The Q-system following thirty years of development and application in tunneling projects

Nick Barton
Nick Barton & Associates, Høvik, Norway

Eystein Grimstad
Norwegian Geotechnical Institute, Oslo, Norway

ABSTRACT

Some key recent developments in using the Q-system for describing rock mass quality and some rock mass parameters are described. Links to seismic P-wave velocity, deformation modulus and simple rock mass cohesive and frictional strength terms CC and FC are discussed and tabulated. The updating of permanent support recommendations is taken two stages further, with specification of energy absorption requirements for the S(fr), and with dimensioning rules for RRS or rib reinforced shotcrete arches.

1 INTRODUCTION

A sound engineering approach should always precede construction in rock. Due however to the complexity of rock masses there is a need for a defensible simplification of the multitude of conditions actually present. One therefore builds a model of the site conditions which, though simplified, is a reflection of the main classes of rock conditions expected to be present. By collecting information from surface logging, sub-surface (core and boreholes) logging, and remote sensing such as refraction seismic and cross-hole seismic tomography, a fairly comprehensive picture of the likely range of conditions and of dominant rock classes is developed, and then successively updated and refined during excavation. This in a nutshell is the framework within which the Q-system is applied. It now has a 30 year international track record, thanks to interest by many engineering geologists and rock engineers in a method for realistically synthesising key information, whether from core logging investigations, or from logging of conditions revealed during excavation. Parts of key publications from the S(fr) shotcrere updating in 1993/94, and extensions of the system in 1995 and 2002/03 are briefly summarized, to help track the improvements.

2 Q-SYSTEM INTERPRETATION FROM SUPPORT NEEDS

The source of the Q-method of quantitatively describing rock masses was some 210 case records (Barton, Lien and Lunde, 1974), mainly describing the need for shotcrete (mesh reinforced cases from the 1960's and 1970's), and fully grouted rock bolts for permanently stabilising tunnels and caverns. A major updating of the Q-system based support recommendations was published by Grimstad and Barton in 1993, with 1050 new case records, this time involving S(fr) i.e. steel-fiber reinforced shotcrete in place of the older mesh reinforced S(mr). Grimstad collected these case records over many

years, and they were mainly from main road tunnels in Norway, specifically cases where the Q-system *had not been used* as the permanent support selection method.
The 'new' product; first used commercially in Norway in the late 1970's, is often called sprayed concrete, and it has revolutionized our ability to rapidly support exposed rock, making an earlier three-process support (shotcreting, mesh-fixing, shotcreting) into a much safer and faster one-step process, with application rates of up to $25m^3$/hour with modern shotcrete robots.

Recently it was realized (Barton, 2002) that these common *surface* support and *internal* rock reinforcement methods actually represent the need for supplementing the *cohesive* and *frictional strength* of the rock masses. This (overdue) realization is of importance because of a simple 1995 development of a direct (as opposed to indirect) normalization of Q by the uniaxial strength (Q_c=Q x σ_c/100). This development was needed for improved correlation of Q with rock mass parameters like deformation modulus and seismic velocity. It was found that Q_c was composed, in approximate terms of 'c' multiplied by 'tan φ'. In Table 1, the 'c' *cohesive component* term is CC = RQD/Jn x 1/SRF x σ_c/100, and the *frictional component* 'φ' term is the remaining parameters in the Q-value calculation, namely FC = Jr/Ja x Jw. (One may add that Q_c appears to have units of ≈ MPa.)

Table 1. Five progressively worsening rock mass qualities and their predicted near-surface properties.

RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	*FC°*	*CC* MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5
10	20	1	6	0.5	5	0.008	10	0.0008	5°	0.01	0.4	0.9

In retrospect, it is not surprising that such a combination of parameters, i.e. CC x tan FC is a powerful prescription for both the overall quality or lack of quality, and for the need of 'assistance' in terms of rock bolting, shotcrete, and sometimes also pre-injection. High pressure pre-injection has recently been predicted to slightly improve many of the Q-parameters (Barton, Buen and Roald, 2001/2002), thereby making a combined (predicted) *improvement* of the Q-value, and therefore of rock mass parameters that correlate with Q. Support needs are of course also *reduced*.

