TBM PERFORMANCE, PROGNOSIS AND RISK CAUSED BY FAULTING

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Abstract.

World records for drill-and-blast tunnelling from Norwegian contractors, bear witness to numerous weeks of more than 100m, and an exceptional 5.8 km in 54 weeks, also from one face. Earlier hard-rock world records using high-powered TBM in Norway, but most frequently and more recently, the records with Robbins TBM through non-abrasive limestones in the USA, provide numbers in meters per day, per week, and per month, which are of course, even more remarkable. Unfortunately there are contrary and undesirable TBM records, which are occasionally recurring events so not records, which see TBM stopped for months or even years in fault zones, or permanently buried in mountains. The many orders of magnitude range of performance suggest the need for better investigations, better choice of TBM, and better facilities for improving the ground ahead of TBM, when probe-drilling indicates that this is essential. Control of water, and improved stand-up behaviour in significant weakness zones and faults may demand drainage, which can be unending, and pre-injection. Fortunately there are increasing signs that this is recognized by TBM manufacturers: more guide-holes for drilling pre-injection umbrellas are seen through front-shields nowadays. A little acknowledged fact is that when all hours are included, TBM will generally decelerate as tunnel length and time increases. This is usually seen after improved performance during the learning curve. Deceleration is also a general trend during world-record setting performances. This means that utilization U is equal to the ratio of actual advance rate and penetration rate, AR/PR, only for specified time intervals, because U is time-dependent. This is rarely quantified by designers, and is therefore a source of risk, by default. Another important item for correct prognosis is the recognition that *reduced* penetration rate PR can sometimes occur when thrust is *increased* by the TBM operator, due to exceptionally resistant rock mass formations. Each of the above, and PR sensitivity to a wide range of cutter forces, UCS and abrasiveness, are provided in the empirical Q_{TBM} method. This method explains variable progress in jointed rock, which is sometimes fast, and also quantifies the likely delays in untreated, or pre-injected, fault zones.

Keywords. TBM, penetration rate, advance rate, time-dependence, cutter force, Q.

1. Introduction

During the last 10-15 years, Norwegian contractors have led the world in the fastest drill-and-blast tunnelling rates, with 165m and even 176m in single 7x24 hour weeks. LNS and Veidekke have had consistent rates of more than 100m/week for several months in specific projects. At the Svea coalmine (one-face) access tunnel, in coal-measure rocks obviously requiring some bolting and shotcreting, LNS achieved 100m per week or more for 32 weeks, and used just 54 weeks to drill-and-blast 5.8 km. The tunnel had a 36 m^2 cross-section. This performance is actually better than many TBM project performances if one considers the whole year of tunneling, but does not appear so impressive in relation to TBM, if shorter time intervals are compared, as typically done with TBM.

TMB have incredible current world records of 172m in 24 hours, 703m in one week, and 2163m in one month. Nevertheless, in the world records for the 3 to 4 m diameter class, the best monthly average is ‘only’ 1189m, and the overall world record monthly average is ‘only’ 1352m, found in the 4 to 5m diameter class. The word ‘only’ is used merely to contrast with the remarkable record best month of 2163m.

Thanks to some detailed TBM world record advance rate statistics provided by Robbins on the internet, it was possible to derive the present (2015) record data shown in Figure 1. The 3 to 6m diameter class shown with the smallest ‘cubes’ is *the mean of three sets* of data given for 3-4m, 4-5m and 5-6m TBM, based on assumed 24 hours, 168 hours and 720 hours. The 6 to10m diameter class shown with the larger ‘cubes’ is *the mean of four sets* of data for 6-7m, 7-8m, 8-9m and 9-10m TBM. This collective averaging helps to see trends more clearly.

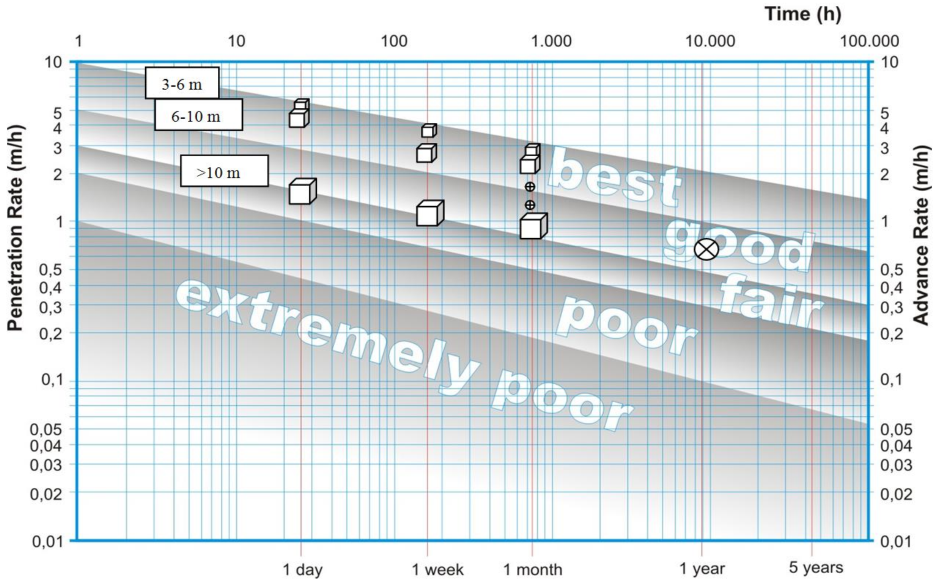


Figure 1. Using a log-log-log plot of PR (penetration rate, left axis only) and AR (advance rate in remainder of plotted area) and time T (total hours), the synthesized **present world-record data** for different sizes of TBM is shown, based on data provided by Robbins.

In Figure 1 the writer has converted day, week and month records (given in meters) to the form AR (m/hr) by dividing by 24, 168 and 720 hours. Data from 8 countries are represented, chiefly USA and China. The record *mean monthly* data plots at AR = 1.7 m/hr for the 3m to 6m class, and at AR = 1.1 m/hr for the 6m to 10m class. These results are shown with the two small circles. The larger crossed-circle to the right represents 54 weeks for 5.8 km at the Svea Mine Access Tunnel, achieved during the LNS drill-and-blast world record. This was driven in coal-measure rocks and obviously required some shotcreting and rock bolting, due to varied Q-values. Slowest progress was made through a near-surface zone of permafrost.

2. Case record evidence of deceleration

There is an all too common habit of reporting utilization (U) of TBM without specifying the time period involved. An estimated average daily utilization is especially an insufficient form of prognosis. Since stand-stills are naturally excluded, the client may get an optimistic view of likely performance. Utilization is estimated from the classic and most used TBM equation:

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

where AR = (actual) advance rate in m/hr, and PR = penetration rate (for uninterrupted boring) in m/hr. U is the fraction of time when boring has (or is expected) to actually occur, as seen on the traditional 'pie- or pizza-diagram'. For convenience U is usually expressed (in speech) as a percentage. Note that in Figure 2, U has been expressed as T^m. This is explained in Table 1 and is also shown in Figure 2 (top-right corner).

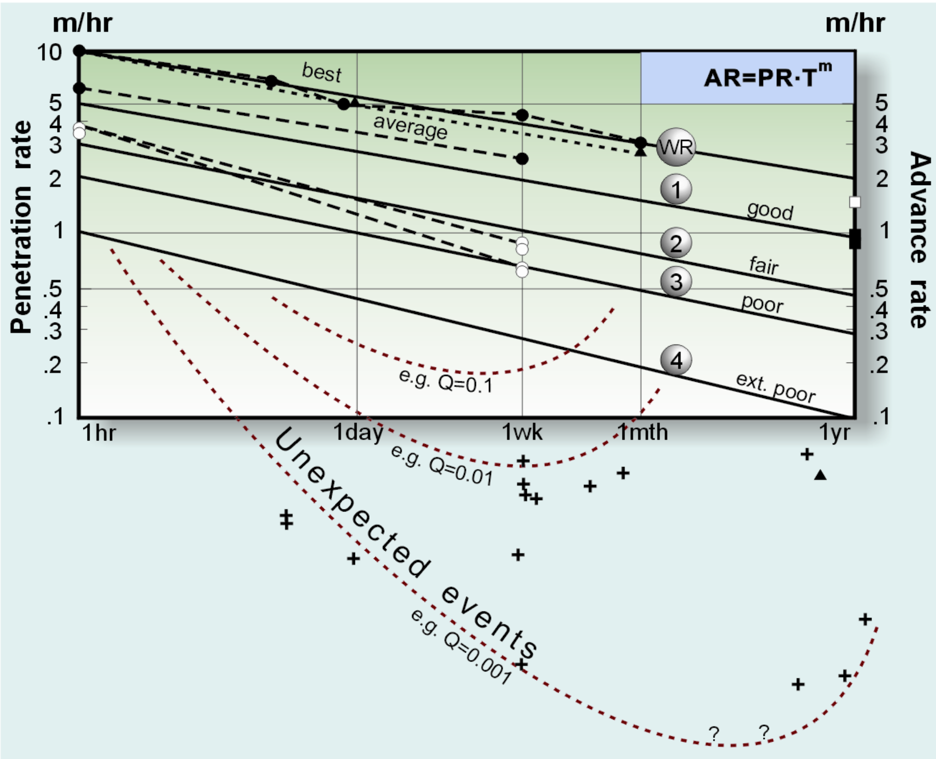


Figure 2. Trends from open-gripper case records representing 145 lengths of well-characterised TBM tunnels, totalling approximately 1000km of tunneling. The performance is represented by log PR – log T – log AR. The PR value applies only to the left axis. T and AR occupy the remainder of the diagram.

The five typical 'lines' of performance are the same as shown in Figure 1. The hand-drawn source of this smoothed data was originally given in [1]. In that reference, and in [2] will be seen numerous sloping red lines (for best performance), and below this numerous and more steeply inclined green lines (for average performance), and below this and even more steeply (adversely) inclined, blue lines (for 'bad-ground' performance). The 'unexpected event' curves (and crosses) in Figure 2, are the low-Q-value-linked worst cases, with (in 2000) three documented permanent TBM burials in the case of older, poorly equipped TBM.

As illustrated by the world records of Figure 1, and as illustrated by 1000 km of mostly open-gripper case records, summarized in Figure 2 from [1], there is actually a time-dependent element in U which is conveniently ignored in a remarkable number of tunnel magazine articles and also in commercial TBM prognoses. Since a client pays for a completed tunnel, a false impression of actual hours (T) is obtained if inevitable standstills, such as in untreated fault zones, are *excluded*. 'Waiting for the train' or broken conveyor belts due to blocky rock may be part of the recorded experience, and cannot be ignored in the prognosis of long TBM tunnels. There are approximately 24 x 7 x 50 ≈ 8700 hours of potential three-shifts of work in one year, and during TBM standstills the clock is still running, with the tunnel completion date likely delayed.

When U is replaced by T^m, more realistic prognoses are possible. Many TBM projects come in 'late' due to ignorance of this element of time / length. So risk (of cost and time over-run) can be reduced by using T^m in place of a potentially misleading U. A 'monthly utilization of 30%' does not give the correct time for tunnel completion, even if a mean PR of say 3m/hr was quite representative for the whole tunnel.

Table 1. Deceleration gradients (-m) for the five trends-of-performance lines in Figure 2, based on 145 cases totalling 1,000 km of mostly open-gripper TBM, from [1]. A specific 56 km of double-shield performance (two Wirth TBM, two Herrenknecht TBM) is also indicated.

Performance Line #	**Description** (refer to Figure 2)	**Deceleration gradient** ***(-) m*** (units of length x t^{-2})
WR	World records	-0.13 to -0.17
1	Good,	-0.17,
2	Fair	-0.19
3	Poor,	-0.21,
4	Extremely Poor	-0.25
Double-shield	Poor PR increasing to Good AR	-0.08 to -0.12

As shown in a later case record, this (optimistic) and at best halving of gradient (-m) seen in the case of limited double-shield data may not apply in tough cases, and is hardly evident in the record mean-monthly performances (small circles shown in Figure 1). An EPB machine may apparently almost double these double-shield (harder rock) gradients for obvious reasons related with the greater challenge of maintaining semi-continuous face support.

In Figure 4, the performance of a large EPB (earth pressure balance) machine is shown [3]. There were 78 disc cutters due to significant sandstone and conglomerate sections of the tunnels, in addition to the numerous soft ground picks. Note that the range of PR was mostly 1 to 2 m/hr, and due to difficult conditions and use of moderate thrust, the deceleration gradient (-) m varied from (-) 0.16 to (-) 0.31 for both tunnels. However, (-) m was (-) 0.38 during the learning curve, and (-) 0.33 when exiting through bad ground. Due to risk of methane gas, operation was always in closed mode, which of course increases delay and makes (-) m more steeply negative.The mean cutter forces used in the weak sandstone and conglomerate/clay were 16.9 and 10.3 tons.

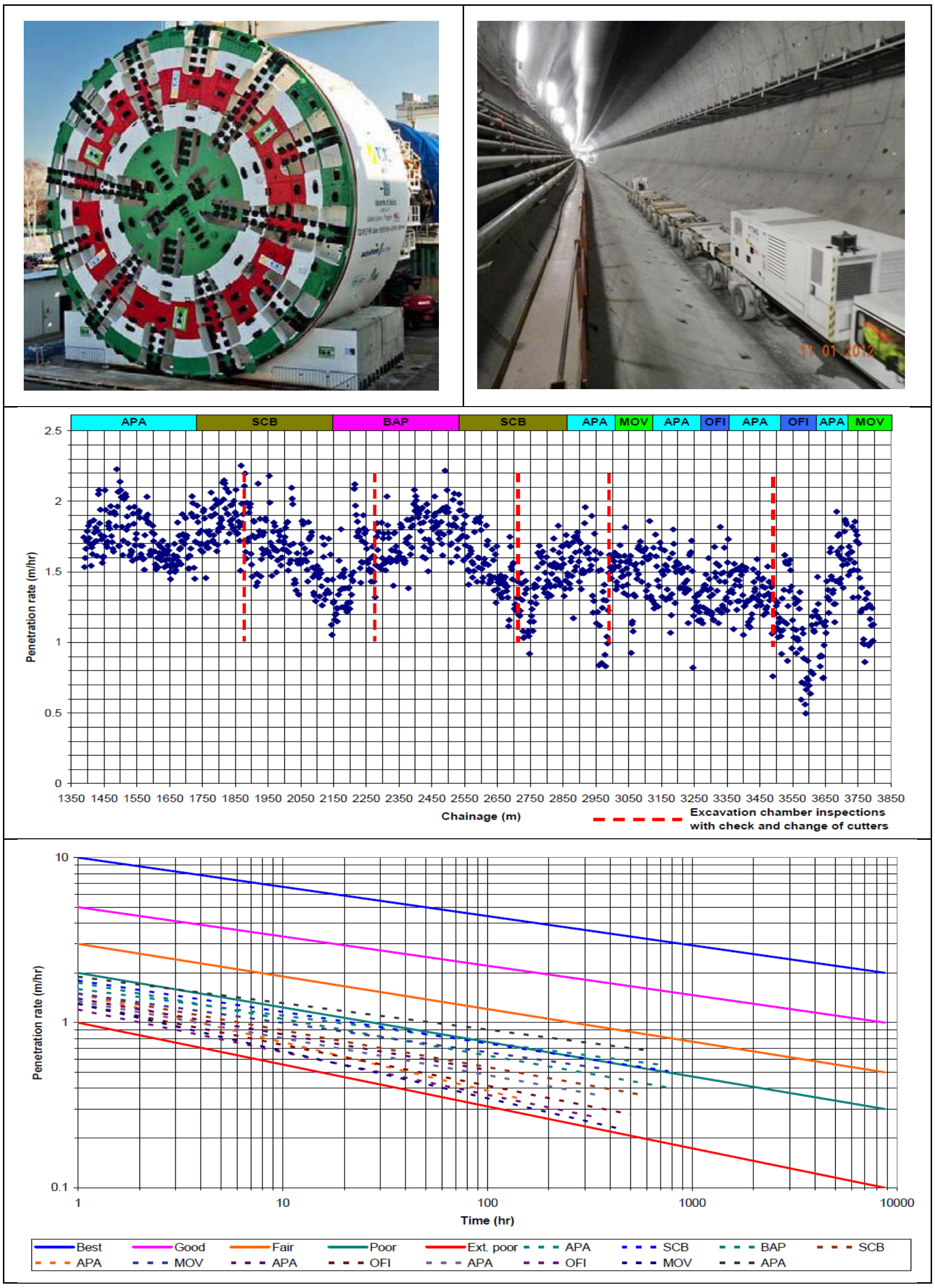


Figure 3. Sparvo Tunnel, driven by the world's (now only) second largest EPB (earth pressure balance) TBM of 15.6 m diameter has twin tunnels of 2.6 km length. [3]. These performance lines match the decelerations described above, though are of course more steeply inclined and have lower PR.

