Risk and risk reduction in TBM rock tunnelling

N. Barton
Nick Baton & Associates, Oslo, Norway

Keywords: tunnels, TBM, risk, rock quality, characterization, seismic velocity, stress.

ABSTRACT: There are many, many potential sources of geotechnical risk in rock tunnels. To state the obvious first, *unexpected discoveries* of significant fault zones, adversely oriented planar clay-coated joints, very weak rock, very hard massive rock, very abrasive rock, very low or high stress, high volumes of stored water and high permeability are clearly among the foremost risk factors. Their partial combination in a given tunnel can be catastrophic. Through appropriate pre-investigation measures, using a combination of *sufficient* surface mapping, refraction seismic, core logging, borehole testing, and their extrapolation by means of geo- and hydro-geological rock mass characterization, the above risk factors can clearly be minimized. However, these risk factors can seldom be eliminated and so-called *unexpected events* may still occur. If in sufficient numbers, both schedule and cost, and the continued existence of a TBM excavation choice (or even the contractor) may each be threatened, in a given tunnel. Clearly, the deeper the tunnel in relation to these mostly near-surface investigation methods, the greater the need for sufficient planning and (unit) pricing of contingency measures for tackling the *unexpected.* Depth effects on seismic velocity also need careful consideration, as a false sense of improved rock quality with depth may be experienced.

1 INTRODUCTION

After a tunnel collapse or TBM cutter-head blockage in a tunnel, it usually becomes quite clear to the experienced tunnelling engineer or engineering geologist what the cause(s) of the collapse or blockage were. *Before* the event it would usually be necessary to have been exceptionally pessimistic to have foreseen the 'unthinkable' – which more often than not is the combination of several adverse factors, which separately are 'expected' though serious events, but when combined are, quite logically, 'unexpected events'.

In the following table, some of the more obvious sources of geotechnical risk are tabulated as reference to the cases cited in the paper.

significant fault zones, adversely oriented planar clay-coated joints,
very weak rock, very hard massive rock, very abrasive rock,
very low stress, very high stress, exceptional stress anisotropy,
high volumes of stored water, high permeability

Sometimes of course, an *individual* risk factor may have been of such magnitude that it could not reasonably have been predicted. Below are listed some cases which are familiar to the writer, where either an *unexpected combination of factors* led to temporary or final failure of the projected tunnel excavation method, or alternatively *an unexpected magnitude of a single factor* led to the problem encountered – which could equally well be multiple problems as a result of this single factor.

A short list of TBM tunnels that suffered (catastrophically) from multiple unexpected events

1. Unpredicted fault swarm parallel to valley-side, together with very high (and fault-eroding) water pressures, at depths of 700-900m. TBM tunnel (diameter 5m) eventually ran sub-parallel to individual faults, causing delays of at least half a year for each 1m wide fault (AR ≈ 0.005m/hr). TBM finally abandoned; new contractor for D+B from other end of tunnel. (*Pont Ventoux HEP, N. Italy*).
2. Alternating massive quartzite (minimum PR ≈ 0.2m/hr), talcy sheared phyllites ('over-excavating' and stand-up time limitations), and fractured quartzite 'aquifer'. Early blow-out of 4000 m3 rounded gravels at 750m depth and

maximum 70 m^3/minute water in-rush. Eventual abandonment of the 8m diameter TBM in a fault zone; D+B from other end of tunnel after years of delay. *(Dul Hasti HEP Kashmir).*

3. Unexpectedly abrasive quartzites and meta-sandstones, clay-coated joint set and exceptional water pressures and inflows. At least twelve D+B by-passes of TBM pilot tunnel during 10 years of delays. Squeezing deformation of pilot tunnel from 26m distant main (11.7m) TBM. Fault zone collapse destroyed one 11.7m TBM, other used to mine invert, needing D+B cutter-head releases and D+B mining and support of top-heading. Great difficulties to drill pre-injection holes. Eventual completion by mainly D+B from other end of tunnel. *(Pinglin Tunnels, Taiwan).*
4. Unexpectedly high water inflows and unexplored regional fault zone due to limited access for marine seismic at container port. Sub-sea TBM of 3.3m diameter took three times longer than contracted, even after abandonment by first contractor. *(Tunnel F, SSDS, Hong Kong).*

A short list of D+B tunnels that suffered from unexpected magnitudes of individual factors

5. Unexpected horizontal stress concentration by river erosion and by massive basalt flows. Stress-induced failures in five 15×17m diversion tunnels reached 2 to 3 m depth in arch and invert, and a total of hundreds of meters of cracking occurred in five concrete-lined pressure shafts when contact grouting. Tangential stresses as high as 120 to 140 MPa, and as low as (-) 30 to 40 MPa were back-calculated. Stress anisotropy ratio of 20 to 25. Spillway scour of exceptional magnitude also occurred. (*Ita HEP, Brazil – drill-and-blasted).*
6. Unexpected, but unforgivable, leakages to largely unexplored 15 km long tunnel (no drill-holes or permeability tests). Ineffective (rushed) pre-injection. Drainage of over-lying lake and numerous building settlement damages. One year delay of completion due to post-injection problems. 'Lowest-bidder-syndrome'. *(Romeriksporten, Oslo – drill-and-blasted, but important lesson).)*

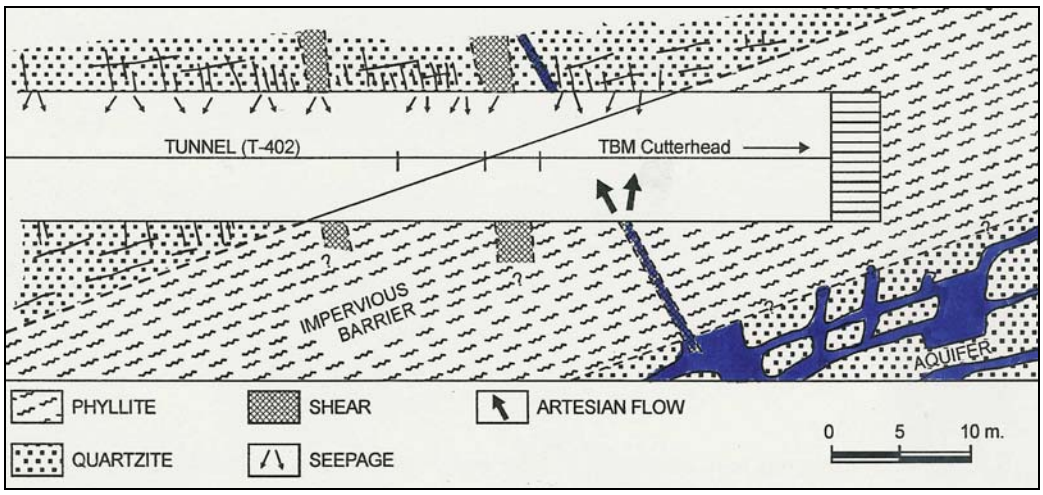

Figure 1. Pre-blowout situation at Dul Hasti HEP. Deva et al. 1994.

