APPLICATION OF THE Q-SYSTEM AND Q_{TBM} PROGNOSIS TO PREDICT TBM TUNNELLING POTENTIAL FOR THE PLANNED OSLO-SKI RAIL TUNNELS

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ABSTRACT

Application of statistics-based rock mass characterization of more than 300 rock exposures totalling some 6 km is described. This was followed by utilization in TBM prognoses for the planned route of a major tunnelling project. Jernbaneverket's planned new high speed Oslo-Ski Follobanen can have up to 19 km of tunnel length, depending on the final decision on alignment. In addition to the logging of the numerous surface exposures, JBV's drillcore logging and GeoPhysix's seismic refraction measurements were also utilised, the latter both focussed on data acquisition for the crossings of assumed weakness zones. The data collection, principally using the Q-system histogram method, was the first stage of input to the Q_{TBM} prognosis modelling of potential penetration rate PR and actual advance rate AR for the two twin tunnels that are likely to be driven by TBM. Laboratory test data from SINTEF concerning strength and abrasion parameters for the mostly granitic/tonalitic gneiss, and also for the quartz- and feldspar-rich gneisses of sedimentary origin, were combined with the Q-data statistics to give estimates of potential tunnelling speeds, assuming five rock mass classes and three weakness zone classes. Characterization of the weakness zones was based on the core logging data and refraction seismic measurements. Prognoses were compared for hard rock open gripper TBM and for double-shield TBM, where robust PC element liner construction concurrent with gripper thrust gives a potentially very fast method of tunnelling. This more expensive method of tunnelling, is compensated by its general efficiencies enabling conversion of a possibly 'poor' PR into a 'good' AR, due to the high utilization, and it also gives a water-tight and fully supported tunnel. It has been used with notable success in some other high-speed rail projects through hard rock masses, despite the need for frequent cutter-changes.

SAMMENDRAG

Det er utført bergmassekarakterisering av mer enn 300 lokaliteter langs utvalgte fjellskjæringer. Bergmassekarakterisering/kartleggingen omfatter totalt en lengde av cirka 6 km. Arbeidet er utført i forbindelse med TBM prognoser for Jernbaneverkets planlagte tunnelprosjekt Oslo-Ski, Follobanen. Follobanen planlegges som en høyhastighetssbane med opptil 19 km tunnellengde avhengig av hvilket trasealternativ som velges. I tillegg til karakterisering av et stort antall fjellskjæringer er det anvendt data fra JBV's borkjernelogging og refraksjonsseismikk utført av GeoPhysix. Disse dataene er spesielt utnyttet for tilleggsinformasjon om svakhetssoner. Dette datagrunnlaget med hovedvekt på Q-histogram logging var første stadium i anvendelse av Q_{TBM} for å gi prognoser på netto inndrift PR og brutto inndrift AR. Denne Q_{TBM} prognosen gjelder for ett av tunnel alternativene hvor TBM vurderes som drivemetode. Laboratorieforsøk angående trykkfasthet og kutterslitasje foretatt av SINTEF for hovedsakelig granitisk/tonalitisk gneis og for kvarts- og feltspatrik gneis av sedimentær opprinnelse, var anvendt i kombinasjon med disse statistiske Q-data, for å gi drivhastighetsvurderinger gjennom fem antatt bergmasseklasser og tre antatt svakhetssoneklasser. Karakterisering av svakhetssonene er basert på borkjernelogging og seismikk. Disse TBM prognoser sammenligner både åpen-gripper TBM og dobbelt-skjold maskiner, de siste med simultan bygging av betongelementforing og boring

som muliggjør en rask drivehastighet. Denne mere kostbare maskintypen gir fordeler som f. eks. muligheter til å bygge en tett og ferdig sikret tunnel vha. betongsegmenter uten å redusere drivehastigheten. Dette er mulig ved å konvertere en mulig 'dårlig' PR inntil en 'god' AR, på grunn av høy tilgjengelighet for boring, og er brukt med merkbar hell i andre høyhastighets tog prosjekter gjennom harde bergmasser, tross behov for frekvent kutterbytte.

THE OSLO-SKI NORTH AND SOUTH TUNNELS

Q-histogram statistics-based rock mass characterization of more than 300 rock cuttings, totalling at least 6 km in length, was used to estimate the likely ranges of rock mass qualities, for the planned tunnel linking the capital Oslo to the town of Ski, some 20 km to the south. If TBM excavation is chosen, the tunnel will be divided in two parts, driving north and south from a single adit tunnel, using a common TBM assembly chamber. Each drive is presently planned to be 9.6 km and 7.9 km. The tunnels may be driven by twin TBM of about 10 m diameter, or by single larger diameter TBM, or by drill-and blast, with its more immediate water-inflow control using systematic pre-injection. Since the tunnels are mostly in the range 40 to 80 m depth, and the Q-logged rock cuttings (e.g. for local roads and a motorway) were up to 15 m height, and depth of weathering was mostly limited in the good quality gneisses, it was possible to obtain a valuable source of rock quality data. These data were utilized in TBM prognoses of the planned tunnels through the *better classes* of rock mass. In the case of TBM tunnelling, the highest quality rockmass may cause slower progress, and more cutter changes.