3. Evidence linking Q-values with TBM performance

When a TBM tunnel is driven in one predominant rock type, such as the case of 5 km through granites in Malaysia, described in [4], there is a surprisingly good correlation of penetration rates (PR) with the Q-value, and with even simpler measures of jointing, such as the volumetric joint count, and even with mean joint spacing. (Other 'necessary' parameters are 'constant' in the continuous granite).

The Q-data PR-correlation shown in Figure 4 is based on 2,825m of data analysed in [4], for medium to coarse grained granites with UCS in the range 130 to 246 MPa (mean 182 MPa). This is similar to that expected in the four-TBM, total 2 x 19km Follobanen Oslo-Ski project, also mostly driven through granites, and granitic gneiss, which will be described later as an example of Q_{TBM} prognosis.

It was found [4] that the *average* Jr/Ja ratio (joint roughness/joint alteration-filling) gave a better correlation of PR to Q than the 'most adverse' Jr/Ja ratio, as traditionally used when selecting suggested tunnel support and reinforcement for single-shell NMT (Norwegian Method of Tunnelling) (See [5] and [6].

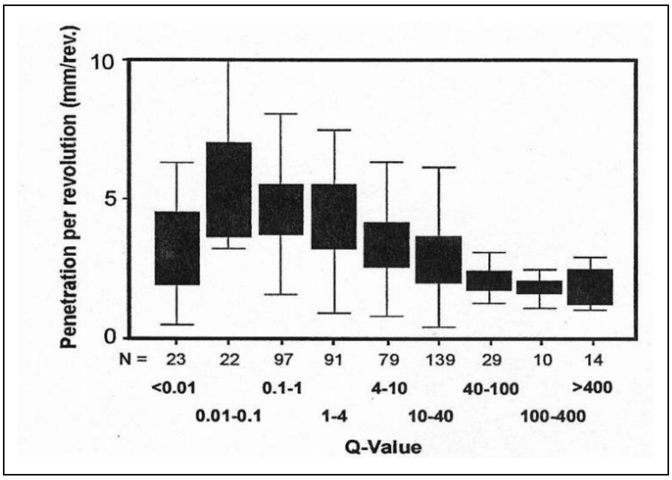


Figure 4. In a project involving only granite, as illustrated here, consistent correlation of penetration rate with Q-values (using mean Jr/Ja) is seen. [4]. Note the matching PR trend in Figure 5.

When logging more than 300 rock exposures and seven cores drilled through weakness zones as input to Follobanen Oslo-Ski prognoses, the writer also logged all the principal Jr/Ja ratios in the form of Q-histograms. This Q_{TBM} study was described in [7].

Figure 5 shows, in principle, how penetration rate (PR) and advance rate (AR) are likely to vary with the Q-value. In a subsequent figure a more representative set of adjectives will be seen, using a new multi-component machine-rock parameter Q_{TBM}, which uses the six Q-parameters for rock mass description, and has extra parameters such as cutter force and rock mass strength.

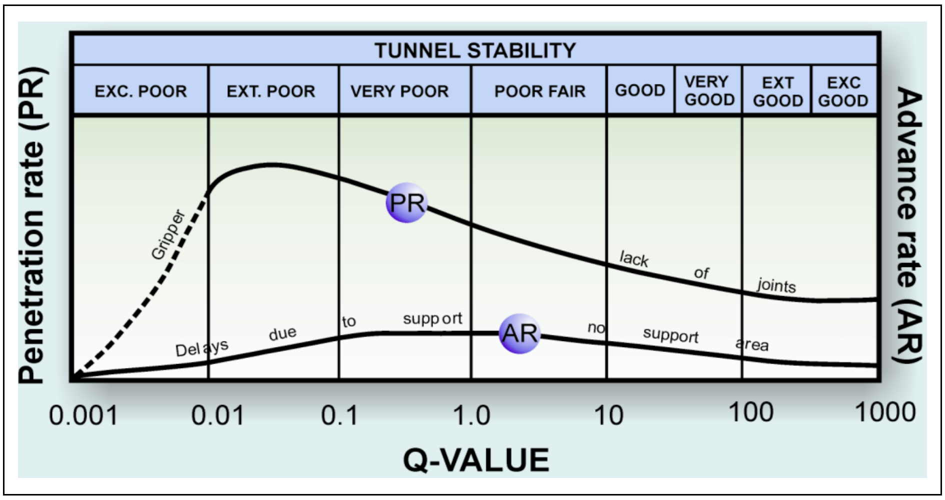


Figure 5. The traditional Q-system adjectives seen at the top of this figure, are clearly not correct for describing TBM performance, as Q-values significantly more than about 30 are adverse for PR, due to lack of joints. Note that the real advance rate AR is likely to be very low at both ends of the Q-scale. [1].

4. Cutter life and the effect of high Q-values and high stress

Manufacturers of new TBM like to claim that their 'cross-over' or 'all conditions' tunneling machines can tackle all conditions and should be selected instead of drill-and-blast, 'because the tunnel is so long', and nowadays even with the argument 'because the conditions are so bad'. This double optimism may not be justified by actual experiences, nor satisfied by the numerous older TBM still in use. As we will see later, and as hinted at by the natural *decelerations* seen in Figures 1 and 2, the *long tunnel argument* is inviting risk, although the ventilation aspect for the long tunnel may weigh heavily in favour of TBM. However, in terms of geotechnical risks, great care is needed before selecting TBM for the long, and probably poorly explored deep tunnel. The prospect of good quality rock may not favour TBM if there is too little jointing and also high cover, as illustrated in Figure 6.

The adverse nature of massive rock with insufficient jointing, especially when this is combined with high UCS and high abrasiveness is typified by the need to change cutters on average every 1 to 2m, as seen in places in Figure 6, and as also occurred in the case illustrated in Figure 7. In practice this means many hours boring with an increasing number of ineffective cutters, because the 5 to 10 (or more) cutters will not be changed until the once-per-24-hours maintenance shift. By then there might be some cutters with 'flats' which consequently have ceased to rotate. So each 24hr period may experience reducing advance rate (AR) if cutter-change needs are significant. A contractors nightmare.

The statistics shown in Figure 6 refers to the mean cutter-change frequency (m/cutter) for two of the 14 km lots, with strong correlation to tunnel depth (minimum m/cutter under two mountain ranges) and therefore implied correlation to the level of confining-stress in the predominantly hard and abrasive granites and gneisses.

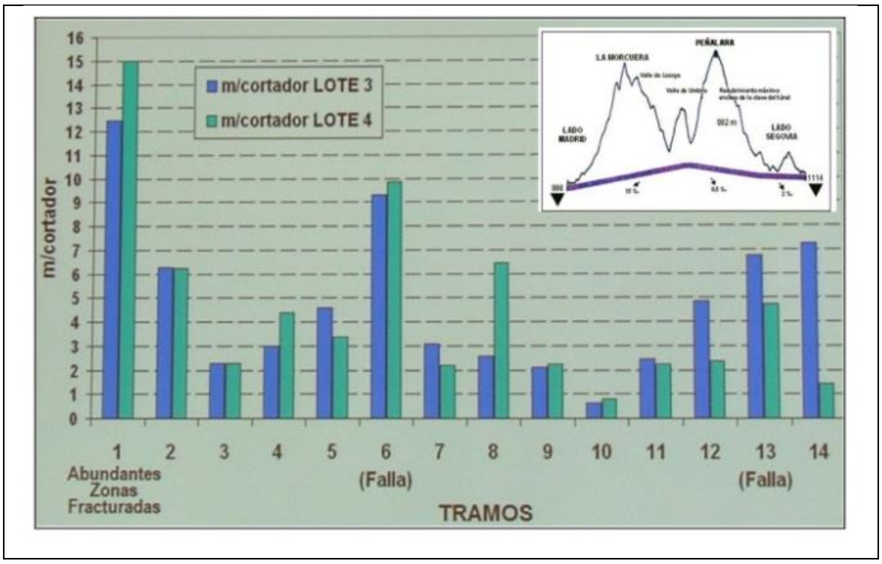


Figure 6 The longitudinal profile for the (4 x 14 km) Guadarrama Tunnels [8]. These were driven in 28 to 33 months by four 'competing' double-shield TBM. The statistics shows frequency of cutter change in units of m/cutter. Abundant fracture zones ('zonas fracturadas') and faults ('fallas') give a positive contribution to reduced cutter wear in several locations.

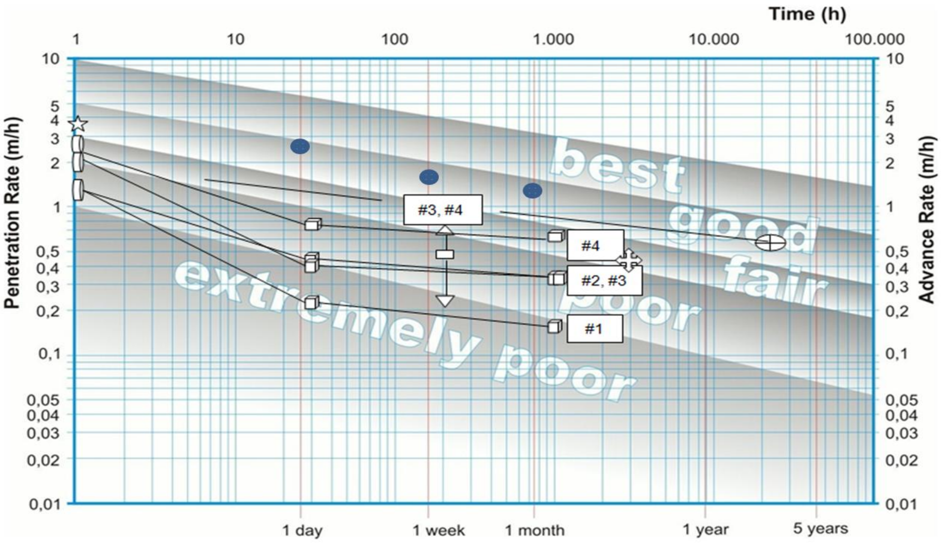


Figure 7. The 'learning curve' performance in the first four months (see the improvement from #1 through #4) of a 5 m diameter and 5 km long double-shield TBM being driven in massive granites with very high RMR (and Q) values.

A common feature of 'learning curves' is the initially lower PR and lower AR due to initially poorer utilization: i.e. a steeper deceleration gradient (-) m. The cutter change frequency in this 5 km project was typically 2 to 3m/cutter. Rock cover was 200-500 m, half that of the mountainous Guadarrama tunnels shown in Figure 6. The 56 km experience from the four competing TBM at Guadarrama showed a similar mean PR = 2.0 m/hr to this 5km case, yet the general efficiencies of the double-shield method eventually allowed overall performance to reach 'good' (see ellipse with cross beyond the 20,000 hours, 32 months location, over to the right side of this Figure7).

The very best results for one day, week and month at Guadarrama are shown by the solid circular symbols, high up in Figure 7. They are 62m in 24 hrs, 250m in 1 week, 970m in 1 month. These are well below world records (Figure 1) but nevertheless very good in the circumstances. The cutter life statistics of the two projects described in Figures 6 and 7, actually emphasize the importance of the NTH/NTNU [9], cutter life index CLI parameter, shown in Figure 8, which has been an important part of the writer's prognosis model Q_{TBM} from the start. On a number of occasions, the results of NTNU rock testing and especially CLI results have been requested, where Q_{TBM} is being used at a foreign project. However, there are many other parameters, which are also important for the Q_{TBM} calculation.

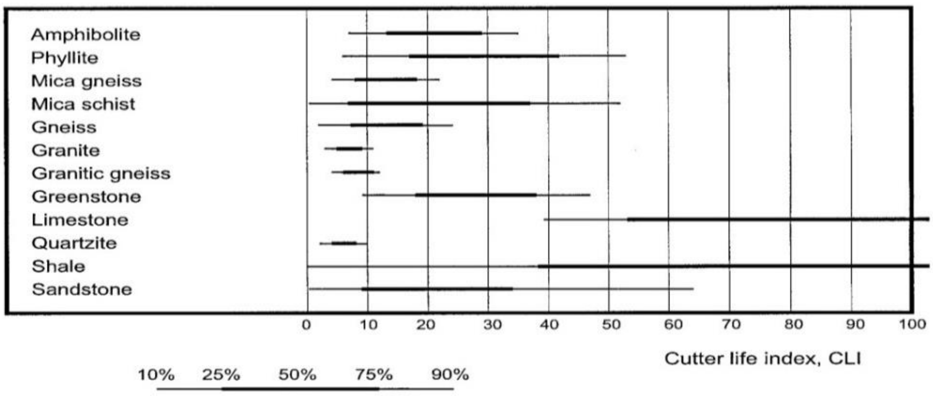


Figure 8. The cutter life index CLI, developed at NTH/NTNU [9] in the 1990's is an important performance indicator, especially when combined with realistic measures of the effect of different degrees of jointing.

Naturally for the application of the Q_{TBM} method, Q is needed in preference to other joint description methods. This is especially so when describing faulted rock, which is incorporated in the prognosis rather than excluded as 'special cases', as so often seen in other methods of prognosis.

A combination of four factors: low CLI (as for granite, granitic gneiss, quartzite), high quartz content, high UCS (obviously linked with these rock types) and massive sparsely jointed rock, with for instance Q-values > 100, and RMR > 80 is an inevitable 'recipe' for frequent cutter change statistics. When the above factors are combined with significant depth of cover, the additional confining-pressure acting across the face of the tunnel, and directly adding to the difficulty of chip formation, may cause cutter life to dip below 2m/cutter, and on occasion even below 1m/cutter.

Clearly this will be a significant task for the daily/nightly maintenance shift, and besides the time for replacement of say 10 cutters, there will be the added effect that for some of the 10 to15 hours of boring, a number of cutters will have become sub-standard due to excessive wear.

4.1 Double-shield logging a poor basis for critique

While addressing the subject of maintenance shifts, it is unfortunately a fact of life that in the case of double-shield TBM which are convenient for allowing simultaneous PC-element ring assembly and push-off grippers advance, there will only be the possibility of observing and (very) approximately logging the rock conditions, when the machine has stopped for cutter change. The 'inner climate' with hot cutters and sauna-like conditions at first, are not conductive to easy Q or RMR or NTH/NTNU joint class mapping. The writer has occasionally tried to perform such logging, and has also been a consultant at some smaller-diameter TBM sites where only the smallest engineering geologists get to log the limited data, as seen in a very confined space, and must share their few observations with larger colleagues (and probably with larger consultants too).

It is therefore remarkable that certain authors who will not be named, both in Norway, Italy and the USA, were happy to present other's 'data' showing apparently poor correlation of PR statistics and Q_{TBM} values, when in reality the only rock mass quality logging was at 15, 20 or 25m intervals (once in each 24 hours). This logging could only occur when the relevant TBM were stopped for maintenance, because the rock could not be observed while boring. Worse still, Q was mostly obtained by subsequent estimation from RMR logging, since original (Italian) authors were not at first aware of the new Q_{TBM} method, so they 'retro-actively' tried to estimate Q_{TBM}.

