Viewpoint:

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This Comment paper is in response to the article: 'Key principles for hydropower tunnel design, construction and operation' by D. Brox, published in *H&D* Issue 4, 2024. The letter responds to the author's opinon on the foreign application of the Norwegian Tunnelling Method and addresses the concerns raised.

The authors of this Comment, and other tunnellers in Norway, were surprised at the strength of Dean Brox's critique of the foreign application of 'the Norwegian Tunnelling Method', or NTM, as Brox had understood from reading possible student lectures in Chile given by Eivind Grov of SINTEF. We have registered some 45 publications with NMT (not NTM) in the title, or with NMT prominently discussed, also by some of the originators of the Q-system and its further development, but rather surprisingly none of these has been referred to by Brox, who based some views on his own opinions, referencing just one research project manager from Trondheim who did not develop Q or NMT or NTM.

Before addressing some of Brox's concerns and actual errors, let us consider how he would react if it was suggested (and prominently published) that for him to practice his opinions outside Canada would represent 'a fatal flaw'. That he should keep to 'best quality Canadian granite', that his 'false and dangerous' application of such and such opinions outside Canada would represent high risk. Brox would not appreciate such comments, and nor does the Norwegian tunnelling community appreciate such comments. His paper contains plenty of valid comments on the need to take great care with water sensitive rock and swelling clays. That has been part of the advice within the Q-system for 50 years and in such case records well before this.

Brox makes an incorrect assumption, as others have done who do not appreciatethe details of the Q-system, by lumping it together with RMR and GSI, and criticizing them collectively for "not providing an appropriate means of characterizing the long-term durability of water sensitive bedrock with adverse mineral constituents". The Q-system, because of this 'lumped critique' has also been criticized on previous occasions, even in a European keynote lecture, for not taking into account water or stress or tunnel depth. This is not correct.

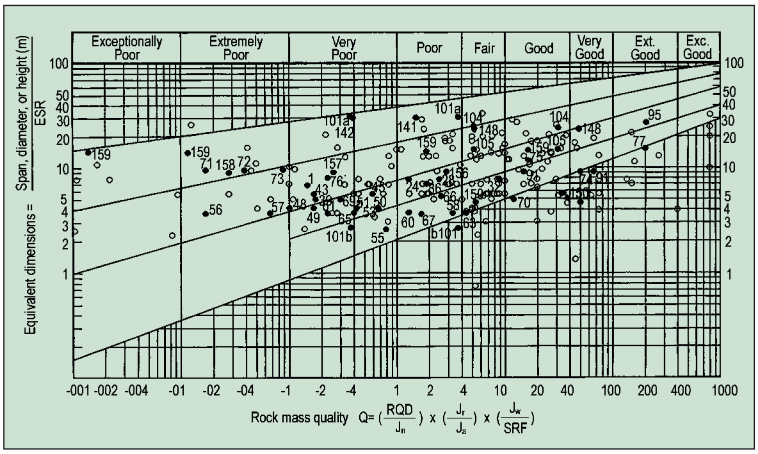
The 'fatal flaw' opinion of Brox regarding the application of Q-system based shotcrete permanent support recommendations, except in the case of what would actually be self-supporting high quality Norwegian granites, is a risky viewpoint, as Brox seems to have misunderstood several key aspects of drill-and-blast tunnels. No, we do not need to fill overbreak, and no, we do not fill so-called 'rock traps' with rock, because at least those who know better do not design with the high flow velocities that would be 'needed'. Another presumed expert from Canada also questioned whether rocks could reach the turbines when nominally 'unlined' tunnels for hydropower (NMT: unsupported or single-shell B + Sfr) were being discussed in a court case in Australia some years ago.

It is sure that those pioneers behind the earlier 99 per cent hydropower-based electric grid in Norway discovered how to avoid 'rocks in the turbines' at least 100 years ago. In this connection, the Brox reference to the problems at Hidroituango in Colombia in his Table 1 of 'updated collapses' is somewhat misplaced as it was specifically the result of much too high flow velocities (10 m/s and even greater) without invert concrete or increased erosion protection. A velocity even in excess of 36 km/hr and flow around a quite sharp bend has no place in Q-system tunnel support strategies and is far different from the 60 per cent of hydropower case records used in Barton *et al* [1974] to develop the Q-system.

