TBM prognoses in hard rock with faults using Q_{TBM} methods

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ABSTRACT

As an indirect result of several seriously delayed TBM projects, where the writer was eventually engaged as an outside consultant, a wide-reaching survey of case records was undertaken Barton (2000), in order to try to find a better basis for TBM advance rate prognosis, *that also included poor rock conditions*. It appeared that 'poor conditions' as relating to faults were usually treated as 'special cases' in the industry, with concentration mostly on solving the penetration rate (PR) and cutter life aspects of TBM prognosis. Experiences with actual tunnelling problems are therefore addressed, in order to show how good performance may be altered either in only minor ways by faults, or sometimes with dramatic consequences. A satisfactory range of penetration rates (PR) is only part of the possible success of TBM. These machines can achieve remarkable advance rates (AR) only when overall conditions are favourable, then out-performing drill-and-blast tunnelling by a wide margin. Without this pre-condition, the TBM results may be less than desired.

1 INTRODUCTION

TBM tunnelling and drill-and-blast tunnelling show some initially confusing reversals of logic, with best quality rock giving best advance rates in the case of drill-and-blast, since support needs may be minimal, whereas TBM may be penetrating at their slowest rates in similar massive conditions, due to rock-breakage difficulties, cutter wear, and the need for too-frequent cutter change, the latter affecting the advance rate AR. This 'reversed' trend for TBM in best quality, highest velocity (V_P) rock is demonstrated by the PR-V_P data from some Japanese tunnels, reproduced in Figure 1, from Mitani et al. (1987).

At the low velocity, high PR end of this data set, there will not be a need for frequent cutter change, but conversely there will be delays for much heavier support. If on the other hand velocities reach as high as about 5.5-6.5 km/s (i.e. Q > 100, and high UCS) due to exceptionally massive rock, this is also 'difficult ground' for TBM, and in exceptional cases PR may dip below 0.5 m/hr, if under-powered.

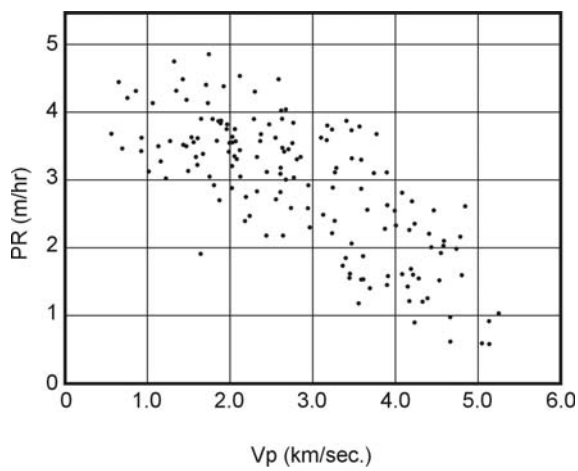

Figure 1: Declining TBM penetration rate PR with elevated seismic velocity. Mitani et al. (1987).

2 A SURVEY OF 145 TBM TUNNELS

A review of TBM tunnelling case records totalling 1000 km, with widely varying rock conditions, that were well described since mostly from open gripper TBM, showed general 'deceleration' trends (equation 2, and Figure 2), when advance rate expressed in m/hr was plotted for various time periods. The classic 'TBM-equation' linking advance rate to penetration rate in fact needs to be modified to a time-dependent form, to capture this reality, as indicated below:

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

(where U= utilization for uninterrupted boring)

$$AR = PR \times T^m \quad (2)$$

(where m is a negative gradient, and T is actual hours)

Equation 2 can accommodate the fact that there is a general, inevitable slowing-up for reasons of logistics (extended services, extended conveyor, rails etc.) plus wear, and maintenance involving replacement of certain TBM components. This stands in strong contrast to the 'learning curve' speed-up, of e.g. monthly rates, usually experienced in the first months of numerous projects. The deceleration is a 'fact-of-life', however much it may be downplayed. AR_{mean} (when expressed in m/hr) has to decline when (1 hour: for PR), 1 day, 1 month, 1 year are each evaluated in turn for any given project, even for record-breakers.

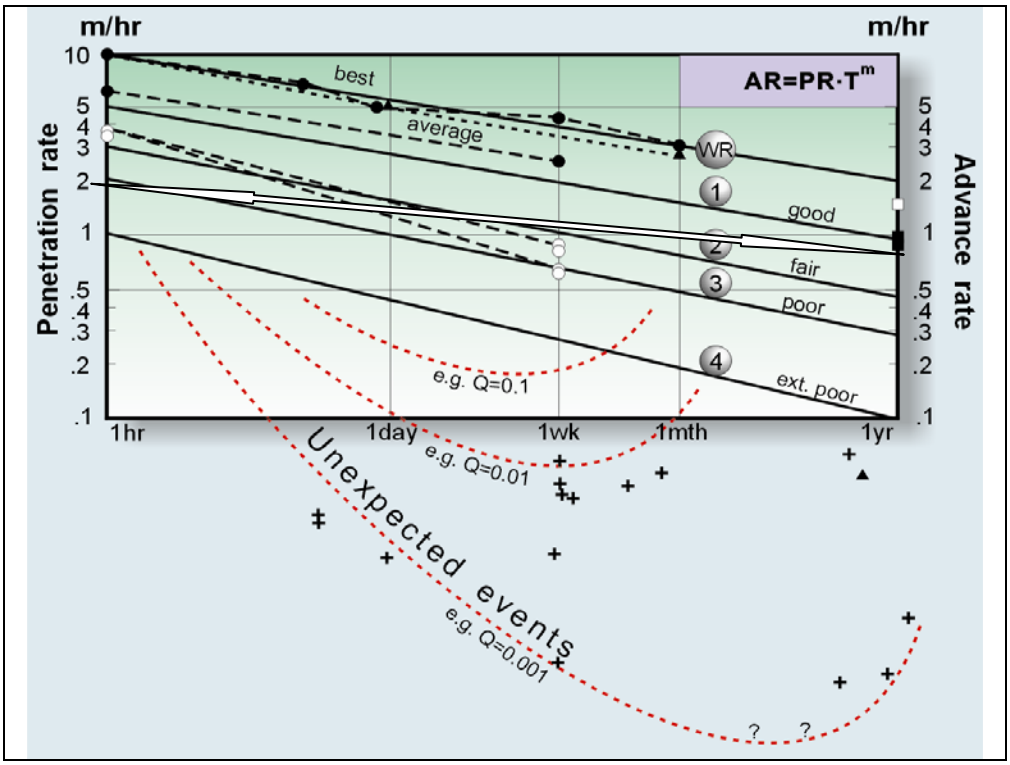

Figure 2: A synthesis of the general trends from 145 TBM tunnelling projects reviewed by Barton (2000). (Note PR = penetration rate, AR = actual advance rate, U = utilization: i.e. when boring, and T = real time in hours). The best performances, termed WR (world record) are represented by the uppermost line showing best shift, day, week, and month. At the other extreme, and often explainable by extremely low Q-values, are the so-called 'unexpected events', where faulting, extreme water, or combinations of faulting and water, or squeezing conditions, or general lack of stand-up time, may block the machine for weeks or months, or occasionally involve drill-and-blast by-passing of a permanently abandoned TBM. The long white arrow, of *reduced gradient*, will be explained later.

Radically changed rock types and ground conditions will disturb the smooth trends shown in Figure 2. The TBM performance trend lines were found to be strongly related to Q-values when the rock mass quality is very, or extremely poor *(i.e. Q << 1.0)* and so-called 'unexpected events' occur. This is illustrated in Figure 3. For Q-values above 1.0, there may be limited variation of this preliminary gradient (-)*m*. Other factors in the Q_{TBM} model are used to 'fine-tune' this gradient, thereby giving the progressively steeper gradients shown in Figure 2.