One may question whether this a valid basis for over-confident critique, and second-hand use by others in Norway and the USA, on similar dismissive missions? Most of the more reliable case record data represented by the decelerating lines in Figure 2 were obtained from open-gripper TBM projects, where rock mass conditions could be well described on a continuous basis, and not only by the most agile (and smallest) engineering geologists, at much too well-spaced daily-advance intervals, somewhere around midnight.

If similar PR-Q_{TBM} scatter as that shown by the critics, had been experienced by the developer, there would obviously have never been Q_{TBM} development or publication for others to criticize. So those with dismissive missions need to evaluate if they are performing valid comparisons, or using other's 'data' in a strictly honest manner.

5. Cutter thrust compared to rock mass strength

Recent trials with instrumented cutter bearings in Austria, described in [10] have demonstrated the actual complexity, though logical nature of cutter force distributions. Of necessity one divides net thrust by the number of cutters, to estimate mean thrust per cutter, and then can compare this with a measure of rock strength. The reality, as shown in Figure 9, is that cutter thrust oscillates strongly about the assumed mean, and in addition varies across the face of the tunnel if the resistance to chip and block formation also varies. This of course will be linked to the relative dominance of massive or jointed/foliated rock, and changes of rock strength.

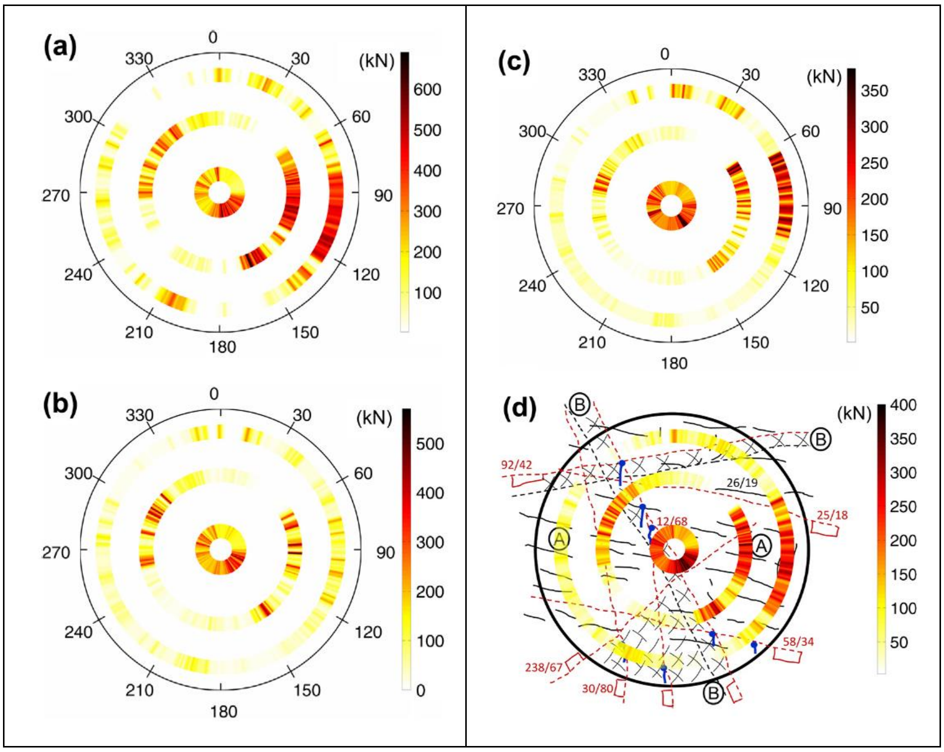


Figure 9. Normal forces monitored during three consecutive cutterhead revolutions (a–c) and the averaged forces of these figures compared with the corresponding geological mapping (d). These interesting measurements were made recently at the Koralm tunnel in Austria, and were reported in [10].

These cutter force oscillations will often be present when the rock mass is frequently varying across the face, which means that comparison of assumed mean cutter force, such as 20, 25 or even 30 tons per cutter, with the assumed chip- or block-formation resistance of the rock mass, is going to be an approximate exercise. Nevertheless it is an obvious advantage if the estimate of resistance of the rock mass is as realistic as possible. This means that the *rock mass* and not just the *rock material* should be used. To base penetration rate prognoses only on rock UCS values is to invite inaccuracies. And to not compare assumed cutter thrust with any measure of rock strength is an invitation to greater lack of reality. The reasons for insisting on this 'thrust/strength' comparison are illustrated in four examples in Figures 10 through 13. Only if the TBM has sufficient thrust in relation to rock mass strength will one obtain the expected result of increased penetration rate with increased thrust, as shown in Figure 10.

A more or less quadratic relation between penetration rate and cutter force is suggested in Figure 10, and this was also seen in high-powered TBM trials in Norway in the nineties, with thrusts in excess of 30 tnf/cutter. There is often a rapid change of gradient beyond about 20 tnf/cutter, if the effective rock mass strength is finally more easily exceeded.

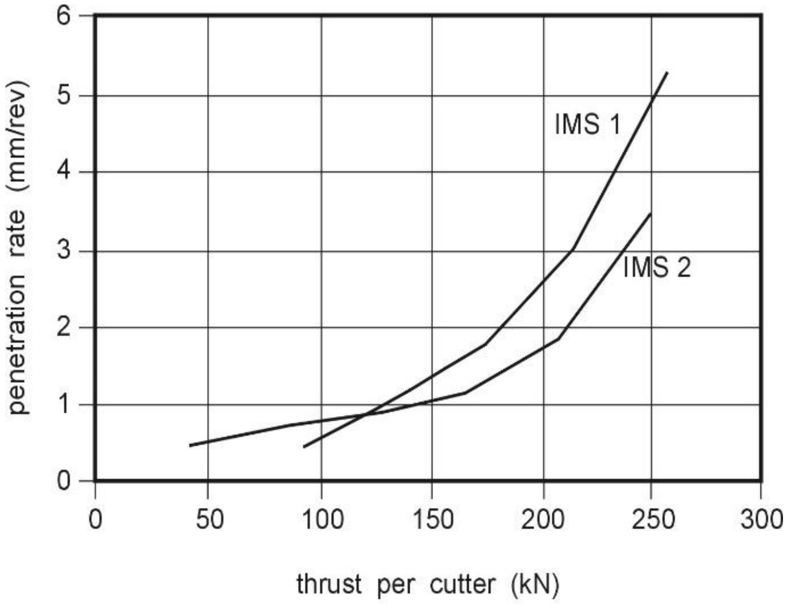


Figure 10. When rock masses are sufficiently jointed and the rock material is not too strong, then increasing the mean thrust on the cutters will often result in the expected increases in penetration rate, as suggested in this data from Hong Kong, where IMS is a local consultant's measure of rock mass class. (Unpredictably, his name is Ian McFeat-Smith). This measure of rock mass class is used in [11] in a publication concerning TBM progress through Hong Kong granites.

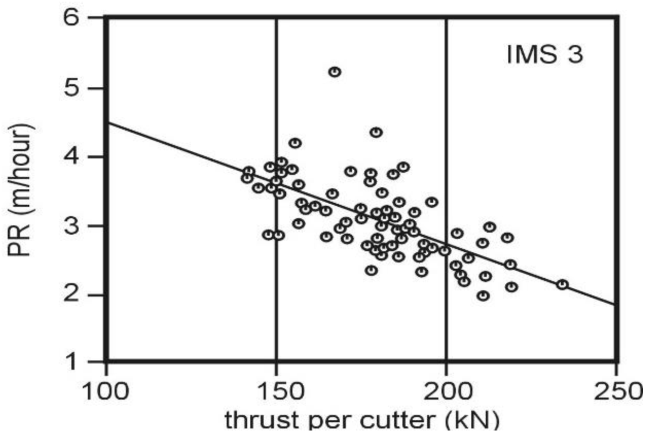


Figure 11. The expected logic of increased PR with increased thrust may break down, as shown here, if the thrust available is insufficient in relation to the effective strength of the rock mass. Too high rock mass strength, including a relative absence of jointing, or too high UCS, would hinder block formation and chip formation. From [11].

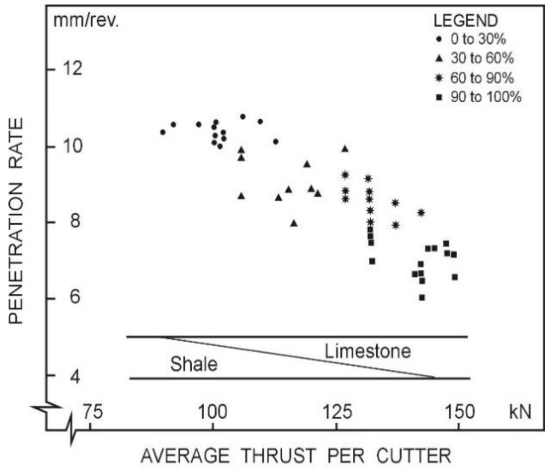


Figure 12. Another example of penetration rate reducing despite increased thrust, from the days when TBM power was more limited. Penetration rate versus thrust per cutter is shown for specified percentages of limestone (σ_c = 130 MPa) and shale (σ_c = 68 MPa), as described in [12]. A similar situation could arise today with more powerful TBM, if the strongest mixed-face component was even stronger and more massive than this limestone.

It seems that the necessity to compare cutter thrust with some measure of rock mass strength more relevant than UCS alone, is not recognised by some who have developed prognosis methods. Cutter thrust increases can be associated with reduced penetration rate, if the rock mass was very strong and sufficiently massive. This is 'confusing' but nevertheless necessary to be aware of. A further example, with a significant body of data, is that shown in Figure 13. The (NTH) method of prognosis missed the actual TBM behaviour, because the meta-sandstones, perhaps with limited jointing, were stronger than available thrust per cutter.

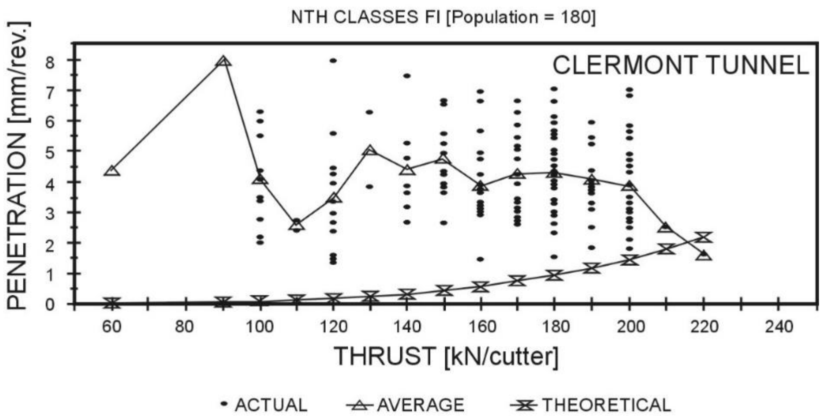


Figure 13. The 'logical' expectation of increased penetration rate with increased thrust may not be experienced if a TBM is underpowered in relation to very hard massive rock. Data rom the Clermont Tunnel in South Africa, back-analysed in [13].

The 'theoretical' (and perhaps not sufficiently empirical) NTH prognosis model clearly misrepresented the situation, and gave especially unrealistic predictions of penetration rate when thrust was low, suggesting that the judgement of joint class (F1), or the functioning of the joint classes term, was not sufficiently realistic.

6. The development of a TBM prognosis model called Q_{TBM}

There are two further empirical results which need to be shown, before presenting the Q_{TBM} prognosis model. These concern the essential separation of PR and AR, because it is clearly insufficient to have a prognosis model that only addresses the penetration rate. Figure 14 (also Figure 5) demonstrates that sometimes there may be limited dependence of AR (the actual advance rate) on the penetration rate PR, despite significant variation in the uniaxial compressive strength, from 50 to 150 to 250 MPa, as for the three rock types plotted in the figure. It is clearly the increased need of tunnel support in the weaker shale which nearly eliminates the 'initial' advantage of a lower UCS, giving the best PR result. In faulted rock the problem is often more extreme, with 'too fast' PR occurring using even low thrust, immediately followed by increased support needs, and maybe also delays. (This is a common error of those attempting to use Q_{TBM}. They need to reduce thrust in the model, just as done – of necessity – by the TBM operator, who registers reduced resistance to penetration, and knows of the consequences of 'getting ahead' of local tunnel support needs.).

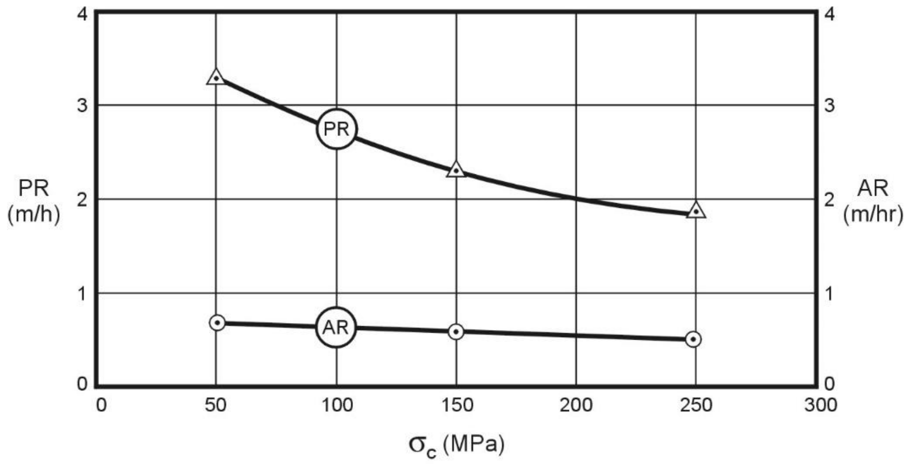


Figure 14. PR and AR data for TBM progress through shale, tillite and sandstone. These curves were derived in [1], from weekly average data reported in [14].

Figure 15 emphasizes the role of jointing, as described by variable Q-values, and the additional influence of UCS reported in [15]. The recorded PR values for a 3.5m diameter tunnel are given in m/hr at the lower end of each sloping line.

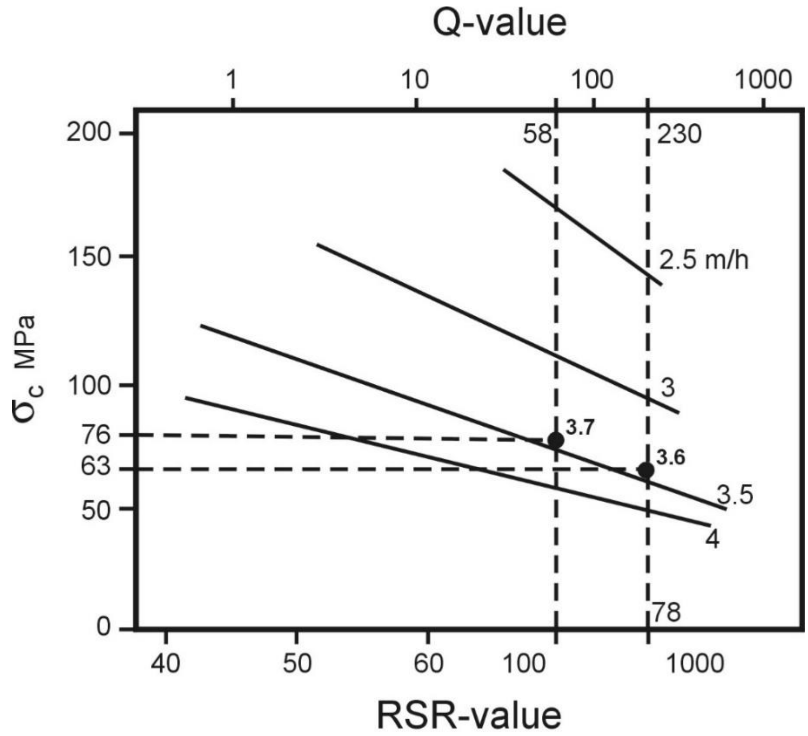


Figure 15. There is a logical correlation between penetration rate (given here in m/hr) and the Q-value. Massive high-Q rock slows progress, and if UCS (σ_c) is also high, an even slower penetration rate is inevitable. Low UCS and low Q-value (but not too low) are positive, as in the left-hand bottom corner. From [15].

