# TBM tunnel construction in difficult ground
# Construcción de túnel con TBM en un terreno difícil

Nick Barton
*Nick Barton & Associates, Oslo Norway*

## Abstract

*Experiences with tunnelling problems are addressed, with particular reference to fault zone and sheared zone experiences in TBM tunnels in Italy, Greece, Kashmir, Hong Kong and Taiwan, together with fault zone cases in the $Q_{TBM}$ data base. TBM achieve remarkable advance rates when conditions are favourable, out-performing drill-and-blast tunnelling by a wide margin, but they suffer great problems when conditions are very poor. The theo-empirical reasons for this are illustrated, and $Q_{TBM}$ prognosis examples are given.*

## Resumen

*Las experiencias con problemas en la construcción de túneles se abordan haciendo referencia especial a los casos con zonas de fallas y cizalla en túneles con TBM en Italia, Grecia, Cachemira, Hong Kong y Taiwán, junto con casos de zonas de fallas existentes en la base de datos $Q_{TBM}$. El TBM alcanza una velocidad de avance notable cuando las condiciones son favorables, sobrepasando por lejos el rendimiento de construcción de túneles con perforación y voladura, sin embargo, tienen grandes problemas cuando las condiciones son muy precarias. Este documento ilustra las razones teórico-empíricas de esto, junto con entregar ejemplos de la prognosis de $Q_{TBM}$.*

## 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 velocities reach as high as about 5.5-6.5 km/s (i.e. Q > 100, and high UCS) in 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. Older cases of PR = 0.1 and 0.2 m/hr are known, but rare (Barton, 2000).

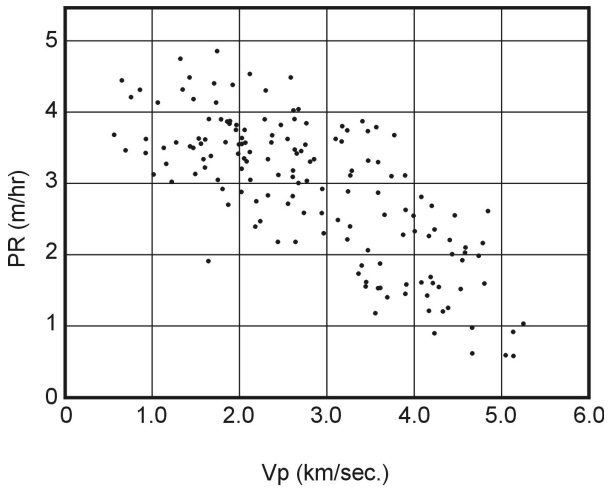



Fig. 1 Declining TBM penetration rate with elevated seismic velocity, due to lack of jointing. The actual advance rate will be a function of opposite effects in the best rock, namely need for frequent cutter change, but little delay for support. Mitani et al., 1987.

## SURVEY OF 145 TBM TUNNELS

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. As might be expected, a prominent proponent of a well-known Norwegian method was critical of this development, due mainly to misunderstanding of the methods employed. (Barton, 2005). While jointing effects may be approximately accounted for, the inclusion of faulting delays is usually avoided. The variable strengths of *rock masses* (as opposed to UCS), compared to cutter thrust levels, seem also to be absent in past and recent competing models of prognosis.

The numerous (140) case records totalling 1000 km of TBM tunnelling showed many things, including the following general 'deceleration' trends (equation 2, and Figure 2), when advance rate 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:

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

(where U= utilization for boring)

$$AR = PR \times T^{m} \qquad (2)$$

(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, usually experienced in the first months of numerous projects. This deceleration is a 'fact-of-life', however much it may be disliked. $AR_{mean}$ (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, including those recently utilised by Bieniawski and his colleagues.

Obviously, radically changed rock types and ground conditions, and changes from two to three shifts (e.g. 110 to 160 hours per week) will disturb the smooth trends shown in Figure 2, and also improve final completion, but not AR. The gradients of *deceleration* (-m) given by the negative slopes of the TBM performance trend lines were found to be strongly related to Q-values when the quality is very 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.

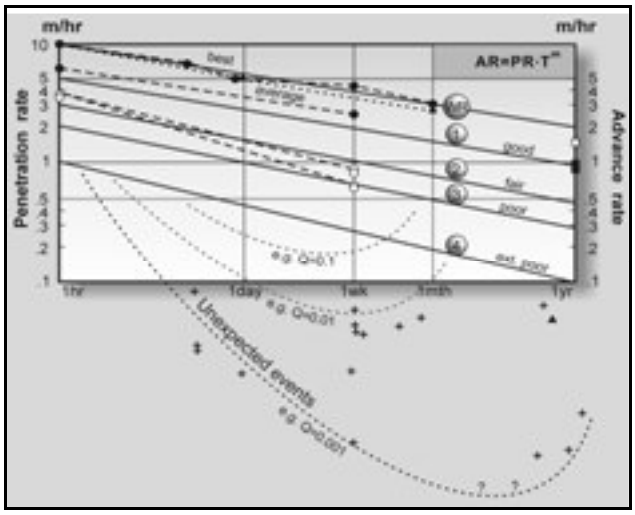



Fig. 2 A synthesis of the general trends from 145 TBM tunnelling projects reviewed by Barton, 2000. (Note PR = penetration rate, AR = actual advance rate, U = utilization when boring, and T = time in hours). The best performances, termed WR (world record) are represented by the uppermost line showing best shift, day, week, and month. At the other extreme, and often explainable by 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 months, or even involve drill-and- blast by-passing of a permanently abandoned TBM.

## 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

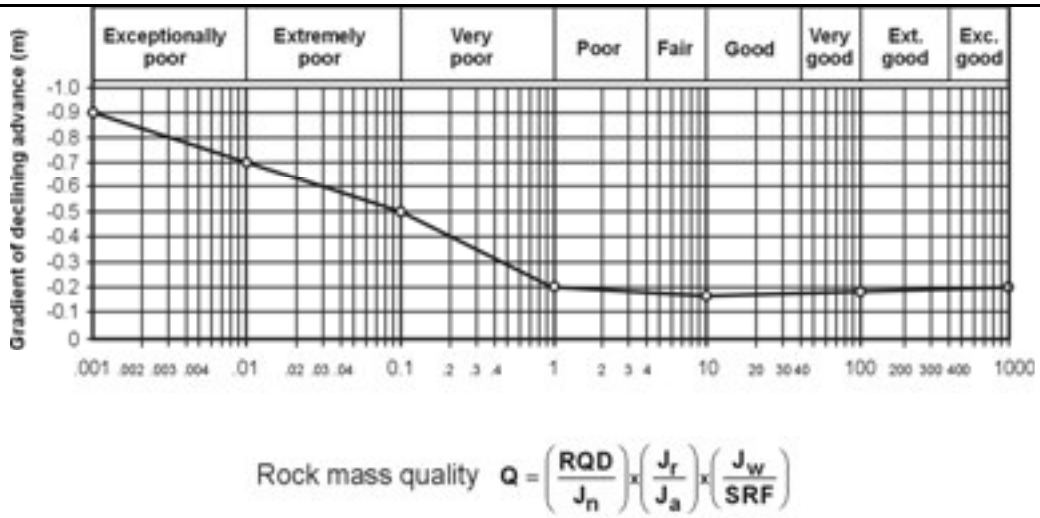



Fig. 3. Preliminary empirical estimation of deceleration gradient (-m) from the Q-value, is clearly of relevance for fault zones, and sheared rock, as these are likely to have Q-values $\leq 0.1$.