ROCK MASS CLASSIFICATION OF ROCK CUTTINGS

Approximately 40 areas were selected along the approximate planned line of the two tunnels, where rock exposures, mostly rock cuttings for roads, were available for classification. In each of these areas, about nine rock cuttings were Q-histogram logged. Two examples of the rock are shown in Figure 1a and 1b. The distribution of logging locations and mean Q-values are indicated in Figure 2. An example of the actual distribution of logging locations for the case of the planned 7.9 km long South Tunnel, and more details of the Q-statistics for each area with multiple rock cuttings is shown in Figure 3.

Figure 1a and 1b. Left: An example of some of the best quality rock along a nearby motorway. Due to its massive nature this would be slower to bore, and is an example of Class 1 rock mass. Right: An example of some of the more jointed rock that would be easier to bore.

Altogether, five rock mass classes and three weakness zone classes were modelled, the latter based on the core logging data and refraction seismic measurements. Table 1 shows the estimated extent and typical depth of the different rock classes. The large amount of 'good

quality' rock suggests limited tunnel support needs, but progress by TBM will not be fast, and cutter change will be frequent.

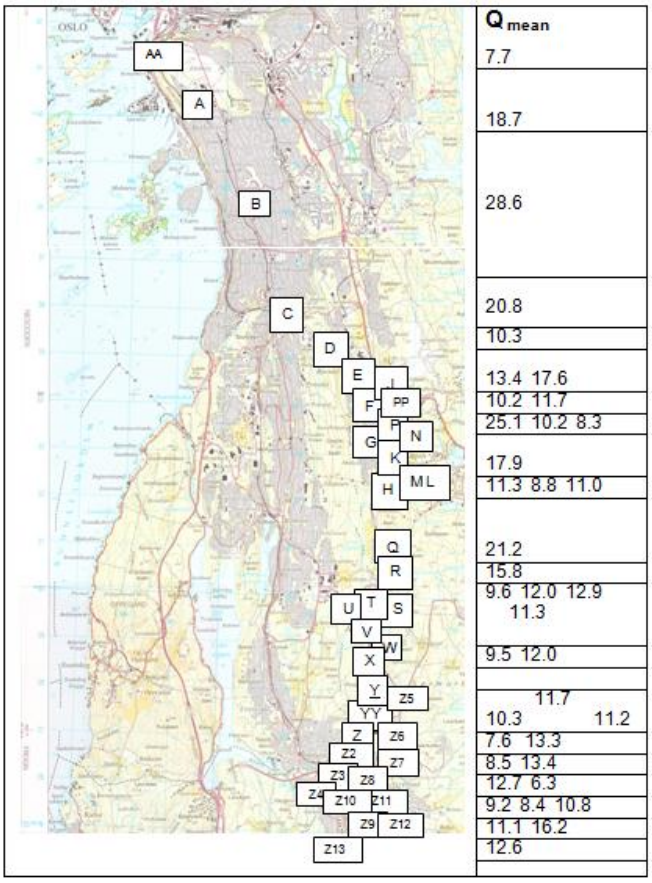

Figure 2. The 38 areas where Q-histogram logging was performed on eight or nine rock exposures per area. Overall mean Q-values are shown by location, covering some 20 km north to south. Oslo is just beyond the top of the map.

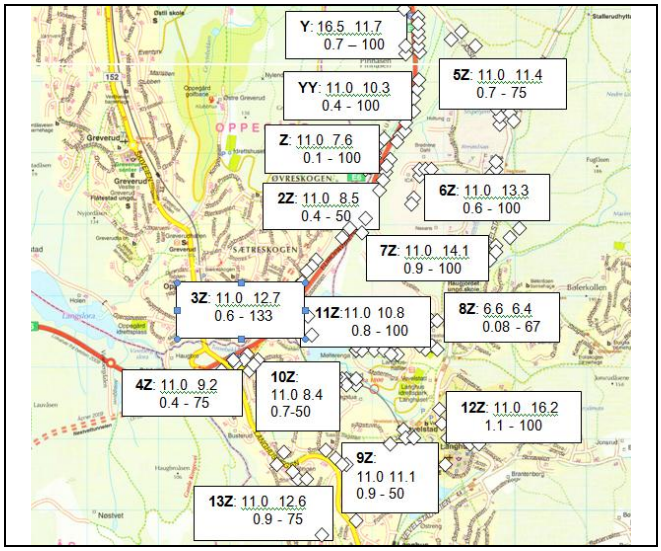

Figure 3. An extract from the southern tunnel logging locations. Boxes show mean values for each area logged, each in multiple (8 or 9) locations, with numbers listed in the following order: $Q_{most\ frequent}$, $Q_{mean,}$ and $Q_{typical\ range}$: minimum to maximum.

