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)

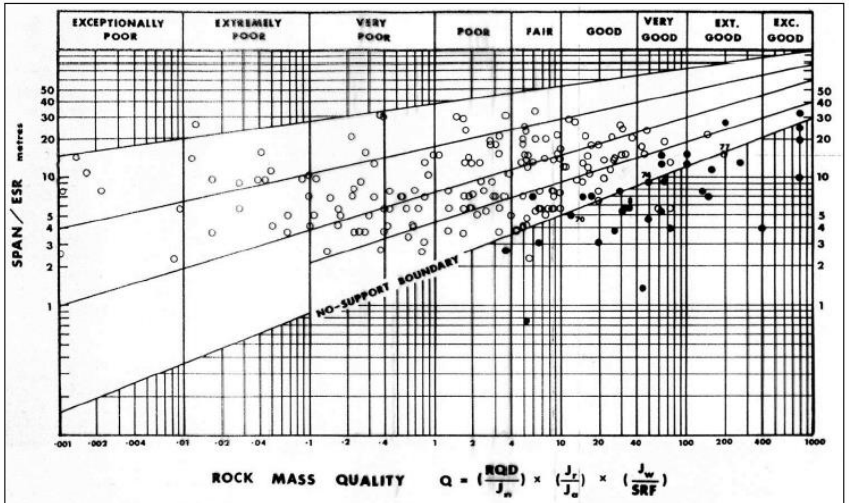
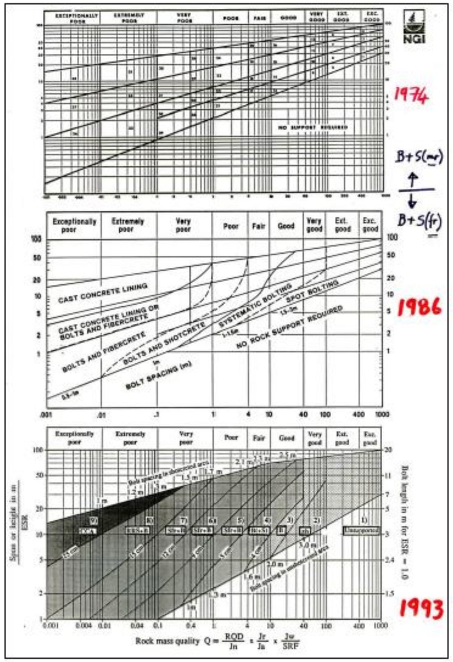


Figure 5. Analysis of case records indicates the approximate boundary between supported (o) and unsupported (•) excavations. The type of support, if any, depends on the rock mass quality (Q), the span, and the type of excavation (ESR).

212 case records, mostly B+S(mr) (from Barton, Lien and Lunde, 1974)



THE PROGRESSION OF PUBLISHED TUNNEL SUPPORT CHARTS FROM 1974 TO 1993

THE 1974 PUBLICATION WAS BASED MOSTLY ON B+S(mr) 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)**

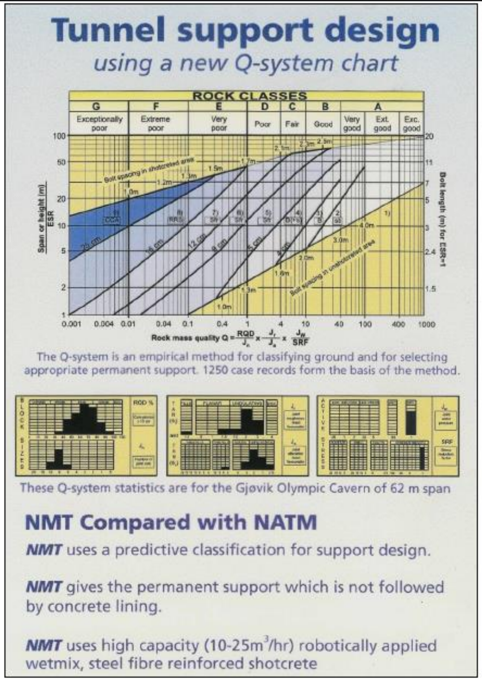
(B+Sfr accepted as final support)

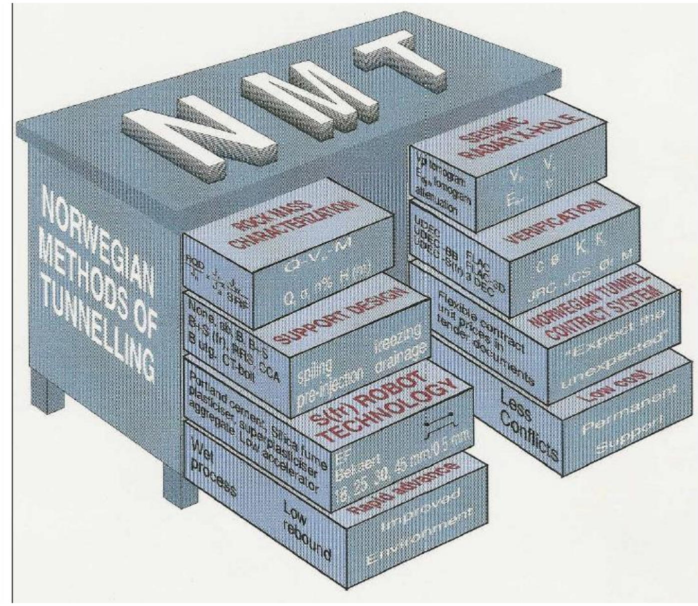
Q-system application:

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)





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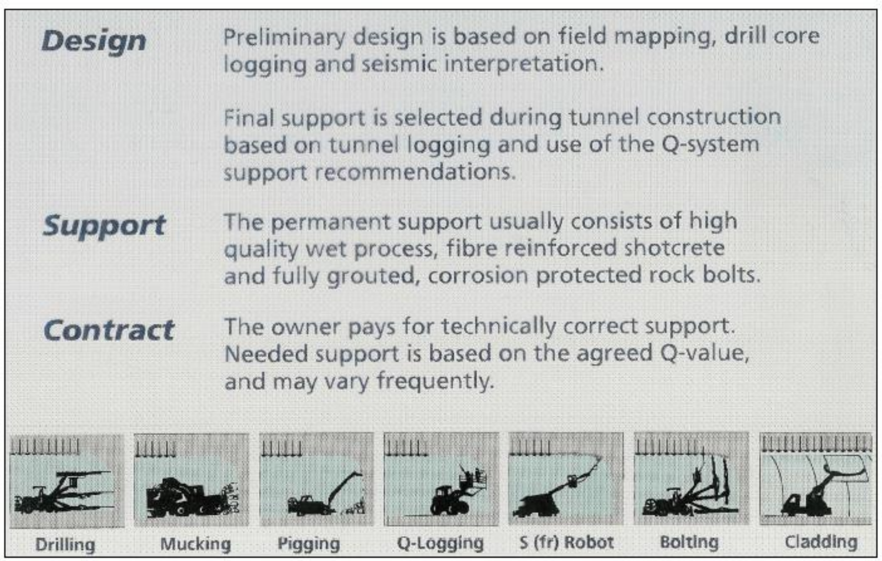
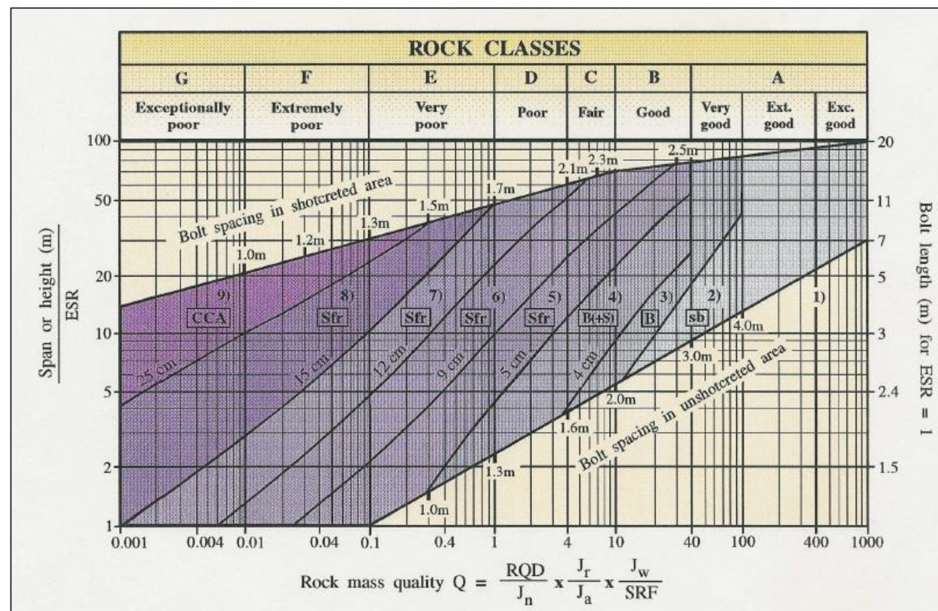


Some details concerning NMT. Tunnels are dry, drained, and PC-element cladded, or pre-injected, if required for road or rail use. ('Pigging' = scaling)



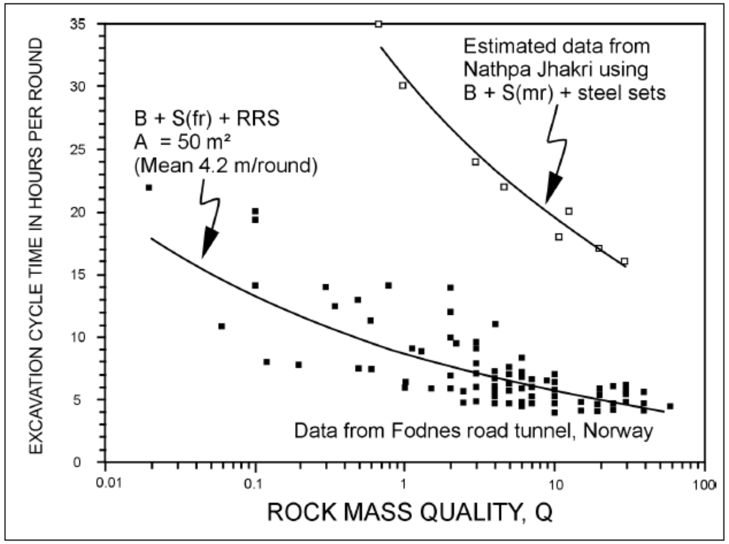
Details of the S(fr) thickness and bolt spacing. Grimstad and Barton, 1993

Design of Tunnels using NMT
and Verification with UDEC-BB 5

Table 2 Summary of recommended ESR values (updated) for selecting safety level.