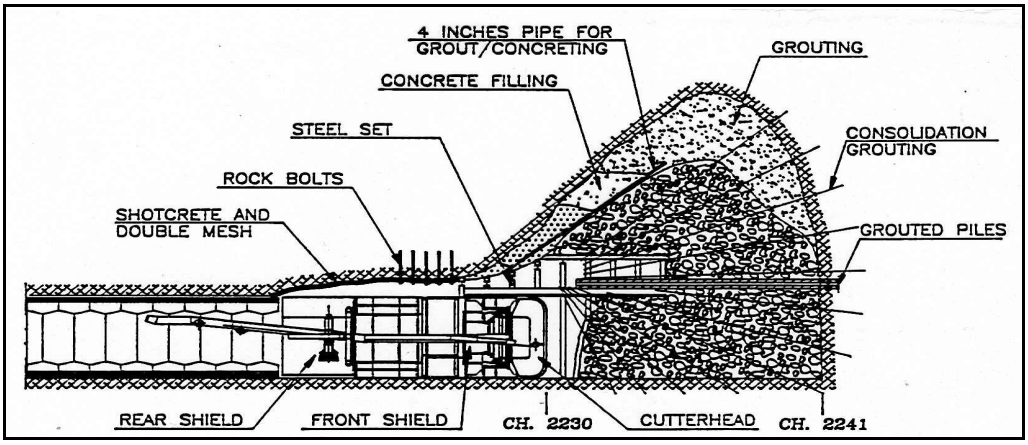



Fig. 4. Loosening of the rock mass in a fault zone was exaggerated by withdrawal of the TBM. Detail of some of the recovery operations described by Grandori et al. 1995. Despite the sophistication of double-shield operations (and their greater cost), hand-mining operations may be needed on occasion.

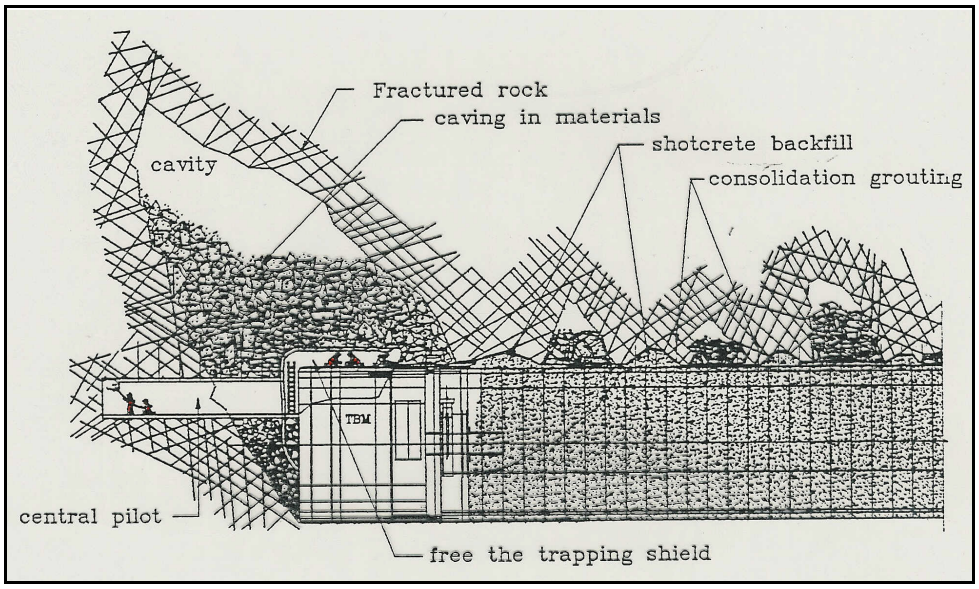
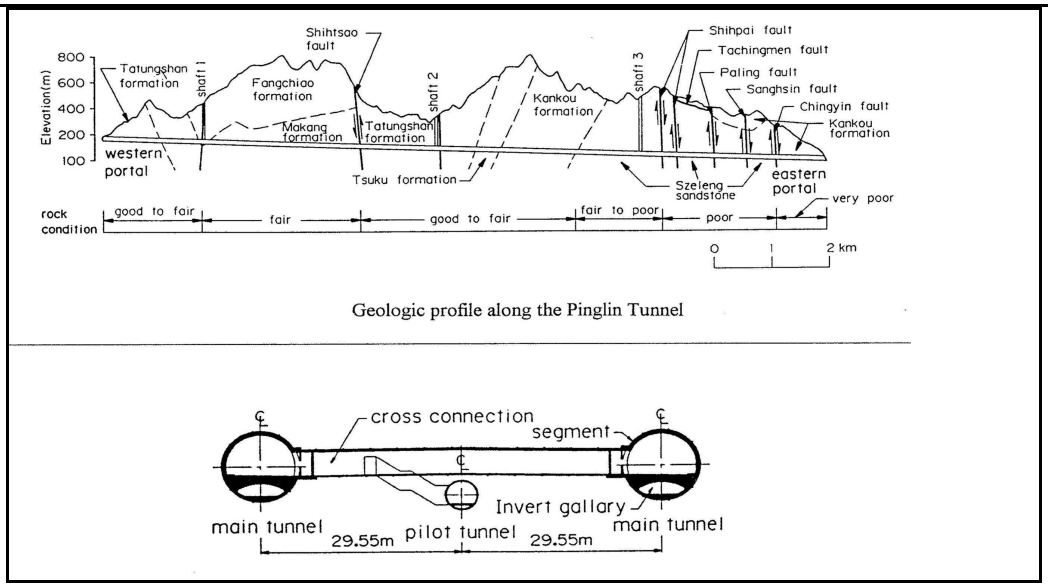



Fig. 5. Graphic illustration of a by-pass situation for one of the TBM at Pinglin. Shen et al. 1999.




Geologic profile along the Pinglin Tunnel

Fig. 6. Geological section along Pinglin Tunnel, and cross-sectional layout of the three parallel tunnels. In very poor rock conditions, the excavation of the main running tunnels actually caused inter-action across the two-diameter wide pillar, causing squeezing of the smaller diameter pilot tunnel, some 20 m distant.