Boring in hard quite high-quality rock masses, will frequently move PR towards the top right-hand corner: i.e. combining high Q and high UCS gives lower PR, and possibly frequent cutter change, if the cutter life index CLI is adversely low. (Note that the infrequently used rock mass classification method called RSR, developed just before RMR and Q is not discussed here).

The case-record basis for the development of a TBM prognosis model, detailed stage-by-stage in [1], later resulted in a user friendly computer program, which was termed Q_{TBM} in [16]. This indeed employs the Q-system, but modified to an oriented Q_o format. RQD needs to be interpreted with respect to tunnel orientation, and is therefore written as RQD_o. A 'conventional' vertical core can give a false high value of RQD (in relation to the low value in the tunneling direction), if there is a strongly oriented steeply dipping structure such as bedding or foliation.

For estimating Q_o, all joint sets are sampled regarding Jr/Ja, unless a particular set is assisting or hindering penetration. It is then allowed to influence the oriented Q_o - value more strongly. Of course a convenient way to gather data is to log rock exposures like recent road cuttings (if available, and not heavily weathered), logging along imaginary horizontal scan-lines. Histogram-based recording of data allows thousands of recordings to be made rapidly. Examples for the Follobanen Oslo-Ski project were given in [7].

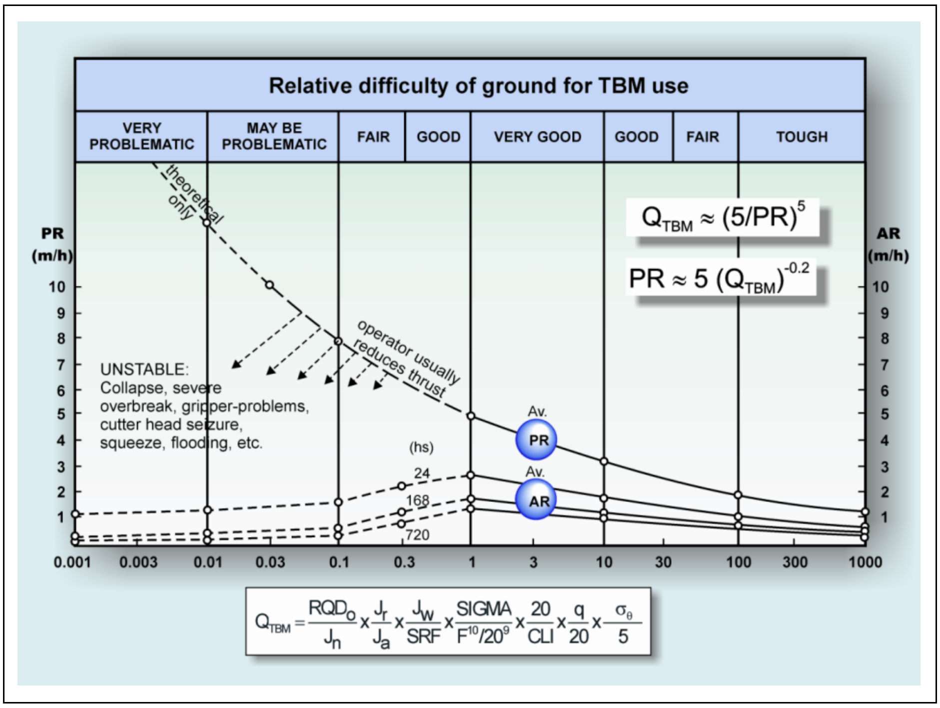


Figure 16. The Q_{TBM} model for TBM prognosis involves an oriented Q_o-value and machine-rock interaction parameters given in normalized form. The Q_{TBM} value [1] is (adversely) increased if CLI (cutter life index) is <20, if q (quartz content %) is >20, and if the estimated σ_θ (biaxial stress state on tunnel face) is more than 5 MPa (the estimated value at 100 m tunnel depth).

Note that the lower set of curves in Figure 16, representing AR estimation for 24 hrs, 1 week, and 1 month are separated, because of declining utilization. Note also the new 'adjectives' (tough, problematic etc) specifically for TBM. It is clear that central Q_{TBM} values of ≈ 0.3 to 30 would be ideal for fast progress.

One of the most important normalized parameters in Q_{TBM} is mean cutter thrust (F, tons) which is normalized by 20 tons. Greater or lesser applied thrust is then compared with SIGMA (rock mass strength estimate = $5\gamma Q_c^{1/3}$) where $Q_c = Q_0$ x UCS/100 and γ = density in gm/cm^3. For most conceivable rock masses, SIGMA ranges from 1 to 100 MPa, but in saprolite SIGMA < 1 MPa. The resulting formula for PR (see top-right inset in Figure 16) which is strongly dependent on cutter thrust compared to rock mass strength, has been tested on numerous occasions, both for high-powered TBM with F > 30tnf, and for blind-hole shaft drilling with F as low as 7 to 8 tnf. Realistic values of PR are obtained when the method is correctly used.

In essence we allow the Q-value to assist in determining delays due to support requirements (it therefore effects – where appropriate - the *deceleration gradient -m)* and therefore overall AR. Furthermore we allow the Q-value, and critical *rock-cutter*, and *rock mass-machine* parameters to *also determine* the speed of cutting (therefore effecting slower or faster PR). These dual roles of Q have been criticized, but empirically speaking the method works well. Figure 17 shows an example of a Q_{TBM} data-input screen, explained in detail in [16], which shows the parameters used in the simple calculations, most of which appear in the x-axis equation of Figure 16.

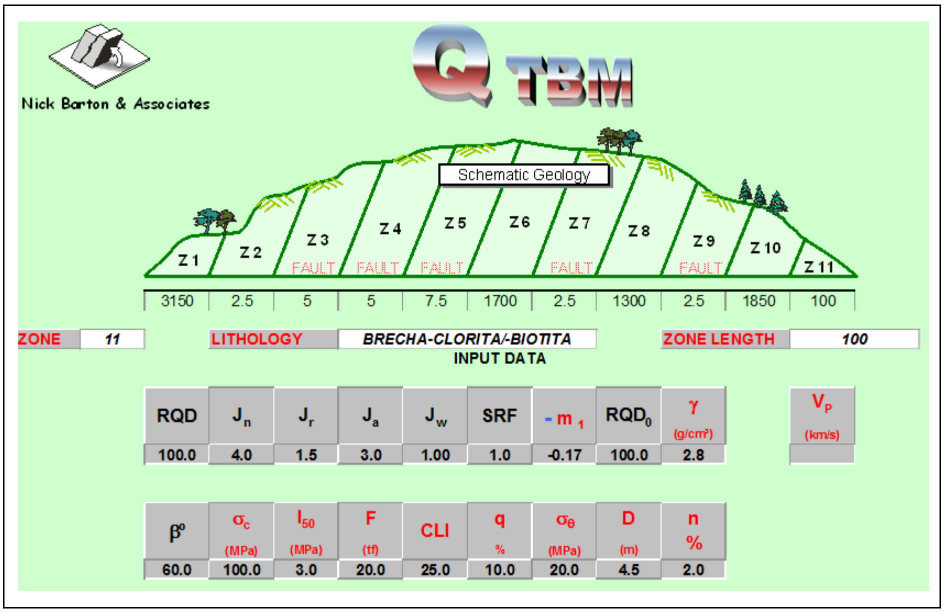


Figure 17. An example of the Q_{TBM} input-data screen showing eleven modelled zones, six of them being assumed fault zones, as logged in adjacent deep (mineral-reserves-related) drill-core. The estimated input-data was for a planned TBM tunnel in Chile, successfully constructed some years ago. For model, see [16].

7. Fault and weakness zones and their representation in Q_{TBM}

The fundamental difficulties of tunneling through fault zones, and prognosis-modeling this successfully, will be summarized later, by combining three extremely simple equations. They provide, when combined and presented in terms of time T, a convincing explanation of why so much time can be lost in an unexpected, and therefore usually untreated fault zone. The key to this understanding is that the universal but variable deceleration gradient (-*m*) is strongly linked to low Q-values. Low Q-values and high negative deceleration gradients (meaning low utilization) go hand-in-hand. U cannot be independent of time T, as clearly shown in Figures 1 and 2, both for extremely fast and slower TBM tunneling.

Before presenting the three equations, it may be helpful to see how fault zones plot on the *log PR – log T – log AR diagram*, which was used as an introduction to the world records shown in Figure 1. Fault zones in general have a potentially delaying effect on overall tunneling rate. Their low Q-values usually demand heavier local support (or some difficulties with PC-element ring building due to over-break), so a steeper deceleration gradient is usually involved. On the other hand they may often (though not always) be ‘easily’ bored through using low cutter thrust, but probably need increased torque, since an unusual amount of contact with the cutter-head is occurring. Unless blocks dislodge and jam the cutter-head, as may sometimes happen in unexplored mountainous terrain, the moderate delays may appear as shown in Figure 18. Only one of the steeply inclined lines suggests a delay of (>) 1 week.

Double-shield TBM with push-off liner capabilities may get severely delayed if a fault zone is serious, as over-boring (void development in front of, to one side, or above the cutter-head) can just as easily develop ahead of these machines as ahead of open-

-gripper TBM, unless pre-injection in the one case, or spiling has been performed. Facilities for these essential operations are illustrated later in this chapter. When faults are encountered deep below the water-table, and delay TBM progress, inflow of water may occur in an uncontrolled manner and for too long, with groundwater drawdown (and subsidence damage) as a likely result in the case of shallow tunnels beneath towns. Risk analysis should address such consequences and their mitigation. It will not be sufficient to have gasketted PC-elements ready to be installed, while the next 15m of slow advance is negotiated before reaching the element erector. In this sense TBM can be 'too long'. Pre-injection 'would have been' the solution.

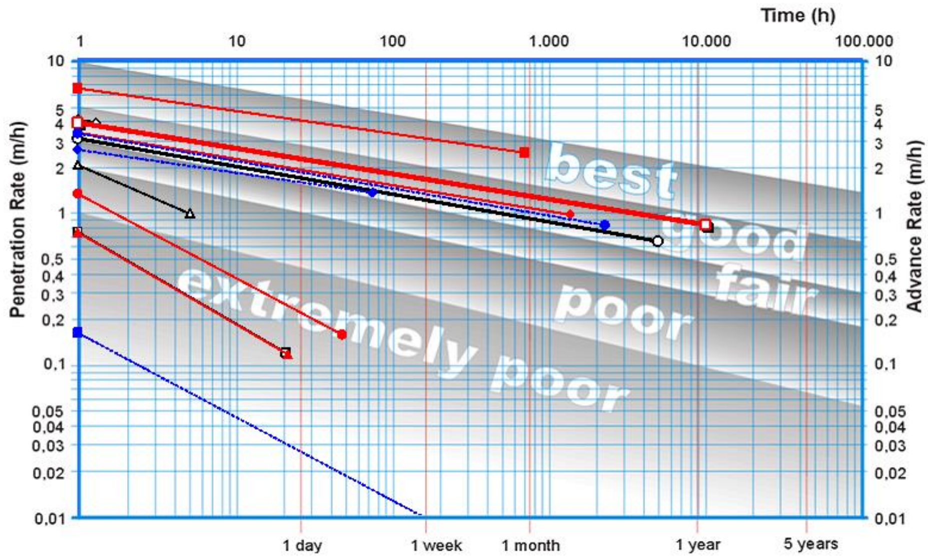


Figure 18 The graphic output concerning the calculated PR and mean AR (both in m/hr) for the eleven separate zones shown in Figure 17. Only one of the faulted rock zones dips below the 'horizon' (T > 1 week) and is therefore predicted to cause trouble even for the double-shield TBM.

A weighted mean of about 10,000 hours for 8 km of tunnelling was predicted for this double-shield TBM, by combining all of the eleven zones modelled. In practice it took longer due to local labour practices, and due to a long delay out of the starting chamber, where unexplored faulted rock was immediately encountered, and over-boring and cutter-head blockage were intermittently experienced for several weeks.

7.1 *Fault-zone delays explained*

We need three basic equations to understand potential delays in fault zones. (The following nomenclature will be used as before: AR= advance rate, PR= penetration rate, U= utilization, expressed as a fraction, for any chosen *total time* period T in hours). Firstly:

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

(All TBM must follow this first equation, which was presented at the start of this article).

$U = T^m$ (2)

(Due to the reducing utilization with time, advance rate decelerates, see Figs 1 and 2).

$T = L / AR$ (3)

(Obviously time needed for advancing length L must be equal to L/AR)

With *continuous* boring T = L/PR, and in fact this simple equation also applies to walking. All readers can agree that these are very simple equations, and also correct equations. But who has seen them combined and employed in prognosis?

By simple substitution we have the following:

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

(Here, T appears on both sides of equation: the final expression for T is therefore:)

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

This is a very important equation for TBM, if one accepts the case record evidence that *(-) m* is strongly related to low Q-values in fault zones and significant weakness zones. It is important because very *negative (-) m* values make the component ($^{1/(1+m)}$) *too big*. If the fault zone is wide (large L) and PR is low (grippers inefficient, water problems etc.) then L/PR may get too big to tolerate a big component ($^{1/(1+m)}$) in equation 4. It is easy (in fact much too easy) to calculate an almost 'infinite' time for a fault zone using this 'theo-empirical' equation. The writer knows of four permanently buried, usually fault-destroyed, occasionally rock-burst destroyed TBM (Pont Ventoux, Dul Hasti, Pinglin, Jinping II). There are certainly many more, and the causes may be related to equation 4 logic.

Fault zones (and extreme stress/strength ratios causing rock bursts) will remain a serious threat to TBM tunneling as we know it, unless the extremely poor rock mass qualities associated with fault zones can be improved by *drainage and pre-grouting*, specifically where Q < 0.1. There are signs that some TBM are being adequately equipped with holes through the front shield for pre-injection. This obvious need seems to have taken several decades to materialize in practice.

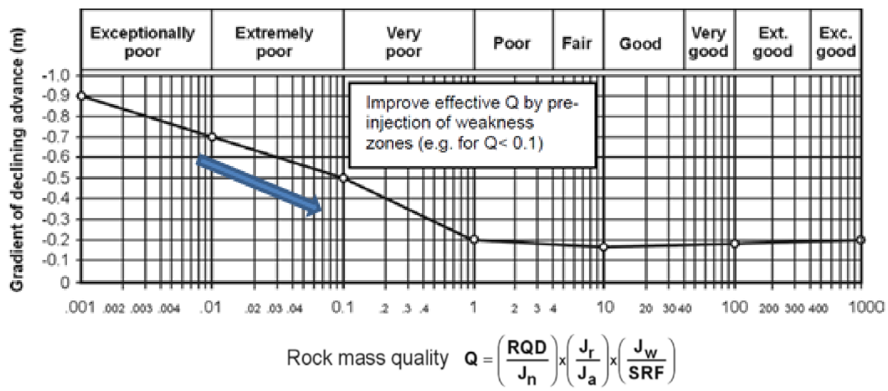


Figure 19. Low Q-values are synonymous with increased delays, represented by steeply (negative) (-) m.

Figure 19 represents an empirical (*a posteriori*, not *a priori*) link between low Q-values and steep deceleration events, as experienced when passing through (or maybe getting stopped) in significant faults or weakness zones. Pre-grouting (in the blue-arrow zone) is the most effective way to prevent such stoppages. It solves other problems as well, such as settlement damage due to groundwater drawdown. Double-shield machines may reduce these adverse gradients by as much as one half, at best. However, over-boring or cutter-head blockage can occur just as 'easily' with open-gripper or double-shield TBM.

