TBM TUNNELLING IN SHEARED AND FRACTURED ROCK AND THE APPLICATION OF Q_{TBM} MODEL CONCEPTS

Nick Barton, Nick Barton & Associates, Oslo, Norway

ABSTRACT

Sheared and faulted rock encountered at great depth, and rock masses that are deeply weathered, and that are encountered when tunnelling is carried out at too shallow depth, represent frequent challenges for TBM tunnellers. In this paper, various experiences with TBM tunnelling problems will be 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 Qtbm data base. TBM achieve remarkable advance rates when conditions are favourable, out-performing drill-and-blast by a wide margin. However, favourable conditions are interrupted by infrequent, sometimes frequent challenges, which are not widely reported. Unless the rock mass character is in the central area of the Q-diagram on a consistent basis, with Q of about 1.0 near the centre of the distribution, marked superiority to drill-and-blast may not be achieved, especially if the tunnel is long, since there is a generally-observed gradual deceleration of the TBM tunnelling advance rate, a reduction unlikely to be seen with drill-and-blast tunnels. Double-shield TBM, designed for thrusting from PC-element liners while resetting grippers, may represent 'over-design' regarding support needs, for much of a given rock mass, but they reduce these deceleration gradients by about half. All but the most serious shear zones and faults may be tackled well by these machines.

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.

As may be imagined, the advance rate (AR) is a function of opposite effects in the best rock, namely the need for frequent cutter change, yet little need or delay for support. At the low velocity, high PR end of this data set, there will not be frequent need for cutter change (slowing AR), but conversely there will be delays for much

heavier support. The 'reversal' of normal 'quality' concepts is illustrated in a 'Q-diagram' in Figure 2.

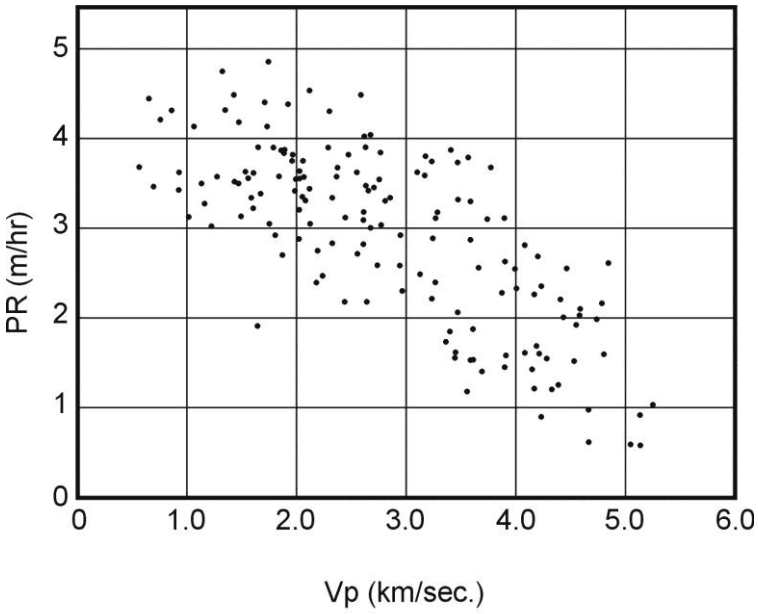


Figure 1 Declining TBM penetration rate with elevated seismic velocity, due to lack of jointing. The actual advance rate will be a function of opposite effects in the best rock, namely need for frequent cutter change, but little delay for support. At the low velocity, high PR end of this data set, there will not be a need for cutter change, but conversely there will be delays for much heavier support.

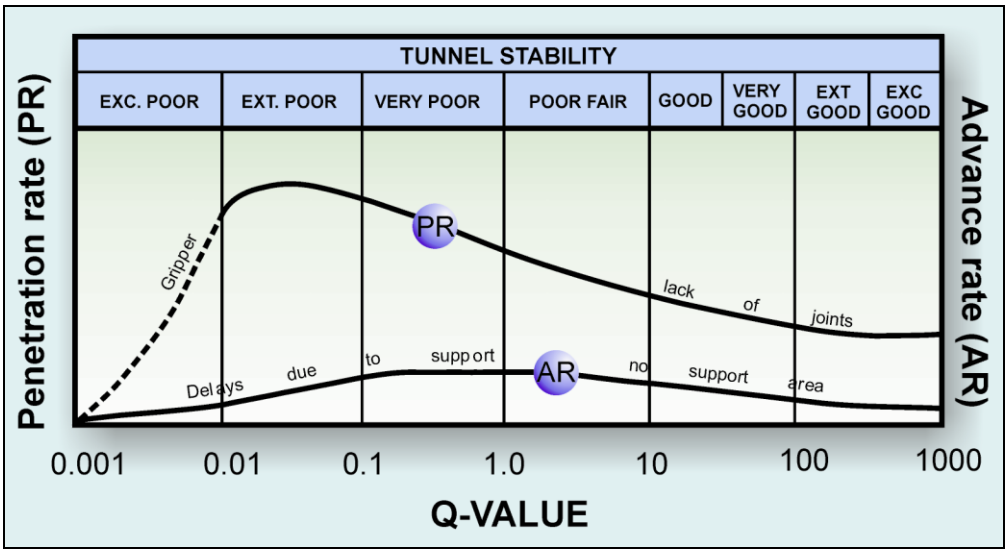


Figure 2 Based strictly on Q-value, and Q-system adjectives 'poor', 'fair', 'good' etc., the decline of PR due to lack of joints, and its 'theoretical' maximum at low Q-value, stands in strong contrast to the declining actual advance rates seen at both ends of the rock mass quality spectrum. The most serious delays, actual 'standstills' obviously occur at the faulted/sheared rock end of the rock mass quality spectrum, when Q is as low as 0.01, where even gripper problems may be experienced. Barton, 2000.

There are obviously innumerable rock conditions that TBM have to tackle, with strong reliance on the consultant's advice to the Owner and to the TBM-designer and manufacturer, concerning the likely range of rock mass conditions likely to be encountered.

Using oilwell-stability sketches from Bradley, 1979 as illustration of just four cases, we can expect that many faults (or boundaries of faults, where there is water), cause a 'ravelling' type of behaviour, like # 4 in Figure 3. The clay core of a fault (if present), may suffer squeeze, like # 3. The well jointed case (#1) may be ideal for TBM due also to its favourable orientation, assuming little support is needed (giving both high PR *and* high AR). However, the sparsely jointed case (# 2) may be tough to bore in hard abrasive rock (low PR, and consequently low AR).

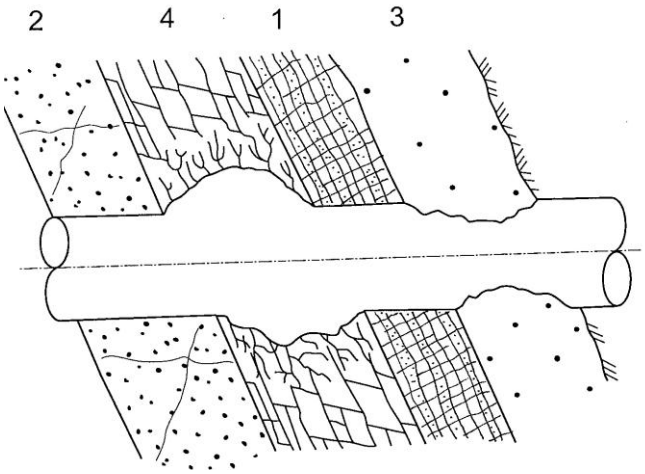


Figure 3. Four characters of ground from oil-well experience (Bradley, 1979). These four classes of ground may have major impact on TBM performance, if conditions persist in any one of the four alternatives,

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, in order to try to find a better basis for TBM advance rate prognosis, for *poor rock conditions*. It appeared that 'poor conditions' were treated as 'special cases' in the industry, with concentration on solving the penetration rate and cutter life aspects as the apparent focus for many methods of TBM prognosis.

The case records showed many things, including the following general 'deceleration' trends, 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 x U (where U= utilization for boring) ……..(1)

AR = PR x T^m……(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, conveyor, rails) 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 month or two of numerous projects.

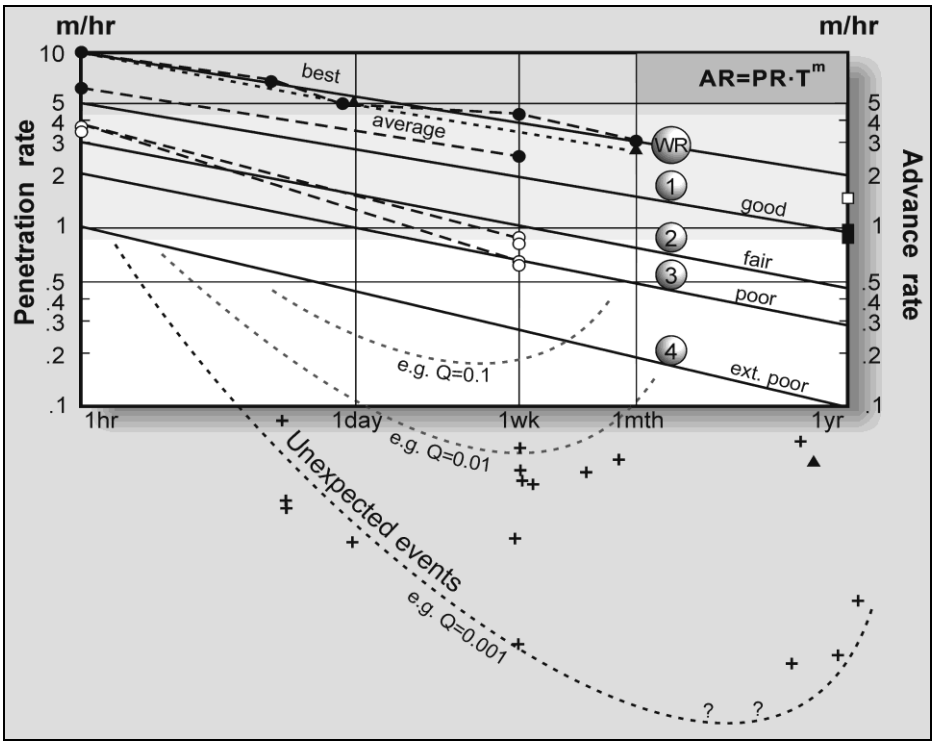


Figure 4 A synthesis of the general trends from 145 TB tunnelling projects reviewed by Barton, 2000. (Note PR = penetration rate, AR = actual advance rate, U = utilization when boring, and T = time in hours). The best performances, termed WR (world record) are represented by the uppermost line showing best shift, day, week, and month. A remarkable case with 16 km excavated in one year is consistent with this exceptional trend line. 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.

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 4. The gradients of *deceleration* (-m) given by the negative slopes of the TBM performance trend lines in Figure 4 are 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 5. 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 3.

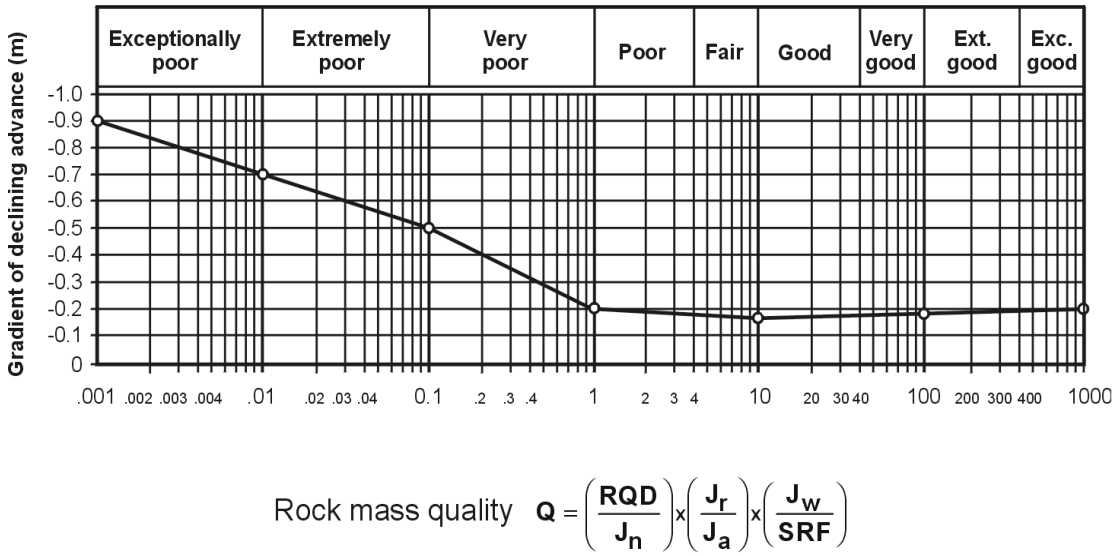


Figure 5. Preliminary estimation of deceleration gradient (-m) from the Q-value, is clearly of relevance for fault zones, and sheared rock, as these are likely to have Q-values $\leq$ 0.1.