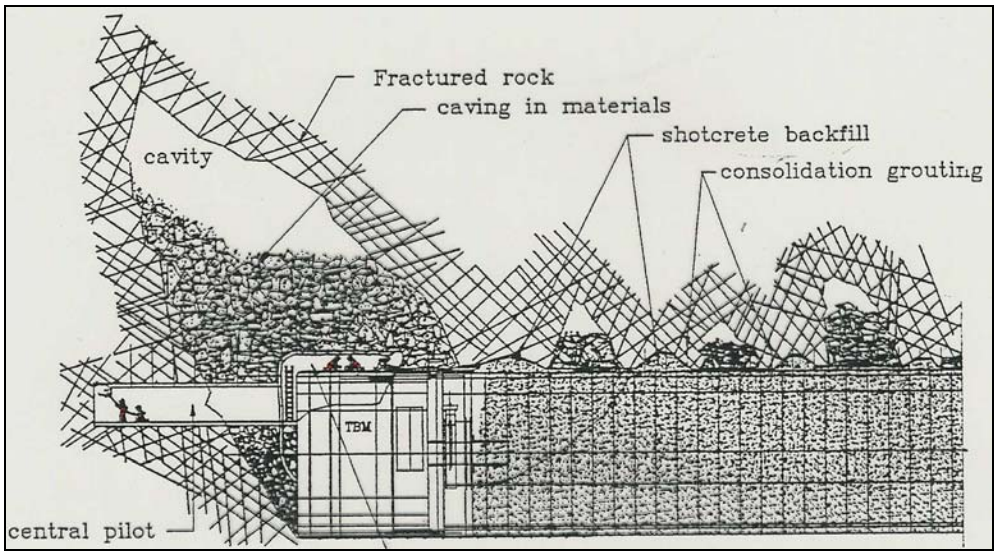

Figure 2. Trapping of shield and cutter-head at Pinglin. Shen et al. 1999.

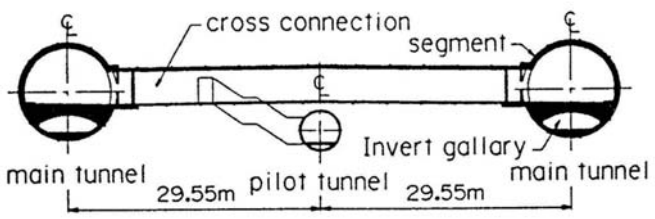

Figure 3. Adverse influence of 11.7m main tunnels on deformation of pre-driven pilot tunnel at Pinglin due to deformation ('plastic') zone.

2 IMPROVED USE OF SEISMIC TO PREDICT CONDITIONS

The traditional use of seismic profiling to extrapolate (actually interpolate) expected tunnelling conditions between investigation boreholes is an important measure for reducing risk. However, there is strong empirical evidence that there can be potential *masking* of the true rock quality, due to the influence of stress (or increased tunnel depth) on the P-wave velocity. The near-surface linkages between V_p, RQD and F m-1 derived by Sjøgren et al. 1979 from 120 km of seismic profiling and 2.1 km of related drill-core shown in Figure 4, apply to near-surface, low-porosity, hard rock. The additional links to Q (and $Q_c = Q \times \sigma_c/100$) shown in Figure 4, also say nothing about the apparent improvement of velocity (and assumed rock quality) at greater depth.

As an example, the Pont Ventoux HEP headrace/pressure tunnel was plagued by sub-parallel valley-side faults, with more than 6 months fault-related delays on several occasions, until TBM tunnelling was abandoned. An attempt to detect the continued presence of a particular fault (see sketches in Figure 5) using *seismic tomography* between two divergent pilot boreholes proved to be unsuccessful, due to the presumed confining effect of the high stresses (from 800m of over-burden) on the fault-zone materials.

Two alternative presentations of the assumed (empirically-derived) depth effect on V_P are shown in Figures 6 and 7. It will be noted that the sensitivity of V_P to rock mass quality Q is successively reduced with increase of depth. There is nevertheless sufficient *differentiation* of quality down to many hundreds of meters depth, to make seismic probing worthwhile.

Note that the 'false' velocity-depth result has on occasion caused expensive mistakes when bidding for projects. The assumption of better quality than actual occurred in the North Cape tunnel in northern Norway, due to an unexpected sea load effect on the velocity, making the rock quality appear much better than it was. In this case the dry sheared material exposed in the tunnel was at least two Q-classes worse than expected.

