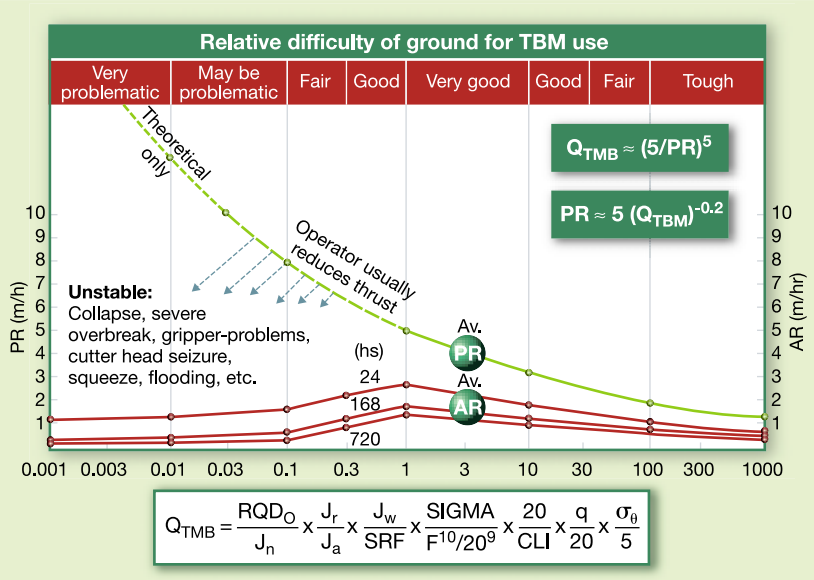
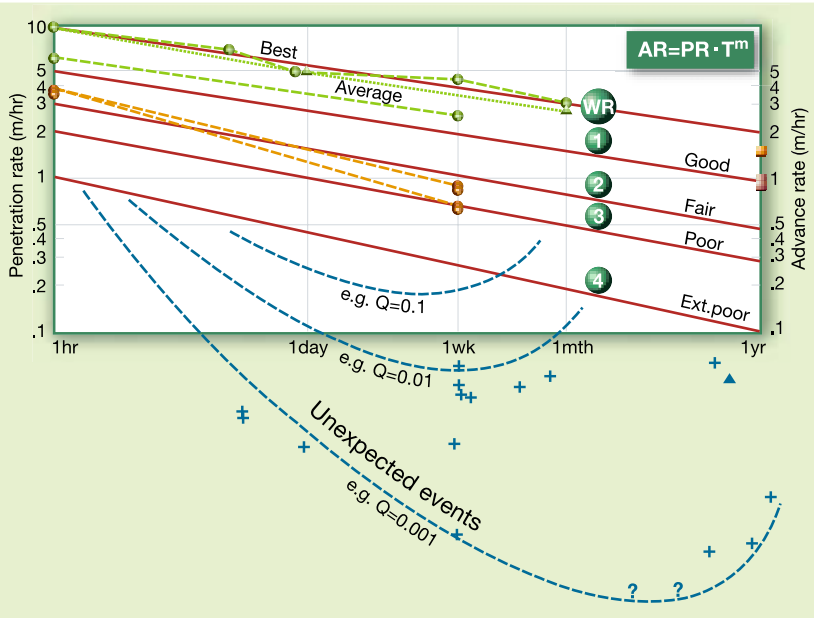
# Employing the $Q_{TBM}$ prognosis model

*Dr Nick Barton, of Nick Barton & Associates, and geologist Ricardo A Abrahão, of Fundação de Ciências Aplicadas e Tecnologia Espaciais (FUNCATE), explain the workings of the $Q_{TBM}$ tunnelling prognosis model, using a variety of geological conditions that give big ranges of tunnelling performance. Their main example reinforces the idea of hybrid tunnelling when great contrasts of conditions are found (see companion article in T&TI, June 2003)*




**Top: Fig 1 - Some principles and definitions of the $Q_{TBM}$ model, that are now incorporated in the numerical version of $Q_{TBM}$**
**Above: Fig 2 - The (usual) law of deceleration as time increases. Typical gradients of decline are m = -0.15 to 0.25, except in fault zones where (m) is steeper, when Q is <0.1**