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 6 is from Grandori et al. 1995, from the Evinos-Mornos Tunnel in Greece. The case illustrated in Figure 7 is from a sheared zone in quartzites and meta-sandstones, from the Pinglin Tunnel in NE Taiwan. This tunnel was later renamed, before completion after about 12 years.

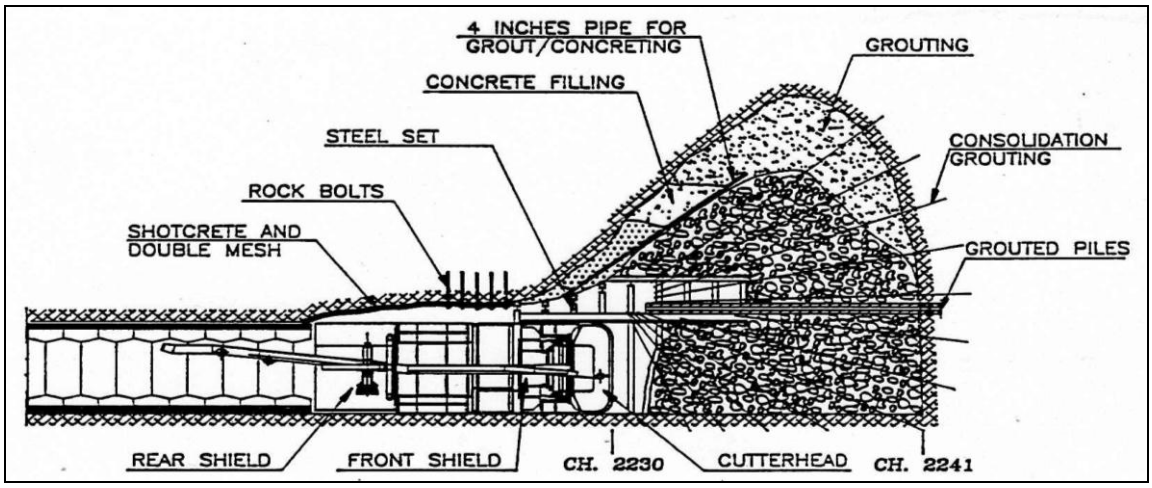


Figure 6. Loosening of the rock mass in a fault zone, resulting from withdrawal of the TBM. Detail of some of the recovery operations described by Grandori et al. 1995. Despite the sophistication of double-shield operations (and their greater cost), hand-mining operations may be needed on occasion.

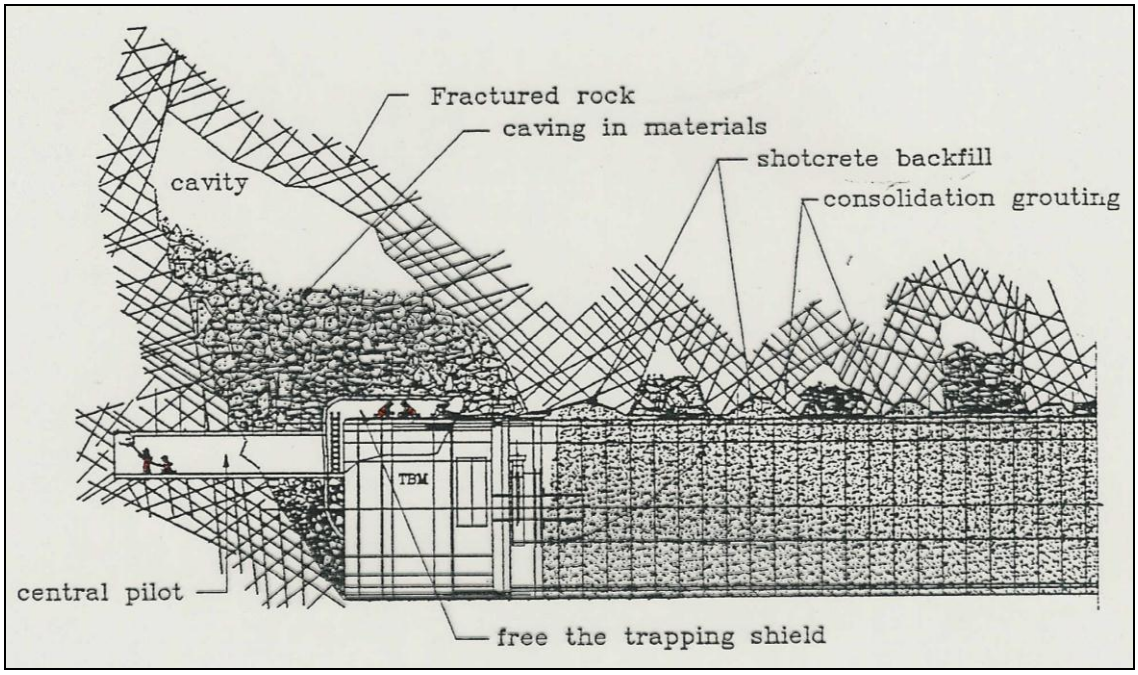


Figure 7. Graphic illustration of a by-pass situation for one of the TBM at Pinglin. This TBM was used to cut the bench material for significant lengths of problem ground, following the advance of a drill-and-blast top-heading. Shen et al. 1999.

The loosening of the rock face that can occur during such delays to TBM advance has parallels in surface excavation loosening, as illustrated with cross-hole V_P measurements in Figure 9.

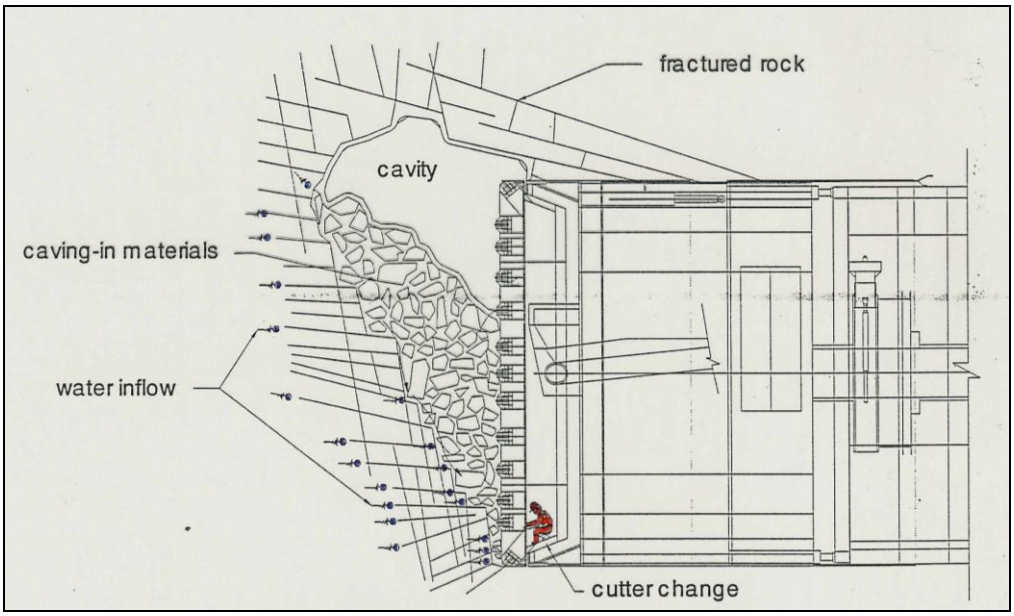


Figure 8. Difficult cutter-change conditions in the meta-sandstones and quartzites of Pinglin. The likelihood of adverse loosening of the face during such delays is clear. Shen et al. 1999.

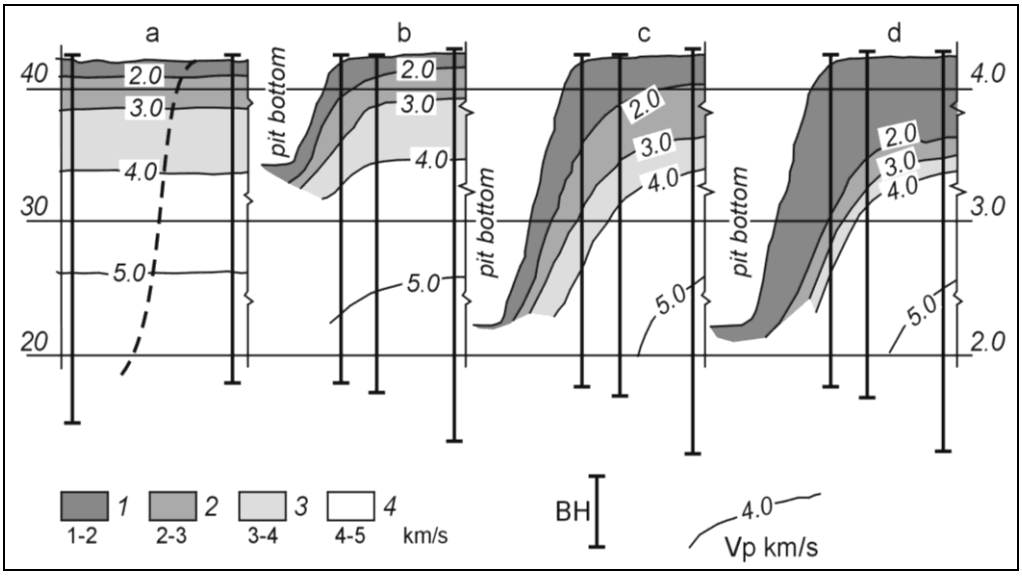


Figure 9 Effect of stress change and time on cross-hole seismic velocity at a Russian ship-lock. There is a 1 year delay between 'c' and 'd'. The reduced velocities are presumably caused by insufficient rock support where shear stresses are high, as also likely to be experienced in a 'flat' TBM tunnel face. Savich et al., 1983.

Fault zones will remain a serious threat to TBM tunnelling as we now know it, unless the extremely poor rock mass qualities associated with fault zones can be improved by 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 should be a separate unit, closer to the face.

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.

1. $AR = PR \times U$ (all TBM must follow this)
2. $U = T^m$ (due to the reducing utilization with time, advance rate decelerates)
3. $T = L / AR$ (obviously the time needed for length L must be equal to L/AR)

Therefore we have the following

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

5. $T = (L / PR)^{1/(1+m)}$ ……(3)

6. This is very important equation for TBM, if one accepts that (-)*m* is strongly related to Q-values in *fault zones,* as shown in Figure 5.

7. It is important because very *negative (-)m* values make 1/(1+m) *too big.*

8. 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.

9. It is easy (too easy) to calculate an almost ‘infinite’ time for a fault zone using this ‘theo-empirical’ equation. 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.

ARE LONG TUNNELS FASTER BY TBM

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’ the larger the ‘sample’. This effect of tunnel length on a hypothetical distribution of rock conditions is illustrated in Figure 10.

In the following a comparison of TBM prognosis and drill-and-blast prognosis will be made, using Q-system based estimates of quality versus cycle time, as illustrated in

Figure 11, and Q_{TBM} based prognosis for a similar size of TBM tunnel. Study will likely show that it is the intermediate length tunnels that are faster by TBM, provided TBM delivery does not prejudice an earlier start.

