

TBM performance estimation in rock using Q_{TBM}

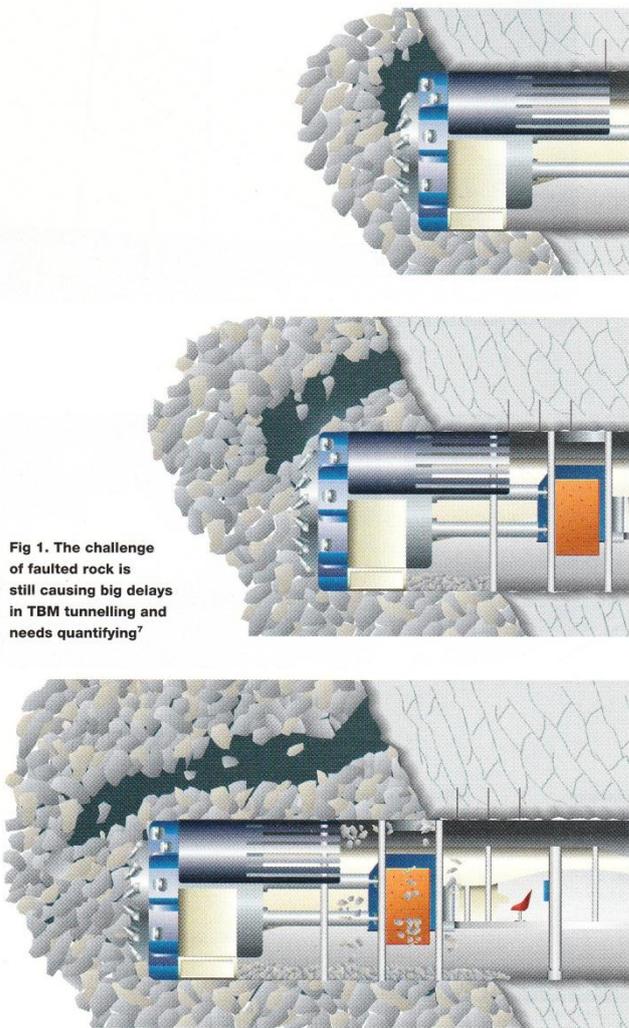
Nick Barton, Technical Adviser, NGI, Norway, Visiting Professor at the University of São Paulo, Brazil, has developed a new method for predicting penetration rate (PR) and advance rate (AR) for TBM tunnelling. This method is based on an expanded Q-system of rock mass classification and average cutter force in relation to the appropriate rock mass strength. Orientation of fabric or joint structure is accounted for, together with the compressive or point load (tensile) strength of the rock. The abrasive or non-abrasive nature of the rock is incorporated via the University of Trondheim cutter life index (CLI). Rock stress level is also considered. The new parameter Q_{TBM} can be estimated during feasibility studies, and can also be back calculated from TBM performance during tunnelling.

TBM tunnelling may give extremes of 15km/year and 15m/year, sometimes even less. The expectation of fast tunnelling places great responsibility on those evaluating the geology and hydrogeology along a planned tunnel route. When rock conditions are reasonably good, a TBM may be two to four times faster than drill+blast. The problems lie in the extremes of rock mass quality, which can be both too bad, as in Fig 1, and too good (no joints), where alternatives to TBM methods may be faster.

There has been a long-standing challenge to develop a link between rock mass characterisation and essential machine characteristics such as cutter load and cutter wear, so that surprising rates of advance (or slowness) become the expected rates. Even from a 1967 TBM tunnel Robbins' could report 7.5km of advance in shale during four record breaking months. Yet, earlier in the same project, 270m of unexpected glacial debris had taken nearly seven months. Advance rates (AR) of 2.5m/h that can decline to 0.05m/h in the same project need to be explained by a quantitative rock mass classification.

A penetration rate (PR) pushing 10m/h for short periods is so different from an advance rate through a major regional fault zone as slow as 0.005 m/h that a large range of quality seems to be required. The new parameter Q_{TBM} can range over 12 orders of magnitude but each end of the scale is exceptionally unfavourable for progress and project economy.

Fig 1. The challenge of faulted rock is still causing big delays in TBM tunnelling and needs quantifying?