In a previous article by the first author, entitled 'TBM or Drill and Blast' (*T&TI*, June 2003), mention was made of the QTBM prognosis model. This is a time saving Excel program, developed by co-author Ricardo Abrahão, for estimating the consequences of TBM tunnelling in the differing geological and rock mechanics properties of a site. The input for this model are a variety of engineering geological parameters that are commonly collected during project feasibility and design phases. The output are estimates of penetration rates (PR), and actual advance rates (AR) over calculated periods of time, as each zone (or geological/structural/rock mechanics domain) of given length are penetrated, and supported as necessary.

The program calculates (and graphs) the overall performance, and estimated time of tunnel completion. We will show various examples, and discuss both strengths and weaknesses, and areas where industry input from new TBM designs needs to be incorporated now, and of course in the future.

## Basic elements of $Q_{TBM}$

There are those who think that the standard Q-system for describing rock masses has too many parameters, and others that feel it is already too much of a simplification. The fact is, that we all need design assistance – whether from a life-time of experience, half a life time, or from models, or from trusted 'rules-of-thumb'.

The $Q_{TBM}$ model has a lot of parameters, for which no apology is made. The rock-machine interaction in TBM tunnelling is very complex after all. But with its foundation in the analysis of 140 TBM case records[1], and frequent application since then, a certain feeling for its strengths and weaknesses has been acquired.

Two important diagrams for a rapid understanding of the principles need to be reproduced here for ready reference. They have been seen before by *T&TI*'s readers. Figure 1 shows an example of the basic model with PR and AR on left and right axes, and the 'logarithmic' scale of $Q_{TBM}$ defined along the bottom axis. Figure 2 shows log PR and log AR on left and right axes and log TIME along the bottom axis, showing 1 day, 1 week, 1 month, etc.

## Deceleration

The classic equation relating PR and AR via utilisation (U) is refined as follows in the $Q_{TBM}$ model, to allow for the important factor of time (and tunnel length):

$$AR=PRxU \rightarrow AR=PRxT^{m} \rightarrow U=T^{m}$$

The basic TBM operations are to cut and provide support for a tunnel. This means 100% utilisation while boring one stroke, or 100% utilisation while continuously boring until cutter change (pushing off the PC lining while re-setting the grippers), must inevitably fall when changing the cutters, when performing maintenance, (or when placing necessary support when not using a double-shield–and–lining operation).

Even with these impressive semi-automated techniques, such as used by all four machines at the current Guadarrama Tunnels in Spain, the utilisation is lower over monthly periods, than the 100% used to define the magnitude of PR. Nevertheless, it is reported that well in excess of 40% utilisation per month has been achieved while driving the four faces at Guadarrama, a combined total of about 25km by the time this article is printed. This utilisation of 40% or more, gives a remarkably shallow gradient (*-m*) of deceleration (see Figure 2), which we can express from the above as:

$$m=\log U/\log T$$

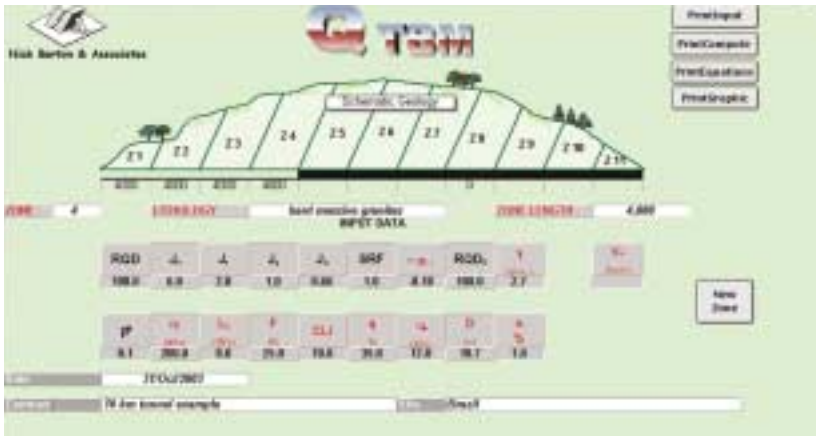
With 1 month expressed as a continuous 720 hours, and the assumed U expressed as a fraction 0.40, the gradient (-)m of deceleration is found to be less than (-) 0.14. This is a remarkable result in view of the hardness of the rock, and the reported need for quite frequent cutter changes.