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 shown in Figure 6. This tunnel was later renamed by the President of Taiwan, before its completion after about 13 years of remarkable struggles and fatalities.

One of the two large diameter TBM at Pinglin (right-side, northern tunnel in Figure 6) 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.

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, after some 13 years of struggle to drive this 15km long twin-road tunnel. The central pilot tunnel TBM had to be 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, 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 drill used for rock bolting and spiling bolts has to be a separate unit, 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.

## WHY DO FAULT ZONES DELAY TBM SO MUCH?

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

$AR = PR \times U$ (All TBM must follow this.)
$U = T^m$
(Due to the reducing utilization with time, advance rate decelerates, but to a lesser *general*

extent with push-off liner double-shield TBM: see later)

$T = L / AR$
(obviously the time T needed for length L must be equal to L/AR, for all tunnels and all TBM.)

Therefore we have the following

$T = L / (PR \times T^m)$
(from #1, #2 and #3). This can be rewritten as:

$$T = (L / PR)^{1/(1+m)} \qquad (3)$$

This is a very important equation for TBM, if one accepts that (-)*m* is strongly related to Q-values in *fault zones,* as shown by the empirical data in Figure 3.

Equation 3 is important because very *negative (-)m* values 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 3.

It is easy (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 certainly many more, and the causes are probably related to equation 3 logic. So far this equation seems to be absent from other literature, as the fundamental importance of deceleration (-m) has not been accepted. 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 100 m in 24 hours, since even here, PR is sure to be greater than the implied and remarkable AR of ≈ 4.4 m/hr.

## VERY LONG TUNNELS MAY NOT BE FASTER BY TBM DUE TO FAULTS

One should not blindly assume that long tunnels are faster by TBM. 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 7.

The 'added' rock conditions assumed here for the long tunnel include 7 or 8 km 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 strength of the rock mass.

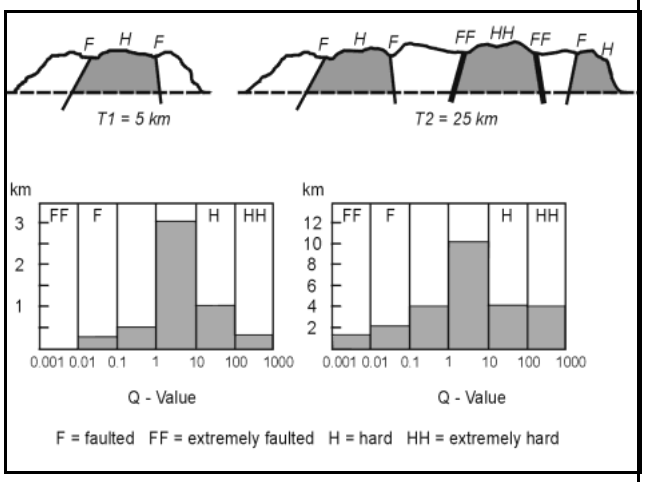



Fig. 7. The longer the tunnel, the more likely that 'extreme value' statistics (of rock quality) will apply, due to a 'large scale' Weibull theory: i.e. larger 'flaws' the larger the 'sample'. Barton, 2001.

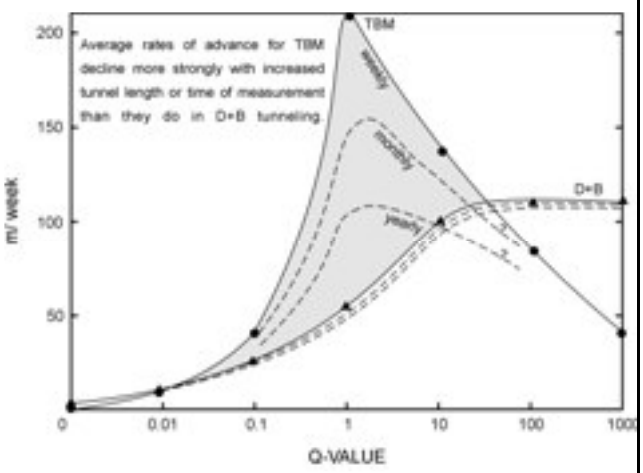



Fig. 8. Comparing TBM and drill-and-blast over a full spectrum of rock classes. The TBM is much faster over short distances, with the proviso that rock mass qualities are not extreme. As tunnel length increases, the 'central' rock quality becomes more important due to the deceleration of advance rate with time, and therefore with tunnel length. Barton, 2000.

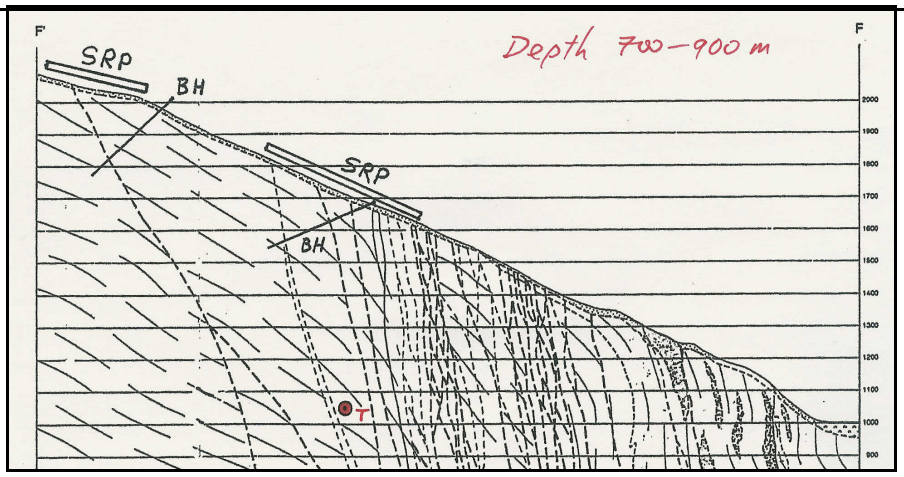



Fig. 9. The tunnel was apparently 'too deep' for satisfactory geological investigations, judging by the 'missed' fault swarms shown here. In fact it was clearly not adequately investigated. BH =boreholes, and SRP =seismic refraction.

In Figure 8, a comparison of TBM prognosis and drill-and-blast prognosis is 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 seen in Figure 8.

## 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 9.

A 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 10.

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 10. 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 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-sections (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 re-commended. (Barton, 1999, NGI contract report). During 2004 the tunnel was completed by drill-and-blast from the other end of the tunnel, by-passing the rusting and abandoned TBM.

