TUNNEL SUPPORT SELECTION FROM Q-CLASSIFICATION, SUPPORT ELEMENT PROPERTIES, PRE-INJECTION, COST OF NMT

NB #2:
- ORIGINAL CASE-RECORD DATA BASE
- NMT CONCEPTS OF TUNNEL SUPPORT
- STRENGTH-DEFORMATION CHARACTER OF S(fr)
- STRENGTH-DEFORMATION CHARACTER OF BOLTING
- RRS FOR TUNNELLING IN BAD GROUND
- WATER CONTROL WITH:
  - CONCRETE AND PC-ELEMENT LINERS
  - PRE-INJECTION FOR IMPROVED PROPERTIES
  - SPRAYED MEMBRANE SANDWICH
  - COST AND TIME (NMT much cheaper/faster than NATM)

THE PROGRESSION OF PUBLISHED TUNNEL SUPPORT CHARTS FROM 1974 TO 1993

THE 1974 PUBLICATION WAS BASED MOSTLY ON B+S(m) CASES

INTRODUCTION OF S(fr) AT THE END OF THE SEVENTIES PROVIDED NEW CASE RECORDS

GRIMSTAD (NGI) USED ONLY NEW CASES WHERE THE Q-SYSTEM HAD NOT BEEN USED

THE LOWEST CHART WAS BASED ON 1050 NEW CASE RECORDS – SEE LATER

INTRODUCTION TO ‘NMT’
(Norwegian Method of Tunnelling)

NMT = single-shell (NATM = double-shell)
(B+Sfr accepted as final support)

Q-system application:
for selecting B spacing m c/c (1 to 2.5 m)
for selecting S(fr) thickness (5 to 25 cm)

(May use systematic pre-injection)
Tunnel support design using a new Q-system chart

NMT Compared with NATM
NMT uses a predictive classification for support design.
NMT gives the permanent support which is not followed by concrete lining.
NMT uses high capacity (10-25 m³/hr) robotically applied wetmix, steel fibre reinforced shotcrete.

Design
Preliminary design is based on field mapping, drill core logging and seismic interpretation.

Final support is selected during tunnel construction based on tunnel logging and use of the Q-system support recommendations.

Support
The permanent support usually consists of high quality wet process, fibre reinforced shotcrete and fully grouted, corrosion protected rock bolts.

Contract
The owner pays for technically correct support. Needed support is based on the agreed Q-value, and may vary frequently.

Some details concerning NMT. Tunnels are dry, drained, and PC-element cladded, or pre-injected, if required for road or rail use. (‘Pigging’ = scaling)

Details of the S(fr) thickness and bolt spacing. Grimstad and Barton, 1993
SOME IMPROVED TECHNOLOGY ASPECTS OF NMT

1. relevant shotcrete technology and equipment (Sfr NOT Smr !!)

2. relevant bolting technology (corrosion protected vitally important)

3. relevant water control (high-pressure pre-injection, sprayed membrane, or the free-standing liner)

B+S (better still B+S(fr)) gives by far the best tunnel-stabilizing result according to 5 years of deformation monitoring at an experimental tunnel in mudstone.

Ward et al. 1983 (left), Barton and Grimstad 1994. (right)
1. Relevant shotcrete technology and equipment

- Road-licensed, diesel/electric, high-output robot trucks, which can serve several tunnel faces.
- Each are capable of 20 to 25 m³/hour on-the-tunnel-wall shotcreting with S(fr).
- Rebound 4 to 6 % with right concrete design.
- Air/water jet cleaning > 15 minutes before each 1 hour of S(fr)!

Typical S(fr) mix design for C45 to C55 (MPa) shotcrete. Note operator location close to nozzle, where rebounds of 4 to 6% (and almost dust-free air) make quality control very easy.

Large-scale testing of S(fr) by Robocon in the mid-eighties. Fracture energy (area under load-deformation curves) was 60 to 80 times that of unreinforced shotcrete, depending on fibre dosage 40 or 60 kg/m³.

The illustrations below show tests used to document the toughness of steel fibre reinforced shotcrete.

The falling block test
The falling block test simulates the ability of the concrete to support a loose block of rock in a tunnel or rock cavern. Results show that steel-fibre reinforced shotcrete has higher strength and toughness than ordinary mesh reinforced shotcrete.
The circular plate test

The circular plate test simulates the load situation around a rockbolt. The test clearly shows that the amount of fibres present in the fractured surface is important in order to avoid sudden collapses. Many small cracks instead of a few large ones are formed, allowing the concrete to retain its strength.