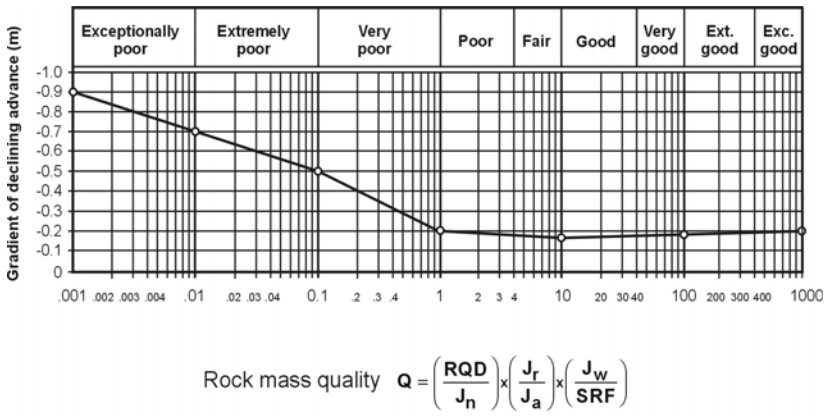

Figure 3: Preliminary empirical estimation of deceleration gradient *(-m)* from the Q-value, is clearly of relevance for fault zones, and sheared rock, as these are likely to have Q-values ≤ 0.1. Barton (2000).

3 SOME CHARACTERISTIC PROBLEMS WITH TBM 'STAND-STILL'

The flat face of a large diameter TBM tunnel is not unlike a vertical rock slope. When a TBM cutter-head gets stuck, and if it is able to be withdrawn from a fault zone to (post) treat the rock mass, there may be a loosening effect, during which time the already poor rock mass conditions deteriorate further, exaggerating the bad conditions that have already been penetrated. Several cases will be illustrated here, in order to focus on some of the problems.

The case of loosening in a fault zone in flysch, shown in Figure 4 is from Grandori et al. (1995), from the Evinos-Mornos Tunnel in Greece. The case illustrated in Figure 5 is from a sheared zone in quartzites and meta-sandstones, from the Pinglin Tunnel in NE Taiwan. This tunnel was later renamed by the President of Taiwan, before its completion after about 13 years of remarkable struggles and numerous fatalities.

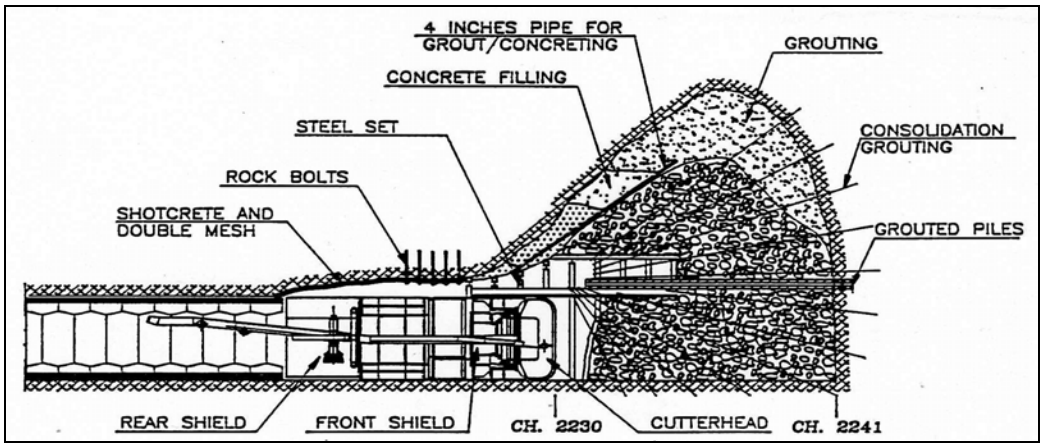

Figure 4: Loosening of the rock mass in a fault zone was exaggerated by withdrawal of the TBM. Detail of some of the recovery operations described by Grandori et al. (1995). Despite the sophistication of double-shield operations (and their greater cost), hand-mining operations may be needed on occasion.

One of the two large diameter TBM at Pinglin was crushed in the first difficult kilometres, by collapse of a major fault zone, that had been 'successfully' passed by the cutter-head. The majority of the northern tunnel therefore had to be excavated by drill-and-blast, also with great difficulties at times, including a 7000 m^3 inrush of clay, rock and water that buried a tunnel worker and diverse equipment, moving the tunnel 'face' backwards by about 100 m.

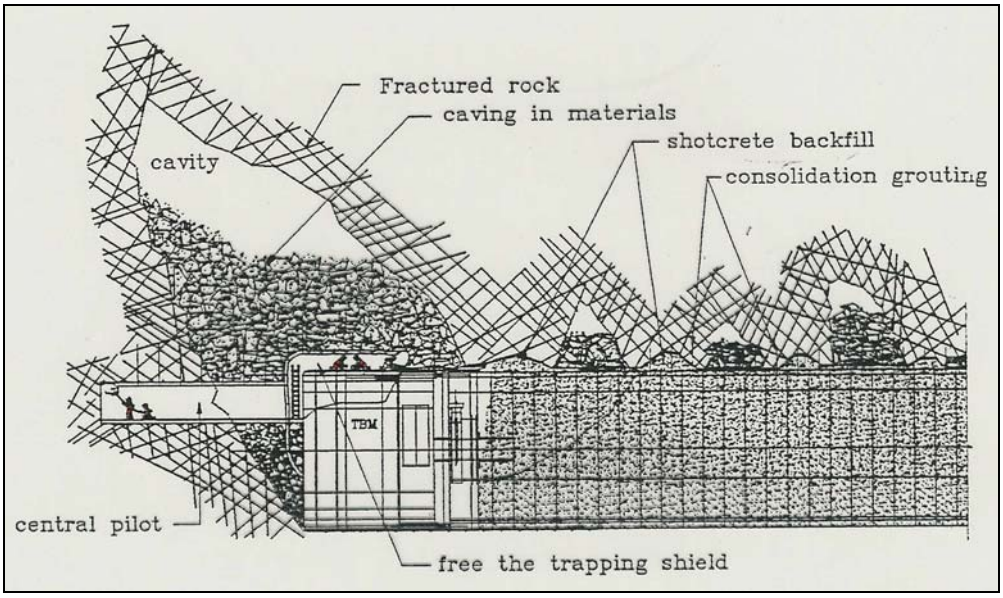

Figure 5: Graphic illustration of a by-pass situation for one of the TBM at Pinglin. Shen et al. (1999).

The Pinglin Tunnel is an example of a TBM tunnel (actually three parallel tunnels) where serious faults caused such large cumulative delays, that drill-and-blast 'rescue' from the other (western) end was essential for completion, finally involving some 13 years of struggle to drive this 15km long twin-road tunnel. The central 5 m diameter pilot tunnel TBM, originally designed for drainage and pre-treatment of the main bores, a method successfully applied at the Channel Tunnel, had to be drill-and-blast by-passed at least 12 times to release the cutter-head.

Fault zones will remain a serious threat, especially to TBM tunnelling as we now know it, with pre-treatment of ground often limited ahead of the TBM, unless the extremely poor rock mass qualities associated with fault zones can be improved by prior knowledge of their location, followed by *pre-planned pre-grouting.* This requires more than normal attention to detailing of drilling equipment on the TBM, and the location of this facility in relation to drilling at suitable 'look-out' angles. The lighter drills used for rock bolting and spiling bolts are separate units, closer to the face. Much heavier-duty drills, and rod-handling facilities, are needed for pre-grouting, set further back on the TBM back-up, and using guide-tubes for penetrating the rock closer to the cutter-head at optimal angles. Clearly this is a much more burdensome practice with TBM, than when starting at the face in a drill-and-blast tunnel, with a multi-boom drill jumbo.