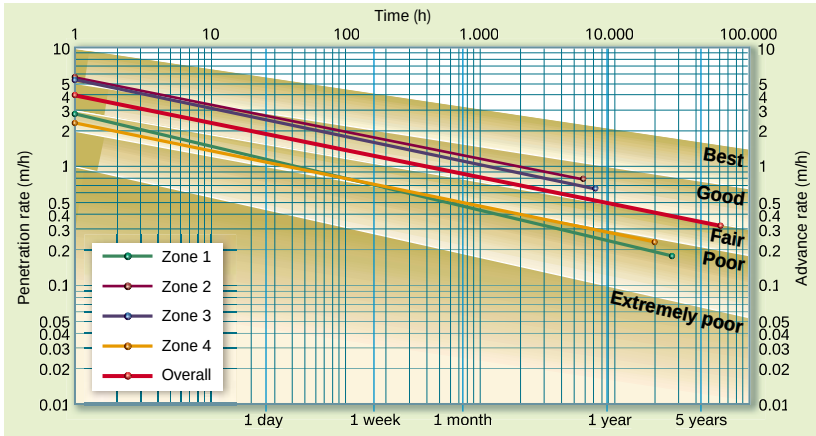
## Hand-worked example and Excel result

A major planned project in Brazil, the San Francisco River Water Transfer Project - to arid regions in the NE of Brazil - had a 16km long tunnel in an earlier stage of planning (this has now been altered a little). The longer tunnel is a convenient project for illustrating the $Q_{TBM}$ model, as it had almost equal lengths of km in hard massive sandstones, jointed phyllites, jointed mica schists and hard massive granites, respectively. These gave contrasting tunnel-speed prognoses, suggesting a hybrid (TBM + drill and blast) solution, a possible solution discussed in Barton, 2003[3], for maintaining the good reputation of both tunnelling methods, when contrasting conditions are found in the same project.

A worked example of this 16km long tunnel shows the successive stages of (hand) calculation, and the equations used at each stage of calculation (see Tables A to H, p22).

Due to decimal rounding, the $Q_{TBM}$ Excel program follows an abbreviated path compared to the above, and in a few minutes of carefully applied input data, on four separated 'key-boards' (the last of which is shown in Figure 3), supplies both the full tabulated calculations in Excel, and the graphic output shown in Figure 4.






**Top: Fig 3 - The last 'key-board' for the 12km-16km zone of the tunnel**

**Above: Fig 4 - The log-log plot of PR and AR and TIME. The phyllite and mica schist show the best result, while the massive sandstone and granite show the worst**

## Tackling variability

In a second example we demonstrate what variable conditions may do to TBM progress, as modelled by the $Q_{TBM}$ model. For purposes of illustration, we

**Right and below: Reproduced 'Input data' and 'Basic calculation' tables; for the first 0.5km of a tunnel with widely different conditions for each 100m**

**Table 2: Basic calculation**

| Zone | Lithology | Stability | oriented | Rock mass strength | | | | | Q | Gradient |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Q | Q0 | Qc | QT | $SIGMA_{CM}$ | $SIGMA_{TM}$ | SIGMA | $_{TBM}$ | m |
| 1 | fault | 3E-3 | 3E-3 | 1.6E-4 | 3.9E-5 | 0.59 | 0.37 | 0.37 | 0.09 | -0.69 |
| 2 | sandstone | 3.30 | 2.20 | 1.10 | 2.20 | 12.90 | 16.26 | 12.90 | 63.01 | -0.19 |
| 3 | granite | 300.00 | 300.00 | 750.00 | 1,125.00 | 127.20 | 145.61 | 127.20 | 2,458.41 | -0.24 |
| 4 | fault | 1.00 | 1.00 | 0.10 | 0.13 | 5.11 | 5.50 | 5.11 | 261.41 | -0.37 |
| 5 | tuff | 2.50 | 2.00 | 1.00 | 1.25 | 11.00 | 11.85 | 11.00 | 0.07 | -0.18 |
| 6 | | | | | | | | | 0.00 | 0.00 |
| 7 | | | | | | | | | 0.00 | 0.00 |
| 8 | | | | | | | | | 0.00 | 0.00 |
| 9 | | | | | | | | | 0.00 | 0.00 |
| 10 | | | | | | | | | 0.00 | 0.00 |
| 11 | | | | | | | | | 0.00 | 0.00 |

