Fast or slow progress with TBM in ideal or faulted conditions

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ABSTRACT: Tunnel lengths of 5km, perhaps 10km, and even a world-record equaling 15km can be driven *in one year* by TBM. In contrast, the very best drill-and-blast record so far is 5.8km in 54 weeks, and usually it is closer to 50m in a week, rather than the 100m per week achieved by just a handful of contractors worldwide, in some portions of their drill-and-blast projects. A factor with TBM tunneling that does not seem to have been widely acknowledged, or used in planning is that there is a general *deceleration* as the tunnel gets longer. This is seen in open-gripper case records and in efficient double-shield, in each case following speed-up in the 'learning curve' period. Perhaps surprisingly, the same trends of *deceleration* are seen in the current world record TBM performances, with diameters all the way from 3m and beyond 12m. The *deceleration* from PR to best day, week, month, and 3-months is seen when total time is used, and advance rate is expressed in m/hr. It is found that the steepest deceleration occurs when the rock mass quality Q is low. This is confirmed by specific case records from Turkey. The time delay is quantifiable. Sometimes hybrid TBM *and* D&B is best.

1 INTRODUCTION

The authors have experiences from both fast and slow TBM excavations, and cases where drill-and-blast 'rescue' was required, although not originally planned. A longer tunnel is automatically a 'larger sample' of the rock mass, with more extremes likely to be encountered. Hard massive rock, faulted clay-bearing rock with water pressure, and high-mountain cover are three extremes that individually or collectively can cause serious delays. The longer, deeper tunnel is also unlikely to have been investigated as thoroughly, so surprises have almost to be expected.

2 SOME EXAMPLES FROM TURKEY

The geology of Turkey is complex with weak rocks and fault zones that tremendously decrease the performance of TBM. Strong deceleration and delays are seen in specific zones which often are related to low or extremely low Q-values, representing the inverse of tunnelling quality. Conventional (drill-and-blast) tunnelling and mechanical excavation methods are sometimes used together in the same project, as the tunnel is getting longer. The three following examples show clearly how TBM performance and machine utilization time are affected by low Q values. The benefit of sometimes using hybrid (drill and blast and TBM excavation) tunnelling methods are demonstrated by practical experiences.

2.1 Uluabat Hydropower Tunnel

The excavation of the headrace tunnel started in June 2006, with a 5.05 m diameter EPB-TBM. The tunnel was eventually finished in March 2010. During the tunnel excavation, the TBM jammed 18 times in different places, due to the highly squeezing characteristics of the ground. Rescue galleries were opened next to the TBM to free the shield, and a total of 192 days were spent on these operations (Bilgin & Algan 2012). One of the galleries opened to rescue the TBM is seen in Figure 1. The tunnel route from chainages 11+465km to 7+750 km (3.7 km) and from 6+000 km to 1+792km (4.2 km), consisted of the Karakaya formation of Triassic-aged meta-detritics such as fine grained meta-claystone, meta-sandstone, schists etc. The tunnel route between chainage 7+750 and 6+000 km (1.75 km) consisted of the Akcakoyun formation of Jurasic-aged limestone with crystallized calcite fillings. Table 1 lists rescues galleries with chainage, Q values and a brief description of the zones where the TBM was trapped. An average daily advance rate of 8.6 m/day was achieved, including all stoppages such as TBM standstills and hand mining. The best daily and weekly advance rates were found to be 28.8 m and 198.4 m, respectively. The best monthly advance rate was 583.2 m in February 2007, as shown in Figure 2. The breakdown of general tunnelling activities is illustrated in Figure 3.

Figure 1. Gallery opened to rescue the trapped TBM.

Table 1. Squeezing zones and Q values in Uluabat Tunnel.

Gal. No	Chainage (km)	Q Values	Lithology
1	785	0.14	Meta sandstone, meta siltstone with clay matrix
2	1066	0.16	Meta sandstone, meta siltstone with clay matrix
3	2178	0.18	Graphitic schist, meta siltstone with clay matrix
4	2203	0.014	Wet meta siltstone, graphitic schist, meta claystone
5	2218	0.016	Wet meta siltstone, graphitic schist, meta claystone
6	2222	0.13	Meta detritics with clay matrix
7	2245	0.15	Meta detritics with clay matrix
8	2279	0.14	Meta detritics with clay matrix
9	2591	0.013	Meta sandstone, meta siltstone, graphitic schist
10	4440	0.14	Meta detritics with clay matrix
11	6205	0.18	Meta detritics with clay matrix
12	6331	0.13	Wet siltstone with graph. shist
13	6908	0.2	Meta detritics with clay matrix
14	6909	0.01	Graphitic shists-meta mudstone
15	6922	0.014	Graphitic shists-meta mudstone
16	7078	0.015	Graphitic shists-meta mudstone
17	7109	0.18	Metadetritics with clay matrix
18	7142	0.18	Metadetritics with clay matrix