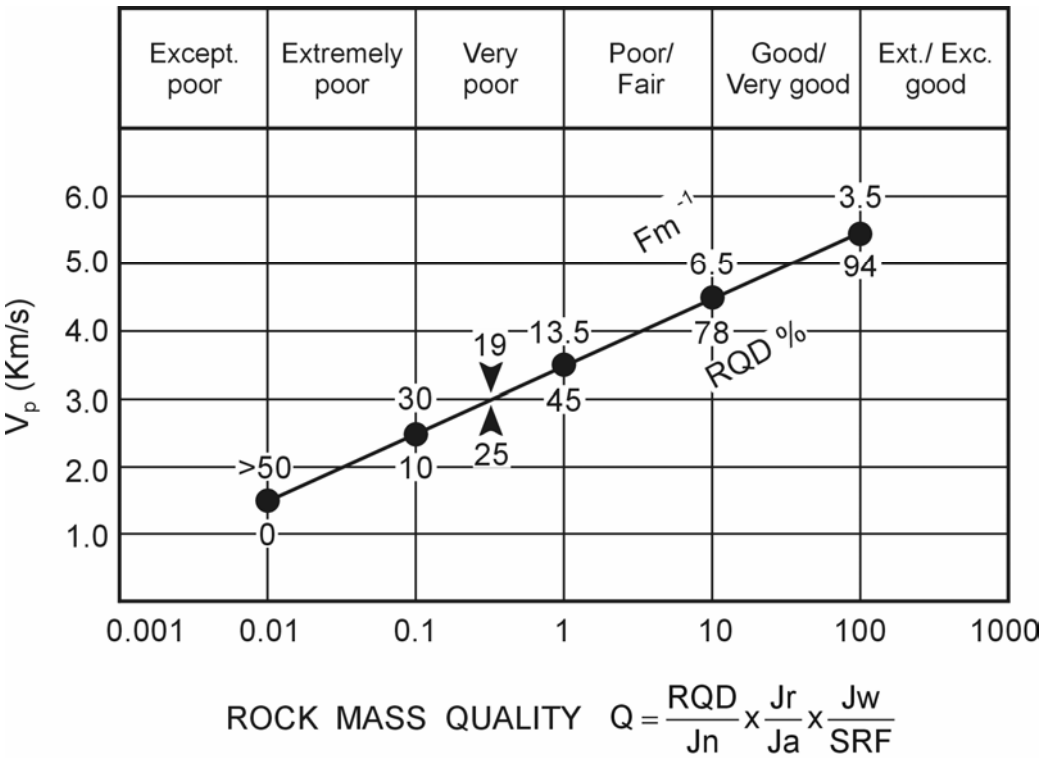

Figure 4. Near-surface, hard rock, low porosity correlations between Vp, RQD, and Fm-1, from Sjøgren et al. 1979, with Q-linkages from Barton 1995.

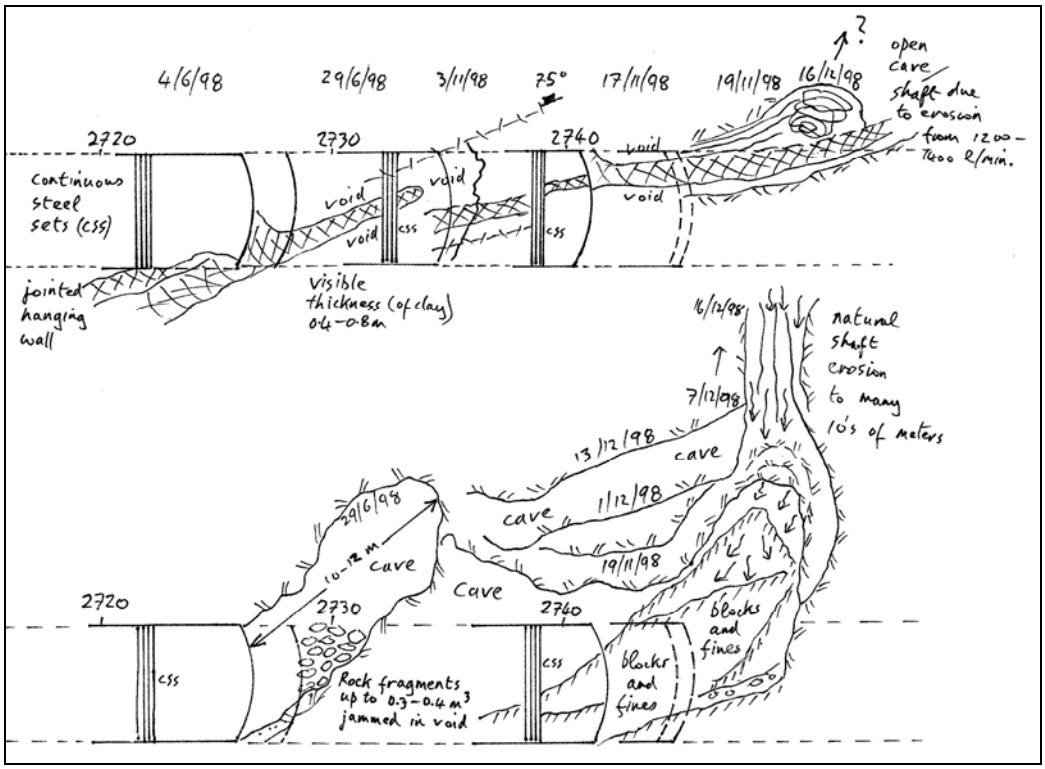

Figure 5. Fault of minimal thickness causing >6 months delay at Pont Ventoux HEP. Cross-hole seismic tomography failed to detect forward presence of fault due to presumed compaction effects of 800m of overburden. Barton, 1999a.

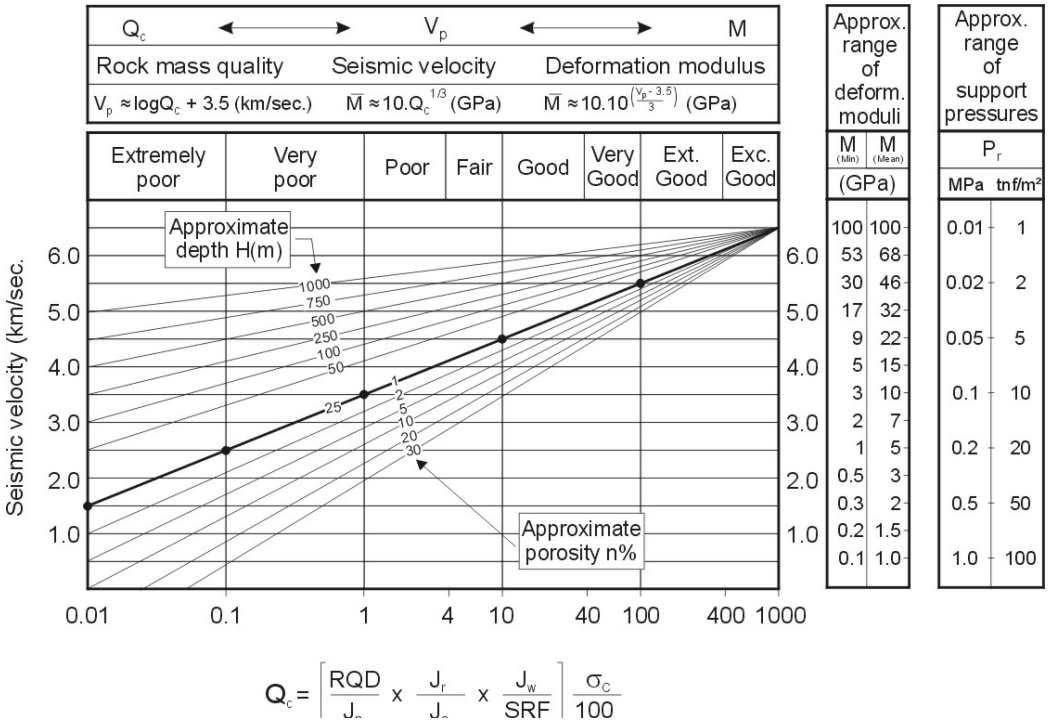

Figure 6. Depth (and porosity-adjusted) $V_P - Q - E_{mass}$ relationship. A velocity of 5 km/sec measured at 500m depth implies a Q-value of 30 with normal interpretation, but only Q = 1 with depth-adjusted interpretation. Barton, 1999b.