Table 1. Approximate distribution of rock classes in the North and South tunnels. (Representative mean depths are shown in parentheses). Poorer rock classes Q6, Q7 and Q8 were evaluated by means of V_P from refraction seismic profiles in known weakness zones.

TUNNEL	Q1 Q > 100	Q2 Q 40-100	Q3 Q 10-40	Q4 Q 10-4	Q5 Q 4-1
North L ≈ 9.6km	500 (160)	2000 (120)	5000 (100)	1500 (80)	500 (70)
South L ≈ 7.9 km	200 (130)	1000 (110)	2500 (80)	1750 1750 (60) (30)	500 (30)

The results of Q-histogram logging of all the exposures used to estimate the rock mass quality for Tunnel South of planned 7.9 km length is shown in Figure 4a, and for comparison, the result of focused logging of weakness zones sampled in seven boreholes is shown in Figure 4b. As mentioned earlier, the results of several kilometers of seismic refraction profiles was the eventual source of Q_{TBM} modeling of three classes of weakness zones, having successively reducing mean velocities. The core logging was a form of 'quality control' of key parts of the seismic profiling results.

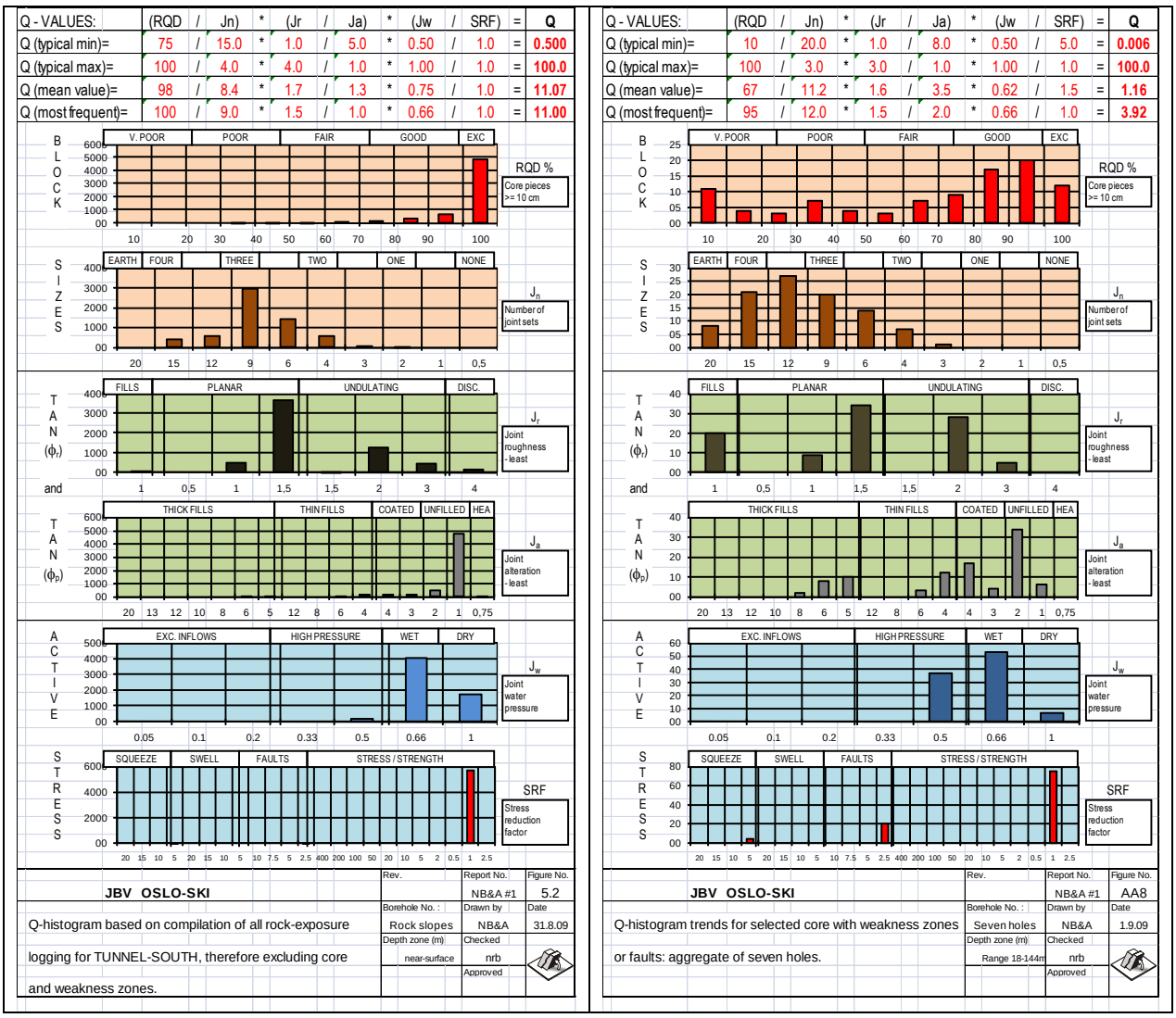