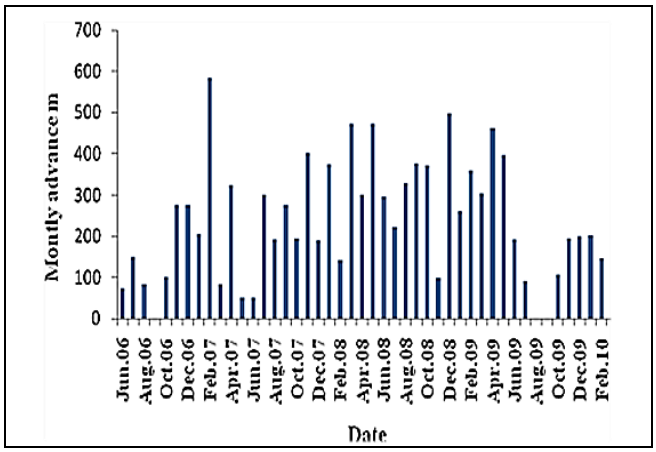

Figure 2. Monthly advance rates of TBM in Uluabat Tunnel.

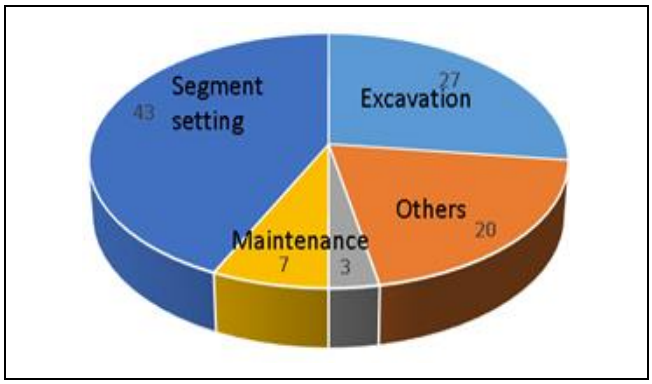

Figure 3. The breakdown of tunnelling activities in general for the Uluabat Tunnel are shown in this 'pie' diagram.

The purpose of Figure 4 is to show that Q values are one of the most important parameters in defining TBM performance in complex geology. The rock masses show squeezing characteristics for Q values below approx. 0.02, where the TBM is trapped. Thereafter, TBM machine utilization time increases steadily between Q values of 0.2 and 1.2, and stays nearly constant thereafter.

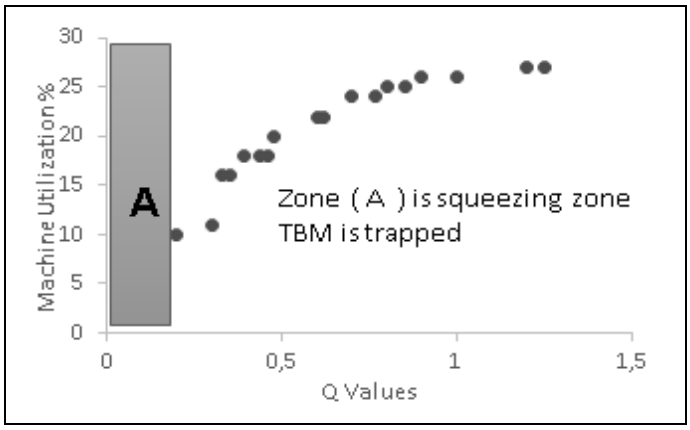

Figure 4. The variation of machine utilization with Q values in Uluabat Tunnel. This is supported by case records shown later.