4 WHY FAULT ZONES MAY DELAY TBM SO MUCH

There are unfortunately very good 'theo-empirical' reasons why major fault zones are so difficult for TBM (with or without double-shields). (*Theo-empirical* means that lack of belief will be penalized). We need three basic equations to start with.). From previous discussion:

$AR = PR \times U$, where $U = T^m$ (see Figure 2)

(Due to the reducing utilization with time increase, advance rate decelerates, but does so to a lesser *general* extent with push-off liner double-shield TBM, where *-m* may be nearly halved: see later). Obviously the time T needed to advance length L must be equal to L/AR, for all tunnels and all TBM:

$$T = L / AR \tag{3}$$

Therefore we have the following from equations 1, 2 and 3:

$$T = L / (PR \times T^{m})$$

This can be re-arranged as follows:

$$T = (L/PR)^{1/(1+m)} \tag{4}$$

This is a very important equation for TBM, especially if one accepts that the deceleration gradient *(-) m* is strongly related to low Q-values in *fault zones,* as shown by the empirical data in Figure 3. Equation 4 is important because negative *(-) m* values almost reaching (-)1.0, make the component $^{1/(1+m)}$ *too large.*

If the fault zone is wide (large L) and PR is low (due to gripper problems and collapses etc.) then L/PR gets too big to tolerate a big component $^{1/(1+m)}$ in equation 4. 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.

The writer knows of three permanently buried, or fault-destroyed TBM (Pont Ventoux, Dul Hasti, Pinglin). There are many more unreported but privately referred cases, and their causes are probably related in one way or another to the logic behind equation 4. So far this equation seems to be absent from other literature, as the inevitability of deceleration *(-m)* does not seem to have been accepted as a useful method of quantifying reduced utilization with increased time. TBM *must follow* a negative m-value, even when breaking world records, like16 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 2 is therefore also showing deceleration, but with a less steep gradient *(-m).*

5 VERY LONG TUNNELS MAY NOT BE FASTER BY TBM

One should not blindly assume that long tunnels are driven faster by one TBM than by drill-and-blast from both ends. The longer the tunnel, the more likely that 'extreme value' statistics (of rock quality and geo-hydrology) will apply, due to a 'large scale' Weibull theory: i.e. larger 'flaws' in larger 'samples' (just as found in laboratory testing of rock UCS). This effect of tunnel length on a hypothetical distribution of rock conditions is illustrated in Figure 6.

The 'added' rock conditions assumed here for the long tunnel include many potential kilometers of hard massive rock, which would speed a drill-and-blast tunnel, but slows a TBM, where the strange phenomenon of PR *reducing* with increased thrust often occurs (see review in Barton, 2000). Insufficient thrust in relation to very hard rock needs to be modelled, but seems not to be in a widely used TBM prognosis model, as thrust is not compared, as it should be, with estimates of the possible high strength of the rock mass.

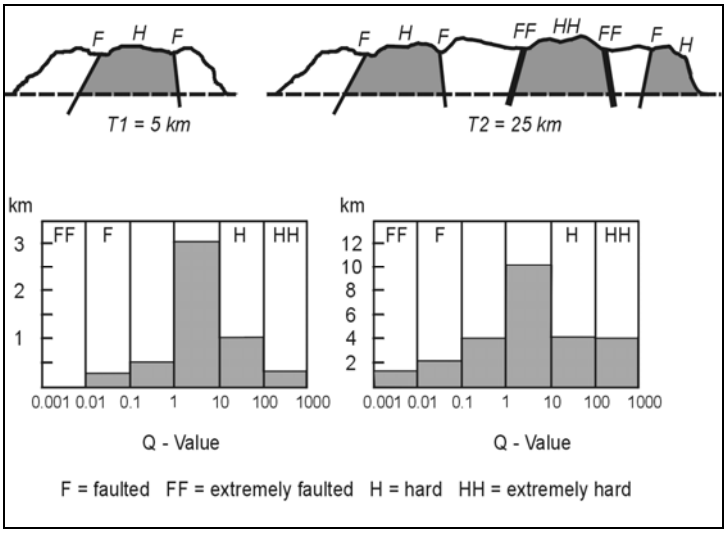

Figure 6: The longer the tunnel, the more likely that 'extreme value' statistics (of rock quality) will apply, due to a 'large scale' Weibull theory: i.e. larger 'flaws' the larger the 'sample'. Barton (2001).

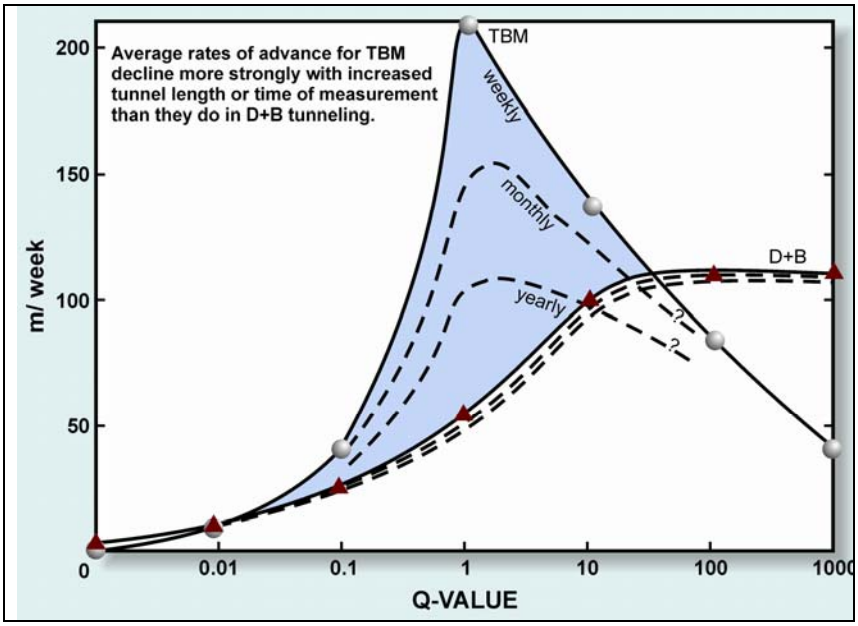

Figure 7: Comparing TBM and drill-and-blast over a full spectrum of rock classes, using examples with similar Q and Q_{TBM} values. (Similar values of Q and Q_{TBM} can readily occur due to the normalization of the additional parameters constituting Q_{TBM}, as shown later). The TBM is much faster over short distances, with the proviso that rock mass qualities are not extreme. As tunnel length increases, the 'central' rock quality becomes more important due to the deceleration of advance rate with time, and therefore with tunnel length. Barton (2000). Note that the usual *distribution* of Q-values explains why drill-and-blast tunnelling may frequently show average 40-60 m per week, though the world record is presently > 160m/week on one face, obviously with no significant rock support needed due to consistently high Q-values.

In Figure 7, a comparison of TBM prognosis and drill-and-blast prognosis has been made, using *Q-system based* estimates of quality versus cycle time, and Q_{TBM} *based* prognoses for a similar size of TBM tunnel. Case records will likely show that it is the *intermediate length* tunnels that are faster by TBM. This is because 'extreme value statistics' will tend to bring parts of the longer tunnels *more frequently* outside the central rock quality region needed to maintain the obvious *potential* advantages of TBM illustrated in Figure 7.

6 EXAMPLE OF A LONG TUNNEL THAT DID NOT GO FASTER BY TBM

The 7 km headrace tunnel for the Pont Ventoux HEP in the extreme north-west of Italy, not far from the Alps, was parallel to a marked NW-SE trending valley, and also parallel to the foliation and to (later discovered) fault zone swarms parallel to the valley side. The structural geology proved to be a disaster for the tunnel route, due to its near-parallel orientation to the later discovered faults. The extremely adverse situation is illustrated in Figure 8.

