4. TUNNEL SUPPORT SELECTION FROM Q-CLASSIFICATION

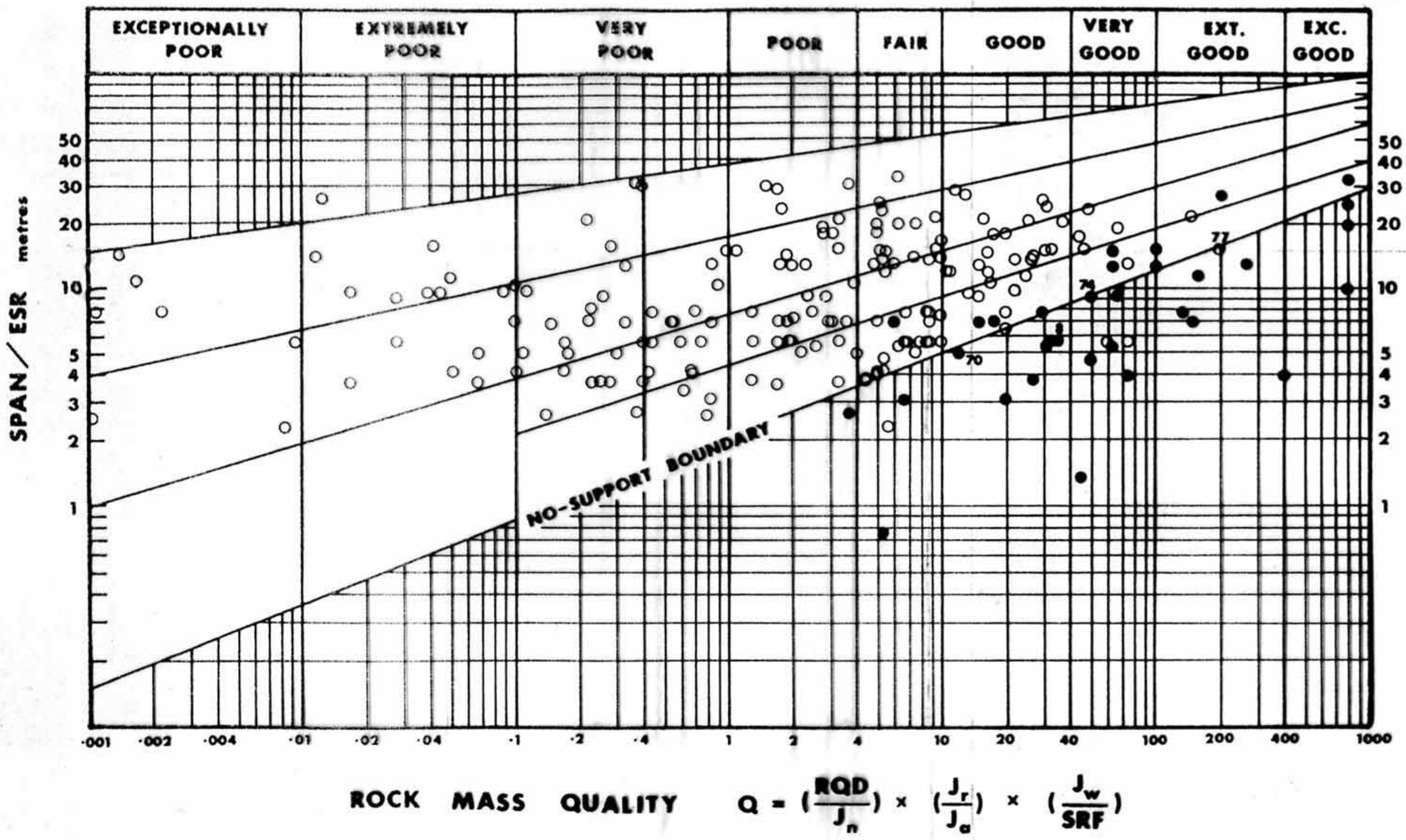
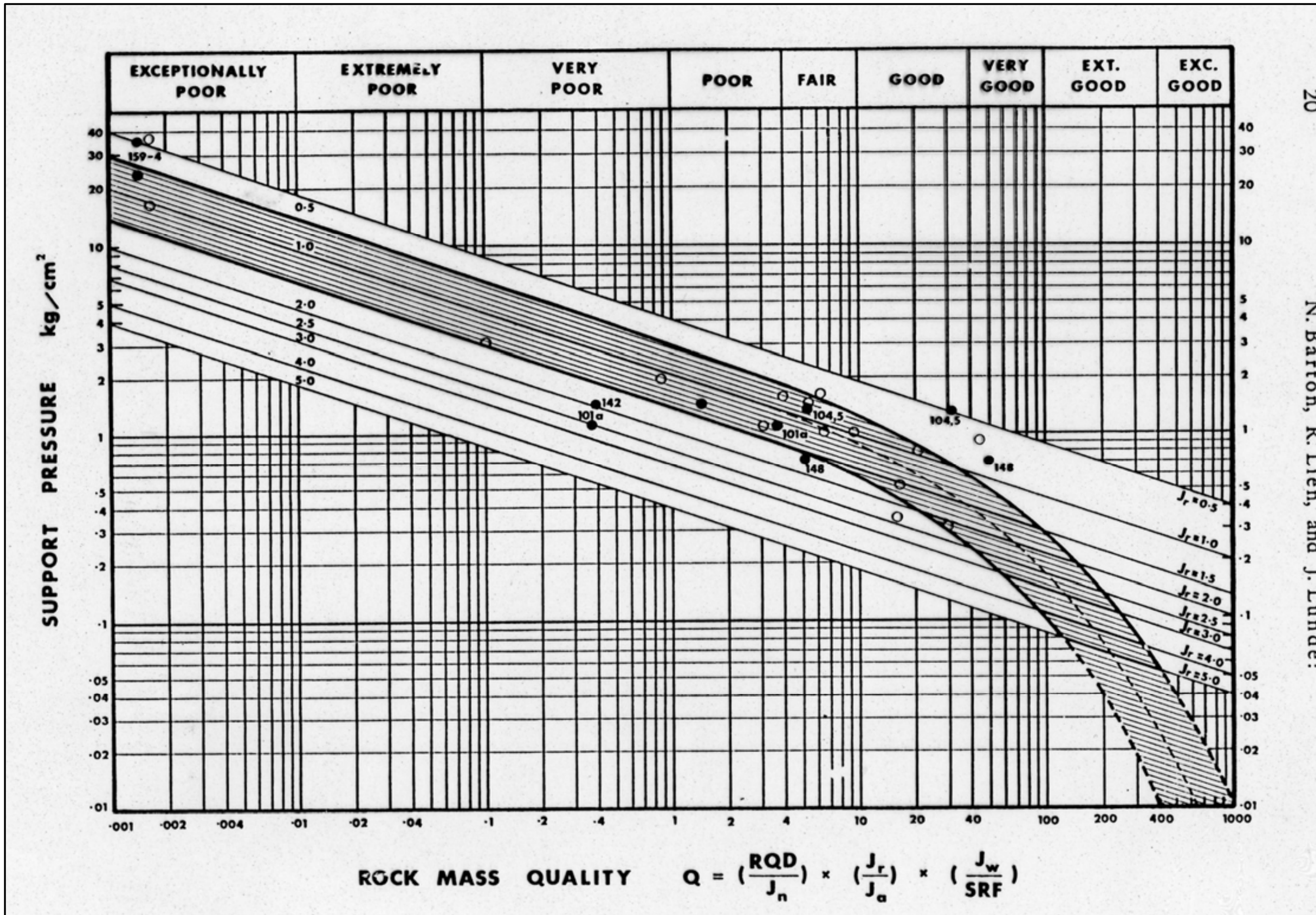


Figure 5. Analysis of case records indicates the approximate boundary between supported (o) and unsupported (•) excavations. The type of support, if any, depends on the rock mass quality (Q), the span, and the type of excavation (ESR).

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



SUPPORT PRESSURE GUIDELINES (FROM 1974) used for checking bolt loads.

1.	*Temporary Support*	a) b) c)	increase ESR to 1.5 × ESR increase Q to 5Q (arch) Increase Q_w to $5Q_w$
2.	*Wall Support* (based on modified quality Q_w for walls)	a) b) c)	select $Q_w = 5Q$ (when $Q > 10$) select $Q_w = 2.5Q$ (when $Q < 10$) select $Q_w = 1.0Q$ (when $Q < 0.1$)
Note 1	Use total excavation height (H) for wall support design.		
Note 2	Q is the general rock quality observed when inspecting the arch *or* walls of a tunnel. For local variations of rock quality (arch or walls), map locally and change support as appropriate. (Q_w is *not* the observed value of Q in a cavern wall.)		

APPROXIMATE GUIDE-LINES FOR TEMPORARY SUPPORT AND FOR (PERMANENT) WALL SUPPORT

3. Recommended bolt and anchor lengths

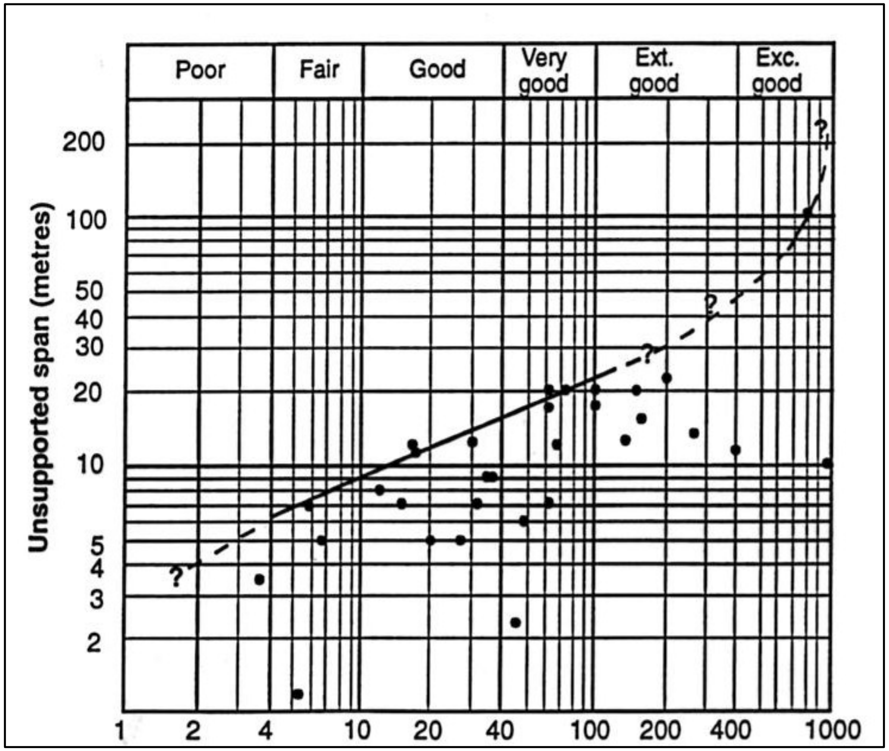
Bolt and anchor lengths for permanent support depend on the dimensions of the excavation. Lengths used in the roof arch are usually related to the span, whole lengths used in the walls are usually related to the height of the excavations. The ratio of bolt length to span tends to reduce as the span increases. This trend has been illustrated by Benson *et al.*, 1971. Accordingly, the following recommendations are given as a simple rule of thumb, to be modified as *in situ* conditions demand.

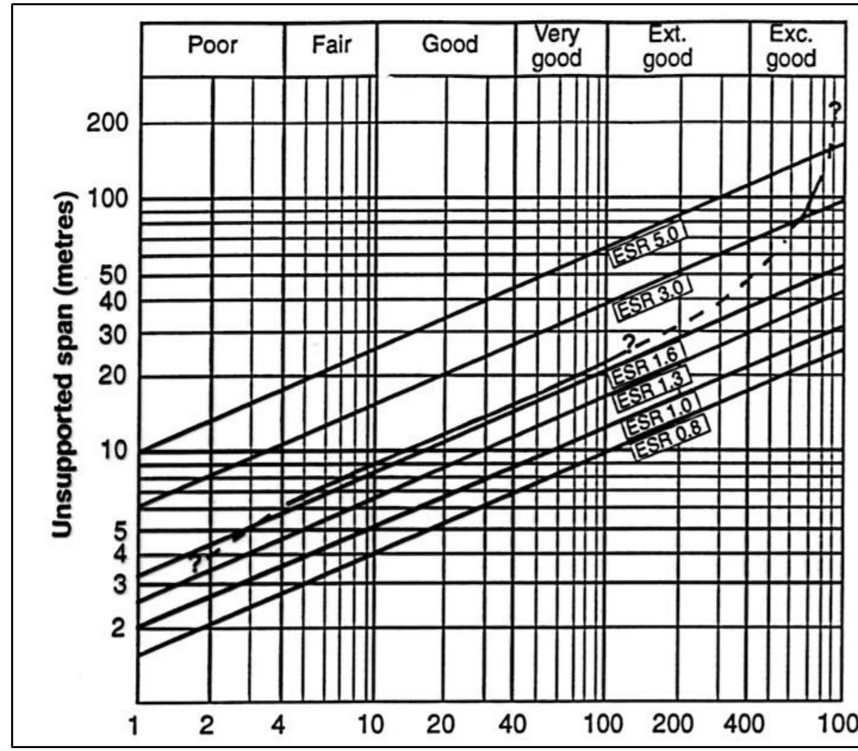
ROOF:	bolts	$L = 2 + 0.15\ B/ESR$
	anchors	$L = 0.40\ B/ESR$
WALLS:	bolts	$L = 2 + 0.15\ H/ESR$
	anchors	$L = 0.35\ H/ESR$

where

L = length in metres
B = span in metres
H = excavation height in metres
ESR = excavation support ratio

(Bolt lengths used as temporary support will usually be only loosely dependent on excavation dimensions. Lengths of between 1.5 and 3.0 metres seem to be used in many types of excavations.)

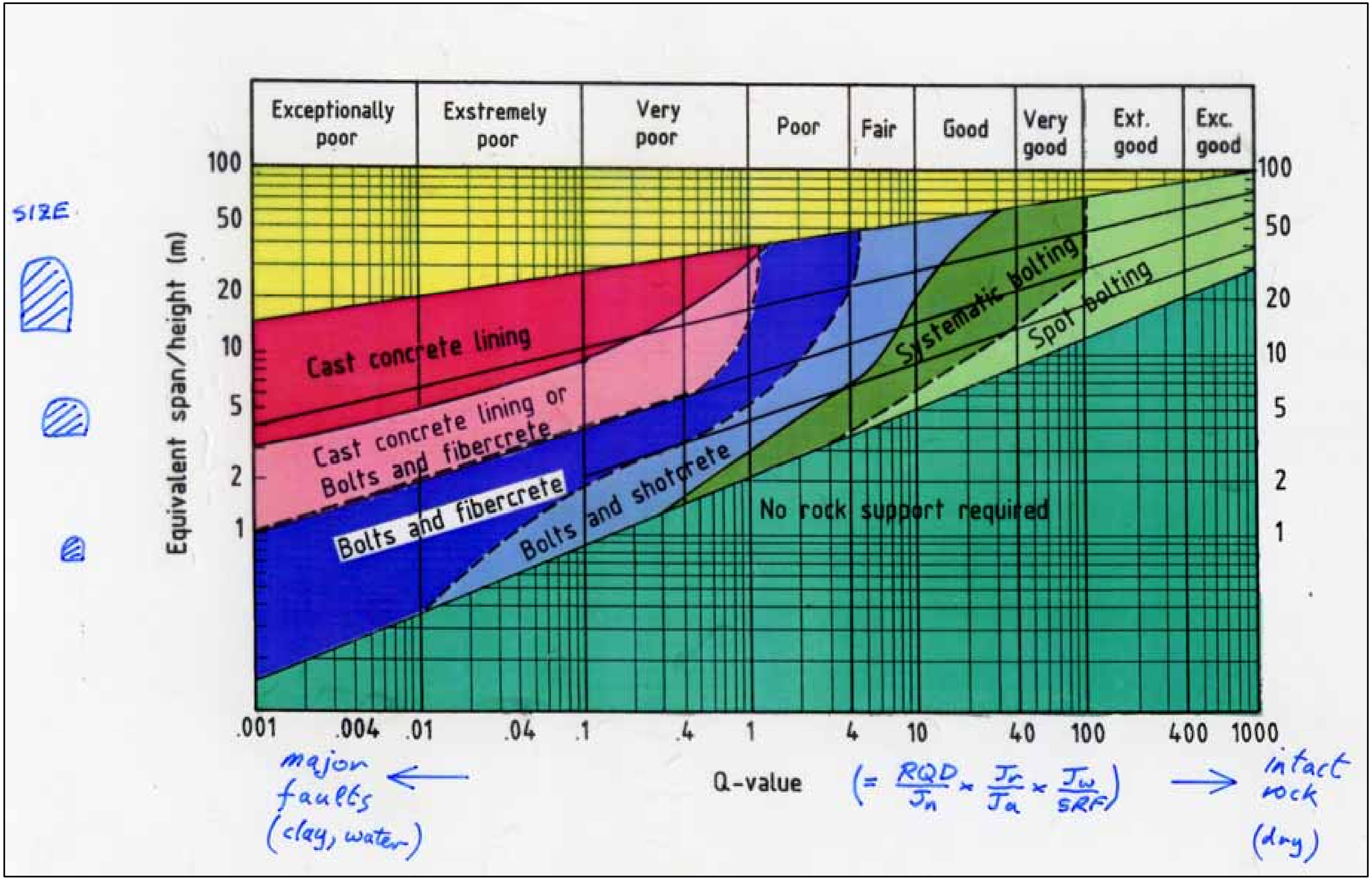




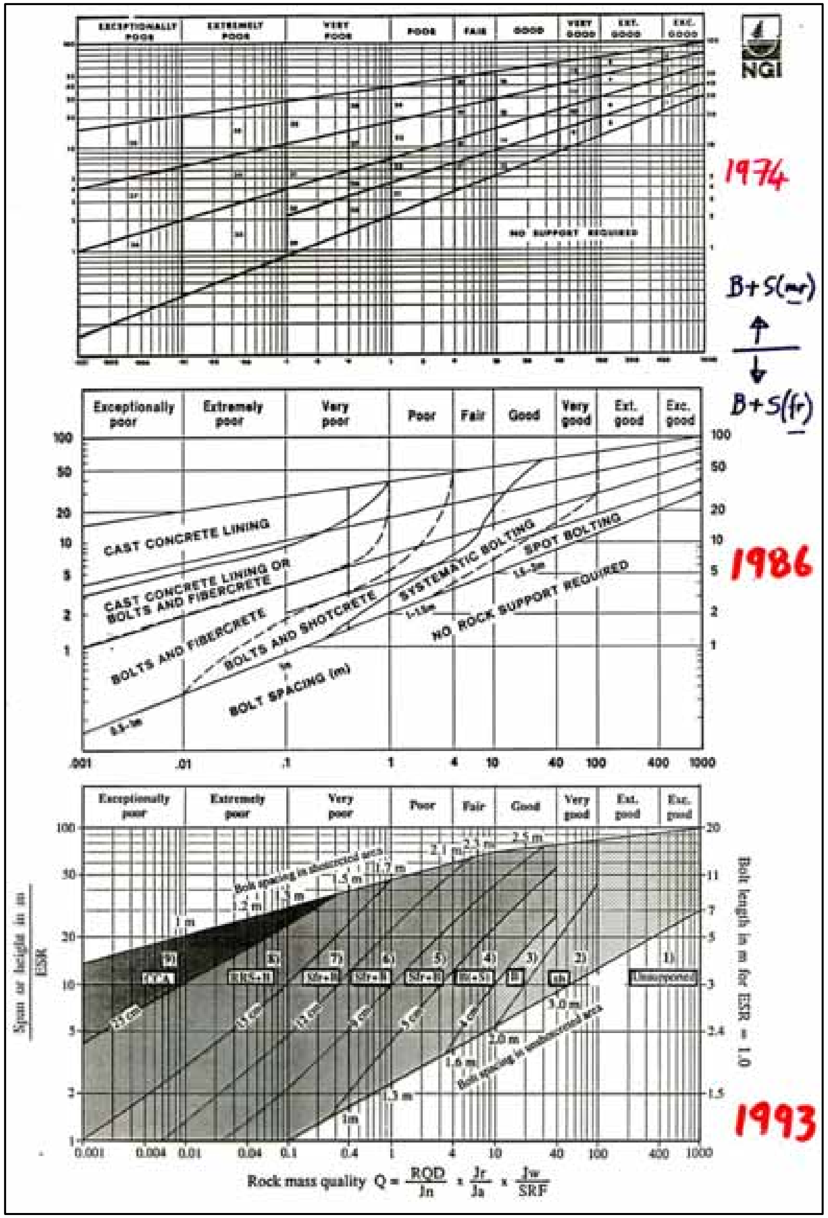
1. $J_n \leq 9$, $J_r \geq 1.0$, $J_a \leq 1$, $J_w = 1.0$, $SRF \leq 2.5$

Conditional requirements

2. If $RQD \leq 40$, should have $J_n \leq 2$
3. If $J_n = 9$, should have $J_r \geq 1.5$ and $RQD \geq 90$
4. If $J_r = 1$, should have $J_n < 4$
5. If $SRF > 1$, should have $J_r \geq 1.5$
6. If SPAN > 10 m, should have $J_n < 9$
7. If SPAN > 20 m, should have $J_n \leq 4$ and $SRF \leq 1$