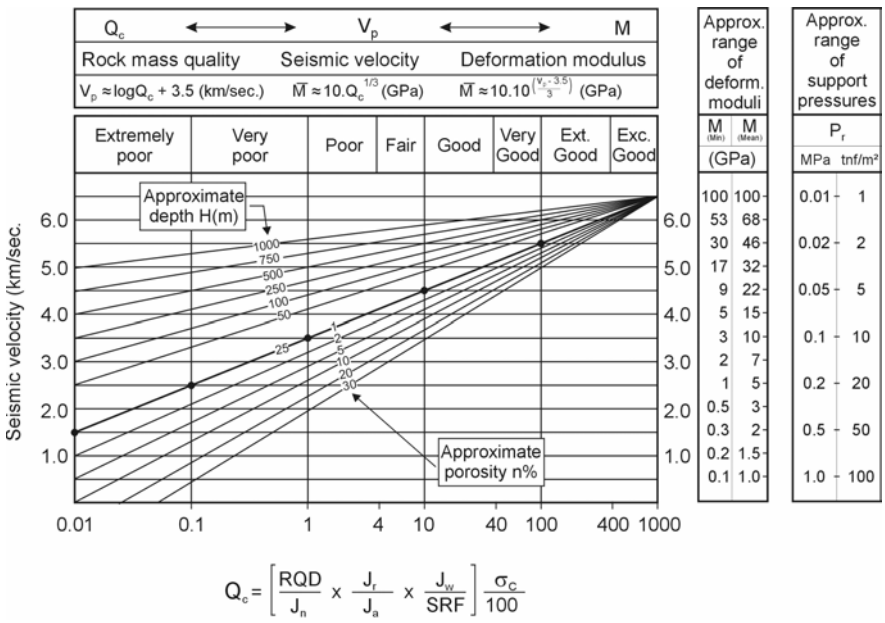

Figure 1. Correlation between Q_c, V_P, E_{mass} (or M) and the approximate support pressure. (Barton, 2002).

Because the Q-value can range over many orders of magnitude, just as physical conditions in nature have a tendency to do also, it is found that empirical correlation to useful parameters such as seismic P-wave velocity, rock mass (static) modulus of deformation, and to tunnel deformation are rather simple, contrasting strongly to those built up around RMR and GSI which allow only about one order of magnitude range in 'rock mass rating' (e.g. usually about 10 to 100). This difference is considered to be one of the main advantages of 'the Q-value'.

All the systems of collecting quantitative ratings to represent rock mass conditions can benefit from a statistical method of collecting the information. For more than 15 years the statistical variation of RQD, J_n, J_r, J_a, J_w and SRF has been collected in histogram format. On larger projects, this is combined with other statistical data needed for numerical modelling using UDEC and 3DEC. On some occasions in the last 20 years, we have found that for instance bolting patterns can be improved, following the added insight given by UDEC-BB modelling of the discontinuous and often anisotropic deformation patterns. In the latest developments in Q-logging, anisotropy in the input data (e.g. RQD and Jr/Ja) can each be accommodated in the predictions of rock mass parameters (Barton, 2002).

3 NMT – THE NORWEGIAN METHOD OF TUNNELLING

In NMT, as opposed to NATM, *direct* use of a rock mass classification method (the Q-system) is frequently made in predicting final tunnel support needs, and these estimates are systematically updated during tunnel advance, without general use of deformation monitoring, except in special cases when significant large deformations are expected. Since the permanent support recommendations for the various rock classes come directly from the Q-value (with modifications if numerical modelling suggests such, or due to mesured deformations.), the final support is frequently a combination of fully-grouted rock bolts (often sleeved CT bolts) and high quality, wet process S(fr). This is visualized on the left hand side in Figure 2. One may also use RRS (rib-reinforced shotcrete arches) in the lower rock classes, both as temporary and permanent support. Figure 3 shows the various support options.