A steep deceleration gradient demonstrates the adverse nature of these 'unexpected events' (faults), which should alternatively be *anticipated beforehand*, by performing probe drilling during part of each maintenance shift. If highly permeable weakness zones were drained and pre-injected, an effectively increased Q-value (as deduced in [17] and [18], would cause *(-) m* to reduce to less negative values, as indicated in Figure 19 (see arrow).

8. Some examples of fault zone challenges for TBM

In the following illustrated section of this article on TBM prognosis and risk (Figures 20 to 24), we can view challenging situations for TBM related with fault zones. The situations illustrated have obviously been a source of delay for contractors, and they hint at the need for more flexibility in detection ahead-of-time, and the ability to pre-treat, so that the inherently adverse 'crushed-rock-and-clay-and-water' properties can be improved, before the TBM exposes the problem, making things worse due to loosening. There are many examples of this loosening. A 'compact' high-velocity zone becomes unloaded (or over-loaded) and the marginal 'rock mass properties' deteriorate so much that the TBM cutter-head gets stopped, and gripper thrust is perhaps also compromised at just the wrong time. We can start in northern Italy, with (in retrospect) an inadequately investigated fault swarm that was not sufficiently detected despite 300m deep boreholes.

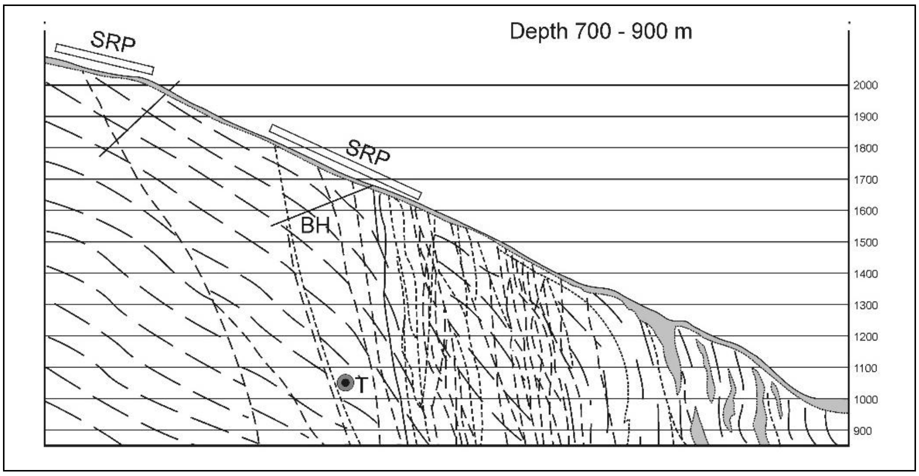


Figure 20. The valley-parallel fault swarm (discovered after tunneling was commenced) were special features of the Pont Ventoux.headrace tunnel.The combination of high water pressures associated with the faulting, causing erosion of the crushed rock and clay, represents an ultimate challenge for any TBM.

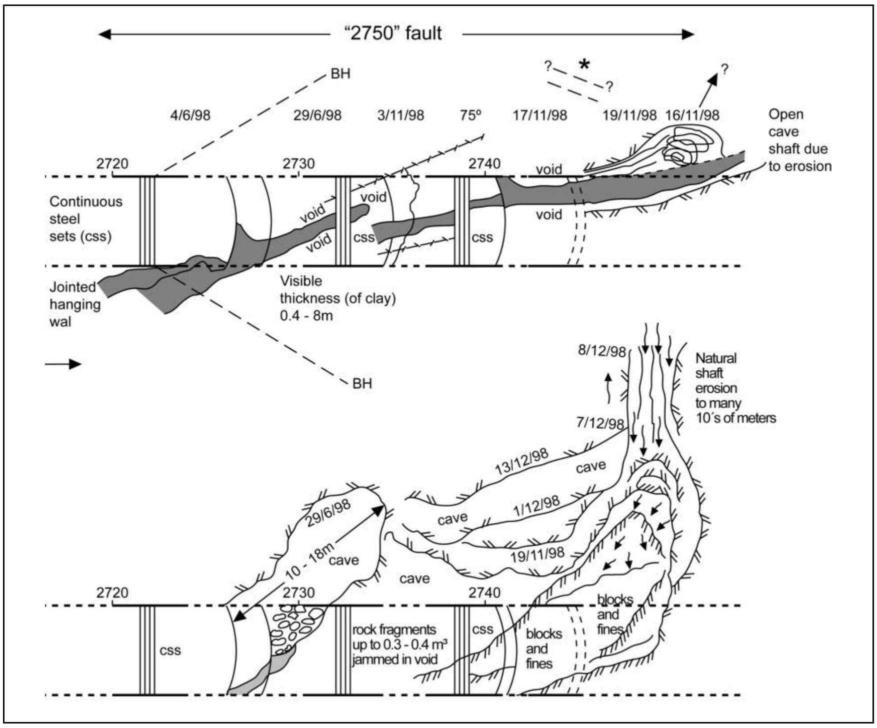


Figure 21. The Pont Ventoux headrace tunnel in northern Italy. A seemingly minor fault zone (but one of many) with a 1 m thick clay core, combined with high water pressure on one side, succeeded in delaying this inherited TBM by 5 months in this 30m long section. Similar features which followed, finally resulted in 'drill-and-blast-from-the-other-end' and eventual by-passing and abandonment of the rusting TBM.

In the situations illustrated in Figure 21, blocks loosened in a steadily eroded 'natural' shaft, due to high-pressure water inflows. Blocks which could be heard falling, frequently blocked the cutter-head, preventing rotation. The TBM was not equipped for probe drilling nor for pre-injection. The new contractor had inherited a TBM whose limitations were a good illustration of future needs for more versatile TBM, which are now being provided, as shown later in this section on fault zones. The sketches are from weekly logging by engineering geologist K.G.Holter, each superimposed to see 'progression'.

Once exposed in the excavation, fault zones, expecially those containing crushed rock and clay and high water pressures, can present nearly insurmountable problems due to loss of profile, difficulty with gripper operation, difficulty with PC-element ring building, and cutter-head blockage, or over-loading of conveyors with eroded over-size blocks. In the case of this older TBM, the recesses in the gripper-pads for allowing a 60 cm c/c (i.e. close) spacing of circular steel sets proved to be futile, as the stability was so poor that the contractor had needed to place steel sets flange-to-flange forming a 'steel-barrel'. This was stable except where adjacent sets were crushed and sheared by the successive gripper action. With a deforming clay core on one side (Figure 21), the right-side grippers also penetrated into the fault, deforming the steel sets like discarded outer-clothing. Of course a modern double-shield TBM would not have suffered this particular problem, but the eroding shaft and cutter-head blockage might be similar.

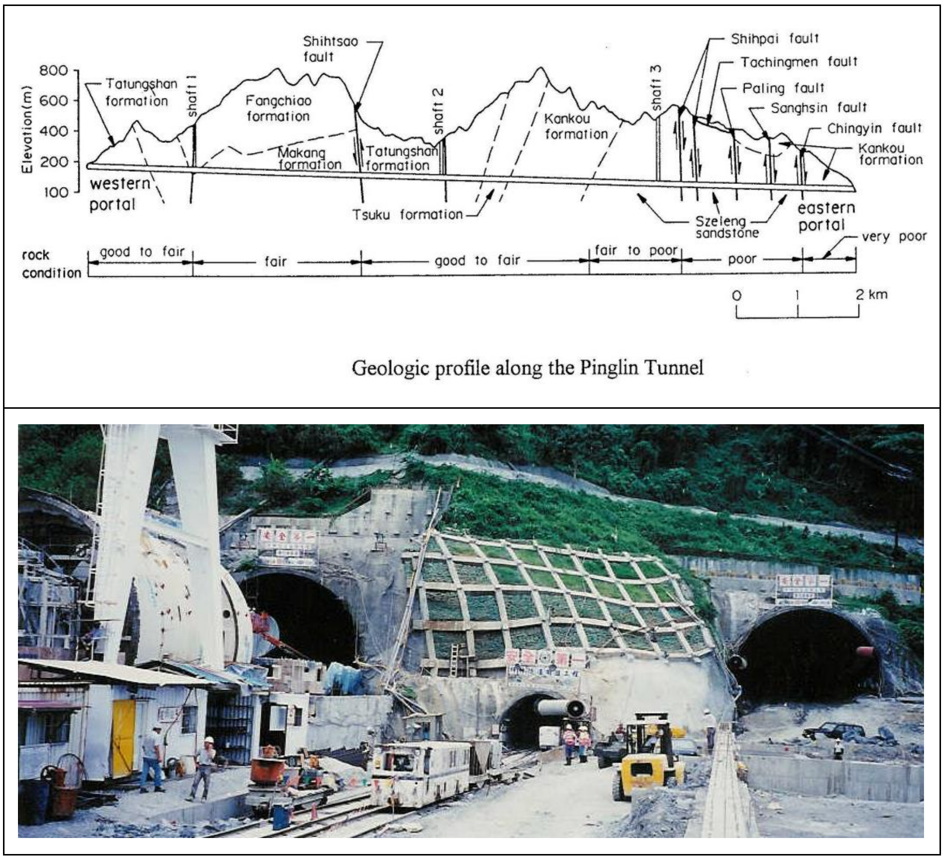


Figure 22. In the ultra-challenging Pinglin project in NE Taiwan, initially employing two 11.7 m diameter TBM and a lower pilot TBM of approx.. 4 m diameter, the contractor had great difficulty even drilling stable holes for pre-injection, due to the intensely jointed, sheared and clay-coated joints and slickensides in the very hard meta-sandstones.

Figure 22 illutrates the challenging and frequently faulted Pinglin tunnel(s) in N.E. Taiwan. A particularly tough situation is illustrated in Figure 23. The twin tunnels in the end were driven by drill-and-blast, due to crushing of one TBM in a major fault zone collapse. The result of a subsequent 7,000 m^3 inrush of clay and rock was witnessed, with a temporary drill-and-blast top-heading tunnel ‘face’ moved 100m backwards. What would have happened if a TBM had still been in use in this second tunnel must remain an open question. There were already many fatalities at Pinglin, and many were the result of not being allowed, in the first years, to drive the tunnel from both ends, for environmental reasons. So all initial resources were directed on three TBM (Figure 22) driving from the eastern end of the planned tunnels. These were gradually defeated by the extreme challenges of the frequently faulted and sometimes very deforming rock mass. An unusual ‘hybrid’ use of the one remaining (not yet fault-destroyed) TBM, was the excavation of a conventional drill-and-blast top-heading, with the TBM used to cut and muck ‘the invert’ (the lower half of the tunnel).

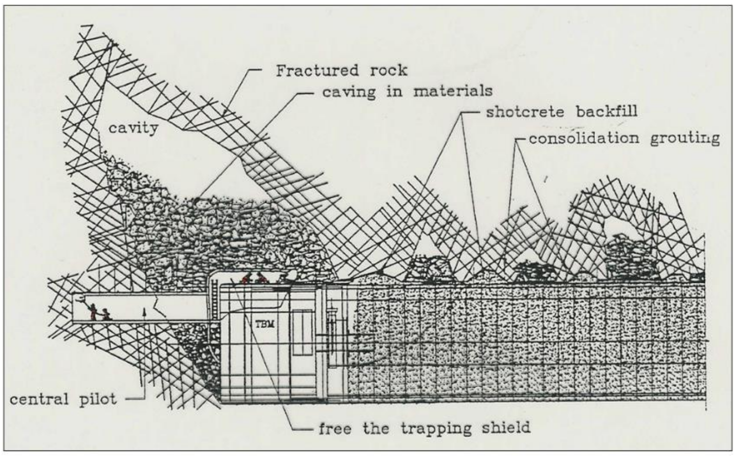


Figure 23. Exceptional problems in faulted meta-sandstones, with the need for a by-pass and top-heading to release the cutter-head. [19]. Such stoppages occasionally provided the opportunity for replacing cutter-head 'armour' which was worn out every 4 to 5 km. One of these situations was observed by the author.

Figure 24. At the Pinglin Tunnel project in Taiwan, the use of a pilot tunnel for drainage and pre-injection across to the two main (future road) tunnels was not successful, due to numerous cutter-head blockages and the need for side-access drifts to reach the blocked cutter-head (at least 13 times). The lower photograph shows a 'conventionally-driven' top-heading for face-armour replacement of the one remaining 11.7 m diameter TBM. (Top photo: Chris Fong).

It is understood from ADIF [8] descriptions of the Guadarrama tunnel project driven in mostly granites and gneisses, that cutter-head face-armour also had to be replaced every 4 to 5 km, as at Pinglin. Many smaller delays and large delays like those illustrated in Figures 23 and 24, contribute to T and therefore to a steeper (-) m deceleration gradient than ever expected by designers, who are usually offering constant m/month tunneling. TBM are seldom so simple, and it is time to included probable fault-delays in prognoses.

Even the world's most experienced TBM contractor (and manufacturer of TBM) can get stuck in faulted rock, also with double-shield TBM and advanced hexagonal PC-elements. Figure 25 illustrates a complicated situation in faulted marls and sandstones described in [20]. With the benefit of hind-sight, note the adverse situation created by withdrawing the TBM (from ch.2241 to ch.2230). This will have released the stress on the fault, effectively converting a 'confined V_P' fault-character of say 4 km/s, into a loosened 'unconfined V_P' fault-character of say 2 km/s. A much longer delay and the need for a large-volume post-grouting/concreting was the result.

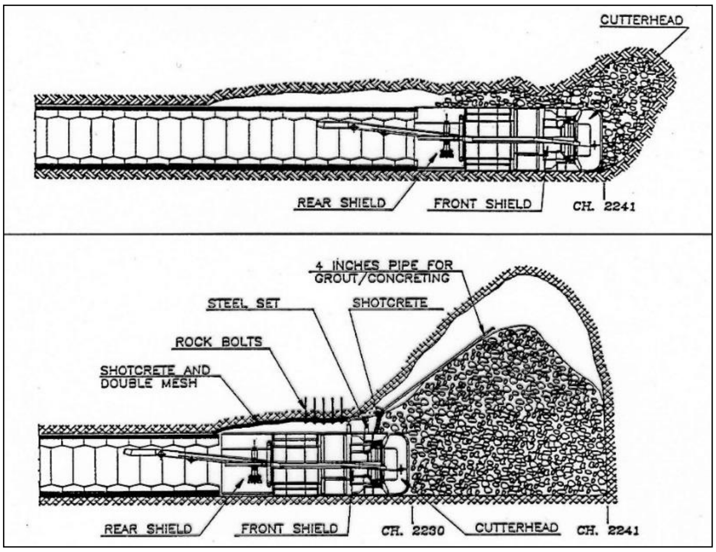


Figure 25. An experienced TBM contractor made an unexpected withdrawal of the TBM in order to treat a faulted zone which had stopped the TBM. (See ch. 2241 in both drawings). The resulting unloading seems to have caused deterioration of 'properties', and an undesirable worsening of the situation. From [20].

In relation to the 'velocity-confinement' trends seen in Figure 26, it can be seen that a stress-confined fault met at depth by a TBM, may be unloaded too much and revert to much more difficult behavior, as if the fault was encountered nearer the surface. (As illustration: follow a constant low Q_c-rock mass quality 'iso-Q' up towards the surface – the equivalent of unloading.) There are experiences of tunnel-seismic 'illuminating' reflectors well ahead of the face, with known reduced velocities such as to 4.0 km/s compared to higher velocities in the surroundings. Yet even when the contractor is prepared, tunnel collapse occurs. This is probably due to the same undesirable but difficult-to-avoid stress release. Avoiding spending one or two days pre-grouting, brings with it the risk of a much, much longer TBM stand-still.