The One Way Slab Test

The One Way Slab test simulates the same thing as the Falling Block test, except in this case there is no bonding between the layer of concrete and the rock. The whole load must therefore be supported by the bolts situated around the falling block. The tests show that the amount of bolts used may be reduced by 10 to 50 per cent, compared to none shotcreted area.

SLAB TEST LOAD-DEFORMATION BEHAVIOUR WITH S(fr)
Torsteinsen and Kompen, 1983.

Conceptual comparison of S(mr) and S(fr)
M. Vandevall (Bekær, Belgium)
The advantages of S(fr) compared to S(mr). There is today the additional advantage of alkali-free accelerator, allowing thick layers of S(fr) to be built up rapidly, without the previous loss of long-term strength when using ‘too much’ accelerator.

Barchip... example of excellent performance, anchorage

<table>
<thead>
<tr>
<th>Característica</th>
<th>Propiedad del Material</th>
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<tbody>
<tr>
<td>Resina</td>
<td>Polietileno</td>
</tr>
<tr>
<td>Largo</td>
<td>48 mm</td>
</tr>
<tr>
<td>Resistencia a la tensión</td>
<td>550 MPa</td>
</tr>
<tr>
<td>Textura superficial</td>
<td>Relieve continuo</td>
</tr>
<tr>
<td>Cantidad de fibras/kg</td>
<td>&gt; 35,000</td>
</tr>
<tr>
<td>Densidad específica</td>
<td>0.90 - 0.92</td>
</tr>
<tr>
<td>Módulo de Young</td>
<td>8 Gpa</td>
</tr>
<tr>
<td>Punto de fusión</td>
<td>150 - 165°C Celsius</td>
</tr>
<tr>
<td>Punto de ignición</td>
<td>&gt; 450°C Celsius</td>
</tr>
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</table>

POLYPROPYLENE FIBRE... gaining ground!

US$50 per m³
ASTM C-1550 Round Determinate Panel

<table>
<thead>
<tr>
<th>Juegos</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
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<tr>
<td>0</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>580</td>
<td>570</td>
<td>560</td>
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<td>1</td>
<td>550</td>
<td>600</td>
<td>650</td>
<td>640</td>
<td>630</td>
<td>620</td>
</tr>
</tbody>
</table>

Barchip kyodo 40mm 8 kg
Dramix RC 65/35BN 25 kg
Dramix RC 65/35BN 35 kg

Barchip kyodo 48mm 8 kg
Energy absorption classes

- E500  15-18kg steel fibre or 5kg PP fibre
- E700  20-25kg steel fibre or 6-7kg PP fibre
- E1000 30-35kg steel fibre or 8kg PP fibre

Energy absorption classes E500, E700 and E1000

<table>
<thead>
<tr>
<th>ROCK CLASSES</th>
<th>G</th>
<th>F</th>
<th>E</th>
<th>D</th>
<th>C</th>
<th>B</th>
<th>A</th>
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<tbody>
<tr>
<td>Exceptionally poor</td>
<td>G</td>
<td>Very poor</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
<td>Extrem. good</td>
</tr>
<tr>
<td>Extremely poor</td>
<td>G</td>
<td>Very poor</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
<td>Extrem. good</td>
</tr>
</tbody>
</table>


Energy absorption classes E500, E700 and E1000

- Bolt spacing in shotcreted area
- Bolt length in m for ESR = 1
- Rock mass quality $Q = \frac{RQD}{Jn} x \frac{Jr}{Ja} x \frac{Jw}{SRF}$
RRS (rib-reinforced shotcrete arches)

FOR VERY BAD ROCK CONDITIONS

(e.g. $Q < 0.1$)

**RRS philosophy**

- When $Q$-values are below approx. 0.1 (i.e. extremely poor), it can be expected that there will be the possibility of large over-break, low stand-up time, and significant early deformations.

- The use of steel sets should be avoided in such situations, due to the actual relatively larger rock-block loosening that they allow, unless followed immediately by bolting or shotcrete, or both.

- It is for this category of problems that RRS (or rib-reinforced shotcrete) has been developed.

- This is a much more effective measure than steel arches or lattice girders when conditions are very bad, because it provides a more rapid and much stiffer support than these two ‘solutions’.

One of the most robust support methods from the Q-system: RRS (rib-reinforced-shotcrete) ....far stiffer than steel sets!

