

Hybrid TBM and Drill-and-Blast from the start

Nick Barton of NB&A, Oslo, Norway describes the importance of considering a mixed approach to long and deep tunnel construction

THE WRITER HAS been involved in the last stages of several TBM projects where the choice of TBM has clearly been incorrect, and the machine remains in the mountain forever, or is severely damaged and has to be removed. He has also been involved in projects where drill-and-blast from the other end has been advised at an early stage, but ignored until very late, with adverse consequences on completion dates, due to too late abandonment of the TBM method, and fatal consequences for some workers. Such extremes are unnecessary if more designers were aware of the inevitable deceleration that accompanies TBM tunnelling, notwithstanding 'learning curves' and some good or extremely good progress through favourable rock masses, the latter also meaning favourable hydro-geologies.

Reversed logic for TBM

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. TBMs may be penetrating at their slowest rates in similar massive conditions, if UCS and quartz % are high, due to rock-breakage difficulties, cutter wear, and therefore the need for too-frequent cutter change, the latter affecting the advance rate AR. This 'reversed' trend for slow TBM tunnelling in best quality, highest velocity (V_p) rock has been demonstrated on many projects. The improved rock mass quality associated with higher V_p may not give the expected advantages for TBMs, as less jointing makes for a reduced penetration rate, and an increased frequency of cutter change reduces advance rate.

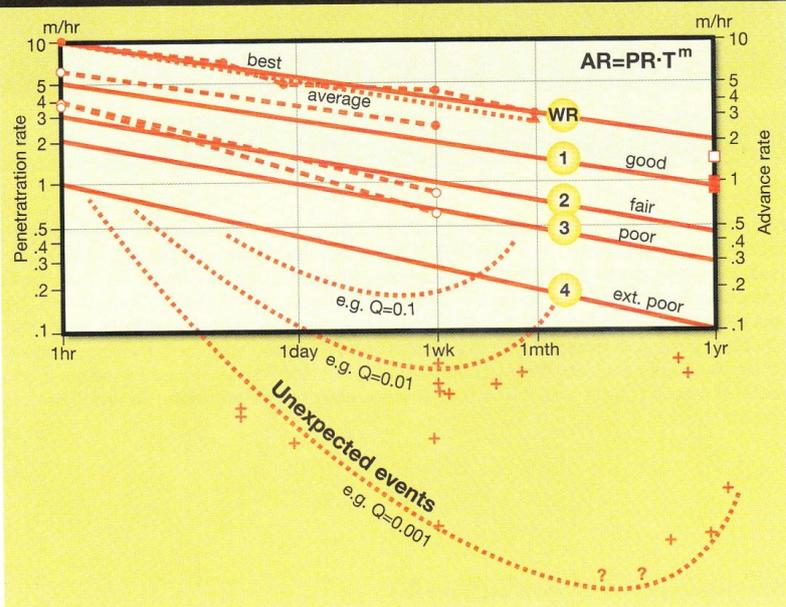
Law of deceleration for TBM

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 Barton (2000), in order to try to find a better basis for TBM advance rate prognosis, which 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. 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,

Figure 1: Results of analyses of 145 lengths of tunnel with specific properties, involving about 1000km of open-gripper TBM case records (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 lines 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 weeks or months. Some examples of the most adverse 'crosses' will be shown later.



seem also to be absent in past and recent competing models of prognosis. Rock mass strengths can be estimated from $5\gamma Q_c^{1/3}$ MPa.

The numerous (145) cases analysed, totalling 1000km of TBM tunnelling, shown in Figure 1, showed 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 the seldom acknowledged reality, as indicated below:

The conventional equation: $AR = PR \times U$ (1)
(where U = fraction of time utilized for boring)

The realistic equation: $AR = PR \times T^m$ (2)
(where m is a negative gradient of deceleration, and T is actual total hours: e.g. 168hrs/week).

This deceleration stands in strong contrast to the expected 'learning curve' or initial speed-up of PR and AR, usually experienced in the first months of numerous TBM projects, as contractors/operators get familiar with a new TBM. The deceleration with time and tunnel length is a 'fact-of-life', however much it may be disliked. AR_{mean} (when expressed in m/hr) has to decline when 1 day, 1 week, 1 month, and 1 year are each evaluated in turn, for any given project. Of course one can 'select' projects where this is not so, but there will usually be geological reasons for breaking this deceleration logic.

Why fault zones may delay TBMs

There are unfortunately very good 'theo-empirical' reasons why fault zones are so

difficult for TBMs, with or without double-shields (Theological-empirical means that lack of belief will be paid for, in one way or another).

We need three basic equations to start with:
 $AR = PR \times U$
 $U = T^m$
 $T = L/AR$
(Obviously the time T needed for length L must be equal to L/AR , for all tunnels and all TBMs.)