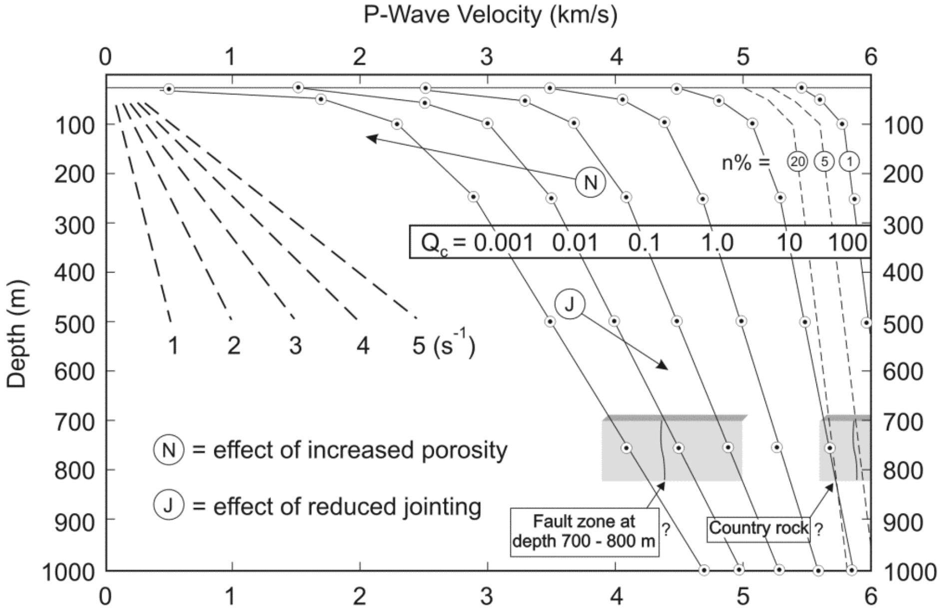


Figure 26. If a highly confined fault zone is remotely sensed ahead of a TBM, its deceptively high P-wave velocity will nevertheless be compromised, when the TBM starts to try to penetrate the zone. Difficult-to-avoid loosening will 'lift' the fault to a near-surface lower rock mass character, with V_P maybe reduced to 2 km/s. See [21].

Figure 25 is an unnecessarily good example of the possible consequences of loosening. Concerning the sloping dotted lines in Figure 26, note that (s^{-1}) is the unit of velocity gradient, derived from km/s per km. Velocity gradient may be very large close to poor quality weathered rock, hence the severe consequences of allowing loosening. From [21].

9. TBM design aspects for tackling weakness zones

Some seemingly obvious points about TBM design for more successful penetration of faults and serious weakness zones can be grouped in the following categories.

9.1 Cutter exposure.

The cutters should not be 'fully exposed' as this invites blockage when blocks of hard but faulted rock start to be released, for instance due to too high ratios of Jn/Jr (number of joint sets and joint roughness) combined with water pressure and erosion of fines. When this ratio Jn/Jr ≥ 6, overbreak and possible over-excavation in front of the cutter-head can occur. (This is illustrated later in Figures 30 and 31).

9.2 Cutter 'protection'

The provision of armour plating across the face of the cutter-head is a good way to prevent seizure due to block-fall wedging. However, there is a price to pay which may

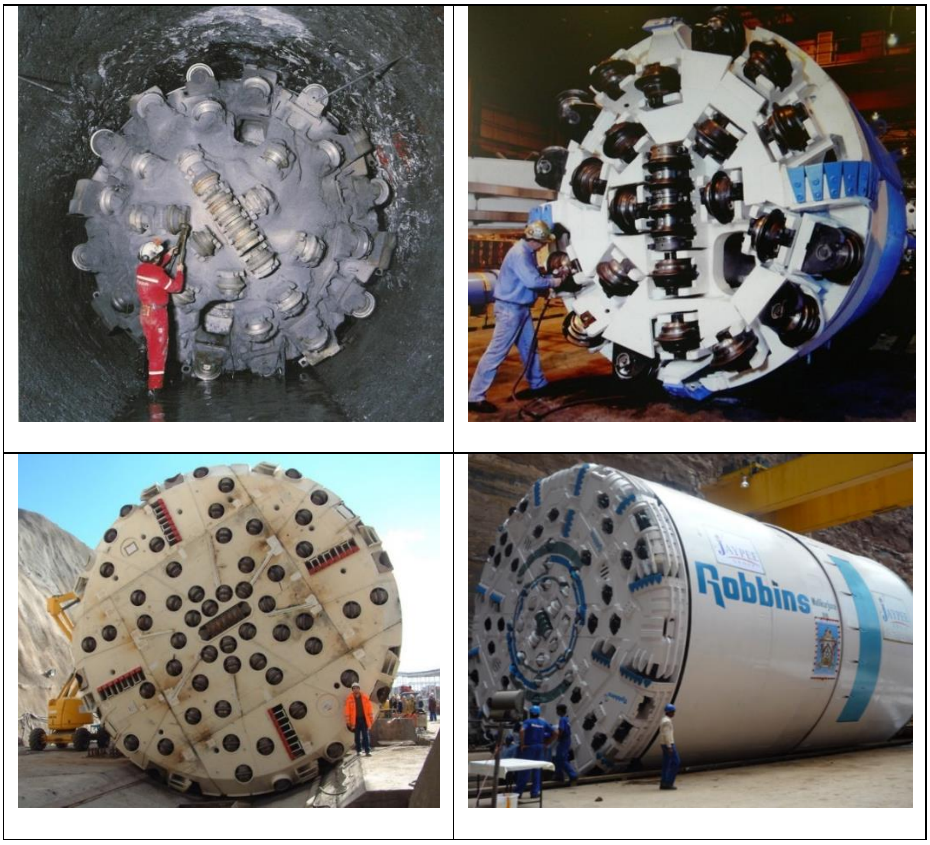


Figure 27. The upper two photographs are of open (and very cutter-exposed) TBM, showing remarkable similarity in relation to cutter layout, in view of their 35 years difference in dates (#1 mid-seventies: Slemmestad, Oslo, #2 mid-tens: Canada). Performance of both was generally good: one in shales and nodular limestones and igneous dykes, the other in granites. However, stoppage in a fault zone was a 'game-changer' (protracted litigation) in the case of the granites. The well-protected cutters in the lower photographs of double-shield machines (#3 Guadarrama, #4 Robbins advertising) are much less likely to be blocked in loosening fault zones.

be experienced when driving long tunnels in hard abrasive rocks: the armour may need in-tunnel replacement at 4 to 5 km intervals. This is obviously not an 'over-night' repair like multiple-cutter change, and requires workers, welders, and lifting-gear access ahead-of-the-cutter-head, if the TBM can be stopped in a stable and preferably dry zone. T is always running, so U reduces.

9.3 Double-shield TBM

Double-shield TBM may in general have increased utilization U, meaning less steeply inclined deceleration (-) m. They are expected to keep advancing even when grippers

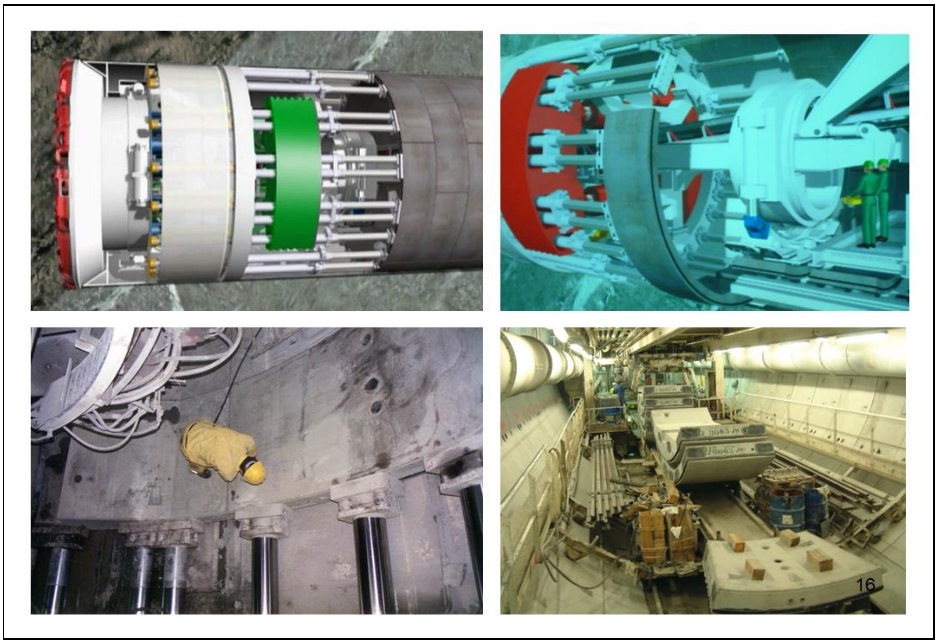


Figure 28. Double-shield animation pictures from Herrenknecht, showing push-off-liner when not using gripper (green) and PC-element ring assembly when thrusting off grippers (red). The two lower photographs show left: thrust off liner (or gripper re-set) and right: PC-element transfer in a northern end Guadarrama high-speed rail tunnel in Spain, near Segovia.

cannot be used in weakness zones due to over-break / over-excavation. Continued advance is then achieved by push-off-liner capabilities, as shown in Figure 28 from a Herrenknecht animation. The photographs are from the Guadarrama Tunnels in Spain. Figure 29 illustrates a double-shield application in a hydropower headrace tunnel, where PC-elements (and therfore push-off-liner capabilities) could be utilized in thirteen specific weakness zones and faults.

The double-shield project illustrated in Figure 29 was used to drive 10 km of a headrace tunnel in Ecuador. It was viewed when we were inspecting it in order to suggest additional bolting. Because the rock mass was mostly massive schist, much of the tunnel could be left unlined. Therefore the PC-element lining had been used only in thirteen specific stretches of bad ground, where the advantages of 'ready-made' support and push-off-liner thrust could be fully utilized when no gripper operation was possible. A serious fault zone nevertheless stopped the machine for several months in the most challenging of the thirteen locations.

In relation to the use of 'nominally unlined' headrace tunnels for economic hydropower, it should be noted that wedges and small blocks that had fallen from some locations in the mostly unlined kilometers were not transported, even by 2.5 m/s water flows in a smooth TBM-driven tunnel. The so-called 'rock trap' just upstream of the pressure shaft, contained only sand and silt and some floating pumice 'pebbles' from an upstream lake. The 'zero velocity' boundary layer ensures transport of nothing larger than rounded, few millimeter size particles. The hydraulic boundary layer phenomenon therefore indirectly ensures extra cheap renewable power in 'nominally unlined' tunnels.

Figure 29. A double shield TBM used to drive a 10 km long headrace tunnel in Ecuador, observed during inspection of stability and remedial bolting needs, when emptied for the second time. (Photo: Dr. Nghia Trinh).

9.4 Pre-injection for improving stand-up time

When a rock mass has insufficient stand-up time due to faulting, rock can start to over-break and the tunnel may start to be over-excavated ahead of and to the side of the TBM. The writer has witnessed this several times in different countries (Italy, Kashmir, Chile, Taiwan). An 8 m diameter tunnel can become 11 or 12 m locally, making grippers inoperable until a large void has been filled with concrete or hundreds of sand-cement bags (solution depending on locality). Pre-injection cannot be effectively used if ring-mounting equipment has to be dismantled, as if pre-injection was 'the last resort'. It should always be available. Figures 30 and 31 illustrate some minor (2 to 3 meter high) void formations and post-treatment needs.

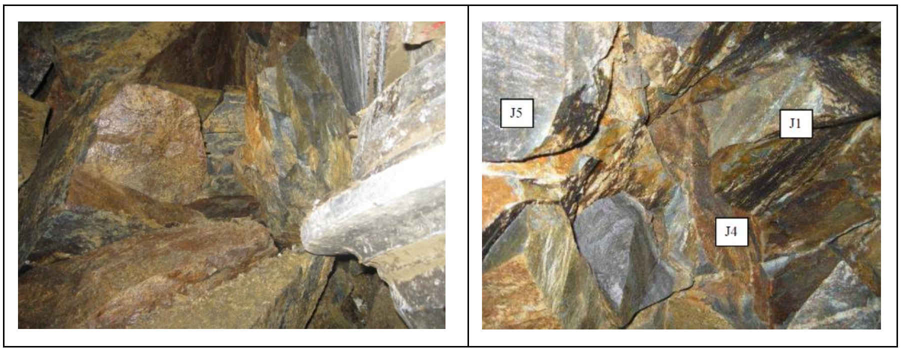


Figure 30. Void formation ahead of a double-shield TBM, due to adverse ratios of Jn/Jr, and no pre-injection.

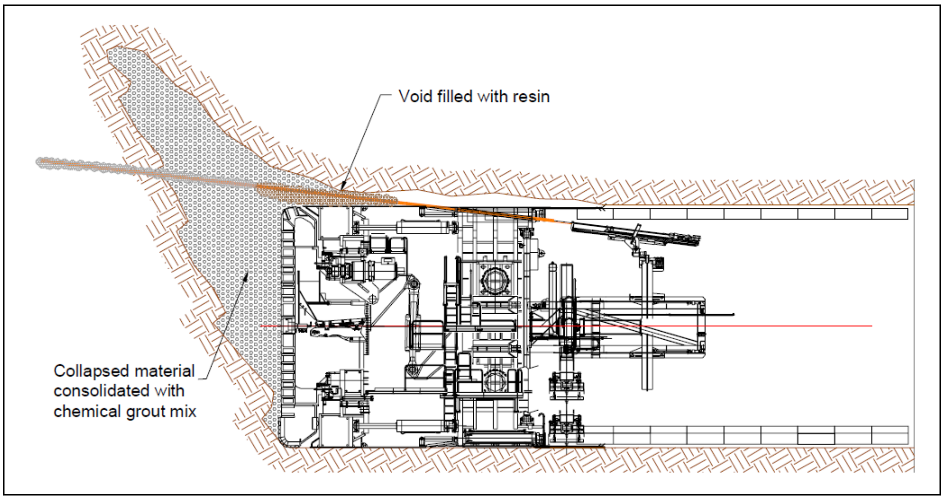


Figure 31. Suggested solution for void formation: an after-the-event measure that is actually too late, as a few meters per day may be the limits of advance in a zone of over-excavation that might continuue for weeks.

In the situation depicted in Figure 30, there were at least four joint/fracture directions, and the joint /fracture surfaces were sometimes smooth-undulating and slickensided, so Jn/Jr could be as high as 15/1.5. Over-excavation due to unstable ground is a phenomenon that loads conveyor belts with more material than would be consistent with tunnel advance. It can be detected by laser, or by real-time weighing and automatic calculation in relation to the weight expected from measured PR, assuming that only a perfect cylinder of rock is excavated.

Note that a tunnel fire can be caused if too large volumes of chemical grout mix are needed for void filling. 'Waiting for the smoke' (to clear), is unexpectedly different from 'waiting for the train' on a pie-diagram. The problem with this TBM was that ring-mounting equipment had to be dismantled before pre-injection drilling could be performed, clearly not the ideal choice of priority if faulted rock is expected. How to do both (build rings and pre-inject) when both were needed was not satisfactorily adressed, so tunnelling was delayed unnecessarily.

9.5 Pre-injection for water control in shallow tunnels

Pre-injection must sometimes be used to ensure that water does not flow uncontrolled into the face and also into the first 5 to 15 m of unlined tunnel, in the area of the single- or double-shielded TBM where impervious (gasketted?) tunnel linings are still 'pending'. The absence of pre-injection could allow a large volume of inflow if one was also advancing more slowly in a faulted area (the –*m* effect).

