A critique of QTBM

Dr Nick Barton introduced the Q_{TBM} as a new prediction model for TBM performance in T&TI, 1999[1], followed up by several papers also in T&TI about its characteristics and use[2,3,4]. Dr Olav T Blindheim has serious doubts about several of the basic assumptions and finds that the method is clouding rather than clarifying the complex interaction between ground conditions and TBM performance

There is a need for practical and reliable TBM performance prediction models, and many models have been introduced over the last 30 years; some have been outdated and gone out of use, others have been updated and the usefulness improved. An overview of the development, status and requirements to such models is given by this author in *T&TI*, Dec. 2004[5].

The development of prediction models is not simple, as the overall interaction between the different factors is complex and quantification tedious. Some models cover penetration rate only. Others attempt to cover the overall performance as well, and become naturally more complex. Results to be covered are:

- Penetration rate, cutter consumption;
- Utilisation and advance rate;
- Costs.

No model can be expected to be perfect, and several of the existing ones are not necessarily easy to use. A complete model has to treat and include guidance about:

- Geological/geotechnical factors;
- Machine factors;
- Organisational factors.

Barton attempts to cover the whole range with an emphasis on geotechnical factors, and includes, or claims to include, TBM and organisational parameters. Detailed explanations about Q_{TBM} are found in Barton's book[6]. A first critique was presented and discussed on the Norwegian Rock Mechanics Conference in 2002[7]. The available space for this paper does not allow detailed discussions.

Penetration rate (PR)

Barton explains the Q_{TBM} as being an "improved" Q-value relevant for TBM penetration rate (PR). It is developed by the "trial and error" method applied on data from literature review. The formula for PR reads:

$$PR = 5 \times (Q_{TBM})^{-1/5} \text{ (m/h)}$$

As an example, if $Q_{TBM} = 1$, $PR = 5 \times (Q_{TBM})^{-1/5} = 5 \times 1^{-1/5} = 5$m/hr.

PR increases with decreasing Q_{TBM} down to $Q_{TBM} = 1$; for lower Q_{TBM} the achievable PR may be reduced ("operator usually reduces thrust", see Fig 1).

Comment:

- *It is unclear how much original 'raw' observation data from tunnel boring has been available, besides the literature review.*

Content of QTBM

The "preliminary" version of the formula for Q_{TBM} read:

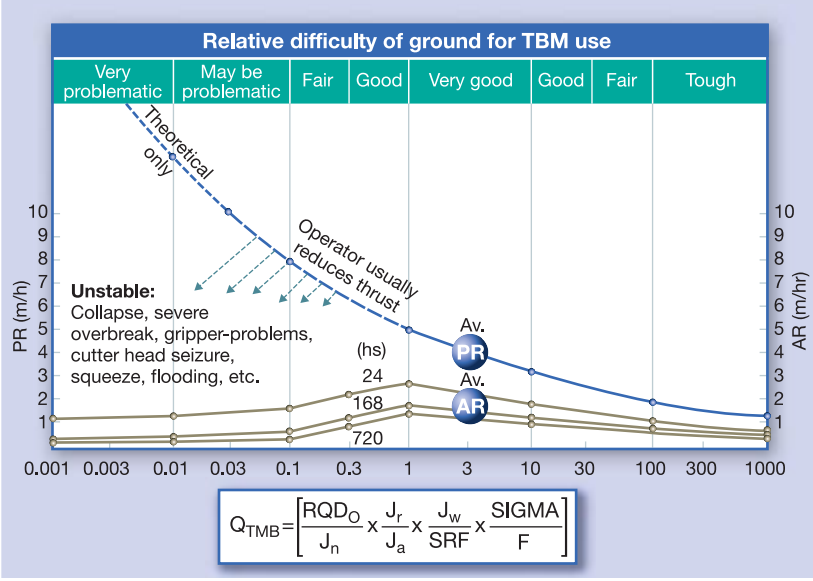

Fig 1 – Penetration Rate (PR) and Advance Rate (AR) as a function of QTBM (Barton, 2003[4])

$$Q_{TBM} = (RQD_o/J_n)x(J_r/J_a)x(J_w/SRF)x(SIGMA/F)$$

In order to better represent his data, Barton introduced a "refined" and expanded version:

