FORTY YEARS
WITH THE Q-SYSTEM
-LESSONS AND DEVELOPMENTS

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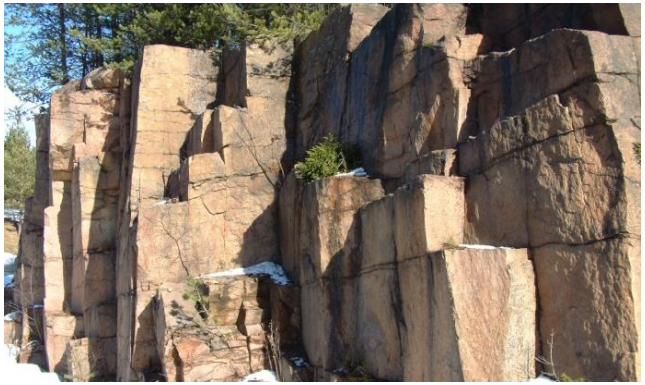
Hong Kong IoM^3 2015

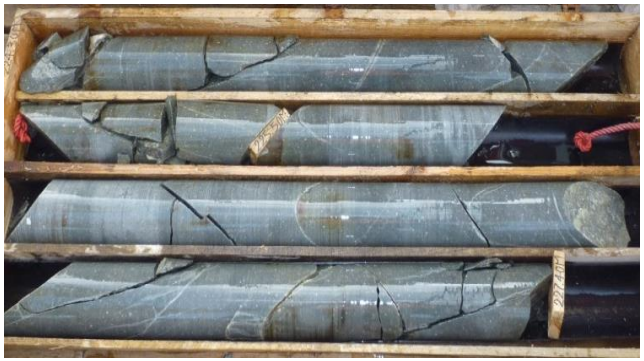
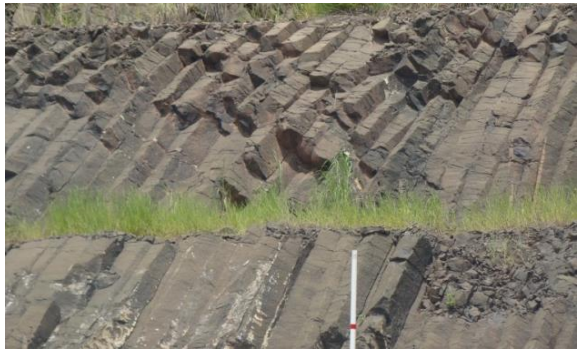
WHY Q?

Why do Norwegian powerhouses, mostly with spans of 18 to 24m, show *significant variation in deformations*?

(A question to NGI given to NB in 1973)

TOOK SIX (Q-development) MONTHS TO ANSWER CLIENT!



WE CANNOT TEST 'A SAMPLE', AS WITH STEEL OR CONCRETE (or soil?)

OUR ROCK *MASS* SAMPLES ARE MINIMUM ~ 500 m3 AND MUST BE CLASSIFIED/CHARACTERISED INDIRECTLY TO GIVE 'PROPERTIES'.

2. ADVANTAGE OF A LOGARITHMIC QUALITY SCALE

0.001 and 1000?
or 5 and 95?
or F7 and F1?

Contrast in modulus, shear strength, construction difficulty, velocity, permeability, etc. demands big scale.

0.001 and 1000, or 5 and 95 ?

3. WHAT PARAMETERS ARE INCLUDED, OR LEFT OUT OF Q

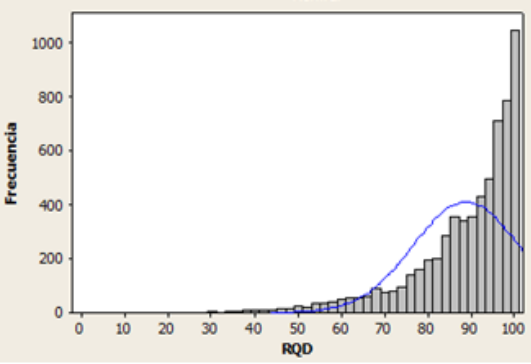
THE FIRST TWO PAIRS OF (Q) PARAMETERS HAVE DIRECT PHYSICAL MEANING:

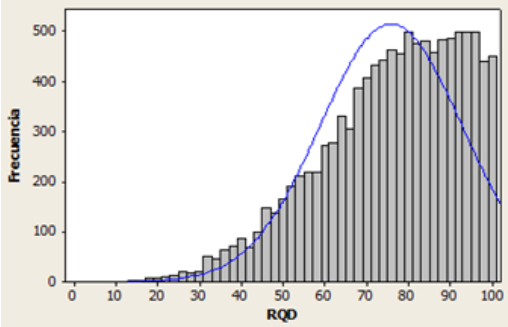
RQD / Jn = relative block size

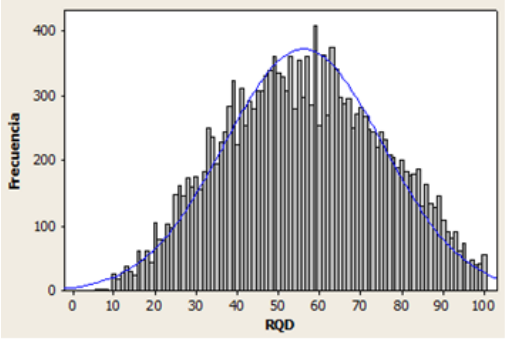
Jr / Ja = frictional strength

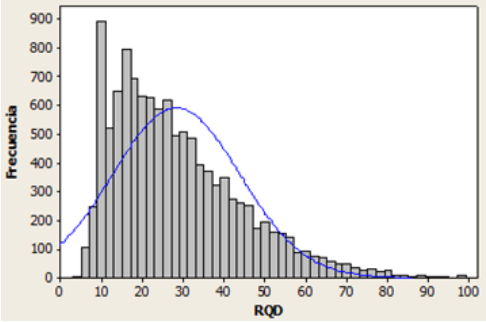
Jw / SRF = effects of water, faulting, strength/stress ratio, squeezing or swelling (an 'active stress' term)

RQD STATISTICS for Q-classes 2, 3, *4* and 5, with Q-VALUES 0.1-1, *1-4*, 4-10, 10-40.



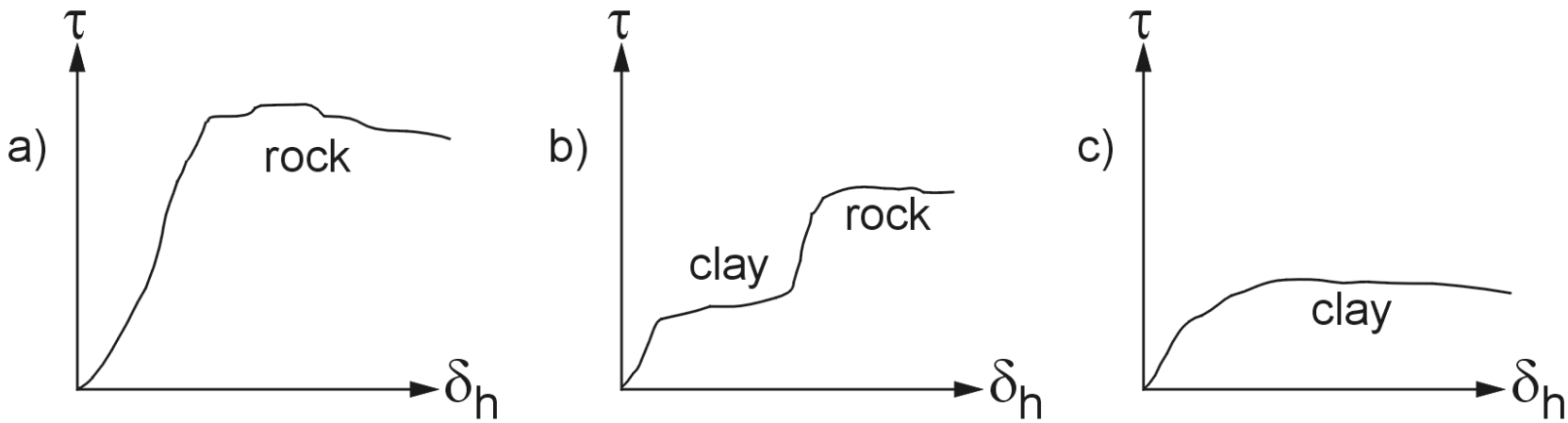






They demonstrate the central role played by RQD in commonly experienced rock mass conditions.

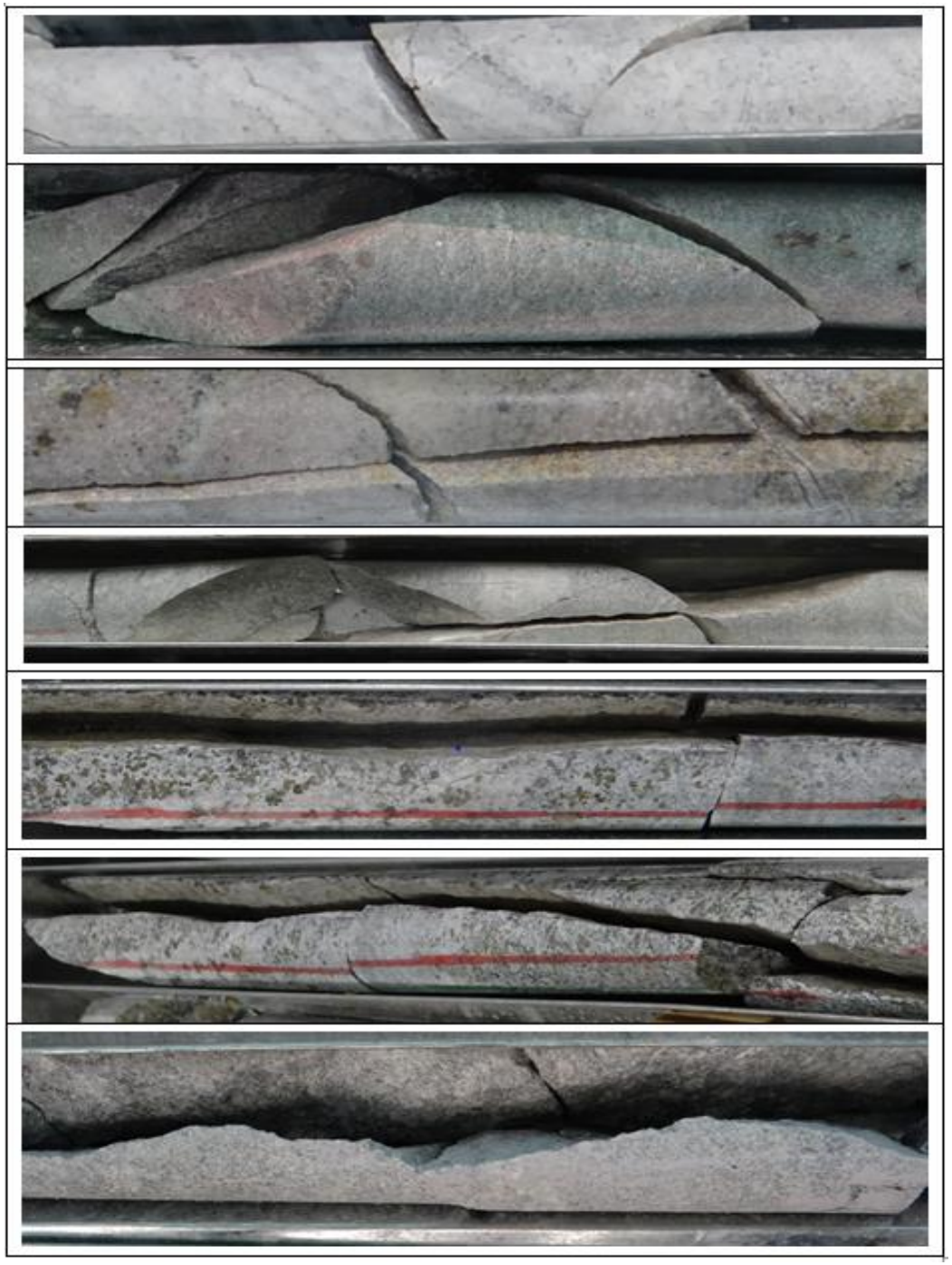
(> 40 km of core)



(a) Rock wall contact

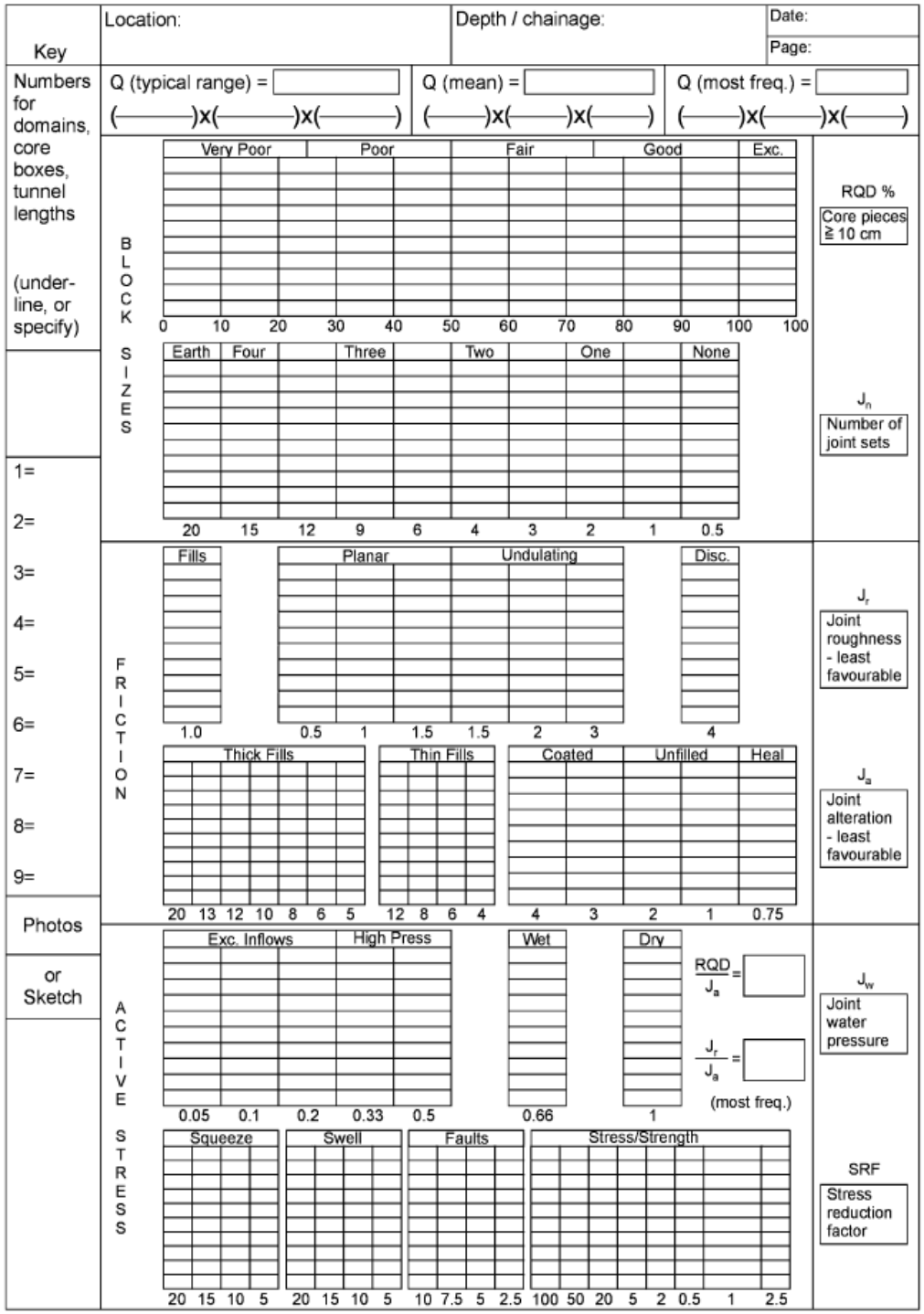
		(thin coatings)				
$Ja/Jr =$		0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)^{o}$				
A. Discontinuous joints	4	79º	76º	63º	53º	45º
B. Rough, undulating	3	76º	72º	56º	45º	37º
C. Smooth, undulating	2	69º	63º	45º	34º	27º
D. Slickensided, undulating	1.5	63º	56º	37º	27º	21º
E. Rough, planar	1.5	63º	56º	37º	27º	21º
F. Smooth, planar	1.0	53º	45º	27º	18º	14º
G. Slickensided, planar	0.5	34º	27º	14º	9.5º	7.1º