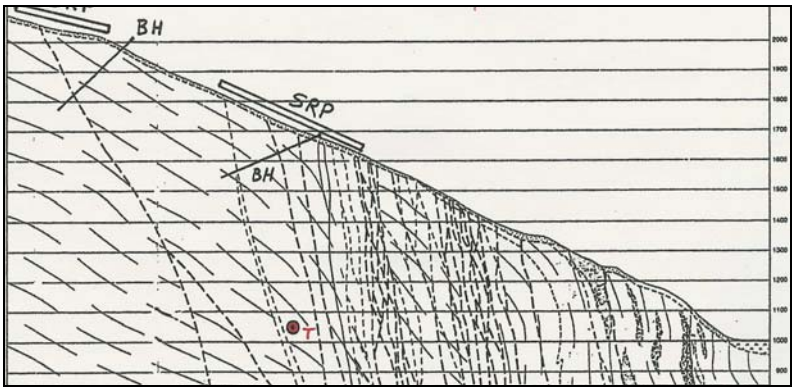

Figure 8: The tunnel was apparently 'too deep' (700-800 m) for satisfactory geological and geophysical investigations, judging by the 'missed' fault swarms shown here. In fact it was clearly not adequately investigated, though this is easy to claim afterwards. BH = boreholes, and SRP = seismic refraction.

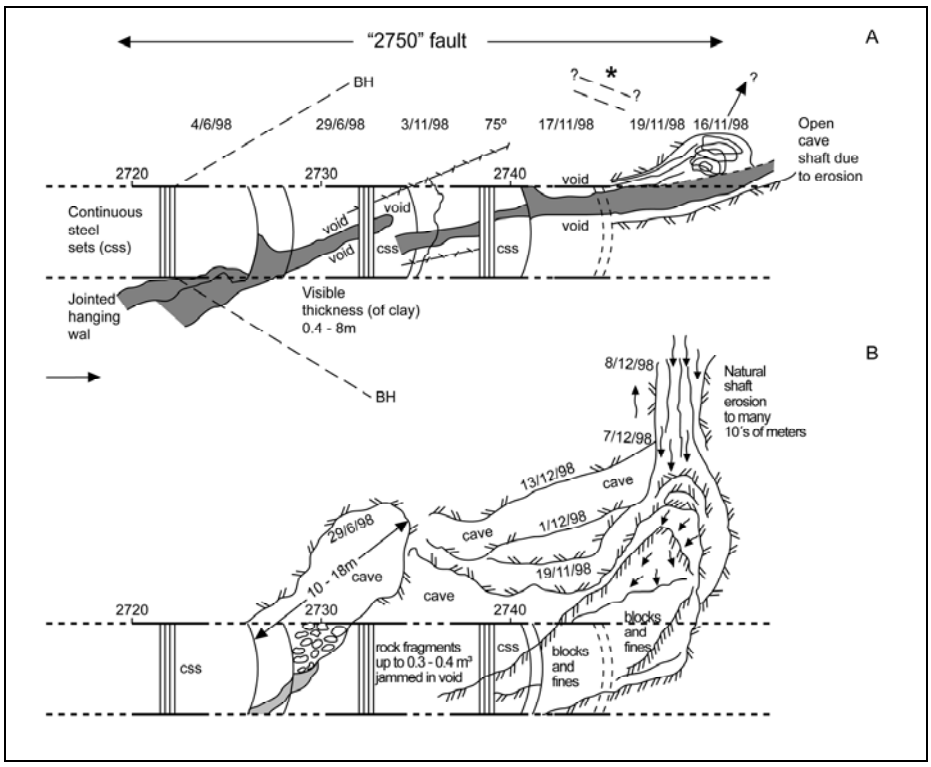

Figure 9: Plan view and vertical section of fault-related problems at Pont Ventoux. The TBM remained in this 25 m faulted section for 6 months due to successively blocked cutter head, caused by intermittent falling blocks from the 'fault shaft', assisted by water and/or water pressure. These sketches are super-imposed on one sheet, by tracing from a selection of the geologist's daily logs. A fault like this one proved 'invisible' in cross-hole seismic tomography subsequently performed between two boreholes drilled ahead of the tunnel face, presumably due to the compaction effect of the 750 m of rock cover. Barton (2006).

A sub-parallel fault zone destroys much of the familiar tangential stress arch, and tunnel stability problems often arise as a result. High pressure inflow and erosion of clay and loosening of rock blocks are other factors. The headrace tunnel was increasingly making a tangent to numerous faults, and suffered a series of delays of 6 months or more, as shown in a particularly difficult chainage in Figure 9.

The adverse effect on tangential stress (arching) when crossing a fault at an acute angle for 50 meters or more, is readily envisaged from the superimposed daily or weekly reports of conditions reproduced in Figure 9. However, it was the adverse water pressures that were to prove the biggest problem with respect to the cutter-head getting stuck in these various narrow fault zones at Pont Ventoux.

The loosened blocks falling from an eroding 'natural shaft' repeatedly blocked the cutter-head. Derailment of the train was also frequent behind the back-up, due to build-up of a 'delta' of sand and silt washed out of the various fault zones. The 'delta' could form in the stiller water behind the constrictions of the long back-up rig.

At another location, the 'fault zone performance' was 7 months for only 20m of advance, representing an average AR = 20/(7×720) = 0.004m/hr. This is almost off the bottom of the chart, in the 'unpredicted events' area of Figure 2, where various case record crosses (+) are plotted.

A drill-and-blast alternative of larger cross-section (to account for head loss) following the same route, or a revised route for continued TBM boring, or either tunnelling methods along a revised route, were three alternatives that were recommended by the writer. During 2004 the tunnel was completed by drill-and-blast from the other end of the tunnel, by-passing the rusting and abandoned TBM.

7 DOUBLE-SHIELD TBM FOR MINIMISING MINOR GEOLOGICAL DELAYS

Use of double-shield TBM with pre-cast PC-element ring-building while boring, and push-off -liner capabilities while re-setting the grippers (due to robust liner design, and large axial thrust), can solve many minor stability problems without encountering significant delays. In addition it allows for very fast tunnelling, with a lowered gradient of *(-m)* when used frequently. The PC-elements support ground that would receive more directly appropriate treatment (steel arches, bolting, mesh, shotcrete) if an open TBM with finger-shield were in use. When significant fault zones are intersected, the double-shield may represent a hindrance to rapid recovery, as pre-treatment of the ground ahead is hindered by the long shields. Examples of such difficulties were shown in Figures 4 and 5.

A lot of hard massive gneisses and granites encountered at the Guadarrama high-speed rail tunnels, driven in Spain between Madrid and Segovia, resulted in the need for frequent cutter change on all four double-shield TBM (two Wirth, two Herrenknecht), and average PR as low as 2 m/hr. Nevertheless the overall efficiency of the 'continuous' thrust abilities described above, allowed for a very shallow (excellent) gradient of deceleration *(-m)* to be achieved, with reference to the various performance gradients drawn in Figure 2 (see long white arrow).Gradients as low as (-) 0.08 to (-) 0.12, or about half those in open gripper TBM without push-off-liner facilities were regularly achieved. A typical PR of only 2 m/hr suggesting 'poor' performance, was in practice elevated through 'fair' and into 'good' performance, meaning 4 × 14 km of TBM tunnelling completed in an excellent 32 months.

8 TBM TUNNELLING THAT SUCCEEDED WITH THE SECOND CONTRACTOR

The SSDS sub-sea sewage project in Hong Kong ran into many problems related with fault zones, and Tunnel F was no exception. A particular difficulty was the need for extensive pre-injection, compromised by the small-diameter of the TBM (Figure 10). This particular contract was completed by Skanska International, following Owner termination of the original contract, and negotiation of separate contracts with several new contractors.