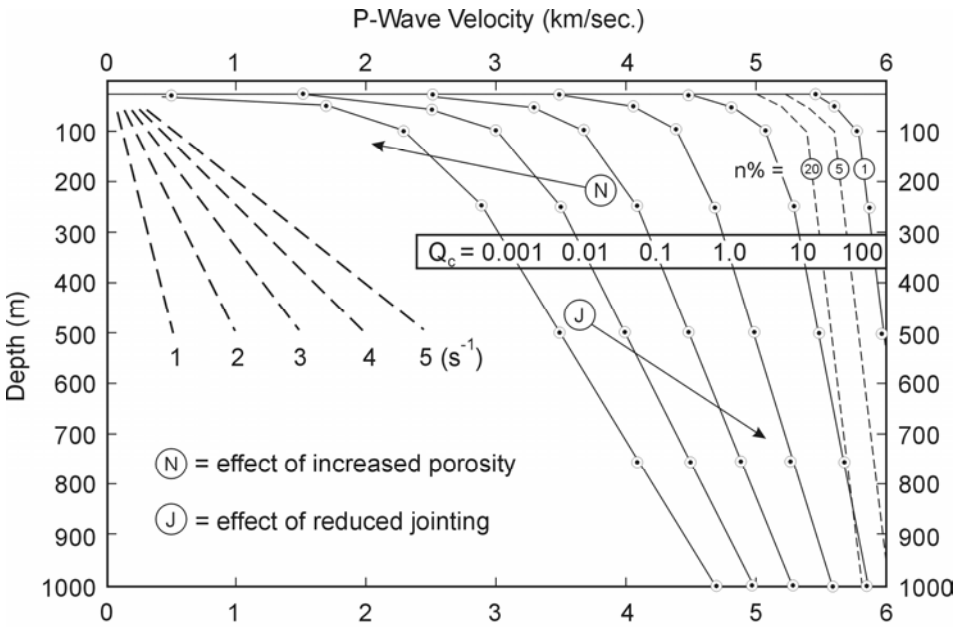

Figure 7. Sensitivity of rock mass quality Qc to the value of V_P reduces with increased depth. The poorer the rock mass quality, the stronger is the compaction effect in the upper 100 to 200m, where large errors of judgment concerning rock quality can be made from V_P values.

3 UNEXPECTED EVENTS IN TBM TUNNELLING BASED ON Q

A wide reaching review of TBM case records performed by the writer (Barton, 2000) revealed a strong correlation of TBM difficulties with Q-values, at *the lower end of* the Q-value spectrum. These difficulties are marked as *unexpected events* in Figure 8. As can be noted, there are severe delays connected with the low Q-values of about 0.1, 0.01 and especially 0.001. Clearly this is an area of greatly increased risk of stand-stills and consequent schedule and cost problems for TBM.

A further finding from the TBM case record analysis was that the penetration rate PR and the advance rate AR could each be estimated from a modified version of the Q-value, termed Q_{TBM}. This multiple-parameter term will not be defined further here. It is sufficient for the present analysis of *tunnelling risk* to state that under 'regular or typical' conditions, the Q-value and Q_{TBM} value can be about equal. This is clearly a convenient simplification for comparing the approximate rates of advance for drill-and-blast tunnels and TBM tunnels. A typical analysis for approx. 50 m^2 tunnels is shown in Figure 9.

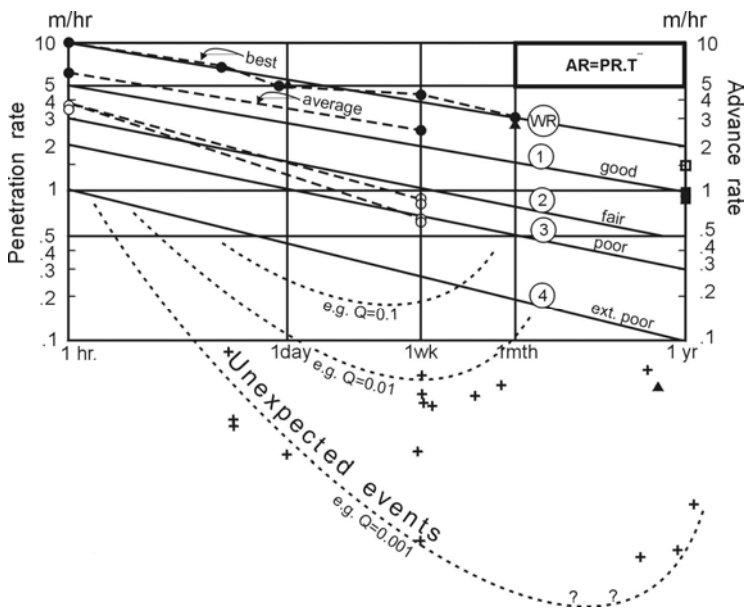

Figure 8. General trends from analysis of 140 TBM case records. Note adverse influence of low Q-values on so-called 'unexpected events. The crosses are from specific stand-still situations, such as blocked cutter head and/or shield, water problems and D+B (drill-and-blast) by-pass requirements.