Figure 4a and b. A comparison of Q-histogram logging of the Tunnel South rock cuttings with focused Q-histogram logging of specific weakness zones exposed in seven cored holes.

WEAKNESS ZONE LOGGING

In addition to the logging of the numerous surface exposures, drill-core logging performed by Jerbaneverket (see example in Figure 5), and two campaigns of seismic refraction measurements performed by GeoPhysix were also utilised. Both the latter were focussed on the reduced rock mass quality experienced when crossing assumed weakness zones and known faults. In the JBV core-logging, it was found that the most noticeable weakness zones had significant alteration and strength reduction of the rock, and parts had quartz cementation of the crushed zones. There were also traces of faulting and slickensides. Typical Q-values (for the weakness zones themselves) were in the range 0.02 to 0.25.

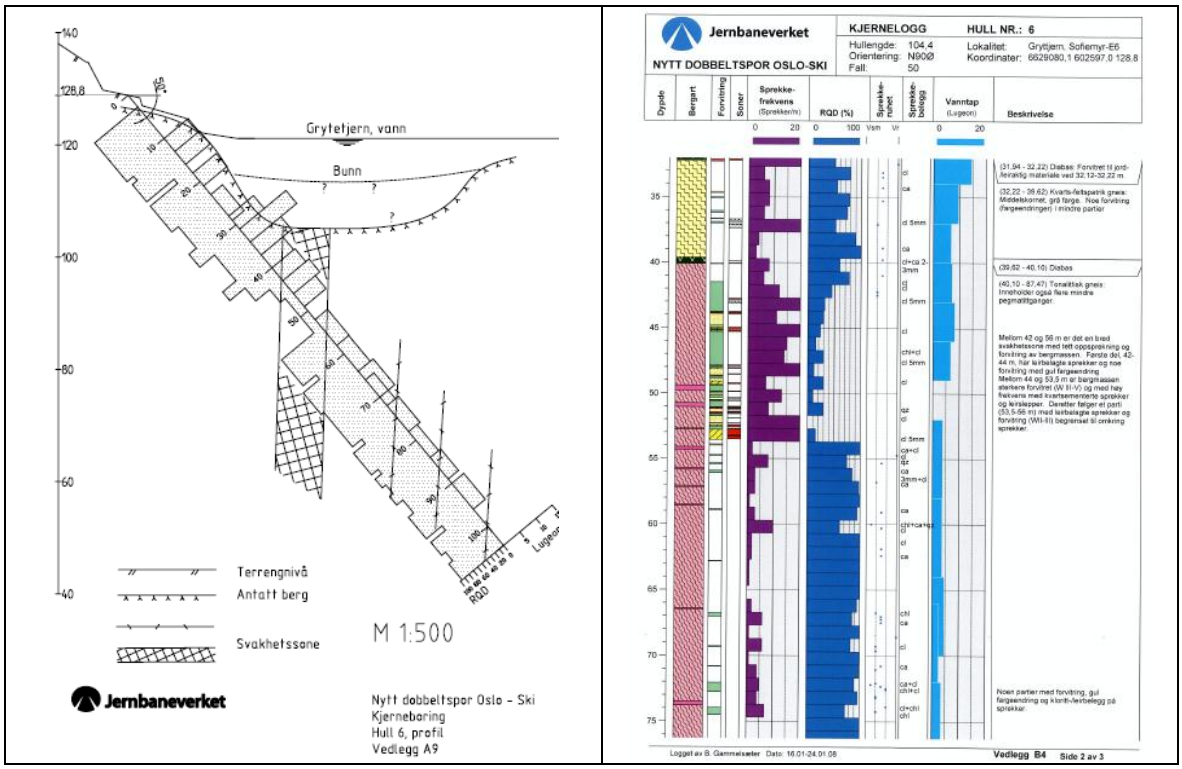

Figure 5. An example of the core-drilling to intersect weakness zones, and reproduction of the JBV core logging. Hole 6 was drilled beneath a small lake called Grytetjern. Some of the weakness zones had several decimeters of clay, and focussed Q-logging suggested that several had Q < 0.01.