## DOUBLE-SHIELD TBM FOR MINIMISING MINOR GEOLOGICAL DELAYS

Use of double-shield TBM with PC-element push-off while re-setting the grippers, can solve many minor stability problems without encountering

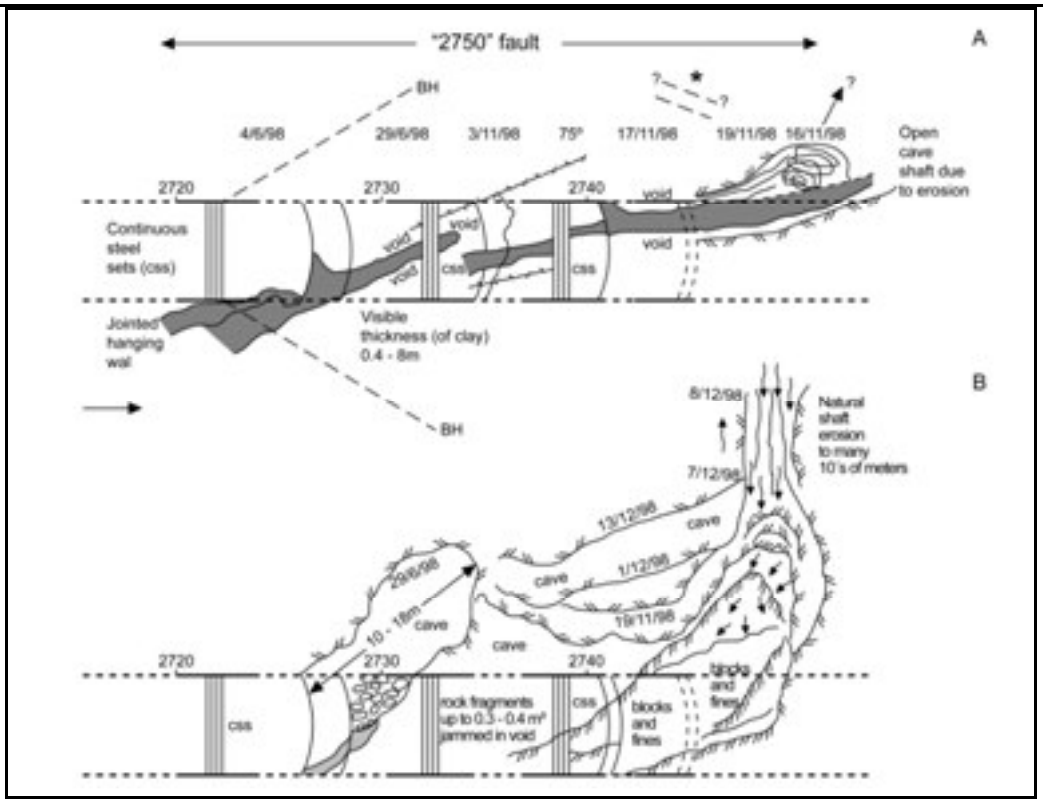



Fig. 10. The Pont Ventoux TBM was stuck here for 6 months (due to blocked cutter head) from intermittent falling blocks from the 'fault shaft', assisted by water and/or water pressure. These sketches are super-imposed on one sheet, traced from the geologist's daily logs. A fault like this one proved 'invisible' in cross-hole seismic tomography performed between two boreholes ahead of the tunnel face, due to the compaction effect of the 750 m cover. (Barton, 2006).

significant delays. The PC-elements support ground that would receive more directly appropriate treatment (steel arches, bolting, mesh, shotcrete) if a single-shield open machine were in use.

When significant fault zones are intersected, the double-shield may however represent a hindrance to rapid recovery, as pre-treatment of the ground ahead is hindered by the long shields. Examples of this potential hindrance to rapid recovery were shown in Figures 4 and 5.

Despite hard massive granites and gneisses at the Guadarama high-speed rail tunnels, driven between Madrid and Segovia, and the need for frequent cutter change on all four double-shield TBM (two Wirth, two Hennenknecht), the overall efficiency of the 'continuous' thrust abilities described above, allowed for a very shallow (excellent) gradient of deceleration (-m), with reference to the various performance gradients drawn in Figure 2. Gradients as low as (-) 0.10 (about half those in 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 about 32 months.

## TBM TUNNELLING IN TECTONICALLY DISTURBED ROCK IN KASHMIR

An extreme water and pebble/sand blow-out marked the first major blow to an extremely difficult TBM project at Dul Hasti, in Indian Kashmir. This HEP was started in the early 1990's. There were subsequent stand-up time problems in inter-bedded sheared and talcy phyllites, and variously jointed quartzites. PR rates as low as 0.2m/hr were recorded in the first kilometre of the tunnel where there was mostly massive abrasive quartzites, in stark contrast to 'over-boring' and void formation around the machine, and later collapse and squeezing and burial for ever, where the cover and rock mass resistance to excavation had become too adverse.

The early blow-out consisted of about 4,000 $m^3$ of sand and quartzite pebbles (partly rounded by sub-surface flow) that buried the 8 m diameter TBM, and an initial 60$m^3$/min water inrush, that

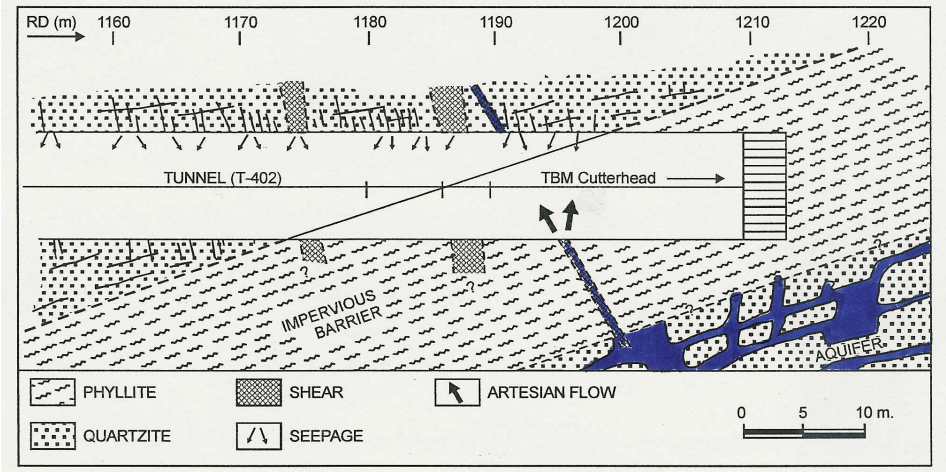



Fig. 11. Geologist's recording of possible cause of the blow-out in the first 1.2 km of the Dul Hasti TBM headrace tunnel. The TBM was withdrawn some meters when invert leakage increased. The blow-out even displaced the heavy TBM. Deva et al., 1994.