Jr/Ja is like a ‘friction coefficient’



Photos of core with the following Jr values:

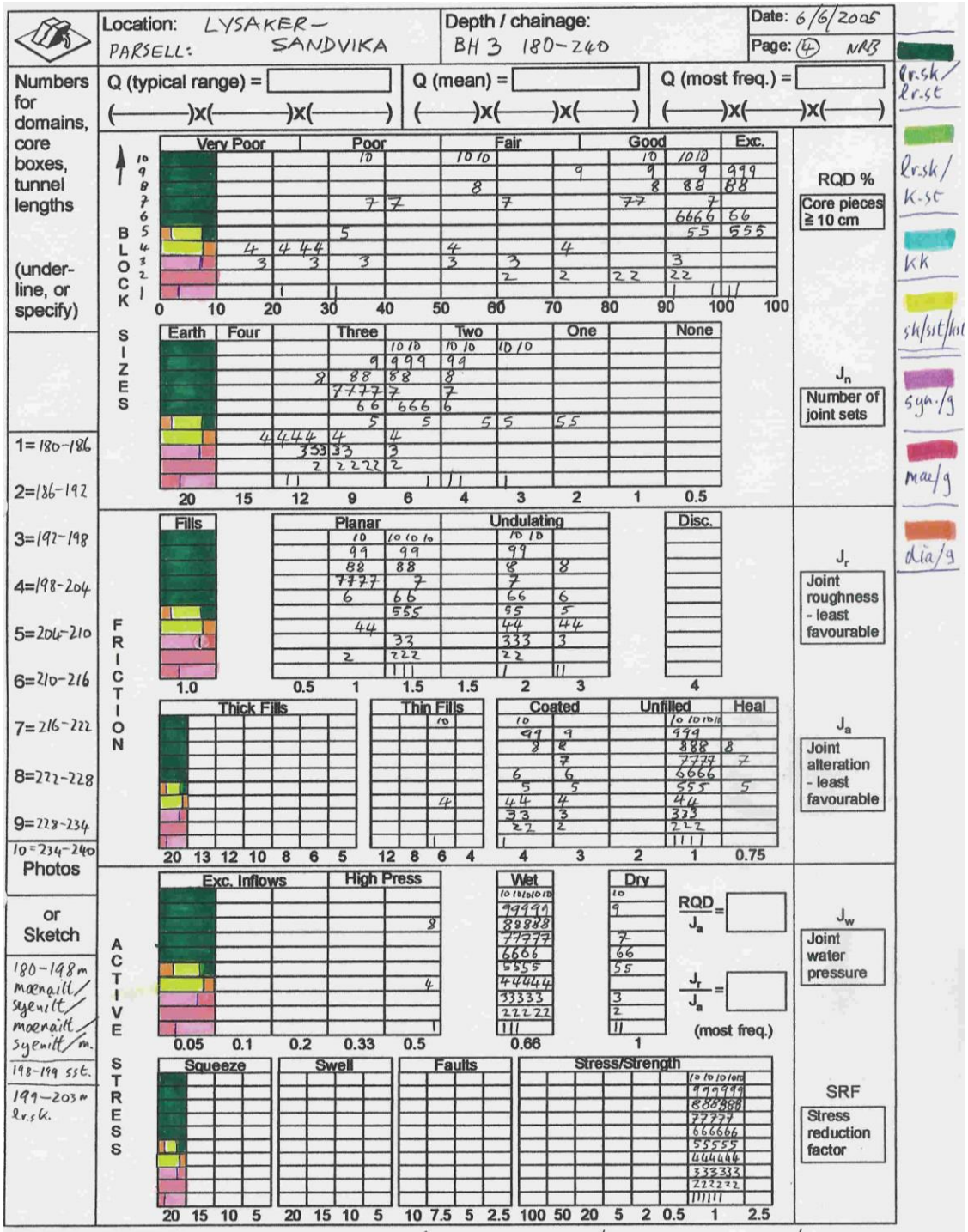
Jr = 1.0 or 1.5, Jr = 1.5, Jr = 1.5, Jr = 1.5, Jr = 2, Jr = 2.5, Jr = 3.5



Q-HISTOGRAM METHOD OF RECORDING DATA

EACH PARAMETER HAS A *VERBAL AND NUMERIC* SUMMARY of the Q-TABLE RATINGS

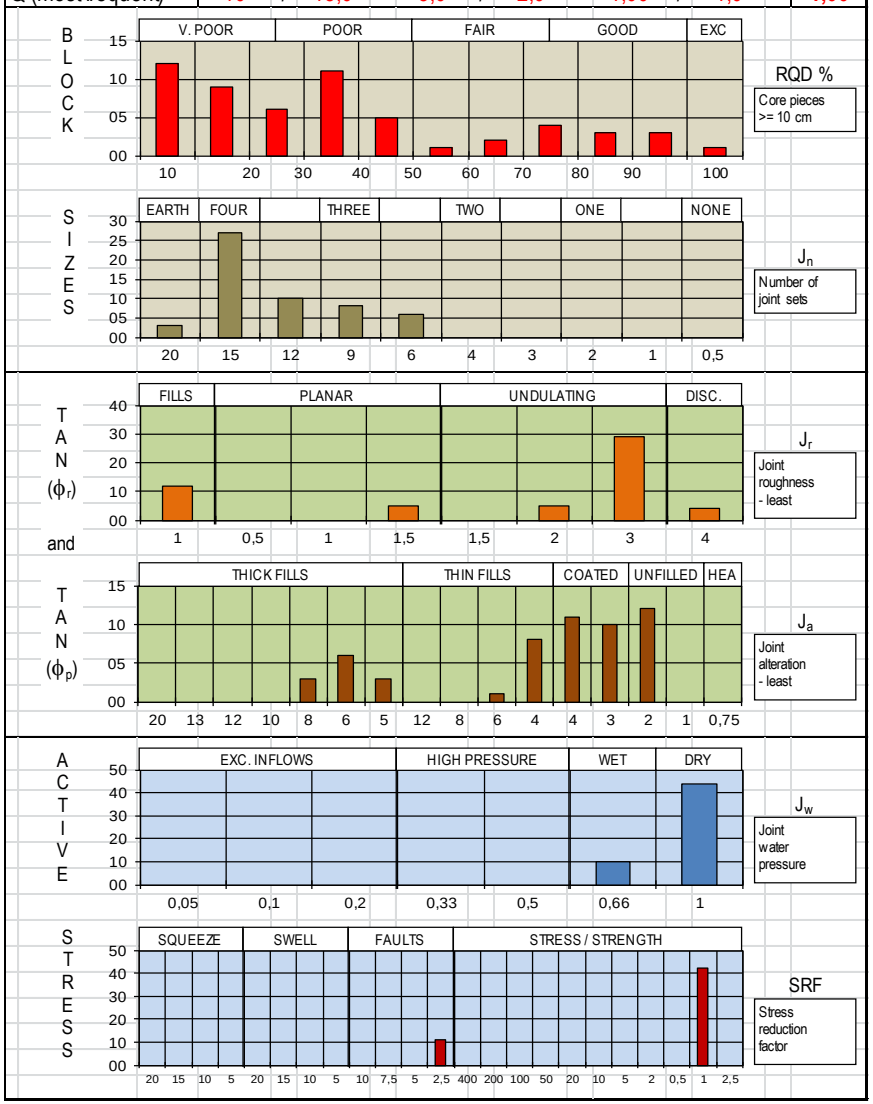
CONVENIENT FOR: *CORE LOGGING, EXPOSURE LOGGING, TUNNEL LOGGING*



EXAMPLE OF COLLECTING Q-PARAMETER DATA. FIRST CHARACTERIZE *CORE*. LATER CLASSIFY TUNNEL (OR MINE) OPENINGS.

Q IS ONLY PART OF A ROCK MASS DESCRIPTION EXERCISE

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,0	/	6,0	*	0,66	/	2,5	=	0,029
Q (typical max)=	75	/	6,0	*	4,0	/	2,0	*	1,00	/	1,0	=	25,0
Q (mean value)=	38	/	12,8	*	2,4	/	3,9	*	0,94	/	1,3	=	1,29
Q (most frequent)=	10	/	15,0	*	3,0	/	2,0	*	1,00	/	1,0	=	1,00



I ROCK MASS STRUCTURE

1 RQD Deere et al., 1967)
2 J_n = joint set number
3 F = joint frequency (per metre)
4 J_v = volumetric joint count (Palmström, 1982)
5 S = joint spacing (in metres)
6 L = joint length (in metres)
7 w = weathering grade (ISRM, 1978)
8 α/ß = dip/dip direction of joints (Schmidt diagram)

block size { Q Q

II JOINT CHARACTER

9 J_r = joint roughness number
10 J_a = joint alteration number
11 JRC = joint roughness coefficient
12 a/L = roughness amplitude of asperities per unit length (mm/m)
13 JCS = joint wall compressive strength
14 ϕ_r = residual friction angle
15 r,R = Schmidt rebound values for joint and rock surfaces

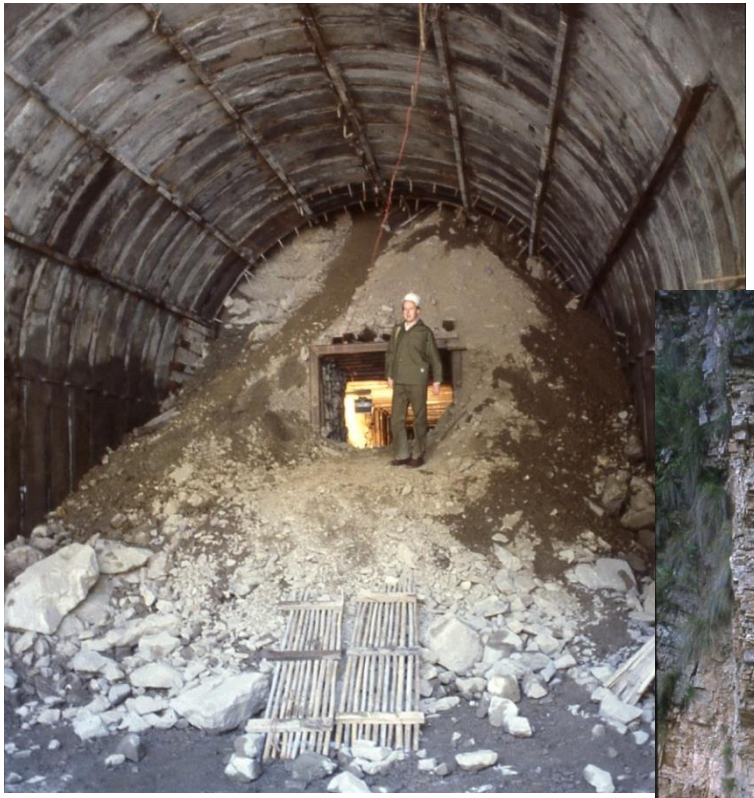
shear strength { Q Q

III WATER, STRESS, STRENGTH

16 J_w = joint water reduction factor
17 SRF = stress reduction factor
18 K = rock mass permeability (m/s)
19 σ_c = compressive strength
20 σ_1 = major principal stress

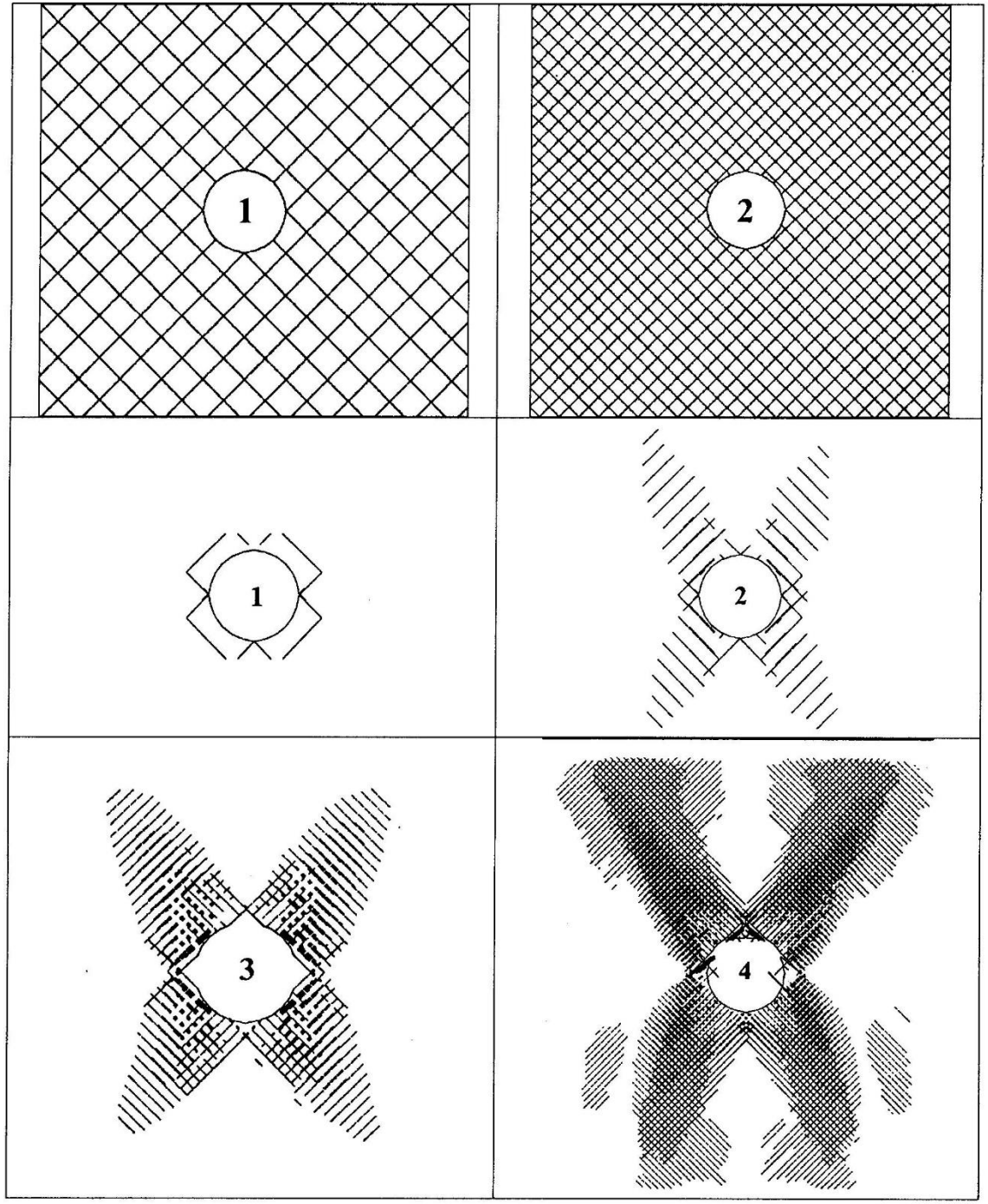
active stress { Q Q

FAULT ZONES ARE UNIQUE CHALLENGES FOR TUNNELLERS BECAUSE…….