It is not known whether we can exactly equate the Brox reference of 'NTM' to NMT as published for many years by the undersigned and colleagues, probably starting in World Tunnelling in 1992 with multiple authors from several Norwegian design, owner and contractor companies. It has become a very big NMT reference list (> 45 publications). When the undersigned have been authors or co-authors the publications never refer to 'NTM' only NMT (Norwegian Method of Tunnelling). None of these NMT publications have been referenced by Brox, who has only referenced what may be a lecture on 'NTM' to students in Chile, by Eivind Grov of SINTEF. This is what is suggested in Google. Apologies if incorrect, but the Brox reference to Grov was not sufficient.

The Q-system and the implicit NMT that followed, that is, 'single-shell' tunnelling (shotcrete and systematic bolting), with Q-based characterization for selecting support and support class, was strongly based on hydropower case records from Norway and Sweden from pre-1974 cases. (60 per cent of the case records for developing Q in 1973 were from hydropower projects). There were 50 different rock types in the first 212 case records, and granite, though very common was not the only common rock type. Brox, even with a tunnelling book to his name, seems to have a very biased (and incorrect) picture of Norwegian and Swedish tunnels. To have the opinion that the Q-system is only reliable in high quality Norwegian granites, where actually no B+S(fr) would even be needed, is clearly absurd, and is an example of his blind bias

There are now > 3500 km of hydropower tunnels in Norway. This is much, much more than in Canada. There are numerous rock types involved, numerous depths including > 1000 m, and extensive water- and unloading-sensitive swelling minerals like montmorillonite in countless hydrothermally altered weakness and fault zones. Thick multi-layered shotcrete and appropriate bolting, maybe in the form of RRS is the recommended tunnel support result. Brox has misunderstood RRS (rib reinforced shotcrete arches), as he refers to a 12 to 15 cm thickness. This is in error by a factor of between 2 to 6, depending on how low the Q-value is, and what the tunnel span is.



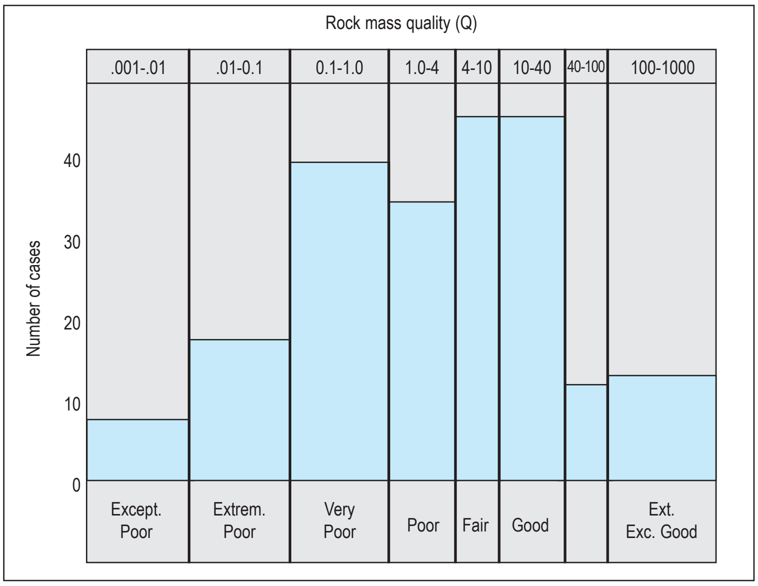


Fig.1. The original 212 case records that were used to develop Q with trial-and-error development of appropriate ratings for the six parameters. Poor quality clay-bearing, and swelling-clay bearing rock masses were deliberately selected, as well as medium and good quality cases, in order to extend the use of Q into tunnel sections requiring heavier support.

Fig. 2. The statistics of the Q-values in the first 212 case records. (ASTM conference, USA, Barton, 1987).

The solution is unlikely to be PC-element-lined and more costly TBM as being recommended by Brox and his TBM contractor and co-author Grandori of SELI because a hydrothermally altered zone could trap a TBM or crush the PC-elements subsequently as the unloading will invite more swelling. For the lowest quality Q-values due to fault zones containing swelling minerals the recommended support used to be CCA (local as needed cast concrete arches and concrete invert). This was until S(fr) was introduced in a big way after 1980, and subsequently RRS which was illustrated in our 1992 joint industry publication on NMT: Barton *et al* [1992[1]]. A deliberate selection of numerous high Ja and high SRF cases due to swelling minerals (montmorillonite etc) was made when developing the Q-system. This tunnel support related rock mass classification method could not have been developed with (actually unsupported) 'granites' (or best quality gneisses or quartzites or leptites. Apparently Brox's primary imagination of Norwegian tunnelling is best quality granite. Figures 1 and 2 show the wide Q-value spread of cases selected for generating the Q-system, and 50 different rock types.