	Type of Excavation	ESR
A	Temporary mine openings, *etc.*	*ca* 2-5
B	Permanent mine openings, water tunnels for hydropower (exclude high pressure penstocks), pilot tunnels, drifts and headings for large openings, surge chambers	1.6-2.0
C	Storage caverns, water treatment plants, minor road and railway tunnels, access tunnels	1.2-1.3
D	Power stations, major road and railway tunnels, civil defence chambers, portals, intersections	0.9-1.1
E	Underground nuclear power stations, railway stations, sports and public facilities, factories, major gas pipeline tunnels	0.5-0.8

UPDATED **ESR** RATINGS (= TUNNEL-USE-and-SAFETY rating for adjusting EQUIVALENT SPAN) (Barton and Grimstad, 1994)



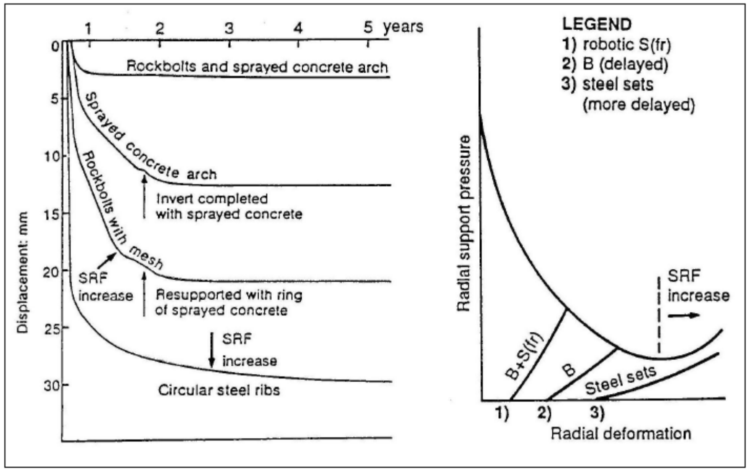
Cycle-time recordings (drilling the next round, blasting, waiting for gasses to clear, mucking, logging, bolting -if needed, shotcreting -if needed, as a function of Q-value. (Grimstad, NGI: pers com.1998).

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+Sfr) 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).

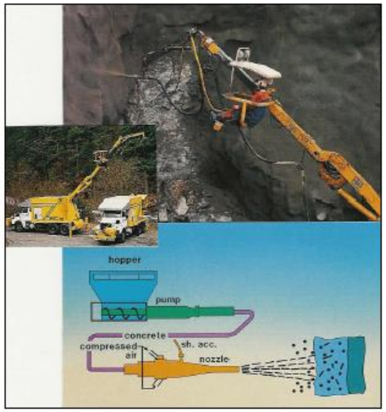
1. Relevant shotcrete technology and equipment

➢Road-licensed, deisel/electric, high-output robot trucks, which can serve several tunnel faces.

➢Each are capable of 20 to 25 m^3/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)!



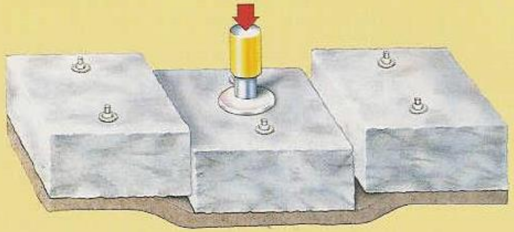
A typical mix design for shotcrete used in Norway:

Portland cement (c)	450 – 550 kg/m³
Silica fume (s)	3 – 10 % of cement weight
Aggregate	0 – 10 mm
Plasticizer	0.3 – 1.0 % of cement weight
Superplasticizer	0.3 – 1.0 % of cement weight
Steel fibre	50 kg/m³ (dependent on toughness requirements)
Water/(c+s)	0.40 – 0.45
Slump	15 – 18 cm
Air content	< 4%
Temperature	15 – 20 °C

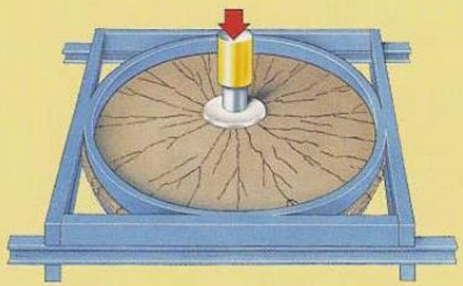
Typical S(fr) mix design for C45 to C55 (MPa) shotcrete.
Note operator location close to nozzle, where rebounds of 4 to 6% (and almost dust-free air) make quality control very easy.

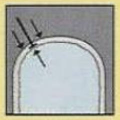
Large-scale testing of S(fr) by Robocon in the mid-eighties. Fracture energy (area under load-deformation curves) was 60 to 80 times that of unreinforced shotcrete, depending on fibre dosage 40 or 60 kg/m^3.

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



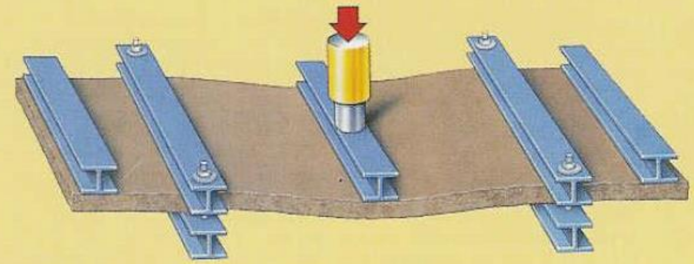
The falling block test
The falling block test simulates the ability of the concrete to support a loose block of rock in a tunnel or rock cavern. Results show that steel-fibre reinforced shotcrete has higher strength and toughness than ordinary mesh reinforced shotcrete.





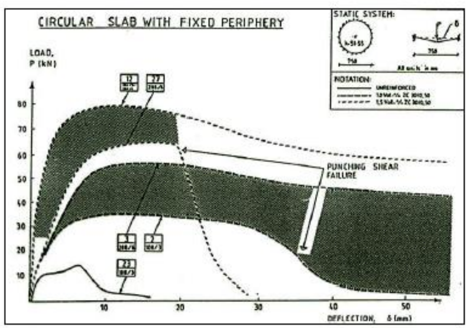
The circular plate test

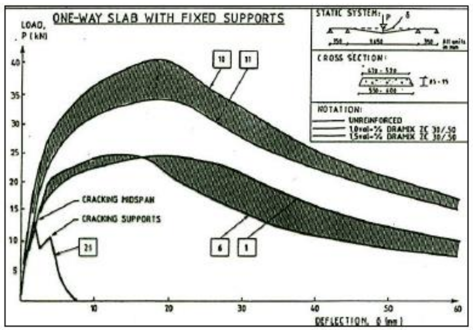
The circular plate test simulates the load situation around a rockbolt. The test clearly shows that the amount of fibres present in the fractured surface is important in order to avoid sudden collapses. Many small cracks instead of a few large ones are formed, allowing the concrete to retain its strength.



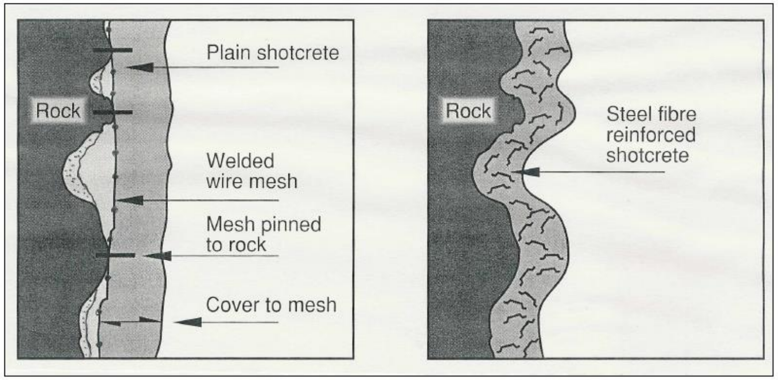
The One Way Slab Test

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 aerea.



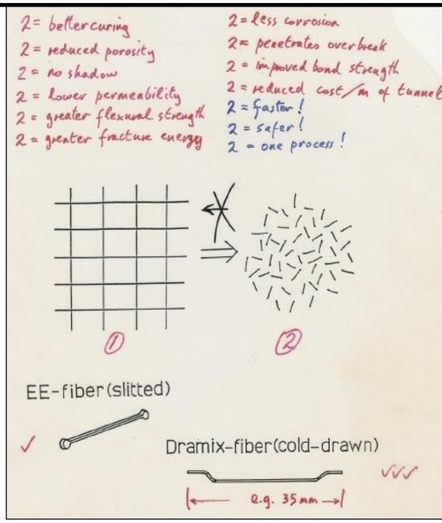


SLAB TEST LOAD-DEFORMATION BEHAVIOUR WITH S(fr)
Torsteinsen and Kompen, 1983.