RQD, Jn, Jr, Ja, Jw and SRF……..

all Q-parameters may be adverse, also TIME + COST



UDEC MODELS SUGGEST POTENTIAL 'TRAUMA' IN (heavily fractured) FAULT ZONES (DEEP EDZ)

(Shen and Barton, 1997)

SRF (HIGH VALUES) ARE ALSO USED FOR ADVERSE *STRESS/STRENGTH* RATIOS IN HARD ROCK.

WATCH OUT FOR RATIOS OF σ_θ/UCS > 0.4

STRESS-SLABBING AND EVENTUAL ROCK BURST ARE INDEPENDENTLY EXPERIENCED IN MINING, AND DEEP ROAD TUNNELS WHEN σ_θ/UCS > 0.4

STRESS-FRACTURING IN THE CHALK-MARL BEAUMONT TUNNEL (1880) WHERE COVER INCREASED DUE TO 70m CLIFF

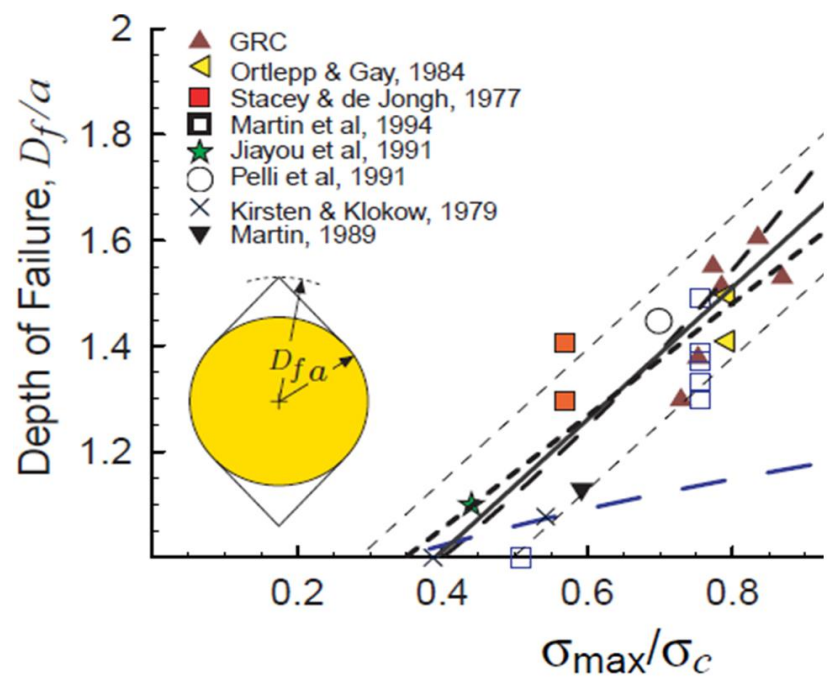
(UCS only 4 to 9 MPa)

EXTRACT FROM Q-SYSTEM SRF (from deep road tunnels)

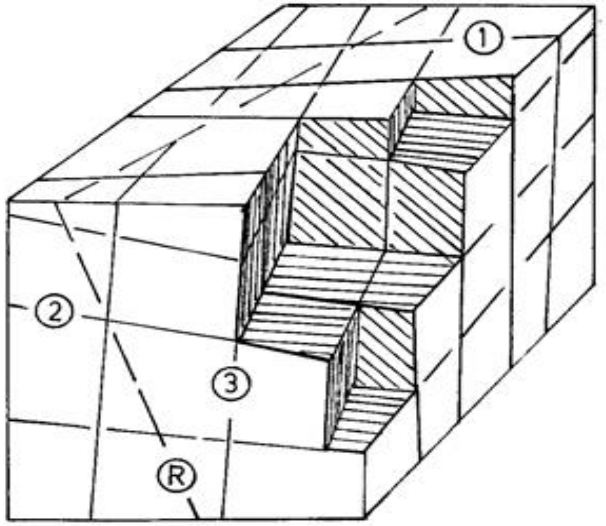
(Barton and Grimstad, 1993)

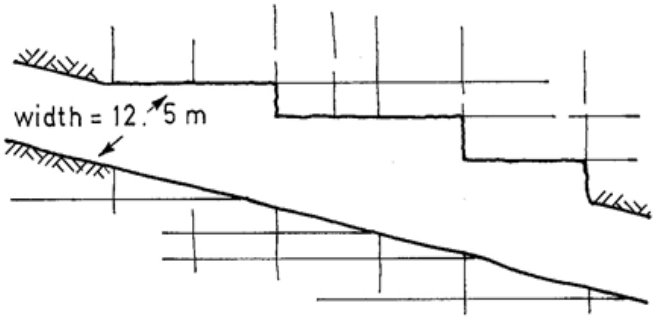
b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c	SRF
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after > 1 hour in **massive** rock.	5-3	0.5-0.65	5-50
M	Slabbing and rock burst after a few minutes in **massive** rock.	3-2	0.65-1	50-200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in **massive** rock.	< 2	> 1	200-400

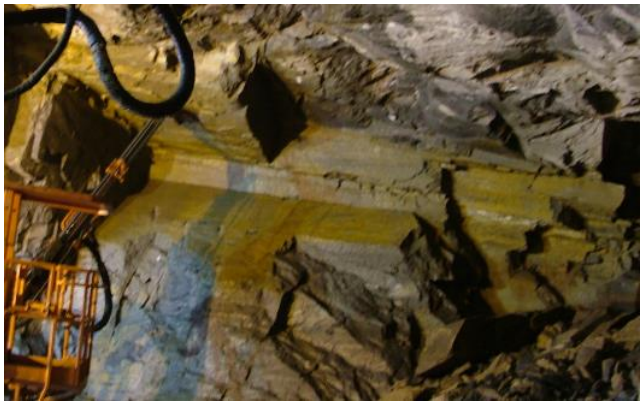
INDEPENDENT CONFIRMATION FROM MINING AND NUCLEAR WASTE URL (Martin et al. 1994, 2001)



4. OVERBREAK ESTIMATION USING THE RATIO Jn/Jr







OVERBREAK IF Jn/Jr ≥ 6

Jn = number of sets

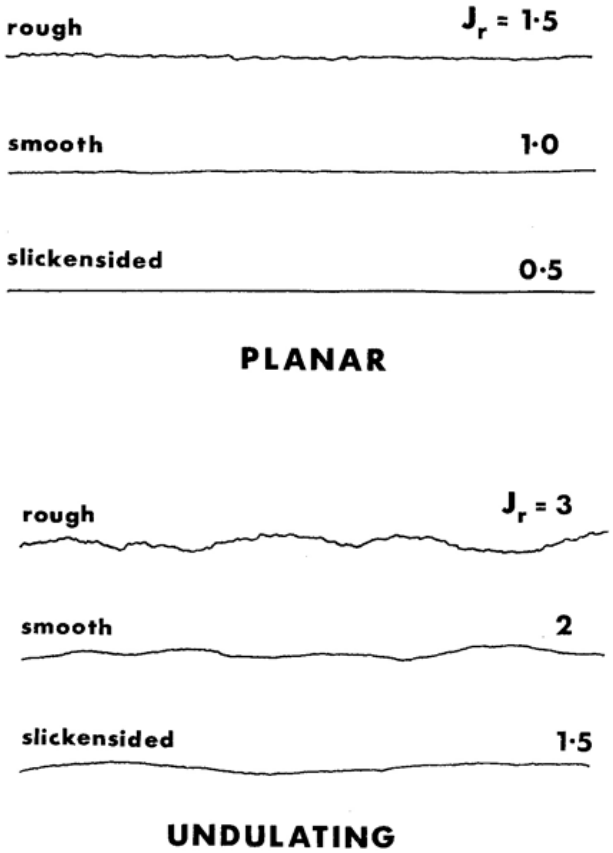
Jr = roughness

6/1.0	9/1.5
12/2	15/3

(DESPITE FOUR JOINT SETS, TOO MUCH ROUGHNESS AND DILATION)

In photos:

Jn/Jr = 9/(1-1.5)

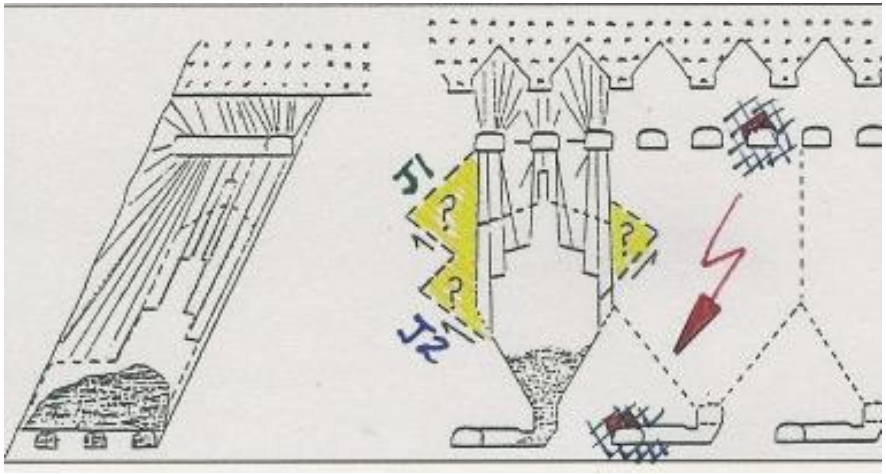


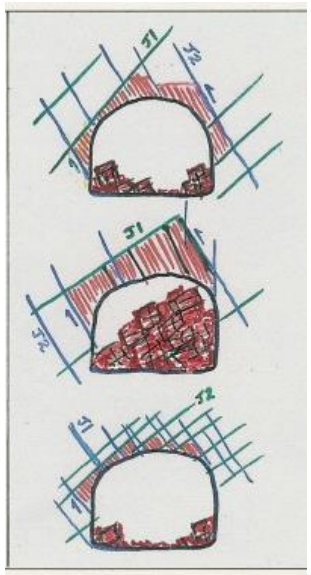
OVER-BREAK IN CIVIL AND MINING EXCAVATIONS

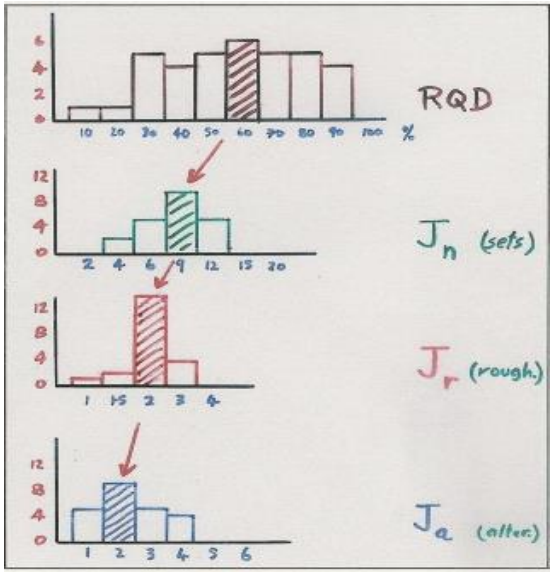
Jn/Jr ≥ 6: 9/1.5 (yes)

9/3 (no, in >150 yrs?)

OVER-BREAK: TUNNEL-SCALE UP TO BLOCK-CAVING







Joint sets J1 and J2 had adverse *Jr/Ja* ratios in some cases (see outliers in the histograms).

The adverse ratios of *Jn/Jr* were of most importance.

<u>Jn/Jr ≥ 6 meant over-break</u>

OVER-BREAK needing 4m of CONCRETE

(or 3.5m void?)

Reason: adverse Jn/Jr

5. TEMPORARY SUPPORT ESTIMATE FROM Q, IN *NATM* EXCAVATIONS

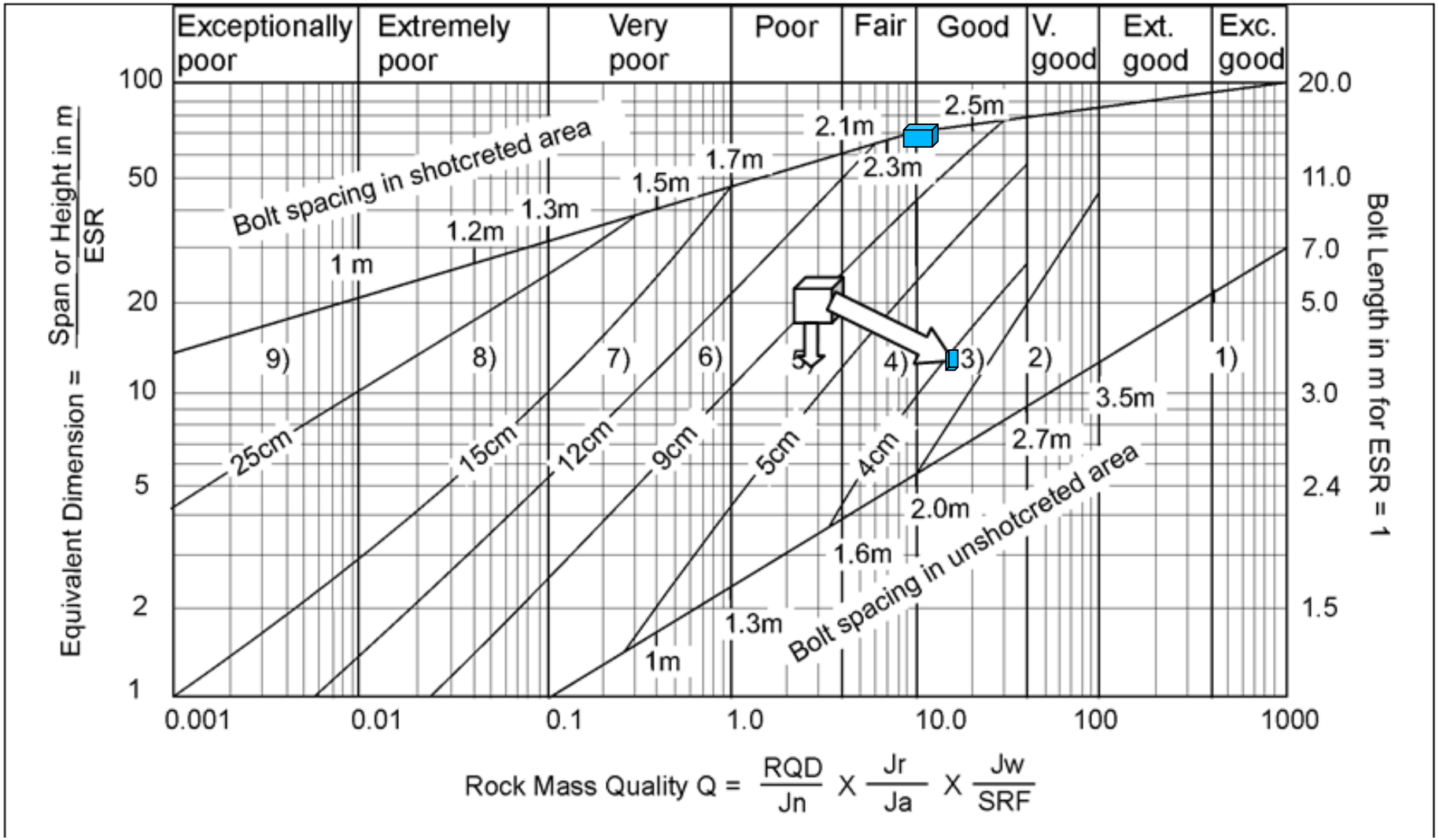
FIRST TWO DEFINITIONS:

1. **‘DOUBLE-SHELL’ (‘NATM’)**
   (Temporary: Sfr/Smr, B, steel/lattice girders,
   Permanent: fleece, membrane, cast
   concrete CCA)……..*needs large work force*

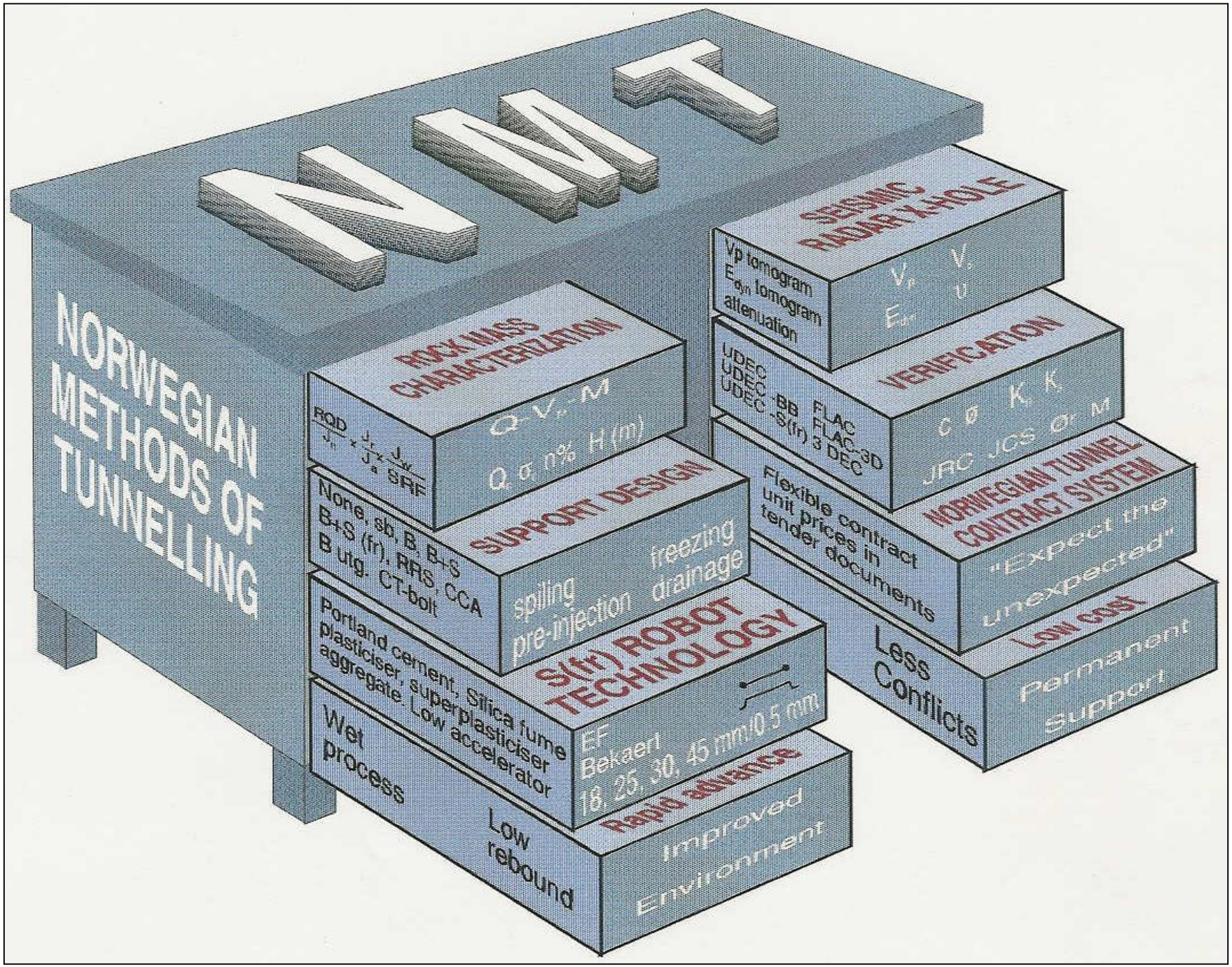
2. **‘SINGLE-SHELL’ (NMT)**
   (pre-grouting?) + B + Sfr + (RRS?)……..
   needs small work force (x 1/10?)

THOSE WHO INSIST ON NATM – CAN USE Q FOR TEMPORARY SUPPORT SELECTION…*'5Q' + '1.5 x ESR'*

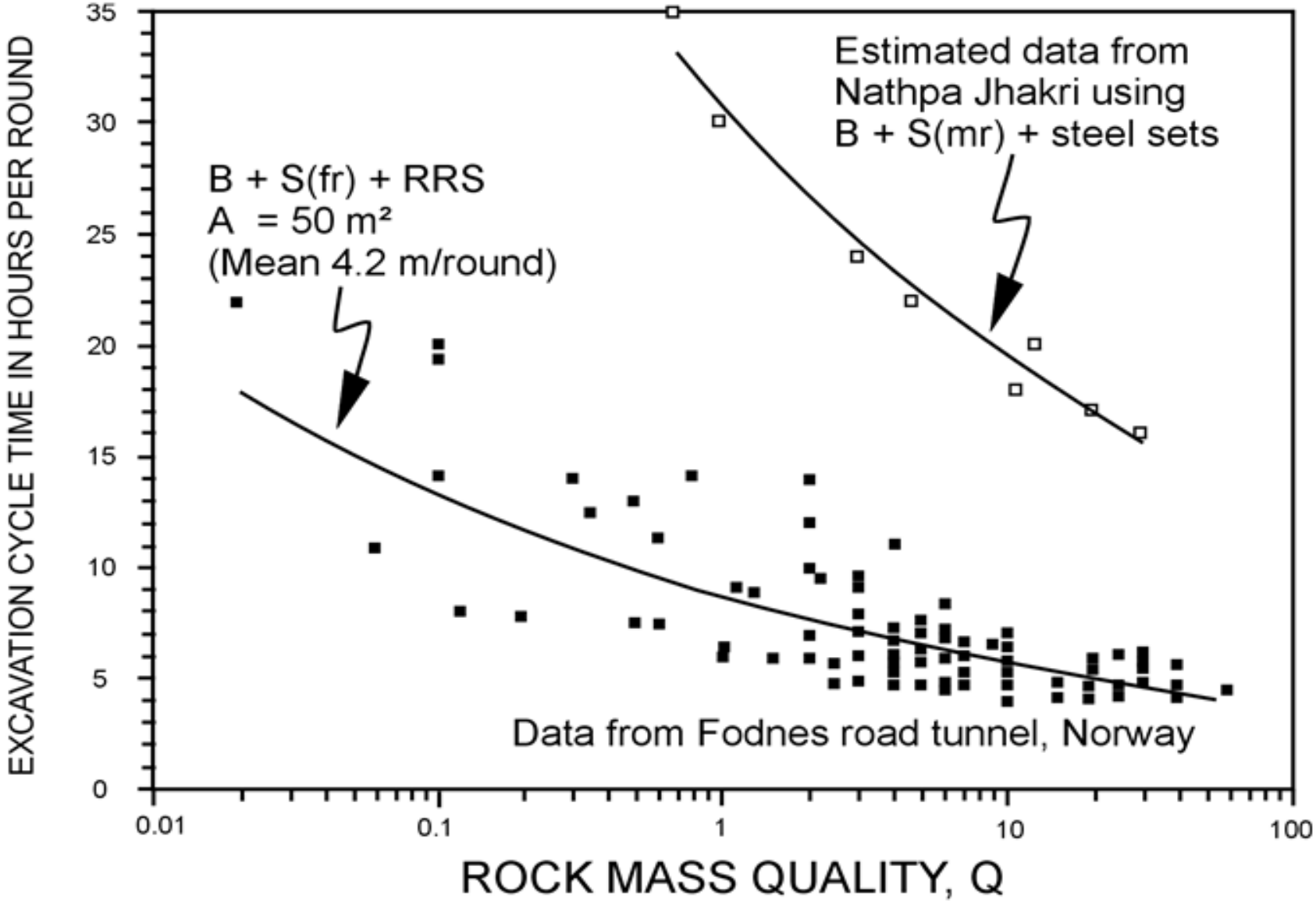
(25 years use in HK road tunnels and metro tunnels)

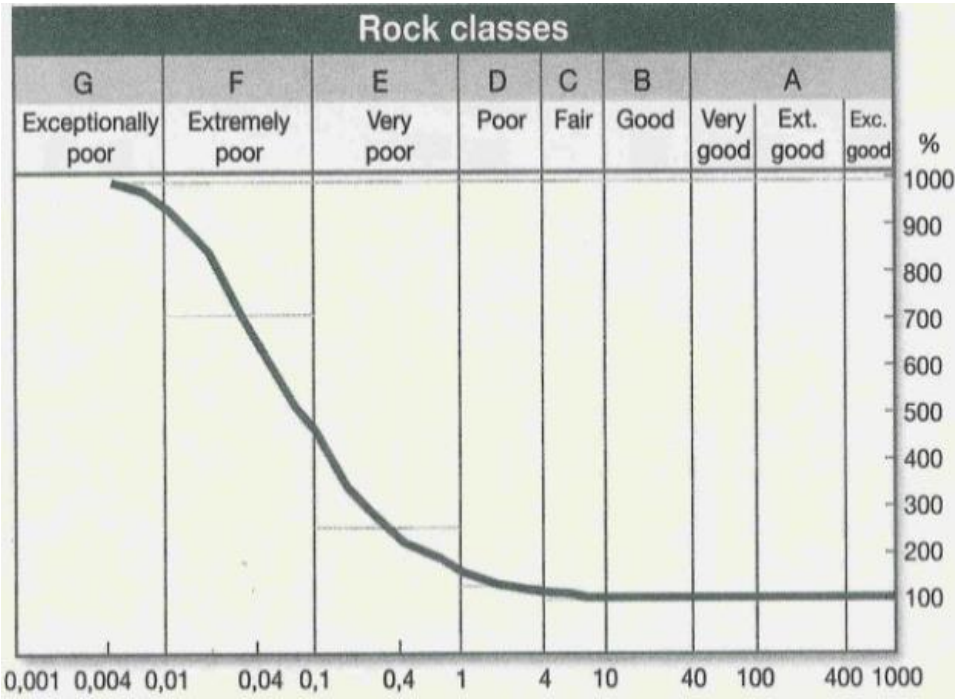


6. THE COMPONENTS OF Q-SYSTEM SINGLE-SHELL *NMT* SUPPORT


NMT
NORWEGIAN METHODS OF TUNNELLING
SEISMIC, RADAR X-HOLE
Vp tomogram
Edyn tomogram
attenuation
Vp Vs
Edyn u
ROCK MASS CHARACTERIZATION
Q-Vp-M
Q σ n% H (m)
RQD/Jn x Jr/Ja x Jw/SRF
VERIFICATION
UDEC
UDEC-BB FLAC
UDEC-S(fr) FLAC-3D
3 DEC
c ø K1 K2
JRC JCS ø r M
SUPPORT DESIGN
None, sb, B, B+S
B+S (fr), RRS, CCA
B utg. CT-bolt
spilling
pre-injection
freezing
drainage
Flexible contract
unit prices in
tender documents
NORWEGIAN TUNNEL CONTRACT SYSTEM
"Expect the unexpected"
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

FAST CYCLE TIMES: best 176, 150 m/wk, 5.8 km in 54 weeks

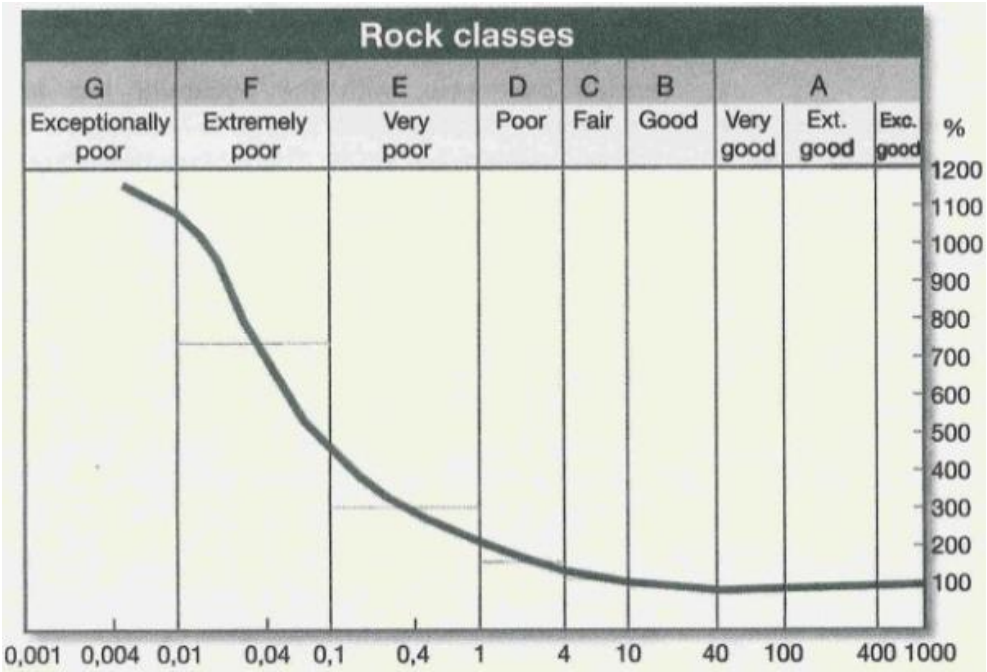




RELATIVE TIME AND COST IN RELATION TO Q-VALUE

According to a 50 km survey of tunnels carried out by Roald, and published as:

Barton, Roald and Buen (2001).