Fig. 12. A subsequent location 400 m further into the mountain was reached many years later (!) under a new contract. There followed a series of stand-up time problems in sheared, talcy phyllites. The figure shows a void of 3 to 4m depth developed in the left wall, due to 'over-excavation' by the TBM, caused by the negligible stand-up time of this sheared rock mass. The 8 m diameter tunnel was locally increased to about 12 m due to the over-excavation.

required the construction of a separate drainage tunnel to the valley-side, 1 km distant. The fractured quartzite 'aquifer' (Figure 11), sandwiched between impermeable phyllites, had its surface exposure more than 1½ km above, and distant from, the river valley. The connection of this 'aquifer' to the tunnel was by a minor shear zone, not even a significant fault.

The sheared, talcy phyllite was difficult to walk on, behaving somewhat like 'dry bars of soap', and not much stronger. Blocks continued to fall from the sheared left wall, while the arch was in quite massive phyllites. Figure 13 shows a photograph of the conveyor, as a reminder of the importance of a conveyor-monitoring system (e.g. laser profiling) in case of over-excavation. This could then be spotted before the extra spoil reached the spoil-dump.

Borrowing the 'stand-up' time and 'roof span' data of Bieniawski 1989, shown in Figure 14, we find that the predicted stand-up time for an unsupported span (measured from last support) can be much too short. The estimates below explain why this TBM cutter-head was able to

'over-excavate'. Even an open-TBM shield of 5 m length was *too long* in this case. The on-site Q-parameter logging reproduced in Figure 15, provided an estimate of $Q_{mean}$ = 0.07 in the sheared phyllite.

Assume RMR ≈ 15 log Q + 50 (Barton, 1995). Then, from Figure 14 we obtain:

- 1m (without support) ≈ 1 hour stand-up
- 5m (no support until finger shield) ≈ 0.1 hr stand-up

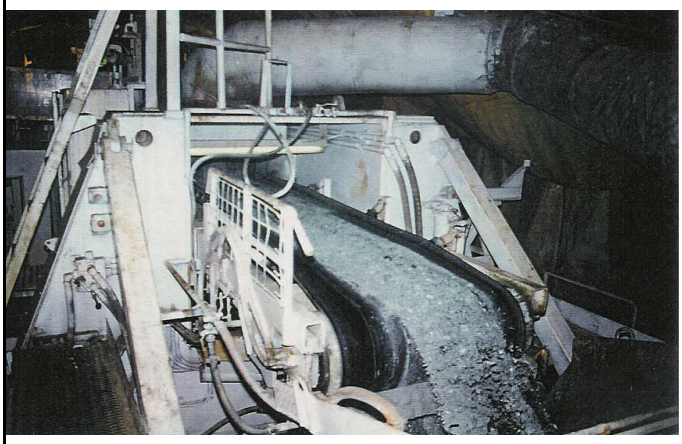


Fig. 13. The TBM had been excavating more material than $(\pi R^2)$ x length of advance, due to the stand-up time limitations of the sheared phyllites ahead and to the left-side of the cutter-head.

Eventually this unsuitable, inherited TBM became permanently buried, and was subsequently by-passed from the power house end of the tunnel many years later, using drill-and-blast tunnelling.

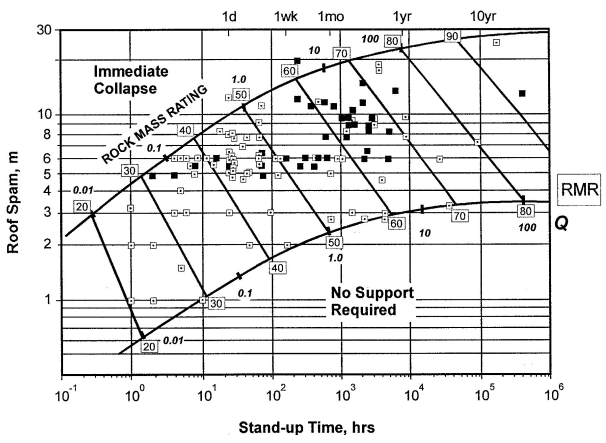



Fig. 14. Stand-up time data plotted by Bieniawski, 1989, with RMR to Q conversion with the equation RMR ≈ 50 + 15 log Q, from Barton, 1995.

As a point of curiosity, a deep borehole drilled in the buried valley next to this planned headrace tunnel, drilled to help decide on the safest route for the tunnel, had encountered *wood* (*not* fossilized wood !) at a drilled depth of 537 m, resulting from a huge landslide in the not so distant past.

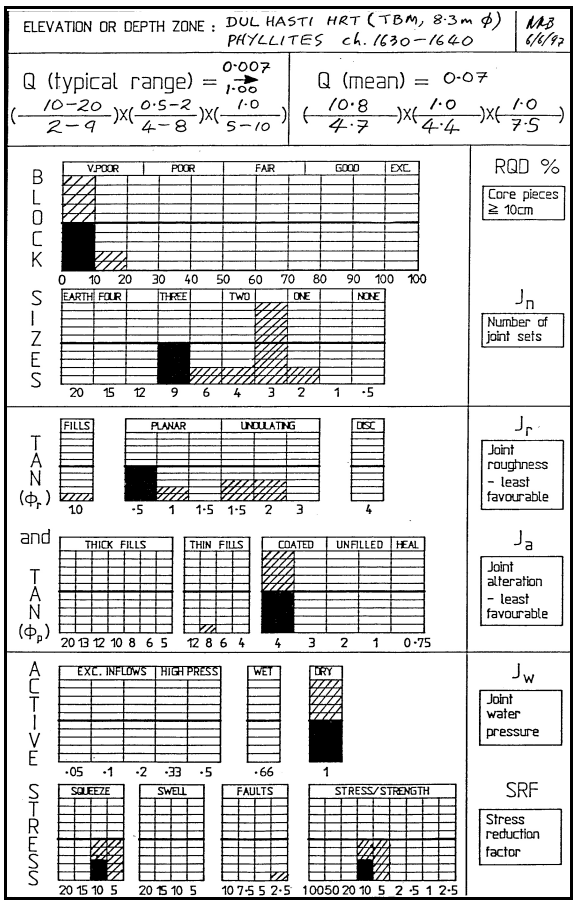



Fig. 15. Q-parameter recordings in histogram format, for the sheared talcy phyllites illustrated previously. Due to contract re-negotiation, this TBM (abandoned by the original contractor) had progressed only 400m in about 4 years.