Q and Q_{TBM}

The Q-system was developed in 1974 from drill+blast tunnel case records and now totals 1250 cases⁴. By good fortune, Q-values already stretch over six orders of magnitude of rock mass quality. Continuous zones of squeezing rock and clay may have Q = 0.001, while virtually unjointed hard massive rock may have Q = 1000. Both conditions are usually extremely unfavourable for TBM advance, one stopping the machine for extended periods and requiring heavy pre-treatment and support, the other perhaps slowing average progress to 0.2m/h over many months due to multiple daily cutter shifts.

The general trends for PR with uninterrupted boring, and actual AR measured over longer periods is shown in Fig 2. The Q-value goes a long way to explain the different magnitudes of PR and AR but it is not sufficient without modification and the addition of some machine-rock interaction parameters.

Recently, a new method has been developed for estimating both PR and AR using both the Q-value and a new term: Q_{TBM}¹. This is strongly based on the familiar 'Q' parameters but has additional rock-machine-rock mass interaction parameters. Together, these give a potential 12 orders of magnitude range of Q_{TBM}. The exact value depends on the cutter force.

Fig 3 can be used to illustrate four basic classes of rock tunnelling conditions that need to be described in some quantitative way:

1. Jointed, porous rock, easy to bore, some rock support
2. Hard, massive rock, tough to bore, frequent cutter change, no support
3. Overstressed rock, squeezing, stuck machine, needs over-boring, heavy support
4. Faulted rock, overbreak, erosion of fines, long delays for drainage, grouting, temporary steel support, back-filling.

The new term Q_{TBM} incorporates parameters that take account of such rock conditions and the all important reaction of the TBM to the conditions.

The conventional Q-value, together with the cutter life index⁵ and quartz content help to explain some of the delays involved. The Q-value can also be used to help select support once differences between drill-blast logging and TBM logging are correctly quantified in the 'central threshold' area of the Q-diagram¹.

A definition of Q_{TBM} is given in Fig 4, and some adjectives at the top of the figure suggest the ease or difficulty of boring. (Note the difference to the Q-value adjectives used in Fig 2, which describe rock mass stability and need of tunnel support.) The components of Q_{TBM} are as follows:

$$Q_{TBM} = \frac{RQD_0}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_0}{5} \quad (1)$$

Where RQD₀ = RQD (%) interpreted in the tunnelling direction. RQD₀ is also used when evaluating the Q-value for rock mass strength estimation (equations 2 and 3).

J_n, J_r, J_a, J_w and SRF ratings are unchanged, except that J_r and J_a should refer to the joint set that most assists (or hinders) boring.

F = average cutter load (tnf) through the same zone, normalised by 20 tnf (the reason for the high power terms will be seen later)

SIGMA = rock mass strength estimate (MPa) in the same zone.

CLI = cutter life index (e.g. 4 for quartzite, 90 for limestone)⁵.

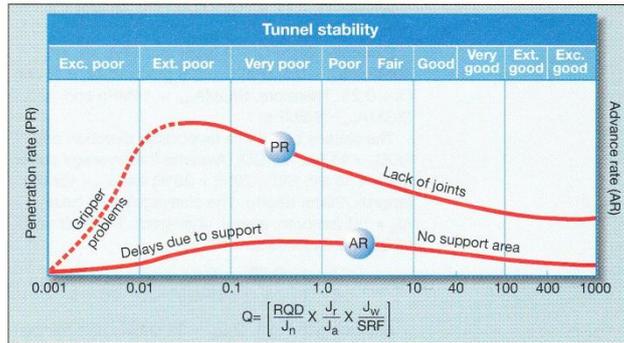


Fig 2 (above). A conceptual relation between Q, PR and AR needs some rock-machine interaction parameters for proper quantification

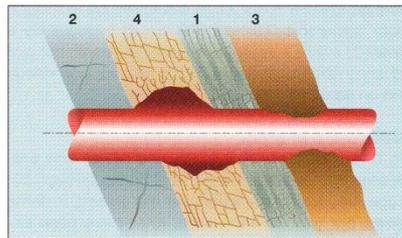


Fig 3 (left). Four broad classes of tunnelling conditions²

q = quartz content in percentage terms
 σ_0 = induced biaxial stress on tunnel face (approx. MPa) in the same zone, normalised to an approximate depth of 100m.