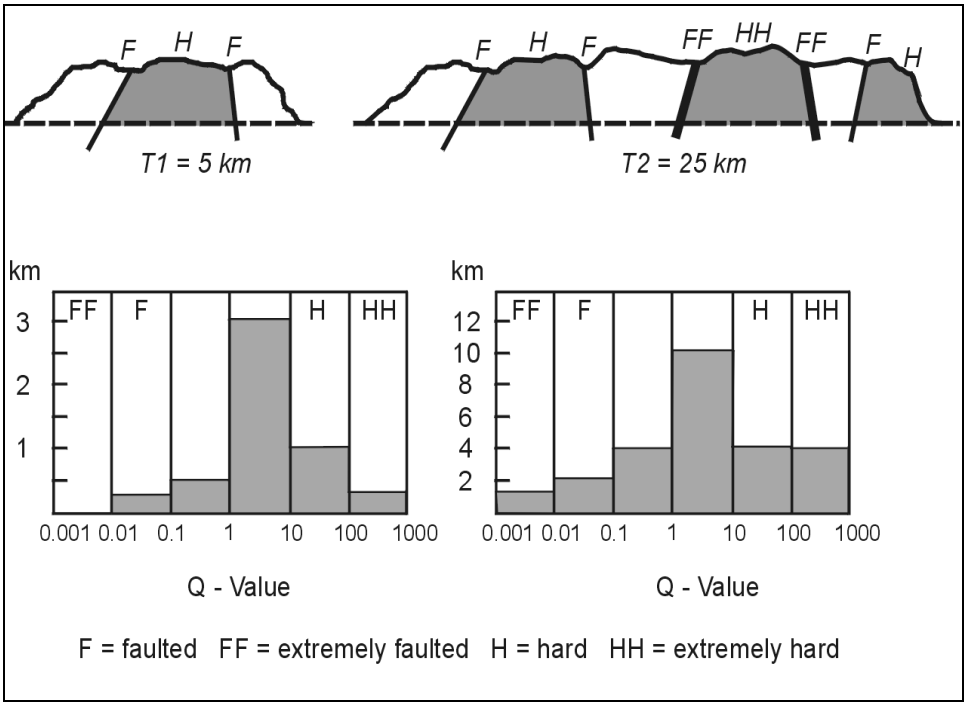


Figure 10. The longer the tunnel, the more likely that 'extreme value' statistics (of rock quality) will apply, due to a 'large scale' Weibull theory: i.e. larger 'flaws' the larger the 'sample'. Barton, 2001.

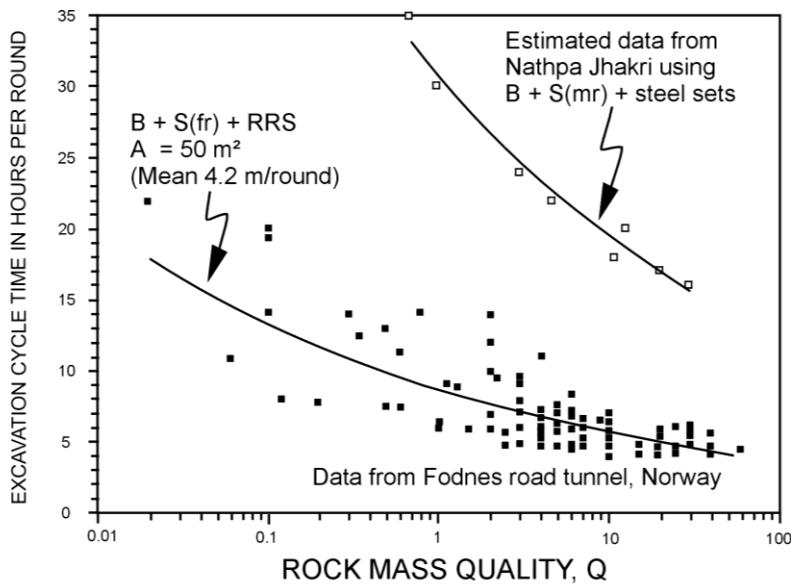


Figure 11. A tunnel construction follow-up by Grimstad, relating cycle-time for drill-and-blast, with the local rock mass quality Q-value. Grimstad, 1999, pers. comm.). Tunnel support, where needed for this main road tunnel, was the main cause of increased cycle time as the Q-value reduced.

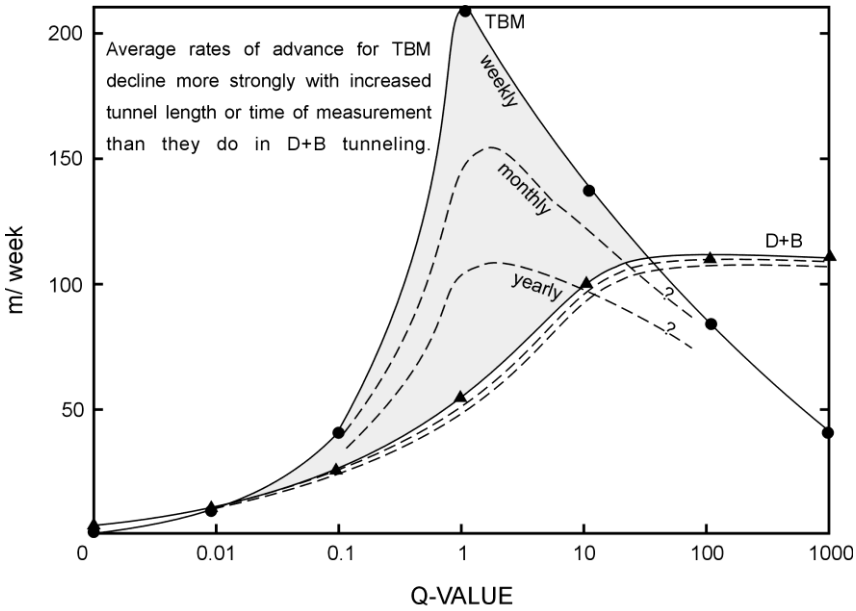


Figure 12. Comparing TBM and drill-and-blast over a full spectrum of rock classes. The TBM is much faster over short distances, with the proviso that rock mass qualities are not extreme. As tunnel length increases, the 'central' rock quality becomes more important due to the deceleration of advance rate with time, and therefore with tunnel length. Barton, 2000.

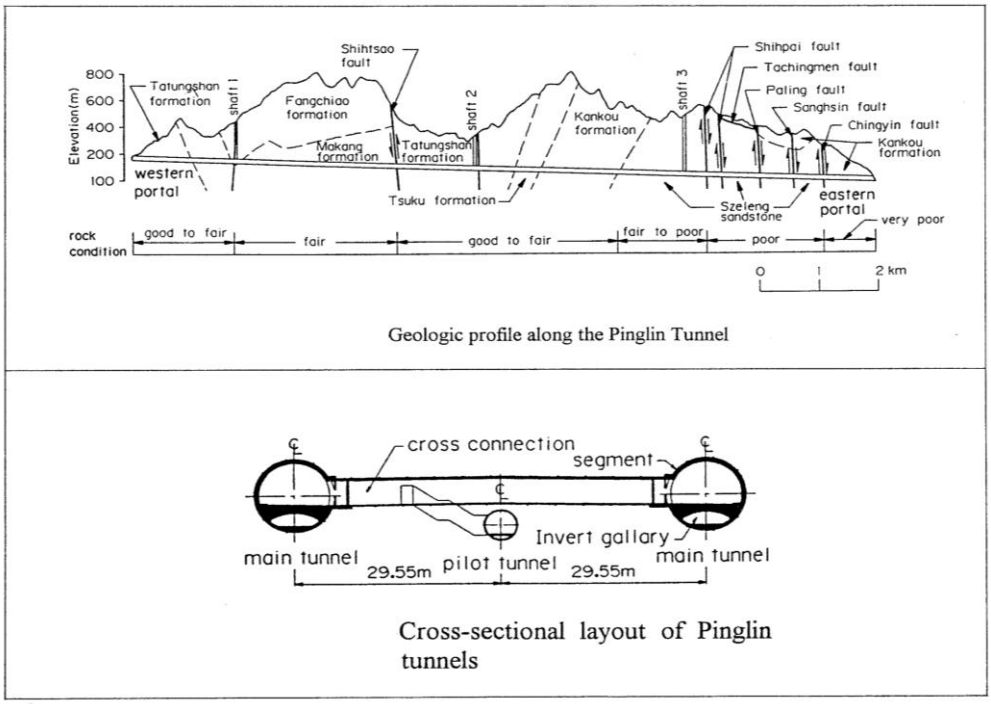


Figure 13. Geological section along Pinglin Tunnel, and cross-sectional layout of the three parallel tunnels. In very poor rock conditions, the excavation of the main running tunnels actually caused inter-action across the two-diameter wide pillar, causing squeezing of the smaller diameter pilot tunnel, some 20 m distant. Such events are statistically more likely the longer the tunnel becomes.

The Pinglin Tunnel in NE Taiwan 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 end was essential for completion, after some 12 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.

SOME ASPECTS CONCERNING SUPPORT IN TBM TUNNELS

The black bars in the Q-system tunnel support chart shown in Figure 14 mark the area where rock quality appears better than it actually is in TBM tunnels, due to almost absent over-break in this quality-size area. It is physically difficult for an engineering geologist to assess the true nature of the rock in this area of the Q-chart. At lower qualities, for a given span (= diameter), over-break makes it equally easy to judge rock quality, whether the tunnel is driven by TBM or by drilling-and-blasting. At the highest rock mass qualities, support is not needed in either case, and the tunnel profile is free of over-break, unless other factors, such as higher tangential stress closer to the TBM tunnel perimeter, causes time-dependent stress-spalling. One then migrates to the left on the quality scale, due to the influence of higher SRF.

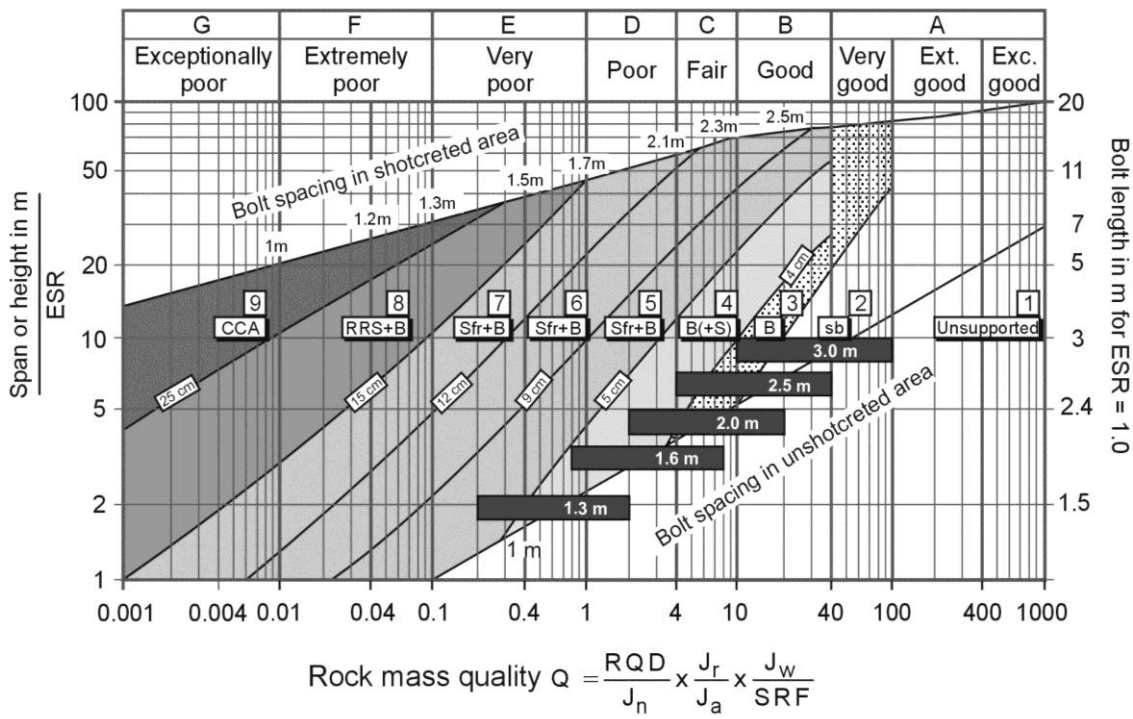


Figure 14 The black bars in the Q-system tunnel support chart mark the area where rock quality appears better than it actually is, due to almost absence of over-break. At lower qualities, for a given span (= diameter), over-break makes it equally easy to judge rock quality, whether TBM or drill-and-blast. At highest qualities, support is not needed in either case, and the high quality is easily judged in both cases.