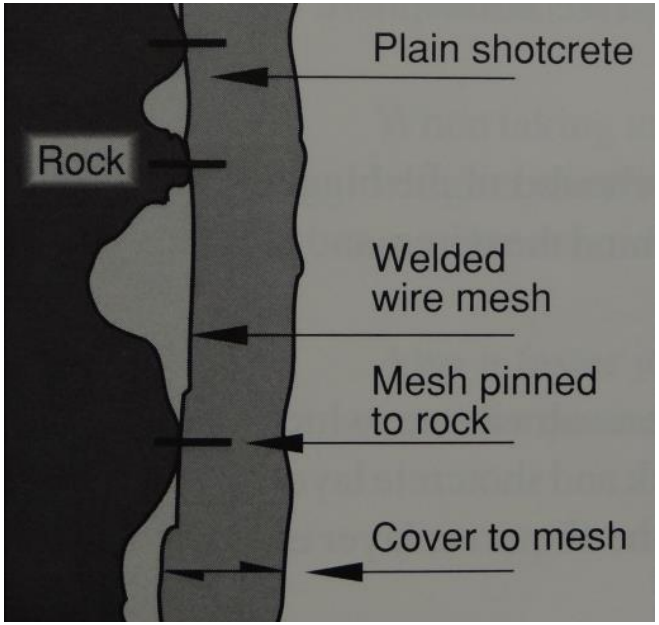


FORTUNATELY:
'EVEN THE AUSTRIANS' USE 'NMT' (i.e. single-shell in *large caverns*)

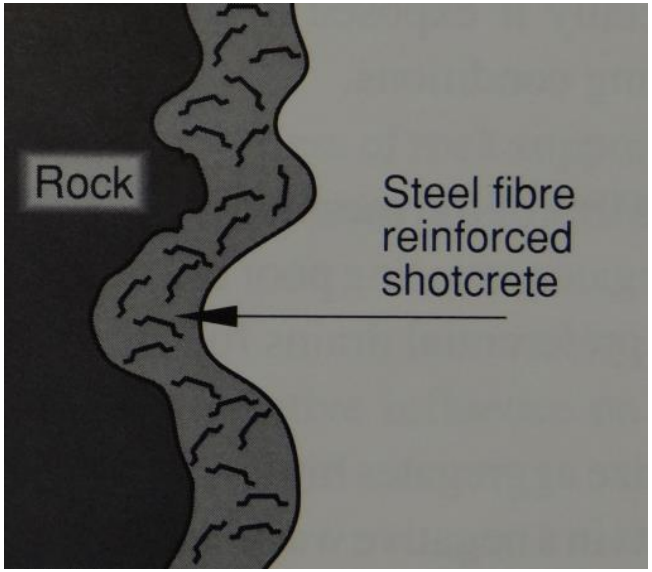
FORTUNATELY:

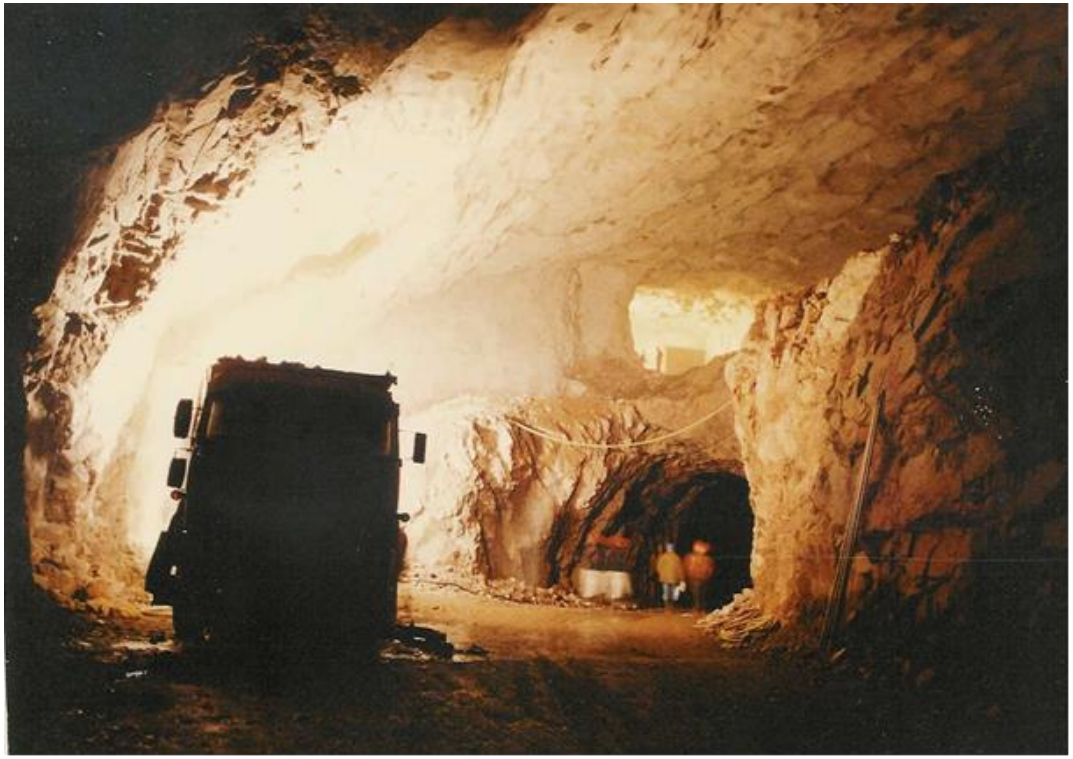
'EVEN THE ENGLISH' NOW USE S(fr) or SCL as FINAL LINING – AND IN LONDON CLAY!

'We' (a Norwegian delegation) recommended S(fr) to Cross-Rail in 1994.



The revolutionary change from S(mr) to S(fr)…1979/1983/1993



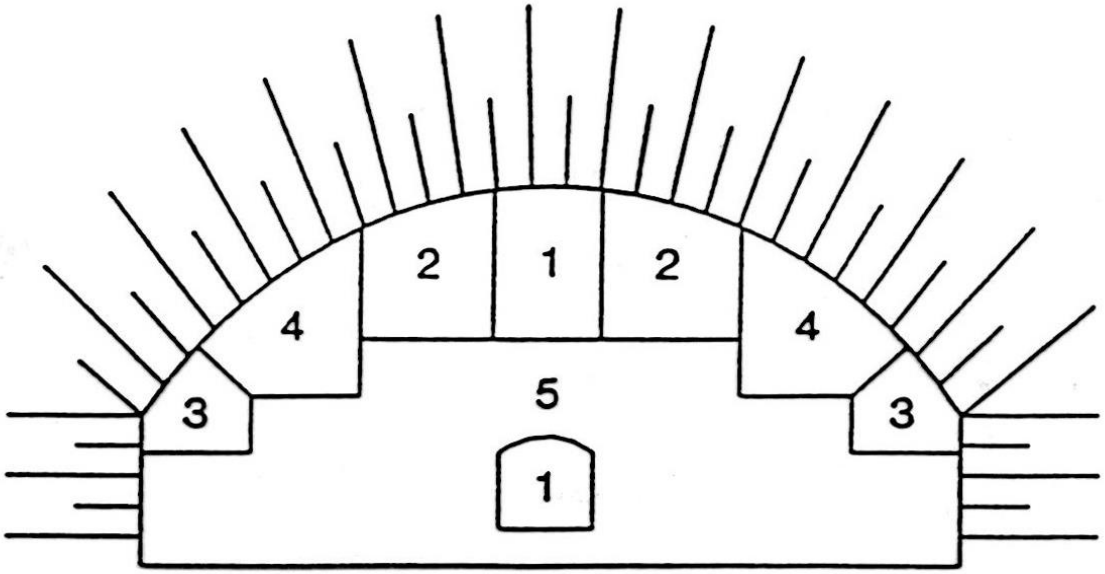


Gjøvik NMT: B+S(fr)

B 2.5 m c/c

L = 6 m (A=12m)