Where water control is demanded in subsea tunnels and for environmental reasons, systematic pre-injection will be performed over the necessary stretches of tunnel. In both grouted and ungrouted tunnels free standing water shielding, often with frost insulation, is installed. In each of the above 'drained' solutions, the cost of an expensive water-proof cast concrete liner and membrane is avoided, and the road-way or rail-way is equally as dry as the more costly solution. It is for the above reasons that we use the term NMT, which is mostly used in harder jointed rock masses.

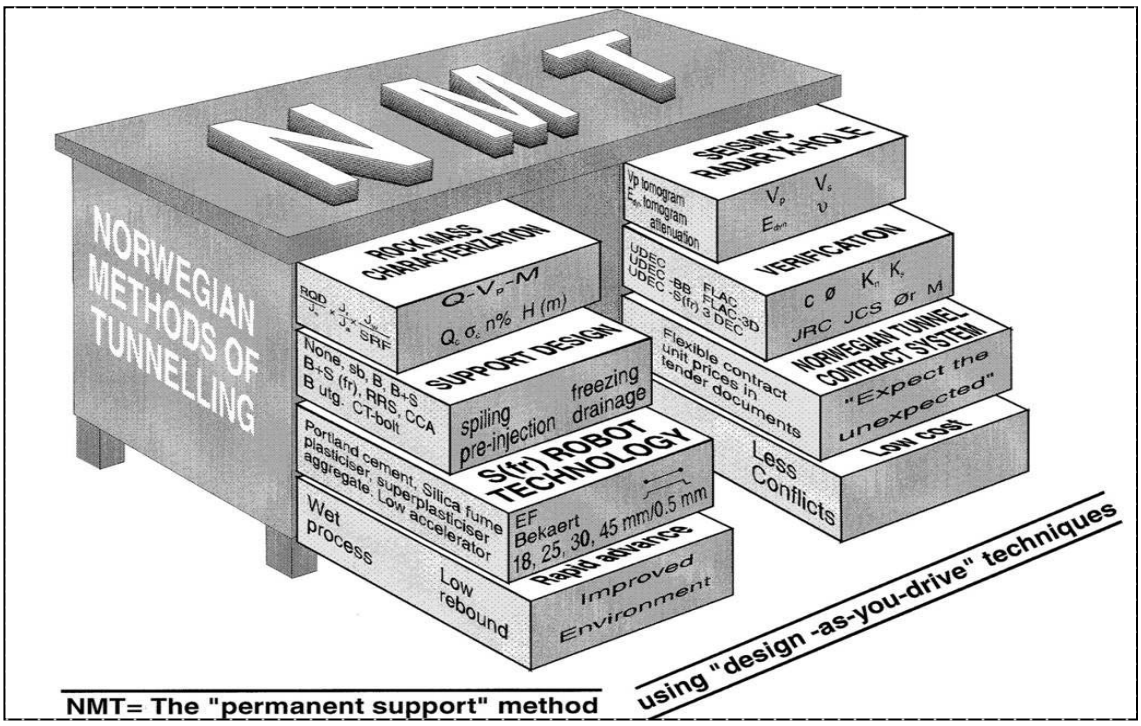

Figure 2. The NMT designer's desk, summarising some key aspects.