A helpful scheme for selecting rock support in TBM tunnels, that can be used in conjunction with the Q-method recommendations is reproduced in Figure 15. This has a combination of authors, the last of whom (Barton, 2000) added a revised RMR and a new Q-scale. Note the potential implications of F1 to F7 classes to TBM utilization, and weekly advance rates, shown by Scolari, 1995, and reproduced in Figure 16.

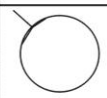
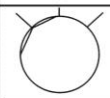
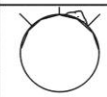
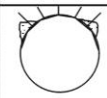
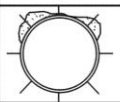
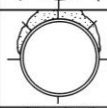
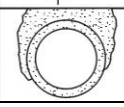
Class	Approx. Q range	Approx. RMR range	Typical Section Diameter 6m	Rock Mass Behaviour
F1	10-100	65-80		Long term stability
F2	4-10	59-65		Local rockfall
F3	1-4	50-59		Frequent rockfall in machine area
F4	0.1-1	35-50		Frequent rockfalls in machine area
F5	0.03-0.1	27-35		Frequent rockfalls in cutterhead area after each stroke
F6	0.01-0.03	20-27		Large overbreak in cutterhead area after partial strokes
F7	0.001-0.01	5-20		No self supporting capacity

Figure 15 Austrian (Ilbau-modified) TBM support scheme, with writer additions of Q and RMR ranges in relation to classes F1 to F7 (after Scolari, 1995). See details of support recommendations in Barton, 2000.

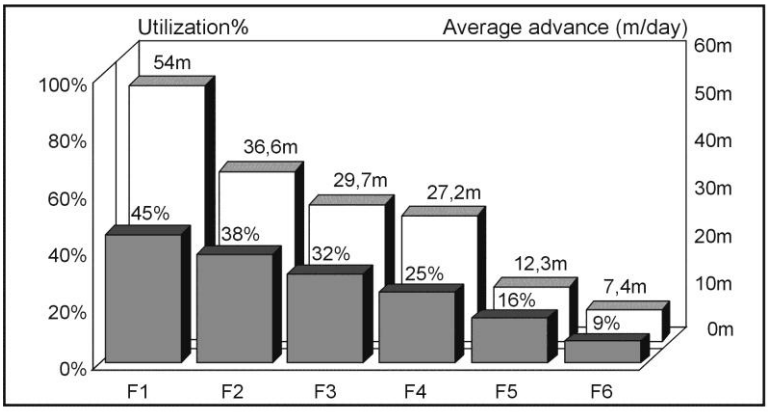


Figure 16 Example of utilization decline, and meters/week reduction, as rock class declines from F1 to F7. Rock bolt usage might increase from 0 to 10 per meter of tunnel, over the same spectrum of rock mass quality. Scolari, 1995.

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

The case of Pont Ventoux, N. Italy

The 7km headrace tunnel for the Pont Ventoux HEP was parallel to a marked NW-SE trending valley , and also parallel to the foliation and to the (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 16.

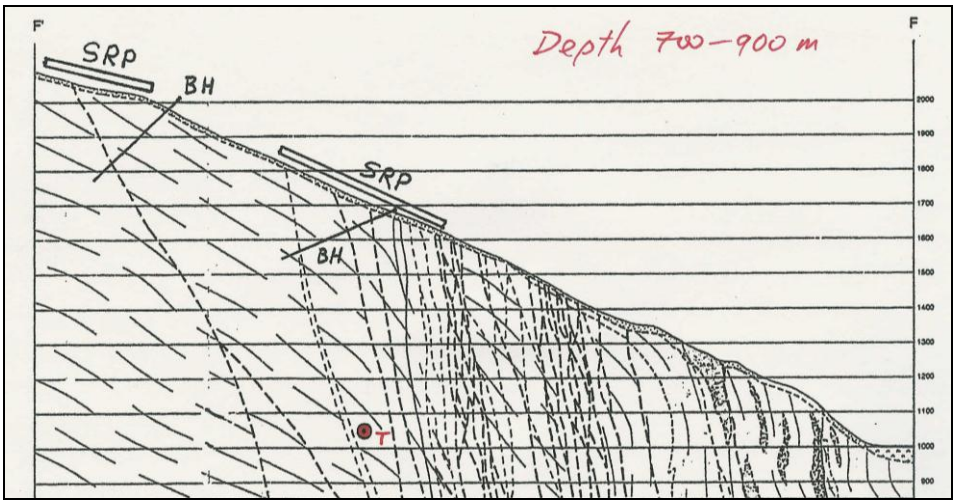


Figure 17 The tunnel was apparently 'too deep' for satisfactory geological investigations, judging by the 'missed' fault swarms shown here. In fact it was clearly not adequately investigated. BH =boreholes, and SRP =seismic refraction.

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 18.

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. 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. 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 loosened blocks remained to block the cutter-head.

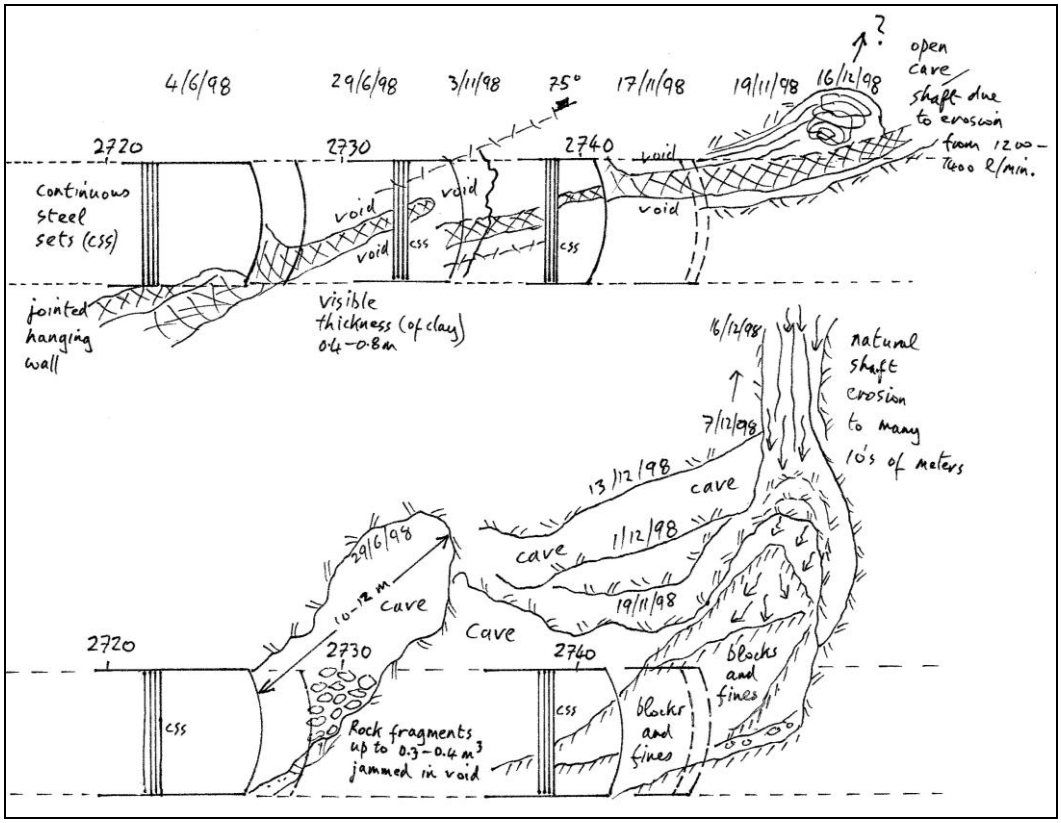


Figure 18. The Pont Ventoux TBM was stuck here for 6 months (due to blocked cutter head) from intermittent falling blocks from the ‘fault shaft’, assisted by water and/or water pressure. These sketches are super-imposed on one sheet, traced from the geologist’s daily logs.

At another location, the ‘fault zone performance’ was 7months for only 20m of advance, representing an average AR = 20/(7x720) = 0.004m/hr. This is almost off the bottom of the chart, in the ‘unpredicted events’ area of Figure 4, where various case record crosses (**+**) are plotted.

The outlook for future tunnelling at Pont Ventoux was bleak if further members of the fault swarm lay sub-parallel, close to, or intersected the future tunnel. 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. (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.

Another problem in fault zones is the grippers, and maybe also the shield, i.e. delayed treatment of rock that actually requires *pre-treatment.* Figure 19, after Wanner 1980, shows the implications in graphic form. Tangential stress indicators have been added in Barton, 2000. At Pont Ventoux, some of the fault zone conditions were so unfavourable that circular steel sets had to be placed flange-to-flange. Since the channels in the grippers were not designed for this 'spacing' of steel sets, the result was partial crushing of the steel sets by the grippers, followed by even greater deformation.

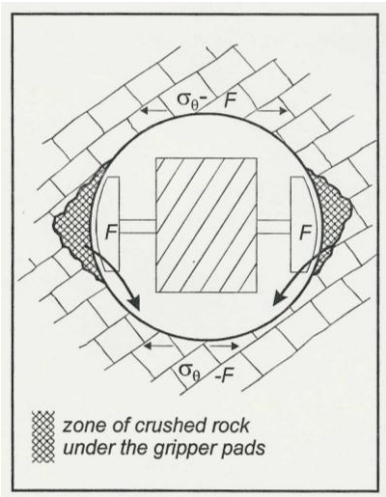


Figure 19 Poor rock conditions may prejudice the effective use of grippers, if over-break prevents gripper-wall contact, or if steel rings have to be placed too close. Presumably, arch stability may also be compromised by gripper action in general. After Wanner, 1980.

Grippers usually have 'rib-spaces' (e.g. at 0.6m spacing), to avoid crushing steel sets that are placed at this regular spacing. But if too many sets are needed (i.e. sets placed flange-against-flange) due to faulted rock as at Pont Ventoux, then there is the likelihood of crushing of the sets just where needed most.

THE BENEFIT OF PRE-INJECTION

In drill-and-blast tunnelling, thorough pre-injection around the complete (360º) profile can be more easily performed than when 'there is a TBM in the way'. The 20 to 24 hours (approx.) needed to drill and inject 20 to 40 holes of about 25m length is balanced by relatively trouble-free advance (of e.g. 4 or 5 rounds) through this (previously) bad ground, until the next cycle of pre-injection is performed to secure the next rounds. Typically 20 to 25m/week tunnel advance can be achieved on a regular basis, despite the (previously) bad ground.

Roald (in Barton et al. 2000/2001) has shown that time and cost of tunnelling are strongly 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 5). 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 be achieved where the Q-versus-cost and Q-versus-time curves are steepest (about 0.01<Q<1.0).

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 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 6 and 7. Figure 20 shows a comparison of open TBM and double-shield TBM from the same project depicted in Figure 6.

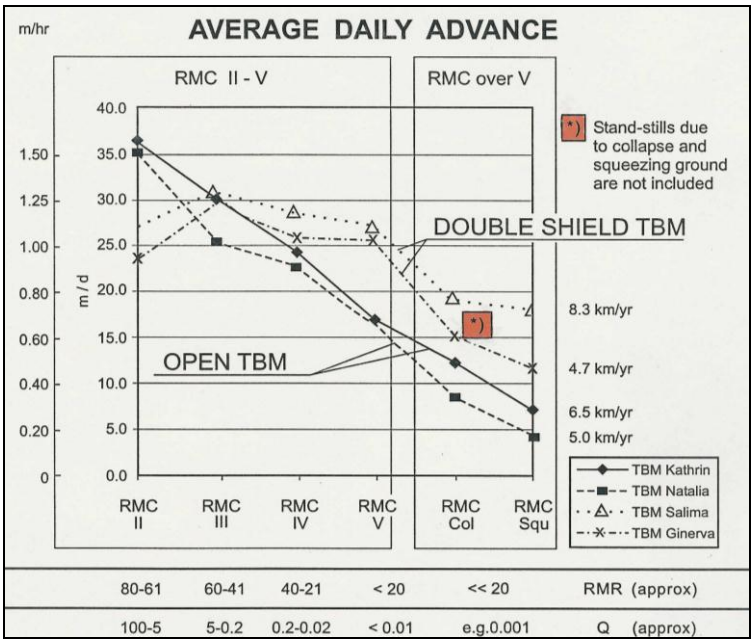


Figure 20 The Evinos-Mornos tunnel had two open TBM, and two double-shield TBM. Grandori et al. 1995 gave this comparative performance data. Tentative RMR and Q scales were added by Barton, 2000. Note that 'stand-stills' caused by fault zones, such as that shown in Figure 6, were not included in Grandori's comparison.