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

The terms mean (for more details, see below):

RQD_o = RQD oriented along the tunnel axis

J_n, J_r, J_a, J_w, SRF are old aquiantences from the Q-system

SIGMA = rock mass strength expressed as:

$5\gamma Q_c^{1/3}$ where $Q_c = (\sigma_C/100) \times Q_o$ (Q_o is oriented Q)

or $= 5\gamma Q_t^{1/3}$ where $Q_t = (I_{50}/4)xQ_o$

F = thrust per cutter, tons (~10kN)

CLI = Cutter Life Index (after the NTH/NTNU prediction model[8])

q = quartz content (%)

σ_θ = average bi-axial stresses along the tunnel face.

Comments:

- *The first three links are the same as in the Q system, except that RQD now is oriented along the tunnel axis as RQD_o*
- *These six parameters are also included (to the power of 1/3) in the estimate of rock mass strength (SIGMA).*

Now we will look closer at the content of Q_{TBM}, link by link.

RQD_o/J_n ("block size")

The fraction RQD/Jn is said to express a measure for relative block size, which would appear reasonable to include.

However:

- *RQD is insensitive for high and low frequencies of joints, and RQD/J_n poorly characterises the block size[7].*
- *RQD used for boreability is not sensitive enough for moderately jointed rock masses with high RQD, as early studies confirmed; the orientation of RQD_o along the tunnel does not change this.*
- *J_n depends on the number of joint sets, which as always has to be counted with care and related to the actual location in question.*

J_r/J_a ("shear strength on joint surfaces")

This link is known from the Q system:
J_r = joint roughness number
J_a = joint alteration number

In the Q system, the numbers for the most unfavourable joint set with respect to stability are applied. For Q_{TBM}, Barton claims that it is more relevant to use values for the joint set that is most favourable for the boreability.

Comments:

- *For a joint set with large spacing, an orientation at a shallow angle to the tunnel axis may be favourable; for a small spacing, an orientation at a blunt angle may be favourable, as also is the case for anisotropy. How does one chose?*
- *A lower J_r/J_a will indicate a higher (potential) PR. Where the reduced stability results in need for rock support just behind the cutterhead, the PR must sometimes be reduced (by reducing the thrust) to allow the support to keep up. Barton has recognised this, and indicates that this happens for $Q_{TBM} < 1$. Any guidance to the the size of this effect is not given.*
- *In reality, this is quite complex. If one bores easily with fast strokes, but has to wait for installation of rock support, the reduction belongs under the utilisation, not PR.*

J_w/SRF ("active stresses")

This link may be the one that is most difficult to understand and use in the Q system. This applies also when it is used in Q_{TBM}.
J_w = rating for water softening, inflow and pressure effects
SRF = stress reduction factor

It is correct that a moist or saturated rock material can possibly be bored a little faster than dry rock, due to the well known reduction in strength with increased moisture content for most rocks.

However:

- *The use of Jw as an indicator for PR is highly suspect. Most of the scale for Jw is irrelevant and directly misleading for boreability, as it actually indicates that large water inflow would give increased PR, which is not the case.*
- *The detrimental effect of increased water inflow on performance has to be dealt with in connection with utilisation, and will cause a reduced utilisation and lower advance rate.*

With respect to high rock stresses, it has indeed been observed that the forming of cracks ahead of the face in massive rocks may allow higher PR. An increased SRF (thus lower Q_{TBM}) would simulate that.

However:

- *A reduction in thrust is often necessary (due to impacts on cutters and cutterhead), so the full potential may not be realised; this being highly dependent on the robustness of the TBM.*
- *An increase in SRF due to higher stresses may also indicate increased stability problems, and need for rock support just behind the cutterhead. This would result in reduced PR to allow the rock support to keep up, giving the opposite effect of what is simulated. The effect should also here be treated under utilisation.*
- *J_w/SRF is misleading and not relevant for penetration rate.*

SIGMA/($F^{10}/20^9$), (strength and thrust)

This ratio is said to express 'resistance to boring' (SIGMA) over the 'influence' (by thrust F), which is the inverse of 'effect' or boreability. It is not explained how the thrust is counted: as net or gross force (including friction), for face cutters only, or as an average for all cutters?