UPDATED SUPPORT CHART PRINCIPLES, FOR 1989 TO 1993 INCORPORATION OF NEW B+ S(fr) CASE RECORDS. Grimstad, 1989



THE PROGRESSION OF PUBLISHED TUNNEL SUPPORT CHARTS FROM 1974 TO 1993

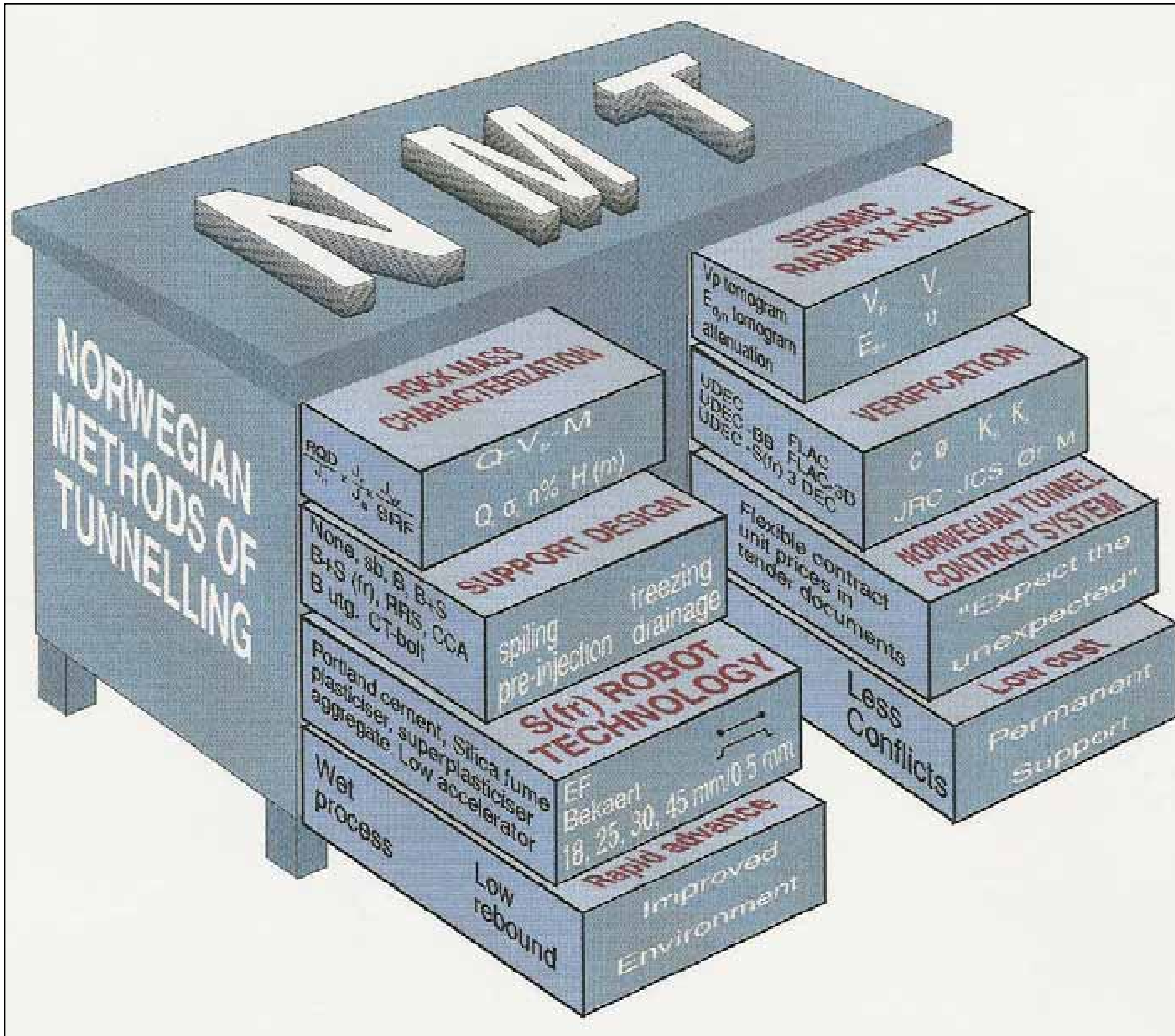
THE 1974 PUBLICATION WAS BASED MOSTLY ON B+S(mr) CASES

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

In 1992 (Barton et al. 1992) coined the phrase NMT – the Norwegian Method of Tunnelling – to differientiate it from NATM which was soon to get so bad publicity from high-profile collapses around the world (Heathrow, Munich, São Paulo), not to mention the strong, widely published criticisms from a prominent Swiss engineer (Prof. Kovari) concerning the questionable scientific/engineering basis for NATM.



NMT
NORWEGIAN METHODS OF TUNNELLING
ROCK MASS CHARACTERIZATION
Q-Vp-M
Q σ n% H(m)
SEISMIC RADAR X-HOLE
Vp tomogram
attenuation
VERIFICATION
UDEC
UDEC-BB FLAC
UDEC-S(fr) 3 DEC
JRC JCS
SUPPORT DESIGN
None, sb, B, B+S
B+S (fr), RRS, CCA
B utg, CT-bolt
spiling
pre-injection
freezing
drainage
NORWEGIAN TUNNEL CONTRACT SYSTEM
"Expect the unexpected"
Flexible contract unit prices in tender documents
S(fr) ROBOT TECHNOLOGY
Portland cement, Silica fume
plasticiser, superplasticiser
aggregate Low accelerator
EF
Bekaert
18, 25, 30, 45 mm/0.5 mm
Less Conflicts
Low cost
Permanent Support
Wet process
Low rebound
Rapid advance
Improved Environment

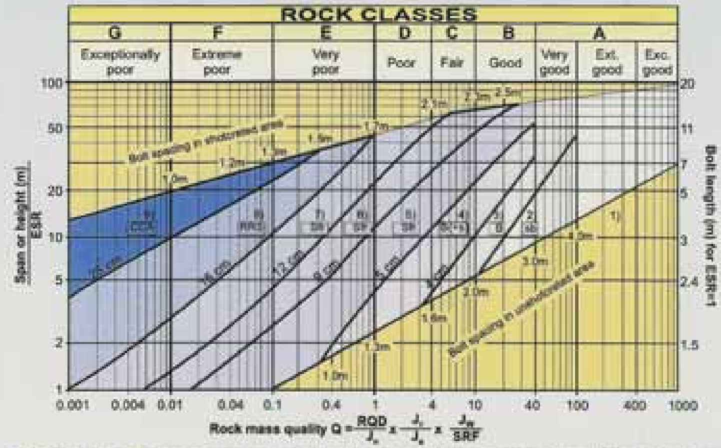
Table 1 Essential features of NMT (after Barton et al., 1992)

1) **Areas of usual application:**
   Jointed rock giving overbreak; harder end of uniaxial strength scale (σ_c = 3 to 300 MPa)
   Clay bearing zones, stress slabbing
   Q = 0.001 to 10 or more
2) **Usual methods of excavation:**
   Drill and blast, hard rock TBM, machine excavation in clay zones
3) **Temporary rock reinforcement and permanent tunnel support may be any of following:**
   CCA, S(fr) + RRS + B, B + S(fr), B + S, B, S(fr), S, sb, (NONE) (see key below and Figure 1)
   - temporary reinforcement forms part of permanent support
   - mesh reinforced shotcrete not used
   - dry process shotcrete not used
   - steel sets or lattice girders not used; RRS and S(fr) are used in clay zones and in weak, squeezing rock masses
   - Contractor chooses temporary support
   - Owner/Consultant chooses permanent support
   - final concrete linings are less frequently used, *i.e.*, B + S(fr) is usually the final support
4) **Rock mass characterisation for:**
   - predicting rock mass quality
   - predicting support needs
   - updating of both during tunnelling (monitoring in critical cases only)
5) **The NMT gives low costs and**
   - rapid advance rates in drill and blast tunnels
   - improved safety
   - improved environment

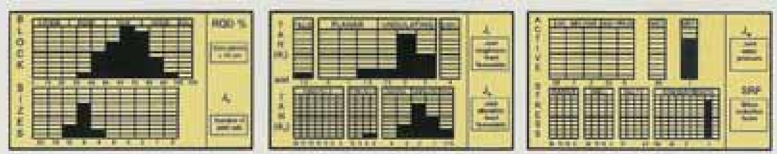
CCA = cast concrete arches, S(fr) = steel fibre reinforced shotcrete, RRS = reinforced ribs of shotcrete, B = systematic bolting, S = shotcrete, sb = spot bolts, NONE = no support needed.

Tunnel support design

using a new Q-system chart



The Q-system is an empirical method for classifying ground and for selecting appropriate permanent support. 1250 case records form the basis of the method.



These Q-system statistics are for the Gjøvik Olympic Cavern of 62 m span

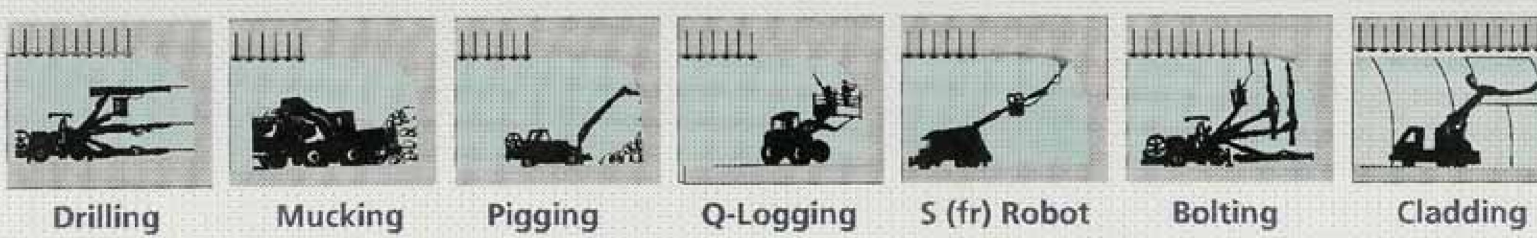
NMT Compared with NATM

NMT uses a predictive classification for support design.

NMT gives the permanent support which is not followed by concrete lining.

NMT uses high capacity (10-25m^3/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 if required for road or rail use

Some of the key differences between NMT and (the sometimes misused term) NATM that were more obvious 10 years ago than today, following technology improvements**.** More NATM operations use S(fr) today than 10 years ago.

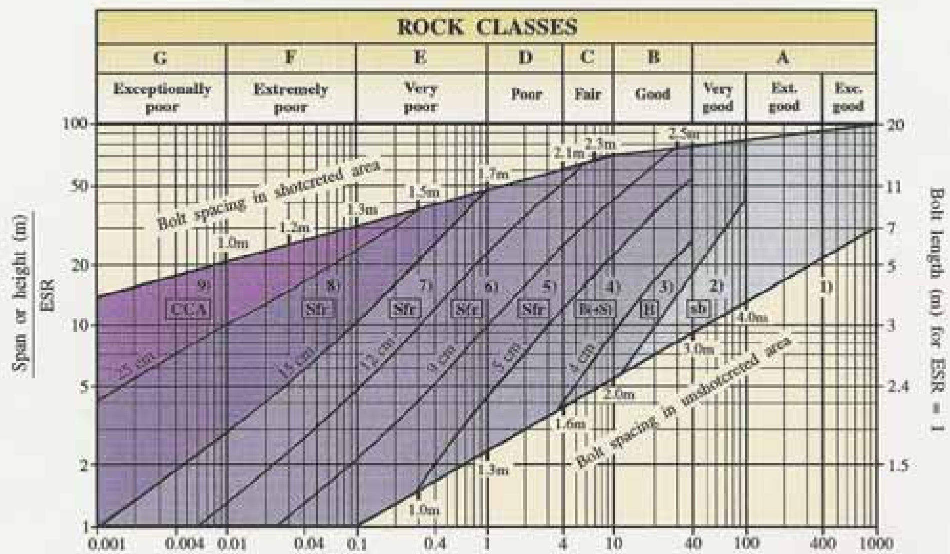
- NMT uses a predictive classification for support design.
- (NATM uses monitoring for support design.)
- NMT gives the permanent support which is not followed by concrete lining.
- (NATM gives the temporary support, which is followed by concrete lining.)
- NMT uses high capacity (10-25m3/hr) robotically applied wet-mix, steel fibre reinforced shotcrete.
- (NATM uses hand placed steel mesh, and usually dry mix shotcrete which is often applied by hand held equipment.)

NMT

The Norwegian Method of Tunnelling

TUNNEL SUPPORT DESIGN

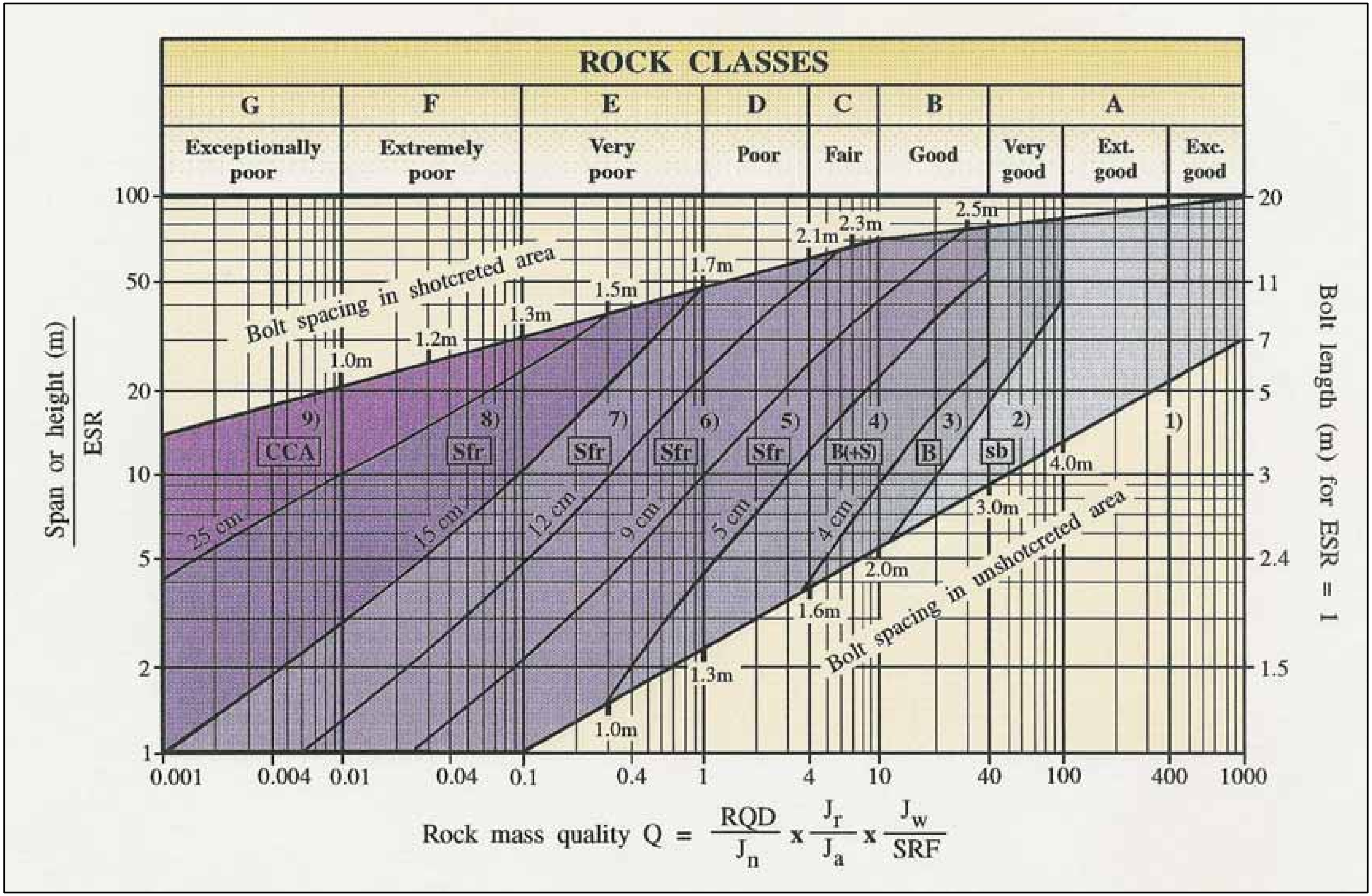
Using a new Q-system chart



Rock mass quality $Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$

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



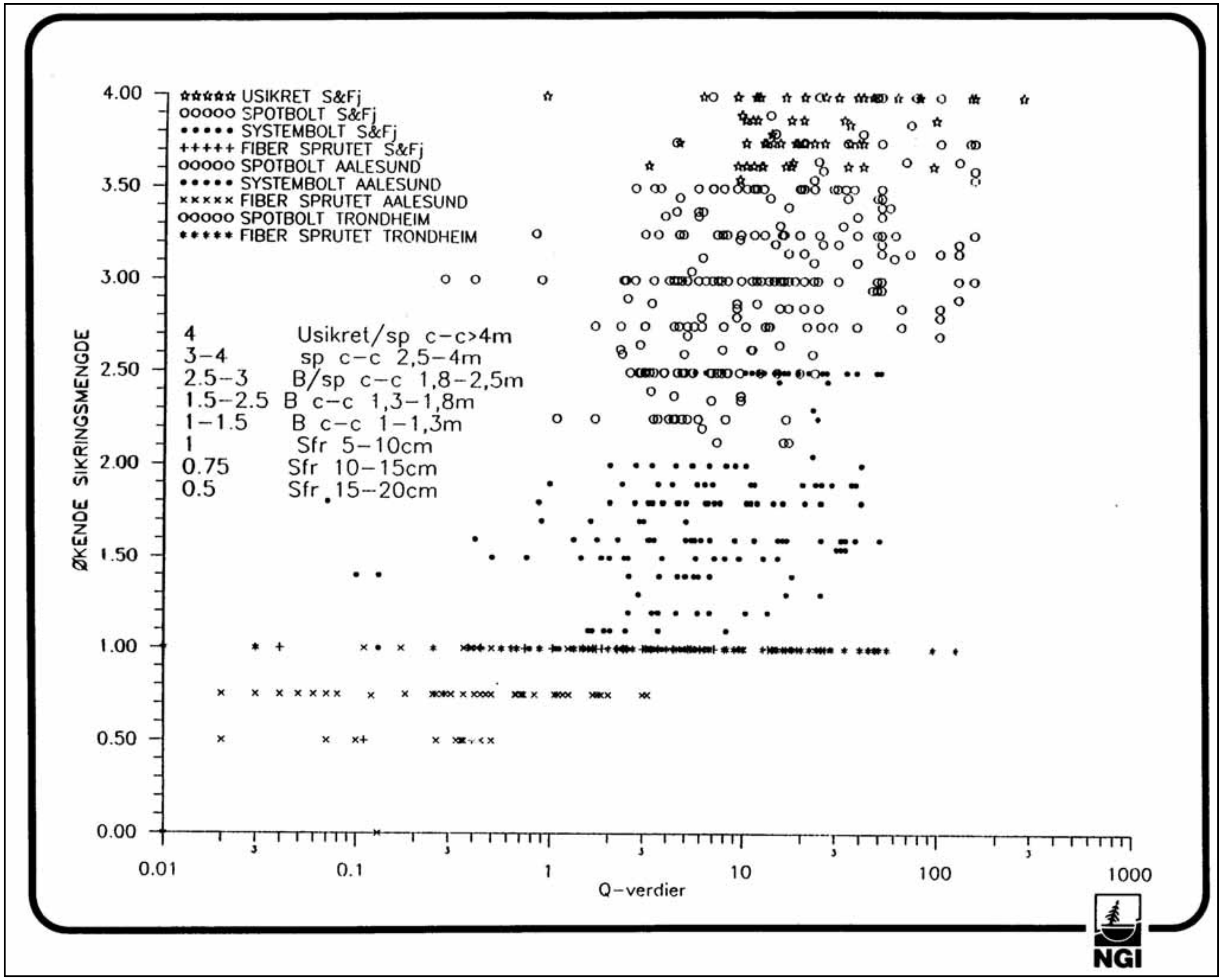
Grimstad and Barton, 1993

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** (TUNNEL-USE) NUMBERS (Barton and Grimstad, 1994)