**Table 1: Input data**

| Zone | Lithology | RQD | $J_n$ | $J_r$ | $J_a$ | $J_w$ | SRF | $m_1$ | $RQD_0$ | γ | ß | $\sigma_c$ | $I_{50}$ | F | CLI | q | $\sigma_e$ | D | n | L | Vp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | fault | 10.00 | 20.00 | 1.00 | 8.00 | 0.50 | 10.00 | -0.70 | 10.00 | 2.20 | 0.00 | 5.00 | 0.05 | 10.00 | 35.00 | 25.00 | 10.00 | 5.00 | 5.00 | 100.00 | 0.00 |
| 2 | sandstone | 60.00 | 9.00 | 1.50 | 2.00 | 0.66 | 1.00 | -0.18 | 40.00 | 2.50 | 25.00 | 50.00 | 4.00 | 15.00 | 20.00 | 25.00 | 10.00 | 5.00 | 5.00 | 100.00 | 0.00 |
| 3 | granite | 100.00 | 2.00 | 3.00 | 1.00 | 1.00 | 0.50 | -0.19 | 100.00 | 2.80 | 0.00 | 250.00 | 15.00 | 25.00 | 5.00 | 30.00 | 10.00 | 5.00 | 1.00 | 100.00 | 0.00 |
| 4 | fault | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.40 | 0.00 | 2.20 | 0.00 | 10.00 | 0.50 | 10.00 | 50.00 | 25.00 | 10.00 | 5.00 | 5.00 | 100.00 | 2.50 |
| 5 | tuff | 50.00 | 15.00 | 1.50 | 2.00 | 1.00 | 1.00 | -0.19 | 40.00 | 2.20 | 0.00 | 50.00 | 2.50 | 25.00 | 35.00 | 10.00 | 10.00 | 5.00 | 25.00 | 100.00 | 0.00 |
| 6 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |
| 7 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |
| 8 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |
| 9 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |
| 10 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |
| 11 | | | | | | | | | | | | | | | | | | | | 0.00 | 0.00 |

## a) Stability (and gradient $m_1$)

$$Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right)_s \times \left(\frac{J_w}{SRF}\right)$$

($_s$=least favourable for **stability**)

| Zone | $m_1$ | $RQD/J_n$ | $J_r/J_a$ | $J_w/SRF$ | Q |
|---|---|---|---|---|---|
| 1 Sandstones | -0.17 | 100/9 | 2/1 | 0.5/1 | 11.1 |
| 2 Phyllites | -0.19 | 35/9 | 1.5/1 | 1.0/1 | 5.8 |
| 3 Mica schists | -0.20 | 50/9 | 1.0/1 | 0.66/1 | 3.7 |
| 4 Granites | -0.18 | 100/6 | 2/1 | 0.66/1 | 22.0 |

## b) Oriented Qo (in tunnelling direction)

$$Q_o = \left(\frac{RQD_o}{J_n}\right) \times \left(\frac{J_r}{J_a}\right)_c \times \left(\frac{J_w}{SRF}\right)$$

($_c$=most affecting **cutters**)

| Zone | Deg (°) | $RQD_o/J_n$ | $(J_r/J_a)_o$ | $J_w/SRF$ | $Q_o$ |
|---|---|---|---|---|---|
| 1 Sandstones | 20/70 | 100/9 | 2/1 | 0.5/1 | 11.1 |
| 2 Phyllites | 60 | 30/9 | 1.5/1 | 1.0/1 | 5.0 |
| 3 Mica schists | 60 | 45/9 | 1.0/1 | 0.66/1 | 3.3 |
| 4 Granites | 10/80 | 100/6 | 2/1 | 0.66/1 | 22.0 |