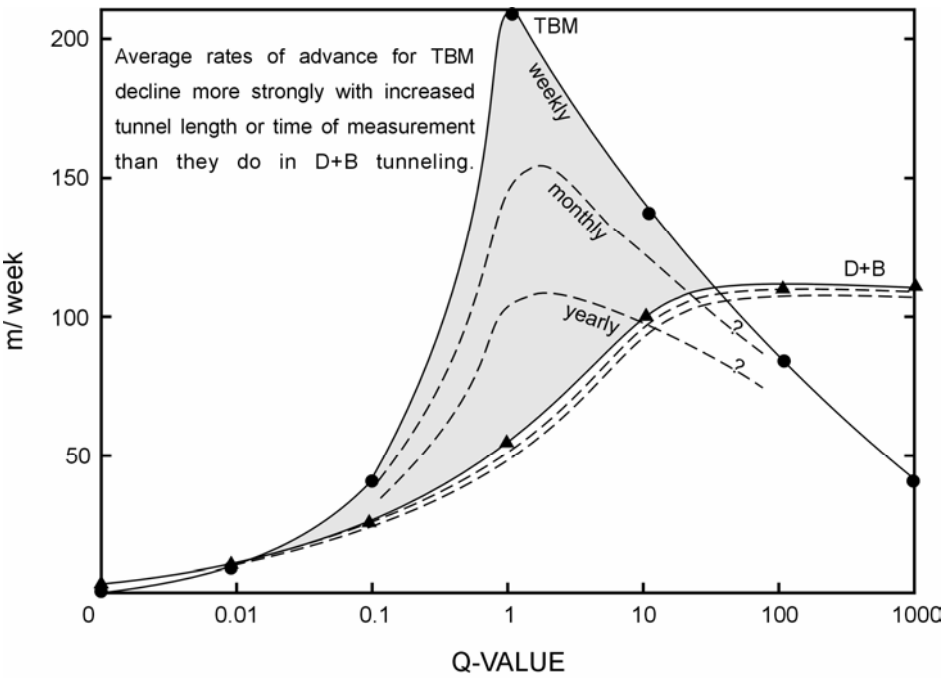

Figure 9. For typical conditions it is feasible for the Q-value of the rock mass and the Q_{TBM} value for the rock-mass-machine-interaction, to have similar magnitudes. The comparison of D+B and TBM tunnelling rates shown here also accounts for the **deceleration** of TBM, as shown by the gradients of the performance lines (-m) in Figure 8. Note AR=PR×U=PR×T^{-m}, Barton, 2000.

Figure 9 is a reminder of another source of risk in tunnelling, namely that *if the TBM tunnel is sufficiently* long, it may require, on average, quite *central* values of Q to compete with the drill-and-blast alternative.

This leads us directly to another source of risk, and this is again related to statistics. A given distribution of rock mass qualities, for instance Q-values or RMR-values, along say a 5 km long tunnel, or along the first 5 km of a longer tunnel, cannot be expected to remain unchanged when the tunnel is much longer than 5 km. In the hypothetical example in Figure 10, a frequency distribution of Q-values for the 5 km tunnel is shown extended for the 25 km tunnel, with assumed tails in the distribution such as more severe faulting (FF) or more abrasive and/or harder rock (HH) as a result of the increased length.

Clearly the same adverse tails in the rock quality distributions also have influence on the progress of drill-and-blasted tunnels over the same route. One will need to change drill-bits more often with 'HH', and 'FF' will also be very troublesome in a drill-and-blasted tunnel. Nevertheless, there are many more measures available to the contractor – and he has more space – when confronted by

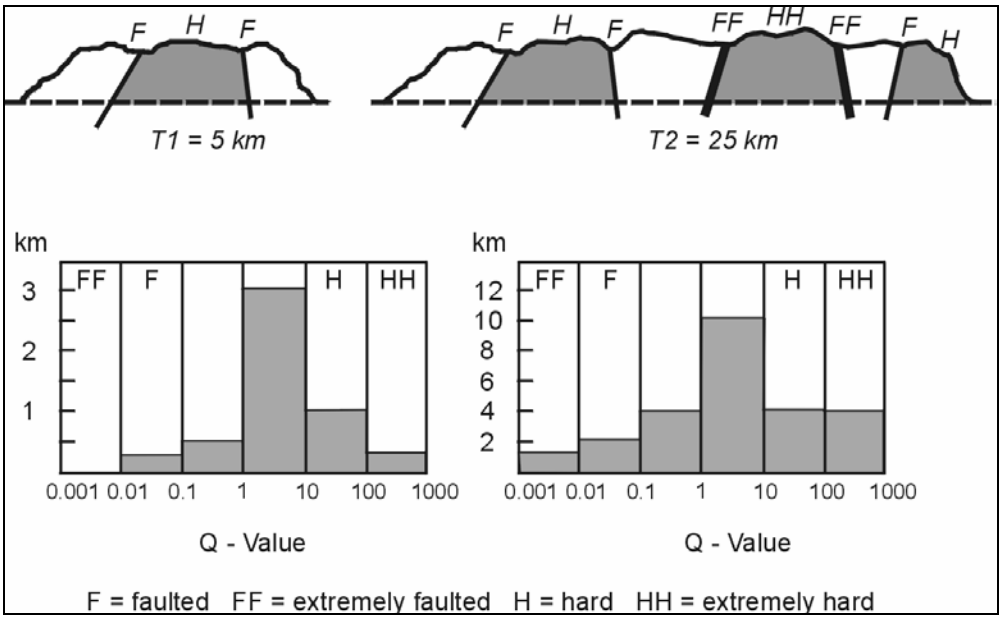

Figure 10. Assumed 'tails' in the distribution of rock qualities, which may be caused as a direct consequence of choosing to drive long tunnels by TBM, in the 'reasonable' belief that they will be faster than drill-and-blast tunnelling.