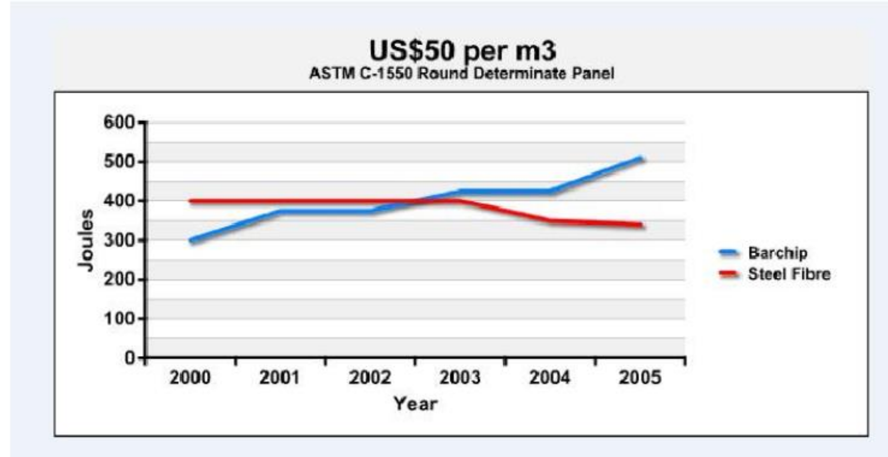
Conceptual comparison of S(mr) and S(fr)

M. Vandevall (Bekært, Belgium)

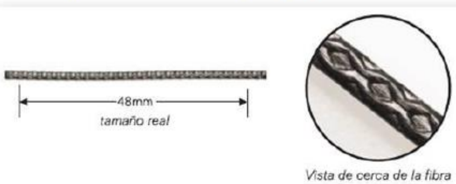


The advantages of S(fr) compared to S(mr). There is today the additional advantage of alkali-free accelerator, allowing thick layers of S(fr) to be built up rapidly, without the previous loss of long-term strength when using 'too much' accelerator. 21

POLYPROPOLENE FIBRE….gaining ground!



Barchip….example of excellent performance, anchorage



Características

Característica	Propiedad del Material
Resina	Poliolefina
Largo	48 mm
Resistencia a la tensión	550 MPa
Textura superficial	Relieve continúo
Cantidad de fibras/kg	> 35.000
Densidad específica	0,90 0,92
Módulo de Young	8 Gpa
Punto de fusión	150 - 165° Celsius
Punto de ignición	> 450° Celsius

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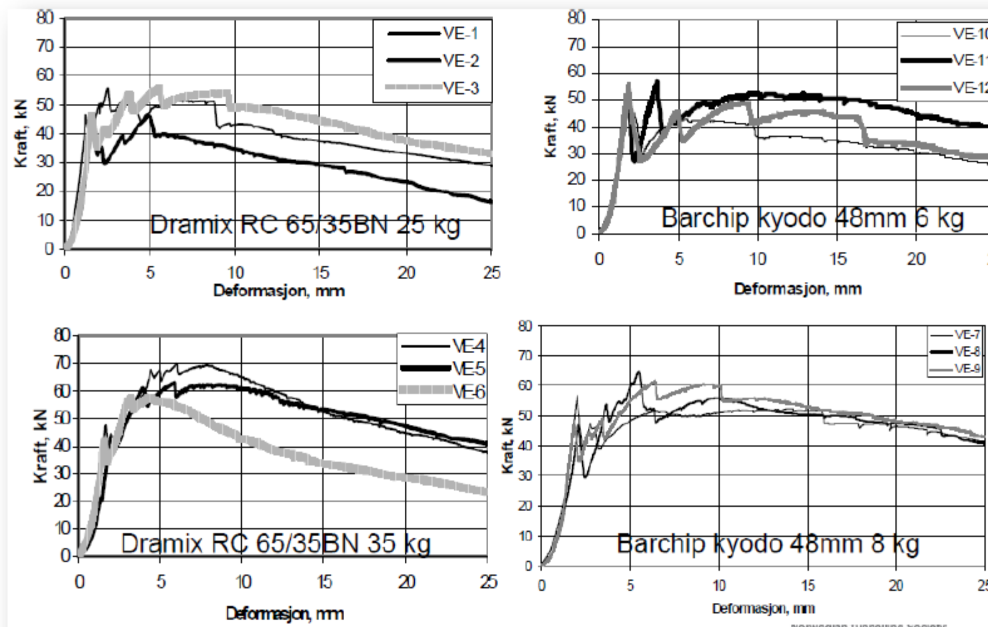
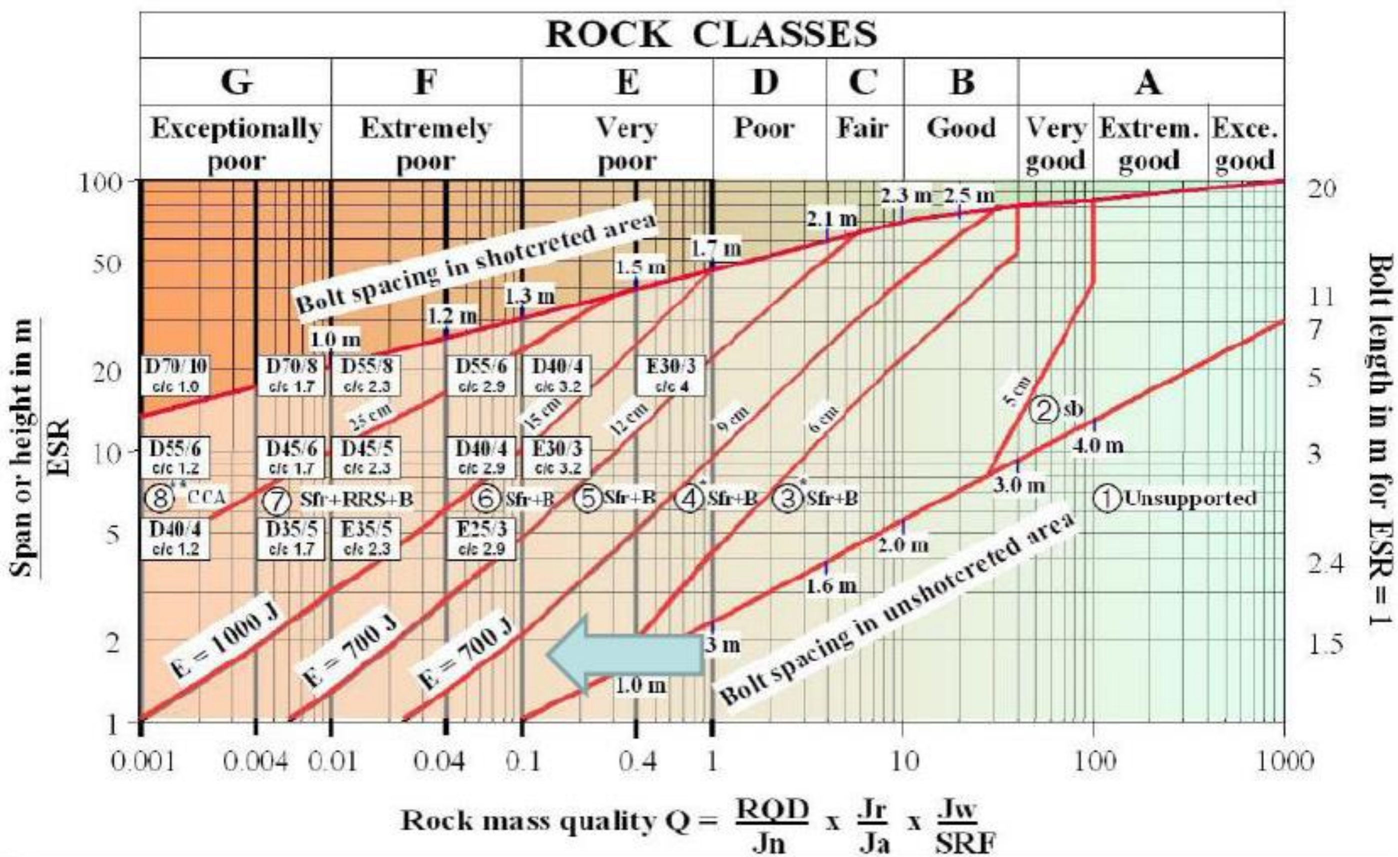


Energy absorption classes

- 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



RRS philosophy

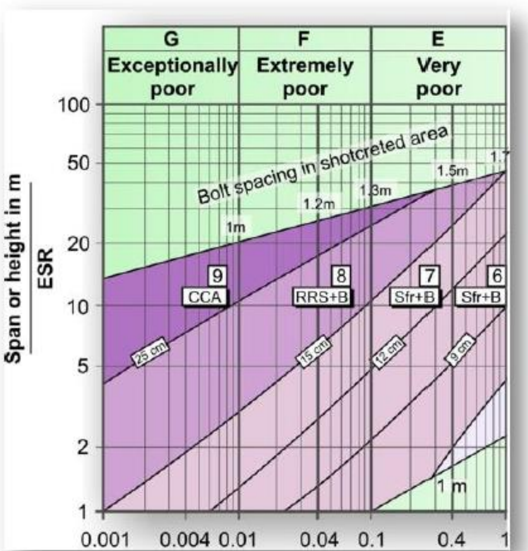
RRS (rib-reinforced shotcrete arches)

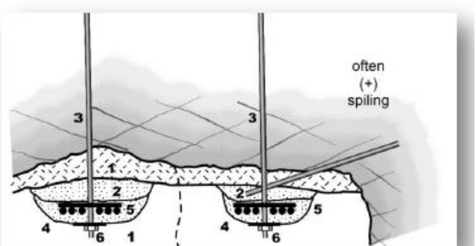
FOR VERY BAD ROCK CONDITIONS

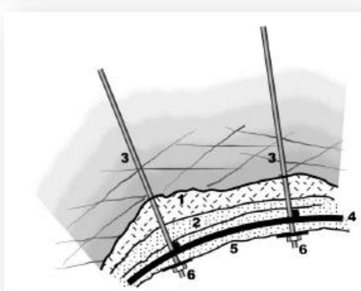
(e.g. Q < 0.1)

- **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!