Therefore we have the following:
 $T = L / (PR \times T^m)$. But T appears on both sides:

Therefore it can be rewritten as:
 $T = (L/PR)^{1/(1+m)}$ (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 (all too easy) to calculate an almost 'infinite' time for passing through a fault zone using this 'theo-empirical' equation. This also agrees with reality, in numerous, little-reported cases. The writer knows of several permanently buried, or fault-destroyed TBMs (Pont Ventoux, Dul Hasti, Pinglin) and rockburst damaged or destroyed TBMs (Olmos, Jinping II). There are certainly many more, and the causes can often be related to the logic and experience which are embedded in equation 3.

So far this equation seems to be absent

Figure 3: Cutter-head trapped in faulted meta-sandstones, as described by Shen et al., (1999).

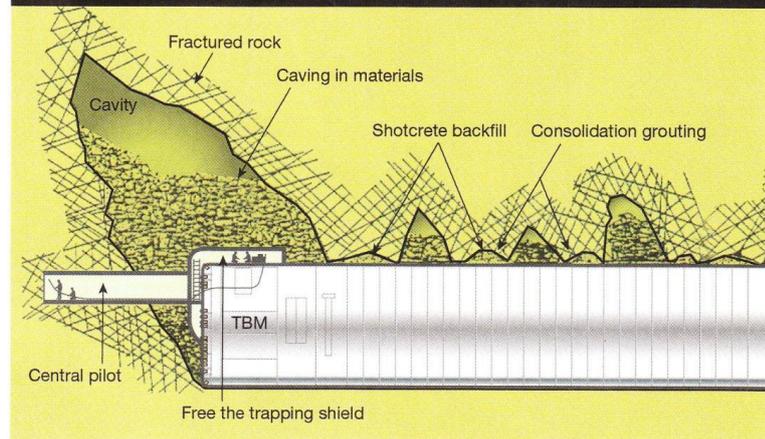
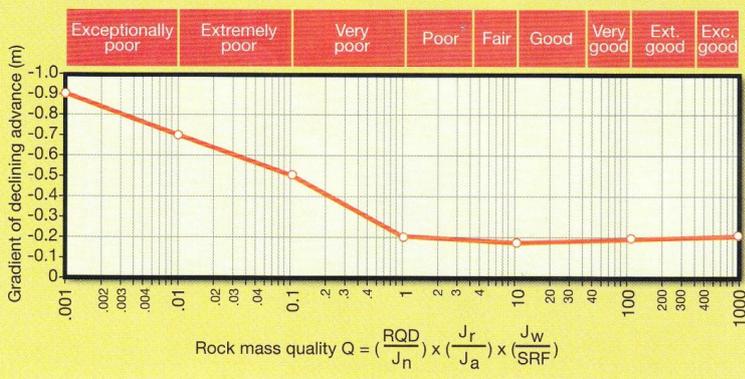


Figure 2: Unexpected events seen delaying TBM performance in Figure 1, can be directly linked to too low Q-values, where steeper gradients of deceleration (-m) are seen. Just as in drill-and-blast tunnels, it is this region of the rock mass quality spectrum that may have greatest benefit from pre-injection.



from other literature, as the fundamental importance of deceleration ($-m$) has not been acknowledged, at least in public. TBMs must follow a negative m -value, even when breaking world records, like 16km in one year, or 2.5km in one month, even 100m in 24 hours, since even here, PR is sure to be greater than the implied and remarkable $AR \approx 4.4$ m/hr.

Examples of fault zone challenges

The Pinglin Tunnel, with a stoppage event shown in Figure 3, is an example of TBM tunnelling (actually three parallel tunnels), where serious faults caused such large cumulative delays, that drill-and-blast 'rescue' from the other (western) end was finally allowed for completion, after some 13 years of struggle to drive this 15km long twin-road tunnel. The pilot tunnel of 5m span had to be by-passed at least 12 times to release the cutter-head, and this was witnessed by the writer several times,

during conferences and courses occurring in Taiwan in this period.

One of the two large diameter TBMs at Pinglin was crushed in the first difficult kilometres, by collapse of a major fault zone, that had been 'successfully' passed by the cutter-head. The majority of the northern tunnel therefore had to be excavated by drill-and-blast, also with great

and capabilities.

The 7km headrace tunnel for the Pont Ventoux HEP in the mountains in the north-west of Italy, was driven parallel to a marked NW-SE trending valley, and also parallel to swarms of faults hidden under slope screens. They represented the ultimate repeated challenge. At one location, the 'fault zone performance' was 7 months for

only 20m of advance, representing an average advance rate $AR=20/(7 \times 720)=0.004\text{m/hr}$. This is almost off the bottom of the chart, in the 'unpredicted events' area of Figure 1, where crosses (+) are plotted. During 2004 the tunnel was completed by drill-and-blast from the other end of the tunnel, by-passing the abandoned and rusting TBM.

Figure 4: Cutter-head of a large TBM (11.9m) and pilot TBM, released on successive occasions. Photo: Dr. Chris Fong.