## c) Rock mass strength (SIGMA)

$$SIGMA_{cm} = 5\gamma Q_c^{1/3}$$

$$SIGMA_{tm} = 5\gamma Q_t^{1/3}$$

$$\left(Q_c = Q_o \times \frac{\sigma_c}{100}\right)\left(Q_t = Q_o \times \frac{I_{50}}{4}\right)$$

| Zone | $\gamma$ | $\sigma_c$ | $Q_c$ | $SIGMA_{cm}$ (MPa) | $I_{50}$ | $Q_t$ | $SIGMA_{tm}$ (MPa) |
|---|---|---|---|---|---|---|---|
| 1 Sandstones | 2.5 | 125 | 13.9 | 30.1 | 5 | 13.9 | 30.05 |
| 2 Phyllites | 2.6 | 75 | 3.8 | 20.2 | 1 | 1.25 | 14.0 |
| 3 Mica schists | 2.6 | 150 | 5.0 | 22.2 | 4 | 3.3 | 19.35 |
| 4 Granites | 2.7 | 200 | 44.0 | 47.7 | 8 | 44.0 | 47.66 |
| | | (‖ or ⊥) | | | (‖ or ⊥) | | |

## d) $Q_{TBM}$

$$Q_{TBM} = Q_o \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

($\times\ 20^9/F^{10}$ =0.0054 with 25tnf/cutter)

F=mean cutter force
CLI=cutter life Index (NTNU)
q=% quartz
$\sigma_\theta$=biaxial stress (5 MPa/ 100m depth

| Zone | $Q_o$ | SIGMA (MPa) | F (tnf) | CLI | q (%) | $\sigma_\theta$ (MPa) | $Q_{TBM}$ |
|---|---|---|---|---|---|---|---|
| 1 Sandstones | 11.1 | 30.05 | 25 | 10 | 70 | 8 | 20.07 |
| 2 Phyllites | 5.0 | 14.00 | 25 | 20 | 20 | 8 | 0.60 |
| 3 Mica schists | 3.3 | 19.35 | 25 | 15 | 20 | 8 | 0.73 |
| 4 Granites | 22.0 | 47.66 | 25 | 10 | 35 | 12 | 44.28 |

## e) Gradient (-)m

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

| Zone | $m_1$ | D | n (%) | m |
|---|---|---|---|---|
| 1 Sandstones | -0.17 | ø 10.7 (m) | 15 | -0.28 |
| 2 Phyllites | -0.19 | | 5 | -0.23 |
| 3 Mica schists | -0.20 | | 2 | -0.24 |
| 4 Granites | -0.18 | | 1 | -0.24 |

## 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 | 20.07 | 2.74 | 0.17 |
| 2 Phyllites | 0.60 | 5.54 | 0.76 |
| 3 Mica schists | 0.73 | 5.32 | 0.63 |
| 4 Granites | 447.28 | 2.31 | 0.23 |

## 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 | -0.28 | 1.39 | 23,204 | 4000 | 2.66 yrs |
| 2 Phyllites | 4000 | -0.23 | 1.30 | 5,256 | 4000 | 0.60 yrs |
| 3 Mica schists | 4000 | -0.24 | 1.32 | 6,307 | 4000 | 0.72 yrs |
| 4 Granites | 4000 | -0.24 | 1.32 | 17,656 | 4000 | 2.02yrs |

∑L=16000 (m) ∑T=52,423 (hrs) =(6.00 yrs)

*rough check of AR x T=L(errors will occur if decimal places are rounded)