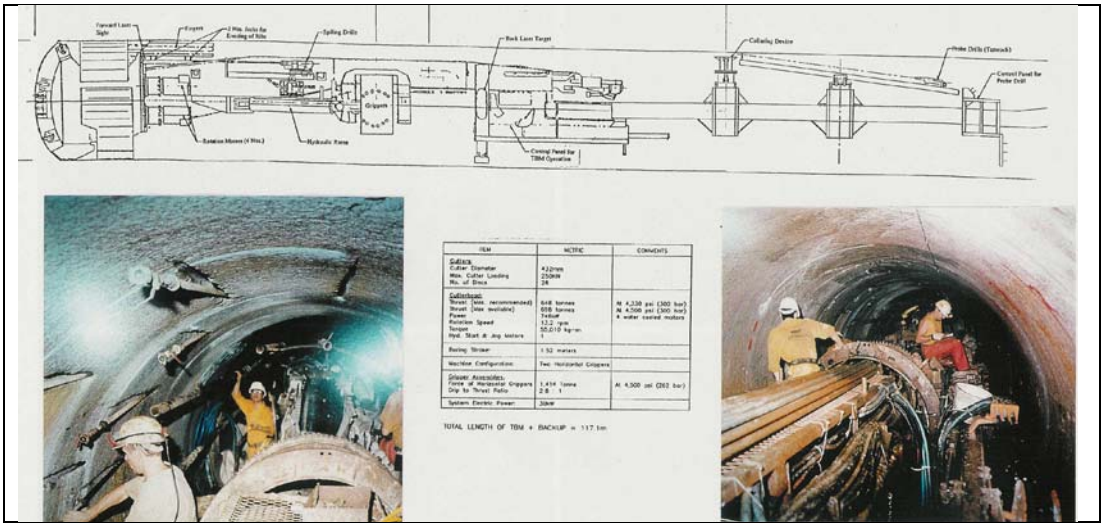

Figure 10: The rock-bolting drill location was not suitable for the extensive requirement for pre-injection at SSDS Tunnel F, and heavier drills further back on the machine were installed by Skanska, to give more appropriate look-out angles.

This particular 3km long tunnel ran from Tsing Yi Island to the (much reclaimed) Stone Cutters Island, and on its way there penetrated underneath the world's second largest container port (Kwai Chung), on the Kowloon side of the harbour area.

Unfortunately, a major regional fault zone: the Tolo Channel fault zone, was not properly detected, and therefore not characterised beforehand, due in part to the impossibility of performing the sub-sea seismic profiling exactly as had been planned. Due to intense shipping activity close to the container port, the seismic velocity profiles could not be extended sufficiently to penetrate what proved to be a wide and very low velocity area. Knowledge of this fault zone had seemingly been 'lost' beneath the many years of intense building developments of Kowloon.

9.1 Slow progress due to faulting and water

Only 481m of the tunnel was completed in the first aborted contract. Some 3098m remained for the new contractor (Skanska International). The Owner/Consultant over-optimistically expected 96m/week, 204m/week and 228m/week (in poor, fair and good rock conditions – with a less than ideal TBM inherited from the previous contractor. The conforming contract demanded 1 year for completion (of 3098m). In fact, during the first 29 months, only 2221m of new tunnel was driven by Skanska, with great difficulty, including a fault by-pass and TBM pull-through, and enormous quantities of cement grout in numerous locations. This overall result represented an AR of 17m/week (or AR = 0.1m/hour) – which was 1/10 of the Owner/Consultant general expectation (and 1/3 of the conforming contract).

Chainage 744-759 (15m) had taken 8 months due to the need for hand-mining a by-pass round the stuck TBM in the first major fault zone (this represents a major 'unexpected event' with AR = 0.003m/hour – and a mapped Q-value of about 0.001. Ch. 2622-2702 (80m) took 4 months and 750,000kg of grout (average AR= 0.03m/hr, i.e. also like an 'unexpected event', as plotted in Figure 2). Approximately 887m of tunnelling remained when the author started advising Skanska in 1999. There was a major regional (Tolo Channel) fault zone ahead, which had not been drilled or seismically profiled, due to heavy shipping traffic, and therefore a fated lack of access for the seismic-survey ship.

Skanska eventually decided to drill a long horizontal 'pilot hole' *backwards* from the exit-shaft on Stonecutter's Island, to try to sample the remaining ground. However, they were almost unable to recover any core from *the back-side* of this major regional fault zone. The hole went only 731m, as it was stopped by the Tolo Channel fault zone – despite three

successful attempts at hole deviation in the last few meters of drilling, before entering the zone.

Despite the fact that only a few meters of this zone could be cored from the shaft location, the TBM later managed to penetrate the wide fault zone from the other side, due to the positive *pre-grouting-cloud* effect on the rock mass, many meters ahead of the TBM. This is quite positive 'proof' that rock mass properties are improved by grouting, as known from seismic measurements at dam sites, where P-wave velocities may be increased by 1 to 2 km/sec i.e. Barton (2006), and from numerous positive tunnelling experiences through systematically pre-injected rock, especially from recent rail tunnels in Norway.

9.2 Analysis of pilot borehole (LH 01) core was used for input to the Q_{TBM} model

The 731 m of core recovered from the pilot hole, provided Q-value input for much of the remaining tunnelling. The core was divided into five classes for convenience of description, with examples shown in Figure 11, and some examples of logging results (0 to 201 m) shown in Figure 12a. The rear of the Tolo Channel fault had characteristics as shown in Figure 12b.

Figure 11: Photographs of the five selected rock classes which, when Q-parameter logged, gave the approximate statistical frequencies of these five classes. Examples of core boxes representing M = massive, S = slightly jointed, J = jointed, Z = zone (weathered) and F = fault. (See corresponding numbers 1 to 5, in Figure 12a histograms).

9.3 Assumptions concerning rock mass improvement by pre-injection

Three scenarios were modelled with the core data obtained from Q-logging of the horizontal core LH 01:

- First with no pre-grouting improvement
- Secondly, with the pre-grouting improved rock mass
- Thirdly, with the pre-grouting cycle time approximately included

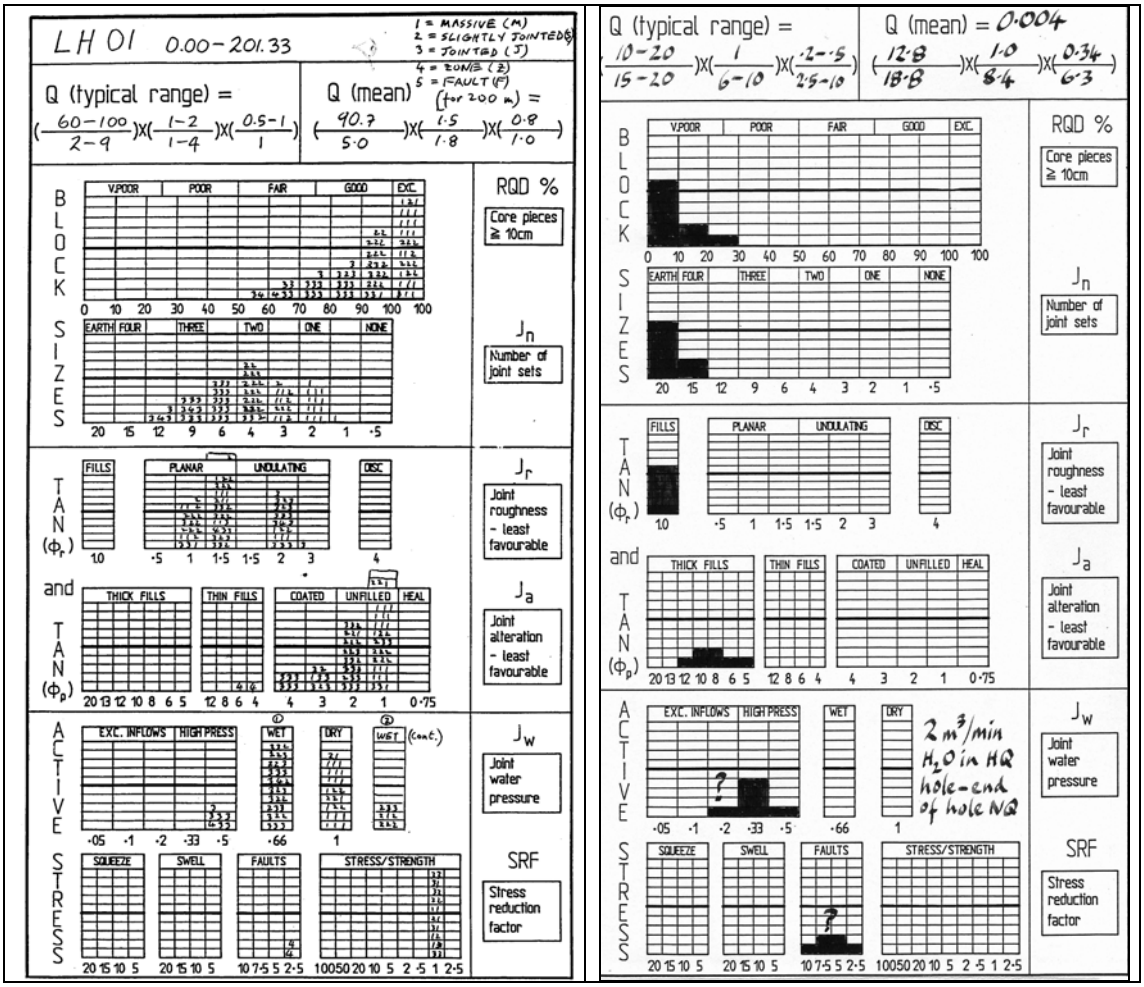

Figure 12: a) Q-parameter field-logging statistics for the first 200 m of the horizontal core LH 01, built up by number of observations of the five classes. b) Q-parameter statistics for the few meters of core that could (with great difficulty) be recovered from the edge of the Tolo Channel fault zone.