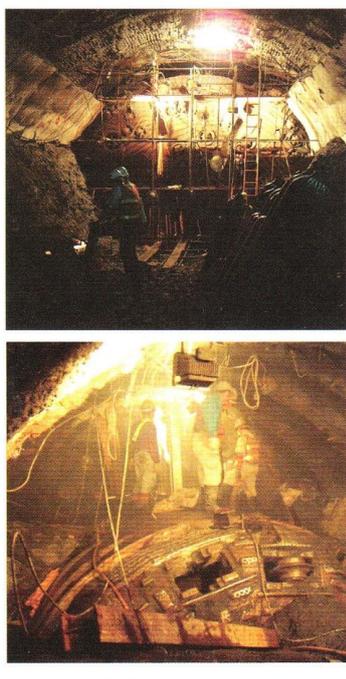
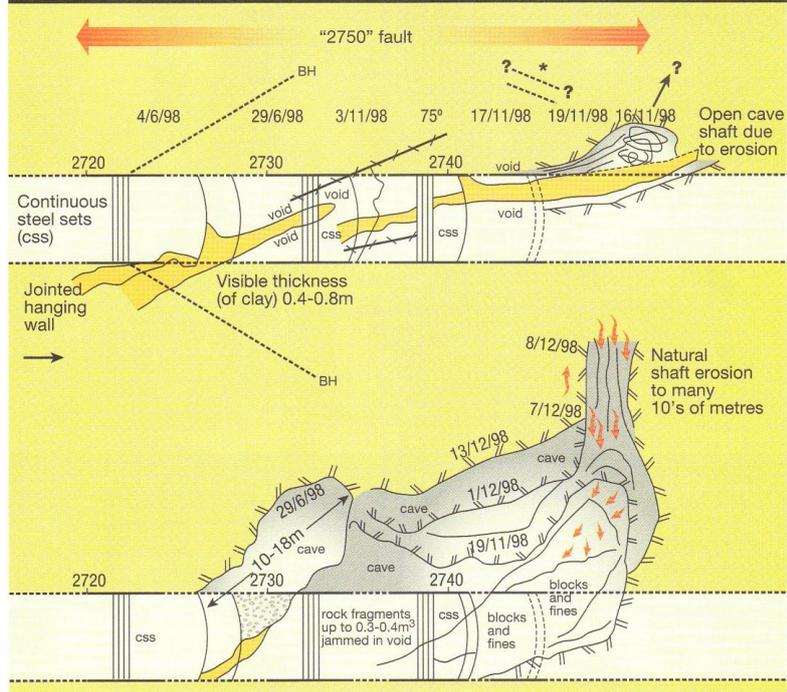


Figure 5: A fault of moderate width with clay core, but with high water pressure on one side, proved to be an insurmountable problem for the poorly equipped 'inherited' TBM. Note the 5 months of superimposed geologist's observations, during 25m of 'stop-go' lack of progress.



difficulties at times, including a 7000m³ inrush of clay, rock and water that buried a tunnel worker and excavation equipment, moving the tunnel 'face' backwards by about 100m. The resulting 'void' 100m ahead had somehow to be negotiated. Unlike with headrace tunnels conducting water, traffic cannot be expected to negotiate a by-pass, especially not speeding trains. So voids have to be solved when reached.

The challenge of faults with water

Faults often consist of more fractured rock, and there may be an increasing frequency of clay-coated discontinuities as a 'central' clay core is approached. If this situation is worsened by the presence of high-pressure water on one side of the clay core, a situation arises that is an especially severe test of the TBM and contractor's ingenuity

Figure 6: The inherited TBM had no probe drilling capability. The cutter-head was repeatedly blocked by falling rock blocks from the rapidly eroding fault 'plane'. The black void extends upwards and forwards by 10 to 15m, and its source is sketched in Figure 5.



Deceiving V_p of faults at depth

Two diverging boreholes can be seen in the top diagram of Figure 5. These were used for cross-hole seismic tomography. Interestingly, because of the 700-800m depth of cover, the obviously known diagonally intersected fault was 'hardly visible' some 10's of meters ahead of the tunnel face. This was presumably because of stress/compaction effects on V_p, as discussed in Barton (2006), and illustrated in Figures 7 and 8. This fault compaction phenomenon has been experienced in tunnels in Japan, as shown in Figure 9, where a tunnel collapse was registered, despite the possibility of 'preparation' for a reduced velocity, some distance ahead of the tunnel face.

There are many examples of double-shield TBMs getting stuck in fault zones, and such delays are often 'removed' from the generally excellent TBM performance

Figure 7: The P-wave velocity increases as a result of depth or stress increase, for any given Q-value of rock mass quality. This means that a fault that is 'illuminated' by seismic at many hundreds of meters depth will have a surprisingly 'high' velocity. However, as illustrated in an alternative presentation of this depth trend in Barton (2006), it is the contrast in velocity to the surrounding 'country rock' that is important, as seen in Figure 8.