**RRS prior to rib-spraying.**

Note bolting – a fundamental aspect
RS or steel-reinforcing-bar reinforced shotcrete arches, for the next-to-worst categories of rock mass, e.g. $0.01 < Q < 0.1$. 1 = first layer of general $S(fr)$ -- accelerated with non-alkali additive, 2 = build-up local, smooth but not necessarily circular arch (or arches) of non-alkali accelerated $S(fr)$, 3 = drill bolt holes at e.g. 1m centres round arch, and install end-anchored bolts with pre-fabricated, welded cross-bars. 4 = attach (wire and weld) 4-6x16mm reinforcing bar 'steel-arches' to each bolt-head cross-bar (pre-fabricate in bundles, for easier attachment. (Note: these bars can be bent into overbreak zone, therefore requiring less shotcrete volumes than with e.g. stiff lattice girder), 5 = spray over reinforcing bars with shotcrete, to complete arch and provide foundation for: 6 = bolts and washer, tensioned (bolt thread pre-protected with plastic caps. 7 = Spray over bolt heads to complete RRS arch.

Left: Appearance of ('bent') RRS in subway station location where central pillar was excavated after side-cuts.

Right: Use in road tunnel (CCA in background) where rock cover was reducing fast.

2. Relevant bolting technology (corrosion protected)

- Because NMT pre-supposes the use of S(fr)+B as the final support of tunnels and caverns (Barton et al. 1992, Barton and Grimsæt, 1984), it is important that also the bolts are of good quality, with suitable long-life corrosion protection.

- The widespread use of NMT principles in Norway for the last 35 years (45 years if S(mr) is included) has meant that there has been an excellent development of corrosion protected bolts in this country.

- The CT-bolt, manufactured by Ørsta Stål, incorporates a simple end-anchoring (wedge-lock) for easy installation and tensioning (if desired), followed by double-annulus grouting using a PVC-sleeve.

- With the layers: galvanising, Combi-coat (epoxy paint), grout, PVC-sleeve, grout: It has five layers of initial corrosion protection, and four are left if when the outer layer of grout is cracked due to joint deformation. (This is the usual start of corrosion for conventional bolts).
The CT-bolt with PVC sleeve (many meters length in practice. Maximum load capacities are 33 and 30 tons in tension and shear, respectively, for the 20mm diameter bolt (22mm with thread).

An over-cored CT bolt showing crack (joint) penetration to outer layer of grout – the usual commencement of corrosion for a conventional bolt.

Direct-shear tests of bolted joints. BJURSTRÖM 1976
3. Relevant water control

- hydrostatic liner and membrane
  - free-standing liner
  - pre-injection

There are several solutions to the water problem, and the different solutions tend to have widely different prices.

An example of one of the most expensive tunnelling solutions, like conventional NATM, with B+S (mr) for primary support, CCA (hydrostatic and membrane) for secondary support.

This high-speed rail tunnel through jointed chalk in Southern England, had final (2000-vintage) costs of US$ 128M /3.2 km, or $ 40,000 per metre.

This was three times higher than a typical NMT tunnel, with similar Q-value rock, using B+S (fr) as permanent rock support, and a PC-element + membrane liner, for a drained-but-dry solution.
3. Relevant water control

- hydrostatic liner and membrane
- free-standing liner
- pre-injection

There are several solutions to the water problem, and the different solutions tend to have widely different prices.

- Primary lining was 25 cm of S(mr): top-heading and bench construction, mostly by road-header, hence lack of overbreak.

- "Value engineering" resulted in 15% reduced price: final concrete thickness was reduced to 35 cm, with fibre reinforcement (TTI): the chalk was stronger than expected. (Watson, 2003, ICE).

- Note high arch / large cross-section, as no pressure-relief shafts.

NMT concepts in diagrammatic form. Note that stage No. 6 must precede stage No. 2 if stability / stand-up time is very poor.

Concerning the ‘dry-but-drained’ final result (for road or rail), note the PC-element (free-standing but bolted) liner.

This has an outer membrane/sheet lying over it, if required due to continued water inflow or drips – e.g. if high pressure pre-grouting had not completely controlled the water.

The liner is completed at rates up to 1000m per month, with suitable mounting machinery.

An example of PC-element final liner, placed after cleaning of muck and fill in the invert. Membrane and frost insulation (sandwich) shown.

An example of PC-element mounting for a two-lane road tunnel. Note the primary B+S(fr) permanent support, and the mostly dry surface of the shotcrete.
9 tons ARCH elements being lifted ready for fixing (bolting) in 220 km/hr double-track rail tunnel.

NMT (B+Sfr) then PC-element liner with outer membrane.

Actually used due to failure to control water.