## TBM TUNNEL THAT SUCCEEDED WITH THE SECOND CONTRACTOR

### Fault related problems at SSDS Tunnel F in Hong Kong

The Tunnel F problems at the sub-sea sewage project in Hong Kong were mostly related with fault zones, and with the difficulty of pre-injection in a small-diameter TBM tunnel (Figure 16). This particular contract was completed by Skanska International, following Owner re-negotiation of all the contracts after the withdrawal of the original contractor. This particular 3km long tunnel ran

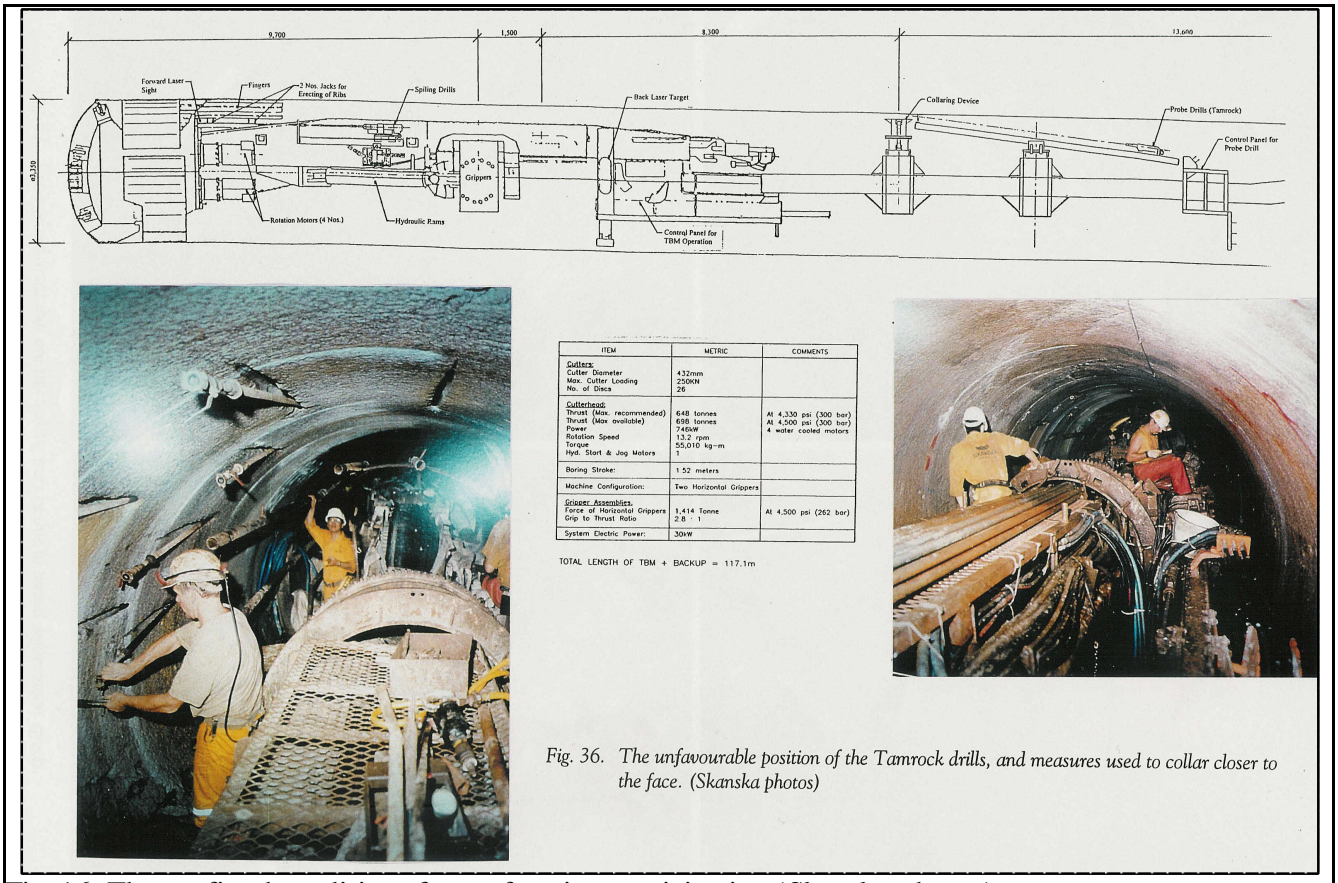



*Fig. 36. The unfavourable position of the Tamrock drills, and measures used to collar closer to the face. (Skanska photos)*

Fig. 16. The confined conditions for performing pre-injection (Skanska photos).

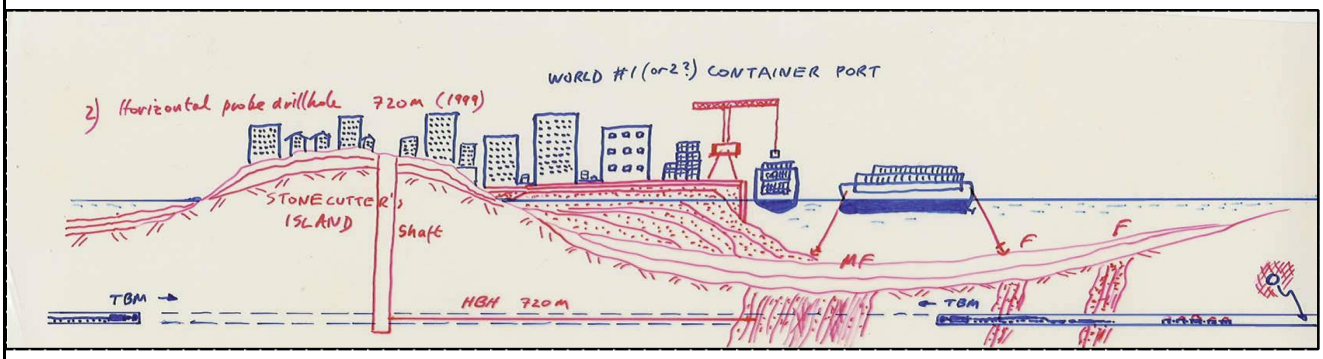



Fig. 17. The remaining 887m of TBM-driven tunnel included the unexplored Tolo Channel fault zone. Only a few meters of this could be cored from the exit-shaft location, yet the TBM later managed to penetrate the fault zone due to the pre-grouting effect on the rock mass. (NB sketch of situation in 1999).

from Tsing Yi Island to the (much reclaimed) Stone Cutters Island, and underneath the world's second largest container port close to Hong Kong.

Unfortunately, the tunnelling contract consultants failed to detect and locate a major regional fault zone: the Tolo Channel fault zone, due in part to the difficulty 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 intense building developments of Kowloon. A rough sketch of the situation is given in Figure 17.

Only 481m of the tunnel was completed in a previous project. Some 3098m remained for the new contractor (Skanska International). The Owner/Consultant 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).

During 29 months, 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 lack of access for the seismic-survey ship.

Skanska decided to drill a long horizontal 'pilot hole' *backwards* from the exit-shaft on Stonecutter's Island (see sketch in Figure 17), 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 of course known from seismic measurements at dam sites (Barton, 2006), and from positive tunnelling experiences through systematically pre-injected rock.

## Analysis of pilot borehole (LH 01) core qualities for input to $Q_{TBM}$ model

The 731 m of core recovered from the pilot hole sketched in Figure 17, 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 18, and with some logging results (0 to 201 m) shown in Figure 19.