Grimstad's new case records

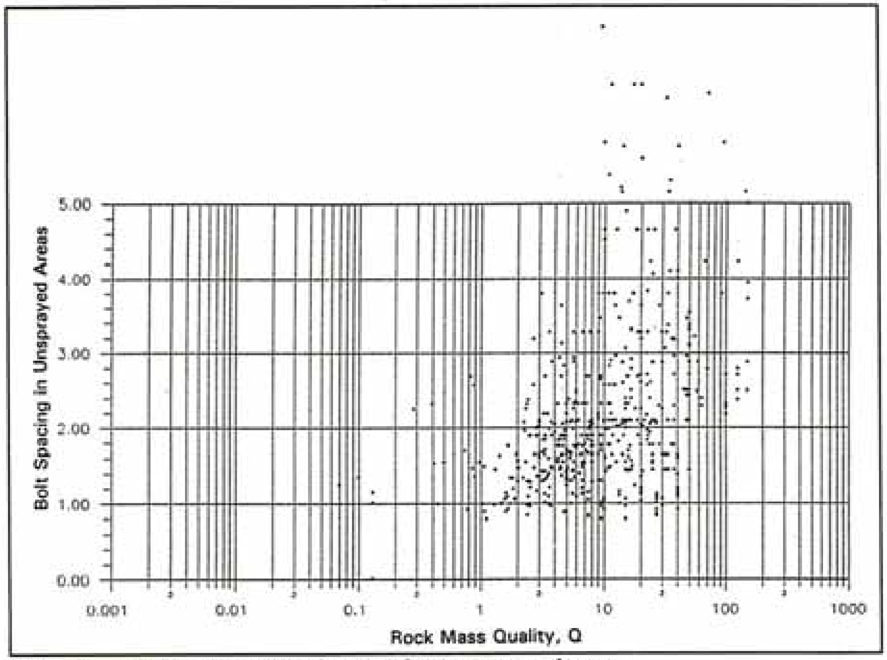


Figure 4 *Bolt spacing related to Q-value in unsprayed areas.*

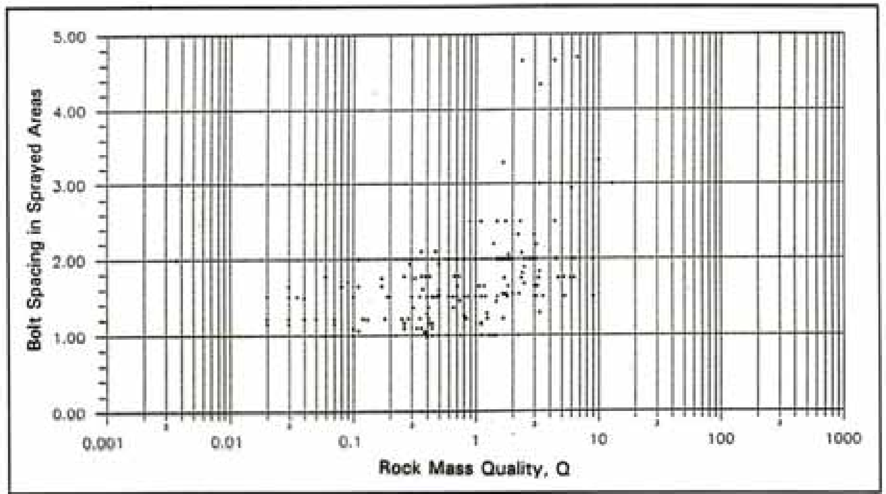


Figure 5 *Bolt spacing related to Q in sprayed areas.*

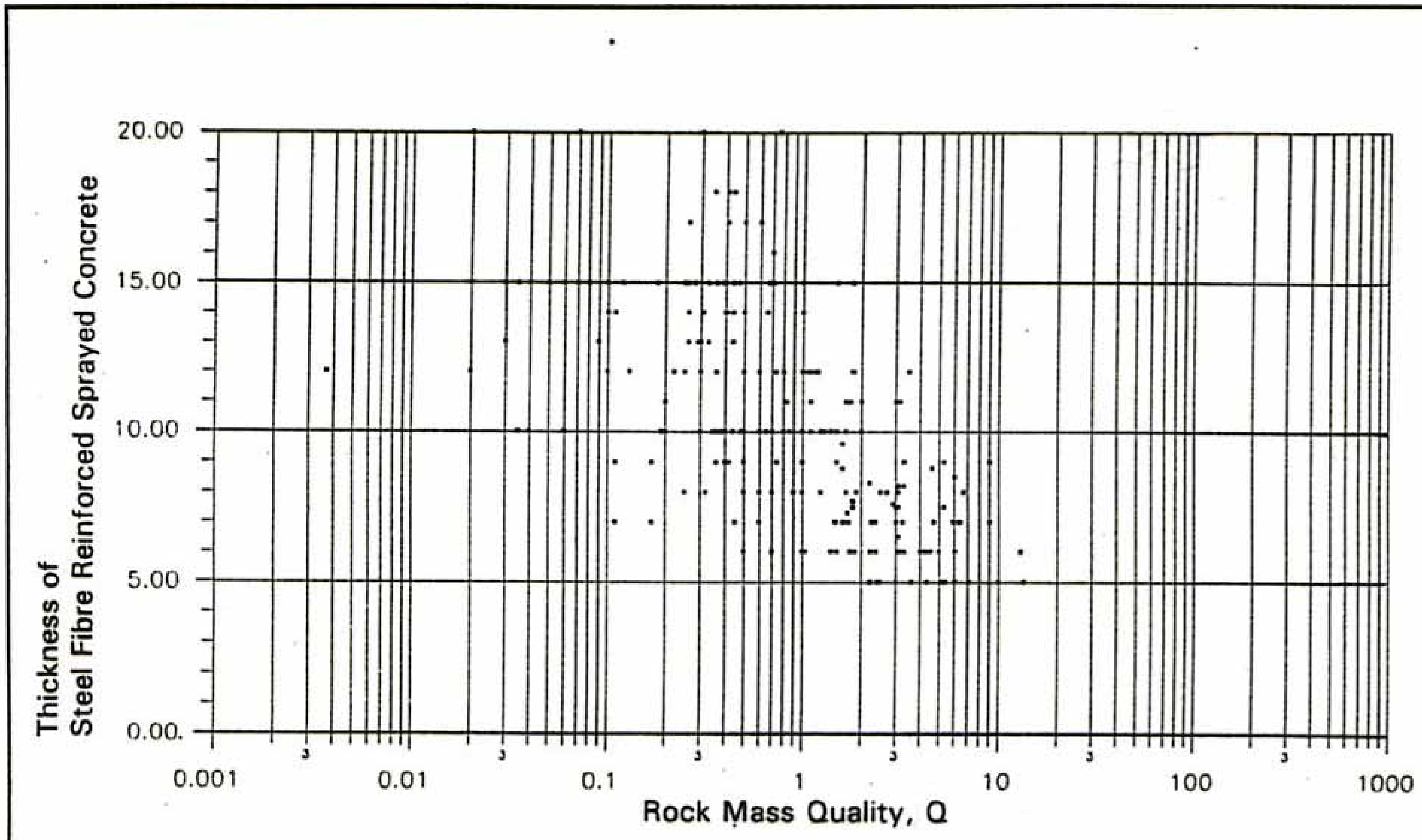


Figure 8 *Case records of S(fr) showing thickness in centimetres as a function of the Q-value.*

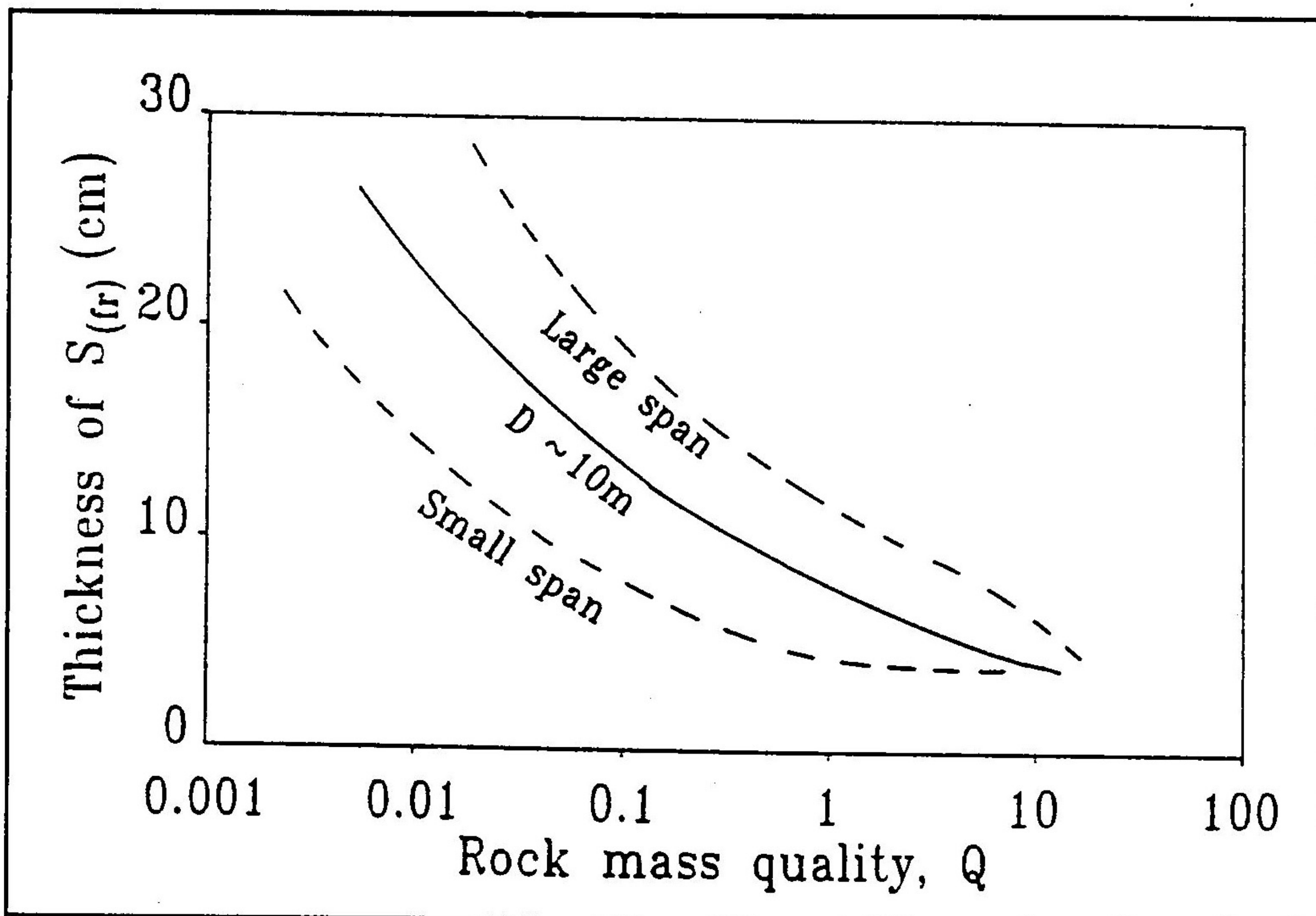
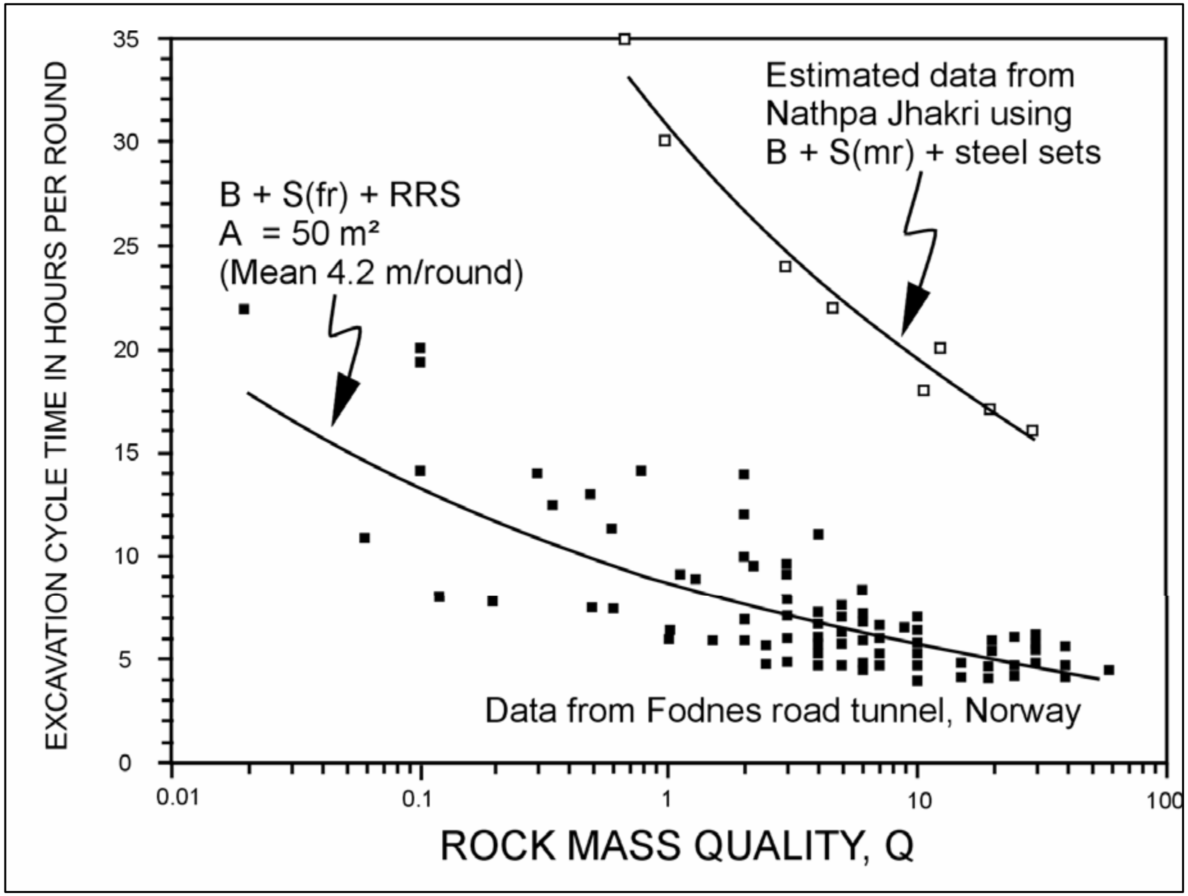


Figure 9 *S(fr) thickness as a function of tunnel span and Q-value*



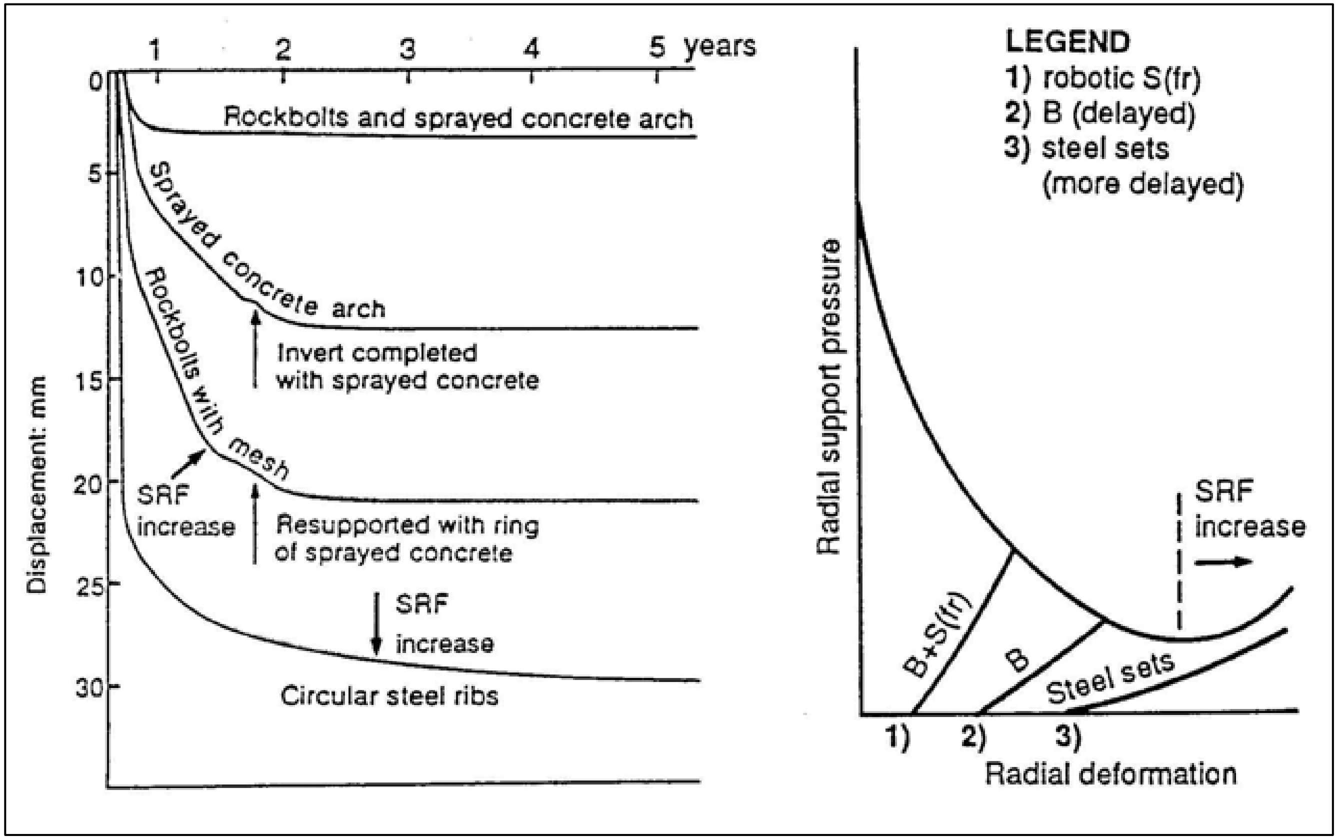
Cycle-time recordings (drilling the next round, blasting, waiting for gasses to clear, mucking, logging, bolting-if needed, shotcreting-if needed) versus Q-value. (Grimstad, NGI: pers com.1998).

SOME IMPROVED TECHNOLOGY ASPECTS OF NMT

1. relevant shotcrete technology and equipment

2. relevant bolting technology (corrosion protected)

3. relevant water control (pre-injection and the free-standing liner)

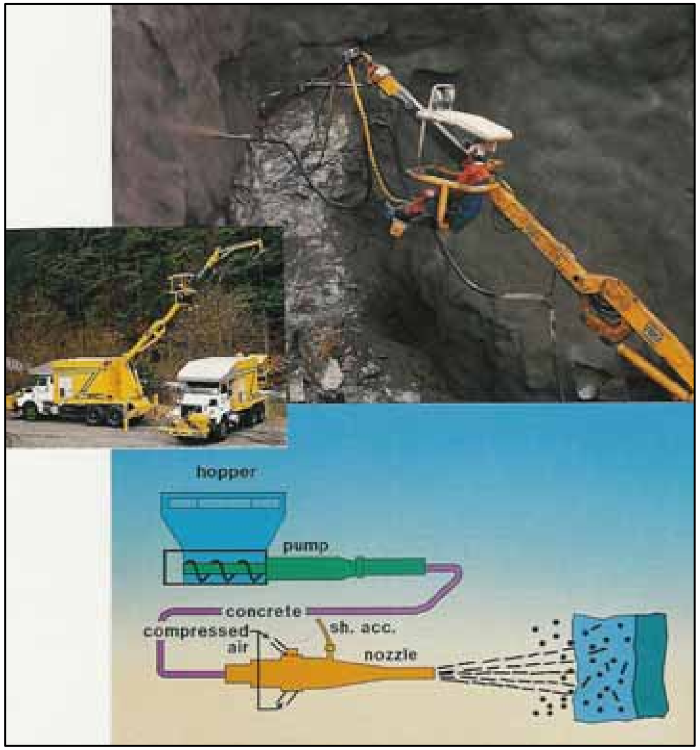


B+S (better still B+Sfr) gives by far the best tunnel-stabilizing result according to 5 years of deformation monitoring at an experimental tunnel in mudstone. Ward et al. 1983, and Barton 1994.

Relevant shotcrete technology and equipment

Road-licensed 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).


AMV 6400 DIESEL
AMV 7000
AMV 6400



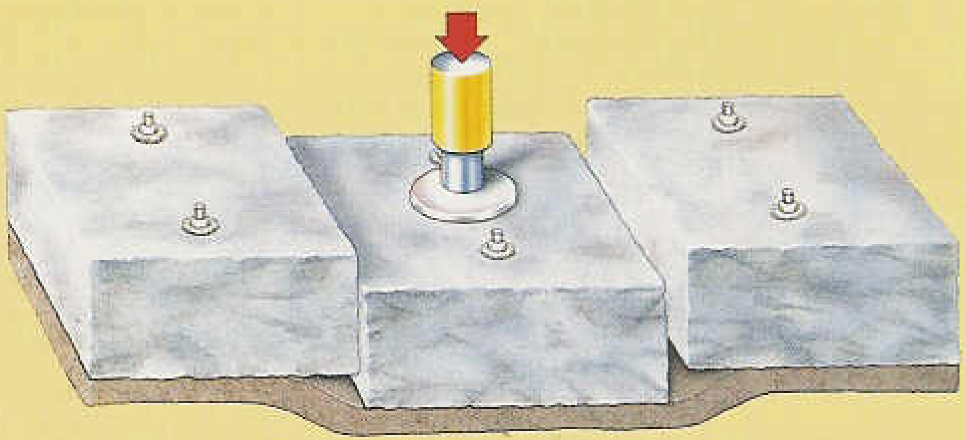
A typical mix design for shotcrete used in Norway:

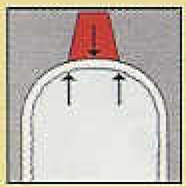
Portland cement (c)	450 – 550 kg/m³
Silica fume (s)	3 – 10 % of cement weight
Aggregate	0 – 10 mm
Plasticizer	0.3 – 1.0 % of cement weight
Superplasticizer	0.3 – 1.0 % of cement weight
Steel fibre	50 kg/m³ (dependent on toughness requirements)
Water/(c+s)	0.40 – 0.45
Slump	15 – 18 cm
Air content	< 4%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

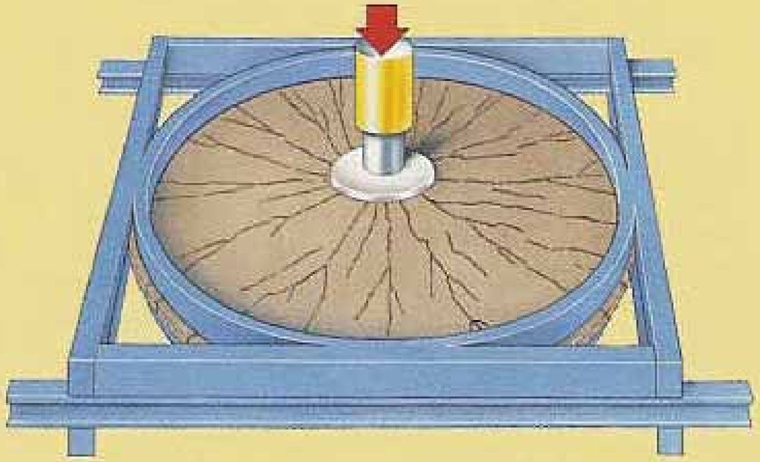
The illustrations below show tests used to document the toughness of steel fibre reinforced shotcrete.