## h) Overall performance

PR,AR (weighted mean),∑L

$$\overline{PR} = \left(\frac{PR_1L_1 + PR_2L_2 etc}{L_1 + L_2 etc}\right)$$

$$\overline{AR} = \left(\frac{AR_1T_1 + AR_2T_2 etc}{T_1 + T_2 + T_3 etc}\right)$$

| Zone | L (m) | T hours | $PR_{mean}$ | $AR_{mean}$ |
|---|---|---|---|---|
| 1 Sandstones | 4000 | 23,204 | = 3.98 m/hr | = 0.31 m/hr |
| 2 Phyllites | 4000 | 5,256 | | |
| 3 Mica schists | 4000 | 6,307 | | |
| 4 Granites | 4000 | 17,656 | | |

∑L=16.000 (km) ∑T=52,423 hours = 72.8 months

**Above: Tables A to H - A worked example of the 16km long San Francisco River Water Transfer Tunnel, in Brazil, shows the successive stages of (hand) calculation, and the equations used at each stage of calculation**

consider five 100m long, consecutive domains, making the first 0.5km of a tunnel. The five 'key-boards' of input data are recorded at the top of the Excel three-part table, reproduced as Tables 1 to 3. Table 2 shows the basic calculations of extremely variable $Q_{TBM}$ values (min = 0.07; max = 2,458). Note also the variable final gradients of deceleration (-)m (derived from the 'fine-tuning' seen in Table E of our hand-calculation for the 16km tunnel).

Figure 5 shows the variability of these domains most clearly. Time of completion for this first 0.5km is predicted to be six months, due to the big initial delay in a serious fault zone, which was penetrated 'too fast' (PR too high due to unnecessarily high F). A blocked cutter-head or local collapse would be the likely result. The need for pre-treatment (from the surface?) or avoidance, is very clear, as the fault spoils the schedule completely, pulling down the overall gradient.

### Discussion

In the above example of 0.5km of variability, we have two fault zones, one of which was 'defined' by seismic velocity. Care should be taken to allow for the compacting effect of significant tunnel depth when using P-wave velocity[2]. We have experience of deeply buried fault zones with unexpectedly high (seismic-tomography-determined) velocities, yet very low Q-values, causing six months delay to the TBM tunnelling.

The contrasting effect of weak, jointed tuff, compared to hard massive granite is well illustrated by the contrasting values of $Q_{TBM}$ in Table 2. The same cutter force of 25t was selected for each, just for illustration. As will be seen in the equations tabulated in our hand-calculation sheets, the $Q_{TBM}$ value can be back-calculated from the PR results at a tunnel project. In our example PR differs from 1.05m/hr in the hard massive granite ($Q_{TBM}$ = 2,458) to 8.57m/hr in the medium strength, jointed tuff ($Q_{TBM}$ = 0.07). As we have seen, the effective gradient of deceleration (-)m can also be back-calculated from the utilisation being achieved in an existing project, but when, and only when, the time period is clearly defined.

From recent, highly successful semi-automated double-shield–and–lining projects, we note that the effective gradient is reduced compared to projects where a cheaper lining is selected, as the re-setting of the grippers is one of the utilisation delays when there is no lining to take the thrust while the grippers are re-set.

So far during the development of $Q_{TBM}$, we have found that the initial gradient (-)m of deceleration is strongly linked to the conventional Q-value of rock mass quality, as per the table below. The strong linkage to Q is weakened however, when the rock is of high quality. If the effective gradients of deceleration (-)m derived from utilisation records can be as low as (-)0.12 to (-)0.13 by the extra investment in double-shield–and–lining methods, the question needs to be raised: "how far into the low Q-value area will this apply?" Can many untreated faults be penetrated with few delays, using such techniques?

| Q | 0.001 | 0.01 | 0.1 | 1.0 | 10 | 100 | 1000 |
|---|---|---|---|---|---|---|---|
| (-)$m_1$ | 0.9 | 0.7 | 0.5 | 0.2 | 0.17 | 0.18 | 0.20 |

Grandori et al. 1995[4], in a classic comparison of two open TBMs and two double-shield TBMs used at the Evinos-Mornos water transfer tunnel, found that general performances were equal, better, and considerably better, with the latter when the RMR value was steadily reducing below about 60 (or Q about 5). However, the comparison did not include stand-stills due to collapse