Since the Q-system is extensively used in major mining nations for stope design (using Q' : the first four parameters) and there are an estimated 3500 km per month of new mine roadways in the top five nations (pers. comm. Antonio Samaniego SRK, Peru) there must be many hundreds of thousands of kilometers of single-shell shotcrete-lined tunnels world-wide, with the Q-system very frequently used for support class selection. Although the mine roadways may only be used for 10 to 20 years (?) they are highly trafficked. Of course they are not water conducting.

There are likely to be >10 000 km, perhaps even 20 000km, of 'single-shell' shotcrete lined (S(fr)+B, or S+ B, or S(mr)+B) and bolt reinforced hydropower, and sometimes unlined hydropower tunnels world-wide. The actual major failures probably amount to a

Table 1

I. Igneous		II. Metamorphic		III. Sedimentary	
Basalt	1	Amphibolite	8	Chalk	1
Diabase	4	Anorthosite (meta-)	1	Limestone	3
Diorite	2	Arkose	1	Marly Limestone	1
Granodiorite	1	Arkose (meta-)	3	Mudstone	1
Quartzdiorite	1	Claystone (meta-)	2	Calcareous Mudstone	1
Dolerite	1	Dolomite	1	Sandstone	4
Gabbro	2	Gneiss	14	Shale	2
Granite	46	Biotite Gneiss	1	Clay Shale	2
Aplitic Granite	1	Granitic Gneiss	4	Siltstone	2
Monzonitic Granite	1	Schistose Gneiss	2	Marl	1
Quartz Monzonite	2	Graywacke	1	Opalinus Clay	1
Quartz Porphyry	2	Greenstone	1		
Tuff	2	Schistose meta Graywacke	1		
		Quartz Hornblende	1		
		Leptite	11		
		Marble	1		
		Mylonite	4		
		Pegmatite	2		
		Syenite	1		
		Phyllite	1		
		Quartzite	13		
		Schist	17		
		Biotite Schist	1		
		Mica Schist	2		
		Limestone Schist	1		
		Sparagmite	2		

combined length of a few hundreds of meters (if we ignore an infamous project in Eastern Europe where the designers were not familiar with the workings of the Q-system). We also have to ignore Hidroituango, Colombia where a water diversion velocity was in the 10-15 m/s (36 to 48 km/hr!) range with only regular single-shell Q-based tunnel support design and no invert treatment.

The Q-system development was based on case records with only a 1.5 to 3 m/s velocity range. The summed length of actual local tunnel failures of a few hundreds of meters in perhaps 20 000 km is a rather small percentage, but of course the consequences of each were very expensive, and debris spread amounted to several kilometres, if combined. When a contractor is cutting corners and, for instance, not even grouting bolts then total distressed lengths can be much more. The undersigned know of one project where temporary support selected on the basis of incorrect numerical modelling and consisting of lattice girders and thick S(fr) finally failed in both motorway tubes for a combined length of 280 m. When inappropriate design is used tunnel failures can occur, even when no water is involved.

The only reference to 'NTM' used by Brox in his recent 2024 article is Grov, 2023. None of the articles published by those perhaps most responsible for promoting single-shell NMT, with the Q-system applied for support class selection were referenced by Brox. It was not possible to find the 'Grov 2023' article in Google, but it may be in relation to a lecture to students in Chile. We do not know how Grov represented the details of NMT and Q in his 'NTM' article/reported lecture.

It should be noted that 'NTM' does not seek to 'maximise unlined sections' or 'minimize shotcrete thickness'. Brox recommends that 'NTM' is not used elsewhere in the world (outside Norway) except in 'very good quality, unaltered granitic bedrock'. It seems from this (actually 'no support needed') opinion that the book of 2021: 'Practical guide to rock tunnelling' (publishing house not given) might not be so practical as one might have hoped!