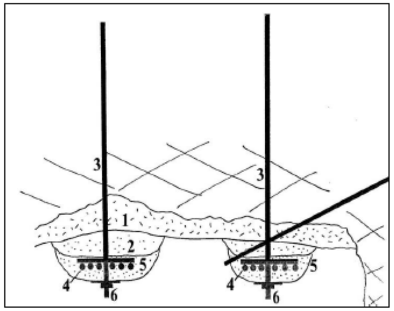


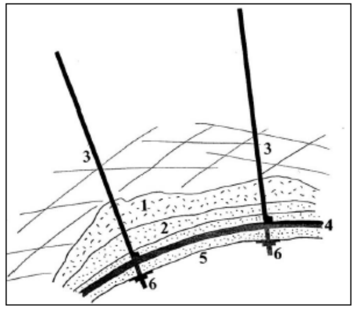




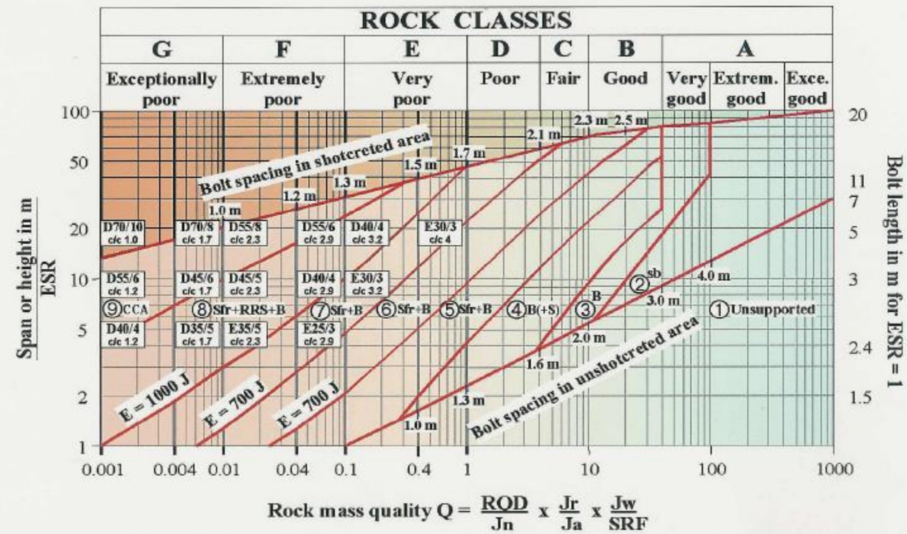
RRS prior to rib-spraying.

Note bolting – a fundamental aspect





RRS 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.

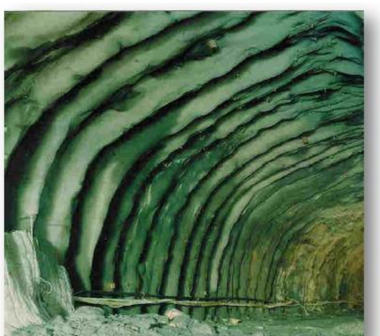


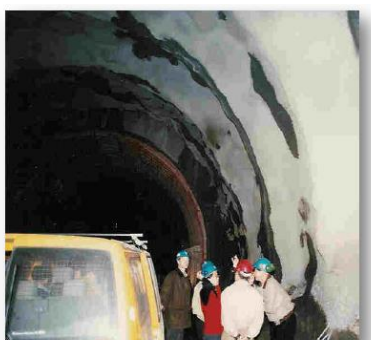
REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, **sb**
3) Systematic bolting, **B**
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), **B(+S)**
5) Fibre reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6) Fibre reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7) Fibre reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8) Fibre reinforced shotcrete > 15 cm + reinforced ribs of shotcrete and bolting, **Sfr+RRS+B**
9) Cast concrete lining, **CCA**

e) Energy absorbtion in fibre reinforced shotcrete at 25 mm bending during plate testing

D45/6 c/c 1.7 = RRS with 6 reinforcement bars in double layer in 45 cm thick ribs with centre to centre (c/c) spacing 1.7 m. Each box corresponds to Q-values on the left hand side of the box. (See text for explanation)





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)

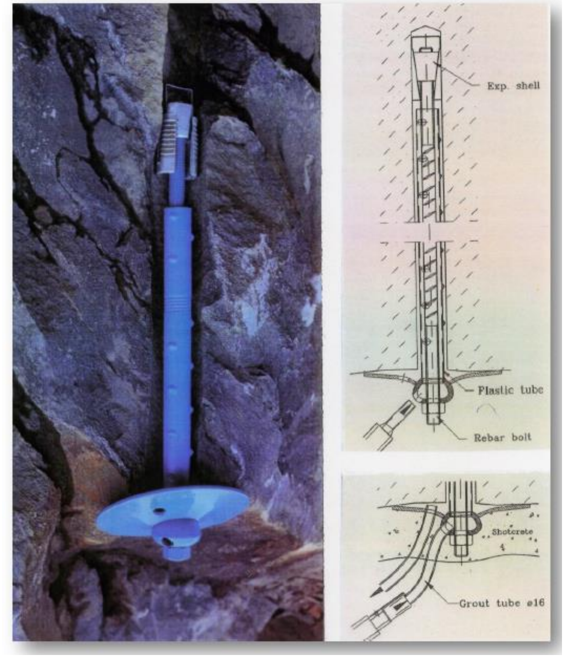
- Because NMT pre-supposes the use of S(fr)+B as the *final support* of tunnels and caverns (Barton et al. 1992, Barton and Grimstad, 1994), it is important that also the bolts are of good quality, with suitable long-life corrosion protection.

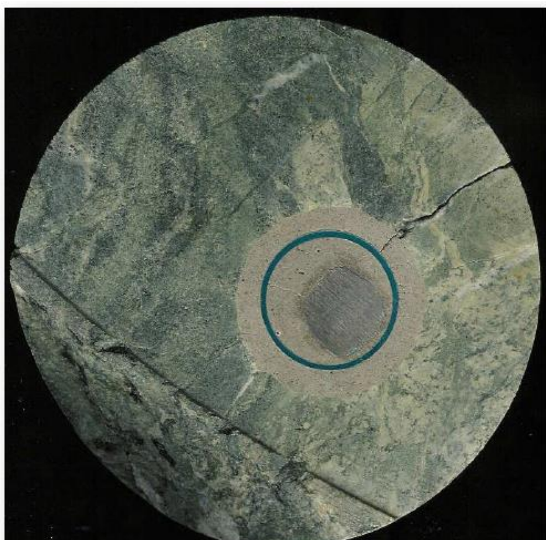
- The widespread use of NMT principles in Norway for the last 35 years (45 years if *S(mr)* is included) has meant that there has been an excellent development of corrosion protected bolts in this country.

- 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.

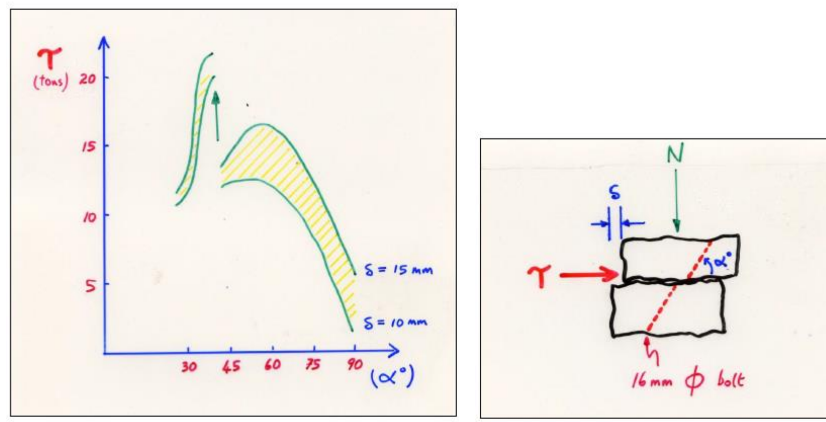
- With the layers: *galvanising, Combi-coat (epoxy paint), grout, PVC-sleeve, grout* : it has five layers of initial corrosion protection, and four are left if/when the outer layer of grout is cracked due to joint deformation. *(This is the usual start of corrosion for conventional bolts).*

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).

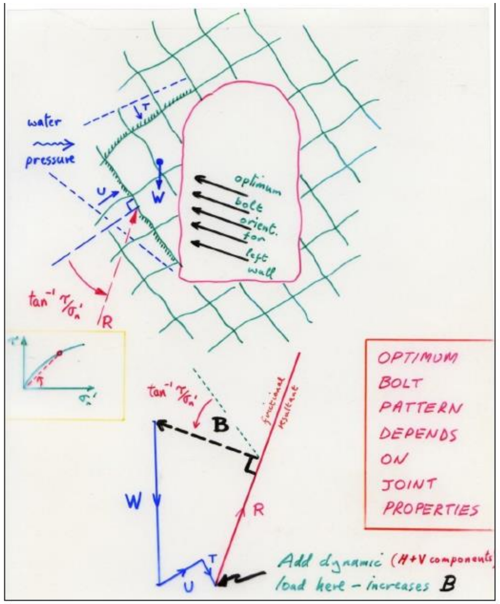




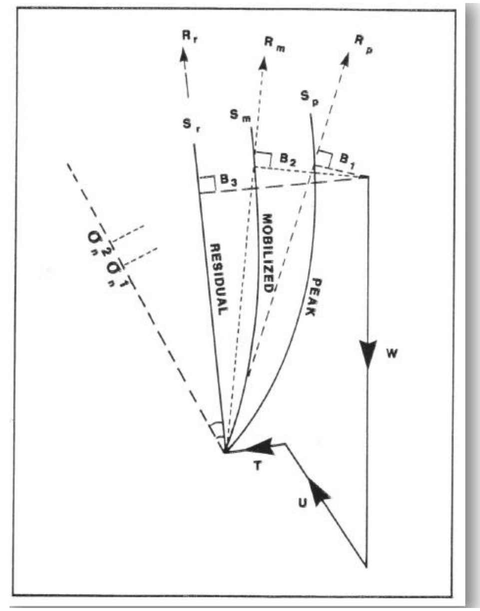
An over-cored CT bolt showing crack (joint) penetration to outer layer of grout – the usual commencement of corrosion for a conventional bolt.