With thrust as the only machine parameter:

- *All TBMs are thrown in the same basket, e.g. the difference between shielded and open TBMs is neglected;*
- *Torque is neglected. It is briefly mentioned how torque can vary in relation to thrust, but not how the torque capacity can be highly variable between different TBMs, and thereby determine the achievable penetration rate (in the softer rocks).*

With respect to thrust, it is noted that Barton in some places refers to the effect of thrust in an unclear manner, as it is stated that PR sometimes decrease as increased thrust is applied. This happens only if the rock material becomes stronger or the rock mass becomes more massive.

- The effect of thrust is not clearly explained (or understood?).

Let us take a closer look at the expression for **SIGMA**.

SIGMA = $5\gamma Q_c^{1/3}$ or $5\gamma Q_t^{1/3}$
$Q_c = (\sigma_c/100) \times Q_o$ to be applied for unfavourable joint orientation (small angle to the tunnel axis);
$Qt = (I_{50}/4) \times Q_o$ for favourable joint orientation (large angle to the tunnel axis);
γ = specific gravity (g/cm$^{3)}$
σ_C = uniaxial compressive strength (MPa)
I_{50} = point load strength index for 50mm cores (MPa)
Q_o = oriented Q

This equation is supposed to provide "fine-tuning" for anisotropy. The idea is that at unfavourable angles crushing will dominate, which can be simulated by compressive strength. For favourable angles chipping will dominate, which can better be simulated by a measure for tensile strength.

Note however that:

- *The whole 'package' of Q parametres are included again (in power of 1/3), now corrected for rock material strength, which is missing in the Q system.*
- *Anisotropy is treated in a complex manner, and the total effect becomes difficult to grasp.*

F is thrust per cutter, (ton ~10kN) and is normalised against 20 ton. It is introduced as $F^{10}/20^9$ in order to get the necessary weight in $PR = 5 \times (Q_{TBM})^{-1/5}$. Barton explains that PR often approximately follows a function of thrust to the second power.

Comments:

- *How shall the guidance that "operator usually reduces thrust" for Q_{TBM} below 1 be applied? If one for example uses F=20 and the Q_{TBM} becomes lower than 1, shall then F be reintroduced with a lower value? This is a loop.*
- *A machine parameter does not have a place in a classification system for rock masses. The engineering geologist performing the geological/geotechnical survey would have to assume the type of TBM, and its condition and operation, to assess the input. This may not be known to him and he may not be qualified for this.*
- *The task of assessing suitable thrust should rather belong to a separate (later) step in the performance assessment. This link obscures comparisons of excepted and encountered rock conditions.*

(20/CLI) x (q/20) ("abrasivity")

These two links are treated together, as both relates to abrasivity.

CLI = Cutter Life Index (from the NTH/NTNU prediction model[8])

q = quartz content (%)

Barton's reasoning to include these links in Q_{TBM} is that dull cutter edges gives lower PR.

However:

- *The effect of a 'sharp' (fresh) cutter edge was significant for old 'angled' cutters (with e.g. 60~90 degrees edge angles), but is negligible in total for todays 'constant cross section' cutters.*
- *Experience data indicates that Q_{TBM} by these links has become oversensitive for abrasivity. With respect to PR, this is an*

uncessesary "refinement". It is sufficient to treat abrasivity in relation to utilisation.

σ_θ/5 ("stresses at face")

This link is supposed to correct for the effect that high rock stresses may cause fallouts that will reduce PR, i.e. the opposite effect of the potential help from slabbing/spalling ahead of the face (see above).

$\sigma\theta$ = average biaxial stress on tunnel face

It is explained that fallouts, due to high rock stresses in the tunnel face and walls, will necessitate or result in lower thrust.

However:

- *This parameter could preferably be used as a supporting parameter for estimating thrust reduction and maybe also utilisation. The effect is anyway strongly dependent on machine type and equipment.*
- *The normalisation against 5MPa is explained by; normally there is no reduction of PR until ~100m depth. This appears to be a low figure.*
- *This is a too simplified treatment of a complex issue.*

Summary for Q_{TBM}

In total, Q_{TBM} appears to be far from lucid. Many geo-parameters are put into one big kettle out of which one figure is extracted. Of course, any prediction model that attempts to cover the whole range of factors may need to include a variety of parameters and may become cumbersome to use.