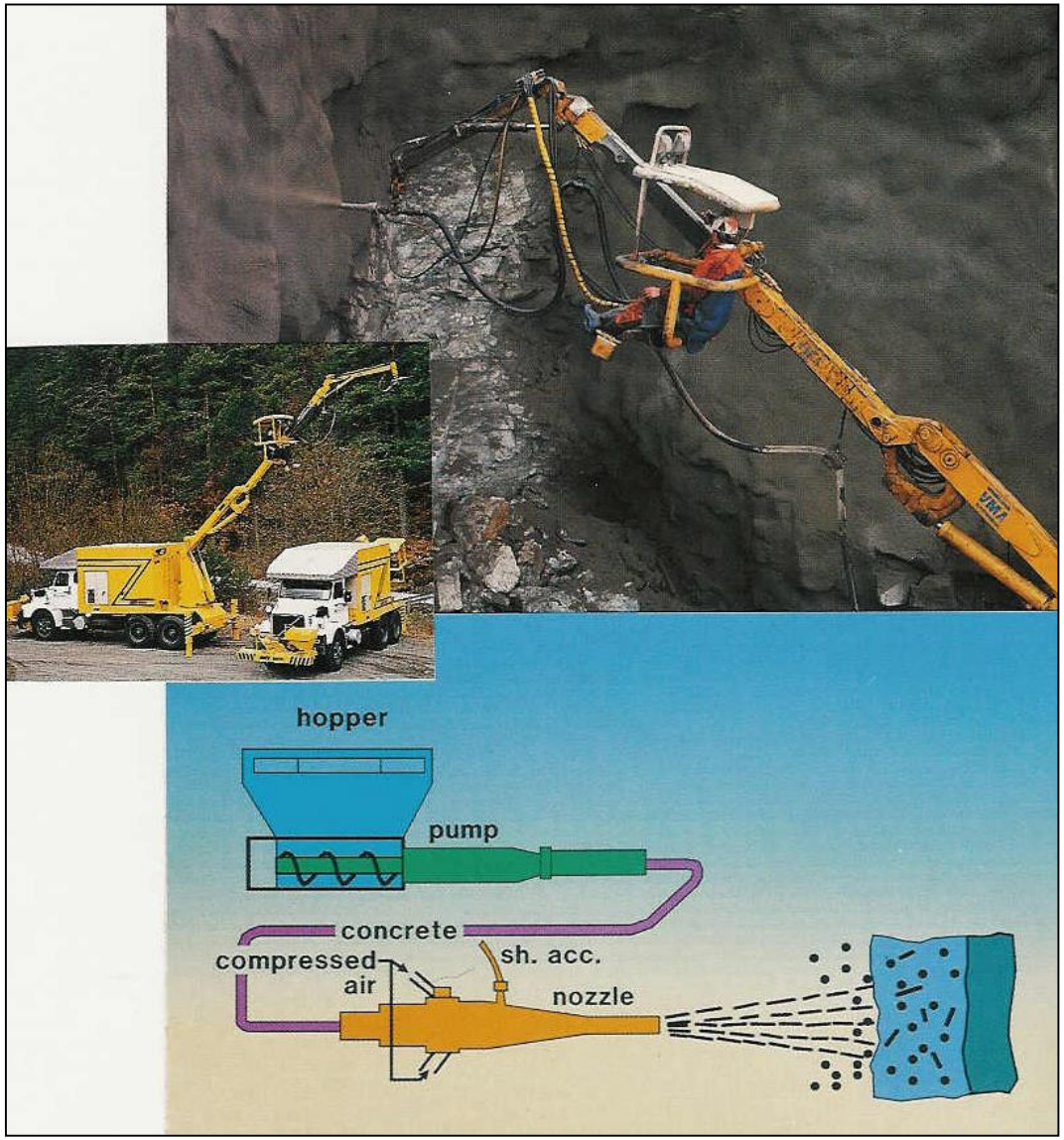
S(fr) 10 cm

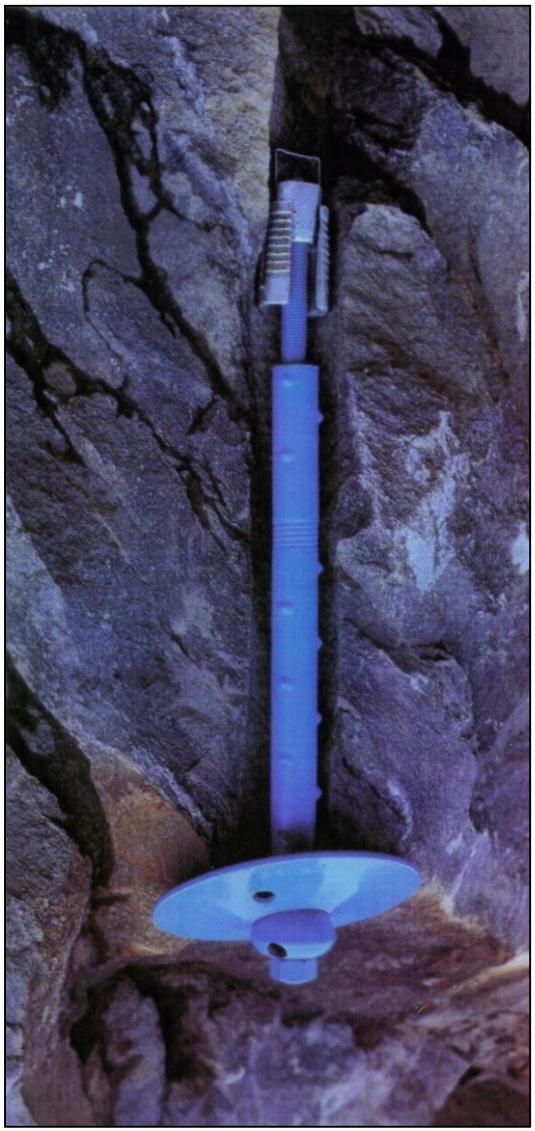


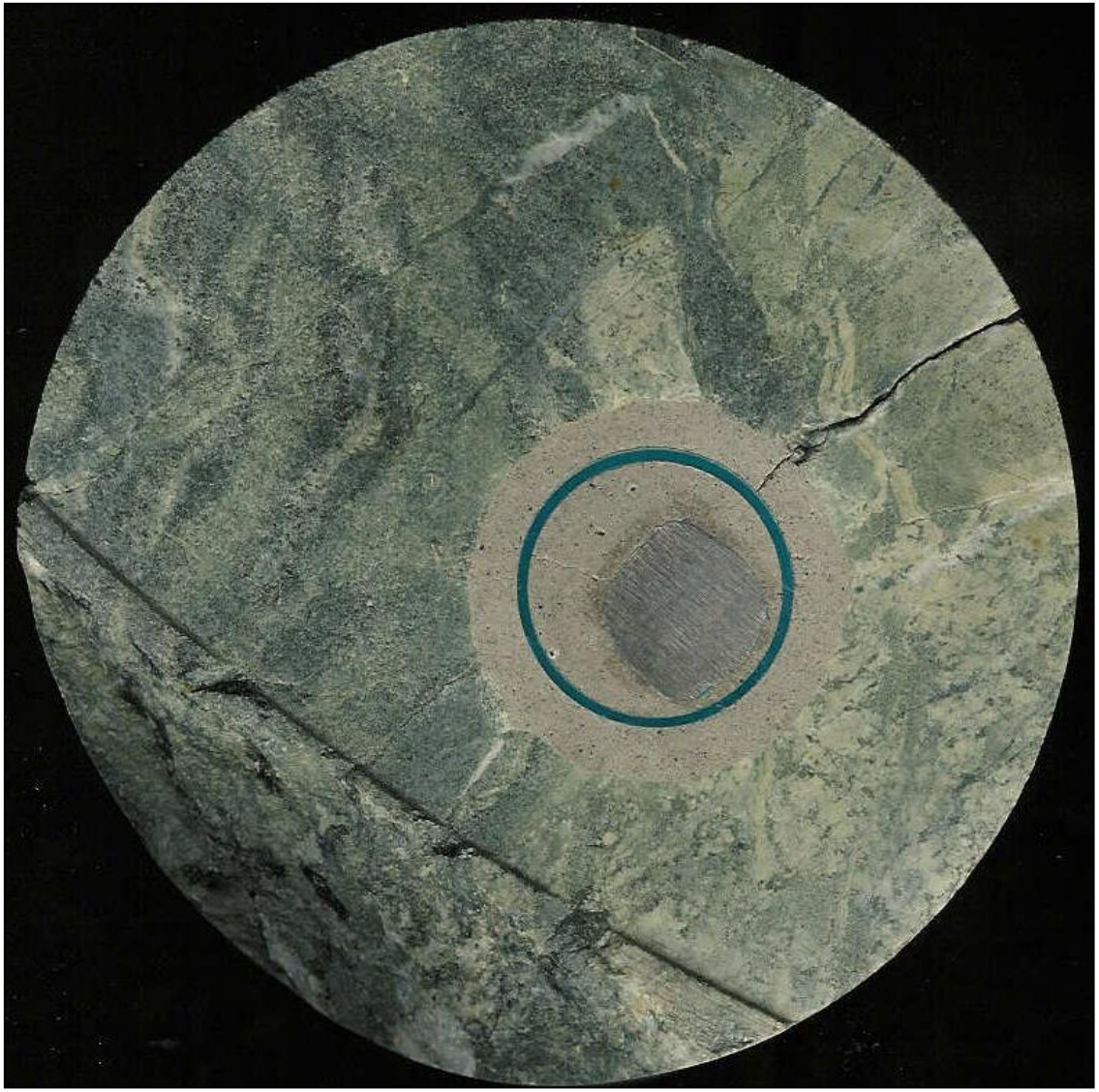
LÆRDAL TUNNEL 24.5 km: lorry-turning caverns (three @ 6km c/c)

30 m span, depths 1,000 to 1,400 m (NMT: B + S(fr) final)

Wet process S(fr) + CT bolts







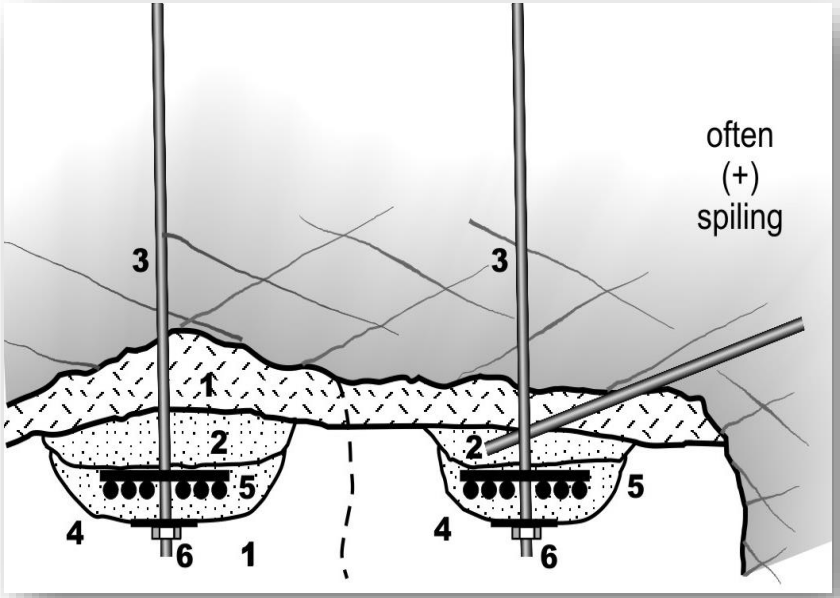
An over-cored CT bolt showing crack (joint) penetration to outer layer of grout.

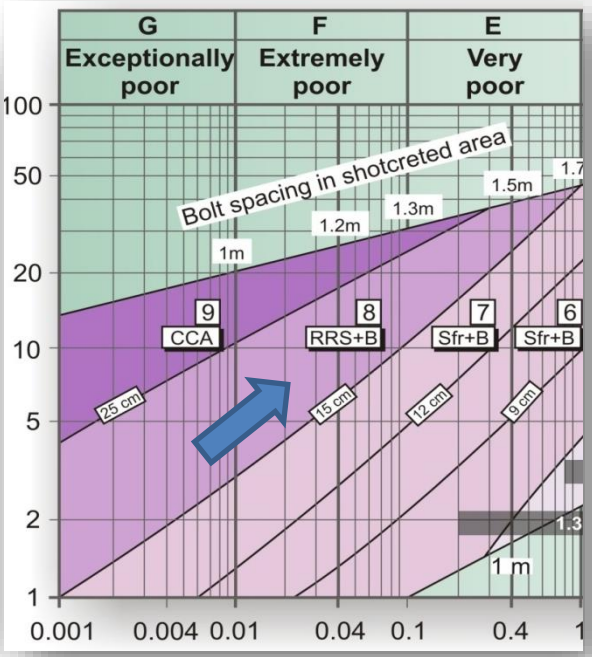
Four layers of corrosion protection remain

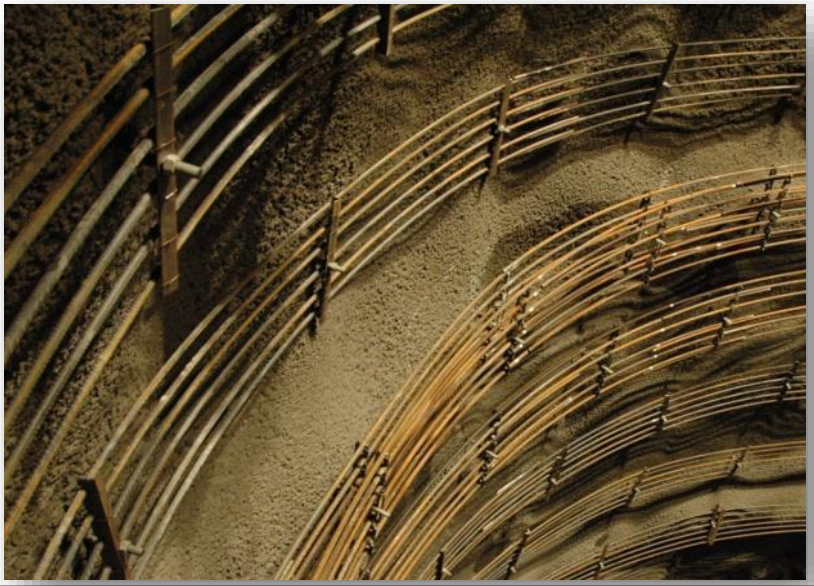
IF VERY POOR STABILITY, LOW Q, B+ S(fr) needs REINFORCED arches

= RRS

(RIB-REINFORCED SHOTCRETE)

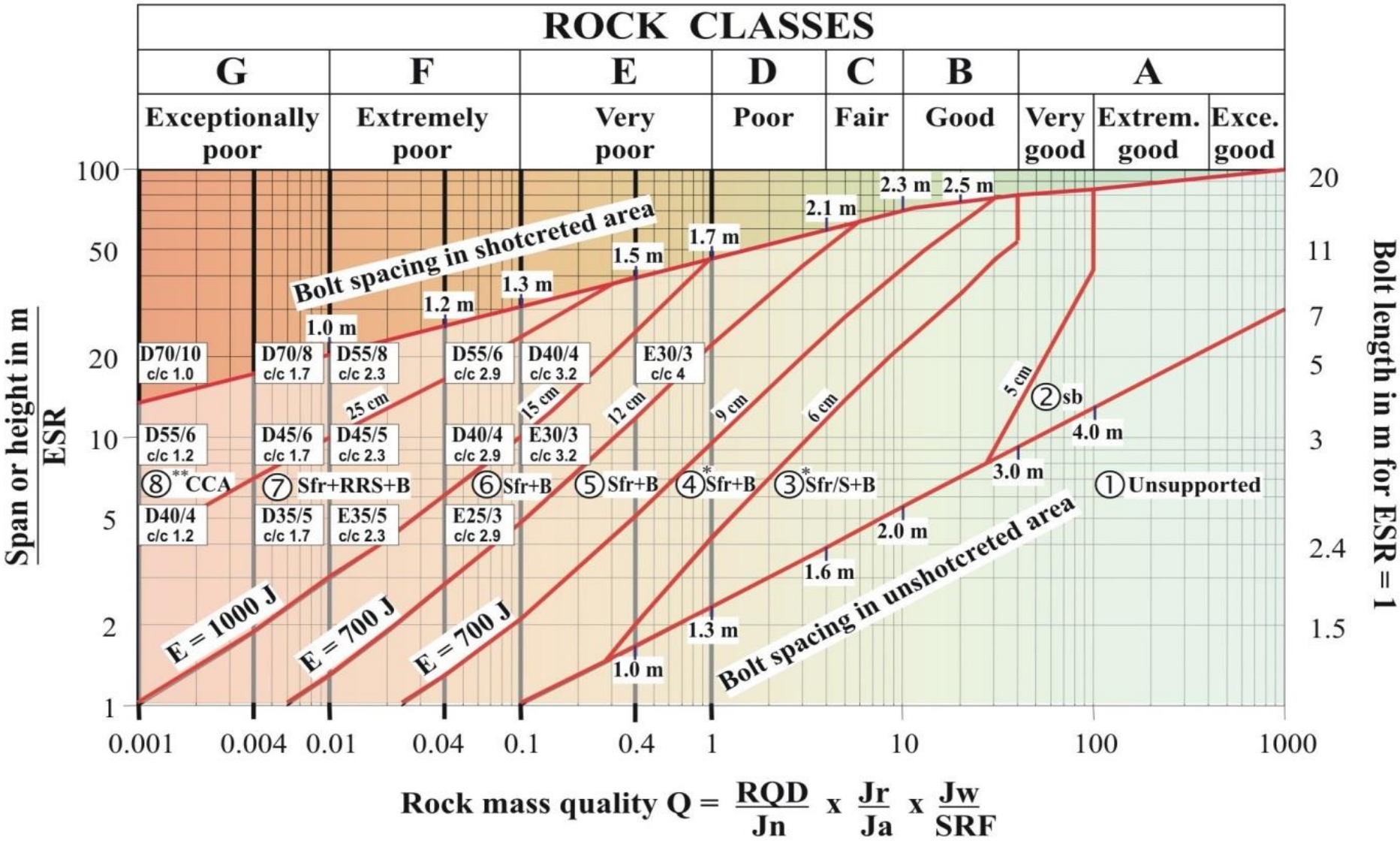






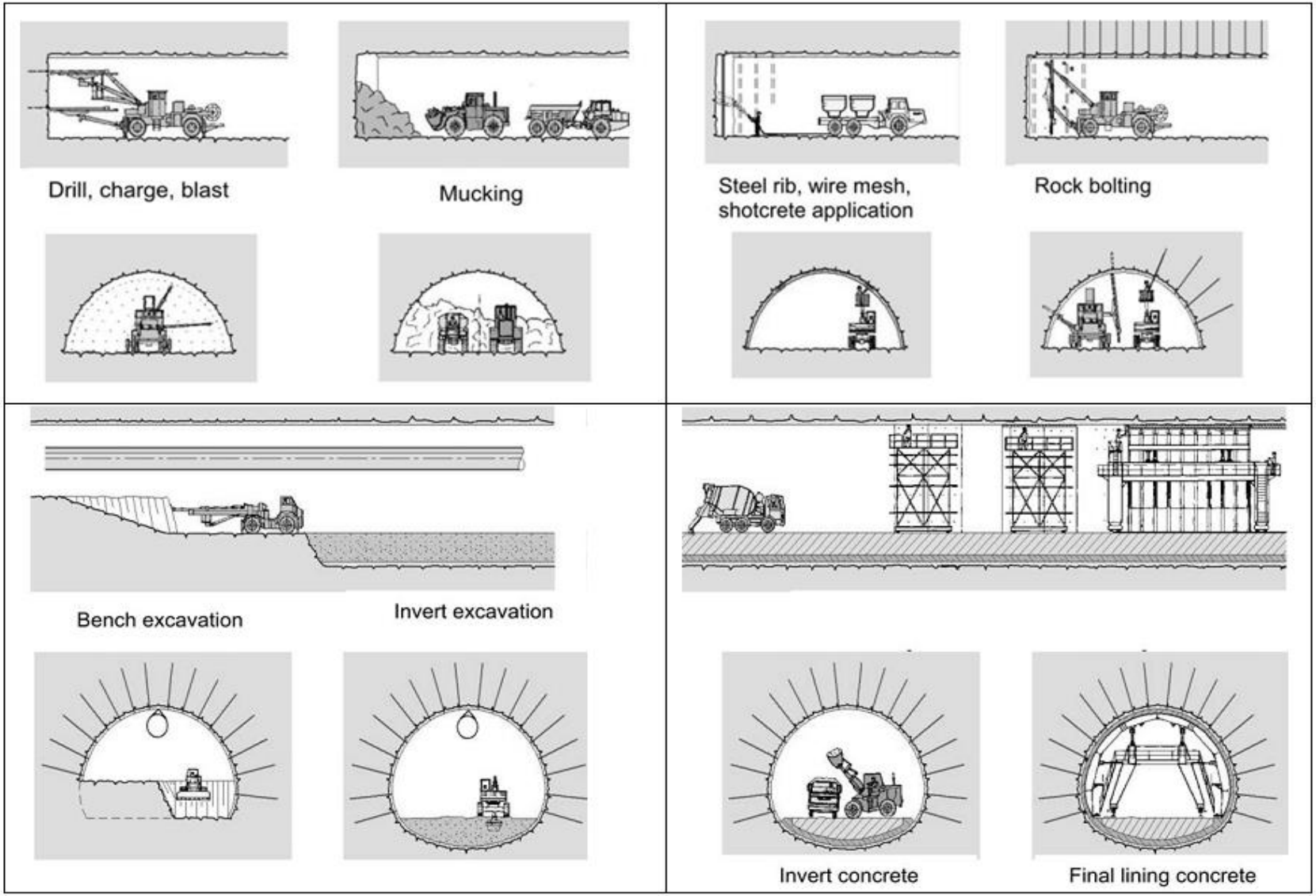
RRS are flexible (until bolted) STEEL ARCHES

3D effect because of S(fr) arches.