Roald (in Barton et al. 2001) has shown that time and cost *of drill-and-blast tunnelling* are strongly, and similarly correlated to Q-values (Figure 13), when the Q-value is less than about 1.0, in fact just the same area of sensitivity to Q shown by *TBM deceleration gradients (-m)* (see Figure 3). The sensitivity to Q actually begins at about Q<10, where support increases begin. So if the effective Q-value can be improved by pre-grouting – *in the case of both drill-and-blast and TBM tunnelling* – the greatest benefit will obviously be achieved where the Q-versus-cost and Q-versus-time curves are steepest (about 0.01<Q<1.0) for both varieties of tunnelling.

Assumed improvements in the rock mass properties caused by the planned pre-grouting of the remaining 900 m of the Hong Kong TBM sewage Tunnel F, were based on the following *types of arguments* for each particular rock class: Barton and Quadros (2003).

Before pre-grouting: $Q = 30/9 \times 1/2 \times 0.5/1 = 0.8$
After pre-grouting: $Q = 50/6 \times 2/1 \times 1/1 = 17$

These assumed improvements are listed on the next page, parameter-by-parameter:

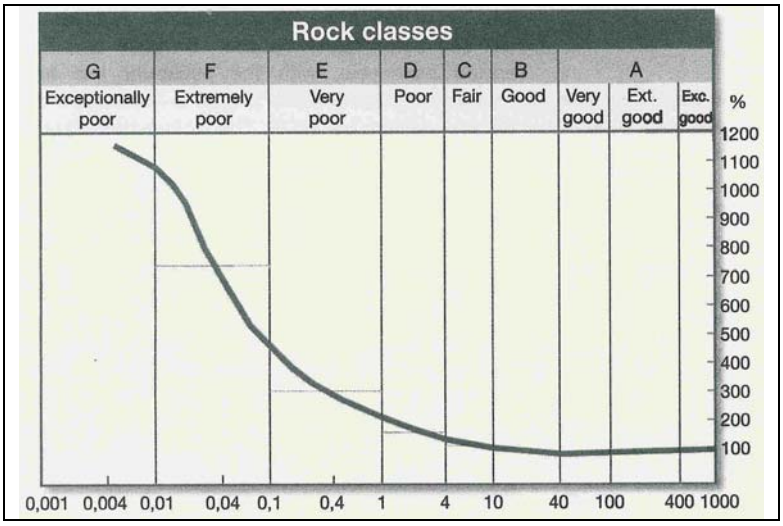

Figure 13: Relative time for *drill-and-blast tunnelling* as a function of Q-value. After Roald, in Barton et al. (2001). A similar curve is obtained for relative cost, with 100% to1000% on the vertical axis.

RQD increases e.g. 30 to 50%
J_n reduces e.g. 9 to 6
J_r increases e.g. 1 to 2 (due to sealing of most of set #1)
J_a reduces e.g. 2 to 1 (due to sealing of most of set #1)
J_w increases e.g. 0.5 to 1
SRF unchanged e.g.1.0 to 1.0

With similar improvements in the different rock classes, due to appropriate assumptions, following recommendations in Barton (2002), there is a reasonable expectation of *improving rock mass properties* through the pre-grouting that was an almost standard and necessary procedure ahead of this TBM. The availability of horizontal core data i.e. *parallel to the tunnelling direction,* as used in this and some other Hong Kong projects, is actually fundamental to a good TBM prognosis, especially when there is a marked anisotropy of structure. Use of vertical holes when there is dominant *horizontal structure*, produces 'artificially low' RQD and Q-values, which do not match the TBM's relatively increased difficulty with structure parallel to the tunnel axis.

Table 1. Example of rock mass and tunnelling improvements that might be achieved by pre-injection. In poorer quality rock masses there could be greater improvements, in better quality rock masses it may be unnecessary to pre-grout. After Barton (2002). Note: Q_c = QxUCS/100, B=systematic bolting, S(fr) = steel fibre reinforced shotcrete.

Before pre-grouting	After pre-grouting
Q = 0.8 (very poor)	Q = 17 (good)
Q_c = 0.4	Q_c = 8.3
V_p = 3.1 km/s	V_p = 4.4 km/s
E_{mass} = 7 GPa	E_{mass} = 20 GPa
B 1.6m c/c	B 2.4m c/c
S(fr) 10 cm	none

10 Q_{TBM} MODEL FOR PR AND AR PROGNOSES IN HARD JOINTED AND FAULTED ROCK

The objective of the Q_{TBM} model is to predict both PR (penetration rate) and AR (*actual* advance rate) for the various domains, rock types, or tunnel lengths in a given project. Naturally, there are important machine-rock interactions that need to be included. The need and development of empirical machine-rock linkages for the Q_{TBM} calculation are fully explained in Barton, 2000, and the model itself is described in Barton and Abrahão, 2003.
Figure 14 summarizes the main component of the method, namely the empirical estimation of the Q_{TBM} value which was designed for direct, simple correlation with PR: (Barton 1999, 2000):

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

Equation 5 includes a *comparison* of the applied average cutter force F in tonnes force (e.g. a 1000 tnf TBM net thrust averaged over 40 cutters, gives F = 25 tnf), and the estimated rock mass strength SIGMA. Crudely estimated, we assume SIGMA is given by the following equation (expressed in MPa). There is also a version based on tensile strength.

$$SIGMA \approx 5\gamma Q_c^{1/3} \qquad (6)$$

where the Q-value has been normalized by σ_c /100 (increased or decreased for rock strengths more or less than 100 MPa), and (γ) is the density of the rock (units gm/cm^3). Cutter life index (CLI), quartz content % (q), and the approximate biaxial stress state (σ_θ) at the face of the tunnel (i.e. 5 MPa at 100m depth) complete the terms in this equation. Note the normalization of cutter force F by 20 tnf. The power term is designed to give a quadratic relation between penetration rate (PR) measured in m/hr and F, using the empirical relation (Barton, 2000):

$$PR \approx 5 Q_{TBM}^{-1/5} \qquad (7)$$

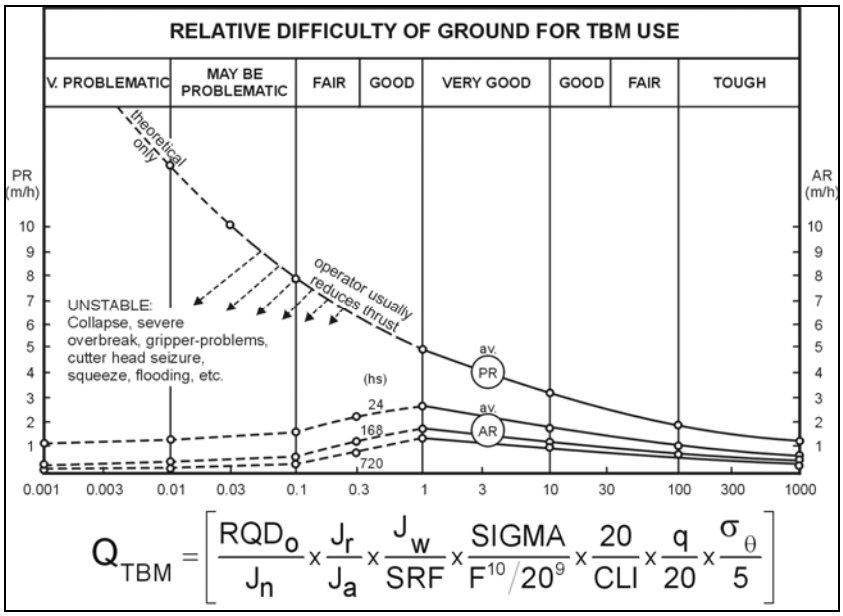

Figure 14: The Q_{TBM} scale of TBM tunnelling difficulty, showing its derivation from Q-parameters and from machine-rock interaction parameters. Note the normalization of parameters. Q and Q_{TBM} *can* have similar values, though normally will deviate, especially if cutter force is insufficient.