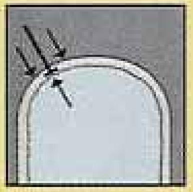




The falling block test

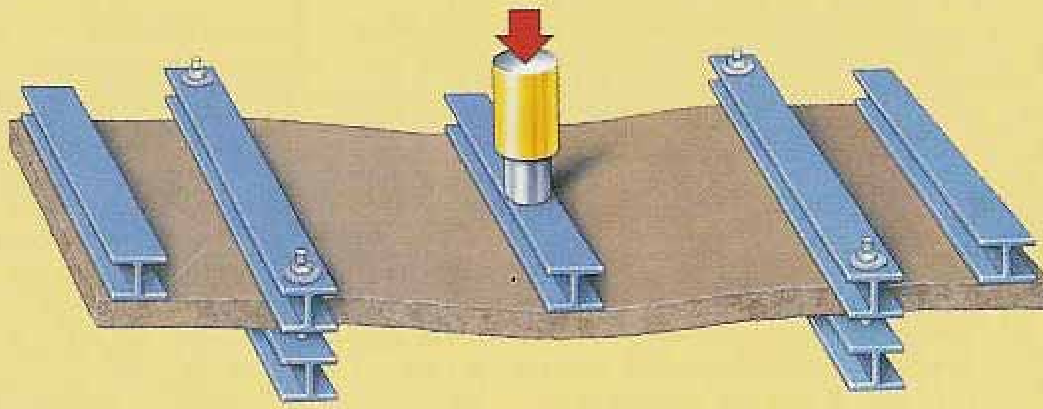
The falling block test simulates the ability of the concrete to support a loose block of rock in a tunnel or rock cavern. Results show that steel-fibre reinforced shotcrete has higher strength and toughness than ordinary mesh reinforced shotcrete.

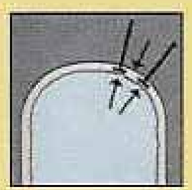




The circular plate test

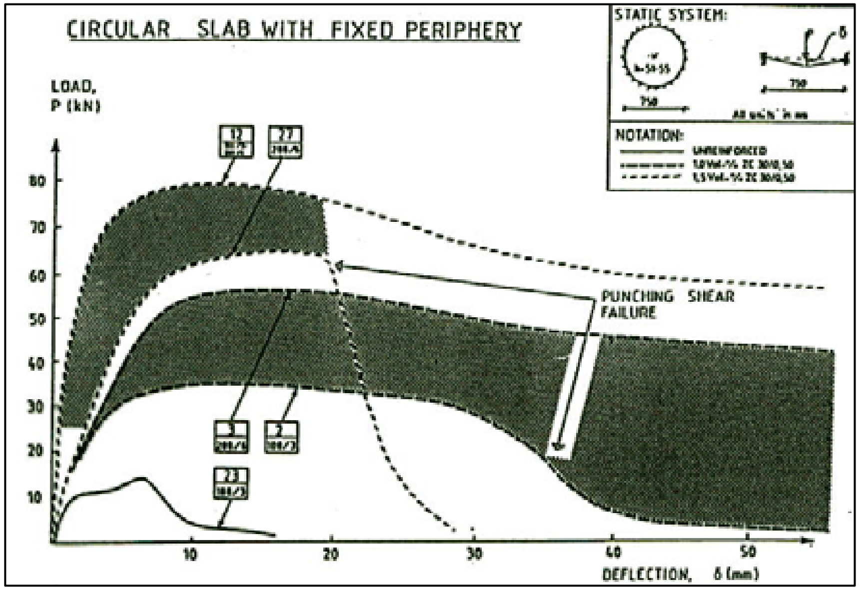
The circular plate test simulates the load situation around a rockbolt. The test clearly shows that the amount of fibres present in the fractured surface is important in order to avoid sudden collapses. Many small cracks instead of a few large ones are formed, allowing the concrete to retain its strength.

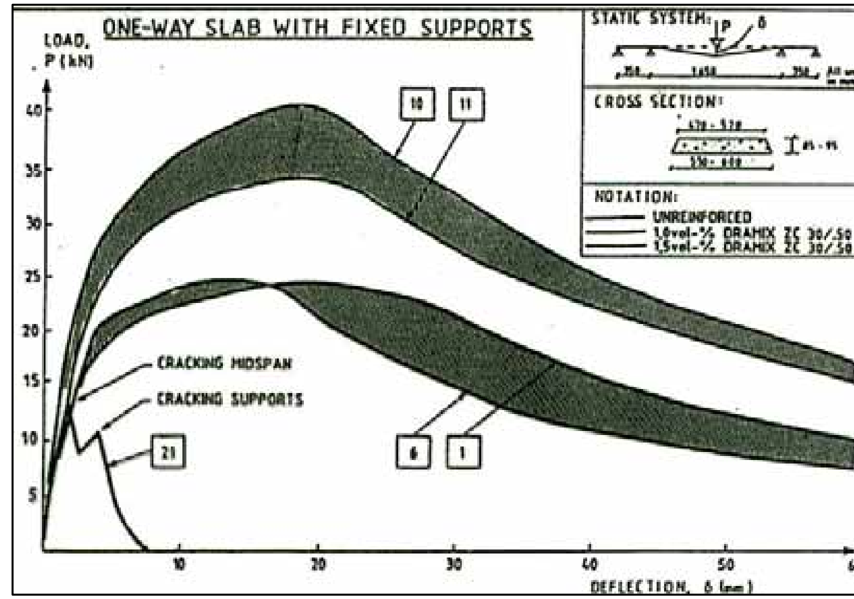




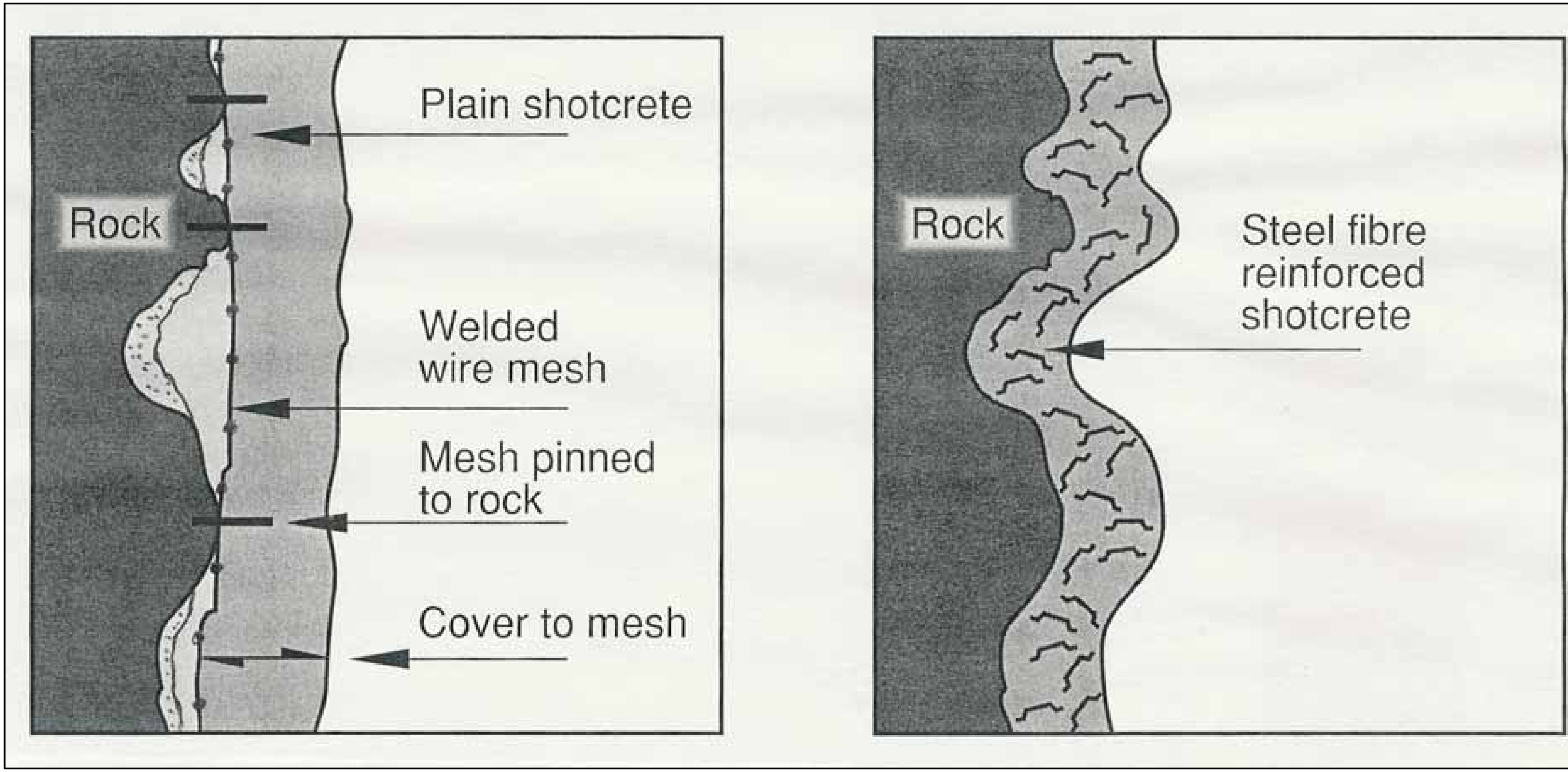
The One Way Slab Test

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.





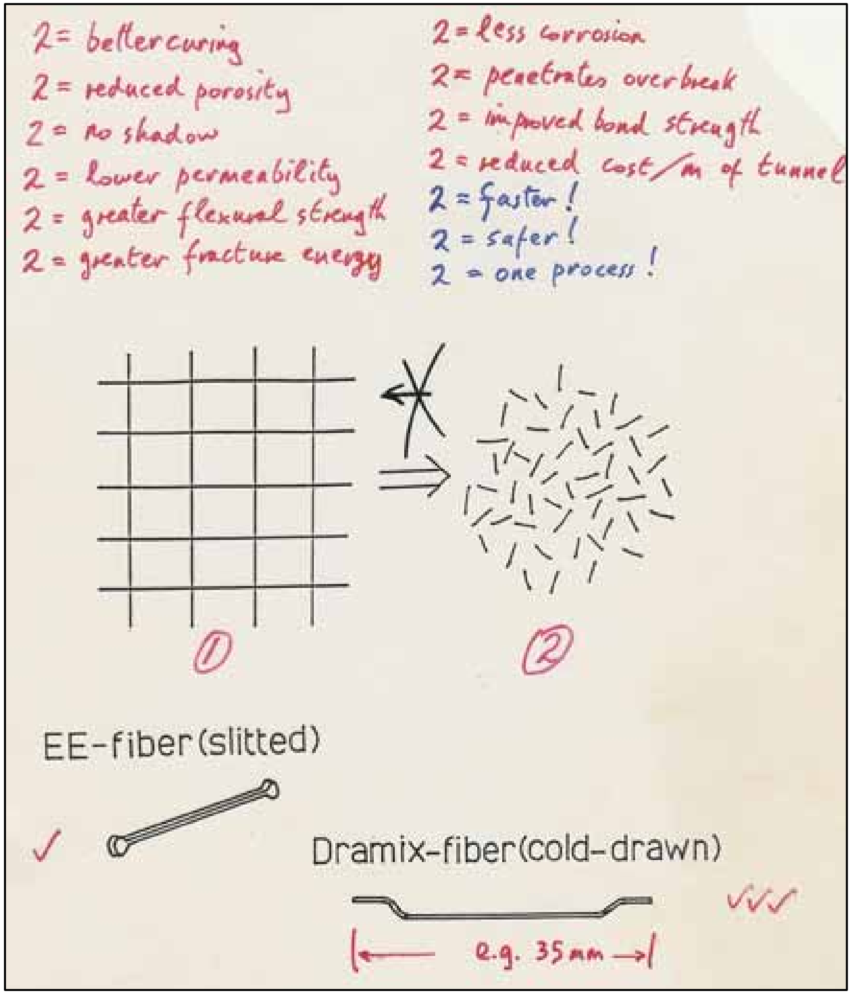
SLAB TEST LOAD-DEFORMATION BEHAVIOUR WITH S(fr)
Torsteinsen and Kompen, 1983.



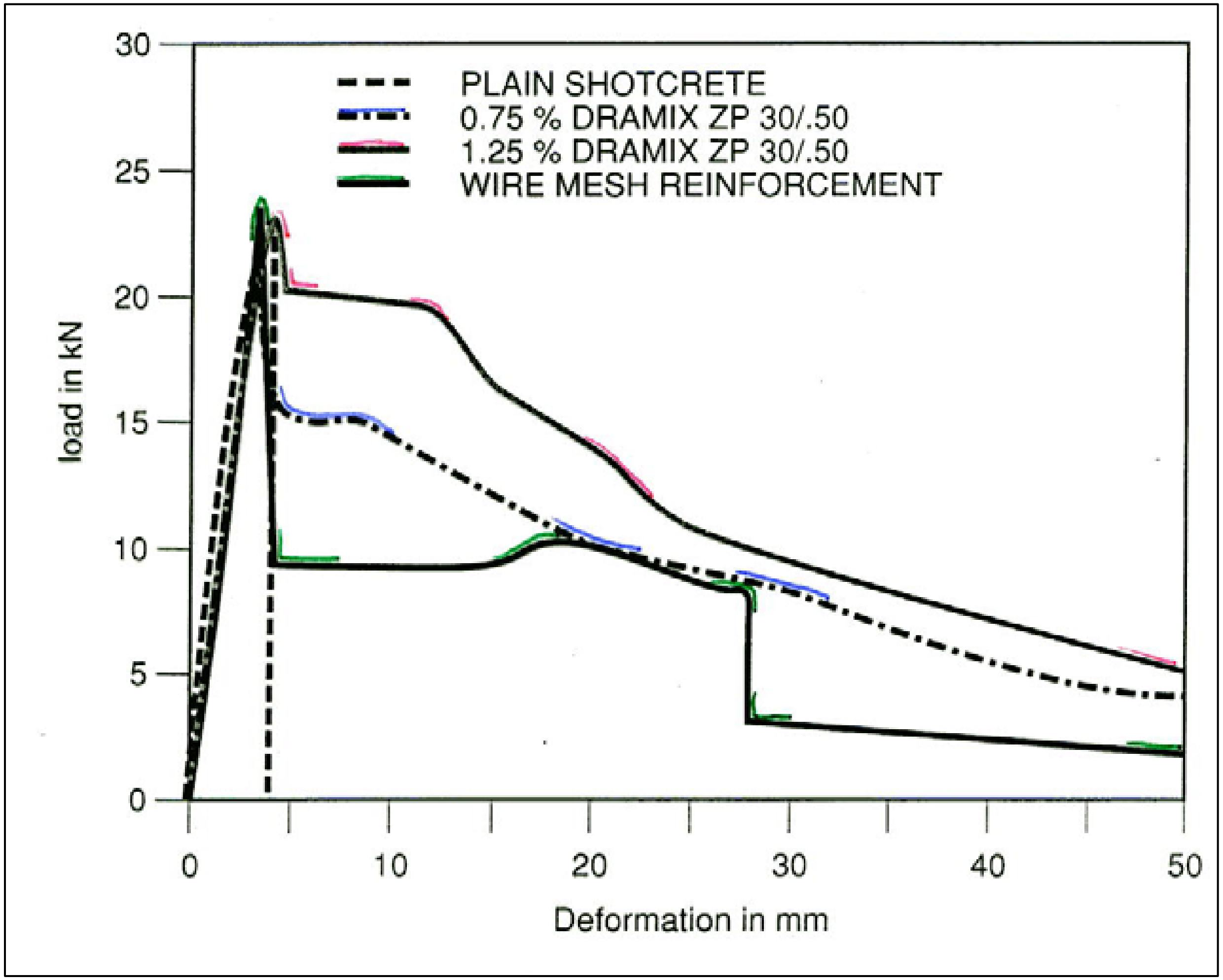
Vandevall (Bekært, Belgium)

CONTRACTOR 'PAINTING' TO AVOID PROBLEMS

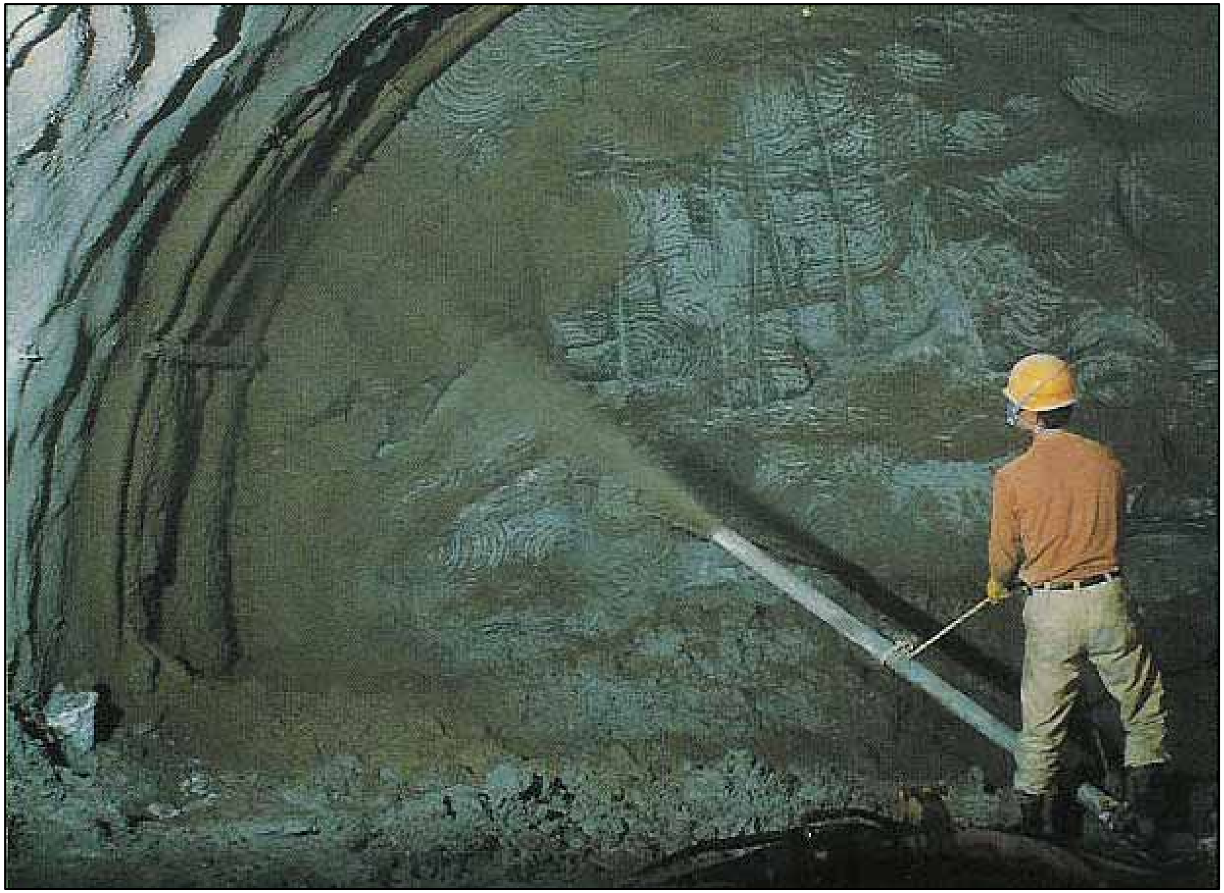
ONE OF THE FIVE MAIN PROBLEMS

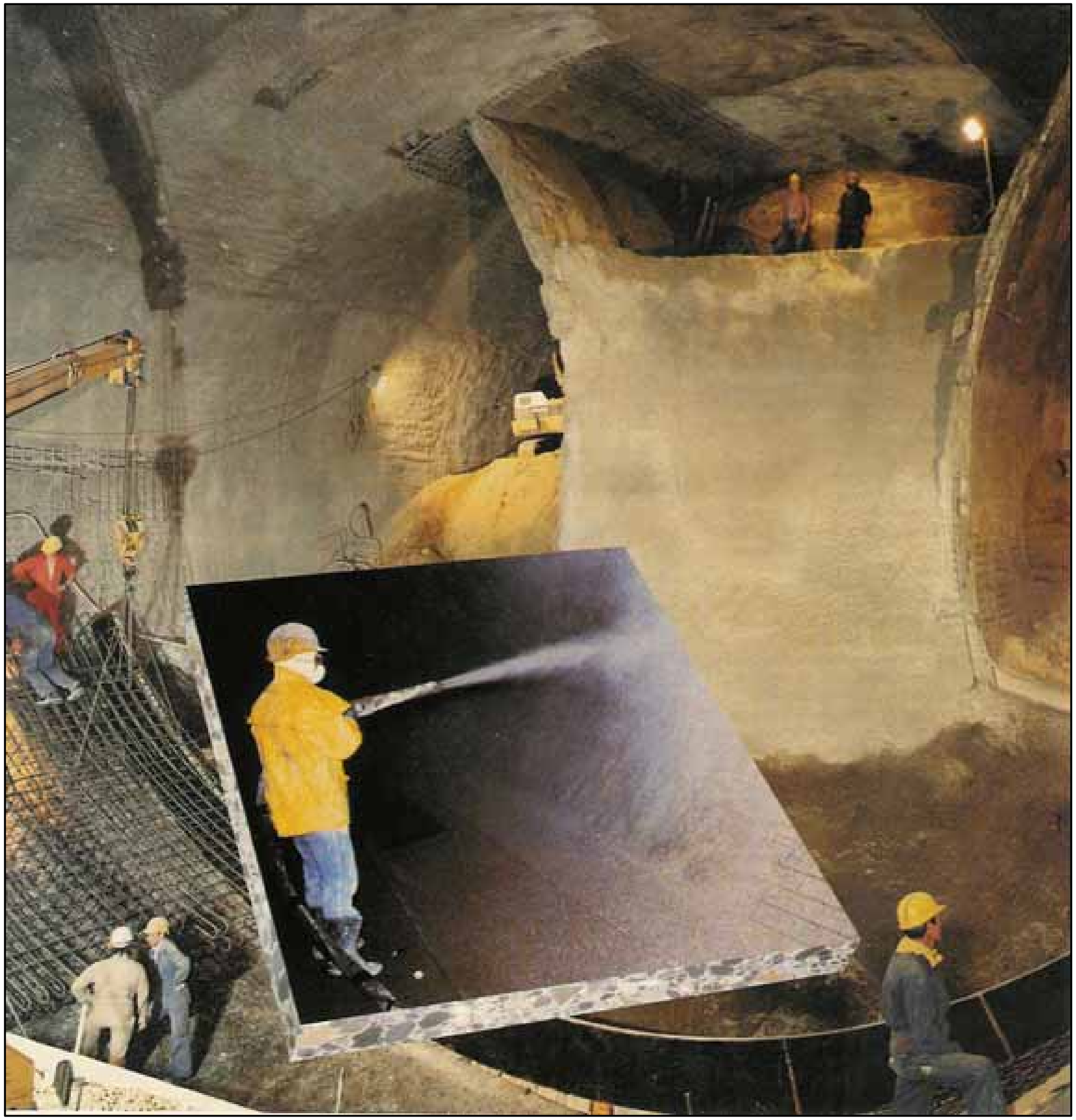


The advantages of S(fr) compared to S(mr). There is today the additional advantage of alkali-free accelerator, allowing thick layers of S(fr) to be built up rapidly, without the previous loss of long-term strength when using 'too much' accelerator.