The weakness zone velocities appeared to be grouped in three main velocity ranges: 2000-2300m/s (6 cases, mean 18 m wide), 2500-2900m/s (9 cases, mean 18 m wide) and 3200-3500m/s (4 cases, mean 20 m wide), so there was no apparent differentiation concerning width and velocity in general. The three following groups of velocities were therefore simulated in the Q_{TBM} prognosis model as a starting point: 2170, 2730 and 3355 m/s, to approximately represent the above ranges. A Q_{TBM} input option for *shallow* tunnels, is to directly apply the P-wave velocity in place of the Q-parameters. Recorded V_P velocities are automatically converted to Q-values, using the empirical relations [1]:

$$V_P \approx \log Q_c + 3.5 \text{ (km/s)} \qquad (1)$$

(where Q_c = Q x UCS/100 with UCS in units of MPa)

$$Q \approx 100/UCS \times 10^{(V_P - 3.5)} \qquad (2)$$

(when V_P = 3.5 km/s, and UCS ≈ 100 MPa, Q ≈ 1)

Laboratory test data from NTNU/SINTEF of Trondheim, concerning strength and abrasion parameters for the mostly tonalitic and also quartz- and feldspar-rich gneisses, were also combined with the above mentioned Q-data statistics to help give estimates of potential TBM tunnelling speeds, using the Q_{TBM} prognosis model. In general UCS values ranged from about 200 to 260 MPa, and CLI was an unfavourable 6 to 10 in general, meaning heavy cutter wear. Quartz contents varied from 25 to 35%, again unfavourable, meaning typically only 3m advance per cutter change, which of course is performed in multiples, where possible.

WHY FAULT ZONES MAY DELAY TBM SO MUCH

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

$AR = PR \times U$, where $U = T^m$ (see Figure 6)

Due to the reducing utilization with time increase, advance rate decelerates, but does so to a lesser *general* extent with double-shield TBM with their single shield mode / push-off liner possibilities. With double-shield TBM, *-m* may be nearly halved, as shown later. Since the time T needed to advance length L must be equal to L/AR, for all tunnels and all TBM:

$$T = L / AR \qquad (3)$$

Therefore we have the following:

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

This can be re-arranged as follows:

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

This is a very important equation for TBM, especially if one accepts that the deceleration gradient *(-) m* is strongly related to low Q-values in *fault zones,* as shown by the empirical data in Figure 7. Equation 4 is important because negative *(-) m* values almost reaching (-) 1.0, make the component $^{1/(1+m)}$ *too large.*

If the fault zone is wide (large L) and PR is low (due to gripper problems, collapses, delayed support, etc.) then L/PR gets too big to tolerate a big component $^{1/(1+m)}$ in equation 4. It is easy (in fact all too easy) to calculate an almost 'infinite' time for passing through a fault zone using this 'theo-empirical' equation. This also agrees with reality, in numerous, little-reported cases. So far this equation seems to be absent from other literature, as the inevitability of deceleration *(-m)* does not seem to have been accepted as a useful method of quantifying reduced utilization with increased time.

TBM *must follow* a negative m-value, even when breaking world records, like16 km in one year, or 2.5 km in one month, even 120 m in 24 hours, since even here, PR is sure to be greater than the implied and remarkable mean AR of about 5 m/hr for the record 24 hours period. The uppermost line of world record performances seen in Figure 6 is therefore also showing deceleration, but with a less steep gradient *(-m).*