However, it is then important that one is allowed (or forced) to keep the overview. Q_{TBM} is clouding instead of clarifying the interaction. Some of the input parameters are irrelevant or directly misleading for PR, and Important machine parameters are neglected.

Advance rate, utilisation

The advance rate AR (m/h) is found from:

AR = U x PR

$U = T^m$

that is: AR = PR x T^m

U = Utilisation (%)

T = Total time

m = Gradient for reduced performance with increasing time (negative)

The parameter 'm' is explained as the "gradient of deceleration". With this, Barton attempts to express the known effect that the utilisaton is time dependent, and that it often decreases with increasing time. This is usually explained as follows; as the drive gets longer, the occurrence of extreme conditions increases, e.g. wider fault zones etc. In a similar manner, the delays due to transport problems etc often increase.

Barton uses the total time, 24 hours, 365 days a year as reference. For example, 50 hour boring per week gives 50/168 = 30% utilisation. Following normal practise, the utilisation would be 50/110 = 45% if the available shift hours were e.g. 110 hours per week.

Comments:

- *The definition of utilisation is not according to industry practice, which is to refer to available time, i.e. the shifthours and workdays available. This will vary from project to project.*
- *The new definition is somewhat confusing. It means that the time that cannot be used for shifthours (e.g. because of local work regulations, there may be a lack of permission for nighttime boring below cities, national vacations etc) is treated in the same manner as delays due to geological conditions and machine problem.*

'm' ("gradient of deceleration")

The parameter 'm' is a kind of performance indicator. It is stated to express the "coupled performance" of the TBM and the rock mass, as well as factors as:

- level of site investigations
- machine design
- stability support design
- tunnel management

This looks interesting, but is not followed up as the effect of these factors (which includes both machine and organisational parameters) is not outlined or detailed other than by the adjectives shown in Table 1. This classification is stated to come from plotting of performance data for 145 tunnels. A further guidance would have been useful.

Barton does give a guidance how the 'm' value can be chosen based on the rock mass quality expressed by Q. This is shown in Fig. 2, with readings listed in Table 2. One can see that an optimum is indicated for Q = 10 ('fair' – 'good').

However:

- *It is difficult to see why the utilisation should decrease faster (with time) for very good rock as expressed by Q, compared to fair to good. In massive rock, the utilisation is normally at the highest. High Jw or low SRF (little water or moderate stresses) should also not reduce the utilisation.*
- *Worse, it is not explained how values established by Q shall be combined with the other factors as shown above and expressed in Table 1. Examples of misuse, due to lack of understanding or intentionally, have already been experienced.*

Table 1. Levels of 'm' as an performance indicator

Level	Term	m-value
WR	World record	- 0.15
1	Good	- 0.17
2	Fair	- 0.19
3	Poor	- 0.21
4	Extremely poor	- 0.25
	Typical mean	- 0.20
	Pre-injection delays	- 0.45
	Unexpected events	- 0.5 to – 0.9 (temporary)

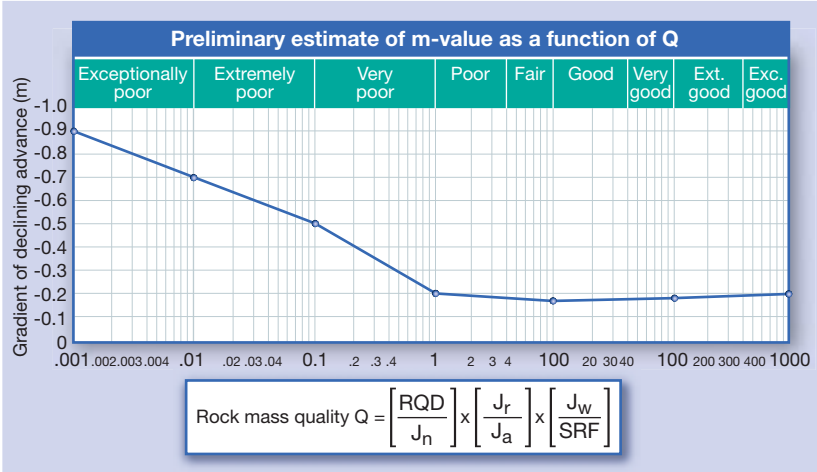

Fig 2. Preliminary estimate of m-value as a function of Q (Fig. 45, Barton, 2000[6])