Direct-shear tests of bolted joints. BJURSTRÖM 1976



Dimensioning of bolting or anchoring assuming that peak strength is (still) available.



Note theoretical need for change of anchor direction and capacity if post-peak deformation has occurred

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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.

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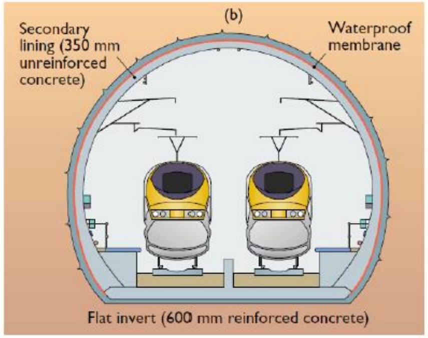
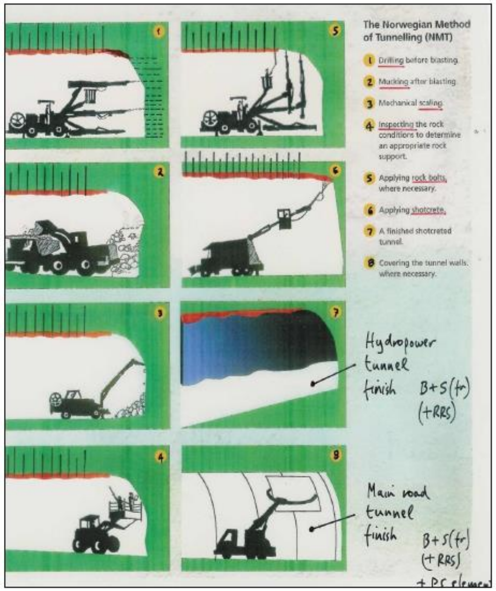


- **Primary lining was 25 cm of S(mr): top-heading and bench construction, mostly by road-header, hence lack of overbreak.**
- **"Value engineering" resulted in 15% reduced price: final concrete thickness was reduced to 35 cm, with fibre reinforcement (TTI): the chalk was stronger than expected. (Watson, 2003, ICE).**
- **Note high arch / large cross-section, as no pressure-relief shafts.**

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.

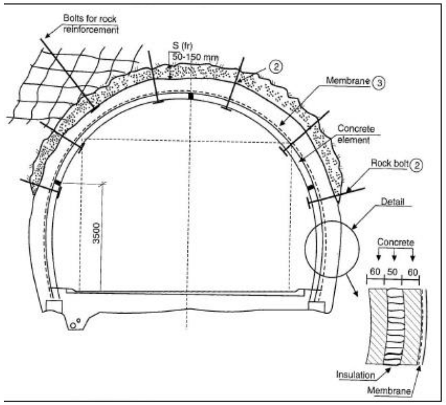


NMT concepts in diagrammatic form. Note that stage No. 6 must precede stage No. 2 if stability /stand-up time is very poor.

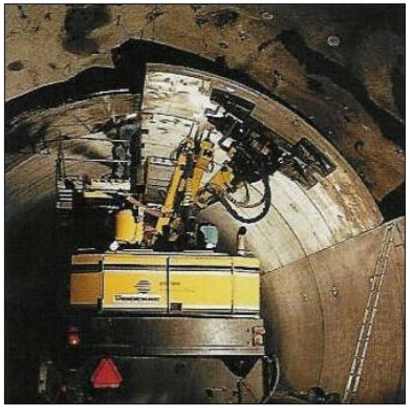
Concerning the 'dry-but-drained' final result (for road or rail), note the PC-element (free-standing but bolted) liner.

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.

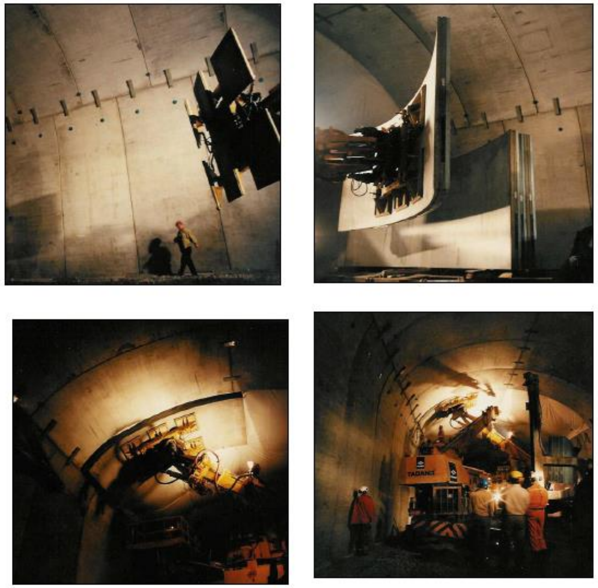
The liner is completed at rates up to 1000m per month, with suitable mounting machinery.



An example of a 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.***

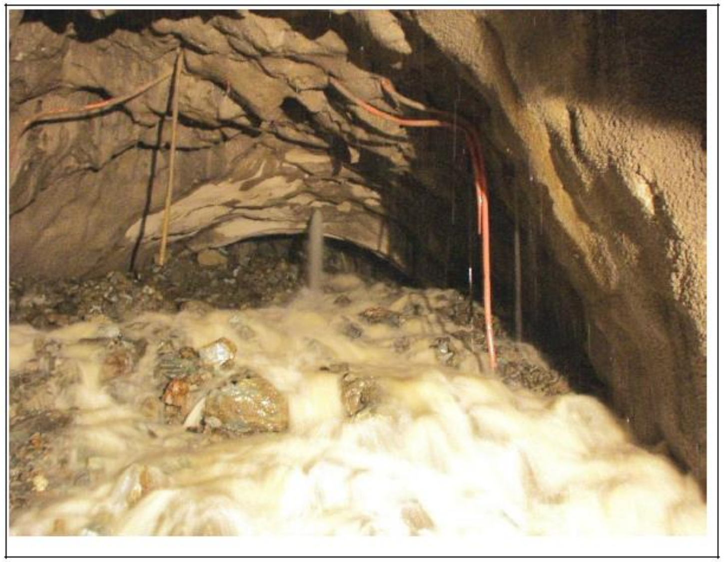
Actually used due to failure to control water.

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.

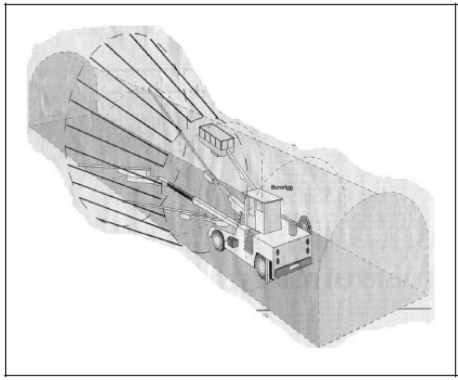


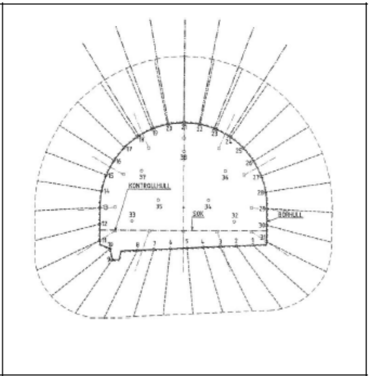
A pre-injection ‘umbrella’ could probably have prevented this (several weeks/months) delay

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*

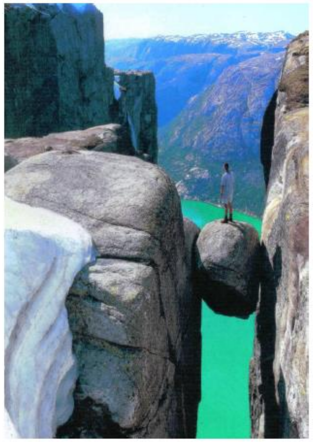
Pre-injection screens, may vary in length from 20 to 30 m, and have from 30 to 70 holes depending on tunnel cross-section. Hole spacing is from 0.5-1.0 m c/c



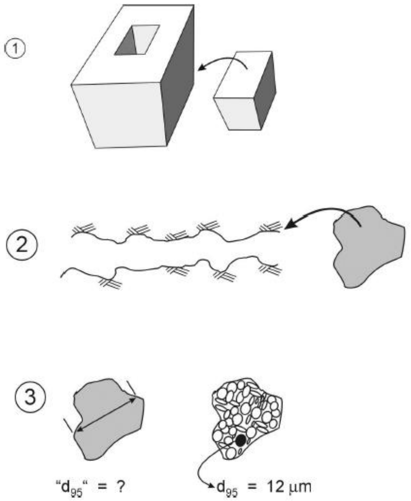


Approximate costs of pre-injection needed to achieve various levels of ‘dryness’ in 90 m^2 tunnels.