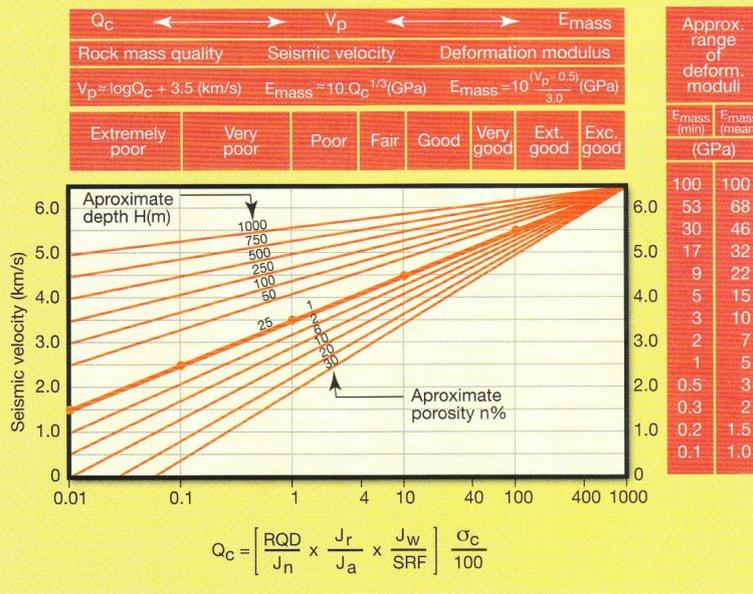
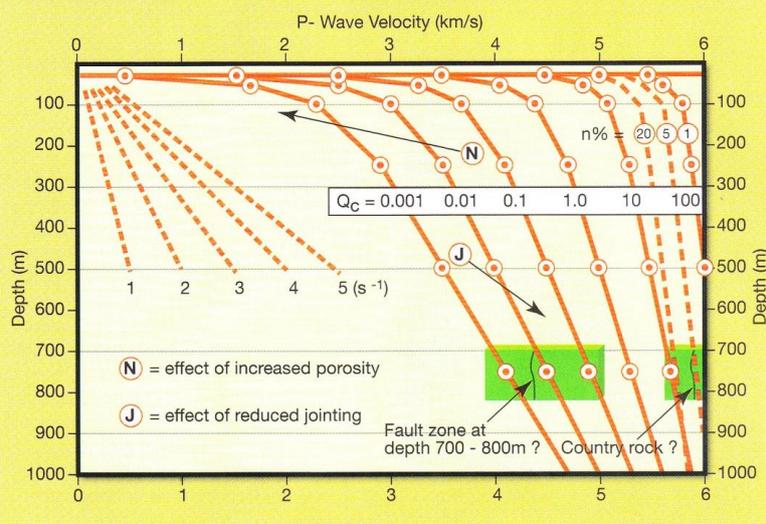


Figure 8: Rock mass quality Q_c -value 'isolines' showing variation of P-wave velocity with depth. The 'high velocity' fault encountered at great depth may be (or will be) a huge threat to tunnelling, especially to TBMs, because when it is exposed or at least unloaded at the face or side of the tunnel, its true character becomes evident. Barton (2006).



reported, as if they were special cases. This is understandable, but 'T' (hours) is still running in reality. Unfortunately '\$' and Euro and

'Yen' are running also, possibly due to the wrong choices (in retrospect) that were made some years earlier.

Double shield or open gripper?

In the sections concerning fault challenges to TBMs just presented, the obvious general physical advantages of double-shield TBMs have not been discussed. These machines of course have the possibility to push off the last ring of PC-elements, if conditions for gripper thrust are lost in faulted, clay-bearing, or over-breaking rock. This ability may 'save-the-day' if the quality of the fault zone is not too low.

A useful case record in this connection is the joint performance of four 9m diameter TBMs, boring 14km each to create the Guadarrama high-speed rail tunnels north of Madrid. The gradients (-)m of deceleration (Figure 1) were about half of the trends from 1000km of open-gripper TBMs for this 56km of mountain tunnelling, often in granites. The mean PR was only 2m/hr, but the efficiencies of double-shield meant that final performance had climbed into 'good' performance, by the end of the 30 to 33 months needed to tunnel 14km. This is shown by the crossed ellipse far to the right in Figure 10. It is naturally a better result than the first kilometer of another double-shield case record, where performance was no better than open-gripper TBM, due to time loss from unexpectedly high RMR and Q-values, and exceptional cutter wear statistics.

The challenge of high rock stress

In recent years there have been many TBM tunnels with depth of cover > 1km, a few also > 2km, and in two cases known to the writer, even 2.5km for short sections. Both have suffered TBM damage or

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destruction due to rock bursting. Lives have been lost in several deep TBM tunnels in the last 20 years, and continue to be lost even in the last few years. For some reason, drill-and-blast was usually

Figure 9: In-tunnel seismic warns of a reduced velocity ahead (4.1km/s reducing to 3.7km/s). Despite the warning, tunnel collapse occurred already at the 4.1km/s location. See Hayashi and Saito (2001).