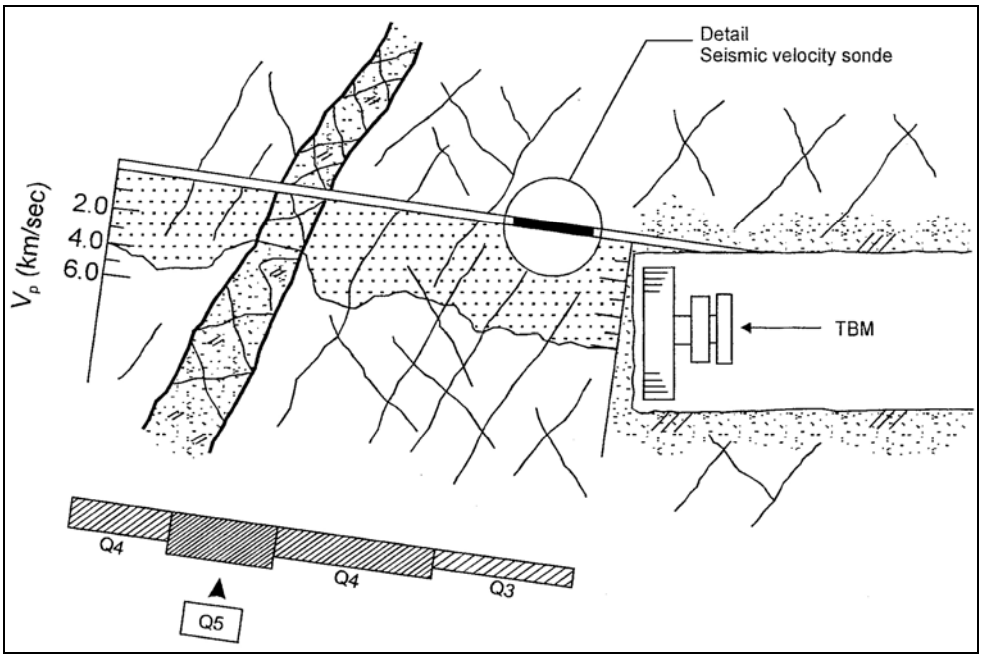

Figure 11. An idealized (percussion) probe drilling and seismic velocity Q-class identification suggested for Hallandsås Tunnel in Sweden. Barton, 1996a. After many years delay, and various reasons for these delay including rock quality, construction now continues.

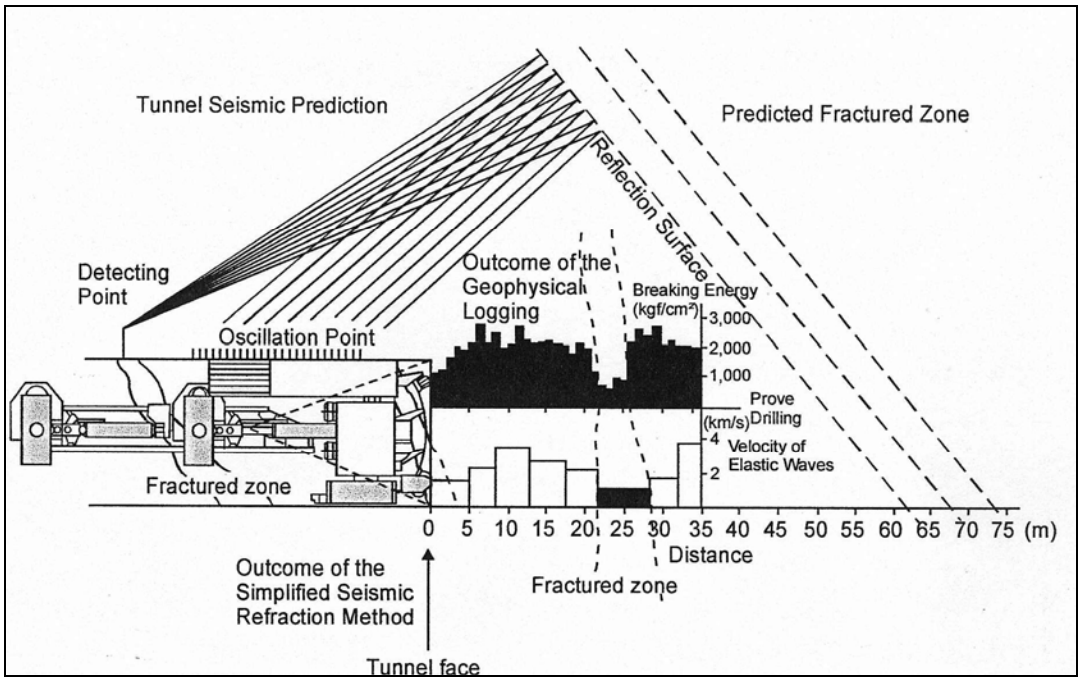

Figure 12. Combined use of seismic reflection and refraction in Japan, for identifying reflectors ahead of the tunnel, and for rock quality assessment in probe drill-holes. This is ideal good practice for reducing risk. After Nishioka and Aoki, 1998.

serious faulting in a D+B tunnel. It is easier to perform efficient drainage when the whole face is available, and probe-drilling and pre-injection can be performed in a more thorough manner than in the restricted geometry presented by the TBM.

4 PROBE DRILLING AND PILOT TUNNELS FOR REDUCING RISK

Referring to Figure 2, one can see that a conventional probe drilling, angled upwards, would have failed to identify the potential problem of water inrush in the Dul Hasti HEP. In other words, if geometrically possible, it is important to probe drill to intersect the part of the geologic structure that first will intersect with the tunnel – in this case angled downwards, not upward or straight ahead. This would apply equally to TBM and D+B tunnels.

Figures 11 and 12 illustrate an important potential for reducing risk, even after route selection is fixed and tunnelling has commenced. Nevertheless, it is necessary to bear in mind not only the general stress effect referred to earlier, but also the potential stress-compaction effect on the rock mass immediately ahead of the tunnel, which may have a similar form

to the (2D) tangential stress effect on velocity in the EDZ, documented (i.e. measured) many years ago.

In the case of the Pinglin tunnels in Taiwan (see cross-section in Figure 3), there was a good intention to use the pilot tunnel both to drain the rock mass ahead of the main (11.7m diameter) TBM tunnels, and to perform pre-injection from the pilot tunnel, to improve conditions ahead of the main tunnels. As we have seen, this proved almost impossible, due to a variety of compounded risk factors.

A pilot TBM technique was used successfully for reducing risk in the case of the Channel Tunnels between the UK and France. However, even here, the unexpectedly wet and jointed conditions of the chalk marl in the early sub-sea chainage of 20 to 24 km caused major problems with cutter-heads, electrical equipment and with the (unbolted) PC-element ring building.

The designers had apparently not expected the 4 to 9 MPa chalk marl to be extensively jointed, with planar, weathered joints and significant water pressure. A typical Q-parameter logging of the poorer conditions in this early chainage was as follows: Q = 90/6 × 1/1 × 0.66/1 = 10.0. Pre-construction sources of data (existing tunnels and marine core) logged by Barton and Warren, 1996b, gave similar results: Q = 100/9 × 1/1 × 1/1 = 11.1. In other words the partly 'unfavourable' blocky conditions for PC element ring-building in the large running tunnels could have been predicted, at least with the benefit of foresight.