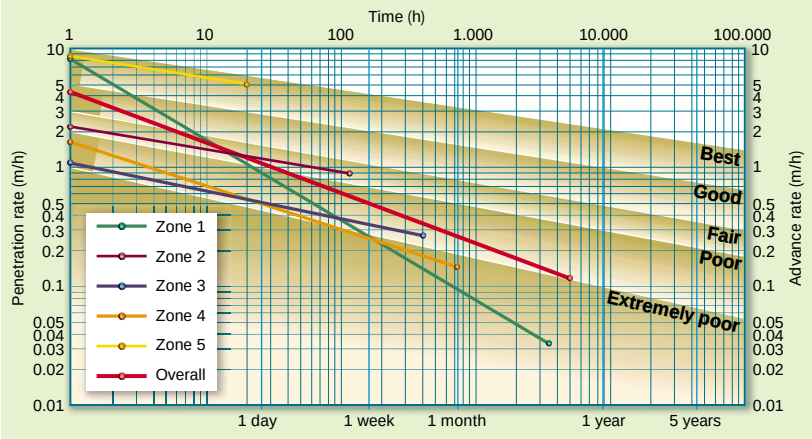
and squeezing ground. It may be so that collapses are more difficult to recover from when the support technique is semi-automated and 'easier' with an open TBM, because of relatively 'easier' access for 'conventional' reinforcement and grouting equipment.

We need at any rate, to be aware of the potentially (25%-30% or more?) reduced deceleration gradient (-)$m_1$ over presumably a quite wide range of conditions (or Q-values), if the extra investment in a double-shield–and–lining tunnelling system is to be used. It would be of great value if the industry would report more widely on utilisation rates over specified time intervals for the different TBM solutions that are presently available.

An all-important additional data set would be the approximate Q-value (or RMR) ranges of rock quality. We may also note that effective Q-values (and RMR values) can be improved by pre-injection (e.g. Barton, 2002[2]), although from behind a cutterhead, this process is usually incomplete, e.g. 10 o'clock to 2 o'clock only, but perhaps enough to improve arch stability. T&T

## REFERENCES


1. N Barton, 2000. "TBM tunnelling in jointed and faulted rock" 173p, Balkema, Rotterdam.
2. N Barton, 2002. "Some new Q-value correlations to assist in site characterisation and tunnel design" Int. J. Rock Mech. & Min. Sci. Vol. 39/2.
3. Barton, 2003. "TBM or drill and blast" Tunnels & Tunnelling International, Vol. 35/6.
4. R Grandori, M Jaeger, F Antonini & L Vigl, 1995. Evinos-Mornos Tunnel - Greece. "Construction of a 30km long hydraulic tunnel in less than three years under the most adverse geological conditions" Proc. RETC, San Francisco, CA.


**Above: Fig 5 - The log PR, log AR and time prognoses for the 0.5km of variable conditions. Each domain is 100m long**

**Below: Reproduced 'Performance' table**

**Table 3: Performance**

| Zone | Lithography | Penetration | | Time to advance | | Overall performance | | |
|---|---|---|---|---|---|---|---|---|
| | | PR | AR | T | check | ∑L | ∑T | |
| 1 | fault | 8.18 | 0.03 | 3,134.12 | 100.00 | | | PRL(av) |
| 2 | sandstone | 2.18 | 0.88 | 114.12 | 100.00 | | | |
| 3 | granite | 1.05 | 0.26 | 387.39 | 100.00 | 500.00 | 4,359.15 | 4.33 |
| 4 | fault | 1.64 | 0.14 | 703.16 | 100.00 | m | h | |
| 5 | tuff | 8.57 | 4.91 | 20.37 | 100.00 | | | |
| 6 | | 0.00 | 0.00 | 0.00 | 0.00 | | | ART(av) |
| 7 | | 0.00 | 0.00 | 0.00 | 0.00 | | | |
| 8 | | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 6.005 | |
| 9 | | 0.00 | 0.00 | 0.00 | 0.00 | km | month | 0.11 |
| 10 | | 0.00 | 0.00 | 0.00 | 0.00 | | | |
| 11 | | 0.00 | 0.00 | 0.00 | 0.00 | | | |