2.2 Kargi Hydropower Tunnel

The Kargi Hydropower Project was developed by Kargi Kizilirmak Energy AS, a subsidiary of Statkraft Energy AS. The project is situated on the Kizilirmak River, downstream of the town of Osmancik, in Corum Province. The headrace tunnel has a length of 11.8 km. The geology consists of Eocene -aged volcanics, mainly agglomerate, andesite, basalt and tuff and 2500m of ophiolites and graphitic schist. A double shield TBM of 9.84 m diameter started excavating the 11.8 km long tunnel from the Northern end (Yurt et al 2014). Due to geological difficulties, the TBM was stuck 7 times, and galleries were opened in various different places, in order to free the cutterhead. In order to reach the predetermined job duration time, it was decided to open another tunnel from the inlet part of the tunnel line, using the drill-and-blast method.

The chainage of the galleries opened to rescue the trapped TBM and associated faults are given in Table 2. This table clearly shows that the TBM cutter-head blockages are associated with fault zones and low Q values, as noticed in the Uluabat Formation. However, the direct effect of Q values on machine utilization was not so apparent as in the previous example, since apart from the geological factors, machine modifications were also engineered. Increasing the cutter-head torque capability by more than 50%, increasing the thrust from the hydraulic cylinders, over-boring capabilities, shield lubrication, and probe drilling of up to **40m?** around and umbrella arch in 9 locations, were the main factors affecting the machine utilization time and low daily advance rates. Overall comparisons of TBM performance before and after modification are given in Table 3.

In most cases if the geological parameters are not in favor of TBM, the performance of conventional excavation with D&B become competitive with mechanical excavation. Table 4 shows that the overall performances of D&B and TBM excavation can be quite close when adding the time to mobilize and total excavation time, even though the TBM has excellent 'sprinting' ability and will always show superior *best* days, weeks and months (Bilgin 2015, Clark 2015, Home 2015).

Table 2. The chainage of the recovery galleries, Q values and associated faults.

Gal. No	Chainage (km)	Q Values	Affected by faults at chainage
1	11+756	0.016	Major East Anatolian Fault at 11+874
2	10+796	0.02	10+900
3	10+671	0.18	not given
4	10+478	0.014	10+478
5	10+445	0.18	10+478
6	10+295	0.012	10+295
7	9+712	0.016	9+712

Table 3. Overall comparisons of TBM performance before and after modification, in Kargi Tunnel.

	Before modification	After modification
Minimum (m /month)	35.7	14.3
Best (m /month)	329.4	723.2
Average (m /month)	154.4	407.7

Table 4. Overall performances of D&B and TBM excavation in Kargi Tunnel.

Performance	TBM	D&B
Best month (m/month)	723	282
Best day (m/day)	40	12
Average week (m/week)	**68?**	**38?**
Average month (m/month)	271	174
Time to mobilize (month)	16	4
Boring length (km)	7.8	4
Months to complete	28	23

2.3 Nurdagi Tunnel

This tunnel is for railway transportation and the project has twin tubes. The tunnel is situated in the South-East part of Turkey between the cities of Adana and Gaziantep next to the Nurdagi Village. Each tube has a length of 9750m. The excavation is planned to start from chainage 13+450km and to terminate in chainage 3+700km. The chainage from 13+450km to 12+400km consists of Karadag Limestone of Mesozoic age, which is affected by the East Anatolian Fault (EAF), which fractures the rock formation to a great extent. High water ingress is expected in this area. Karadag Limestone discharges the water at the toe of the mountain at the Nurdagi side. Several springs are seen along the EAF. Due to technical difficulties and the time necessary to mobilize the TBM, the first 550 m were currently opened by conventional tunneling methods, where Q values are generally less than 0.5. During this time the TBM arrived at the jobsite and will be ready to start excavating soon.

The above three examples from TBM projects in difficult grounds in Turkey clearly show that Q values are of primary importance in the characterization of the ground for an efficient use of TBM. The D&B method becomes competitive to TBM excavation where the tunnels are planned to be excavated where there are numerous fault zones. Low Q values are an indication of squeezing zones and low machine utilization times.

3 THE LAW OF DECELERATION

The Turkish cases described above confirm a trend which became clear when analyzing a large number of cases (140 cases representing 1,000 km of TBM tunnels), as reported in Barton, 2000. While the best and average performances were little related to Q-values, the 'unexpected events' causing delays, were always related with low Q-values. This of course was partly because mechanical failures like main bearing failures were not selected as case records. Delays due to bad rock conditions were prioritized.