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 4. Gradients as low as (-) 0.10 were regularly achieved, with a typical PR of only 2 m/hr suggesting 'poor' performance, actually 'elevated through 'fair' and into 'good' performance. This 'recovery' is illustrated with hand-written data in Figure 22, showing one of the graphic Q_{TBM} model sheets.

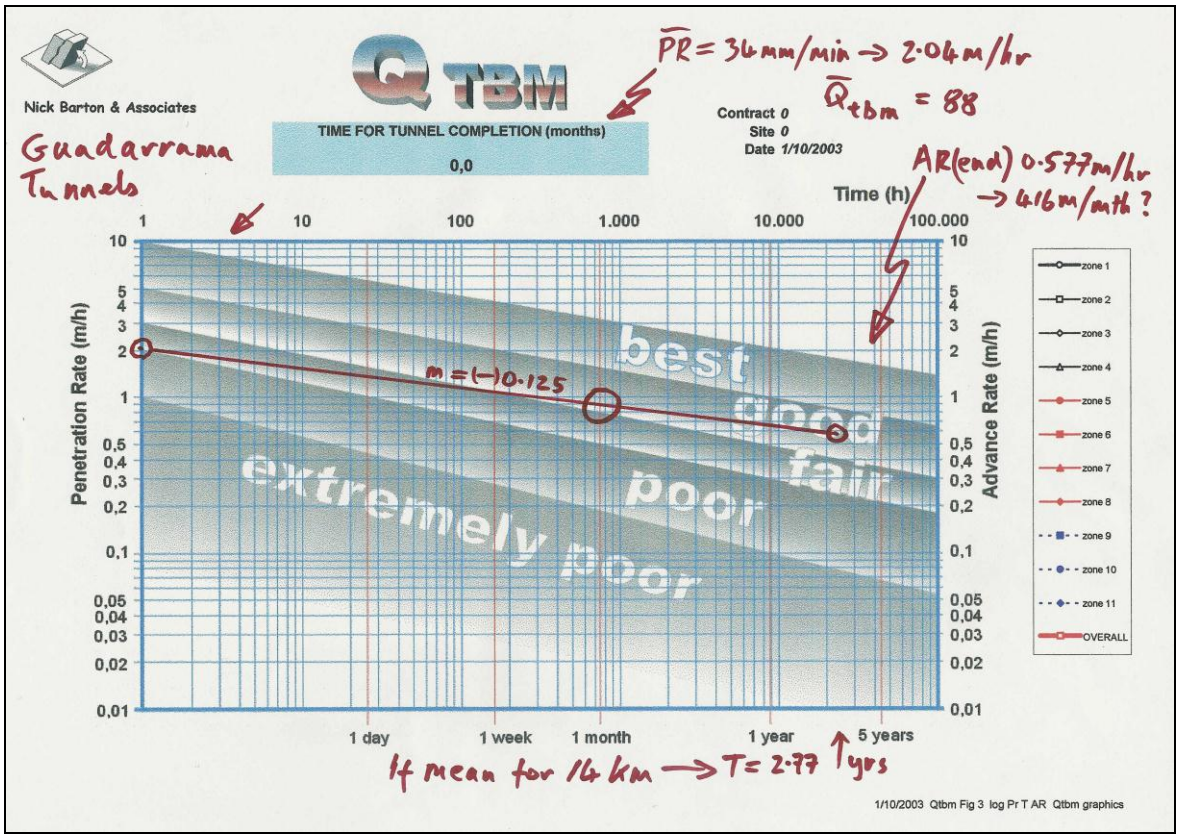


Figure 21. Despite frequent cutter changes, and a relatively low PR and therefore a high (unfavourable) Q_{TBM} value of 88 (see later), the high efficiency of 'continuous' boring at the Guadarama Tunnels, gave an extremely small gradient of deceleration crossing 'normal' performance trends (i.e. single-shield, without second thrust option). In the location analysed here, m = (-)0.125.

By completion, gradients of (*m*) as low as (-) 0.08 were achieved for certain lengths of the tunnels. Of course the question may be asked whether the 2 x 14+14 km tunnels could have been completed faster by drill-and blast in the mostly massive or jointed granites and gneisses, as compared to an expensive double-shield-thrusting-

off-PC-element-liner solution, and the capital outlay on four TBM and large amounts of PC elements. The answer in this particular case was that reliability of completion on time was considered of over-riding importance, and the higher investment achieved this goal in this case, despite occasional delays in faulted ground.

TBM TUNNELLING IN TECTONICALLY DISTURBED ROCK IN KASHMIR

The case of Dul Hasti HEP

We will now move into the foothills of the Himalayas, and record an extreme water and pebble/sand blow-out, plus stand-up time problems in inter-bedded sheared and talcy phyllites, and variously jointed quartzites, with PR rates as low as 0.2m/hr in the first kilometre of the tunnel where there was mostly massive abrasive quartzites

The 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 $60m^3$/min water inrush, that subsequently required a separate drainage tunnel to the valley-side, 1 km distant. There was talk of miners having escaped from the flooded/buried TBM by escaping above the water, inside the air-ventilation ducts.

The fractured quartzite 'aquifer', 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 fault.

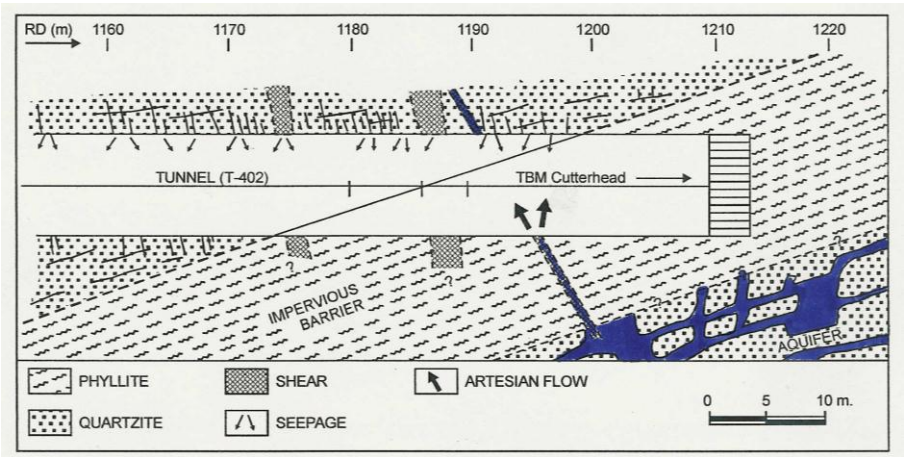


Figure 22 Geologist's recording of possible cause of the blow-out in the early kilometres of the Dul Hasti TBM headrace tunnel. The TBM was withdrawn some meters when invert leakage increased. The blow-out even displaced the heavy TBM. Deva et al., 1994.

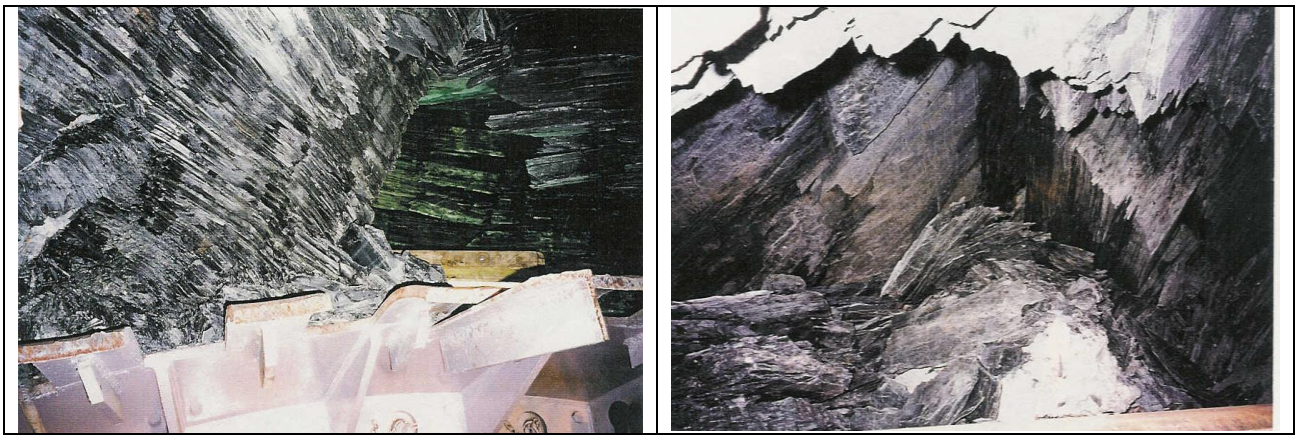


Figure 23. A subsequent location (around ch 1630) of stand-up time problems in sheared, talcy phyllites, where a void of 3 to 4m depth developed in the left wall, due to 'over-excavation' by the TBM, caused by the negligible stand-up time of this sheared rock mass.

Figure 24. A detailed view of the sheared phyllite next to the single shield TBM. The 8 m diameter tunnel was locally increased to about 12 m due to the over-excavation of sheared phyllite.

The sheared, talcy phyllite was difficult to walk on, behaving like dry bars of soap. Blocks continued to fall from the sheared left wall, while the arch was in quite massive phyllites. Figure 25 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.

Figure 25. The TBM had been excavating more material than (π R^2) x length of advance, due to the stand-up time limitations of the sheared phyllites.

Borrowing the 'stand-up' time and 'roof span' data of Bieniawski 1989, we find that the predicted stand-up time for an unsupported span (measured from last support) can be much too short. The estimates shown on the next page 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.

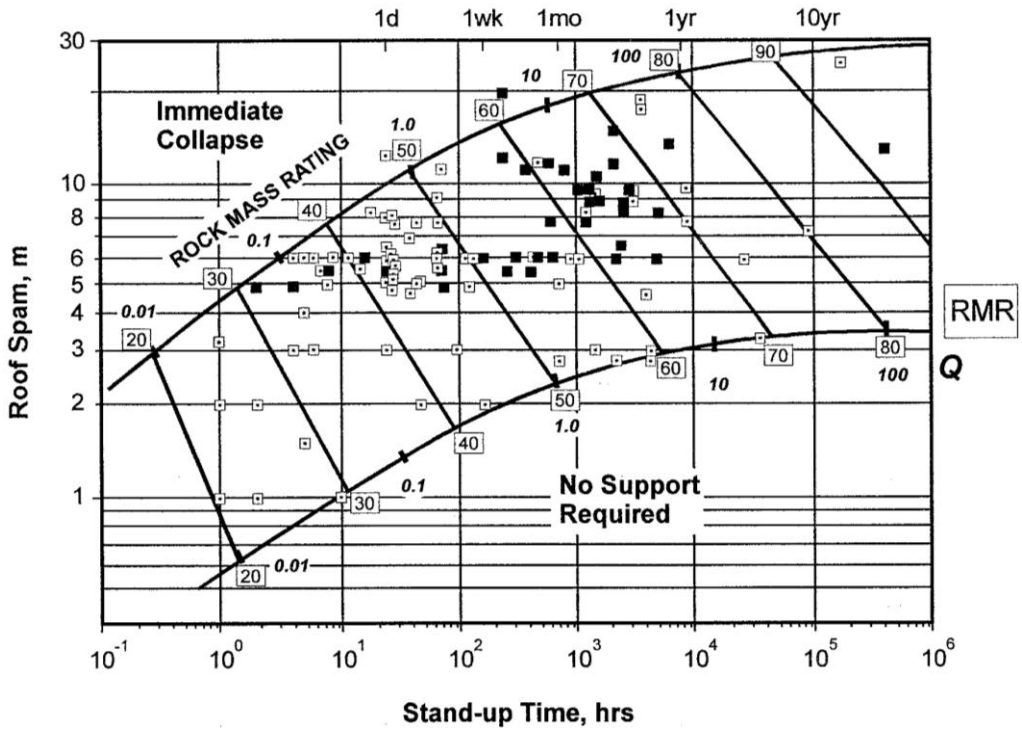


Figure 26. Stand-up time data plotted by Bieniawski, 1989, with RMR to Q conversion with the equation RMR ≈ 50 + 15 log Q, from Barton, 1995.