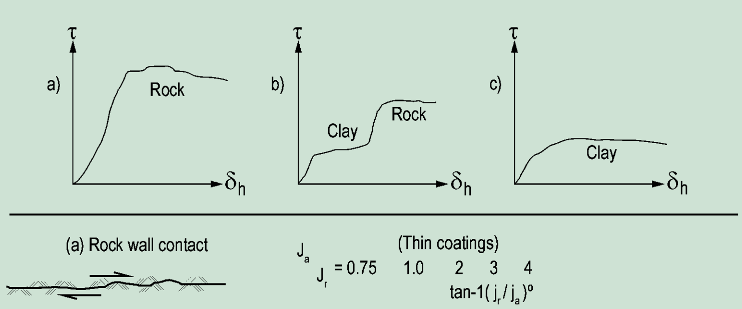
'Application of the 'NTM' beyond Norway represents a fatal flaw'. This amounts to an almost libelous opinion that is clearly absurd. Brox continues in the same almost libelous vein: 'It has been, and continues to be, falsely and dangerously promoted'.

Concerning Brox's Table 1 it can be mentioned that the TBM driven Glendoe headrace tunnel was locally left without shotcrete and bolting support in the arch despite the fact that a relevant close-by borehole had indicated a highly fractured zone at the location of the failure. Fracturing in the tunnel, presumably present, was apparently missed by those logging. In fact it is not easy to see fine fracturing in a TBM tunnel especially if overbreak does not occur and if the tunnel surface is not washed before inspection.

Concerning the massive progressive failures that occurred at Hidroituango, it can be mentioned that the initial failure of perhaps 10 to 20 m extent (at the base of a large final erosion 'cone') occurred immediately after an incongruously sharp bend in the large diversion tunnel (the fourth diversion tunnel at this project), where in this case standard Q-system based support and reinforcement was 'correctly applied' but based on the designer's failure to understand that possible flow velocities in the 10 to 15 m/s range lay far outside the most frequent 1.5 to 3.0 m/s range of velocities in 'nominally unlined' (only B+Sfr) headrace and pressure tunnels. Fatal flaws here were the failure to clean and concrete-line the large invert which had marked overbreak due to unfavourable Jn/Jr ratios (Barton, 2007), and the failure of the designer to understand the 'off-the-scale' velocity of 36km/hr or more and it's potential erosive powers. It is also not normal to have

Table 2

4. Joint alteration number approx.		Φ_r approx.	J_a
a) Rock-wall contact (no mineral fillings, only coatings).			
A	Tightly healed, hard, non-softening, impermeable filling, i.e., quartz or epidote.	25-35°	0.75
B	Unaltered joint walls, surface staining only.	25-30°	1.0
C	Slightly altered joint walls. Non-softening mineral C coatings, sandy particles, clay-free disintegrated rock, etc.	25-30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non- softening).	20-25°	3.0
E	Softening or low friction clay mineral coatings, i.e., E kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8-16°	4.0
b) Rock-wall contact before 10 cm shear (thin mineral fillings).			
F	Sandy particles, clay-free disintegrated rock, etc.	25-30°	4.0
G	Strongly over-consolidated non-softening clay mineral fillings (continuous, but < 5 mm thickness).	16-24°	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous, but < 5 mm thickness).	12-16°	8.0
J	Swelling-clay fillings, i.e., montmorillonite (continuous, but < 5 mm thickness). Value of J_a depends on per cent of swelling clay-size particles, and access to water, etc.	6-12°	8-12
c) No rock-wall contact when sheared (thick mineral fillings).			
KL M	Zones or bands of disintegrated or crushed rock and M clay (see G, H, J for description of clay condition).	6-24°	6, 8 or 8-12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening).	- -	5.0
OP R	Thick, continuous zones or bands of clay (see G, H, J for Rdescription of clay condition).	6-24°	10, 13 or 13-20



	J_r	J_a = 0.75	1.0	2	3	4
A. Discontinuous joints	4	79°	76°	63°	53°	45°
B. Rough, undulating	3	76°	72°	56°	45°	37°
C. Smooth, undulating	2	69°	63°	45°	34°	27°
D. Slickens ided, undulating	1.5	63°	56°	37°	27°	21°
E. Rough, planar	1.5	63°	56°	37°	27°	21°
F. Smooth, planar	1.0	53°	45°	27°	18°	14°
G. Slickensided, planar	0.5	34°	27°	14°	9.5°	7.1°

Fig. 3. The operations of the Jr/Ja ratio. As J_a increases as shown in Table 2, the implied (and extremely conservative) tan-1 (J_r/J_a) 'friction angles' get successively lower, causing successively heavier support, because virtually all parameters are adversely affected.

tight bends in water tunnels.