M = massive
S = slightly jointed
J = jointed
Z = zone (weathered)
F = fault

Fig. 18. Photographs of the five selected rock classes which, when Q-parameter logged, gave the approximate statistical frequencies of these five classes.

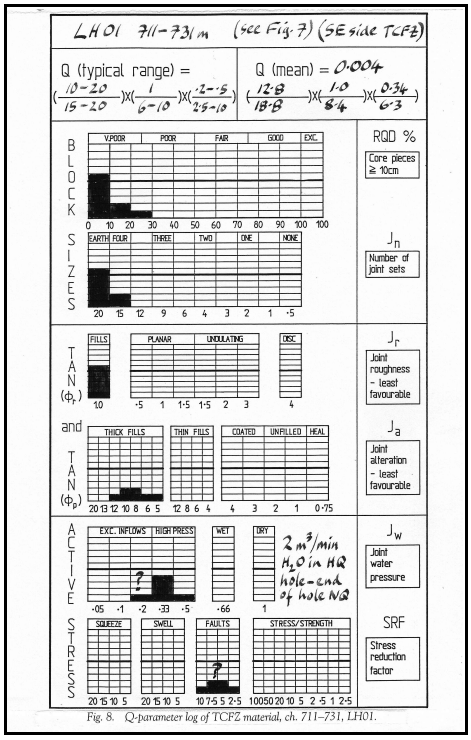



Fig. 19. Q-parameter histogram logging of frequency of occurrence and ratings for the five rock classes, in the first 200m of hole LH 01 (i.e. the last 200m of the tunnel).(Note numbers 1 to 5 in each histogram, corresponding to rock class).

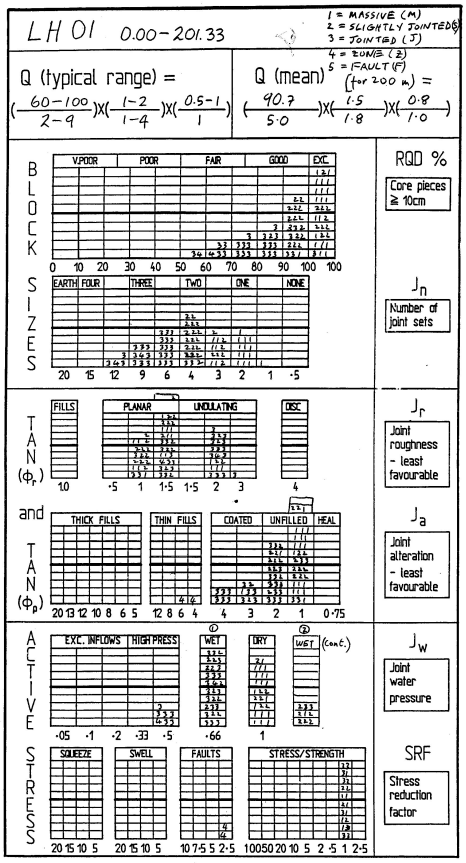



Fig. 20. Essentially all the Q-parameter characteristics of the faulted rock (all that could be sampled of the fault zone) plot 'to the left' in the Q-histogram method of collecting site data. $Q_{mean}$ = 0.004, i.e. needs improvement by pre-grouting if TBM penetration should be achieved.

## Assumptions concerning rock mass improvement by pre-injection

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

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

Roald (in Barton et al. 2001) has shown that time and cost (Figure 21) of tunnelling are *strongly, and similarly correlated to Q*-values 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).

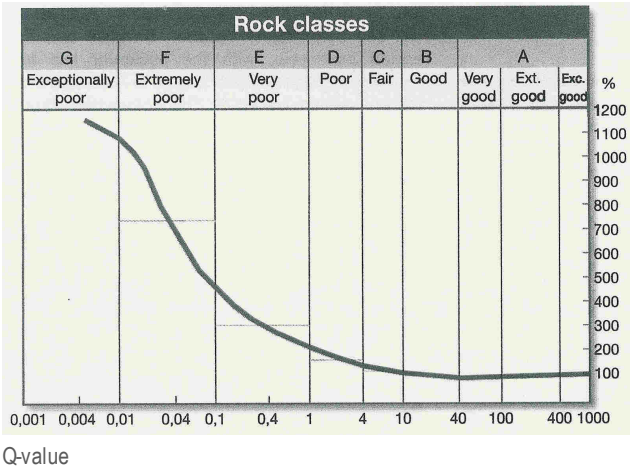



Fig. 21. Relative time for tunnelling as a function of Q-value. After Roald, in Barton et al. 2001.

Assumed improvements in the rock mass properties caused by the planned pre-grouting of (also) the remaining 800 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.

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

***Before pre-grouting:***

*Q= 30/9 × 1/2 × 0.5/1 = 0.8*

***After pre-grouting:***

*Q = 50/6 × 2/1 × 1/1 = 17*

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 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

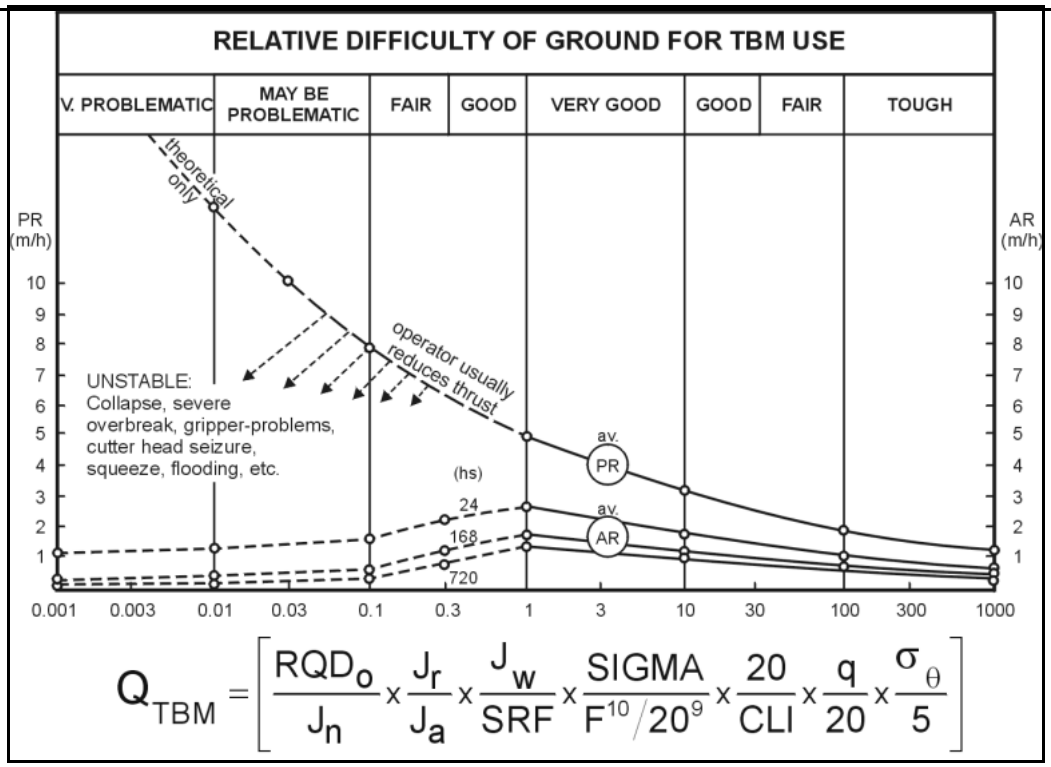



Fig. 22. The $Q_{TBM}$ scale of TBM tunnelling difficulty, showing its derivation from Q-parameter and machine-rock interaction parameters.