The on-site Q-parameter logging reproduced in Figure 27, provided an estimate of Q_{mean} = 0.07 in the sheared phyllite.

Assume RMR ≈ 15 log Q + 50 (Barton, 1995). Then, from Figure 26:

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

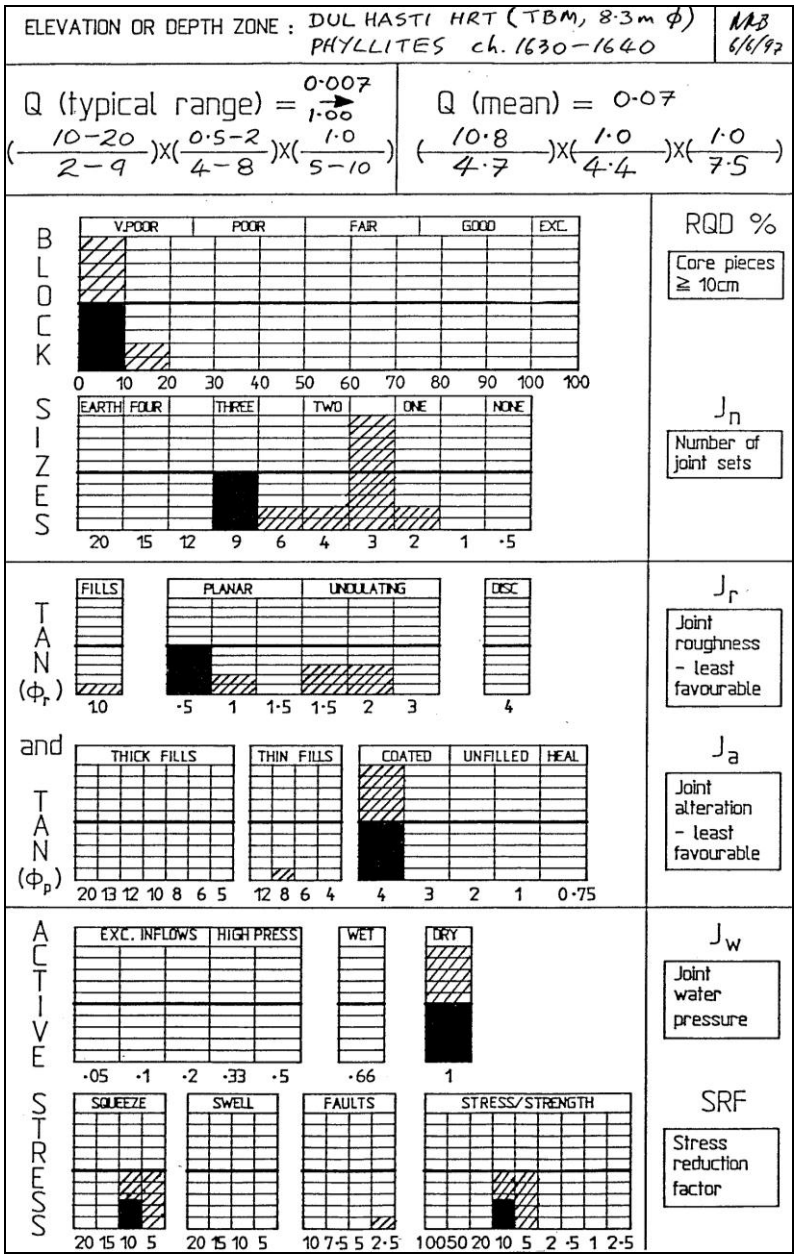


Figure 27 Q-parameter recordings in histogram format, for the sheared talcy phyllites illustrated previously. Note that due to contract re-negotiation, this TBM (abandoned by the original contractor) had progressed only 400m in about 4 years.

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. 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 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 intended. 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 very low velocity area.

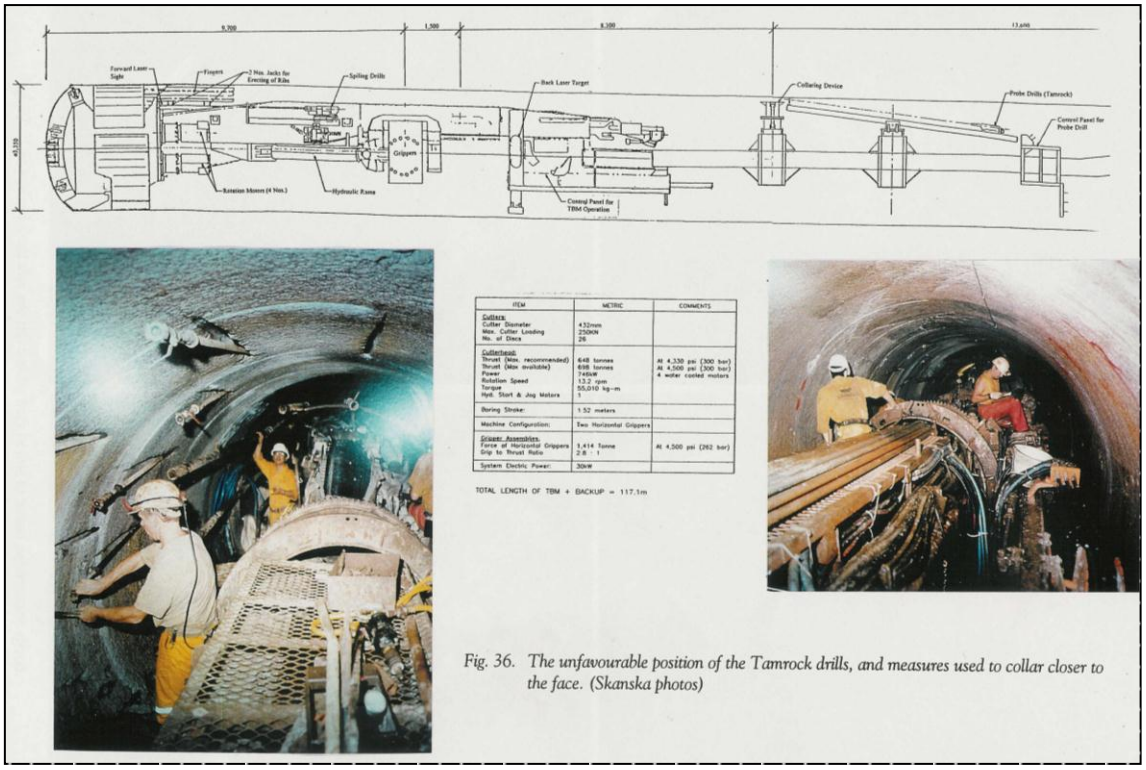


Figure 28. The confined conditions for performing pre-injection (Skanska photos).

A summary of the past and present situation at Tunnel F prior to final completion

- 481m of the tunnel was completed in a previous project.
- 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 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.
- This 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 4)
- 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, to try to sample the remaining ground. They were almost unable to recover any core from this major fault zone.
- The hole went only 731m, as it was stopped by the Tolo Channel fault zone – despite three attempts at hole deviation
- Only a few meters of this zone could be cored from the shaft location, yet the TBM later managed to penetrate the fault zone due to the positive *pre-grouting* effect on the rock mass, many meters ahead of the TBM.

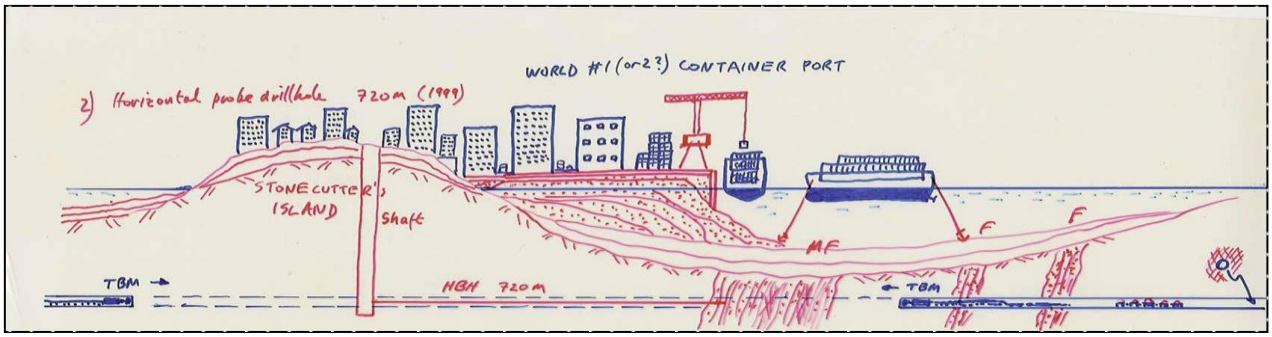


Figure 29. The remaining 887m of TBM-driven tunnel included the unexplored Tolo Channel fault zone. Only a few meters of this could be cored from the exit-shaft location, yet the TBM later managed to penetrate the fault zone due to the pre-grouting effect on the rock mass. (NB sketch of situation in 1999).

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 29, provided Q-value input for much of the remaining tunnelling. The core was divided into five classes for convenience of description:

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

Photographs showing these five classes are reproduced in Figure 30. Q-histogram logging for 1/3 of this core is shown in Figure 31. The nature of the only part of the major fault zone material that could be recovered is shown in Figure 32, and Q-histogram logging of this adverse material is shown in Figure 33.

Use of Q_{TBM} prognosis at Tunnel F based on core analysis

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

Assumptions concerning rock mass improvement by pre-injection

Assumed improvements in the rock mass properties caused by the planned pre-grouting of (also) the remaining 800 m of tunnel, were based on the following *types of arguments* for each particular rock class: following 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 x 1/2 x 0.5/1 = 0.8*

After pre-grouting Q = 50/6 x 2/1 x 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.

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.

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

The availability of horizontal core data i.e. *parallel to the tunnelling direction,* as used here, 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.

Figure 30 Photographs of the five selected rock classes which, when Q-parameter logged, gave the approximate statistical frequencies of these five classes.