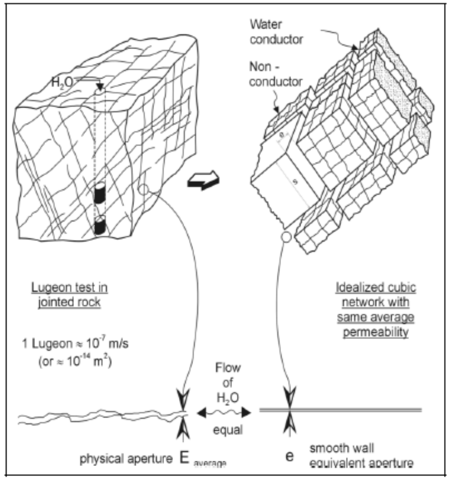
Inflow (approx.)	Cost (Norway)
20 l/min/100 m	1,400 US $ /m
10 l/min/100 m	2,300 US $ /m
5 l/min/100 m	3,500 US $ /m
1-2 l/min/m/100 m	≈ 5,000 US $ /m

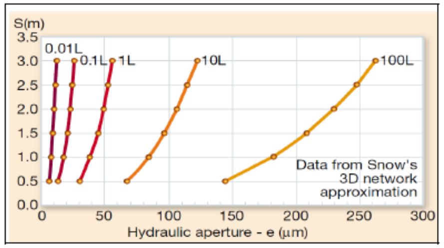


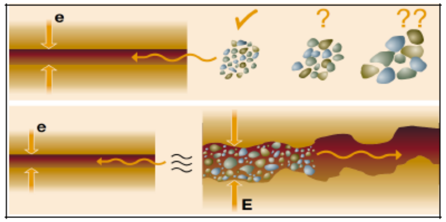
The dilemma is how to get blocks (i.e. particles) that are too large in joints that are too tight.



.....smaller particles! ..... wider joints!

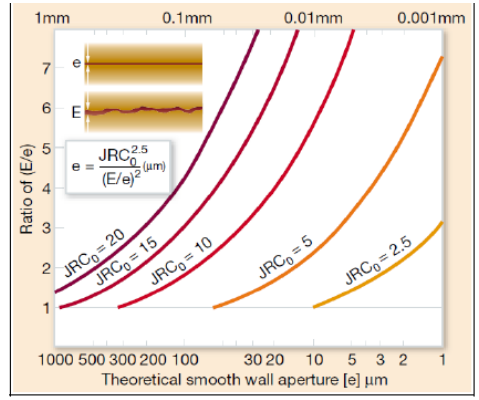






Left: Representing a regularly-jointed rock mass with a cubic network of hydraulic conductors of mean aperture (e) and mean spacing (S), based on Snow (1968).

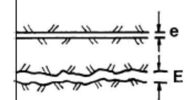
Right: Estimates of (e) and (S), and the aperture inequality E ≥ e (Barton et al. 1985) which allows grout particles to penetrate real joints (E) even when (theoretical) hydraulic apertures (e) are apparently too small.



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).

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)

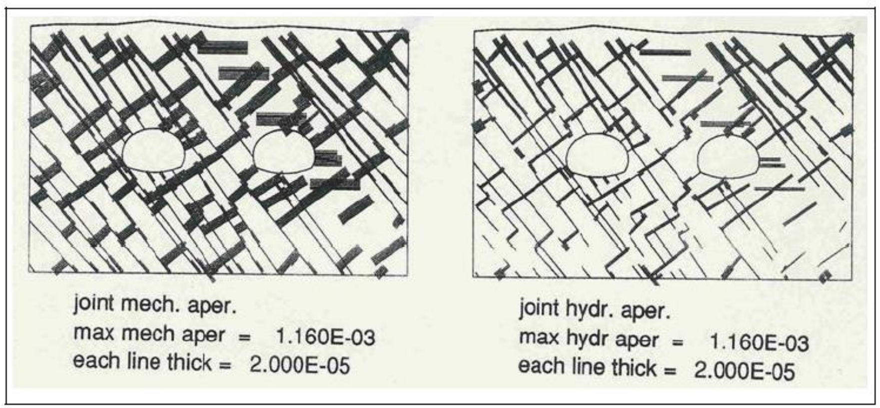
Depth zones	S(m)	e(μm)	E(μm)
5 - 15m	0.3	150	218
15 - 25m	0.4	110	186
25 - 45m	0.6	80	159
45 - 60m	0.7	60	138



$$E = \sqrt{e.\ JRC^{2.5}}$$

Grout-Take Estimates / $1m^3$ rockmass

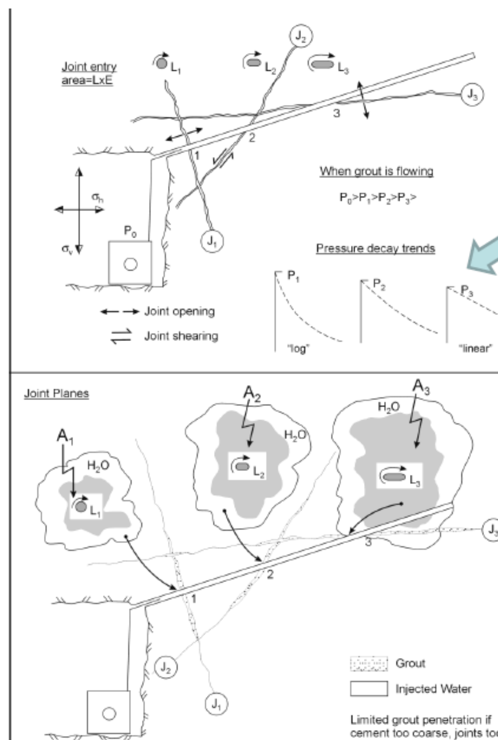
Depth zone	5 - 15m	15 - 25m	25 - 45m	45 - 60m
Grout (litres)	2.2	1.4	0.8	0.6



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).

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)



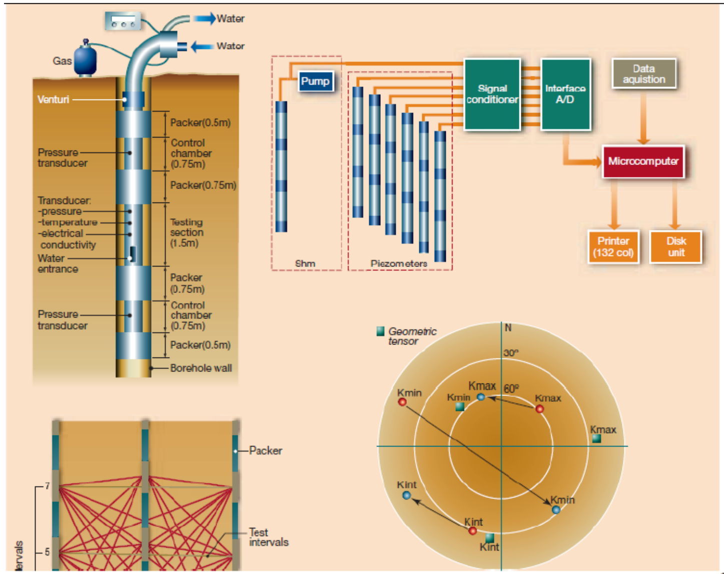
Use high injection pressures when pre-grouting! (Pressure decay 50% in first 1m)

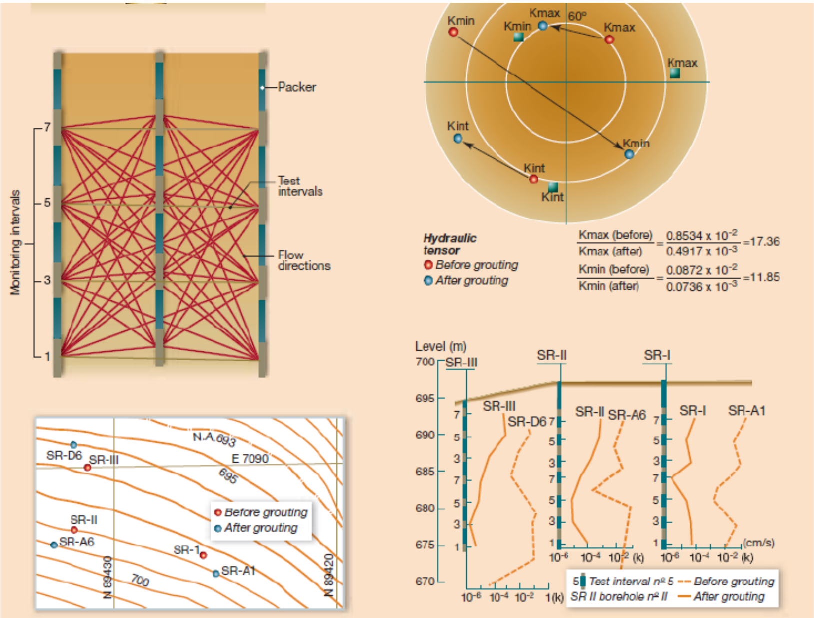
(Use 5 to 10 MPa where possible)

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





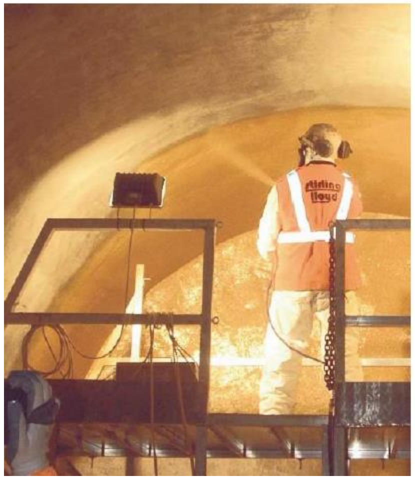
E Quadros & D Correa Filho, 1995. "Grouting efficiency using directional (3-D) hydraulic tests in Pirapora Dam, Brazil" Proc. of 8th ISRM Cong., Tokyo, editor Fujii, Balkema.