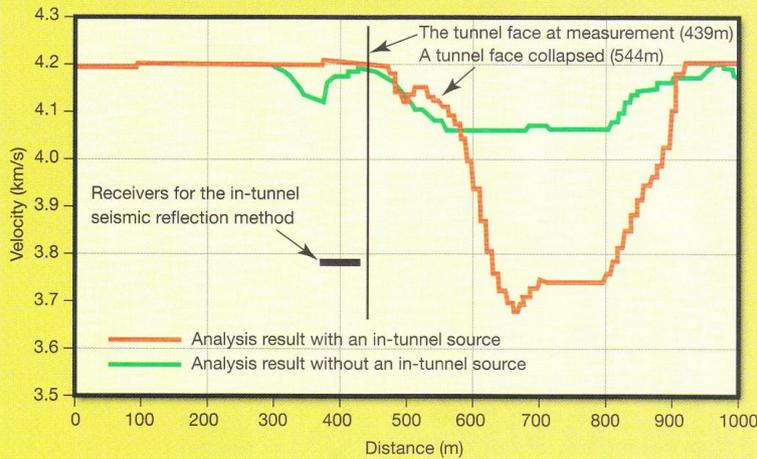
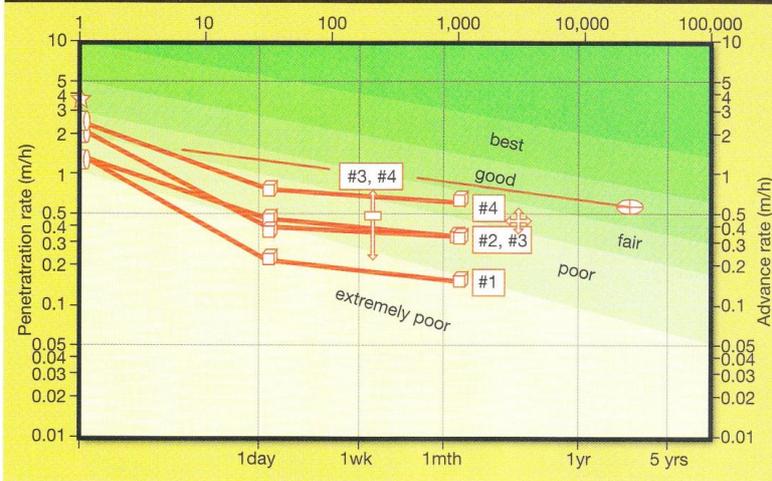


Figure 10: Early 'learning-curve' months (1 to 4) of a double-shield project in massive abrasive granites. The ellipse to the right-hand side shows the mean performance of four 9m diameter double-shield TBM boring a total of 56km. See Figure 1 for the source of this PR-AR-T method of plotting TBM progress, starting with PR on the left axis, and showing advance rate (AR) progress with time T, each on a log-log basis. Note the typical deceleration trends.



not the method of first choice in these projects, and 'because the tunnels were long', the TBM method was chosen. This may be a recipe for delay and worker injury, if not loss of life. Many projects first driven by TBM have been 'rescued' by late decisions to drill-and-blast from the other end, or to drill-and-blast in the high cover sections. The need for changed plans seems to have been caused by unjustified optimism that TBM are faster for long tunnels.

In 1993 the case-record based Q-system

was updated to include the dimensioning of S(fr) or steel fiber reinforced shotcrete, which could be used to increase safety when excavating deep road tunnels. A notable case was the 24.5km Lærdal Tunnel in western Norway, where mountain cover reached 1.4km, and where stress-fracturing and rock bursting were frequent in some sections.

On the basis of case records of about fifteen deep road tunnels in Norway, where maximum tangential stresses (σ_{θ}) were mostly estimated to be in the range of 50 to 100MPa, and from some even higher stress experiences in China, the recommended SRF (stress reduction factor) ratings shown in Table 1 were developed for excavations in massive, burst-prone rock masses (Barton and Grimstad, 1994).

Independently from the above SRF update dating from 1993/1994, and this time coming from the field of mining as opposed to deep transport tunnels, the collection of case records shown in Figure 13 also shows stress-fracturing initiating when the stress/strength ratio σ_{θ}/σ_c exceeds about 0.4-0.5.

There is some controversy concerning the reason for the stress-fracturing starting already when the maximum stress is 'only' 0.4 to 0.5 x the UCS (laboratory-scale

Figure 11: Four types of rock mass, only one of which is actually positive for TBM (#1, ideally jointed: very fast progress possible). Case #2 is designed to represent a hard massive abrasive rock like quartzite or granite, with PR as low as 1 to 2m/hr, and 2 to 3m per cutter change. This poor performance would be related to low values of cutter-life index CLI, one of the parameters used in the Q_{TBM} method of Barton (2000), shown briefly in Figure 12. Case #3 may trap a TBM shield due to squeezing. Case #4 is designed to represent either erosion in faulted rock, sometimes giving cutter-head blockage, or stress-induced fracturing.