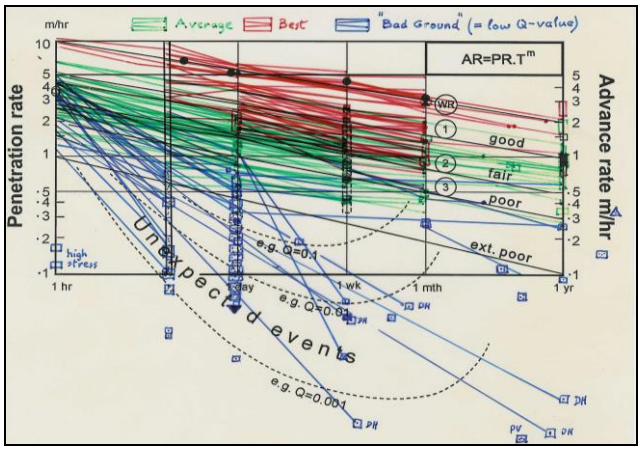

Figure 5. Approx.1,000 km of case records for PR, AR, T. This raw data is synthesized into 1+4+3 categories in Figure 6.

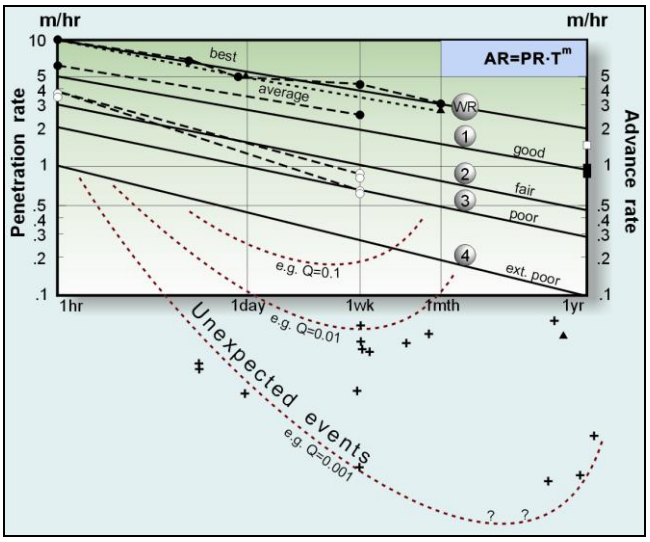

Figure 6 The raw data from case records shown in Figure 5 (red: best, green: average, blue: unexpectedly bad) are synthesized by these five lines (and three curves) of performance. They have increasing deceleration gradients (-m). Note the low Q-values associated with the curves/crosses of 'unexpected events'. The lowest three (see lower-right) needed D+B completion and the TBM are permanently buried. Barton, 2000.

Figure 6 shows a synthesis of the raw data given in Figure 5. The red-coloured lines include world records and best day, week, and month results, while the green-coloured lines with steeper gradient and lower PR and AR represent the average results. The blue-coloured curves and crosses labelled 'unexpected events' (which would be less unexpected if there was probe drilling) are shown in Figure 7 to be related to low Q-values. As can be seen, when Q-values are higher, the Q-value alone is not a good way to distinguish between slow or fast behavior. Nevertheless, if the Q-value is too high (e.g. >>100) and if the rock is hard and abrasive, both PR and AR are much reduced. TBM perform poorly 'at both ends' of the Q-scale, obviously for very different reasons: blocked cutterhead / low PR and too frequent cutter change. (Sometimes only 1 to 2m per cutter, meaning numerous ineffective cutters during 20 hours of progress, prior to the maintenance shift).

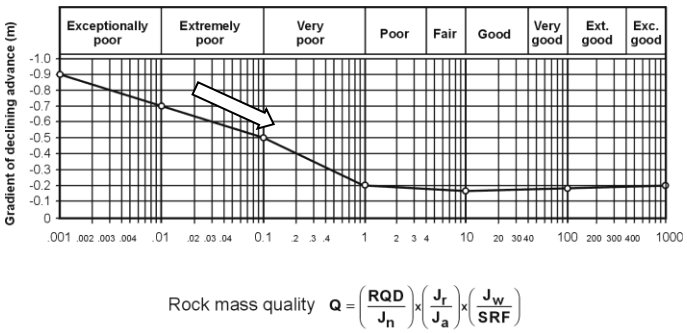

Figure 7. The different gradients of deceleration have increasingly negative (-m) values as Q reduces, meaning ever-more time-dependent utilization (U = T^m with T in total hours). When Q is low, and there is lack of drainage and lack of pre-injection, big delays must be expected. (e.g. Table 1).