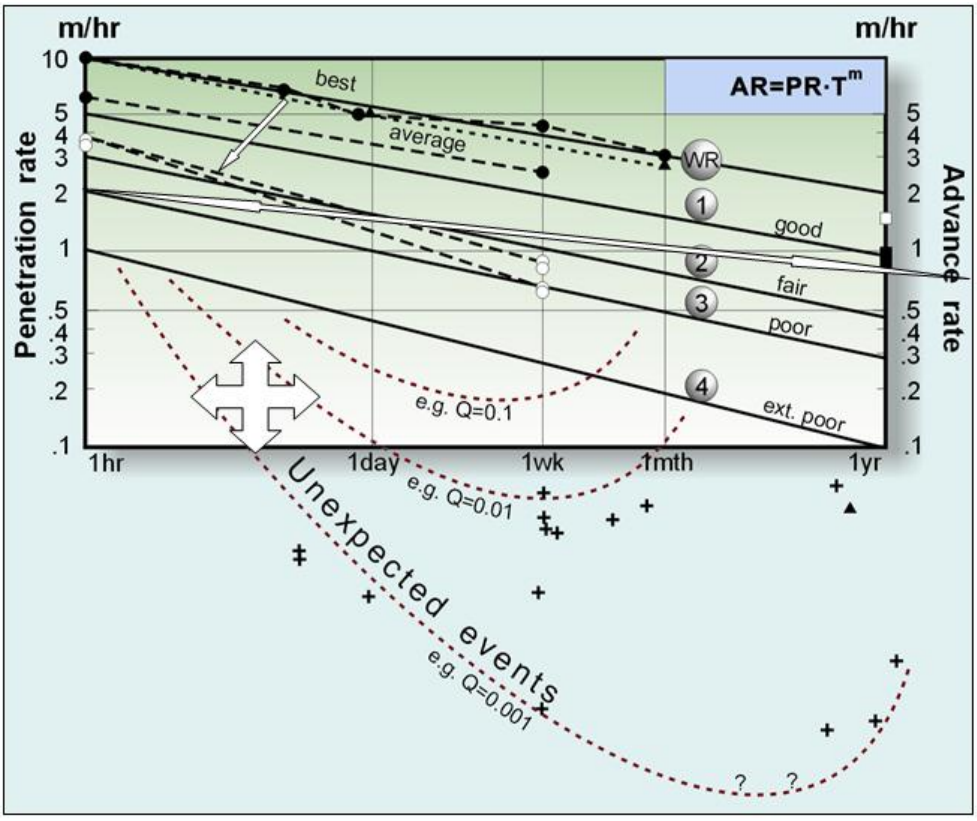

Figure 6. The trends of declining advance rate with increased time period, derived from an analysis of 145 cases and about 1000 km of mostly open-gripper TBM [2]. Note that the utilization equation has been re-cast as AR = PR x T^m, where *-(m)* is the negative gradient of deceleration. The three arrows from top to bottom represent: 1. Typical delays when pre-injecting . 2. Double-shield TBM efficiencies, giving about *0.5 x (-m), to 0.66 x (-m),* can convert a 'poor' PR to a 'good' AR. 3. Arrow in form of cross indicates where Q-values have strong links to TBM 'unexpected events', which without pre-injection may compromise completion.

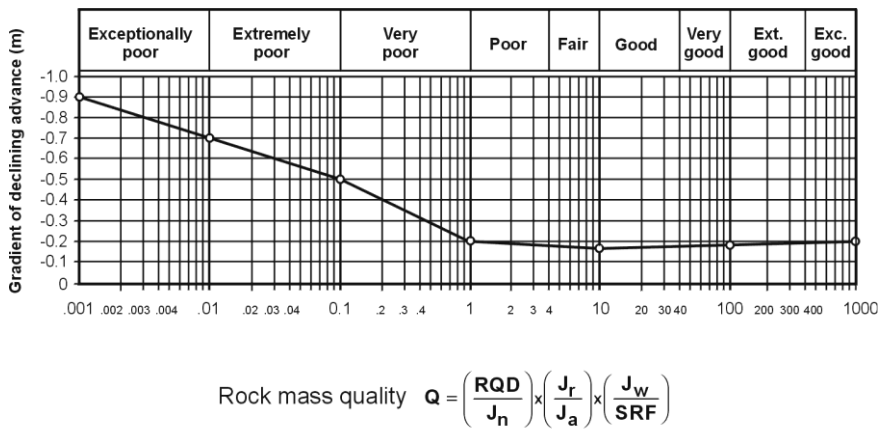

Figure 7. The gradient of deceleration (or declining advance) derived from mostly open-gripper TBM case records that were analysed in [2], is strongly linked to the Q-values in the case of poor rock conditions, which are marked by the arrow-in-the-form-of-a-cross seen in Figure 6 (so-called 'unexpected events'). Pre-treatment, capable of improving the effective Q-value, due to potential improvements of all six Q-parameters, will also effectively reduce the initial estimate of the negative gradient *(-m).*Other machine-rock interaction parameters, including CLI (cutter life index) and quartz content, modify or 'fine-tune' this initial Q-based gradient, to slightly steeper or to shallower gradients.

PROGNOSES USING Q_{TBM}

For each part of the planned Oslo-Ski tunnel, prognoses were compared using hard rock open-gripper TBM and double-shield TBM, where robust PC element liner construction concurrent with thrust from the grippers gives a very fast method of tunnelling. This more expensive method has the possible advantage of converting a possibly ‘poor’ PR (due to rock hardness) into a ‘good’ AR, due to the high utilization, despite frequent cutter changes. With suitable design of gaskets it can also give a water-tight and fully supported tunnel (after some initial leakage in the first 10 to 15 m from the face), and has been used with notable success in some other high-speed rail projects through hard rock masses.