ROCK CLASSES
G
F
E
D
C
B
A
Exceptionally poor
Extremely poor
Very poor
Poor
Fair
Good
Very good
Extrem. good
Exce. good
Span or height in m / ESR
Bolt length in m for ESR = 1
Bolt spacing in shotcreted area
Bolt spacing in unshotcreted area
D70/10 c/c 1.0
D70/8 c/c 1.7
D55/8 c/c 2.3
D55/6 c/c 2.9
D40/4 c/c 3.2
E30/3 c/c 4
D55/6 c/c 1.2
D45/6 c/c 1.7
D45/5 c/c 2.3
D40/4 c/c 2.9
E30/3 c/c 3.2
D40/4 c/c 1.2
D35/5 c/c 1.7
E35/5 c/c 2.3
E25/3 c/c 2.9
⑧ **CCA
⑦ Sfr+RRS+B
⑥ Sfr+B
⑤ Sfr+B
④ *Sfr+B
③ *Sfr/S+B
② sb
① Unsupported
E = 1000 J
E = 700 J
E = 700 J
25 cm
15 cm
12 cm
9 cm
6 cm
5 cm
1.0 m
1.2 m
1.3 m
1.5 m
1.7 m
2.1 m
2.3 m
2.5 m
1.0 m
1.3 m
1.6 m
2.0 m
3.0 m
4.0 m
100
50
20
10
5
2
1
20
11
7
5
3
2.4
1.5
0.001
0.004
0.01
0.04
0.1
0.4
1
10
100
1000
Rock mass quality Q = RQD/Jn x Jr/Ja x Jw/SRF

7. USE OF STEEL-SETS/LATTICE GIRDERS IN *DOUBLE-SHELL NATM*

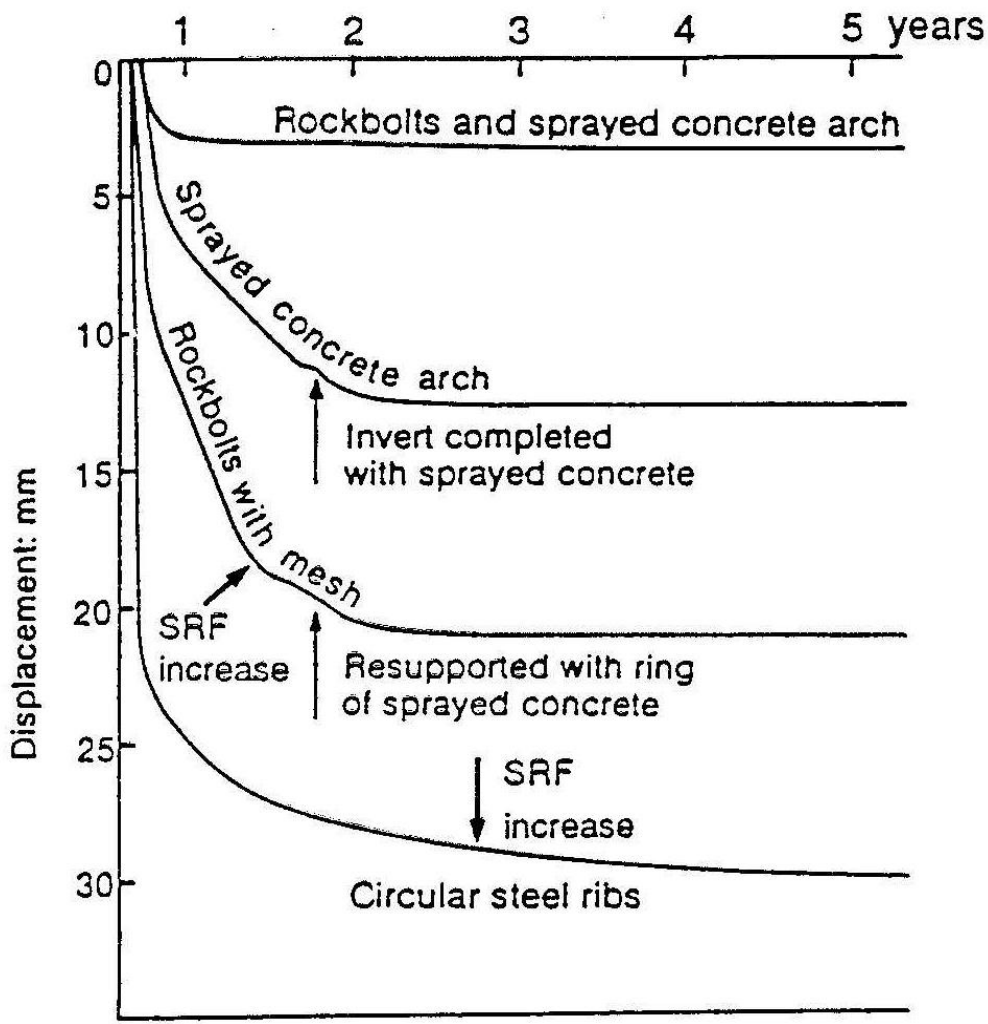
“Austrian Society for Geomechanics, 2010. NATM, ‘The Austrian Practice of Conventional Tunnelling’. **This method has been observed in several countries when Q is ‘poor’, ‘fair’, ‘good’ i.e. Q = 1 to 40, where NMT would be suitable and much faster and cheaper.**

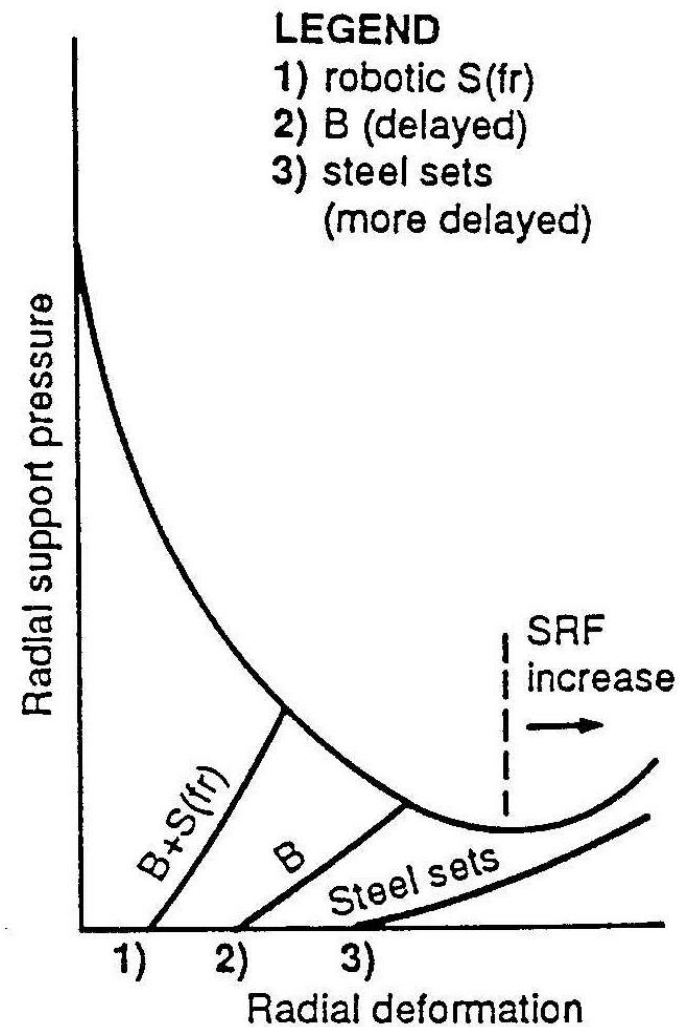


POTENTIAL PROBLEMS WITH ('RIGID') STEEL ARCHES, LATTICE GIRDERS

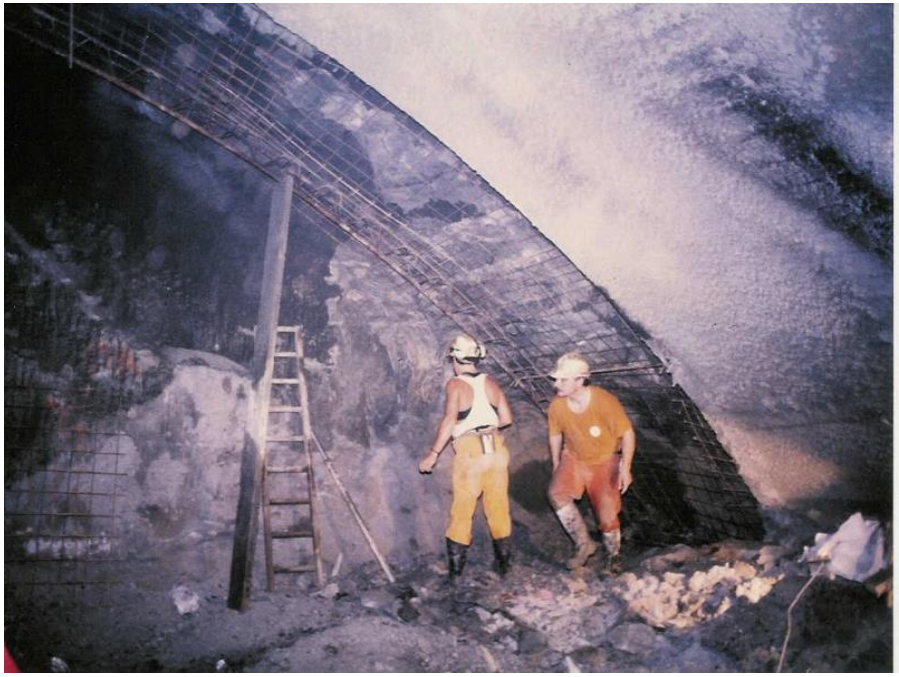
Ward et al. 1983 Kielder experimental tunnel

Barton and Grimstad, 1994 Update of Q-system for NMT



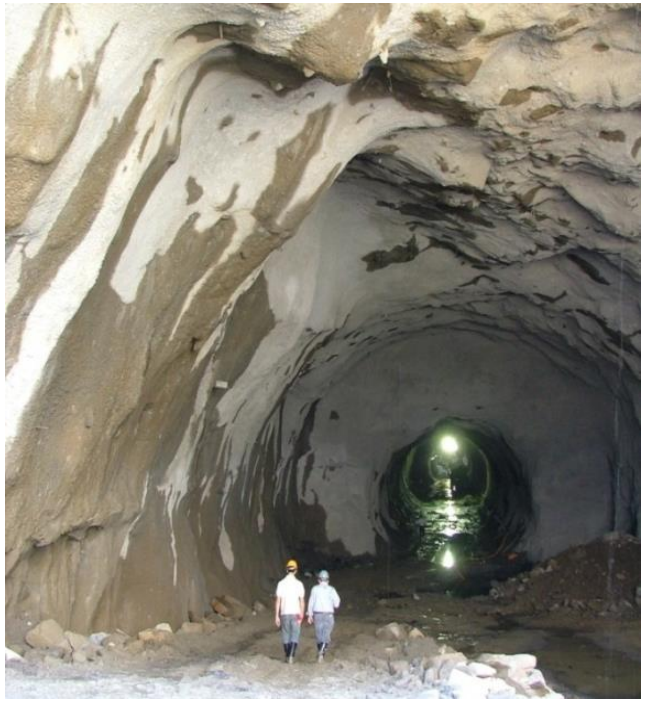


Eurotunnel sub-sea Cross-Over Cavern, Channel Tunnel Project. Final CCA (internet photo)