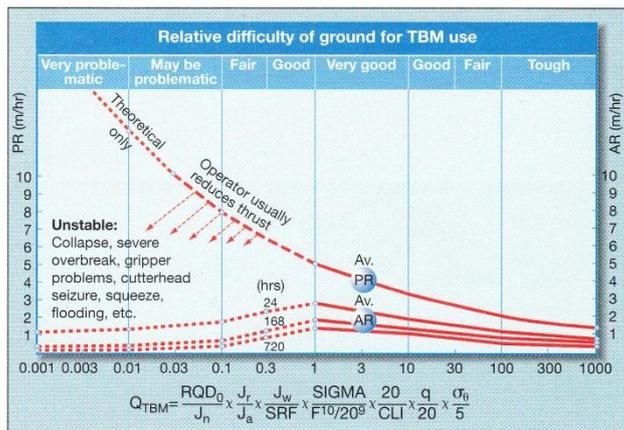
The statistics for each parameter, or best estimates, should be assembled on a geological/structural longitudinal section of the planned (or progressing) tunnel.

The rock mass strength estimate (SIGMA) incorporates the Q-value (but with oriented RQD₀), together with the rock density (from an idea by Singh⁶). The Q-value is normalised by uniaxial strengths (σ_c) different from 100MPa (typical hard rock) and is normalised by point load strengths (l_{50}) different from 4MPa. A simplified (σ_c/l_{50} conversion of 25 is assumed. Relevant l_{50} anisotropy in relation to the direction of tunnelling should be quantified by point load tests in the case of strongly foliated or schistose rocks. The choice between SIGMA_{cm} and SIGMA_{tm} will depend on orientation¹.

$$SIGMA_{cm} = 5.7 Q_c^{1/3} \quad (2)$$

$$SIGMA_{tm} = 5.7 Q_t^{1/3} \quad (3)$$

Fig 4. Suggested relation between PR, AR and Q_{TBM} (see text for explanation of symbols)



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Where: $Q_c = Q \cdot \sigma_c / 100$; $Q_t = Q \cdot I_{50} / 4$; and $\gamma =$ density (gm/cm^3).

Example: Slate $Q \approx 2$ (poor stability); $\sigma_c \approx 50\text{MPa}$; $I_{50} \approx 0.5\text{MPa}$; $\gamma = 2.8 \text{ gm/cm}^3$; $Q_c = 1$; and $Q_t = 0.25$. Therefore, $\text{SIGMA}_{cm} \approx 14\text{MPa}$ and $\text{SIGMA}_{tm} \approx 8.8\text{MPa}$.

The slate is bored in a favourable direction and $\text{RQD}_0 = 15$ (i.e. $< \text{RQD}$). Assume that average cutter force = 15 tnf; $\text{CLI} = 20$; $q = 20\%$; and $\sigma_a = 15\text{MPa}$ (approx. 200m depth). The cleavage joints have $J_a / J_s = 1/1$ (smooth, planar, unaltered). The estimate of Q_{TBM} is as follows:

$$Q_{\text{TBM}} = \frac{15}{6} \times \frac{1}{1} \times \frac{0.66}{1} \times \frac{8.8}{15^{10}/20^9} \times \frac{20}{20} \times \frac{20}{20} \times \frac{15}{5} \approx 39$$

According to Fig 4, $Q_{\text{TBM}} \approx 39$ should give fair penetration rates (about 2.4m/h). If average cutter force were doubled to 30 tnf, Q_{TBM} would reduce to a much more favourable 0.04 and PR would increase by a factor $2^2 = 4$ to a potential 9.6m/h. However, the real advance rate would depend on tunnel support needs and on conveyor capacity.

Case record analysis

Fig 5 is a log-log plot of PR and AR as one progresses from average PR for 1h of boring through average AR per day, per week, per month and, in some cases, per year. In each case, rates have been expressed as m/h. The figure is based on data from 145 TBM tunnels totalling more than 1000km, and includes hard rock, soft rock, faulted rock and many exceptional cases¹.

The usual relationship between AR and PR is via the utilisation factor U, where:

$$\text{AR} = \text{PR} \cdot U \quad (4)$$

The decelerating trend of all the data can be expressed in an alternative and more useful format:

$$\text{AR} = \text{PR} \cdot T^m \quad (5)$$

where the negative gradient (m) which has units LT^{-2} (deceleration) has the following values, and T is time in hours. (Numbers 1 to 4 refer to trend lines in Fig 5.)