LOAD-DERORMATION COMPARISON OF S (mr) and S (fr)




AMV
6400 Dround

Relevant bolting technology (corrosion protected)

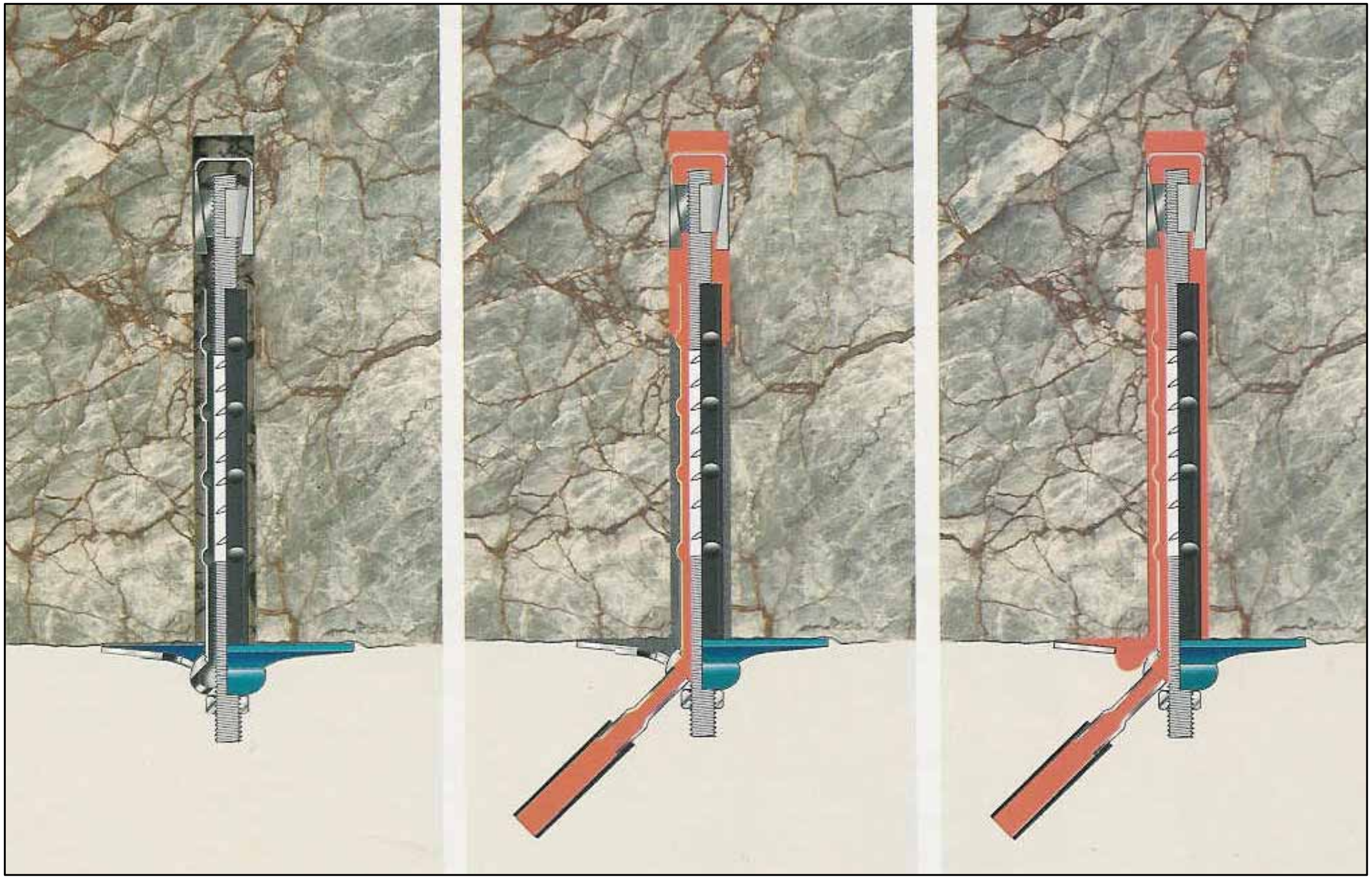
- **Because NMT pre-supposes the use of S(fr)+B as the *final support* of tunnels and caverns (Barton et al. 1992, Barton and Grimstad, 1994), it is important that also the bolts are of good quality, with suitable long-life corrosion protection.**

- **The widespread use of NMT principles in Norway for the last 25 years (35 years if *S(mr)* is included) has meant that there has been an excellent development of corrosion protected bolts in this country.**

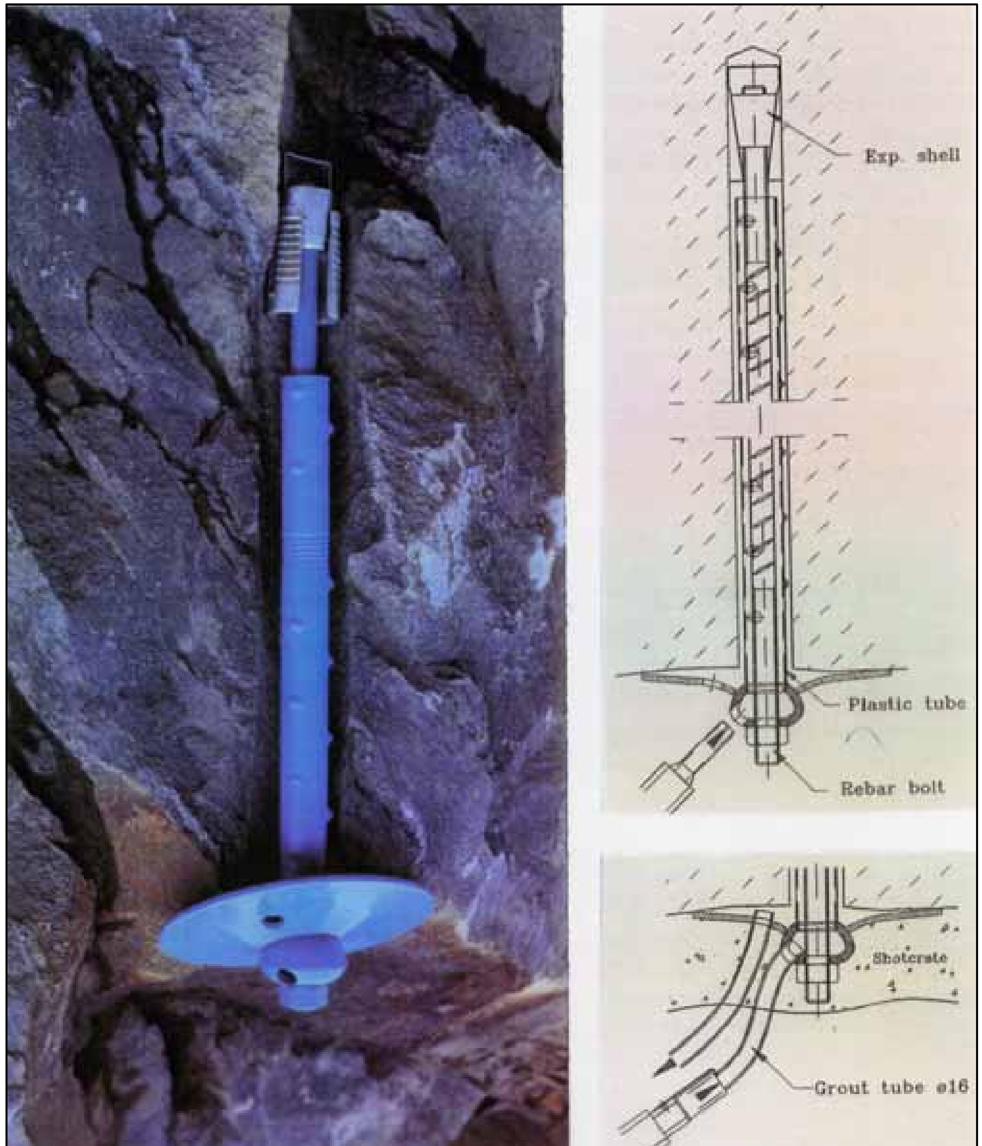
- **The CT-bolt, manufactured by Ørsta Stål, incorporates a simple end-anchoring (wedge-lock) for easy installation and tensioning (if desired), followed by *double-annulus* grouting using a PVC-sleeve.**

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

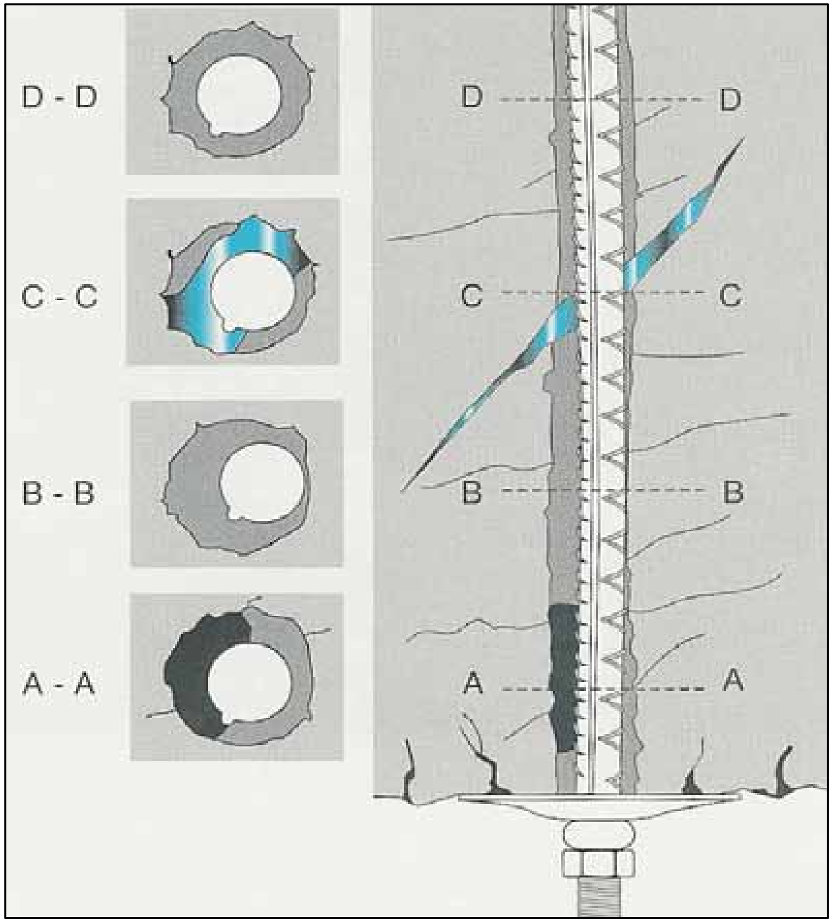
The CT-bolt with PVC sleeve (many meters length in practice. Maximum load capacities are 33 and 30 tons in tension and shear, respectively, for the 20mm diameter bolt (22mm with thread).



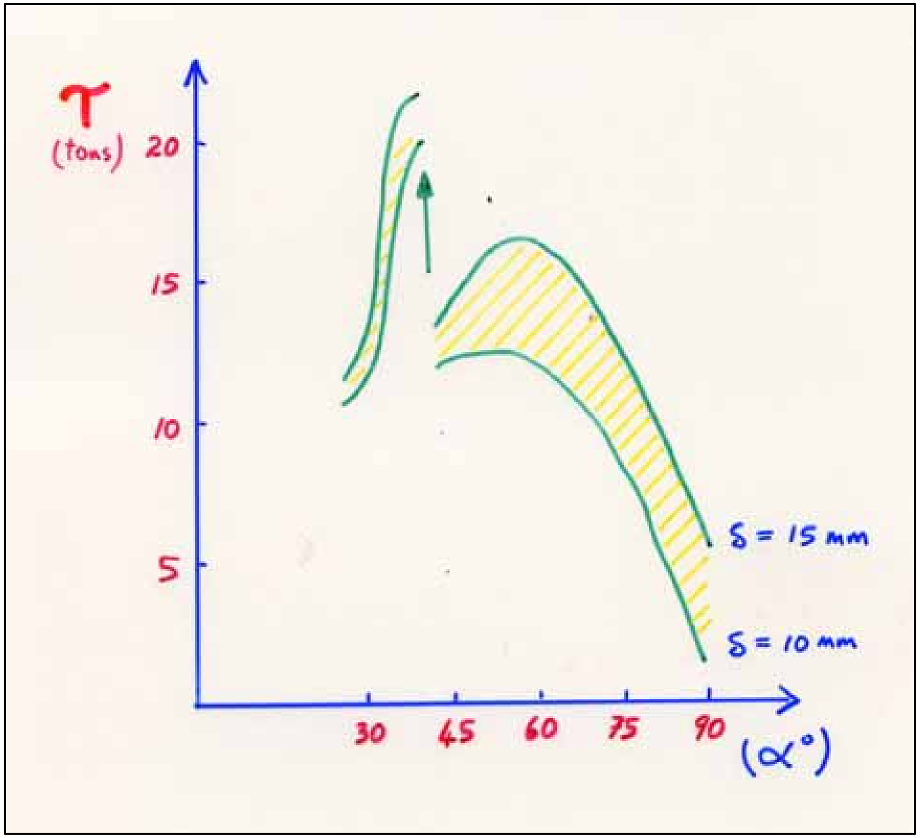
The double-annulus grouting (shown in red). Shotcreting can be performed after end-anchoring and before grouting of the bolt, if desired, using a tube extension. See www.CTbolt.com for good 3D animation of process.

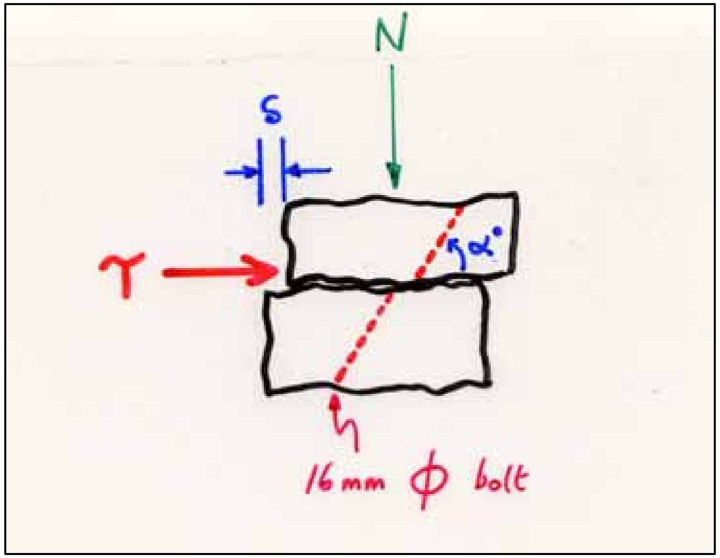

Exp. shell
Plastic tube
Rebar bolt
Shotcrete
Grout tube ø16

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

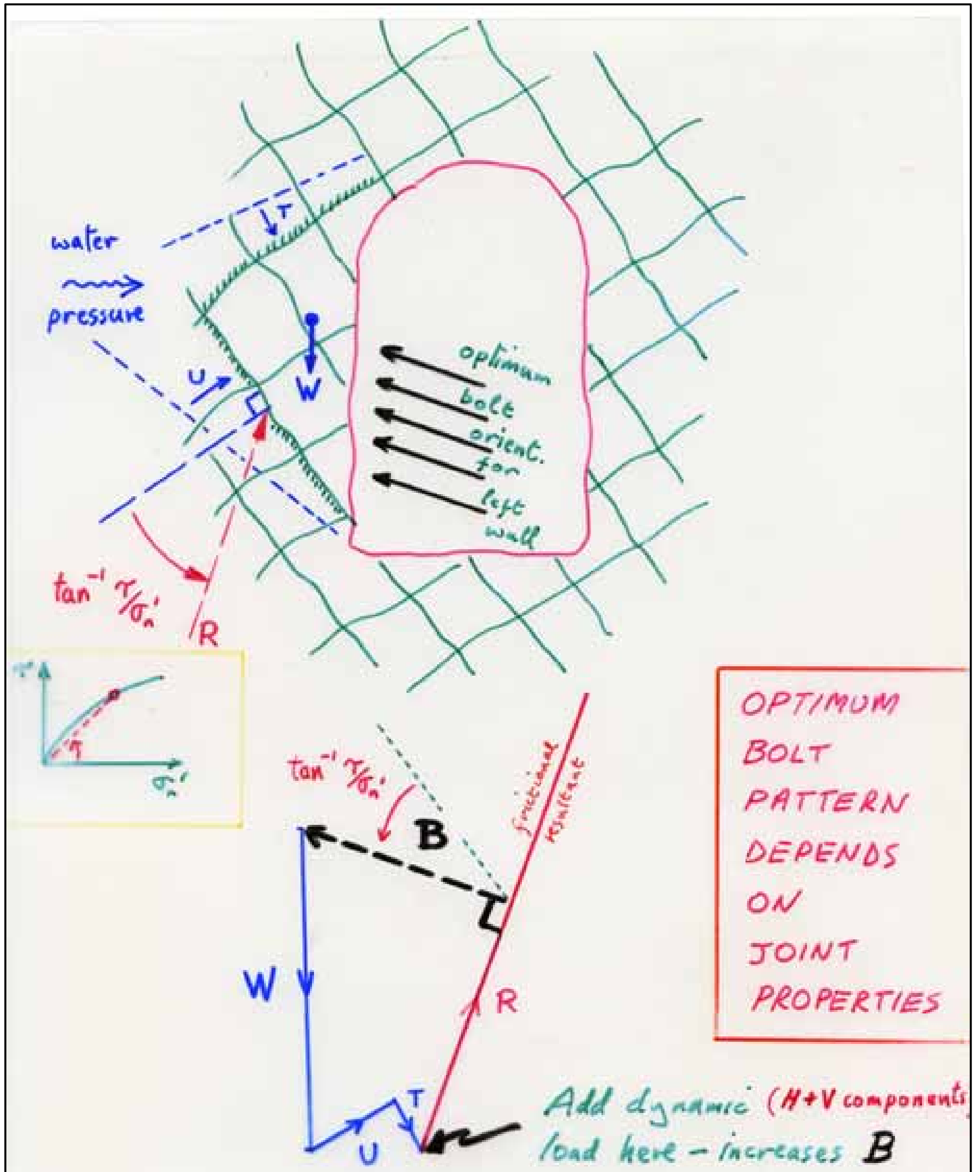


Some (slightly exaggerated) potential problems with un-sleeved conventional rock bolts. (Blue is lost grout due to water flow, black is void, DD is acceptable, BB).





BJØSTRØM 1976



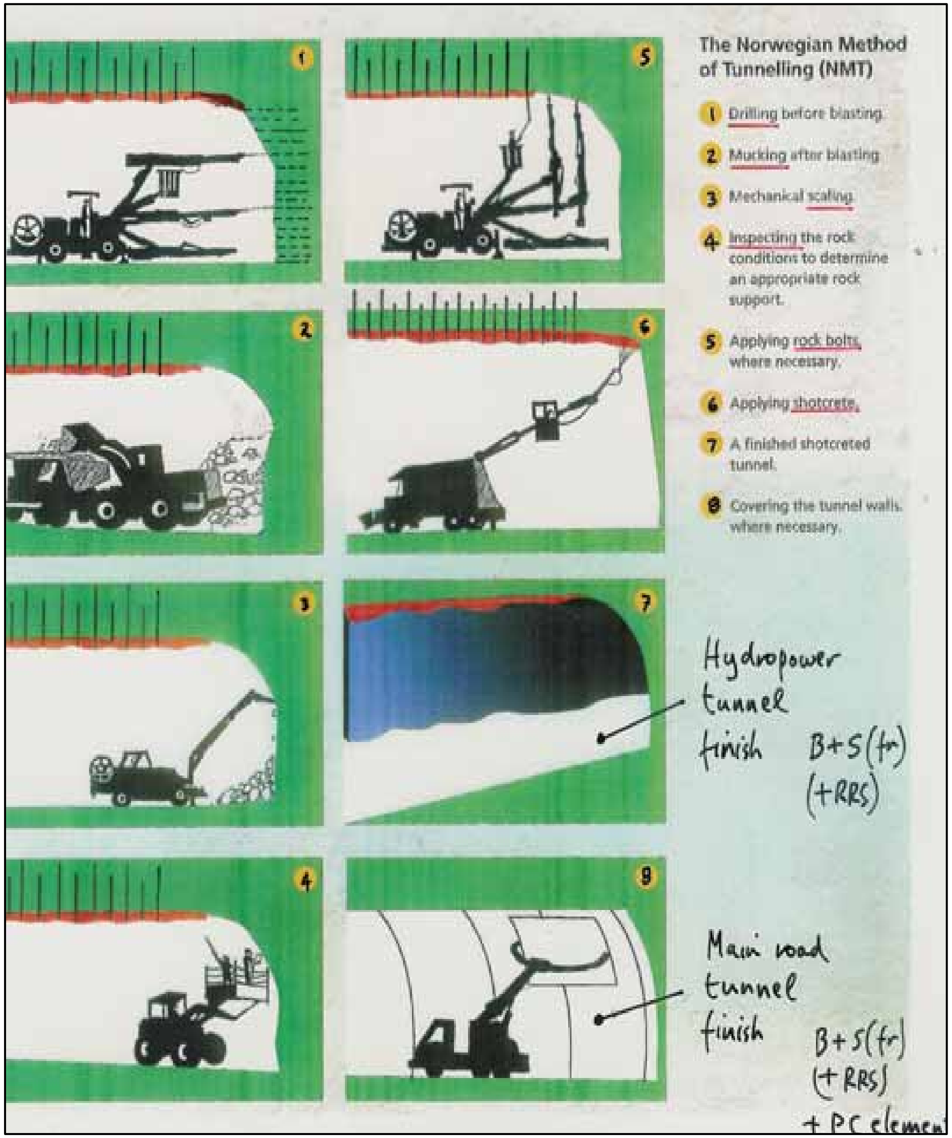
water
pressure
T
U
W
optimum
bolt
orient.
for
left
wall
tan⁻¹ τ/σn'
R
τ
σn'
tan⁻¹ τ/σn'
B
frictional
resultant
W
R
T
U
OPTIMUM
BOLT
PATTERN
DEPENDS
ON
JOINT
PROPERTIES
Add dynamic (H+V components)
load here - increases B

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 costs of US$ 128M /3.2 km, or $ 40,000 per kilometre. This is three to four 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.