Table 5. Gradients of deceleration (-m) meaning different degrees of utilization, according to the 'line of expected performance' in different geologic domains. Note: numerous (1,000km) of open-gripper gradients, but limited double-shield data, suggest halved gradients as the best result. In massive hard rock, double-shield may be slower than open-gripper.

PERFORMANCE Line # (refer to Figure 6)	DECELERATION Gradient *(-) m* *(units of LT^{-2})*
WR (world records)	-0.13 to -0.17
1, 2, (good, fair)	-0.17, -0.19
3, 4 (poor, extremely poor)	-0.21, -0.25
Q ≈ 0.1 (delays)	-0.5
Q ≈ 0.01 (big delays)	-0.7
Q ≈ 0.001 (stuck TBM)	-0.9
(trends from 145 cases)	*(Σ ≈ 1000 km, mostly open-gripper)*
DOUBLE-SHIELD at Guadarrama tunnels (2x Wirth, 2x Herrenknecht)	*-0.08 to -0.12 (best ≈ 50% of open-gripper) (4 x 14 km)*

Many of those involved with TBM may have already come to the conclusion that the gradients of deceleration shown in Figures 5 and 6 are because of the inevitable (pre-2000) use of case records. (The exception would be the ca. 2002-2005 case records of four double-shield TBM shown in Table 5). Interested readers may be using more optimistic prognoses on their own projects: one of these could be to suggest, for example, that '600m per month for most of project A' is expected. In other words no deceleration gradient. Before proceeding with this over-optimistic line of thought, Figure 7 should be studied. This was assembled in Barton, 2013 from an analysis of Robbins web-site-assembled TBM *world records*, as listed in 2013. For convenience and to better illustrate trends (such as the effect of TBM diameter), the records are grouped into three size ranges in Figure 8, and all the m/day, m/week, m/month records are converted to m/hr, where 24, 168 and 720 hours are the assumed totals.

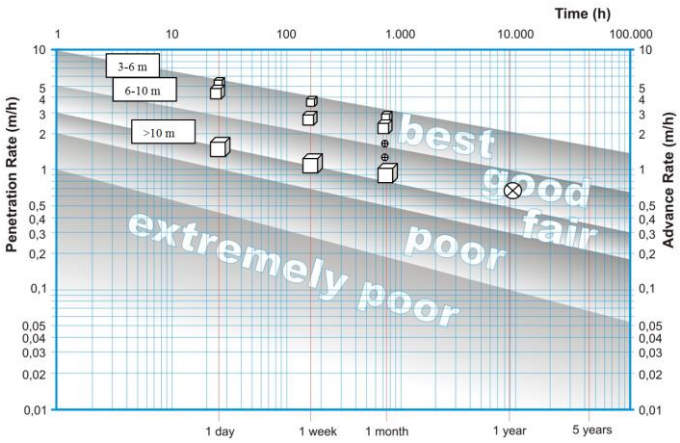

Figure 8. A synthesis of (mostly Robbins) TBM world records (as per 2013), grouped in three sizes (from top: 3-6m, 6-10m, >10m diameter). The largest circle-and-cross is the world record drill-and-blast by the Norwegian contractor LNS (5.8km in 54weeks).

The consistency of the deceleration trends in Figures 5, 6 and 8 (there are no horizontal sectors seen anywhere) might seem 'remarkable'. In fact what is remarkable is that this trend seems never to be admitted by TBM manufacturers or by most prognosis-makers. Nevertheless, it seems to be justified to refer to it as a not yet acknowledged 'law of deceleration'.

4 WHY FAULT ZONES DELAY TBM

This paper began with a description and documentation of fault-delayed TBM projects in Turkey. The first author also has experiences along these lines, to the extent that the TBM concerned had eventually to be replaced by drill-and-blast completion (in Italy, Kashmir, Taiwan, China). So we must ask: can such traumatic happenings be explained? The fifth equation listed below, which is simply derived from the following elementary sequence (1, 2 and 3) provides a convincing explanation, provided that the empirical (*a posteriori*) data (the crosses) in Figures 5 and 6 are accepted. They represent steep *(-)m* gradients. Low Q-values are the root cause of these events.