WR (best performances) $m \approx -0.13$ to -0.17 (variable)

1 (good)	$m \approx -0.17$
2 (fair)	$m \approx -0.19$
3 (poor)	$m \approx -0.21$
4 (except. poor)	$m \approx -0.25$

The value of (-) m has a weak relationship with the Q-value when rock conditions are good and a strong relationship with the Q-value when rock conditions are bad. The approximate Q-values: 0.1 = very poor; 0.01 = extremely poor; and 0.001 = exceptionally poor are shown among 'unexpected events' in Fig 5. Table 1 shows approximate values of (-) m in relation to Q-values. These can be refined in the future when it becomes more normal to log Q-values during TBM tunnelling progress.

Cutter wear

The final gradient (-) m will be modified by the abrasiveness of the rock, which is based on a normalised value of CLI, the cutter life index⁵. Values less than 20 give rapidly reducing cutter life, and values over 20 tend to give longer life. A typical value for quartzite might be 4 and for shale, 80. Because of the additional influence of quartz content (q %) and porosity (n %), both of which may accentuate cutter wear, these are also included to give 'fine tuning' of the gradient.

Finally, one must consider tunnel size and support needs. Although large tunnels can be driven almost as fast as (or even faster than) small tunnels in similar good rock conditions¹⁰, more support-related delays occur if the rock is consistently poor in the larger tunnel. Therefore, a normalised tunnel diameter (D) of 5m is used to slightly modify the gradient (m). (Q_{TBM} is already 'adjusted' for tunnel size by the use of average rated cutter force.)

The 'fine tuned' gradient (-) m is estimated as follows:

$$m = m_1 \left(\frac{D}{5} \right)^{0.20} \left(\frac{20}{\text{CLI}} \right)^{-0.15} \left(\frac{q}{20} \right)^{0.10} \left(\frac{n}{2} \right)^{0.05} \quad (6)$$

To give a feel for the influence of (-) m on utilisation and on the declining advance rate, an example is given in Table 2.

Sometimes, PR becomes too fast for the logistics and muck handling. There will then be a local increase in gradient from 1h to 1 day as a more rapid fall in AR occurs¹¹.

Penetration and advance rate in relation to Q_{TBM}

Development of a workable relationship between penetration rate PR and Q_{TBM} was based on a process of trial and error using case records¹. Striving for a simple relationship, and rounding decimal places, the following was obtained:

$$\text{PR} \approx 5 (Q_{\text{TBM}})^{-0.2} \quad (7)$$

From Equation 5 we can therefore also estimate AR as follows:

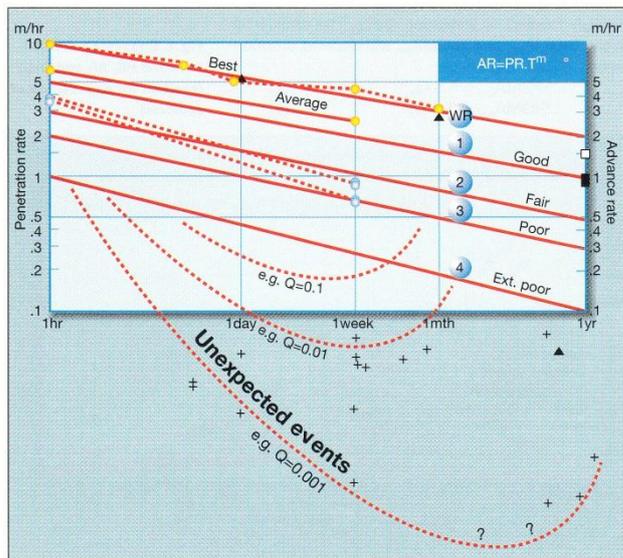
$$\text{AR} \approx 5 (Q_{\text{TBM}})^{-0.2} \cdot T^m \quad (8)$$

We can also check the 'operative' Q_{TBM} value by back calculation from penetration rate:

$$Q_{\text{TBM}} \approx (5/\text{PR})^5 \quad (9)$$

An idea of the big numerical range of Q_{TBM} is given by the values in Table 3 on p34.

Fig 5. Decelerating average advance rate is seen as the unit of time (day, week, month) and tunnel length increase, based on 145 TBM tunnels totalling > 1000km. The three black triangles refer to the Robbins⁷ case records for shale and glacial debris. Yellow (small) circles refer to best and average results at Meraaker HEP⁶. Squares refer to average and best UK Channel Tunnel results⁸ at one year only. Crosses refer to diverse fault zones from widely different geologies. Small (blue) circles refer to a tunnel requiring systematic pre-injection⁹



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We can also back calculate Q_{TBM} from advance rate if the deceleration gradient (-) m is estimated from Table 1 and Equation 6. A weighted mean Q -value for the relevant stretch of tunnel should be adequate for this estimate.

$$Q_{TBM} \approx (5.T^m/AR)^5 \quad (10)$$

For example: if the weekly average is 220m, where 1 week = 110h, this will give $AR = 2m/h$, and $T = 110h$. With $m = (-) 0.2$, $T^m (= U)$ would then be 0.39, and Q_{TBM} would be about 0.9, i.e. mid-range and quite ideal for rapid penetration rate, in this case $PR \approx 5.1m/h$. This almost follows line 1 in Fig 5.