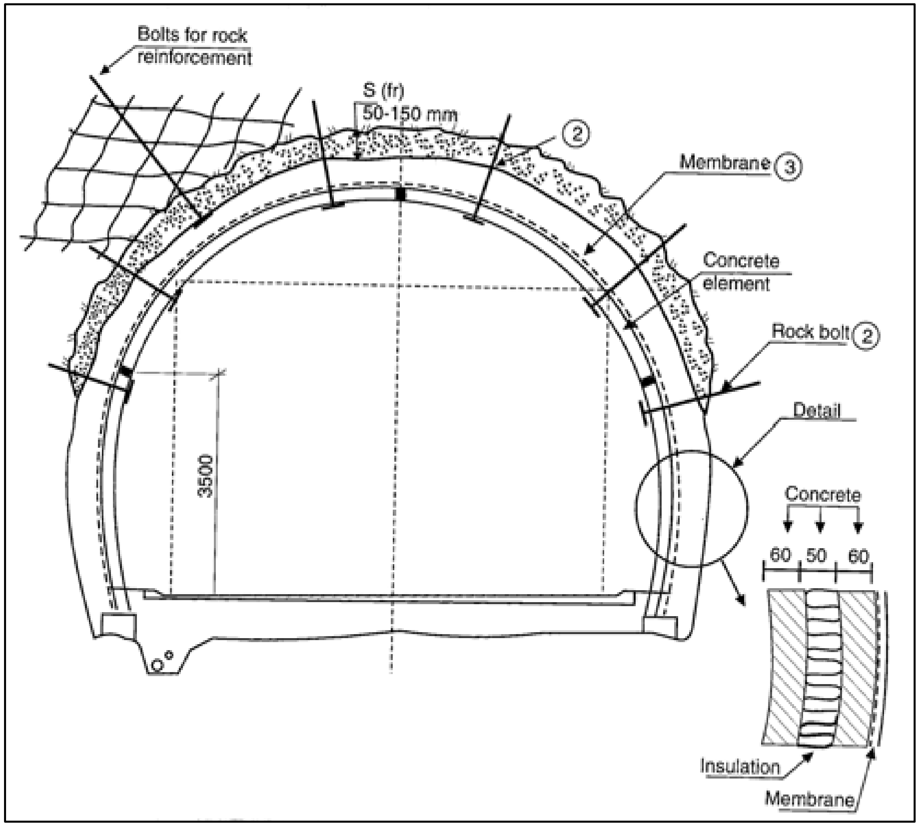


NMT concepts in diagrammatic form. Note that stage No. 6 must precede stage No. 2 if stability /stand-up time is very poor.

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.

This 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.

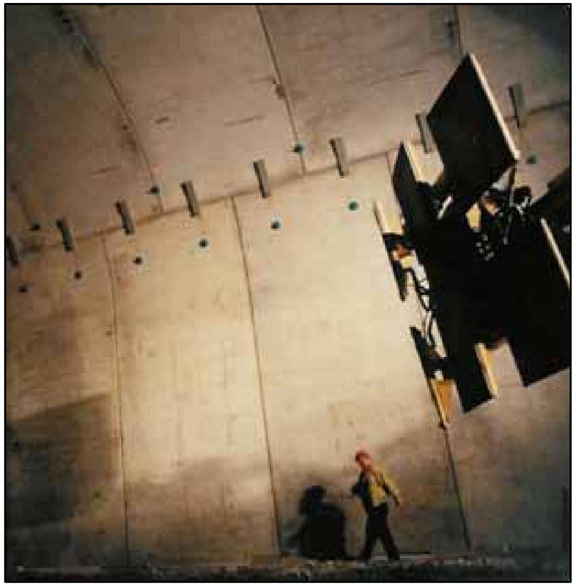
An example of PC-element mounting for a two-lane road tunnel. Note the primary B+S(fr) permanent support, and the mostly dry surface of the shotcrete,.

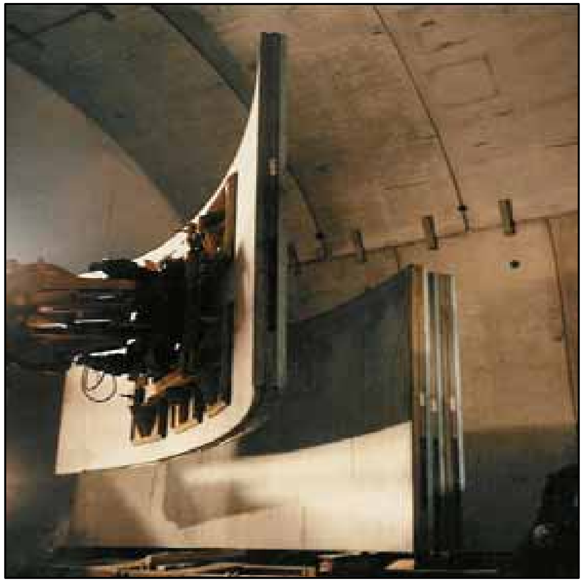
An example of the primary rock reinforcement and support.

This consists of B+S(fr) in the arch and upper walls of a heavily jointed (and therefore heavily over-breaking) rock mass.

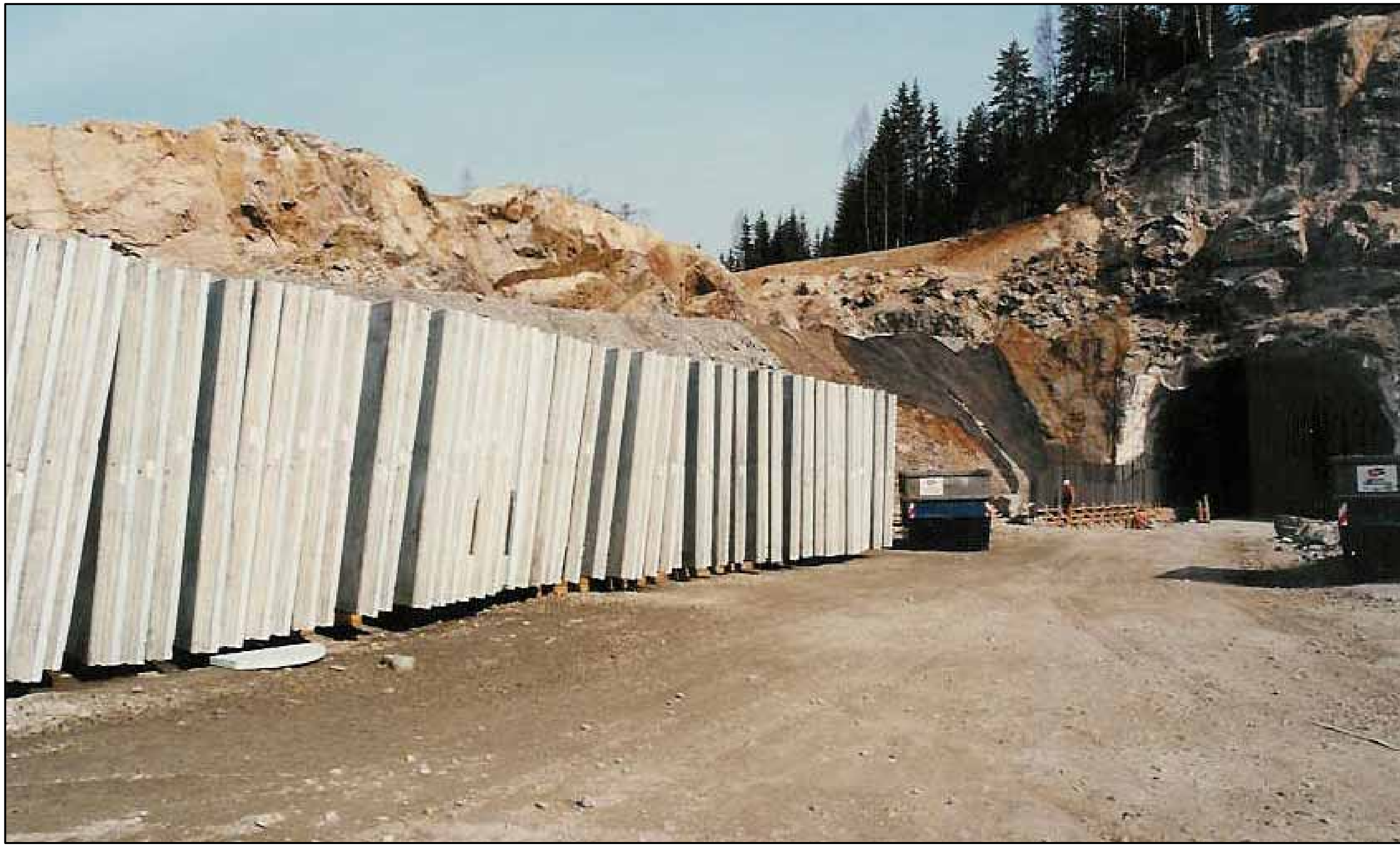
Photographed while checking the shotcrete for any signs of ‘druminess’.

This was followed by a free-standing liner with outer membrane for this motorway tunnel.






TADANO



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

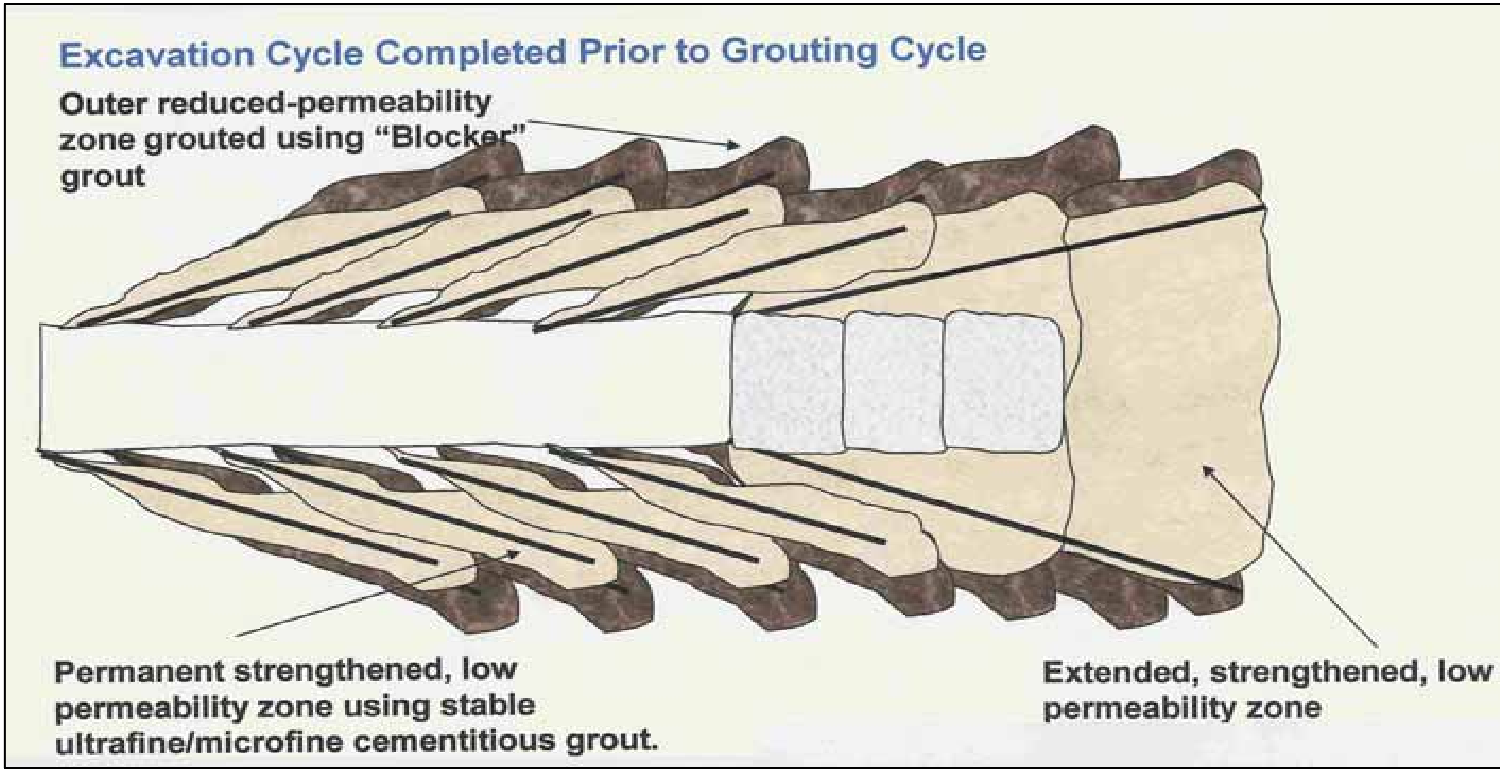
THE GROUT PRE-INJECTION OPTION

FOR WHEN INFLOW

AND

GROUNDWATER DRAWDOWN

ARE UNACCEPTABLE



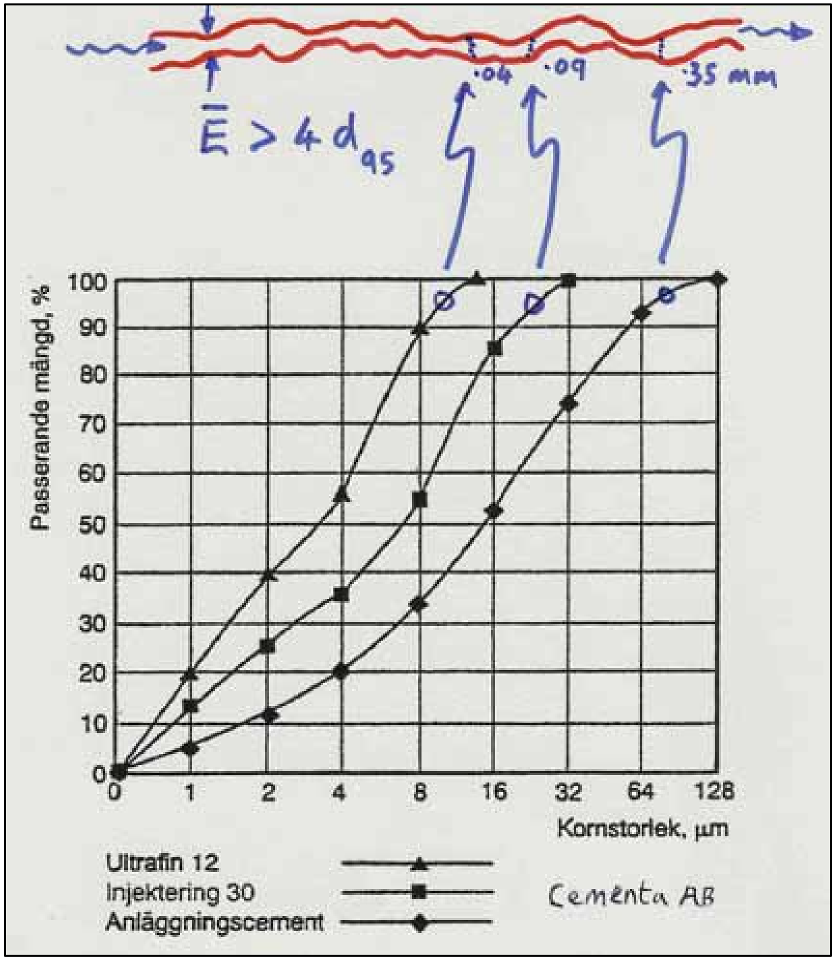
Pre-grouting ‘umbrellas’ for water control (and rockmass property improvement). Grout material choice will be industrial, micro or ultrafine cements, based on the rule-of-thumb $E > 4 \times d_{95}$ concerning initial entry into the joints.
Pre-grouting layout from Elkem.

Some pre-grouting results

Pre-grouting data derived from Åndal et al., 2001.

Rock type	**kg/m² tunnel surface**	**≈ kg/m³**	**≈ litres/m³**
gneiss	11.0 to 16.5	1.8-2,8	**1.0-1.6**
granite	12.0 to 52	2.0-8.7	**1.1-5.0**
phyllite	26	4.3	**2.5**
rhomb porphyry	28 to (99)	4.7-(16.5)	**2.7-(9.4)**
syenite (dike)	30 to (186)	5.0-(31)	**2.9-(17.7)**
fracture zone	19 to 50	3.-8.3	**1.8-4.7**

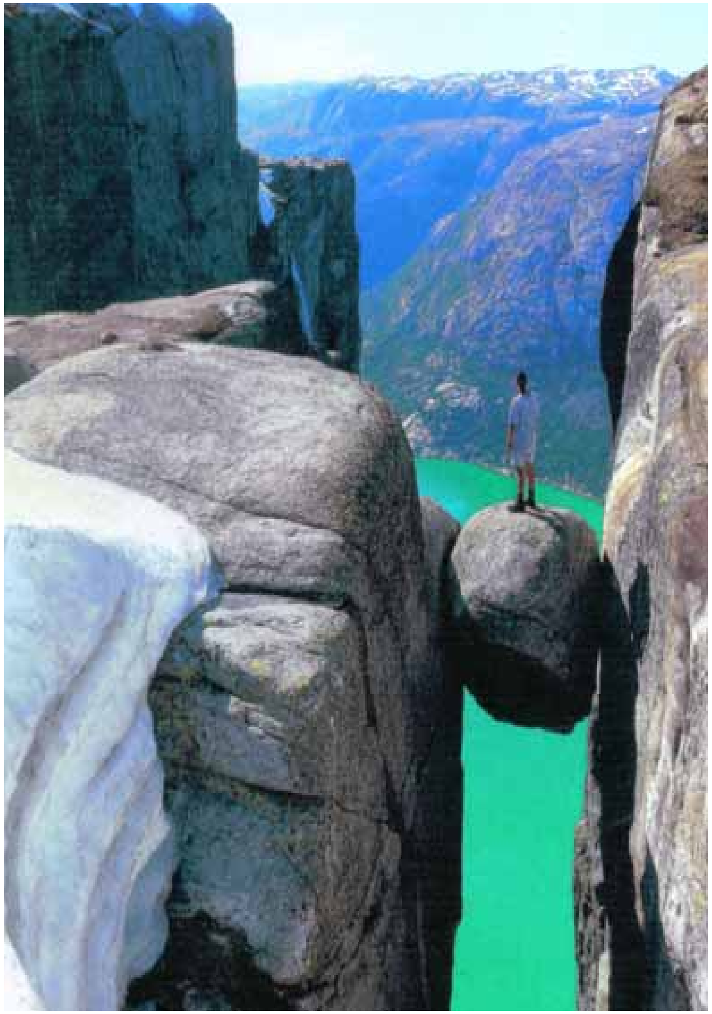
ASSUME 6M THICK CYLINDER (ON AVERAGE) IS GROUTED



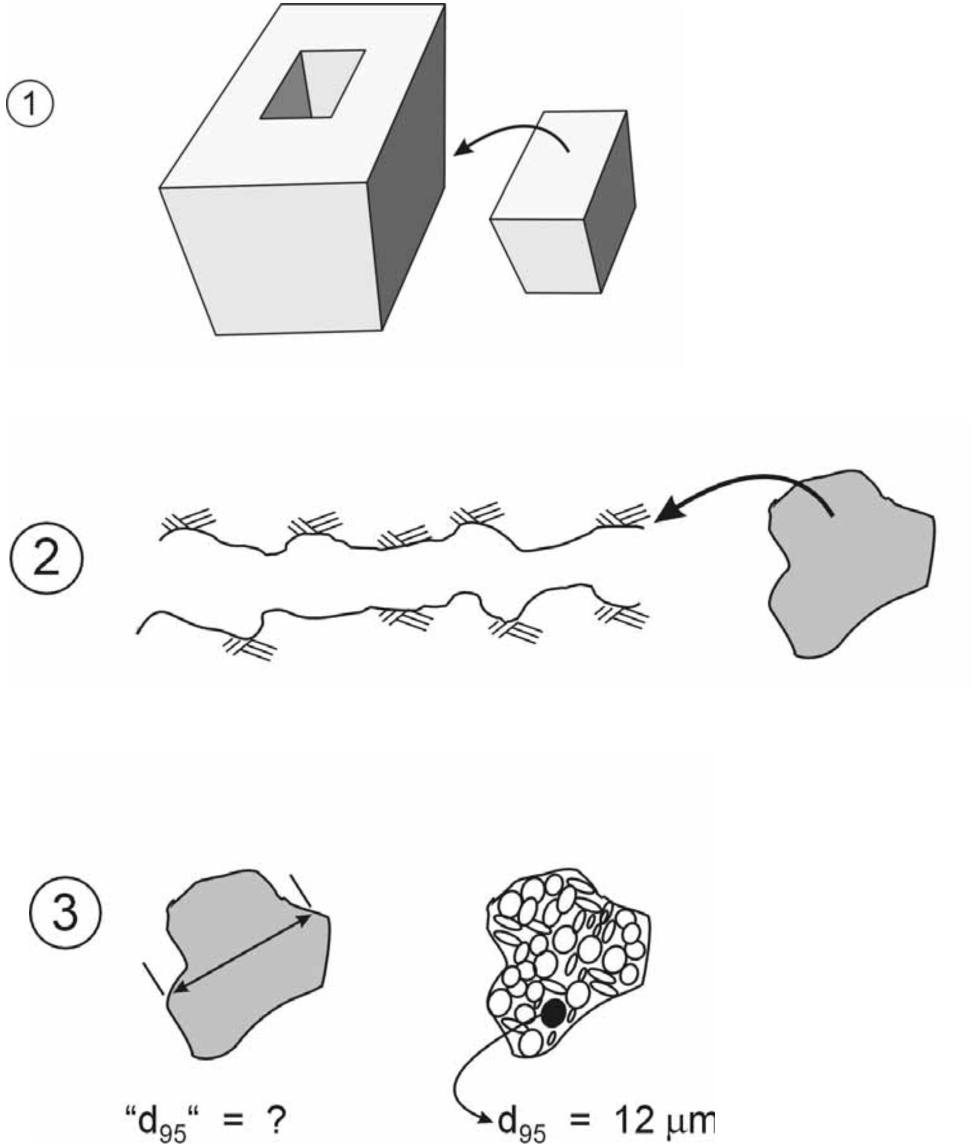
- **Choice of a suitable grout depends on the estimated (e) and (E) values and then use of the rule-of-thumb that E > 4 x d_{95}.**