Figure 8 illustrates the input data screen for the last of five rock mass classes used to define the likely quality ranges of Tunnel North. As may be noted, the first six parameters are the (almost) conventional Q-parameters, but with a specific requirement to consider the RQD in the horizontal (visual scan-line) direction, and preferably also in the planned tunneling direction. Anisotropically distributed RQD logged conventionally in vertical holes therefore represents a potential source of error if used to predict PR.

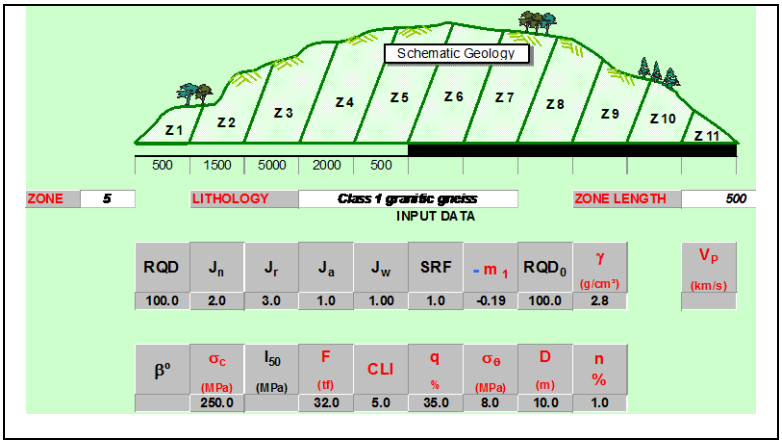

Figure 8. An example of the input data screen for the best quality rock mass. Successive zones (or combined lengths) of the same assumed rock classes 5 (poorest), 4, 3, 2 and 1 (best, as in the figure), plus the various weakness zone classes, gradually complete the modelled tunnel.

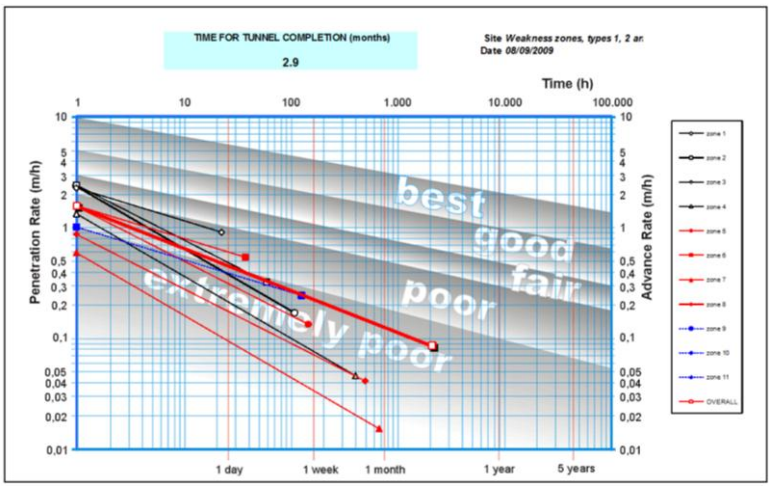

Figure 9. The modeling of nine potential weakness zones, with some variation in cutter force F, and three sets of geotechnical input data, suggest a potential 3 months delay. This is preliminary data.

The cumulative time for the nine simulated weakness zones, shown modelled in Figure 9, is nearly three months. In these simulations, no pre-treatment has been modelled: neither the delay caused by pre-injection (doubled *–m*, approx: see shortest arrow in Figure 6), nor the tougher boring through improved rock on either side of a weakness zone, nor the faster boring through the 'Q-improved-by-grouting' weakness zone itself. For a discussion of the possibility of effectively improving Q-parameters, and therefore the effective Q-value itself, by high pressure particulate pre-grouting, using for instance micro-cements with micro-silica, see [3].

