{TBM})^{-0.2}$$

$$AR = PR \times T^m$$

Zone	$Q_{TBM}$	PR (m/hr)	AR (m/hr)
1 Sandstones	20	2.7	0.18
2 Phyllites	0.6	5.5	0.77
3 Mica schists	0.7	5.4	0.67
4 Granites	48	2.3	0.22

#### G) TIME TO ADVANCE LENGTH L

$$T = \left( \frac{L}{PR} \right)^{\frac{1}{1+m}}$$

Zone	L (m)	m	$\left( \frac{1}{1+m} \right)$	T (hr)	T×AR =L*	Assume max. 8736 hrs/yr
1 Sandstones	4000	-0.27	1.37	22070	4002	2.53 yrs
2 Phyllites	4000	-0.23	1.30	5250	4026	0.60 yrs
3 Mica schists	4000	-0.24	1.32	6140	4087	0.70 yrs
4 Granites	4000	-0.24	1.32	18933	4097	2.17 yrs

$\Sigma L=16000$  (m)       $\Sigma T= 52393$  (hrs)      = (6.00 yrs)  
 \* rough check of AR and T (errors due to rounding)

#### H) OVERALL PERFORMANCE

PR (weighted mean),  $\Sigma T$ ,  $\Sigma L$

$$\overline{PR} = \left( \frac{PR_1 L_1 + PR_2 L_2 \text{ etc.}}{L_1 + L_2 \text{ etc.}} \right)$$

$$\overline{AR} = \left( \frac{AR_1 L_1 + AR_2 L_2 \text{ etc.}}{L_1 + L_2 + L_3 \text{ etc.}} \right)$$

Zone	$\Sigma L$ (m)	$\Sigma T$ (hr)	$\overline{PR}$ m/hr	$\overline{AR}$ m/hr
1 Sandstones	4000	22070	63600	7280
2 Phyllites	4000	5250		
3 Mica schists	4000	6140		
4 Granites	4000	18933		

$\Sigma L=16.000$  (km)       $\Sigma T= 72$  months  
 1→n      1→n

#### I) AR at END OF PROJECT

$$AR = \overline{PR} \times \Sigma T^m$$

(end)

Zone	$\overline{m}$	$\overline{PR}$	$\overline{AR}$	AR (end)
1 Sandstones	0.245	3.98	0.46	0.28
2 Phyllites				
3 Mica schists				
4 Granites				

The ideal tunnelling predicted in the phyllites and schists clearly indicates the great benefit of TBM tunnelling. In this example the massive, hard-to-bore sandstones and granites occur at either end of the tunnel, and could be drill-and-blasted while waiting for TBM delivery.

## 12 CONCLUSIONS

This brief comparison of the two principal tunnelling methods used in rock, has drawn attention to some potential errors in our profession, and the need for careful planning for the best alternatives

In rock tunnelling it is clear that costly and time-consuming errors can be made by the wrong choice of method (TBM instead of drill-and-blast *or* vice versa). We have seen that sometimes the *hybrid* solution can be the best choice from the start. While waiting for TBM delivery, one or both portals can be driven, or a central section opened in one or both directions, as recently done at the Qinling Tunnel in China, when TBM progress was less than expected.

In a worked example we have seen that estimation of TBM progress rates through different geological zones may highlight the need for a hybrid solution. Both drill-and-blast and TBM tunnelling will benefit from such decisions; the excellent reputation of both can be preserved, and there will be less claims and conflicts.

The key to such decisions is a good pre-investigation (geological mapping, seismic refraction, core drilling, rock mass characterisations, some lab testing). Longitudinal logs of  $Q$ ,  $Q_0$  and an estimate of  $Q_{TBM}$  (depends on assumed cutter force) are required to make the estimates of relative tunnelling rates (TBM or drill-and-blast) as reliable as possible. The consequences of errors of judgement are extremely costly to the tunnelling industry, as evidenced by too many well-publicised cases.

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