- **It is normal to use micro- (or ultra-fine) cements with microsilica and plasticizers, to give the most stable grouts that give the best final results**

- **i.e. <10^{-8}m/s or < about 2 or 3 liters/min/100m inflow.**

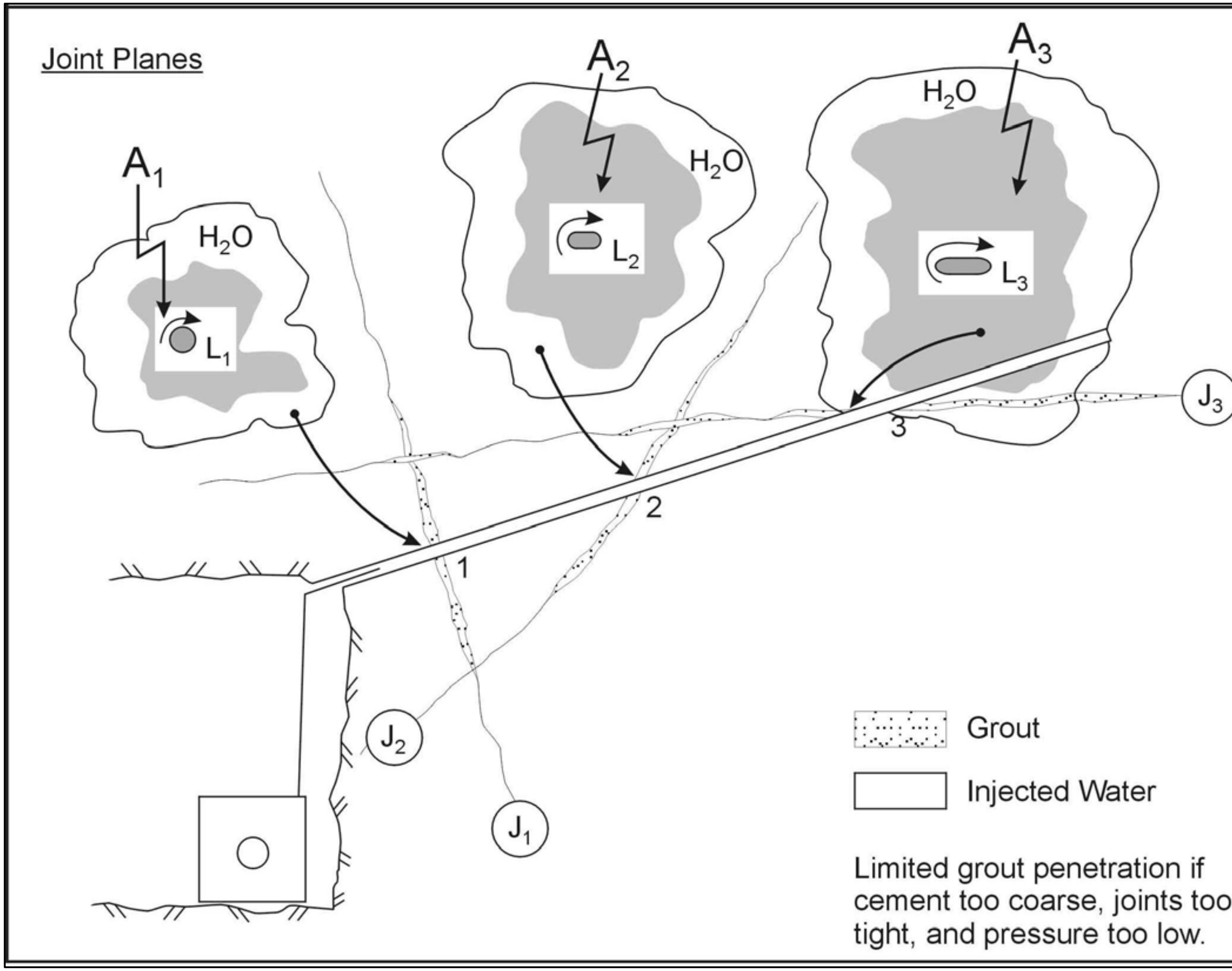


The dilemma is how to get blocks (i.e. particles) that are too large in joints that are too tight.



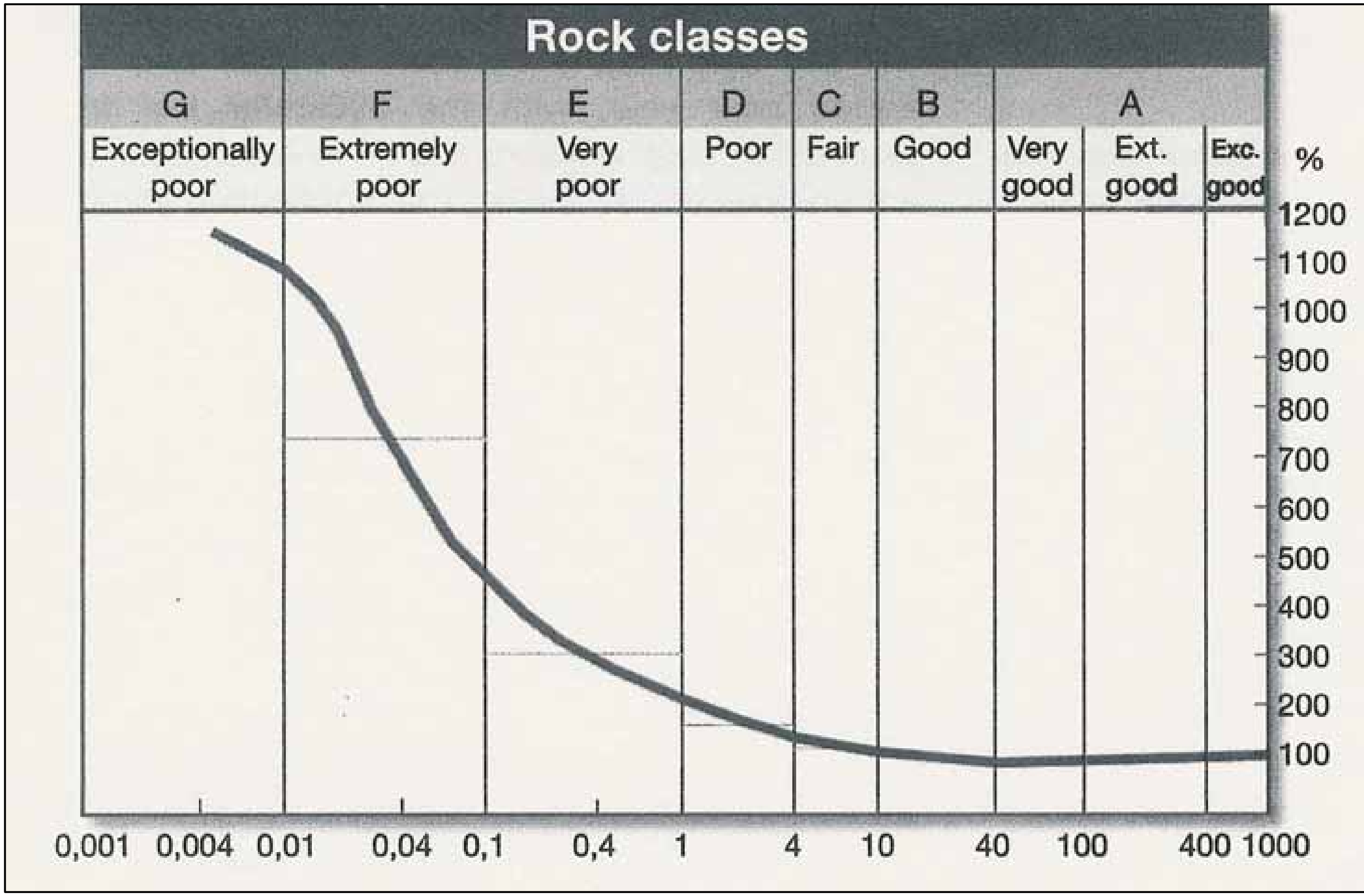
…..smaller particles! ….. wider joints!


WORLD
TUNNELLING
AND SUBSURFACE EXCAVATION
Nov 1991
ANNUAL
TECHNICAL
REVIEW
CONTRACTORS
& CONSULTANTS



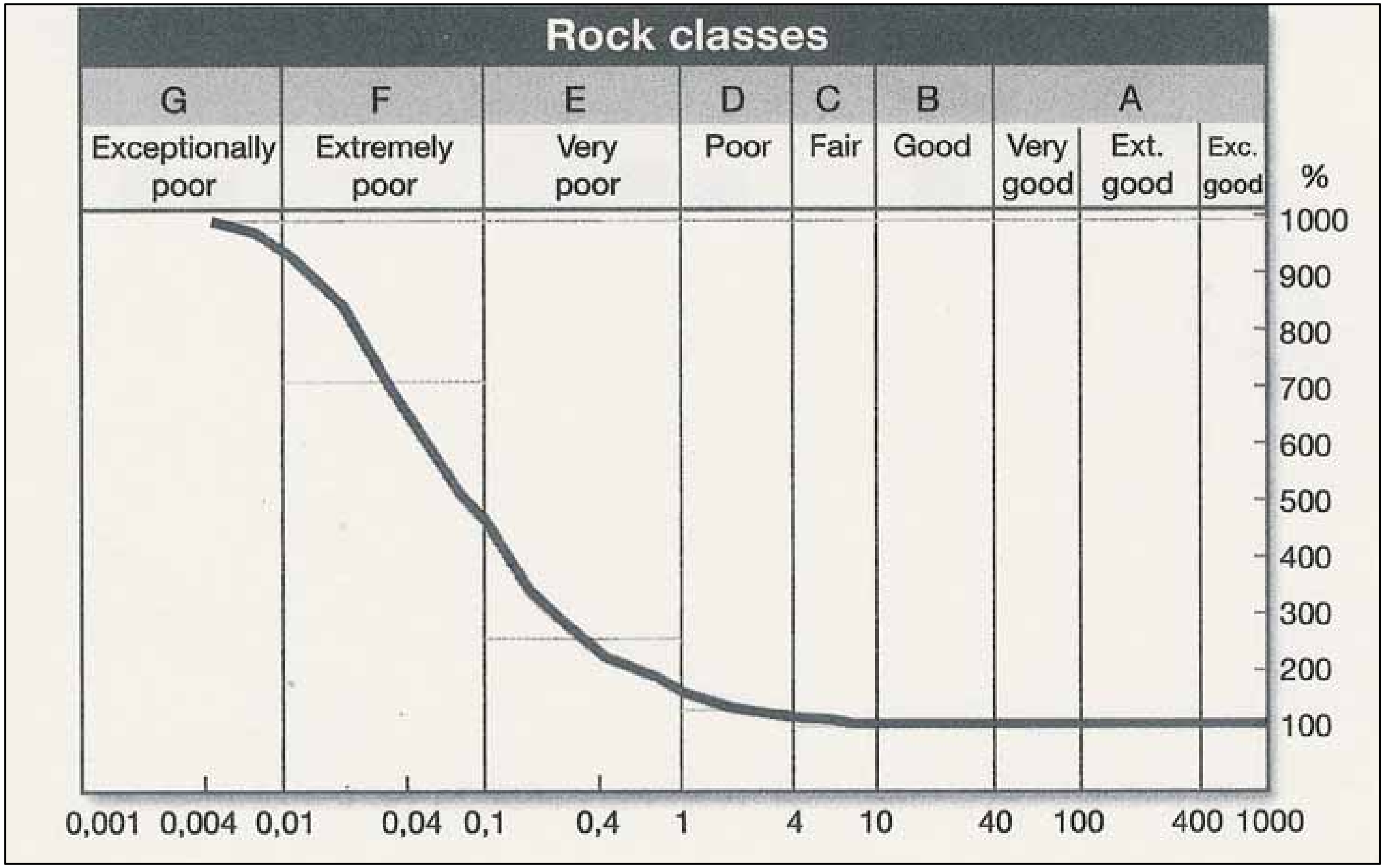
‘Water-sick’ rock, due to too coarse cement particles, too tight joints, and too low injection pressure.

WATER-SICK ROCK – MORE WATER AFTER INJECTION THAN BEFORE



Q = RQD/Jn x Jr/Ja x Jw/SRF

RELATIVE COST FOR TUNNELLING IN RELATION TO Q-VALUE



Q = RQD/Jn x Jr/Ja x Jw/SRF

RELATIVE TIME-EXPENDITURE OF TUNNELLING IN RELATION TO Q-VALUE

Improvements in rock mass 'quality' due to grouting

Joints are obviously opened more than in the preceding Lugeon tests, and many rock mass properties can apparently be improved if stable micro-cement based materials are used.

Pre-grouting may cause moderate, individual effects like the following:

RQD increases e.g. 30 to 50%, J_n reduces e.g. 9 to 6, J_r increases e.g. 1 to 2 (due to sealing of most of set No. 1), J_a reduces e.g. 2 to 1 (due to sealing of most of set No. 1), J_w increases e.g. 0.5 to 1 (even with J_w = 1, tunnel ventilation air may contain moisture), SRF (might increase in faulted rock with little clay, or if under low stress i.e. near-surface).

Before pre-grouting $$Q = \frac{30}{9} \times \frac{1}{2} \times \frac{0.5}{1} = 0.8$$

After pre-grouting $$Q = \frac{50}{6} \times \frac{2}{1} \times \frac{1}{1} = 17$$

RRS (rib-reinforced shotcrete arches)

FOR VERY BAD ROCK CONDITIONS

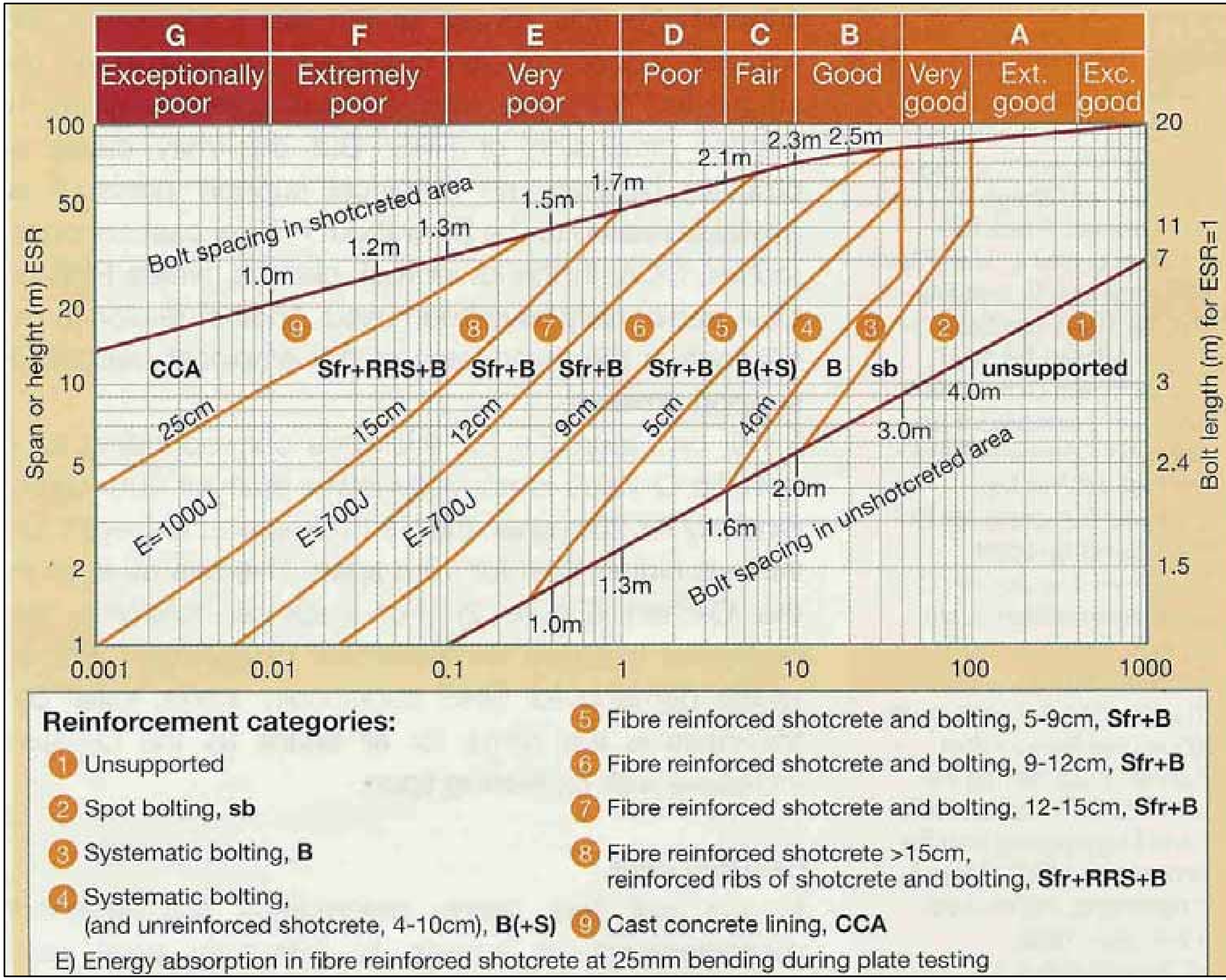
(e.g. $Q < 0.1$)

- **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.**

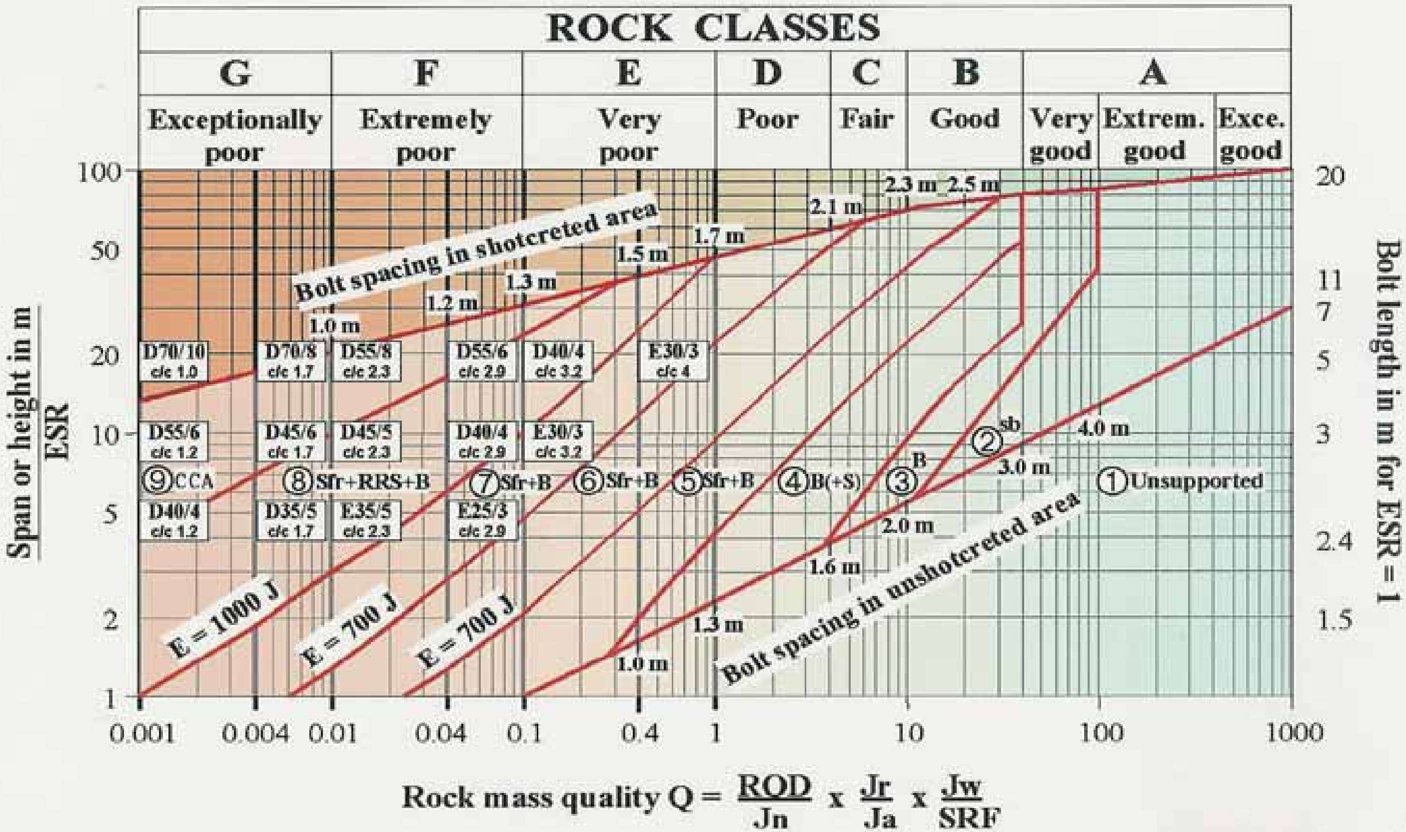
- **The use of steel sets should be avoided in such situations, due to the actual relatively larger rock-block loosening that they allow, unless followed immediately by bolting or shotcrete, or both.**

- **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'.**



Latest Q-support diagram for permanent support of tunnels and caverns, with energy absorption classes for S(fr). Grimstad et al. NGI, Tunnels and Tunnelling International, 2003.