PC-elements stacked at rail tunnel portal ready for mounting with outer membrane sheet – at rates of 900m/month (after learning curve)

3. Relevant water control

- hydrostatic liner and membrane
- free-standing liner
- pre-injection

There are several solutions to the water problem, and the different solutions tend to have widely different prices.

A pre-injection ‘umbrella’ could probably have prevented this (several weeks/months) delay
ADVANTAGES OF PRE-INJECTION:

1. Much less, or zero water (of course)
2. Less over-break (much less!)
3. Therefore less S(fr) volume: cheaper
4. Increased safety / stability during drive
5. Increased life-time for all components
6. Improved Q-parameter ratings (5 or 6)
7. Increased Vp (P-wave velocity)
8. Increased E modulus (less deformation)
9. Actual reduced need for heavy support
10. Easier to apply sprayed membrane

Pre-injection screens, may vary in length from 20 to 30 m, and have from 30 to 70 holes depending on tunnel cross-section. Hole spacing is from 0.5-1.0 m c/c

Approximate costs of pre-injection needed to achieve various levels of ‘dryness’ in 90 m² tunnels.

<table>
<thead>
<tr>
<th>Inflow (approx.)</th>
<th>Cost (Norway)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 l/min/100 m</td>
<td>1,400 US $ /m</td>
</tr>
<tr>
<td>10 l/min/100 m</td>
<td>2,300 US $ /m</td>
</tr>
<tr>
<td>5 l/min/100 m</td>
<td>3,500 US $ /m</td>
</tr>
<tr>
<td>1-2 l/min/m/100 m</td>
<td>≈ 5,000 US $ /m</td>
</tr>
</tbody>
</table>

The dilemma is how to get blocks (i.e. particles) that are too large in joints that are too tight.

...smaller particles! .... wider joints!
Left: Representing a regularly-jointed rock mass with a cubic network of hydraulic conductors of mean aperture (s) and mean spacing (S), based on Snow (1968).

Right: Estimates of (s) and (S), and the aperture inequality $E \geq e$ (Barton et al. 1985) which allows grout particles to penetrate real joints (E) even when (theoretical) hydraulic apertures (e) are apparently too small.

**Examples of joint apertures E and e in an NGI UDEC-BB model of twin tunnels. The larger (physical/mechanical) aperture is groutable – not the theoretical hydraulic aperture.** (Makurat and Barton, 1988).

**Left:** The inequality of (E) and (e) for mated joints under normal closure (or opening) is a function of joint roughness coefficient $JRC_0$. (Barton et al., 1985)

**Right:** an example of application of the above methods (e, S, $JRC_0$ and E), from 1978, at a permeable dam site in Surinam, where joints in the core were roughness-profiled. Barton et al. (1985).

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**Table: Grout-Take Estimates / m³ rockmass**

<table>
<thead>
<tr>
<th>Depth zones</th>
<th>$E(m)$</th>
<th>$e(m)$</th>
<th>$E(p m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-15m</td>
<td>0.3</td>
<td>150</td>
<td>218</td>
</tr>
<tr>
<td>15-25m</td>
<td>0.4</td>
<td>110</td>
<td>186</td>
</tr>
<tr>
<td>25-45m</td>
<td>0.6</td>
<td>80</td>
<td>159</td>
</tr>
<tr>
<td>45-60m</td>
<td>0.7</td>
<td>62</td>
<td>136</td>
</tr>
</tbody>
</table>

**THE RESULT OF TOO LOW PRESSURE, TOO COARSE GROUT: ‘WATER-SICK’ ROCK – MORE WATER AFTER INJECTION THAN BEFORE!**
An exemplary pre-injection result (Bærum Tunnel, Oslo)

Use high injection pressures when pre-grouting! (Pressure decay 50% in first 1m)

(Use 5 to 10 MPa where possible)

Then can avoid the ‘water-sick’ rock which comes with use of too low pressures, when unstable (bleeding) grouts are used.
WHAT ABOUT ROCK MASS PROPERTY IMPROVEMENT AS A RESULT OF SUCCESSFUL (HIGH-PRESSURE) PRE-INJECTION?

Next screens show 3D permeability changes as a result of grouting.

ROTATION (and of course reduction in magnitude) OF PERMEABILITY TENSORS, SUGGESTS SUCCESSIVE SEALING OF JOINT SETS IS OCCURRING, AS A RESULT OF THE GROUTING.