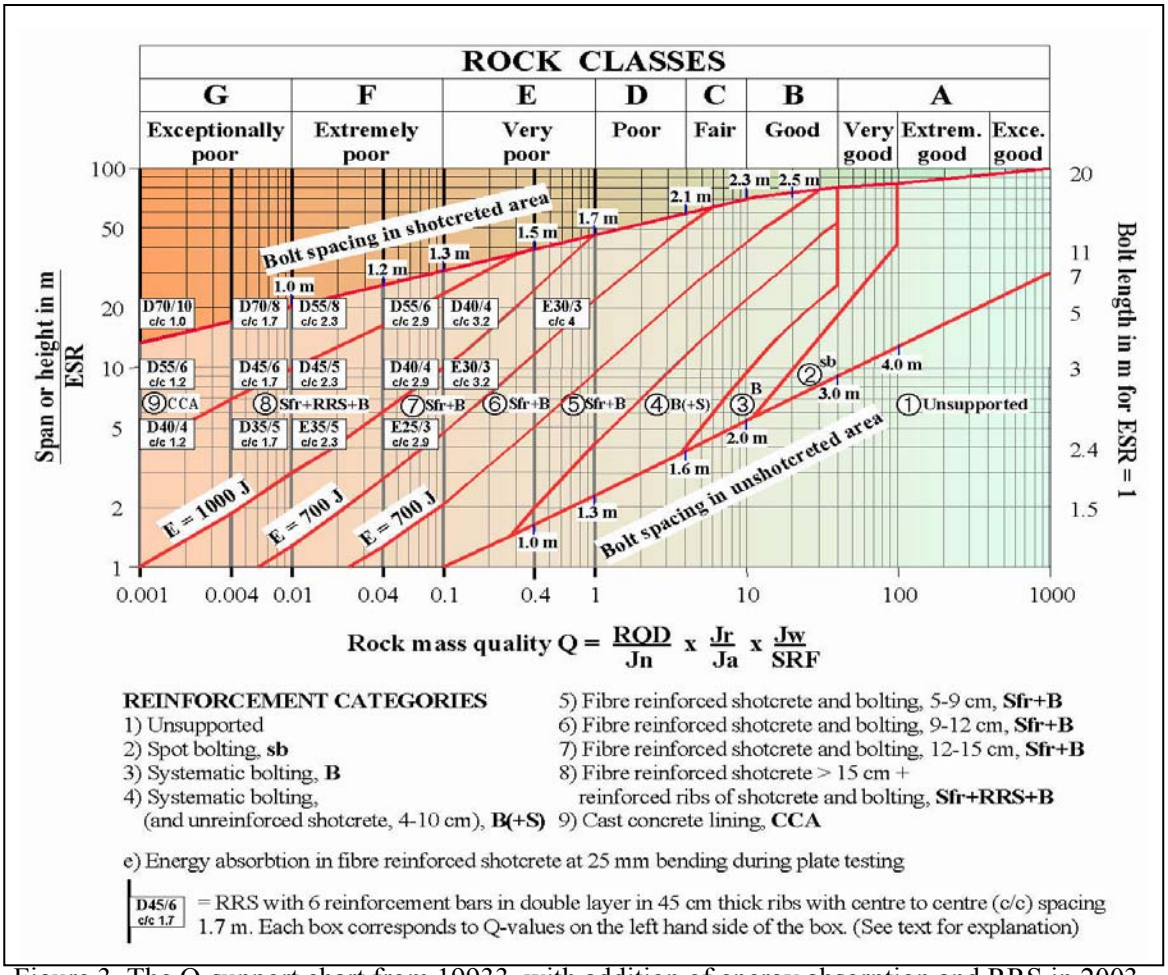

Figure 3. The Q-support chart from 19933, with addition of energy absorption and RRS in 2003.

4 UPDATED PERMANENT SUPPORT RECOMMENDATIONS

When rock mass quality is poor, deformation can easily amount to tens of millimeters, sometimes more than 100mm, and primary layers of shotcrete must therefore tolerate, together with the rock bolts, these deformations, without losing all the residual strength. It then becomes particularly important to apply primary shotcrete with more energy absorbtion, using fibres with high aspect ratio in the shotcrete. When the final S(fr) treatment is made, one may apply a more ridgid permanent suport with high strength shotcrete, eventually combined with RRS. Figure 3 illustrates an update of the Grimstad and Barton 1993 recommendations, with the addition of suggested energy absorption or toughness classes, as defined by EFNARC (see Norwegian Concrete Association Publication no. 7 (1999 and 2003). The Q-chart also shows the dimensioning of RRS in these poor rock conditions (together with the initial S(fr) and bolting). This has been detailed by Grimstad, Bahsin, Wold Hagen, Kaynia and Kankes (2003).

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