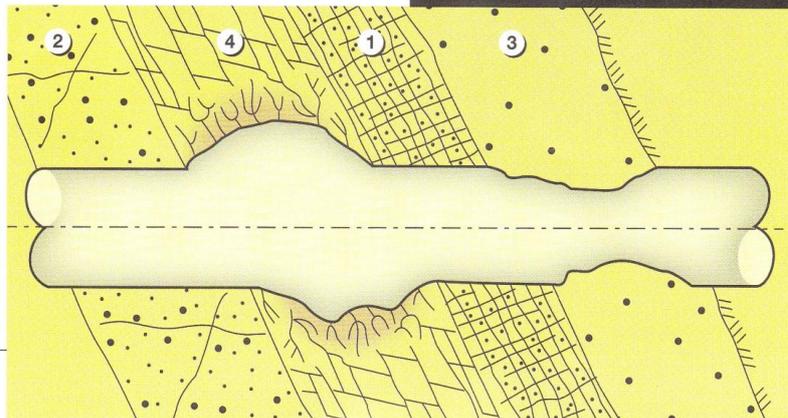
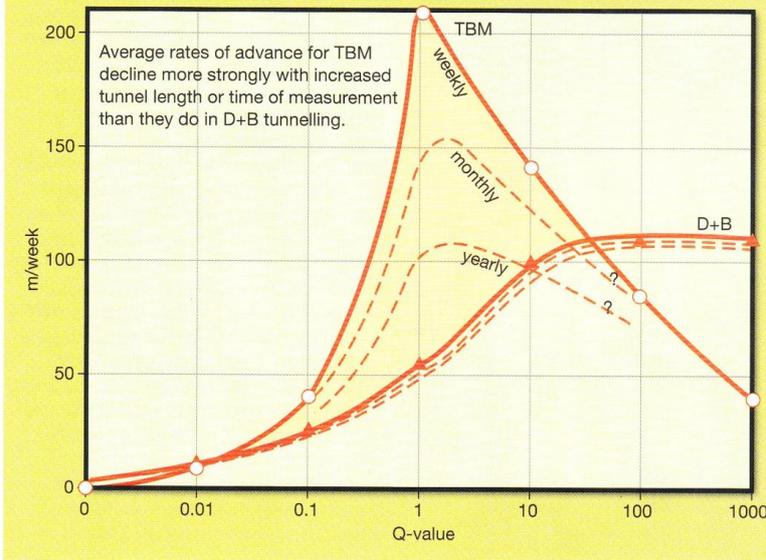


Figure 14: A Q-value and Q_{TBM} -value based comparison of drill-and-blast and (open-gripper) TBM tunnelling, using respectively cycle-time and PR-AR-m estimation. The tabulations of respective Q and Q_{TBM} could have similar magnitudes (e.g. with cutter force = 20 tons in rock masses with 20MPa rock mass strength SIGMA ($= 5\gamma Q_c^{1/3}$), where $Q_c = Q \times \sigma_c/100$ and $\gamma =$ density).



ends of the rock quality statistic.

Recent RMR and Q statistics at a tunnel in very massive granites, and the slow progress by double-shield TBM, following incorrect site description, suggest that drill-and-blast tunnelling would have been faster, at least in the absence of a higher-powered TBM. There are also examples of slow TBM progress being 'rescued' by drill-and-blast, in the case of a Chinese tunnel that needed to be completed by the millennium of 12 years ago.

The problem is that very adverse (massive rock) with Q-values mostly in excess of 200, plus adverse quartz content, adverse UCS, and adverse cutter life index, will collectively guarantee the need for a generous budget of time and

cost for perhaps thousands of cutter changes, if these adverse (HH) conditions last for many kilometers.

Drill & Blast single shell NMT

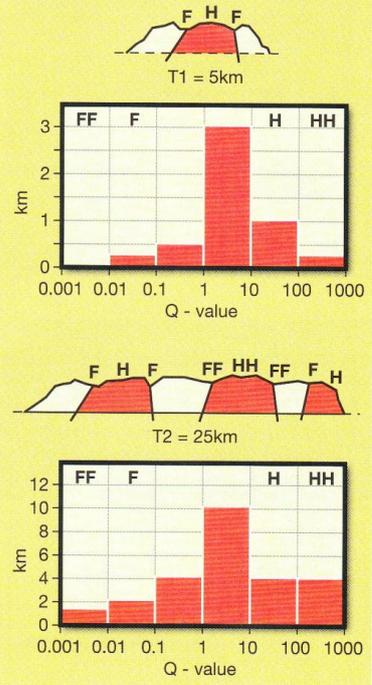
During the last 35 years there have been huge improvements in TBM technology, with the wide-spread use of high-thrust, high torque and double-shield technology, and the gradually increasing possibility to efficiently probe drill in several directions, and to pre-inject in many more locations 'around-the-clock' than was possible with TBMs just a few years ago.

The appreciation of the benefits of pre-injection has probably come from the use of successively higher pressures (5 to 10MPa, as in Figure 16), and the use of more expensive micro- or ultrafine cements, from the world of single-shell (e.g. NMT) tunnelling. The investment in time and money has been found to pay off in overall cheaper and faster tunnelling, partly because over-break is reduced and less S(fr) is needed as permanent support.