Figure 13. A marine (English Channel) core drilling result (PB7) for the Channel Tunnel chalk marl, which was not apparently expected to be jointed, or permeable, due to its low compressive strength of 4 to 9 MPa. This proved to be a costly 'assumption'.

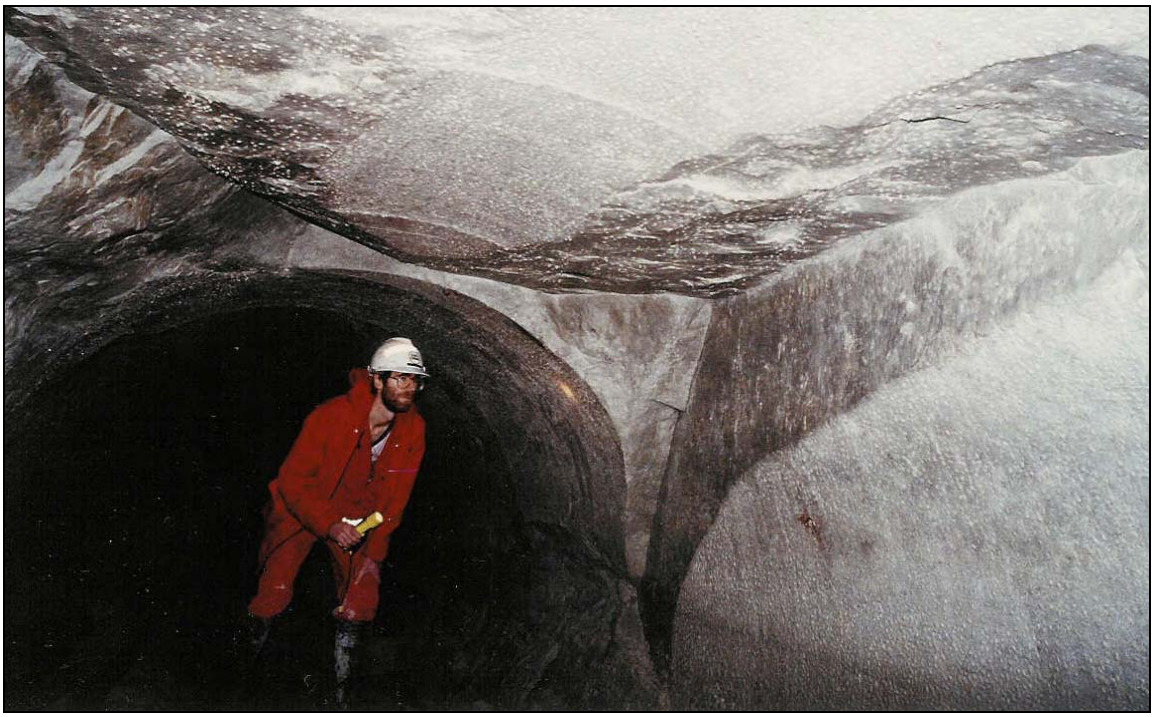

Figure 14. Jointing is evident in the world's first TBM pilot tunnel (Beaumont TBM, 1880), showing classic two-set (or three set?) wedge fall-out in this 4 to 9 MPa chalk marl. Some 110 years later, this rock was tunnelled at much faster speeds with 8.7m diameter TBM between England and France.

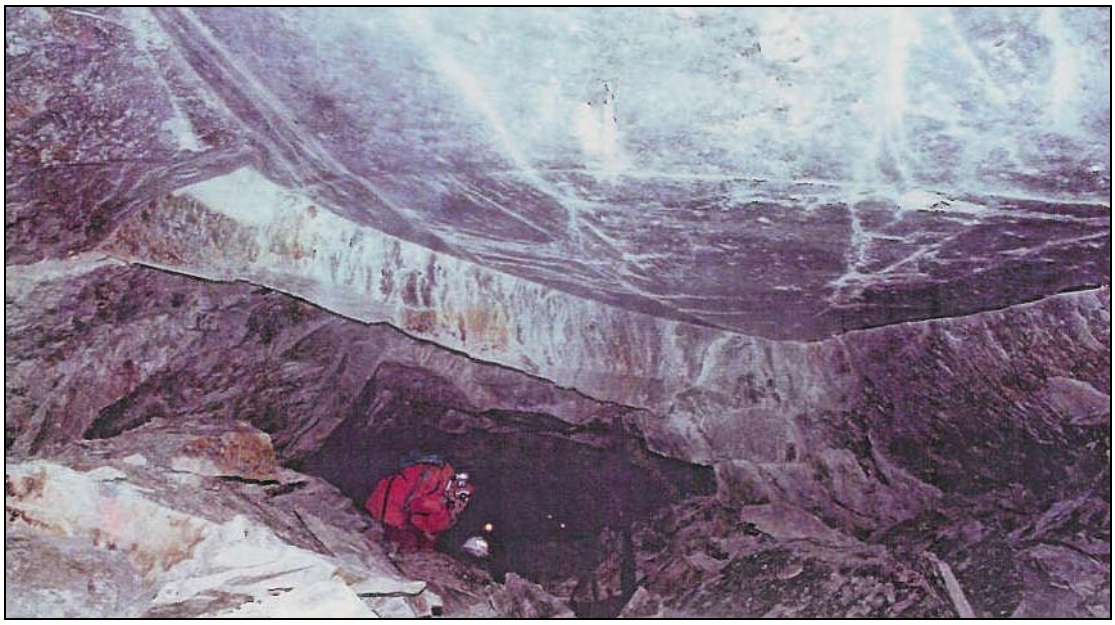

Figure 15. The same (1880) TBM tunnel at a location under the sea, showing breakage to bedding planes due presumably to increased water pressures.