As mentioned earlier, Brox commits the common error of 'lumping the three classification methods' (Q, RMR and GSI) together, as if they had the same characteristics. Brox seems to be ignoring the fact that there were numerous actual cases of fault zones with hydrothermal alteration and montmorillonite that were deliberately incorporated in the case records used to develop the Q-system, so high Ja and SRF values are part of such support selection designs. (There is a potentially 1/20 x 1/20 = 1/400 lowering of local Q-values and correspondingy beefed up support).

The Brox Table 2 with an example as above with high Ja and SRF is labelled: 'Example of non-applicability of rock mass classifications'. This Brox opinion is strange in the extreme. He appears to have misunderstood tunnel support class selection using Q/NMT. It may also be remarked that the RQD is likely to be in error. It would most likely be 10 in the Q-calculation because of an actual 0 per cent result. For reference purposes, Table 2 and Fig. 3 show the way Ja takes account, with other parameters, of adverse mineralogy. The other parameters that may be adversely affected by hydrothermal alteration are in reality almost all the other parameter: RQD, Jn, Jr, Jw and of course SRF.

The choice of photograph of disintegrated rock cores from Esti, Panama is meaningless. The whole idea of a thicker, Q-value based (high Ja, high SRF) lining is that unloading is minimised. Correctly applied Q-based designs are not just for temporary support, but of course if further investigations of rock type demand thicker support due to an initial error of classification, then this is/should be provided.

There are detailed provisions for high stress designs in the Q-system, though not with RMR or GSI. In the Q-calculation SRF is based on the ratio of estimated tangential stress (for instance 2 to 3 times the maximum in situ stress) as compared to the UCS of the intact rock. Minimum stress (HFRAC) measurements have also been a regular feature of numerous HP projects in Norway in the past, and of course in numerous other countries where single-shell designs are planned or already in use.

Brox appears to be uncomfortable with sloping headrace/pressure tunnels. Enhanced final tunnel linings may or may not be needed. Rock stress increases faster than water pressure, even if the tunnel is under a horizontal surface. Stress anisotropy might be an issue, though usually it is less at depth.

Brox appears to have not understood that the larger cross-sections involved with drill-and-blast to give similar head loss to an idealized circular shape, tolerate overbreak. Single-shell tunnel lining is not expected to fill overbreak with thick shotcrete. If however he is just focusing on weak rock then overall thicker shotcrete would likely be needed.

The paper by Brox makes some incorrect assumptions about rock traps, as was also the case in a Canadian court case, that rock traps collect rock, and that if they get full there can be 'rocks in the turbines'. Of course if hydraulic theory is ignored (including the Hjulstrøm diagram) and plants are designed with velocities which are too high, then they could not be recommended for international practice.

One of the undersigned had the task of leading a group of more than 20 inspecting both drill-and-blast kilometers and principally many kilometers of mostly unlined TBM at the San Francisco plant in Ecuador, on behalf of the Brazilian contractor. Only very small gravel (and floating pumice) had reached the rock trap. A 'rock trap' inspected many years previously in Norway also did not 'collect rock' either. Dozens of larger block falls, and hundreds of smaller blocks do not (and did not) get transported in the San Francisco HEP at 2.5 m/s in the D+B tunnel, nor at 3.5 m/s in the smaller cross-section and smooth-invert TBM. Of course there are dynamic pulses, with start and stop of turbines, but the full tunnel of water can hardly be accelerated to high velocities due to questions of the inertia of perhaps 'million-ton' horizontal or sub-horizontal water columns.

In his Conclusions and Recommendations, Brox suggests that 'the application of rock mass classifications for the design of final shotcrete linings for hydropower tunnels sited in water sensitive bedrock with adverse mineralogy is a dangerous practice, which has resulted in collapses at multiple projects during early operations'. On this basis, the numerous case records used to develop the Q-system which had heavy support due the presence of hydrothermally altered rocks that had produced swelling clays such as monmorillonite, would be considered invalid and be ignored by Brox. With such an attitude the Q-system would never have been developed. ◊

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