Table 2. 'm'-values read from Fig 2

Q-value	Quality	m-value
1000	≥ Exc. good	- 0.20
100	Very to Ext. good	- 0.19
10	Fair to Good	- 0.18
1	Very poor to Poor	- 0.20
0.1	Extr. to Very poor	- 0.5
0.01	Exc. to Ext. poor	- 0.7
0.001	≤ Exc. poor	- 0.9

Complete formula for 'm'

The complete formula for 'm' reads:

$m \approx m_1 \times (D/5)^{0.20} \times (20/CLI)^{0.15} \times (q/20)^{0.10} \times (n/2)^{0.05}$

m_1 = basis derived from Q (+ other factors?)
D = tunnel diameter, m (normalised against 5m)
CLI = Cutter Life Index (NTH/NTNU[8])
q = quartz content (%)
n = porosity (%)

The explanation indicates that m_1 is derived from Q (Fig 2, Table 2). Are the other factors mentioned by Barton included? How are the two tables combined?

The tunnel diameter is included, normalised against 5m. This link appears to be explained by the general experience that increased tunnel diameter gives reduced stability, and hence higher 'm' and lower utilisation.

However:

- *The effect may easily be the opposite as increased space besides the TBM allows introduction of support units with high capacity. For small tunnels, lack of space may force inefficient manual support work.*

The next two links (which we recognise from Q_{TBM}) refer to abrasivity, supplemented by porosity in the last link. The latter is explained by that porous (and weak) rocks may give 'selfsharpening' (i.e. wear on the side of the cutter edge, keeping it sharp), which may reduce cutter life.

However:

- *Selfsharpening may also increase penetration rate, thereby increasing cutter life per m^3 rock excavated.*
- *The last link (porosity) should rather have been included in Q_{TBM}.*

Summary for 'm'

The parameter is incomplete; even elementary machine and operational factors are lacking. The basis in relation to Q is very sensitive. Other factors are mentioned but not treated. 'm' can easily be misunderstood or misused.

The use of 'total time' as a basis for utilisation instead of 'available shift hours' is unaccustomed and awkward, and mixes reasons for how the total time is or can be utilised.

Concluding remarks

In general, penetration and advance rate result from a complex interaction of many factors, which are difficult to analyse and even more difficult to quantify. There is a need for several prediction models. Attempts to bring this field forward should be welcomed and not dismissed just because the approach may be different from known models. However, such attempts should contribute to clarification.

Both Q_{TBM} and 'm' are not only highly complex (numerous parameters are mixed into one number), but they do not contribute to clarification. Several of the input parameters are irrelevant or even misguiding for TBM performance, and the total effects are difficult to follow.

Comparisons so far indicate very poor or no correlation to obtained resultats. The model is therefore not recommended for use by this author.

REFERENCES

1. N Barton, 1999: "TBM performance estimation in rock using QTBM", Tunnels & Tunnelling International, Sept.
2. Editorial: 2001:"Are tunnels faster by TBM?", Tunnels & Tunnelling International, June 2001.
3. N Barton, 2003: "TBM or Drill and Blast", Tunnels & Tunnelling International, June.
4. N Barton, 2003:"Employing the QTBM prognosis model", Tunnels & Tunnelling International, December.
5. O T Blindheim, 2004: "TBM performance prediction models", Tunnels & Tunnelling International, December
6. N Barton, 2000: "TBM Tunnelling in Jointed and Faulted Rock", Balkema.
7. A Palmstrøm, O T Blindheim & E Broch, 2002: "The Q-system-possibilities and limitations", Rock Mechanics Conference, Oslo, (in Norwegian).
8. A Bruland, 1998: "Hard Rock Tunnel Boring", Dr. ing. thesis, 10 Volumes of Project reports, Dept. of Building and Construction Engineering, NTNU, Trondheim.