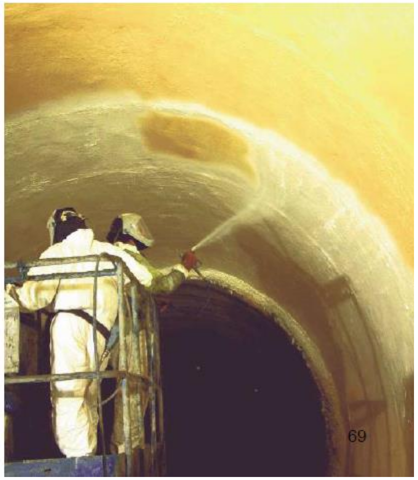
ROTATION (and of course reduction in magnitude) OF *PERMEABILITY TENSORS*, SUGGESTS SUCCESSIVE SEALING OF JOINT SETS IS OCCURING, AS A RESULT OF THE GROUTING

CONSERVATIVE MODEL	MORE REALISTIC MODEL
RQD increases e.g. 30 to 50%	RQD increases e.g. 30 to 70%
Jn reduces e.g. 9 to 6	Jn reduces e.g. 12 to 4
Jr increases e.g. 1 to 2 (due to sealing of most of set #1)	Jr increases e.g. 1.5 to 2 (due to sealing of most of set #1)
Ja reduces e.g. 2 to 1 (due to sealing of most of set #1)	Ja reduces e.g. 4 to 1 (due to sealing of most of set #1)
Jw increases e.g. 0.5 to 1	Jw increases e.g. 0.66 to 1
SRF unchanged e.g.1.0 to 1.0	SRF improves e.g. 2.5 to 1.0 due to consolidation of loose material
WET WET WET WET WET WET WET	WET WET WET WET WET WET WET
Before pre-grouting *Q = 30/9 x 1/2 x 0.5/1 = 0.8*	*Before pre-grouting* Q = 30/12 x 1.5/4 x 0.66/2.5 = 0.2
Vp ≈ 3.4 km/s E_{mass} ≈ *9.3 GPa* *K ≈ 1.3 x* 10^{-7} m/s **10 m Tunnel: B 1.6 m c/c, S(fr) 10 cm**	*Vp ≈ 2.8 km/s* E_{mass} ≈ *5.8 GPa* *K ≈ 5.0 x* 10^{-7} m/s **10 m Tunnel: B 1.4 m c/c, S(fr) 13 cm**
DRY DRY DRY DRY DRY DRY DRY	DRY DRY DRY DRY DRY DRY DRY
After pre-grouting **Q = 50/6 x 2/1 x 1/1 = 17**	***After pre-grouting*** **Q = 70/4 x 2/1 x 1/1 = 35**
Vp ≈ 4.7 km/s E_{mass} ***≈ 25.7 GPa*** ***K ≈ 5.9 x*** 10^{-9} ***m/s*** **10 m Tunnel: B 2.4 m c/c**	***Vp ≈ 5.0 km/s*** E_{mass} ***≈ 32.7 GPa*** ***K ≈ 2.9 x*** 10^{-9} ***m/s*** **10 m Tunnel: sb (spot bolts)**

Sterling Lloyd – "Integritank HF"
(brown layer first, white layer second)

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

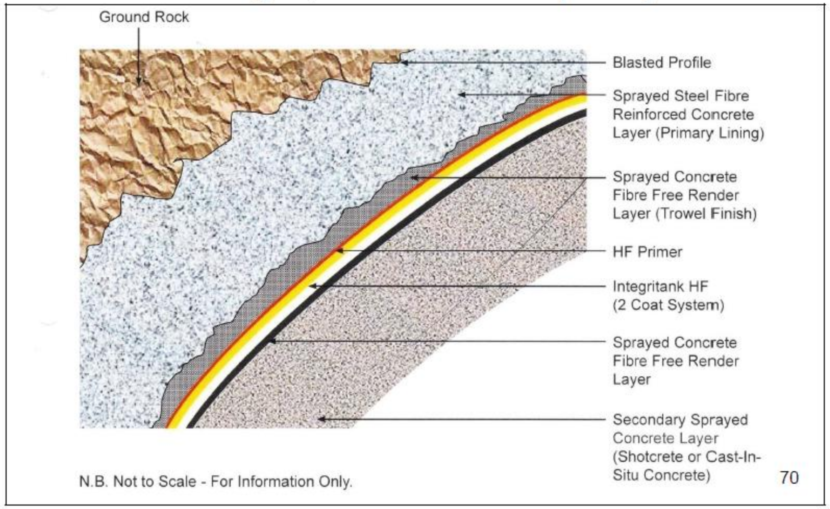


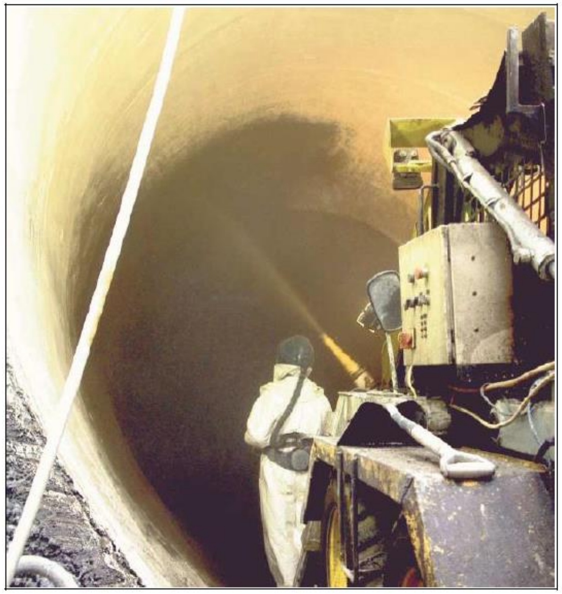


SPRAYED MEMBRANES as final water control

1. "INTEGRITANK HF" – Stirling Lloyd
2. "MASTERSEAL 345" - BASF

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.



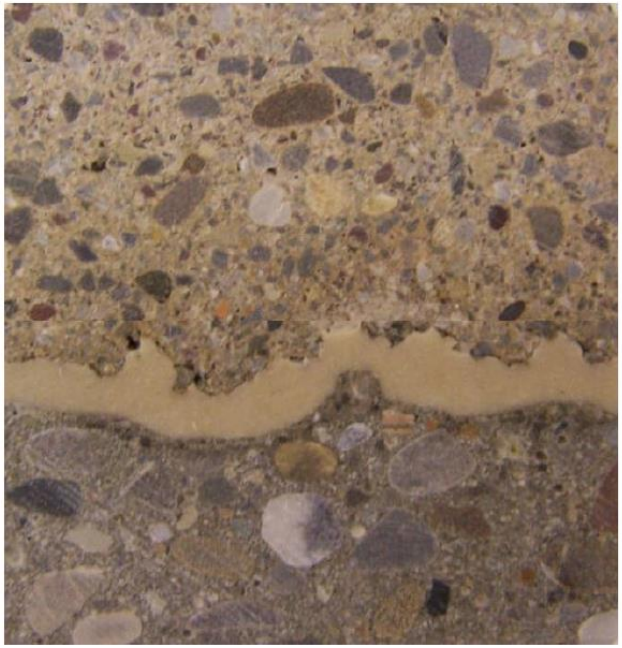


Last layer of shotcrete directly onto the INTEGRITANK HF

Masterseal 345

Advantage that it is simply a powder mixed with water.

Can use same robot as with S(fr)



Example of "Masterseal 345"

(Holter and Nermoen, 2011)

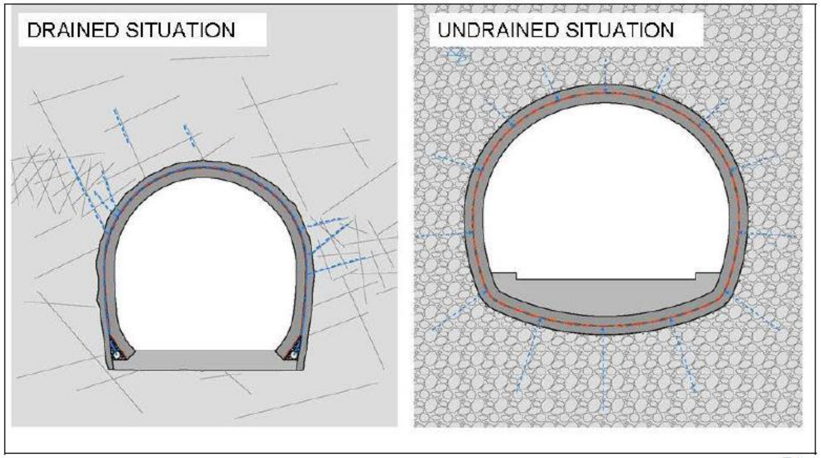
Can spray directly onto S(fr), and spray the final S(fr) directly onto the membrane.

(An etyl-vinyl-acetat co-polymer)

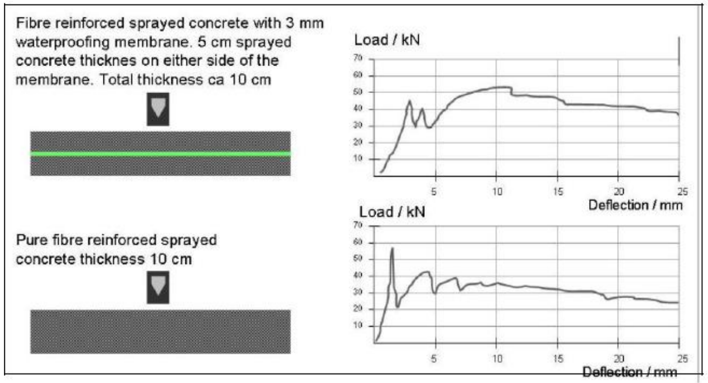
Width of photo = 4 cm

Holte and Nermoen, 2011. Permanent Waterproof Tunnel Lining Based on Sprayed Concrete and Spray-Applied Double- Bonded Membrane.