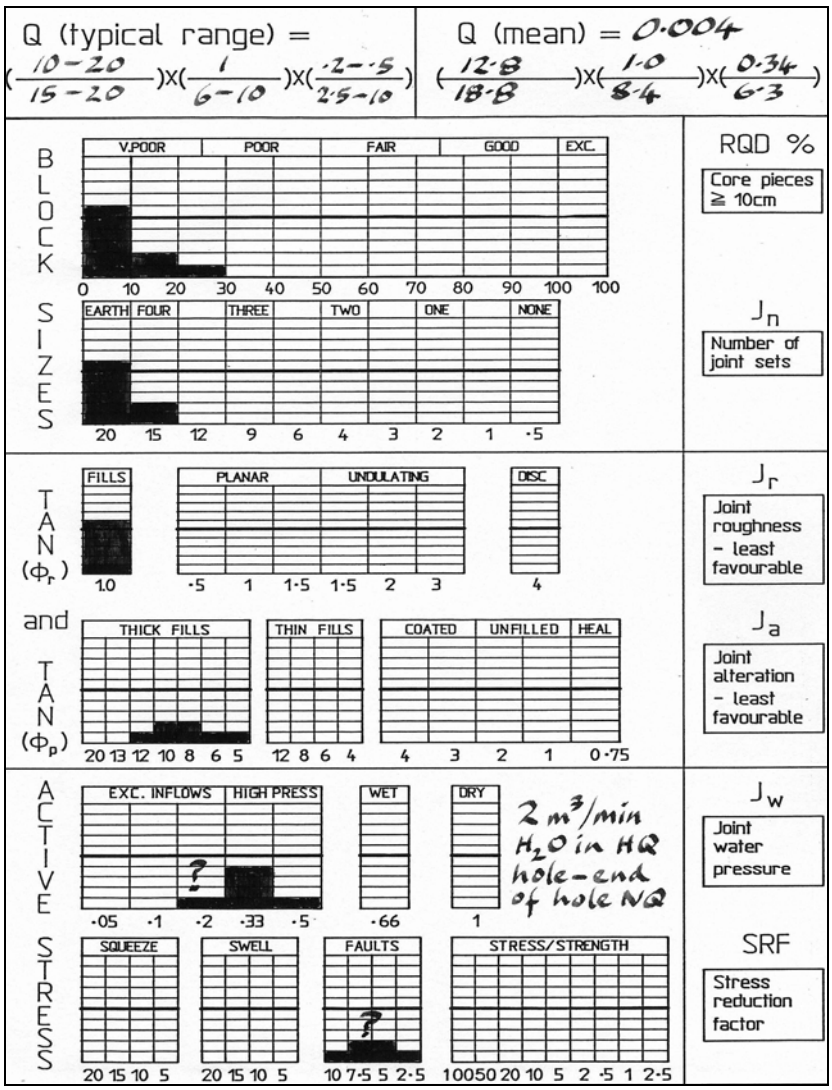

Figure 16. Core logging of horizontal pilot hole, ch. 711 to 731m, which was drilled from ahead of TBM Tunnel F, in the SSDS project in Hong Kong, to intersect the unexplored Tolo Channel regional fault zone. NB & A Contract report to Skanska, 2000.

5 LOGGING USING THE Q-PARAMETER HISTOGRAM TECHNIQUE

When logging conditions as revealed by core boxes, by surface exposures, or in tunnel walls and arches are variable from place to place – which is the rule rather than the exception, it is both *easier* and *more correct* to log all of this variability. Especially in a TBM tunnel, where logging is difficult when over-break is slight, *there is a tendency to concentrate logging where structure is evident, thereby neglecting the locations in a given chainage, where the rock is more massive – and actually less ideal for TBM tunnelling.*

Since about 1987, the writer has always logged the six Q-parameters using the so-called *histogram* logging method. This is illustrated in Figure 16, for the case of logging a regional fault zone ahead of the F1 sewage tunnel in Hong Kong.

It can be noted from this, and numerous other examples, that *extreme value* statistics will result in both lower and higher values of Q than the logging itself may have encountered. In other words, the possible combination of less favourable conditions (both 'too low' and 'too high') may already be captured implicitly by the histograms. This may be very useful! In the 'typical range' box in the top left of Figure 16, we see a possible minimum quality of Q = 10/20 × 1/10 × 0.2/10 = 0.001, i.e. lower than Q_{mean} – and representing a *catastrophically* difficult fault zone for a TBM in particular. It was only through heroic pre-injection efforts that the contractor managed to complete this 3.3m diameter sub-sea tunnel, after 3 years of difficulties.

6 CONCLUSIONS

1. Tunnelling risks caused by geotechnical factors are easy to list as individual factors, but difficult to predict (or imagine) as combined factors. Yet it is often the unfavourable combination of extreme values that are the 'unpredictable' causes of major tunnelling problems. Q-histogram logging helps to capture these possibilities, thereby potentially reducing risk.
2. The use of probe drilling and seismic logging ahead of the face can be a very powerful method for reducing risk, even when seismic refraction has been used prior to tunnelling, to interpolate rock mass conditions between boreholes.
3. Due to stress and fault-zone compaction effects caused by deep siting, it is important to apply depth (or stress) correction to V_p. A given velocity may give a false impression of good quality, due to stress effects causing elevated values of V_p.
4. Efficient drainage and pre-injection ahead of the tunnel face may be two of the most effective ways of reducing tunnelling risk. Unfortunately, in TBM tunnelling, these measures are also unusually difficult to apply effectively, but they are extremely important.
5. Pre-injection should be carried out using high pressure, but having regard for structural details. Effective improvements in rock mass properties may be achieved, at least locally.

REFERENCES

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

Barton, N. 1996a. Rock mass characterization and seismic measurements to assist in the design and execution of TBM projects. Proc. of 1996 Taiwan Rock Engineering Symposium, Keynote Lecture, pp. 1-16.

Barton, N. & Warren, C. 1996b. Rock mass classification of chalk marl in the UK Channel Tunnels. Channel Tunnel Engineering Geology Symposium, Brighton, September 1995.

Barton, N. 1999a. NGI contract report to NOCON.

Barton, N. 1999b. General report concerning some 20th Century lessons and 21st Century challenges in applied rock mechanics, safety and control of the environment. Proc. of 9th ISRM Congress, Paris, 3: 1659-1679, Balkema, Netherlands.

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

Barton, N. 2000. NB&A contract report to Skanska.

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

Nishioka, K. & Aoki, K. 1998. Rapid tunnel excavation by hard rock TBMs in urban areas. Tunnels and Metropolises. Negro Jr. & Ferreira (eds). 655-661. Rotterdam: Balkema.

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

Sjøgren, B., Øftshus, A. & Sandberg, J. 1979. Seismic classification of rock mass qualities. Geophysical Prospecting, 1979, 27, 409-442.