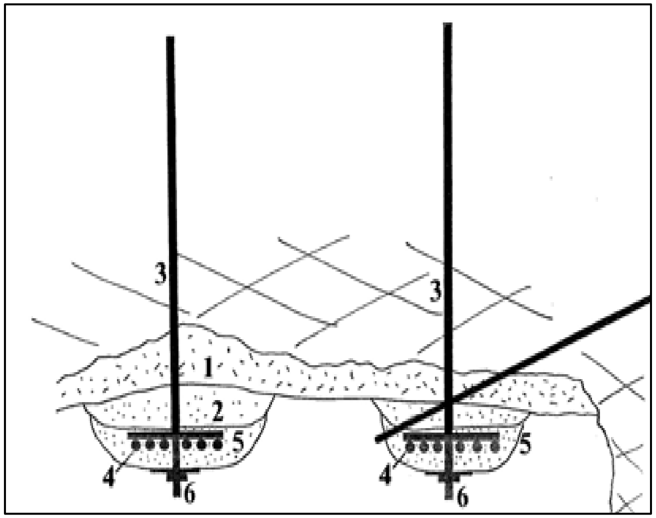


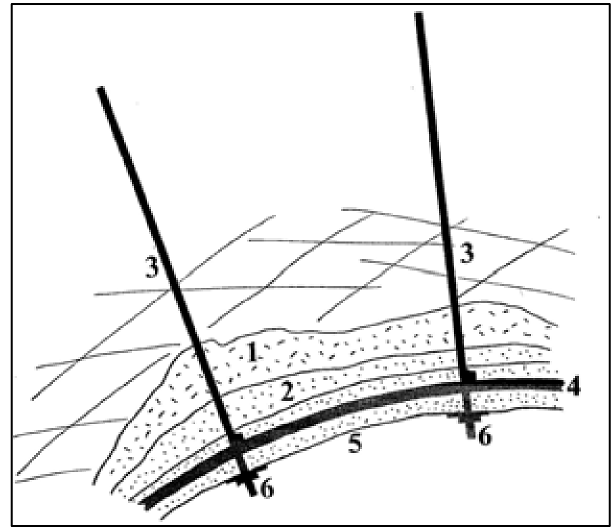
REINFORCEMENT CATEGORIES

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**

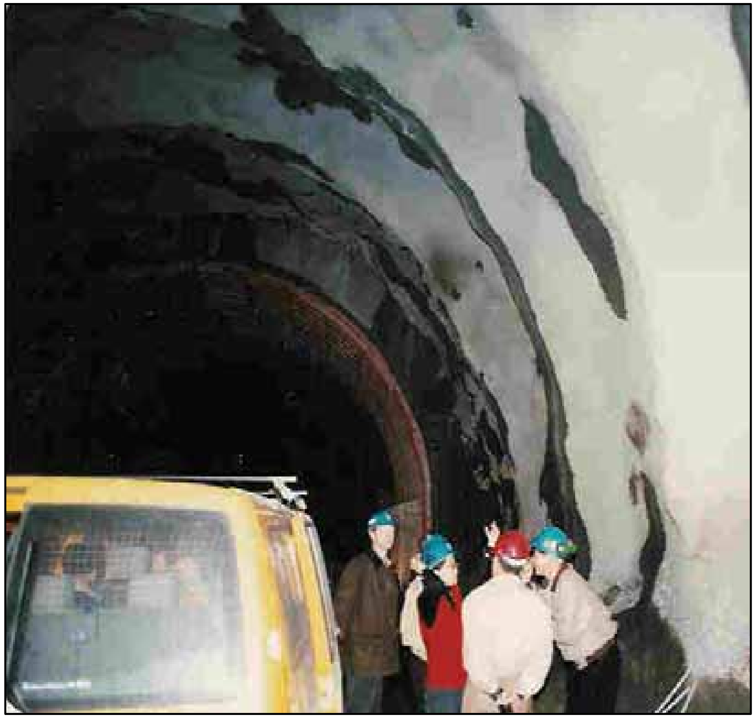
e) Energy absorbtion in fibre reinforced shotcrete at 25 mm bending during plate testing

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)





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. (Grout bolts later), 4 = attach (wire and weld) 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. Optional – spray in bolt heads to complete RRS arch.



Appearance of ('bent') RRS in subway station location where central pillar was excavated after side-cuts, and in road tunnel (CCA in background).

The consequences of insufficient attention to the details of immediate rock support when conditions are extremely poor, can be illustrated by three ‘failure’ scenarios.

The day invested in forming RRS arches, preferably with spiling bolts inclined into the arch ahead of the next excavation step, can save weeks of struggling to recover ‘unnecessary situations’ as those illustrated.

Recent dimensioning suggestions for RRS that are based both on case records and careful modelling are shown in next figure.

Uncontrolled developments due to failure to correctly pre-treat and support the 0.01<Q<0.1 ground ahead of the face.

FINALLY:

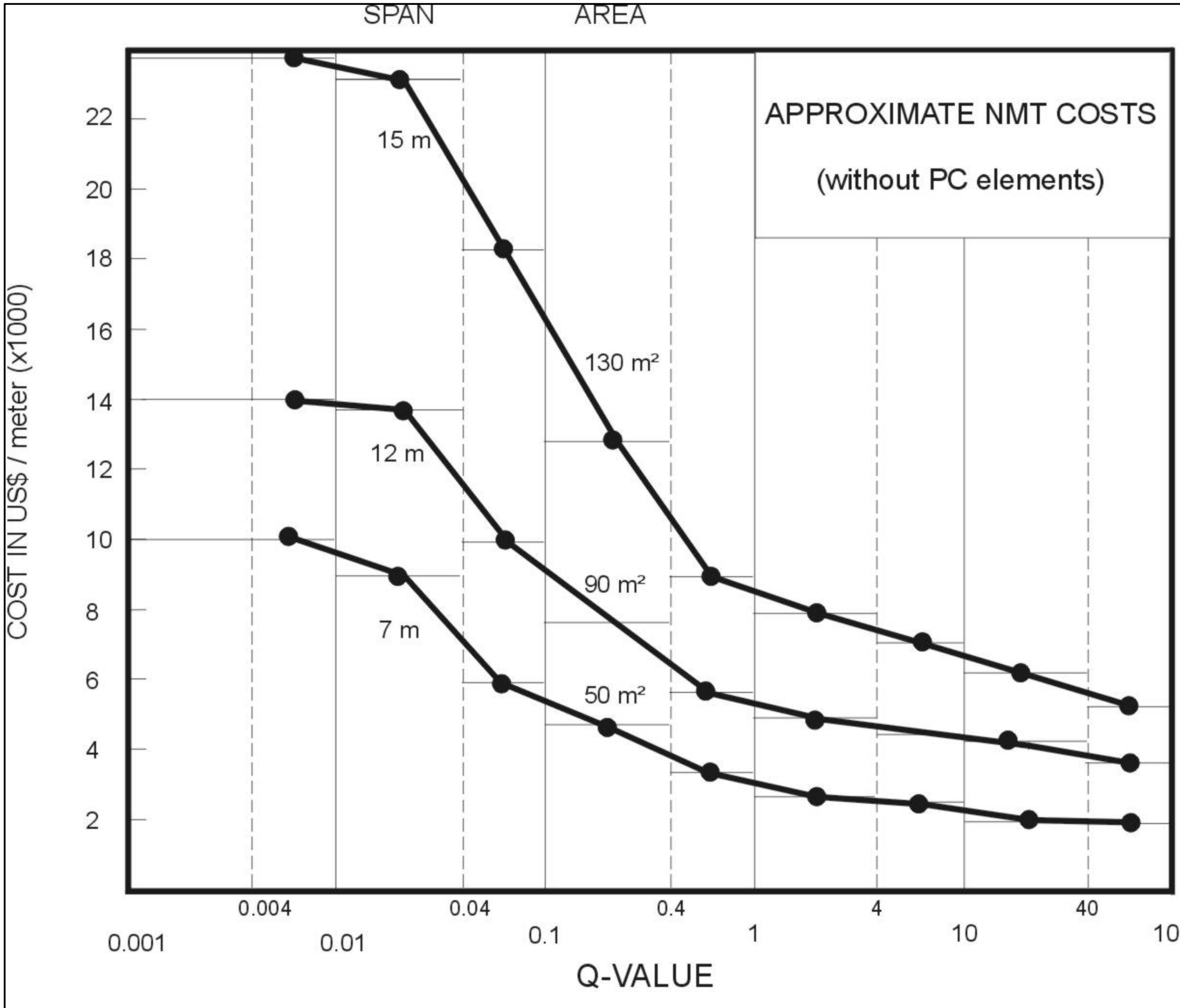
COST ESTIMATION

IN

RELATION TO

THE

Q-VALUE


SPAN
AREA
APPROXIMATE NMT COSTS
(without PC elements)
15 m
130 m²
12 m
90 m²
7 m
50 m²
COST IN US$ / meter (x1000)
22
20
18
16
14
12
10
8
6
4
2
0.004
0.04
0.4
4
40
0.001
0.01
0.1
1
10
100
Q-VALUE

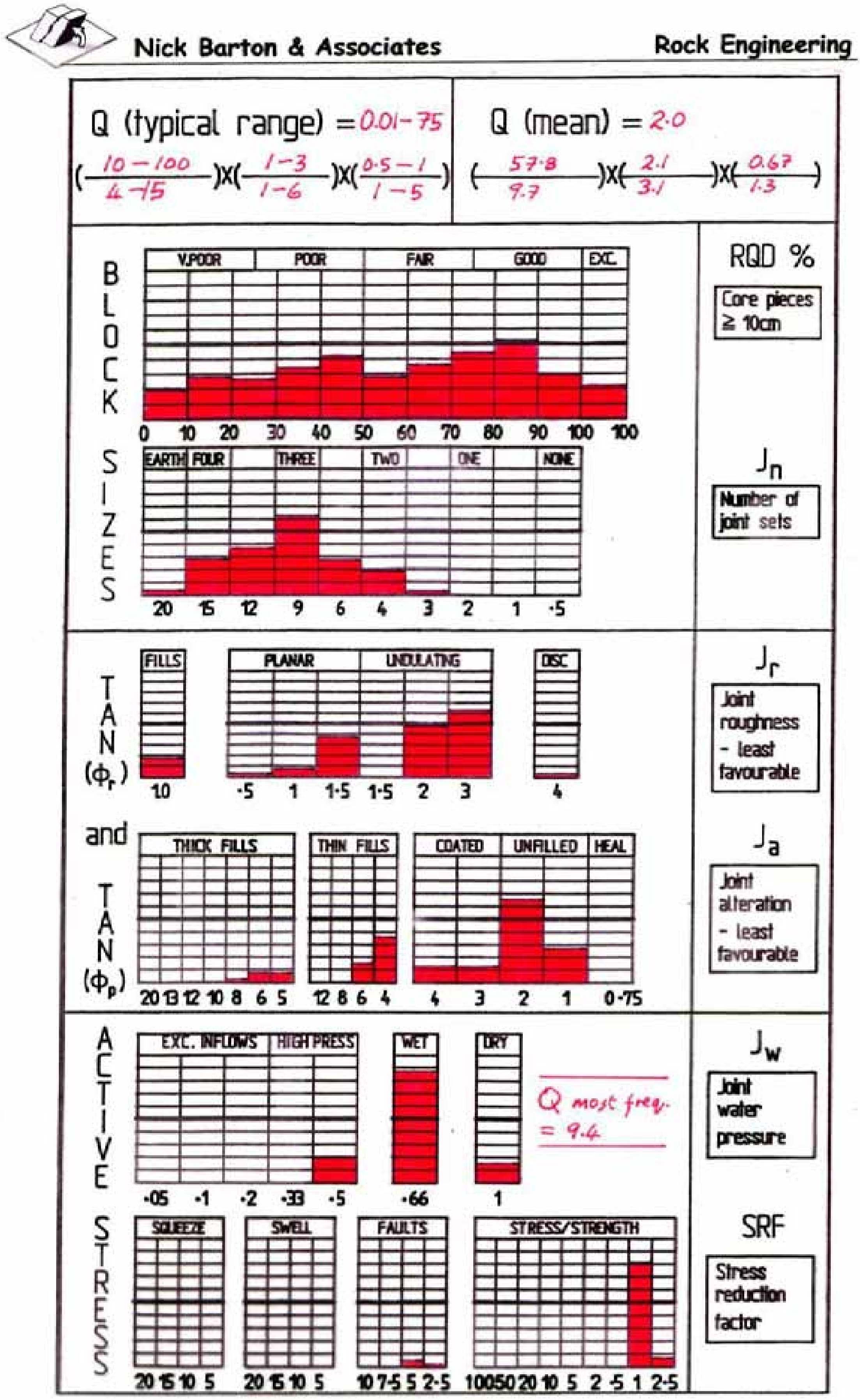
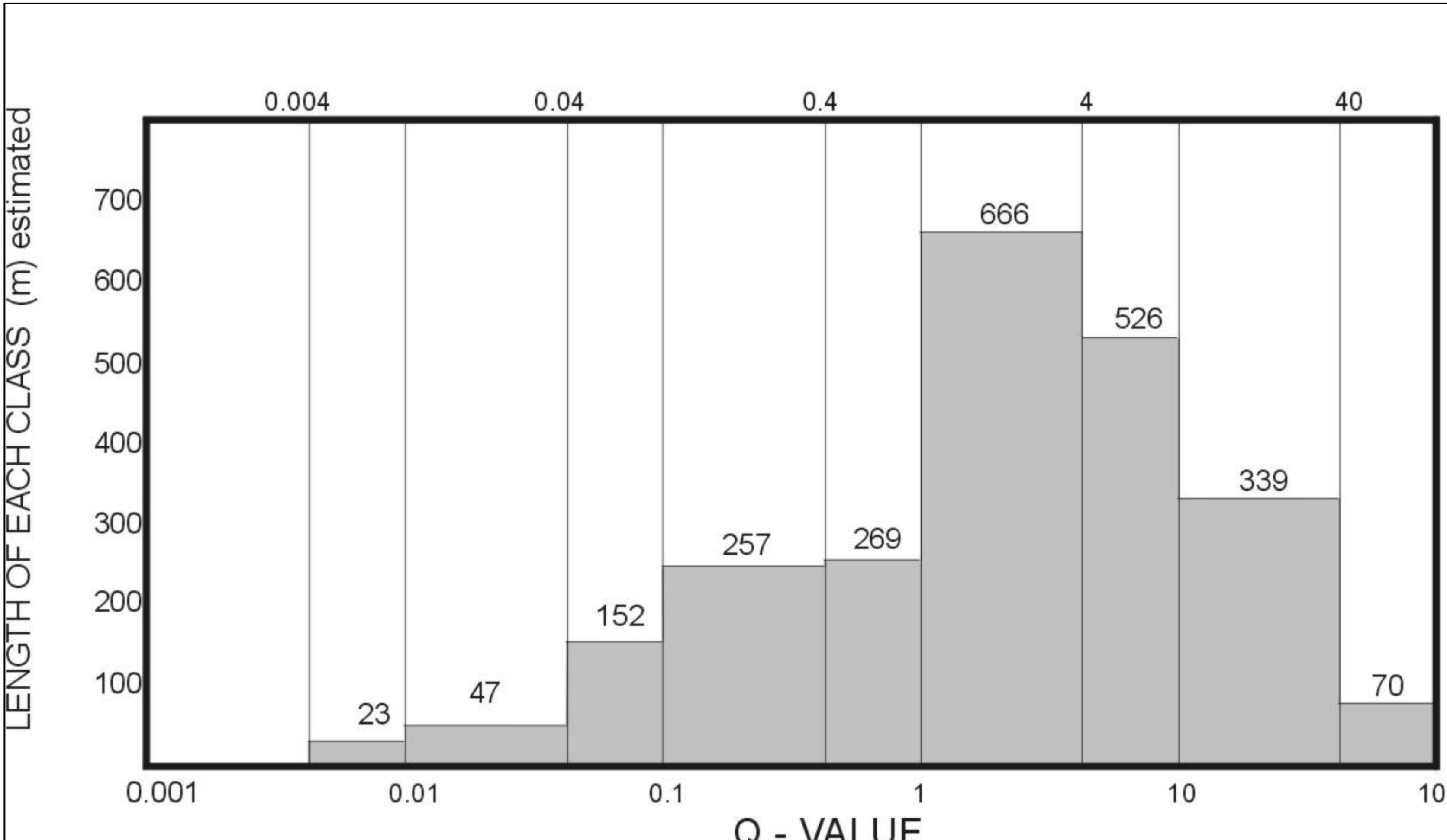
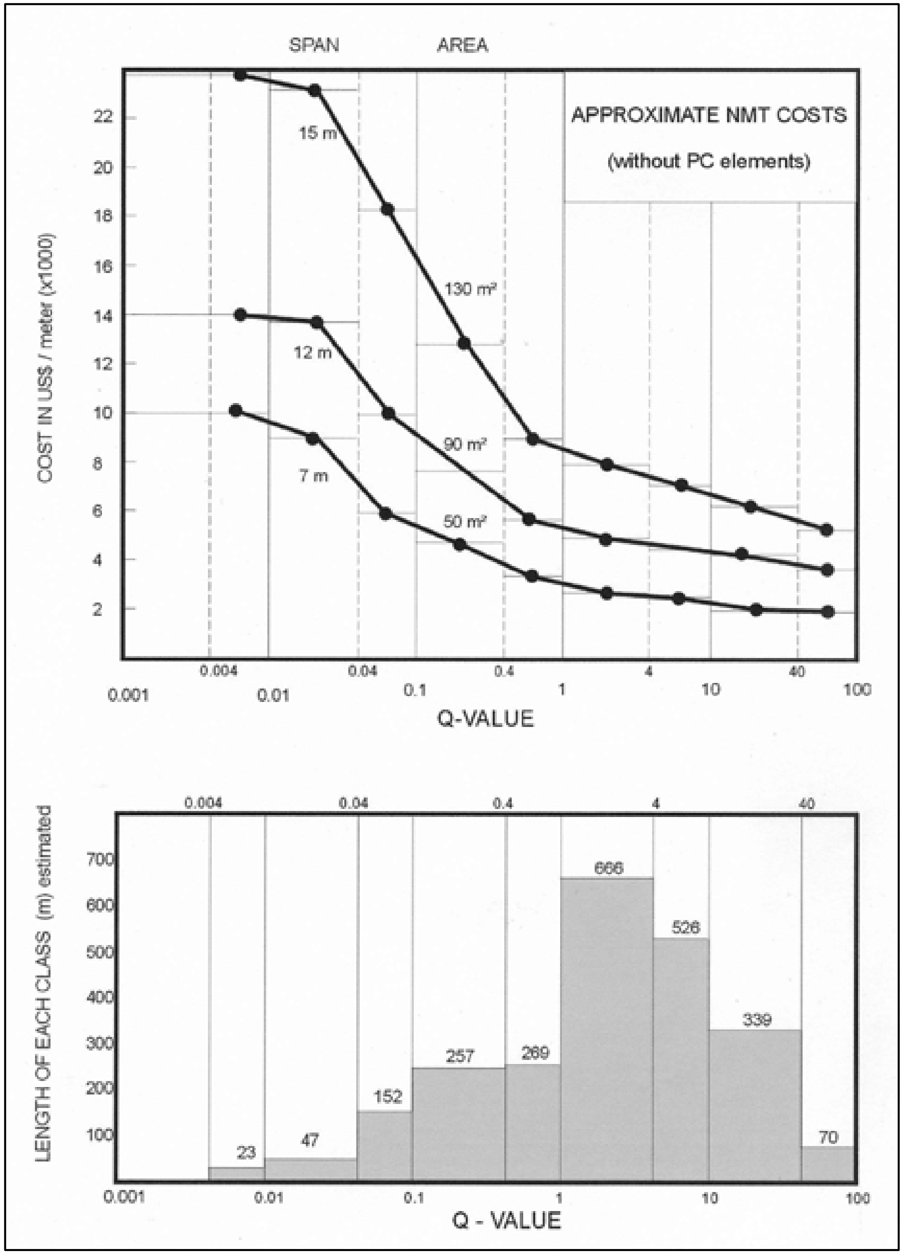


Figure A2.18 Cumulative histograms for 1093 m of logged core from a total of 17



0.004
0.04
0.4
4
40
LENGTH OF EACH CLASS (m) estimated
700
600
500
400
300
200
100
666
526
339
257
269
152
47
23
70
0.001
0.01
0.1
1
10
100
Q - VALUE


SPAN
AREA
APPROXIMATE NMT COSTS
(without PC elements)
COST IN US$ / meter (x1000)
15 m
12 m
7 m
130 m²
90 m²
50 m²
Q-VALUE
LENGTH OF EACH CLASS (m) estimated
23
47
152
257
269
666
526
339
70
Q - VALUE