This has been especially experienced in Norway where permanent single-shell B+S(fr) reinforced and supported tunnels, that have also been systematically pre-injected to control water, may even then be only 1/4 to 1/5 the cost of double-shell NATM-style tunnels, which use temporary support of B+S(mr) – but

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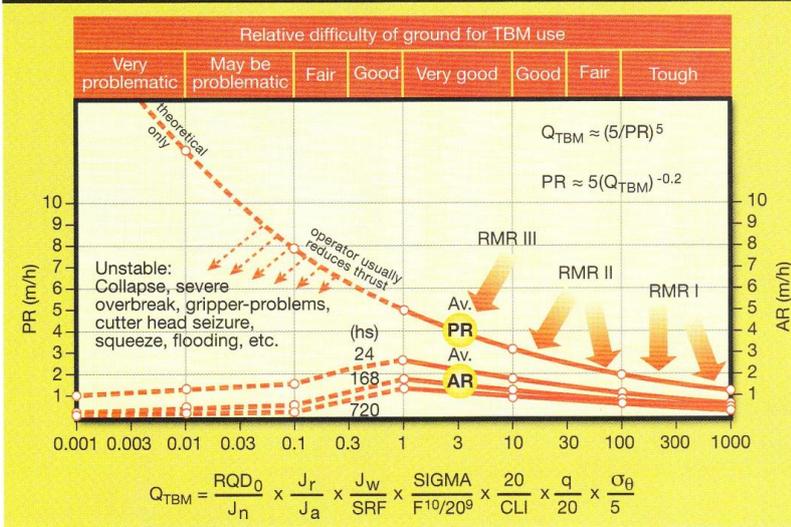
Figure 15: The long tunnel by TBM or hybrid? Adverse 'extreme value' statistics for rock mass quality suggest avoidance of TBM where there is FF-HH-FF rock in the area of highest cover. (FF means 'more serious faulting, HH means very hard massive rock). Solution: drive left half with TBM, drive right half by drill-and-blast, starting at least 1 year before, so as to get through the second FF feature before meeting the TBM, which may have gone very fast. Of course 'central' access adits are an advantage for the drill-and-blast section, if they are physically possible.



increasingly S(fr) - followed by a membrane, a drainage fleece, and the final reinforced concrete liner, the latter of variable thickness, if over-break has not been filled by other means (i.e. shotcrete). The relative costs of single-shell NMT in Scandinavia and double-shell NATM in Europe and elsewhere, are about 1 to 5, or roughly US\$20-25,000/m in the case of NMT (single-shell), for typical rock mass quality Q-values in the range 0.01 to 100. This can be compared to US\$80-120,000/m for full-blown NATM, as briefly described above.

Of course it is not infrequent that NMT is used where the predominant quality Q

Figure 12: This chart shows some elements of the Q_{TBM} method of TBM prognosis developed by Barton (2000). High Q and high RMR rock mass quality values are (also) bad news for TBM because low PR means low cutter-life, also reducing AR, as seen by the five arrows used to locate the three highest RMR classes at their approximate Q-values. Note that the Q-value can have similar magnitude to the Q_{TBM} value, provided that sufficient cutter force F is available in relation to the estimate of rock mass strength SIGMA. Other parameters shown are quartz content (q) and the biaxial stress on the face of the tunnel (σ_{θ}), which is estimated for convenience of calculation, to be about 5MPa per 100m depth.



(refer to the empirically based Figure 2 gradients of (-)-m.)

Since Q is a much used method of quantifying rock mass quality in numerous countries, and since it also correlates with seismic velocity, it is logical to suggest that the rock mass quality estimates, when sufficiently well documented (e.g. '3km of Class 1, 10km of Class 2, 1.2km of Class 3, approx. 650m of Class 4, and approx. 150m Class 5' for an imaginary 15km long planned tunnel) should or could form the basis for selecting the method of excavation.

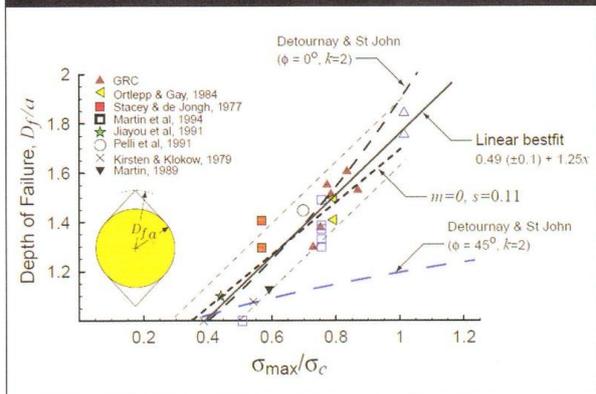
In this exercise one must especially note the dominance (or absence) of ideal 'central qualities', where TBM will easily win the race with drill-and-blast. Even more important: where in the project, and how many kilometers, are the adverse qualities for TBMs? Unfortunately severely faulted rock and the extremes of massive hard rock are both adverse for TBMs. Many parameters are important, including UCS (uniaxial compressive strength), q% (quartz content), CLI (cutter life index), and specific information about the character of known fault zones (from characterization of core, from refraction seismic, and from cross-hole seismic tomography).