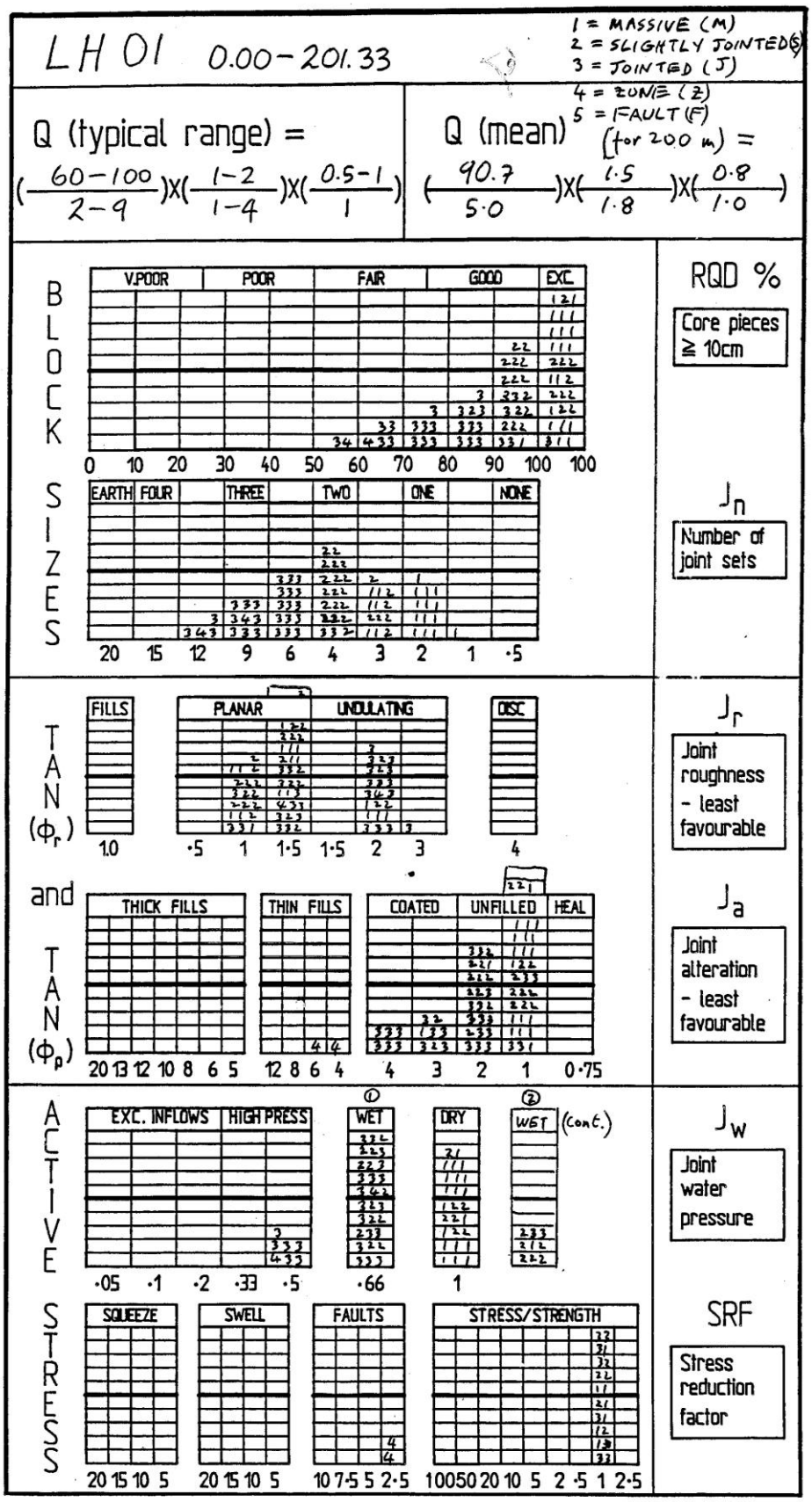


Figure 31 Q-parameter histogram logging of frequency of occurrence and ratings for the five rock classes, in the first 200m of hole LH 01 (i.e. the last 200m of the tunnel). (Note numbers 1 to 5 in each histogram, corresponding to rock class).

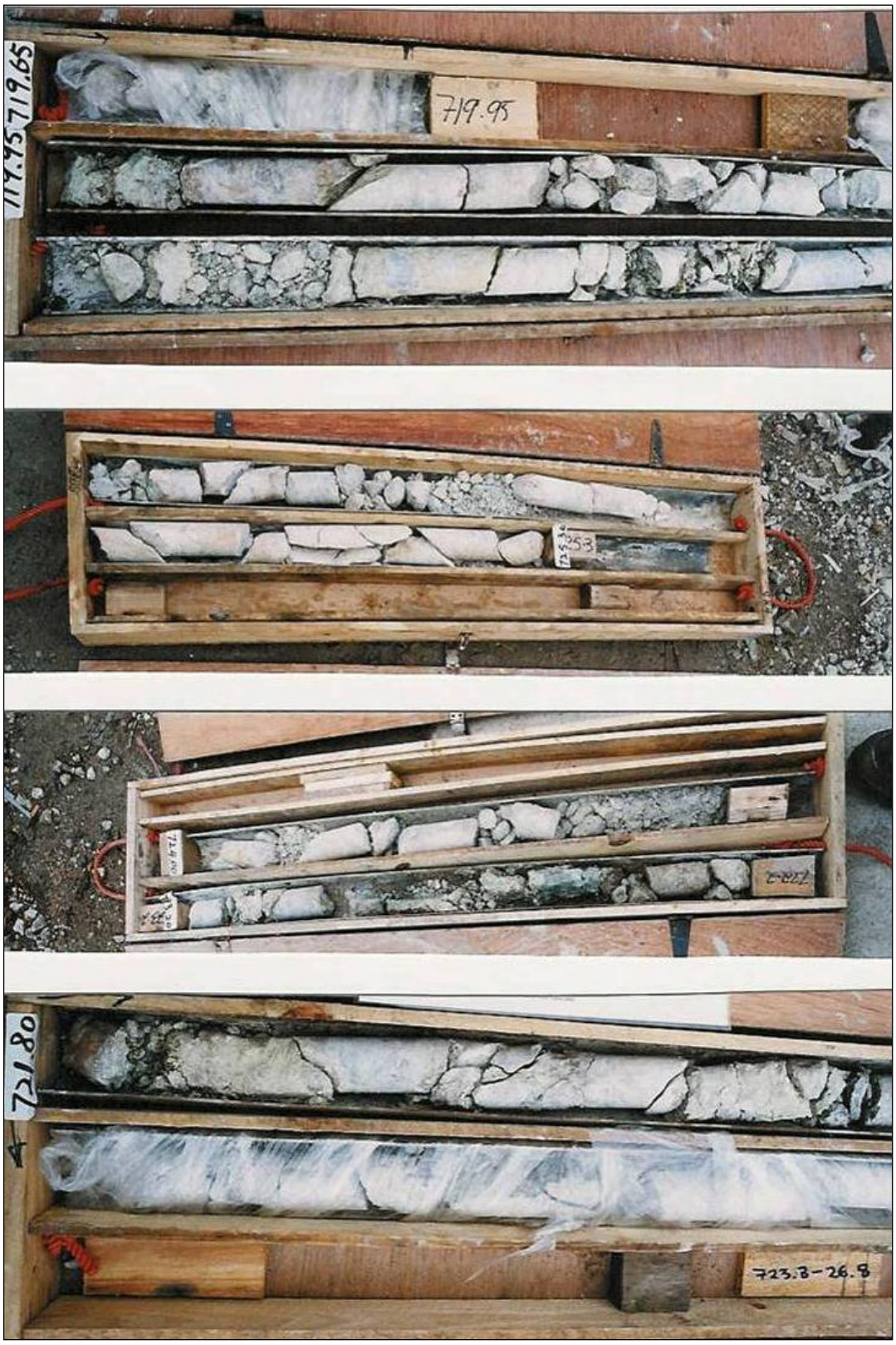


Figure 32 Three attempts were made to (deviate) drill into the Tolo Channel Fault Zone. These are the results - from the end of the 720m long horizontal pilot hole.

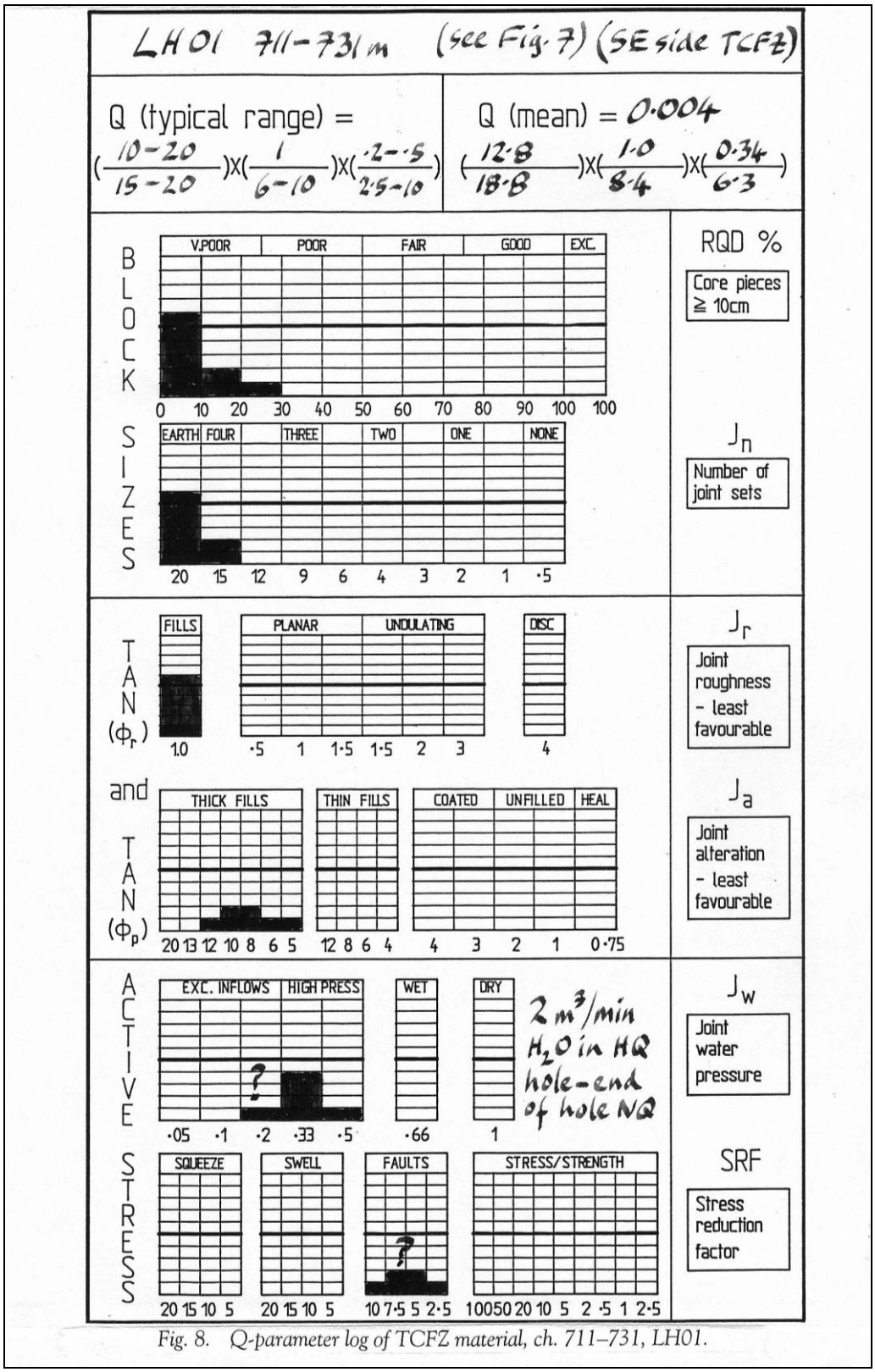


Figure 33 The Q-parameter characteristics of the fault zone (all that could be sampled) all plot 'to the left'. Q_{mean} = 0.004, i.e. needs improvement by pre-grouting.

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

The objective of the Q_{TBM} model, which will be very briefly described here, is to enable one to utilize Q-logging of core, or seismic velocity alone (suitably depth-interpreted, see companion paper: Barton, 2006b) in order to predict both PR (penetration rate) and AR (*actual* advance rate) for the various domains, rock types, or tunnel lengths. 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 34 summarizes the main component of the method, namely the empirical estimation of the Q_{TBM} value which was designed for direct correlation with PR: (Barton 1999, 2000):

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

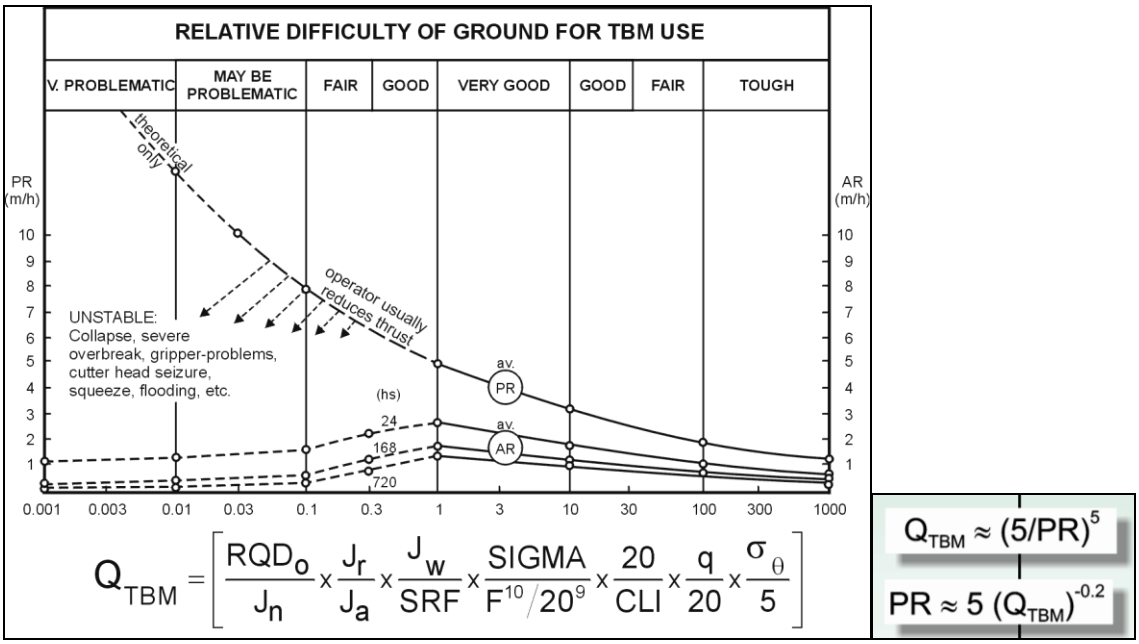


Figure 34 The Q_{TBM} scale of TBM tunnelling difficulty, showing its derivation from Q-parameter and machine-rock interaction parameters (see text). Note the simple correlation between Q_{TBM} and PR. This means that PR achieved in different sections of the tunnel can be converted into estimates of Q_{TBM}. Using the deceleration law $U = T^m$, estimates of AR can be obtained from PR or from Q_{TBM}, provided that the gradient (-)m can be estimated, using Figure 5 followed by an empirical fine-tuning with machine-rock parameters. Barton, 2000.