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.

| 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 |

## $Q_{TBM}$ MODEL FOR (PR) AND (AR) PROGNOSIS AND COMPLETION ESTIMATES

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 22 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):

$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{\left(F^{10}/20^9\right)} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5} \qquad (4)$$

Equation 4 includes a *comparison* of the applied cutter force F (e.g. a 1000 tnf TBM thrust averaged over 40 cutters, gives F = 25 tnf), and the estimated rock mass strength SIGMA. Crudely estimated, we assume SIGMA (the estimated strength of the rock mass), is given by the following equation (expressed in MPa).

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

where the Q-value has been normalized by $\sigma_c$ /100 (increased or decreased for rock strengths more or less than 100 MPa), and ($\gamma$) is the density of the rock. Cutter life index (CLI), quartz

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.

| 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 |

percentage (q), and the approximate biaxial stress state ($\sigma_\theta$) 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 approximation (Barton, 2000).

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

Due to the complexities of TBM operation, the actual advance rate (AR) over longer periods of tunnel boring is a fraction of the "instantaneous" value PR. This fraction is the utilisation U (the time when boring is actually occurring). The classic TBM (equation 1: 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 only as low as (-)0.10 when using modern double shield machines with PC-element liner push-off, *due to continued advance while resetting the grippers*. Note the log scales of PR, AR and time in this figure, which were derived from analysis of the 145 TBM case records totalling some 1000 km, as mentioned in the introduction. 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.

When on the other hand, conditions are very favourable and PR is as high as say 6 m/hr, and m is as low as –0.15, we can evaluate AR at the end of 1 year of tunnelling by combining equations 3, 4 and 5.

$$AR \approx 5\, Q_{TBM}^{-1/5} \times T^m \qquad (7)$$

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 16km 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 23. 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.

## Application of $Q_{TBM}$ model to Hong Kong Tunnel F pre-grouting effects

Application to the Hong Kong Tunnel F pre-grouting estimation is illustrated in Figure 24a and 24b, showing before-and-after 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, actually caused by the systematic pre-grouting performed by Skanska.

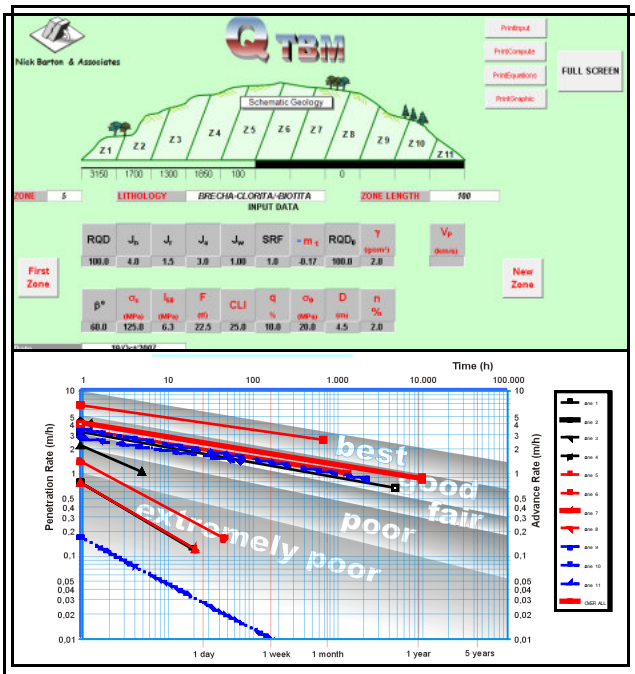



Fig. 23. An example of the $Q_{TBM}$ 'input data' screen and zone-by-zone progress predictions, including fault zones. Part of the prognosis of a TBM tunnel about to start in S. America, where a lot of deep coring was available from mineral exploration holes. Barton, 2007, contract report.

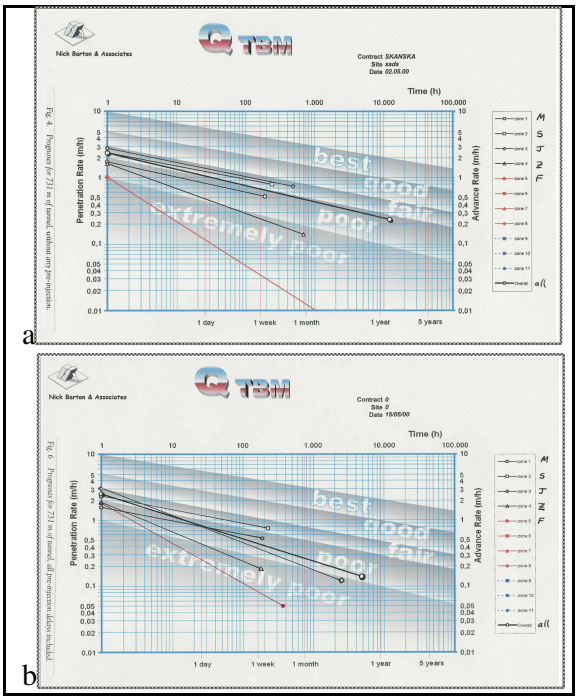



Fig. 24 a and b. Application of the $Q_{TBM}$ model to Hong Kong Tunnel F pre-grouting predictions. In the first screen, no pre-grouting improvements were assumed, and more than 1 year was predicted for completion of some 800 m. Grouting made regional fault penetration possible, instead of impossible.

## CONCLUSIONS

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.

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.

Because TBM slowly decelerate as time and tunnel length increase, it is even more 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, and they 'all' have various problems.

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).

Double-shield machines, with PC-elements for both support and 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 concrete rings required, mostly produces a 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 AP result by 'curve-jumping' in Figure 2.

This may be sufficiently attractive from a scheduling point of view, to make the probable 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.

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.

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.*

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.

The effect of rock mass compaction due to tunnel depth, causes an increase in the seismic velocity, if seismic profiling ahead of a (TBM) tunnel is being used to probe conditions. The recording of a reasonable velocity of say 4km/s may mask actual fault zone qualities, which might reveal a 2 to 2.5 km/s velocity, if encountered nearer the surface.

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