In Figure 15, imaginary rock mass quality statistics are presented for a

Table 1: SRF, the 6th parameter in the Q-value estimation, is based on the ratio of maximum tangential stress/UCS for the case of rock-burst prone massive rock. Note initiation of steep SRF gradient when σ_{θ}/σ_c exceeds 0.4-0.5. Extracted from Barton and Grimstad (1994).

6 b) Competent rock, rock stress problems		σ_c/α_1	σ_{θ}/σ_c	SRF
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after > 1 hour in massive rock.	5-3	0.5-0.65	5-50
M	Slabbing and rock burst after a few minutes in massive rock.	3-2	0.65-1	50-200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in massive rock.	< 2	> 1	200-400

Figure 13: Initiation of stress fracturing and increased break-out when the stress/strength ratio σ_{θ}/σ_c exceeds 0.4-0.5, from Martin et al. (2001). The case records are mostly from mining and nuclear waste research tunnels.



uniaxial compressive strength). A simple-minded explanation is that there is a strong (Weibull-based) scale effect on UCS as sample size increases, so that UCS x 0.4-0.5 can be an approximate in situ estimate of large-scale strength. Two equations for this strength reduction, from Hoek and Brown and Wagner were compared and simplified in Barton (1987), and show a reduction of about 50% or more, at scales of 1 to 2m.

TBM or Drill & Blast?

In Figure 14 the choice between drill-and-blast and TBM tunnelling is clearly shown to be Q-value dependent, with adverse effects for TBMs at extremely low and high rock mass qualities. Q appears as the first six parameters in Q_{TBM} (see Figure 12) and Q also determines the utilization (or (-)m = deceleration gradient), but only when Q -values are significantly below 1.0

planned 5km long tunnel, and for a much longer 25km long tunnel. As may be noted, there are assumed to be more 'extreme value' rock quality statistics in the longer tunnel, such as harder rock (HH) and more serious faults (FF), and greater cover. It is clear from the Figure 14 comparison of drill-and-blast and TBM progress, each as a function of Q-value, that the TBM will struggle more at both

TBMS

is 1 to 10, while the NATM is used where the dominant quality Q is 0.1 to 1.0. But the cost difference is nevertheless an unnecessary expense, if NMT with pre-injection is used. The concept of hybrid tunnelling (TBM and drill-and-blast) in the same project becomes more attractive if the drill-and-blast section(s) can progress at rates that are less affected by hydro-geological variability, and if they are complete at break-through, i.e. no further lining required. In fact it has been suggested that most if not all of the Q -parameters improve with high-pressure pre-grouting. (Barton, 2002, 2011).

Conclusions

1. There are significant numbers of TBM projects that end up with difficult decisions to be made, namely to

3. The deliberate selection of both TBM and drill-and-blast may often be a simple matter of common sense, giving schedule advantages and cost savings. This is the preliminary level of hybrid tunnelling.
4. Very often it is seen that time is lost while waiting for TBM delivery and assembly, and great advantages could be gained by selective use of drill-and-blast for more than just the standard TBM assembly chamber and starter tunnel.
5. A second level of hybrid tunnelling will be the deliberate choice, because of the perceived advantages, of open-gripper TBM and drill-and-blast, or double-shield TBM and drill-and-blast.

excellent stability. TBMs also exhibit adverse characteristics at the lowest (severely faulted rock) end of the rock quality spectrum.

8. TBMs gradually decelerate with time and tunnel length, even when breaking records. This is a natural process that should be a part of any realistic TBM prognosis, in preference to denial of its existence.
9. TBMs that are operating in mostly favourable conditions, may record remarkable progress, and are therefore an excellent investment for part or all of many tunnelling projects.
10. More uniform tunnelling progress can be obtained, both in the case of drill-and-blast and TBM tunnelling, if the advantages of systematic pre-injection through problematic stretches is better appreciated. The typical 24 hours 'delay' for a pre-injection 'umbrella' may save weeks or months in lost production.

Figure 16: An illustration of the use of pre-injection using up to 70 holes of 25m length, which are drilled and injected in approximately 24 hours, in a 105m² high-speed double-track rail tunnel driven in shales, limestones and through numerous igneous dykes with too much water. Progress was a steady 20m/week for the completed tunnel, virtually independent of pre-conditions.



complete the projects by drill-and-blast from the other end of the tunnel.

2. This on its own suggests that the TBM could or should have been used only on the better investigated portion of such projects, for instance the lower-cover section, with drill-and-blast started already from the other end, and deliberately chosen for the less investigated high cover sections in the case of tunnelling
6. A third level of hybrid tunnelling will be the deliberate choice, because of length of tunnel and perceived advantages, of both open-gripper and double-shield TBM, together with drill-and-blast on high cover and therefore poorly investigated sections.
7. TBM tunnelling and drill-and-blast tunnelling show quite different performance in hard, massive abrasive rock masses, which are adverse for TBM performance, despite the

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