If this temporary lack of water control is 'planned' since not solved by pre-injection, and if the tunnel is relatively shallow (say 20 to 200 m) and if the tunnel is passing near (< ½ km) from built-up areas founded on clay, then groundwater pressure drawdown must be anticipated, with potential for settlement damage. Bolted and gasketted PC-elements may be questionable long-term (100 years) solutions for ensuring no inflow and permanently dry tunnels. This method has not yet been sufficiently tested, while

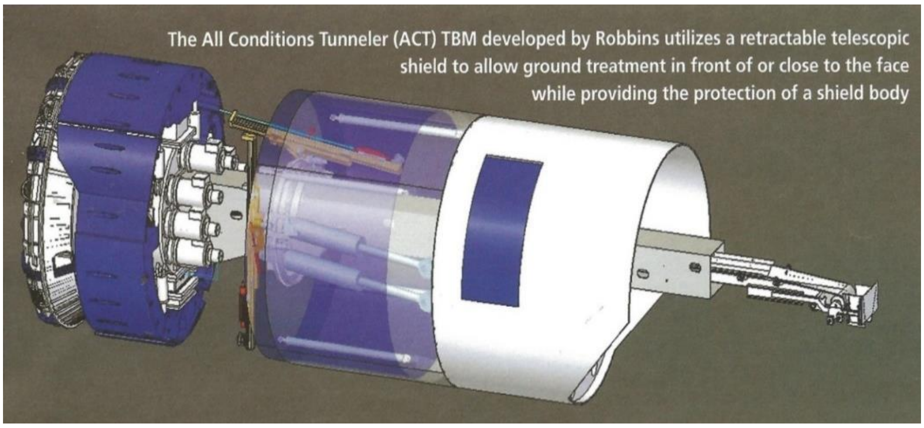


Figure 32. One stage closer to the ideal TBM (Robbins, [22]) with full acknowledgement of the possible need of pre-injection with minimum delay. Note recesses for drill-rods in the front shield.

(pre-) grouting of rock masses has a much longer track record, in a variety of contexts. Post-grouting in a 'completed' tunnel is famously difficult: a well known Norwegian experience with 15 km of unexplored tunnel (Gardamobanen) needing post-injection, after penetrating below two lakes in a rift valley, should be a reminder of this.

The need for pre-treatment of rock masses ahead of TBM seems now to be acknowledged by some TBM manufacturers. It seems finally to be accepted that rock masses (and hydro-geologies) can exceed the capabilities of 'standard' TBM. Burials and stand-stills have forced this acknowledgement, but it has taken the costly consequences of many decades of stoic optimism, under the sometimes costly motto: 'because the tunnel is long we chose TBM'. This decision has enhanced risk of delays more than most other decisions in tunnelling history.

9.6 Pre-injection for water control in deep tunnels

Pre-injection may also be needed in response to probe-drilling evidence that a wet, high-pressure zone is being approached in deeper tunnels. If the TBM equivalent of 'MWD' (measurement while drilling) also suggests that the rock ahead is heavily jointed, high-pressure injection may be just the measure needed to prevent the very adverse loosening that may occur when a TBM enters such a zone and slows down or stops. The effective 'quality' of a fault zone is reduced when it becomes unconfined: permeability is inevitably increased, and if erosion of finer materials also begins, the long delay may be just the beginning of a sequence of problems that have been known to end in TBM burial. Drill-and-blast 'from the other end' is not so infrequent a decision. It has been used many times, with cases known to the writer in China, Taiwan, Kashmir, Italy etc. Drill-and-blast has even been used to complete a tunnel where two TBM were going to fail their planned meeting by the millenium of 2000. Thus the seriously proposed hybrid-from-the-beginning suggestion described in [23] and [24], meaning drill-and-blast combined with TBM, each where most appropriate.

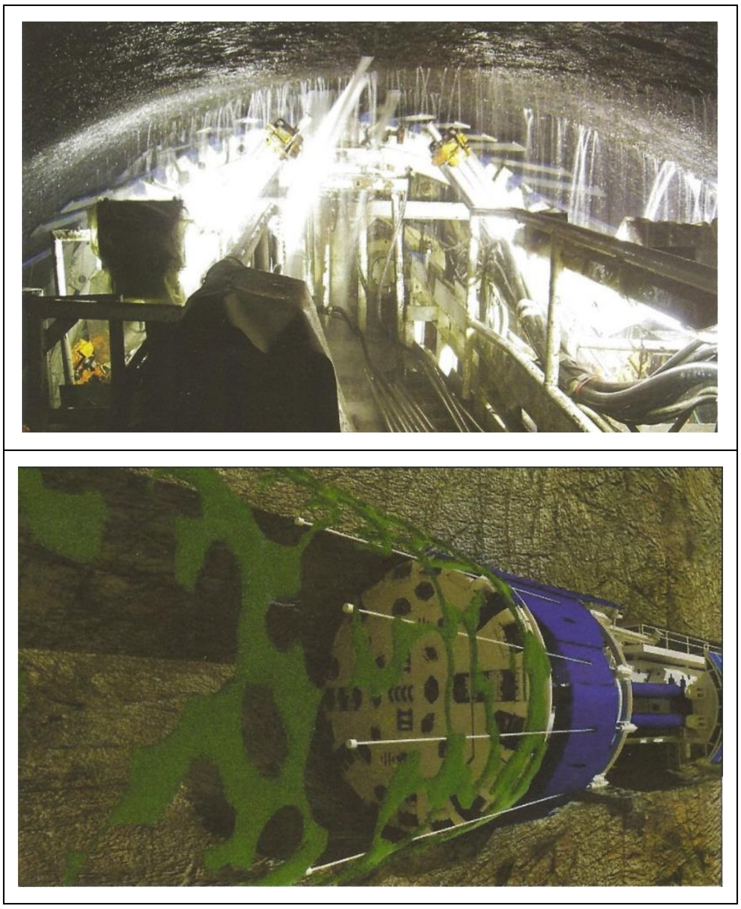


Figure 33. Robbins [22] illustrations of the need for pre-injection and its solution with the ACT All Conditions Tunneller illustrated in Figure 32.

Water is a remarkably adverse 'partner' in tunnelling, but its unwanted presence can be severely curtailed if timely high-pressure (5 to 10 MPa) pre-injection is an accepted measure. However pre-injection may be ineffective if too low injection pressures are used. At least 50% of the injection pressure at the pump has been lost, just 1m away from each injection borehole. When flow stops, pressure must not be maintained.The job is complete [18].

10. Care needed with automatic choice of TBM 'because the tunnel is so long'

There are many ways to compare TBM and drill-and-blast, such as using over-optimistic 'constant' TBM utilization (say 600 m/month) and conservative (say 40m/week) drill-and-blast progress. The reality will obviously not be so uniform. In Figure 32 an alternative method has been chosen. The D+B curves were derived from single-shell (B + Sfr) cycle-time measurements, performed by Grimstad at a 60m^2 road tunnel, and recorded over a wide range of Q-values (see [6]).

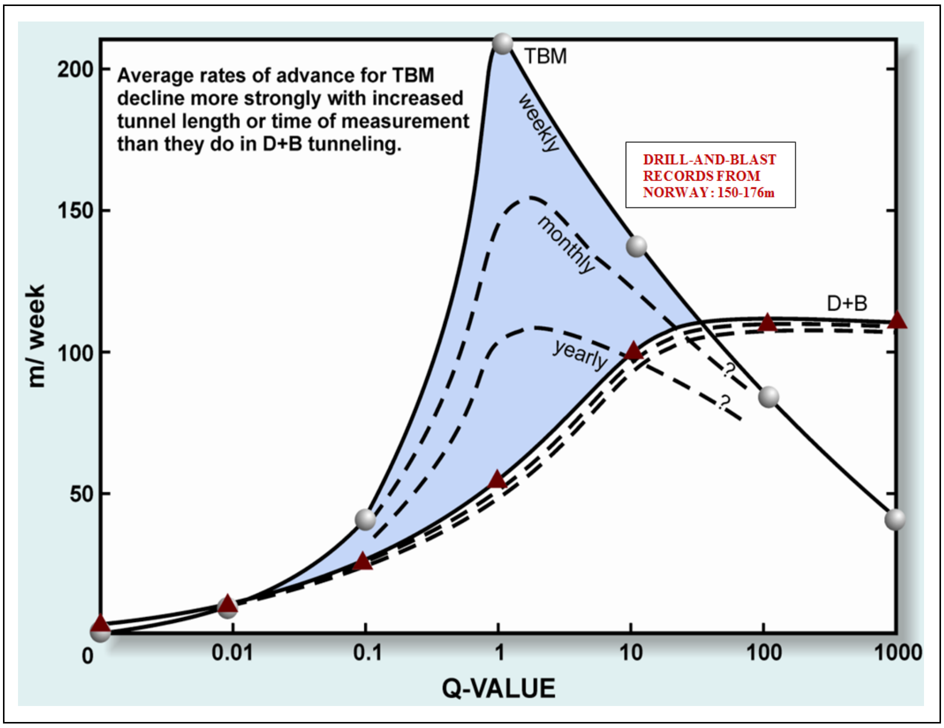


Figure 34. Comparison of TBM and drill-and-blast rates of advance, based on a moderate (>5 km in one year) TBM prognosis, and comparison with Norwegian drill-and-blast cycle-times versus Q-value measurements. Since publication of this figure in [1], there have been some remarkable drill-and-blast records. (See box).

The TBM prognoses, with the time-dependent utilization discussed earlier, was based on the Q-value dependent (-) m values plotted in Figure 19. Application of cutter thrusts was appropriate to the different rock masses. Selection of moderate parameter values allowed the approximation $Q \approx Q_{TBM}$. As may be noted in Figure 34, in one year of tunnelling, the predicted mean weekly rate has dropped to about 100 m/week, from more than 200 m/week if the TBM prognosis was on this optimistic short-term basis. As can be imagined, as the TBM tunnel gets longer, and time exceeds 1 year and perhaps even 2 years, more central rock mass qualities will be needed for continued TBM superiority. The more 'extreme-value' qualities will usually favour drill-and-blast.

So the longer the tunnel the more the need for central (well jointed but not faulted) rock qualities if the TBM is going to be faster than drill-and-blast. Q-values consistently higher than 100 suggest drill-and-blast superiority, bearing in mind recent records of 150, 165 and 176 m in a 7 x 24 week (high up in the right-hand top quadrant of the figure. LNS has a mean 104 m/wk for a 5.8 km long drill-and-blasted mine-access tunnel in coal-measure rocks, with Q probably mostly 1 to 10, but sometimes 0.1 to 1 needing more support.

Whether to choose TBM or drill-and-blast, or a hybrid solution using both, should be based on an honest (not over-optimistic, nor over-pessimistic) assessment of the rock masses likely to be penetrated. In Figure 35, hypothetical 'Q-statistics' have been assembled for a 5 km long tunnel (hardly long enough to choose TBM) and for a 25 km long tunnel with similar 'geology' but somewhat deeper cover. Sampling theory and

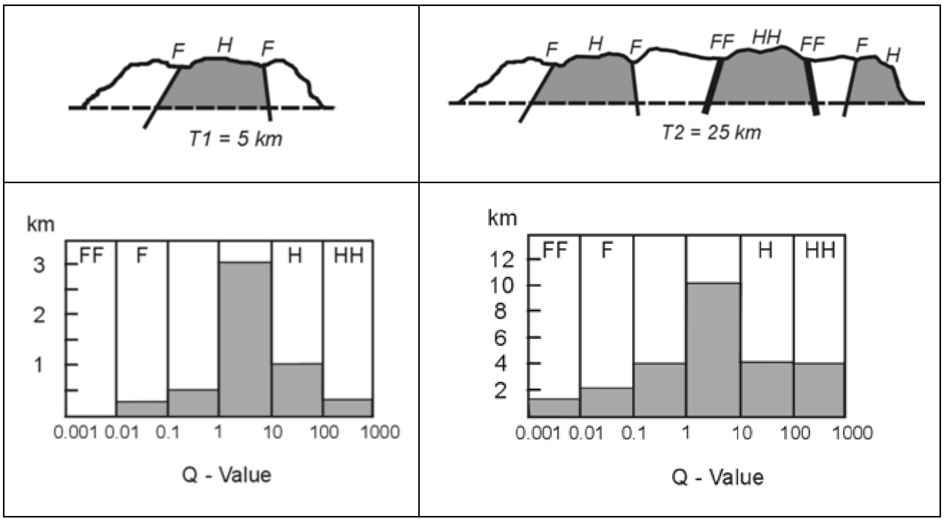


Figure 35. Choosing TBM 'because the tunnel is so long' invites the liklihood of more 'tail distributions' of rock quality, rock hardness, fault-zone severity, rock stress etc. Here, two hypothetical tunnels of 5 km and 25 km length are compared, using feasible distributions of Q-values. Note the increased 'tails' for the long tunnel.

logic would suggest more 'extreme value' structural geology, hydrogeology and rock strength for the longer tunnel, and of course the likelihood of higher stress, and lower penetration rates, if cover is locally greater than in the shorter tunnel. In relation to the empiricism-based prognoses of Figure 34, more 'extreme value' conditions will not be ideal for TBM, especially if the tunnel is likely to take several years to complete [25].

It may be that a given distribution of UCS will be adversely 'intersected' by the distribution of expected maximum (tangential) rock stress, thereby guaranteeing some localized stress-fracturing and possible rock burst problems. High rock stresses generally present greater difficulties for TBM because of the maximising of tangential stress in the less disturbed tunnel wall.

When $\sigma_{\theta\ max} > 0.4$ UCS the onset of stress fracturing must be expected. In the Q-system, elevated values of SRF begin at this stress/strength ratio [26]. If high cover is planned, serious consideration of drill-and-blast tunnelling through such sections should be made, if access for intermediate ventilation can be made. This is one way to reduce risk, as a serious rock burst with TBM carries with it the risk of greater loss of life and much greater material damage than in the case of drill-and-blast, with traditionally far fewer personell and much less costly drill-jumbos or shotcreting robots.

11. An example of prognosis for open-gripper and double-shield TBM

This article related to TBM prognosis and risk due to faults will be concluded with a brief glimpse of a recent application of the Q_{TBM} method in prognoses for possible open-gripper or double-shield TBM for twin tunnels of 8.5 and 9.5 km length. At the time when the studies were performed these two machine-type options remained open.