Due to the complexities of TBM operation, the actual advance rate (AR) over longer periods of tunnel boring is only a fraction of the "instantaneous" value PR. This fraction is the utilisation U (the time when boring is actually occurring). The classic TBM equation: (AR = PR × U) was modified to a time-dependent form in equation 2 ($AR = PR \times T^m$), shown earlier in this paper.

The four lines and three curves shown earlier in Figure 2 have negative gradients that may range from –0.15 for best performance, to –0.5 or even steeper in the worst rock conditions (the "unexpected events" shown with low Q-values in Figure 2). However, there is the likelihood of deceleration gradients as low as *(-)0.10* when using modern double shield machines that are supplied with the capacity for axial thrust off robust PC-element liners, *due to continued advance while resetting the grippers.* Note the log scales of PR, AR and time in Figure 2, which presents data derived from analysis of 145 TBM case records totalling some 1000 km, mostly from open gripper TBM where the rock conditions were well described.

This significant data base and its message needs to be criticised with greater care by those who do not like the development of a case-record based prognosis model. The general, long term, slowly decelerating tunnelling speed, that usually follows the contractor's learning curve in the first weeks or months of a TBM tunnel project, is what makes drill-and-blast and TBM tunnelling an interesting field for comparison, *when significant lengths of tunnel are involved.*

The example given in Table 2 shows how advance rate may decline as the tunnel length increases. In the case shown, the numbers imply a completed tunnelling length of 8760 × 0.5 ≈ 4380 metres, after 1 year of fairly difficult TBM tunnelling with m ≈ −0.20. The assumed PR = 3 m/hr represents a somewhat underpowered machine in hard massive rock, an example that is not so uncommon, for the purpose of illustrating potential difficulties.

Table 2. PR, AR and U and their interpretation with time period, for the case of a somewhat under-powered TBM. Gradient m = −0.20, which is quite common, is assumed. See other Figure 2 examples.

Period	PR	1 shift	1 day	1 week	1 month	3 months	1 year
Hours	1 hr	8 hrs	24 hrs	168 hrs	720 hrs	2160 hrs	8760 hrs
U	100%	66%	53%	36%	27%	22%	16%
AR m/hr	3.0	2.0	1.6	1.1	0.8	0.6	0.5

We can evaluate AR at the end of 1 year of tunnelling by combining equations 2 and 7 as:

$$AR \approx 5\, Q_{TBM}^{-1/5} \times T^m \tag{8}$$

When conditions are very favourable and PR is as high as say 6 m/hr, and m is as low as –0.15, a value of PR = 6 m/hr implies $Q_{TBM} = (5/PR)^5 = 0.40$, and the average AR for 1 year (= 8760 hours) will then be 1.54 m/hr or almost 13.5 km in the year, which is an exceptionally good result (though even this is below the TBM world record that at least by the year 2000 was about 16 km in one year: (see Barton, 2000 for description and analysis of numerous case records).

The Q_{TBM} model, developed by Ricardo Abrahão in Sao Paulo, has an input data sheet and gives zone-by-zone estimates of performance, as illustrated in Figure 15. The delaying effect of fault-zones is shown by the steeply inclined lines, which can if desired, contain the cumulative delays of faults in a given rock-type domain.

Information about fault zones may be obtained before tunnel construction begins by means of core logging and/or seismic refraction analysis. For the case of shallow TBM tunnels, the P-wave velocity can be used as an alternative to the Q-value, using the empirical relation $V_P \approx 3.5 + \log Q_c$ (km/s). This method was used in some of the analyses for Tunnel F of SSDS.

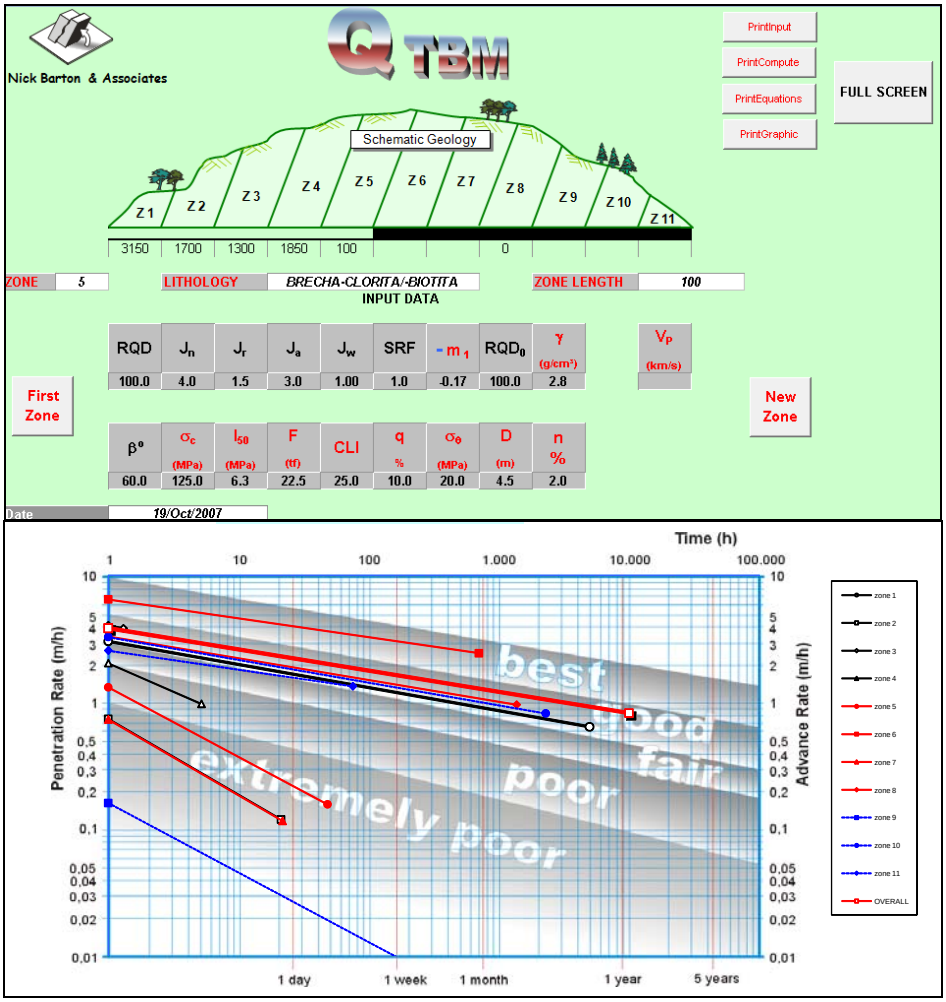

Figure 15. An example of the Q_{TBM} 'input data' screen and zone-by-zone progress predictions, including fault zones. Part of the prognosis of a TBM tunnel recently started in S. America, where a lot of deep coring was available from mineral exploration holes. (see examples in Figure 16).