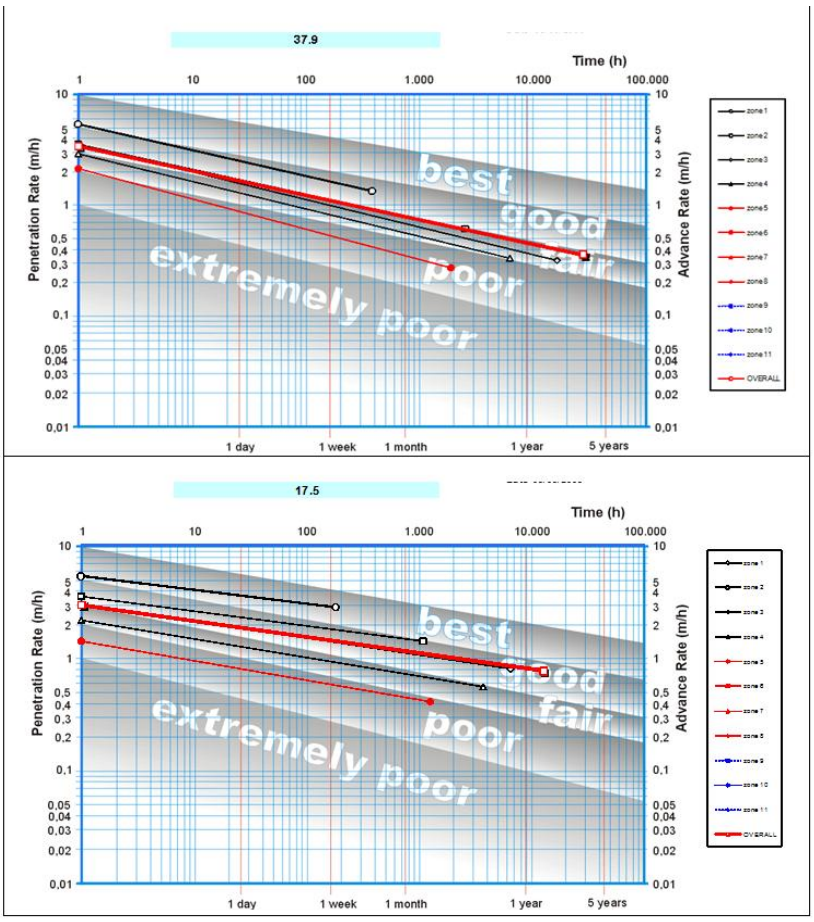

Figure 10. Examples of Q_{TBM} simulations for the planned 9.6 km long Tunnel North, showing the modelled contrast of open-gripper (about 3 years) and double-shield (about 1.5 years) predicted performance, with weakness zone modelling to be added to either solution. The initial Q-based deceleration gradients (from Figure 7) ranged from -0.17 to -0.19 (for the open-gripper TBM) and from -0.10 to -0.12 (for the double-shield TBM), becoming respectively -0.23 to -0.27 and -0.12 to -0.17 after 'fine-tuning'. This is due to the adverse rock-cutter interaction in the case of hard granites and gneisses. Improved efficiencies in modern open-gripper TBM might reduce the above gradients.

Figure 10 shows examples of the Q_{TBM} simulations for the planned 9.6 km long Tunnel North, showing the contrast of open-gripper and double-shield predicted performance, with numerous weakness zones to be added to either solution. The reduced gradients of deceleration *(-m)* seen in the case of the double-shield machine, are based on the back-analysed results of four TBM (two Wirth, and two Herrenknecht machines) which 'competed' with each other over a tunneled distance of 14 km each. [4]. These four machines eventually formed twin tunnels of 28 km length during about 30 to 33 months of tunneling, linking Madrid to Segovia through predominantly gneissic and very abrasive rock masses, also with high cover under the two principal mountain chains.

All four machines were double-shield, giving simultaneous lining and improved efficiency also through wide, but partly pre-treated fault zones. Tough-sounding mean-PR of only about 2 m/hr were nearly converted to 'good' final AR performance, due to these reduced gradients of deceleration, roughly following the mean trend of the *long arrow* seen in Figure 3. This was despite cutter change on average each 2.7 to 3.0 m of tunnel advance, and the need for continuous water-cooling of the cutter head.

CONCLUSIONS

1. The Oslo-Ski rail-tunnel project has a large number of generally relevant rock exposures, which were Q-histogram logged in detail. The input data for modelling representative weakness zones was obtained from 'statistical' analysis of the refraction seismic measurements of V_P . Velocities of 2.2, 2.7 and 3.4 km/s were found to be the mean values for three major groups of weakness zones. Drill-core was also available for cross-checking Q-values and P-wave velocities. These drill-holes were deviated to cross the weakness zones. Nine weakness zones were modelled with the Q_{TBM} method, in a 'generic' type study, using various cutter force F assumptions.

2. For the TBM prognosis modelling, the characteristic gneissic rock types were represented in five Q-classes (Q1 to Q5), with an additional three weakness-zone classes (Q6, Q7 and Q8). The assumed Q1 to Q5 rock mass classes, assuming for preliminary simplicity: Q1 at greater depth, and Q5 at shallower depth, represented quality ranges of Q > 100, Q = 100-40, Q = 40-10, Q = 10-4, and Q = 4-1.

3. As an example, Tunnel-North of 9.6 km length was first modelled with open-gripper TBM, then by double-shield/single-shield TBM with the assumed push-off-liner option for bad ground. These two simulations needed respectively 37.9 and 17.5 months for passing through an assumed 500m, 2000m, 5000m, 1500m and 500m of the five chosen rock classes Q1 to Q5. PR varied from 2.1 to 5.3 m/hr, with cutter force F varied respectively from 32 to 22 tnf. In the case of double-shield/single-shield with push-off-liner model, PR varied from 1.4 to 5.3 m/hr.

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