**CONSERVATIVE MODEL**

<table>
<thead>
<tr>
<th></th>
<th><strong>MORE REALISTIC MODEL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>RQD increases e.g. 30 to 50%</td>
<td>RQD increases e.g. 30 to 70%</td>
</tr>
<tr>
<td>Jn reduces e.g. 9 to 6</td>
<td>Jn reduces e.g. 12 to 4</td>
</tr>
<tr>
<td>Jr increases e.g. 1 to 2</td>
<td>Jr increases e.g. 1.5 to 2 (due to sealing of most of set #1)</td>
</tr>
<tr>
<td>Jr reduces e.g. 2 to 1 (due to sealing of most of set #1)</td>
<td>Jr reduces e.g. 4 to 1 (due to sealing of most of set #1)</td>
</tr>
<tr>
<td>Jw increases e.g. 0.5 to 1</td>
<td>Jw increases e.g. 0.66 to 1</td>
</tr>
<tr>
<td>SRF unchanged e.g. 1.0 to 1.0</td>
<td>SRF improves e.g. 2.5 to 1.0 due to consolidation of loose material</td>
</tr>
</tbody>
</table>

**WET WET WET WET WET WET WET WET WET WET WET**

**Before pre-grouting**

\[ Q = \frac{30/9 \times 1/2 \times 0.5/1}{0.8} \]

\[ V_p \approx 3.4 \text{ km/s} \]

\[ E_{max} \approx 9.3 \text{ GPa} \]

\[ K \approx 1.3 \times 10^{-3} \text{ m/s} \]

10 m Tunnel: B 1.6 m c/c, S(fr) 10 cm

**After pre-grouting**

\[ Q = \frac{30/12 \times 1.5/4 \times 0.66/2.5}{0.2} \]

\[ V_p \approx 2.8 \text{ km/s} \]

\[ E_{max} \approx 5.8 \text{ GPa} \]

\[ K \approx 5.0 \times 10^{-3} \text{ m/s} \]

10 m Tunnel: B 1.4 m c/c, S(fr) 13 cm

**DRY DRY DRY DRY DRY DRY DRY DRY DRY**

**Before pre-grouting**

\[ Q = \frac{50/6 \times 2/1 \times 1/1}{17} \]

\[ V_p \approx 4.7 \text{ km/s} \]

\[ E_{max} \approx 25.7 \text{ GPa} \]

\[ K \approx 5.9 \times 10^{3} \text{ m/s} \]

10 m Tunnel: B 2.4 m c/c

**After pre-grouting**

\[ Q = \frac{70/4 \times 2/1 \times 1/1}{35} \]

\[ V_p \approx 5.0 \text{ km/s} \]

\[ E_{max} \approx 32.7 \text{ GPa} \]

\[ K \approx 2.9 \times 10^{3} \text{ m/s} \]

10 m Tunnel: sb (spot bolts)

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**SPRAYED MEMBRANES**

as final water control

1. **“INTEGRITANK HF”** – Stirling Lloyd
2. **“MASTERSEAL 345”** - BASF

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**Sterling Lloyd – “Integritank HF”**
(brown layer first, white layer second)

Two-component / two work sequences, also need to smooth.

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**NOTE:** Need fibre-free shotcrete both before and after INTEGRITANK HF “two-coat” system. Maybe cheaper to invest e.g. 5,000 US$ / m in pre-injection.
Last layer of shotcrete directly onto the INTEGRITANK HF

Masterseal 345

Advantage that it is simply a powder mixed with water.

Can use same robot as with S(fr)

Example of “Masterseal 345”
(Holte and Nermoen, 2011)

Can spray directly onto S(fr), and spray the final S(fr) directly onto the membrane.
(An etyl-vinyl-acetat co-polymer)

(BASF and Norwegian Railways)

Width of photo = 4 cm
Loading test on 60 cm diameter by 5cm+5 cm membrane sandwich.

This composite type of sample has superior fracture energy.

(Average of three samples of each type)

Holte and Nermoen, 2011

Hindhead Road Tunnel

A traditional technical solution with primary lining sprayed concrete, secondary lining cast in-situ concrete with a sheet membrane for waterproofing, was the basis for the calculation and tendering.

In design-and-build contract, this was changed to S(fr) and double-bonded membrane. Saving of GBP 3,400,000 was reported.

• Lausanne Metro: BASF Masterseal 345
FINALLY:
COST / TIME ESTIMATION
IN
RELATION TO
THE
Q-VALUE
RELATIVE TIME FOR TUNNEL EXCAVATION AND SUPPORT

........potential benefits of pre-grouting, especially if Q ≈ 0.1

“Strengthening the case for grouting”