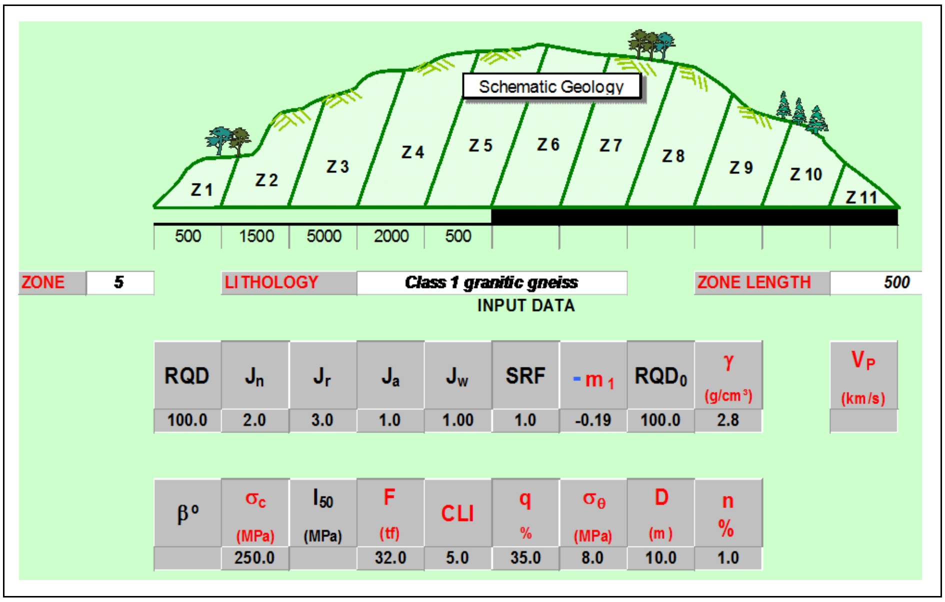


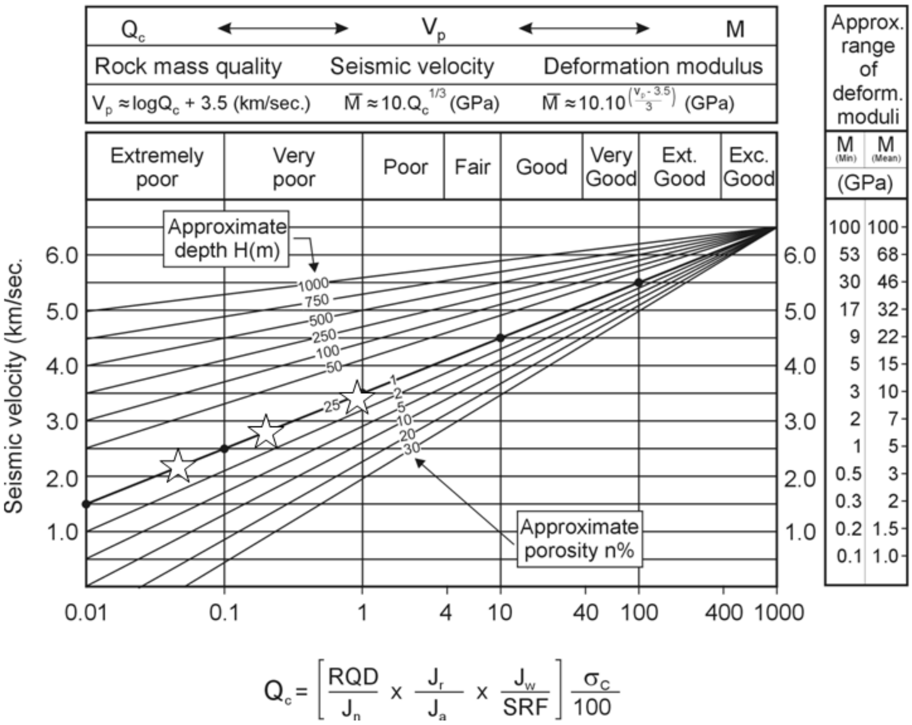
Figure 36. The Q_{TBM} prognosis model input data ‘keyboard’, which is entered with appropriate Q-parameter numbers for each zone (rock class) modelled. In the case illustrated, Class 1 was represented by 500m of massive granite. Slow progress is predicted in this case, despite the high assumed cutter force of 32 tnf.

The six Q-parameters were recorded on field-logging sheets, with five observations for each 10m of rock mass exposure, which were usually road-cuttings. The two planned tunnels totaling nearly 19 km length were logged in this way. For the shorter 8.5 km long tunnel, some 200 rock cuttings could be logged in the general neighbourhood of the planned tunnel, and logging was of course focused on the same granites and granitic gneisses, some of which were very hard and abrasive and in places also sparsely jointed. Class 1 had mean Q = 150, which is too high for a fast PR, and will likely be associated with high cutter wear.

Five rock classes were identified (Class 1 input data assumptions are represented in Figure 36). In areas where there were no road-cuttings and where there were wet areas or deeper valleys, logging of deviated core and seismic refraction analysis provided the Class 6, 7 and 8 Q-parameter input. P-wave velocities were occasionally as low as 2 km/s.

The three groups of weakness zones with their typical V_P velocities and Q-value interpretations are shown by three stars in Figure 37. The whole range of expected qualities, with probable differentiation of UCS (due to weathering), are indicated in approximate terms, in Figure 38.

The final illustration of the application of the Q_{TBM} prognosis method is illustrated in Figures 39 and 40. These show the large amount of Q-parameter statistics, presented in the form of Q-parameter histograms.



$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}\right]\frac{\sigma_c}{100}$$

Figure 37. Inter-relationships between P-wave velocity and Q_c (=Q x UCS/100). Note empirically based correction for depth of measurement (+ve) and porosity (-ve) using diagonal lines. The nominal 25 m depth 'shallow-refraction-seismic' line for hard, low porosity rock with UCS about 100 MPa, has the equation $V_P \approx \log_{10} Q + 3.5$ km/s. [27].

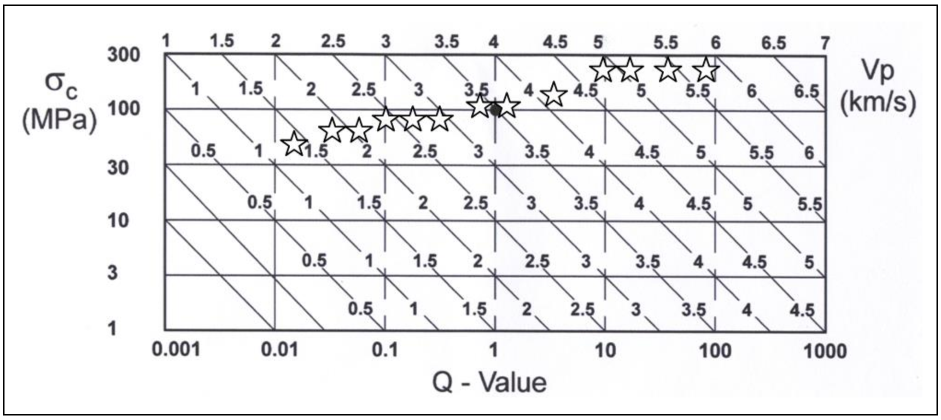


Figure 38. The broken line of 'stars' is designed to follow both the declining UCS and the reducing Q-values, as rock strength reduces, jointing increases, and the weakness zones are approached with lowest V_P. (The black circle is plotted to focus on the easily remembered Q = 1, V_P = 3.5 km/s, UCS = 100 MPa). [21].

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	5.0	*	0.50	/	1.0	=	**0.500**
Q (typical max)=	100	/	4.0	*	4.0	/	1.0	*	1.00	/	1.0	=	**100.0**
Q (mean value)=	98	/	8.4	*	1.7	/	1.3	*	0.75	/	1.0	=	**11.07**
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	0.66	/	1.0	=	**11.00**

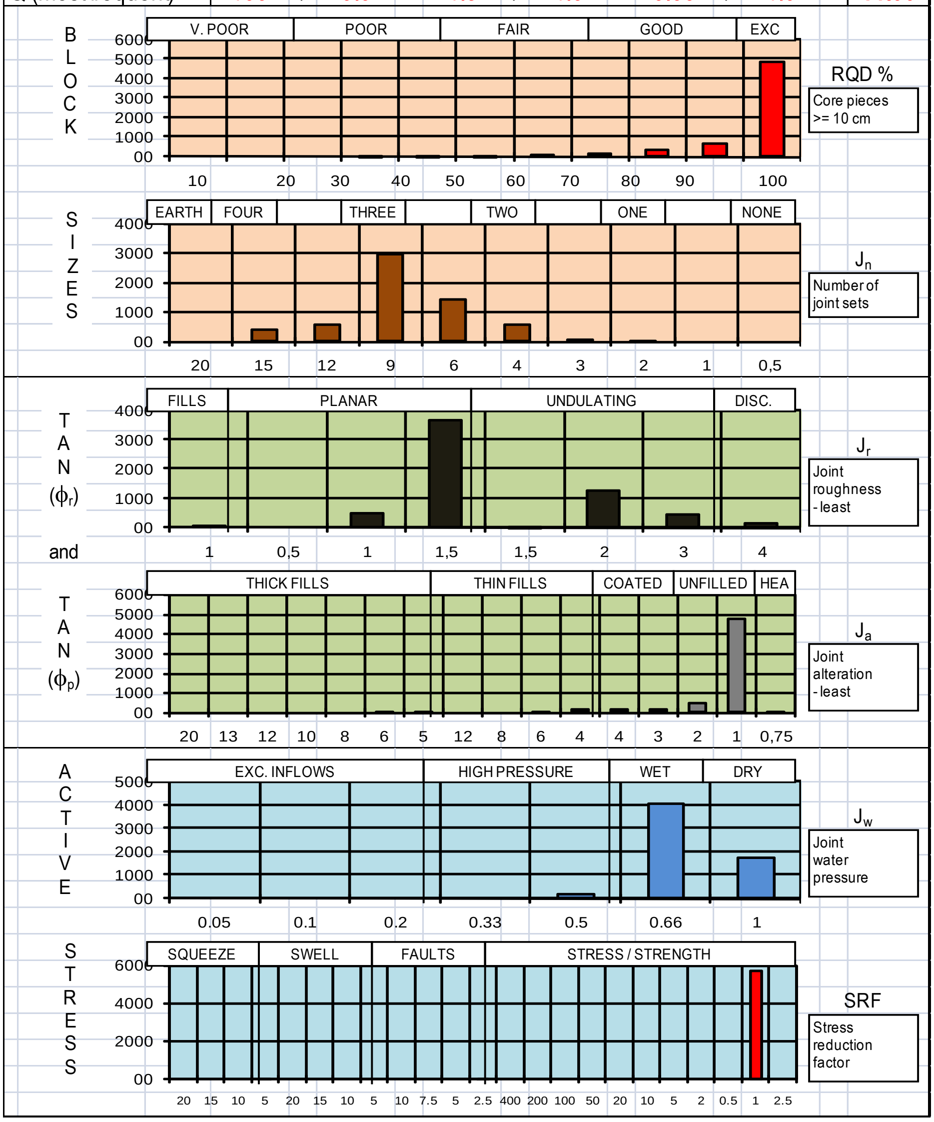


Figure 39. The Q-histogram logging result for the ‘best’ five rock classes expected in the southern tunnel. Note the large number of observations which were collected for this tunnel (and also for a second longer tunnel) during a few weeks of field work. Logging core from seven deviated boreholes drilled through low-velocity weakness zones are the source of the third set of prognoses shown in Figure 40, indicating that weakness zones might collectively delay the TBM by three months.

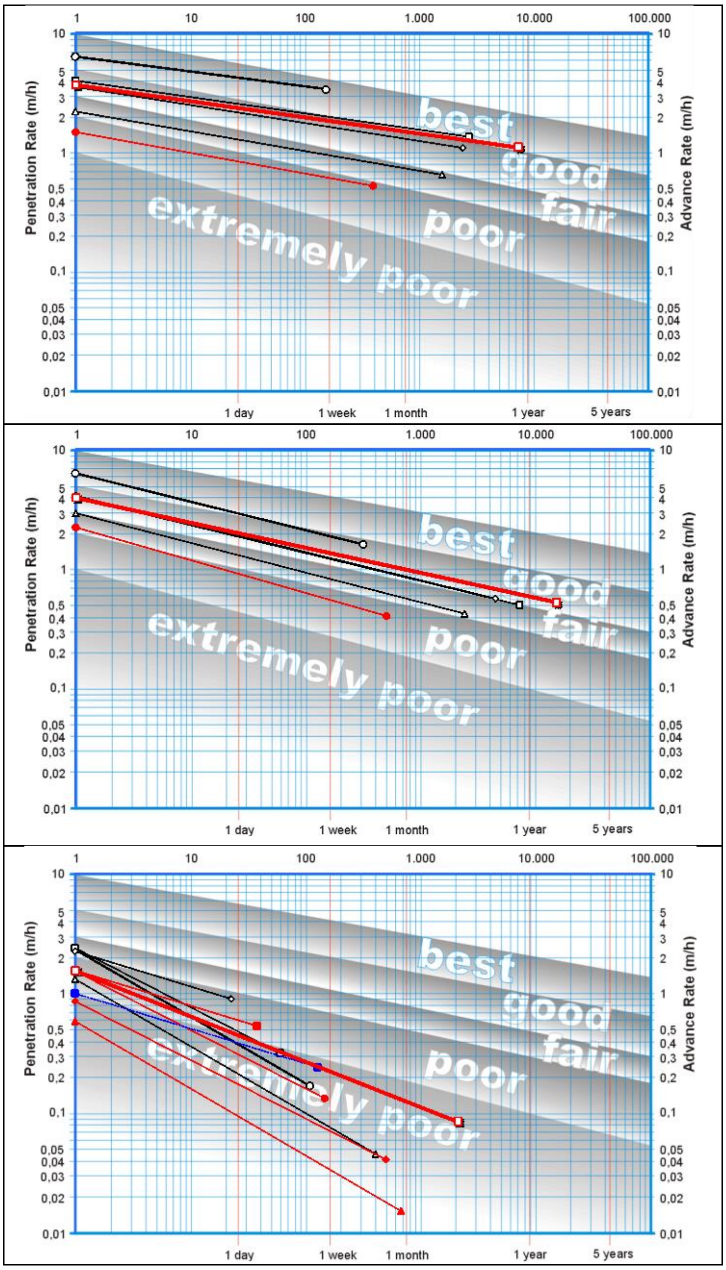


Figure 40. The results of Q_{TBM} prognosis for the 8.5 km long tunnel, made in three parts: Top: double-shield with PC-element liner, showing reduced gradient (-) m due to the assumed efficiencies with 'push-off-liner' capabilities for advance in weakness zones. This therefore indicates the fastest result of 10 months. Centre: open-gripper, presently without the 'delaying' effect of selective pre-injection, indicating a longer 21 months. Bottom: a selection of weakness zones and faults, also not pre-injected as first modelled, taking an additional 3 months. In each case the thickest red line is the predicted weighted-mean performance, with weighted mean PR (left-end) and weighted mean AR (right-end).

12. Conclusions

1. It is misleading to quote a single utilization % for a given TBM project, and worse still to not specify a time interval. It is also misleading to assume that a given tunnel can be driven at a consistent average, say 400 m/month. The advance rate is not a constant in time. Numerous open-gripper case records, and numerous world record results consistently show deceleration with time and tunnel length, if all of time T is included, considering 7 x 24 x 52 hours per year.

2. Deceleration is a natural process that should be a part of realistic TBM prognosis, in preference to denial of its existence. TBM may still be performing very well, despite the deceleration trend. But they get closer to the best drill-and-blast, in long tunnels.

3. TBM prognosis requires a mix of rock mass description and rock-cutter interaction. So the number of joint sets, their character, the rock UCS, the abrasivity, the quartz content, and the average cutter force, are fundamental requirements for realistic prognosis. In faulted rock with low Q-value, the deceleration is faster, and utilization is often compromised.

4. A very important component of actual advance rate is the penetration rate. However AR and PR tend to diverge where rock strength is low or where a lot of tunnel support is needed. With double-shield TBM and push-off-liner capabilities, and continuous PC-element lining (if selected), the advance rate is expected to be closer to the penetration rate. If over-excavation (void formation) and ring-building is not compromised, this expectation can be realized. In the case of massive, hard abrasive rock with frequent cutter-change, especially if the tunnel is deep, PR and AR will both be adversely affected.

5. To avoid over-excavation, compromised ring-building, and unwanted inflows before the liner (and gaskets) are in place, it is necessary to employ high-pressure pre-injection, as if in a drill-and-blast operation, with fast-drilling hydraulic jumbos. This should be available on a continuous basis, and not need disassembly of ring-building equipment. Both are needed as separated facilities. Probe-drilling during the maintenance shift is also a good way to reduce risk.

6. There are significant numbers of TBM projects that end up with the difficult decision of whether to complete the project by drill-and-blast from the other end. 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. Intermediate access for ventilation is of course an advantage, but stiff-tube negative-pressure ventilation is a way to get round this, and removes blast gasses fastest.

7. 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.

8. TBM tunnelling and drill-and-blast tunnelling give quite different performance in hard, massive abrasive rock masses. TBM also exhibit adverse behaviour at the lowest end of the rock quality spectrum, in water- and clay-bearing fault zones. Since TBM gradually decelerate with time and tunnel length, even when breaking records, it is found that central rock qualities are needed for TBM to consistently out-perform drill-and-blast.

9. TBM that are operating in mostly favourable conditions, may record remarkable progress, and are therefore an excellent investment for part or all of many tunneling projects where multiple tunnel cross-sections are not required.

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