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 is given by the following (expressed in MPa).

$$\text{SIGMA} \approx 5\gamma Q_c^{1/3} \tag{5}$$

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. Cutter life index (CLI), quartz percentage (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 approximation (Barton, 2000).

$$\text{PR} \approx 5 Q_{\text{TBM}}^{-1/5} \tag{6}$$

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 x U) was modified to a time-dependent form in equation 2 (AR = PR x T^m), shown earlier in this paper.

The four lines and three curves shown earlier in Figure 4 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 4. However, there is the liklihood 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 mentioned in the introduction.

The general, long term, slowly decelerating tunnelling speed, that usually follows the contractors 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 below shows how advance rate may decline as the tunnel length increases. In the case shown in Table 2, the numbers imply a completed tunnelling length of $8760 \times 0.5 \approx 4380$ metres, after 1 year of fairly difficult TBM tunnelling with $m \approx -0.20$. 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. Typical PR, AR and U and their interpretation with time period. Gradient m = −0.20 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

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 of about 16km in one year).

The Q_{TBM} model input data sheet is illustrated in Figure 35, and application to the Hong Kong Tunnel F pre-grouting estimation is finally illustrated in Figs. 36 and 37.

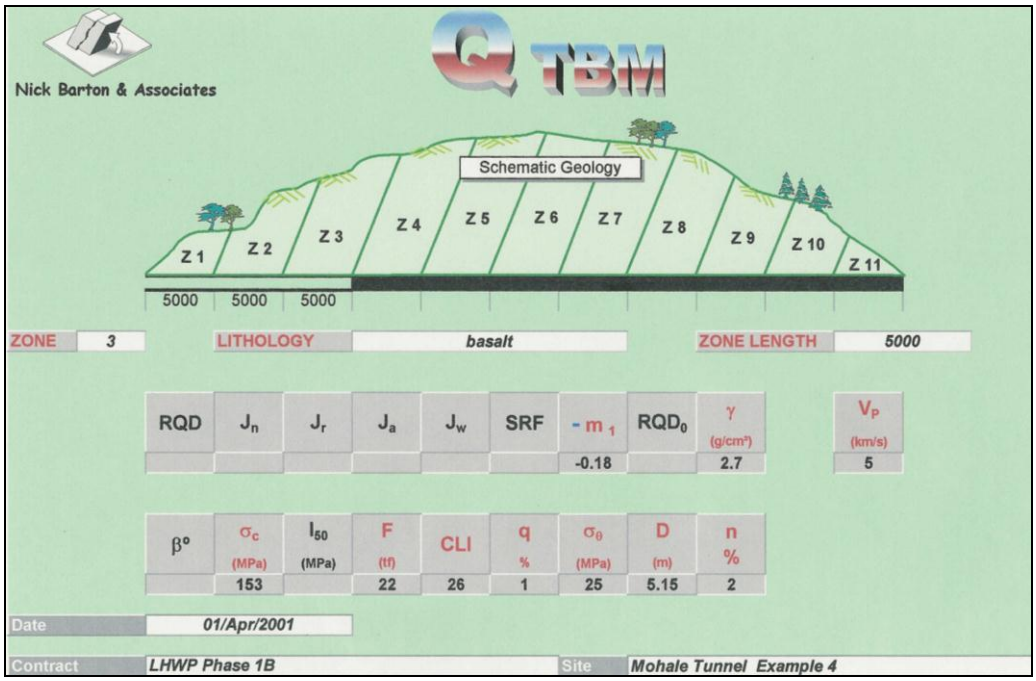


Figure 35 An example of the Q_{TBM} 'input data' screen. This is activated for separate lengths or domains of the tunnel, with data from Q-logging plus machine-rock interaction parameters. In the case illustrated V_P is used in place of the Q-parameters. Barton and Abrahão, 2003.

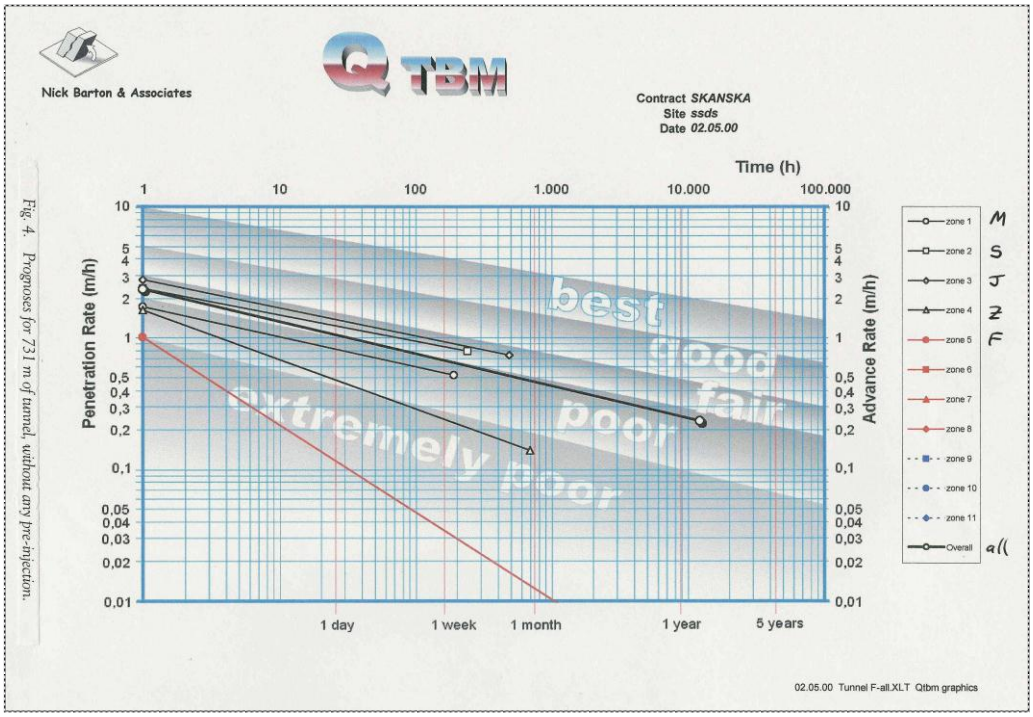


Figure 36 Application of the Q_{TBM} model (Barton and Abrahão, 2003) to Hong Kong Tunnel F pre-grouting predictions. In this first case, no pre-grouting improvements were assumed, and more than 1 year was predicted for completion of the 730 m that was core-logged. Note the steepest gradient (-)m, and longest completion time for the fault zone material.

Fig. 6 Prognoses for 731 m of tunnel, all pre-injection delays included.

Figure 37 Total tunnelling time with pre-grout cycles included. These estimates proved to be conservative, due to the better than modelled improvements to rock conditions, caused by the systematic pre-grouting.

CONCLUSIONS

1. 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.

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. 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.

4. 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, harder or more abrasive rock, and squeezing (or eroding) conditions in fault zones because of high over-burden (or high water pressures).

5. 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 , at a significant extra cost per meter of tunnel, produces a minimal deceleration gradient, of about half the value when thrust is only available from grippers. This solution therefore 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) shields.

6. 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.*

7. 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 less hazardous.

8. 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 would reveal a 1.5 to 2Km/s velocity if encountered nearer the surface.

REFERENCES

1. Barton, N., Lien, R. & Lunde, J. 1974. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics. 6:4:189-236. Springer-Verlag.

2. Barton, N. 1995. The influence of joint properties in modelling jointed rock masses. Keynote Lecture, 8th ISRM Congress, Tokyo, 3: 1023-1032, Balkema, Rotterdam.

3. Barton, N. 1999. TBM performance estimation in rock using Qtbm. Tunnels and Tunnelling International, Sept. 1999, pp. 30-34.

4. Barton, N. 2000. TBM tunnelling in jointed and faulted rock. 173p. Balkema, Rotterdam.

5. Barton, N. 2001. Are long tunnels faster by TBM? Proc. Rapid Excavation and Tunnelling Conf. RETC, San Diego, USA. Soc. Min. Eng., 819-828.

6. Barton, N., Buen, B. & Roald, S. 2001. Strengthening the case for grouting. Tunnels & Tunnelling International, Dec. 2001: 34-36, and Jan. 2002: 37-39.

7. Barton, N. 2002. Some new Q-value correlations to assist in site characterization and tunnel design. Int. J. Rock Mech. & Min. Sci. Vol. 39/2:185-216.

8. Barton, N. & de Quadros, E. 2003. Improved understanding of high pressure pre-grouting effects for tunnels in jointed rock. Proc. of 10th ISRM Congress, South Africa, Vol.1, 85-91.

9. Barton, N. 2003. TBM or drill and blast. Tunnels and Tunnelling International, 20-23, June.

10. Barton, N. 2006a. Rock Quality, Seismic Velocity, Attenuation and Anisotropy. Text book, 650p. Taylor & Francis, London & The Netherlands.

11. Barton, N. 2006b. Rock mass characterization and modelling aspects of mining and civil engineering. Invited lecture, Proc. of VI South American Rock Mechanics Cong., Cartagena, Colombia.

12. Barton, N. and Abrahao, R. 2003. Employing the Q_{TBM} prognosis model. Tunnels and Tunnelling International, 20-23, December.

13. Bradley, W.B. 1978. Failure of inclined boreholes. Transactions of the American Society of Mechanical Engineers. 101:232-239.

14. Deva, Y., Dayal, H.M. & Mehrotra, A. 1994. Artesian blowout in a TBM driven water conductor tunnel in Northwest Himalaya, India. *Proc. 7th IAEG congress, Lisbon*. Oliveira et al. (eds) 4347-4354. Rotterdam: Balkema.

15. Grandori, R., Jaeger, M., Antonini, F. & Vigl, L. 1995. Evinos-Mornos Tunnel - Greece. Construction of a 30 km long hydraulic tunnel in less than three years under the most adverse geological conditions. *Proc. RETC. San Francisco, CA.* Williamson & Gowring (eds). 747-767. Littleton, CO: Soc. for Mining, Metallurgy, and Exploration, Inc.

16. Mitani, S., Iwai, T. and Isahai, H. 1987. Relations between conditions of rock mass and TBM's feasibility. *Proc. 6th ISRM congress, Montreal*. 1:701-704 Rotterdam: Balkema.

17. Savich, A.I., Mikhailov, A.D., Koptev, V.I. & Iljin, M.M. 1983. Geophysical studies of rock masses. *Proc. 5th ISRM Congress, Melbourne. 1:* A19-A30. Rotterdam: Balkema.

18. Scolari, F. 1995. Open-face borers in Italian Alps. *World Tunnelling*, November 1995. 361-366.

19. Shen, C.P., Tsai, H.C., Hsieh, Y.S. & Chu, B. 1999. The methodology through adverse geology ahead of Pinglin large TBM. *Proc. RETC. Orlando, FL*. Hilton & Samuelson (eds). Ch.8: 117-137.Littleton, CO: Soc. for Mining, Metallurgy, and Exploration, Inc.

20. Wanner, H. 1980. Stability problems by fullface tunnel boring. *Fjellsprengningsteknikk. Bergmekanikk/Geoteknikk.* 25.1-25.7. Trondheim: Tapir Press.