(BASF and Norwegian Railways)



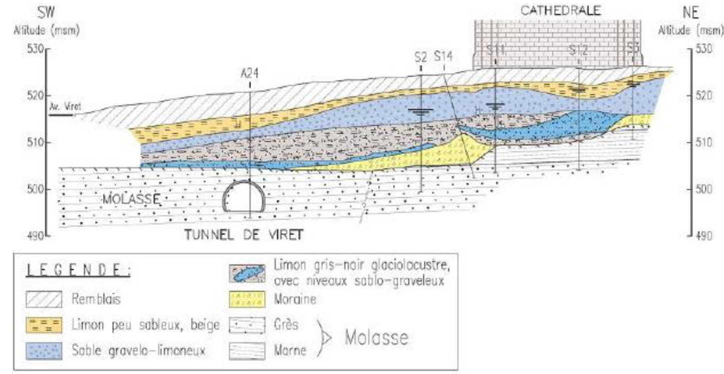
Loading test on 60 cm diameter by 5cm+5 cm membrane sandwich.



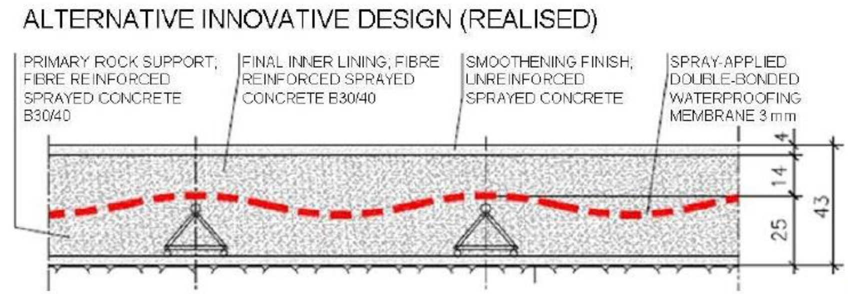
This composite type of sample has superior fracture energy.

(Average of three samples of each type)

Holte and Nermoen, 2011



Lausanne Metro



- Lausanne Metro: BASF Masterseal 345

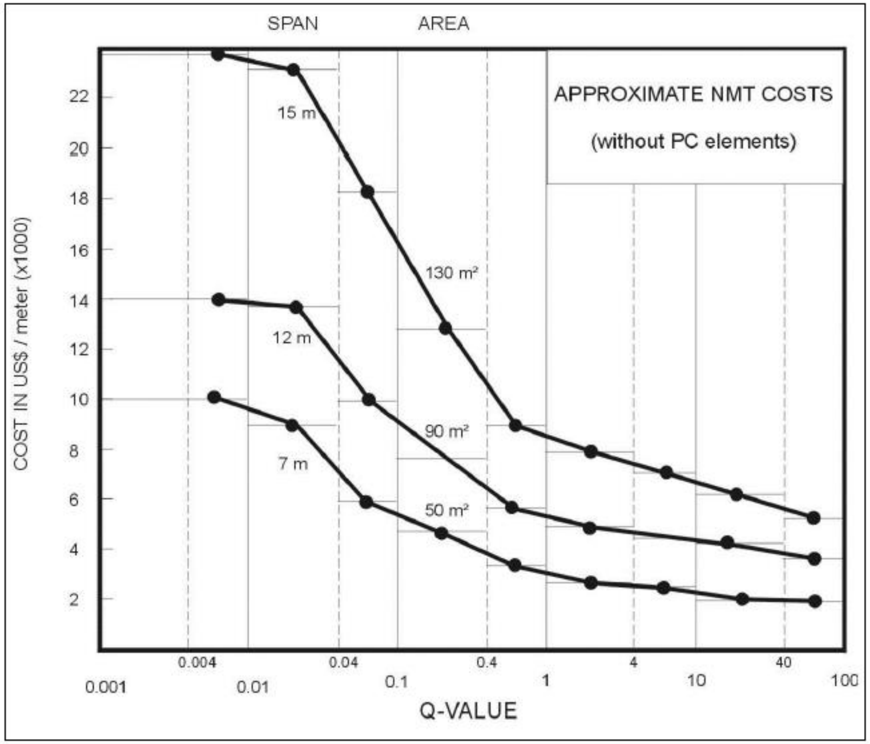
Hindhead Road Tunnel

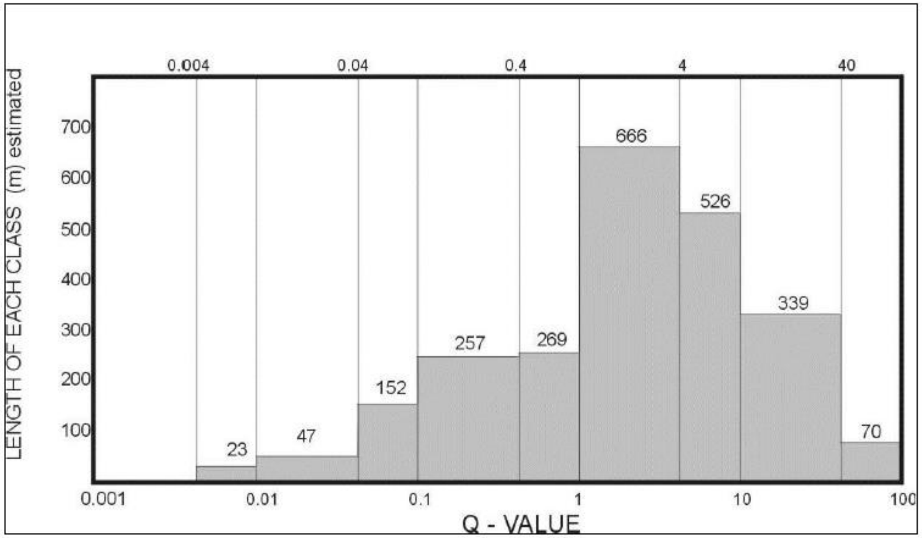
A traditional technical solution with primary lining sprayed concrete, secondary lining cast in-situ concrete with a sheet membrane for waterproofing, was the basis for the calculation and tendering..

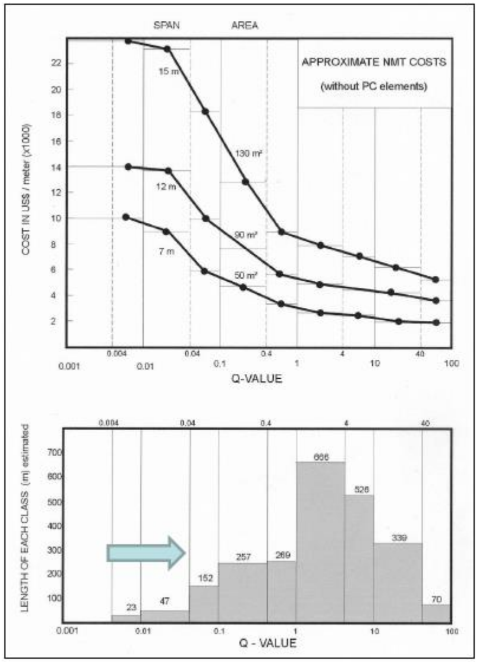
In design-and-build contract, this was changed to S(fr) and double-bonded membrane. Saving of GBP 3,400,000 was reported.

FINALLY:

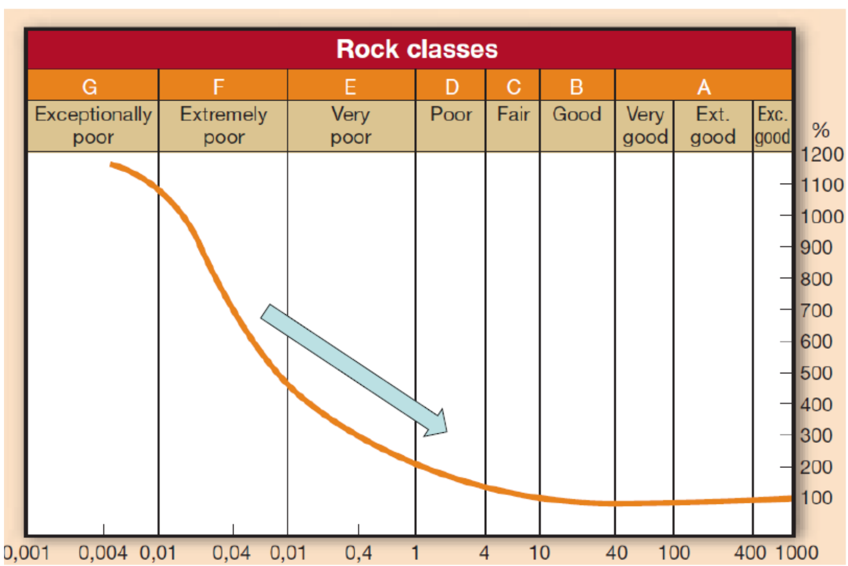
COST / TIME ESTIMATION IN RELATION TO THE Q-VALUE







RELATIVE _COST_ FOR TUNNEL EXCAVATION AND SUPPORT
.........potential benefits of pre-grouting, especially if Q ≈ 0.1



RELATIVE **_TIME_** FOR TUNNEL EXCAVATION AND SUPPORT
.........potential benefits of pre-grouting, especially if Q ≈ 0.1

N Barton, B Buen & S Roald, 2001/2002.
"Strengthening the case for grouting"
T&T International, Dec 2001 & Jan 2002.