We need three basic equations:

1. $AR = PR \times U$ (all TBM must follow this)
2. $U = T^m$ (*decelerating advance rate* means time-dependent U, as in Figures 5, 6 and 8)
3. $T = L / AR$ (time for length L depends on AR, as indeed when walking, or crawling)

Therefore we have the following:

4. $T = L / (PR \times T^m)$ (from #1, #2 and #3)
5. $T = (L / PR)^{(1/(1+m))}$

This 5th equation is *very* important for TBM because *negative (-) m* values make the *1/(1+m)* component too large, so that time T gets too long (months or years). The practical solution, more easily written than performed, is to probe-drill and therefore be more prepared, and to drain the fault zone if the water is not too sediment-bearing. Otherwize high-pressure pre-injection with accelerated cement grouts and polyurethane might help to improve properties, and effectively 'slide' the *effective Q-value* in the direction of the arrow in Figure 7, towards improved Q-values. Figures 9, 10 and 11 show by means of modelling and TBM reality, why fault zones can be such traumatic, delaying features.

5 ARE LONG TUNNELS FASTER BY TBM?

Possibly driven more by ventilation considerations than by hydro-geologic (and TBM) 'common-sense' it is common to hear the argument: 'because the tunnel was so long we chose TBM'. This can be a sound choice, up to some tunnel length, but maybe

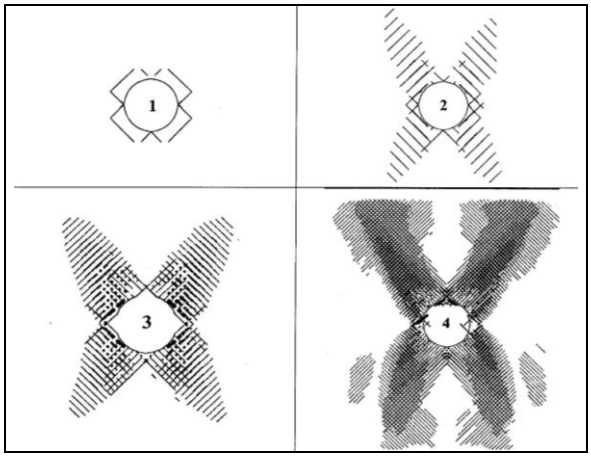

Figure 9. Simple UDEC-MC models with successively halved block sizes. The EDZ expands to an alarming degree. Imagine that a fault zone has similarly more crushed rock, with added clay, silt and high-pressure water. From Shen and Barton, 1997.

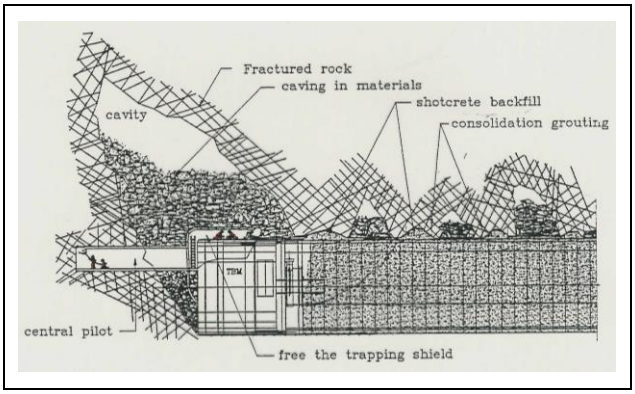

Figure 10. Graphic detailing of difficulties from Shen et al. 1999. All three TBM at Pinglin were eventually replaced by drill-and-blast, and there were many fatalities. There were too many fault zones, plus hard, abrasive, clay-coated meta-sandstones that were difficult to drill for pre-injection.

Figure 11. Pilot tunnel bypass at Pinglin, one of at least 13 needed to free the cutter-head. Photo: Dr. Chris Fong.

not beyond the comfort zone. The problem is the deceleration, which is hardly seen in drill-and-blast, but is widespread with TBM. As suggested in Figure 12, there is likely to be more unexplored ground and many more hydro-geologic extremes in the longer deeper tunnel. These may include wider fault zones, harder rock, and higher stress (so greater strength).