Figure 16. Contrasting Q and Q_{TBM} values in faulted clay-bearing rock and hard sparsely-jointed rock.

11 APPLICATION OF Q_{TBM} MODEL TO HONG KONG TUNNEL 'F' PRE-GROUTING EFFECTS

Application of the Q_{TBM} model to the Hong Kong Tunnel F pre-grouting estimation is illustrated in part, in Figure 17a and 17b, showing before-and-after pre- grouting prognoses. Note the steepest gradient *(-)m* in the fault zone (red), which prevents tunnel completion without improvement by pre-grouting. The post-injection estimates proved to be slightly

conservative, due to the better than modelled improvements to rock conditions, caused by the successful systematic pre-grouting performed by Skanska.

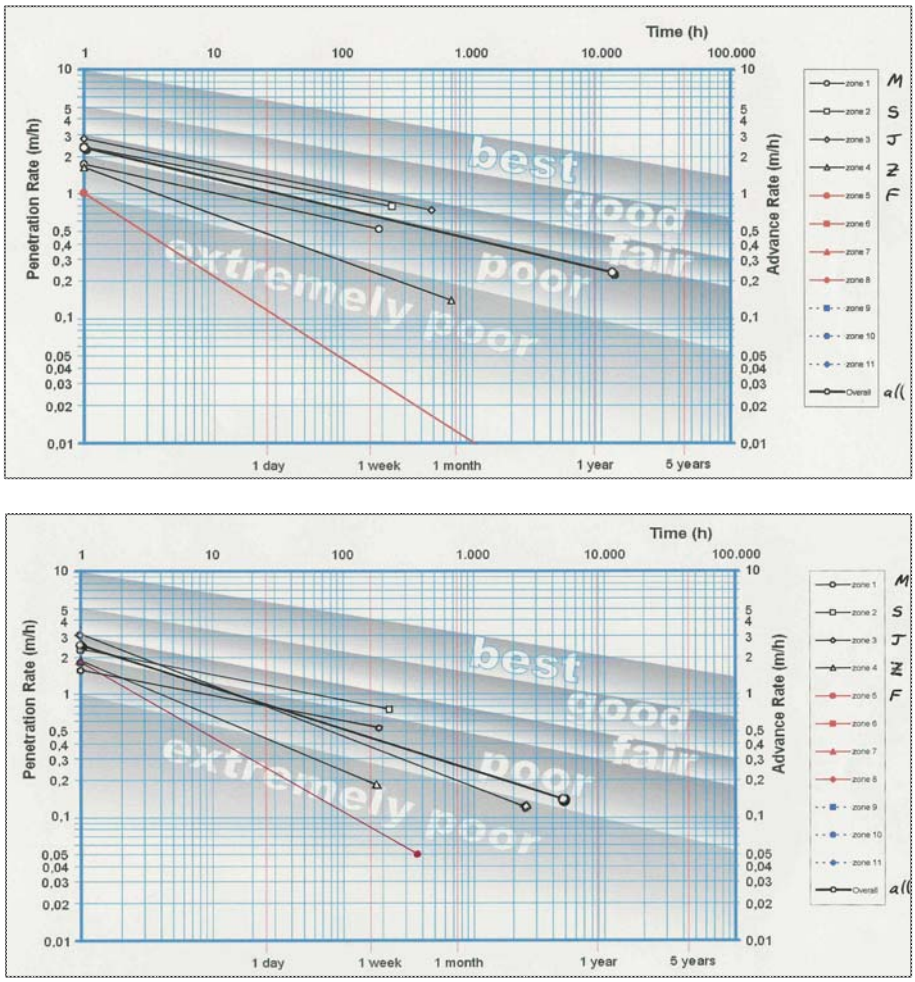

Figure 17 a and b: Application of the Q_{TBM} model to Hong Kong Tunnel F pre-grouting predictions. In the first screen, no pre-grouting improvements were assumed, and more than 1 year was predicted for completion of some 800 m. Grouting made regional-fault penetration possible, instead of impossible.

12 CONCLUSIONS

1. Major, and sometimes seemingly minor fault zones represent the 'Achilles heel' of TBM because, if sufficiently serious, they present the contractor with a situation where the TBM itself is actually 'in the way' of the most efficient pre-treatment or recovery methods that are usually available to a creative contractor.

2. Fault zones are a form of 'extreme value' in terms of characterization or classification of the degree of difficulty (and support needs) that they represent. They therefore lie far outside the ideal 'central' qualities where TBM give advance rates that are much superior to those of drill-and-blast tunnelling.

3. Fault zones that are associated with adjacent heavy inflows of water under high pressure are a special threat to TBM as it is difficult to pre-inject in a very thorough manner, and the high pressures may dislodge blocks of loosened rock thereby blocking the cutter-head. Even drill-hole drilling can be difficult. If the bad ground to be penetrated by the TBM is improved by a pre-injection 'cloud' a little earlier when approaching a fault, the possibility of fault penetration without blockage is improved.

4. Because TBM slowly decelerate as time and tunnel length increase, and are adversely affected by extremes, it is important that the rockmass has mostly 'central' qualities. So when a TBM is chosen 'because the tunnel is very long and needs to be driven fast', the opposite may actually occur, as extreme value statistics of rock quality are more likely to be encountered in a long tunnel, which possibly has high over-burden and reduced pre-investigation as a result. There are many of these tunnels, and they have various problems, which tend to be under-reported.

5. Extreme values of rock quality, that may be 'enhanced' by the tunnel length being too long for the choice of TBM, include larger fault zones, higher water pressures, massive (high Q-value) rock, which may also be harder or more abrasive, and squeezing (or eroding) conditions in fault zones, because of high over-burden (or high water pressures).

6. High overburden may not necessarily correspond with hard rock, so rock-burst delays may result, as presently being experienced in projects with 2 km or more over-burden. The choice of TBM tunnelling is a high risk if rock bursts are likely to occur over significant lengths of the tunnel, as the highest tangential stresses are attracted to the low-damage periphery. This may not be the case with drill-and-blast, unless 'half-pipes' are visible due to very massive rock.

7. Double-shield machines, with robust PC-elements that give the possibility of continued thrust while re-setting grippers, have been claimed by some as the answer to 'all' variable rock conditions. Such a solution, often at a significant extra cost per meter of tunnel, due to all the reinforced concrete rings required, may nevertheless produce a very favourable minimal deceleration gradient, of about half the value when thrust is only available from grippers. A poor PR can then recover to a good final AR result by 'curve-jumping'.

8. This may be sufficiently attractive from a scheduling point of view, to make the extra cost of support acceptable, in relation to the support that the tunnel might actually need from a stability point of view. This is especially true for high-speed rail tunnels, provided that pre-injection control of water inflows is not a stringent requirement, because this is more difficult to achieve ahead of TBM.

9. The 'push-off-liner' double-shield solution minimises the slowing advance rate with increasing time or tunnel length, *unless the rock mass conditions are extremely poor.* When/if such machines get stuck in significant fault zones, the time to recover and pre-treat the ground may tend to be longer, due to the now adverse total lengths of the double shield. When problems are encountered, it may be a disadvantage to withdraw the cutter-head too far, as loosening and worsening of the collapse may occur.

10. TBM tend to get stuck when several 'predictable' events combine into an unpredictable 'unexpected events' scenario, usually with extremely low Q-values. It is in avoidance of such situations that TBM can most benefit from probe drilling, *both downwards and upwards, and preferably to both sides as well.*

11. A degree of preparedness for approaching 'no-longer-unpredictable' unexpected events, can stimulate the use of drainage and systematic pre-injection, which is believed to effectively improve many (or all) of the six Q-parameters, thereby making advance both possible, and less hazardous.

12. The effect of rock mass compaction due to tunnel depth, causes an increase in the seismic velocity, which may be important if seismic profiling ahead of a TBM tunnel

is being used to probe conditions. The recording of a reasonable velocity of say 4 km/s may mask actual fault zone qualities, which might represent a fault zone of 2 to 2.5 km/s velocity, if it had been encountered nearer the surface.

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