It will be noticed that dotted lines have been used for PR and AR estimates in Fig 4 wherever $Q_{TBM} < 1.0$. This is due to uncertainty as to what operator practices will be and also to the destabilising nature of fault zones, where wrong decisions or non-optimal machines may enhance problems.

The large gradients of (-) m in major fault zones will tend to stop TBM according to Equation 8. Pre-treatment (or post-treatment) to increase the effective Q -value to reduce (-) m and to increase stand-up time will each be needed before TBM progress can be resumed¹.

Estimating times for completion

The time (T) taken to penetrate a length of tunnel (L) with an average advance rate of AR is obviously L/AR . From Equation 5 we can therefore derive the following:

$$T = (L/PR)^{\frac{1}{1-m}} \quad (11)$$

This fundamental equation also demonstrates instability in fault zones, until (-) m is reduced by pre- or post-treatment.

Example: Slate: $Q_{TBM} \approx 39$ (from previous calculation, with 15 tnf cutter force). From Equation 7, $PR \approx 2.4m/h$. Since: $Q = 2$, $m_1 \approx -0.21$ from Table 1. If the TBM diameter is 8m and if $CLI = 45$, $q = 5\%$, and $n = 1\%$, then $m \approx -(0.21) \times 1.1 \times 0.89 \times 0.87 \times 0.97 = -0.17$ from Equation 6. If 1km of slate with similar orientation and rock quality is encountered, it will take the following time to bore it, according to Equation 11:

$$T = (1000/2.4)^{\frac{1}{0.17}} = 1433h \approx 2 \text{ months}$$

i.e. $AR \approx 0.7m/h$, as also found by using Equation 8 and $T = 1433h$.

The advance rate would be affected by cutter shift delays (a less favourable gradient m) if the rock had been more abrasive and more porous. (The latter gives self-sharpening wear due to deeper cutter penetration.) With diameter = 8m and $Q = 2$, light but continuous permanent support would be needed.

Conclusions

A working model for estimating TBM penetration rates and advance rates for different rock conditions, lengths of tunnel and time of boring has been developed. It can be used for prediction and for back analysis. Since the model is new, improvements and corrections will be possible as future case records are tested.

In order to facilitate this process and to quantify any logistical or machine peculiarities at a site, a correction factor F_1 can be added to Equation 6 and a correction factor F_2 can be added to Equation 7. When F_1

and F_2 are appropriately close to unity, no correction to the model is required. The estimations of PR and average gradient (-) m are critical to the successful outcome of the new method and also to the successful outcome of each and every TBM project.

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Table 1. Deceleration gradient (-) m and its approximate relation to Q -value

$Q =$	0.001	0.01	0.1	1	10	100	1000
$m_1 \approx$	-0.9	\approx -0.7	\approx -0.5	-0.22	-0.17	-0.19	-0.21

Unexpected events or expected bad ground. Many stability and support-related delays and gripper problems. Operator reduces PR . This increases Q_{TBM} .

Most variation of (-) m may be due to rock abrasiveness, i.e. cutter life index CLI , quartz content and porosity are important. PR depends on Q_{TBM} .

Note: The subscript (1) is added to m for evaluation of Equation 6

Table 2. Example of declining advance rates for $PR = 3m/h$, $m = (-) 0.2$. Maximum hours (= real time) is assumed here.

Period	PR	1 shift	1 day	1 week	1 month	3 months	1 year
hours	1h	10h	24h	168h	720h	2160h	8760h
U	1.00	0.63	0.53	0.36	0.27	0.22	0.16
AR	3.0	1.9	1.6	1.1	0.8	0.6	0.5m/h

Table 3. Q_{TBM} estimated from mean PR values, using Equation 9

$PR = 0.1$	0.5	1.0	5	10	m/h
$Q_{TBM} = 3.1 \times 10^8$	10^5	3125	1	0.03	