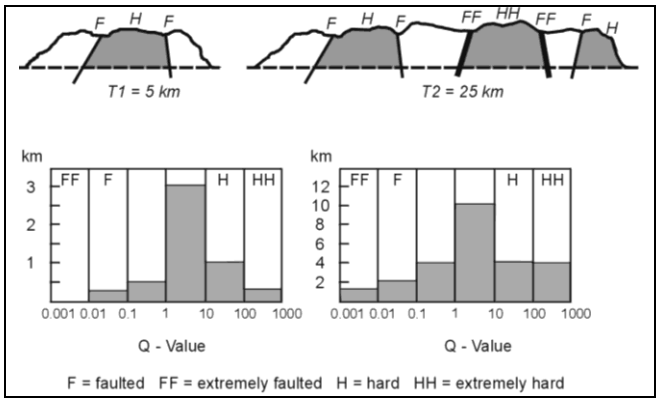

Figure 12. Left: A hypothetical well-investigated 5km with few hydro-geologic extremes, in contrast to a less well characterized 25km tunnel with some higher cover, and more extreme (FF-low, HH-massive) Q-values, both of which slow the TBM.

A direct comparison of a moderately slow (5 km in one year) TBM tunnel, and cycle-time-based estimates of m/week for drill-and-blast tunneling, each in relation to Q-values, is shown in Figure 13. This figure shows that 'central' rock mass qualities may be bored significantly faster by TBM until the tunnel length or time exceeds two or more years (in this example). The more extreme rock mass qualities (both high and low Q) will be faster by drill-and-blast. This is probably why a Chinese 'millenium' tunnel running behind schedule with two TBM was completed on time by D&B. Why not hybrid from the start? This could be expected to finish earlier.

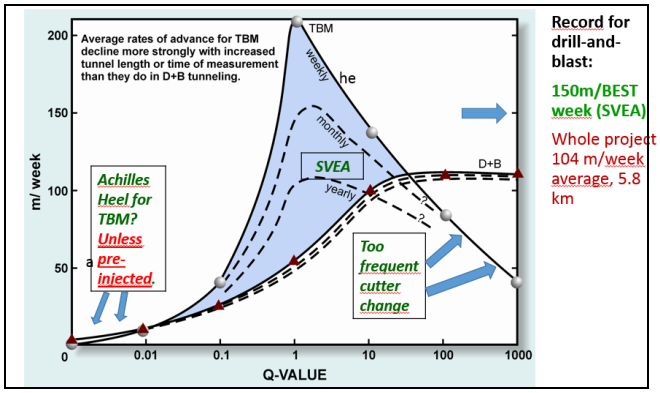

Figure 13. Cycle-time-based drill-and-blast in relation to Q, as recorded by Grimstad in Norway (priv. comm.) was converted to m/week for comparison with a moderate 100m/week TBM tunnel prognosis. In the right margin the fastest D&B tunnel (Svea mine access) is shown. (See circle-and-cross in Figure 8).

The 'FF' wide fault zones indicated in Figure 12, which in practice would probably result in valley access for intermediate adits, could suggest an early start with D&B on several fronts (at the 'north' end of the tunnel) while waiting for TBM delivery, which would be used for the better investigated 'southern' end of the tunnel, where less extremes were expected, where tunnel depth was moderate.

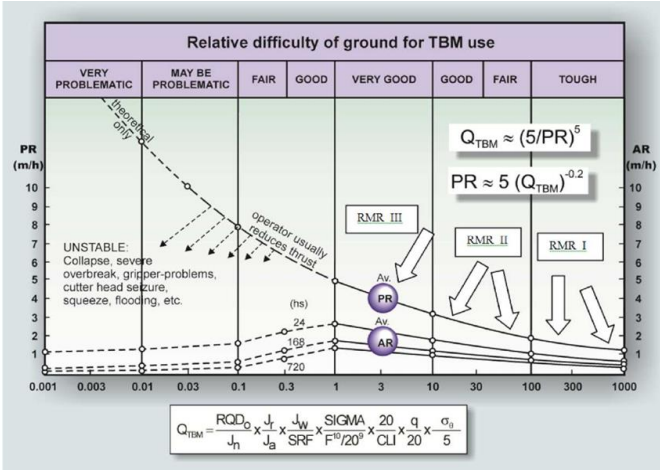

Figure 14. The Q_{TBM} prognosis method includes the all-important comparison of cutter force and rock mass strength, cutter life index, and quartz content. The latter, and high Q or RMR values can slow TBM seriously, in high cover areas.

6 CONCLUSIONS

Low Q-values in faulted rock are often the cause of slow TBM progress, as shown in Turkish case records, and in wide-reaching reviews of TBM performance. When a long tunnel is planned a hybrid approach from the start may be a cost-and-time saver.

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