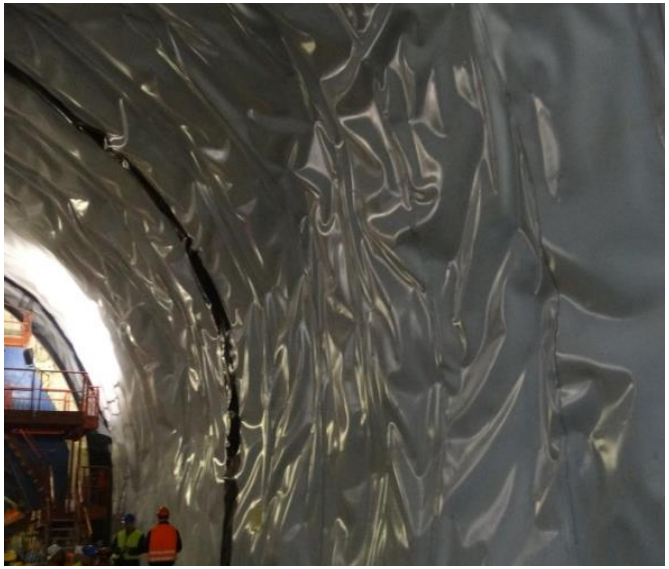


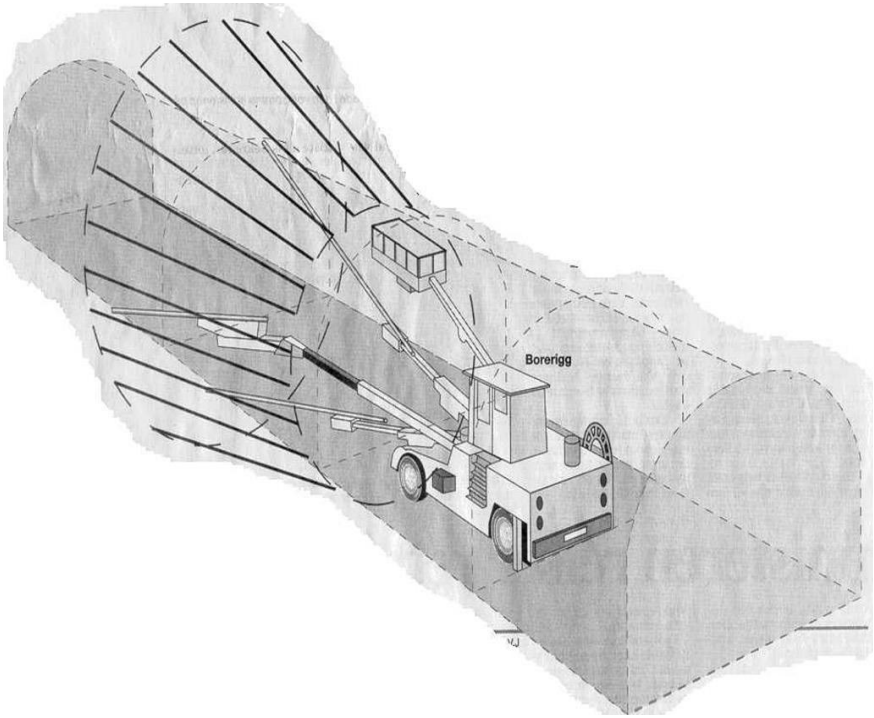
140 m collapsed in parallel tube

8. CONTRASTING WATER CONTROL IN *NATM* AND *NMT*



OVER-BREAK PREJUDICES MEMBRANE CONSTRUCTION (3D is difficult),
AND INCREASES S(fr) AND CONCRETE VOLUMES





IF THE CHOICE IS *SINGLE-SHELL NMT*: ECONOMY AND PERFORMANCE ARE ENHANCED WITH PRE-INJECTION

- **EXAMPLE OF PRE-INJECTED SHALES: 110 m2 TWIN-TRACK HIGH SPEED RAIL TUNNEL**

9. GJØVIK CAVERN Q-LOGGING AND *NMT* SINGLE-SHELL B+S(fr)

DEPTH ZONE: 0 TO 60m

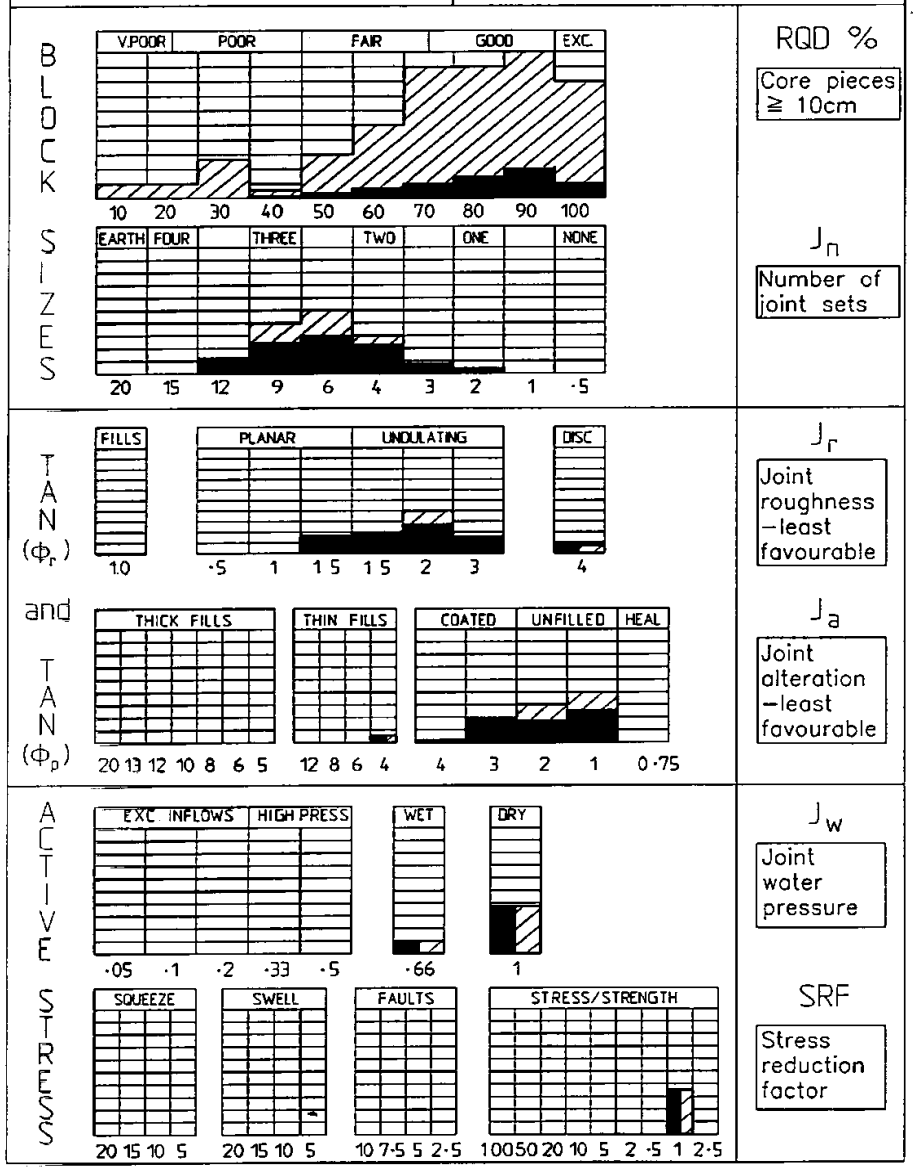
EXISTING CAVERNS AND CORE – GJØVIK

Q (typical range) = 1.1–75

$$\left(\frac{30-100}{4-9}\right)\times\left(\frac{1.5-3}{1-3}\right)\times\left(\frac{.66-1}{1.0}\right)$$

Q (mean) = 12.2

$$\left(\frac{73}{6.6}\right)\times\left(\frac{2.2}{1.8}\right)\times\left(\frac{0.9}{1.0}\right)$$

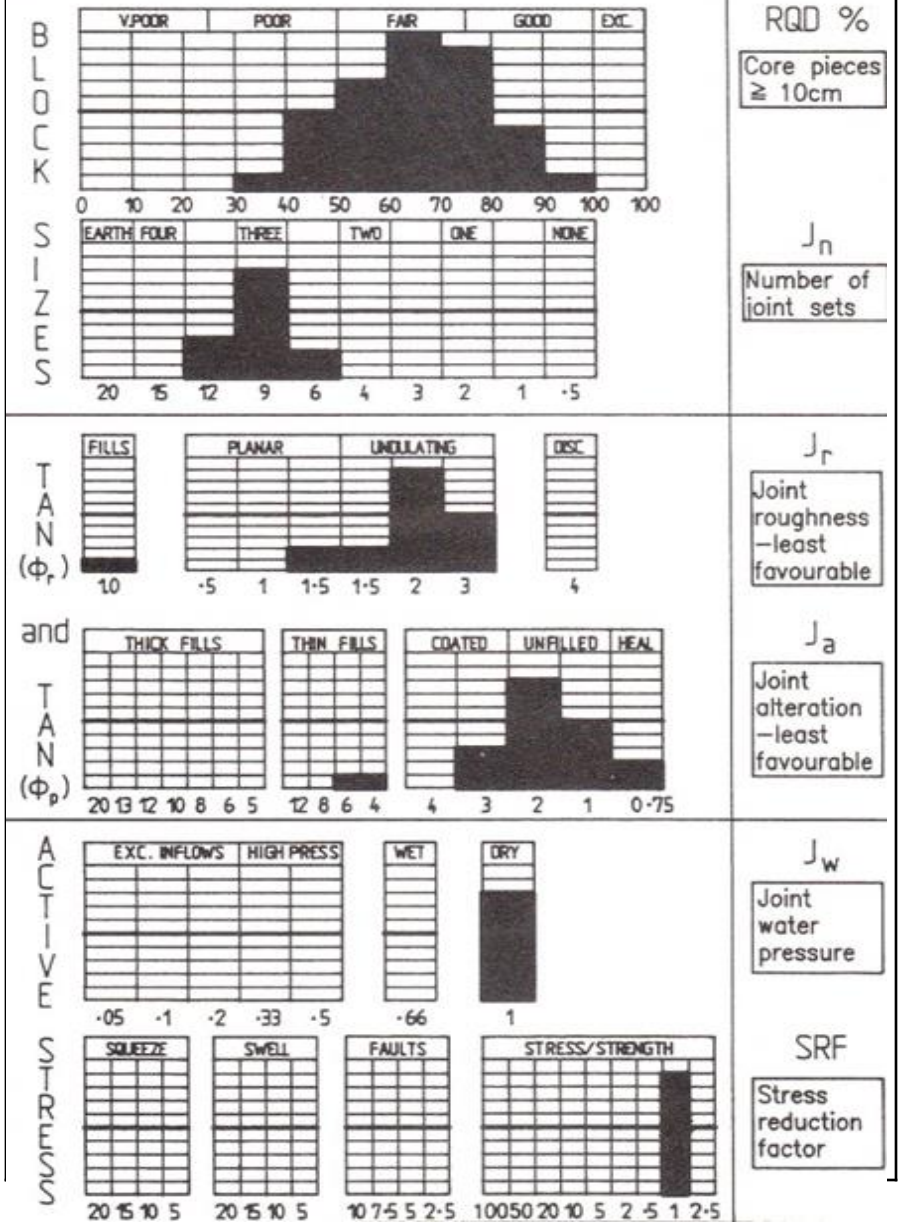


Q (typical range) = 4–27

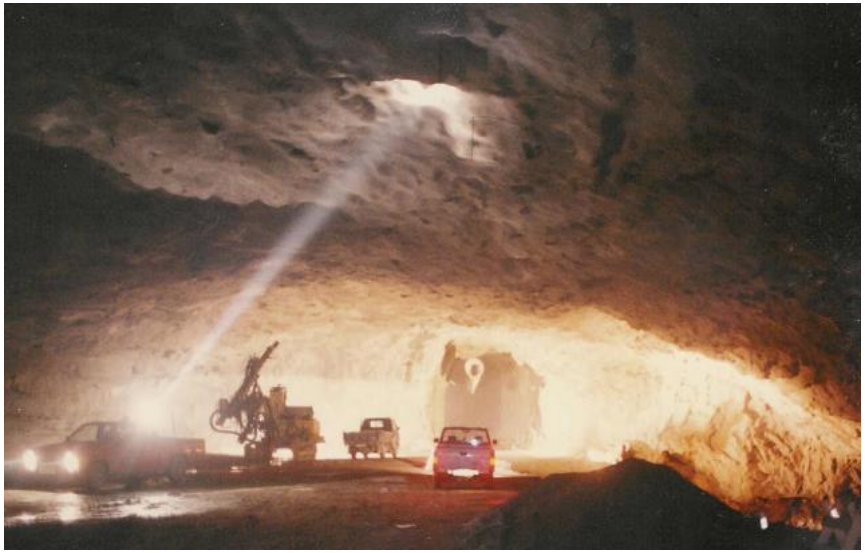
$$\left(\frac{50-80}{9-12}\right)\times\left(\frac{2-3}{1-2}\right)\times\left(\frac{1}{1}\right)$$

Q (mean) = 7.4

$$\left(\frac{65}{9.2}\right)\times\left(\frac{2.1}{2.0}\right)\times\left(\frac{1.0}{1.0}\right)$$

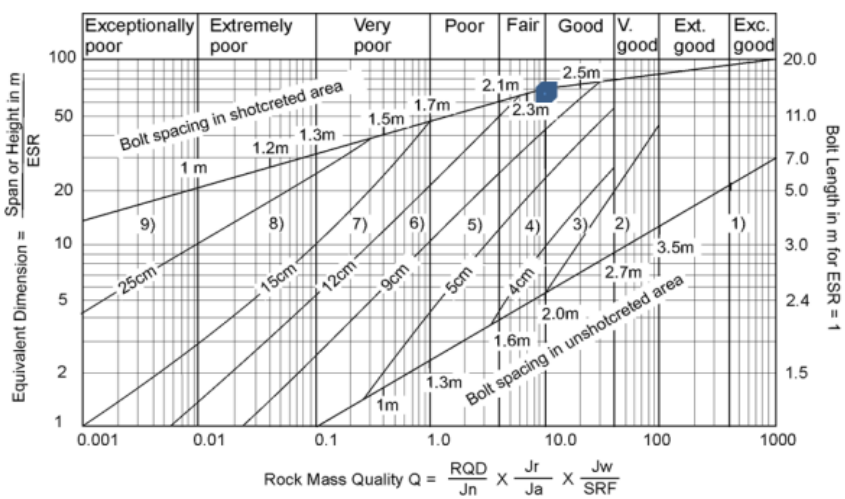


Gjøvik Olympic Sports Cavern

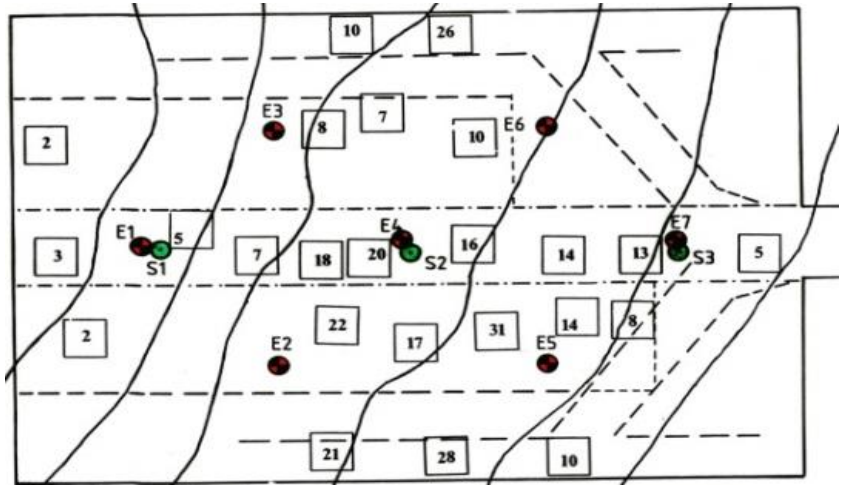


World's largest top-heading of 62 m span.

Mean 10cm of S(fr). Note some over-break >1m

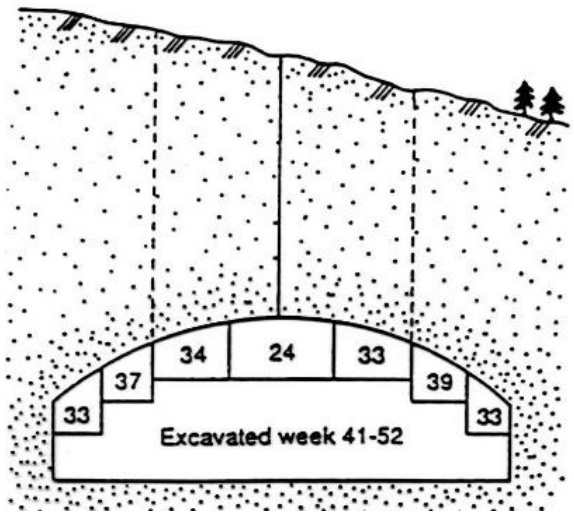


Q mean ≈ 10, span = 62m, ESR = 1.0 . The upper 'boundary' of Q-support chart (1993) extended.

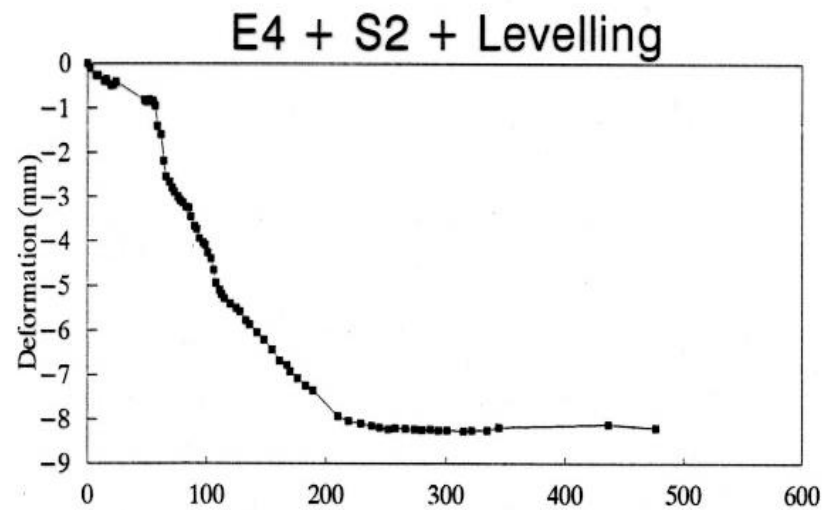


Q-value of arch (boxes): range 2 to 31. Long external MPBX from surface (red).

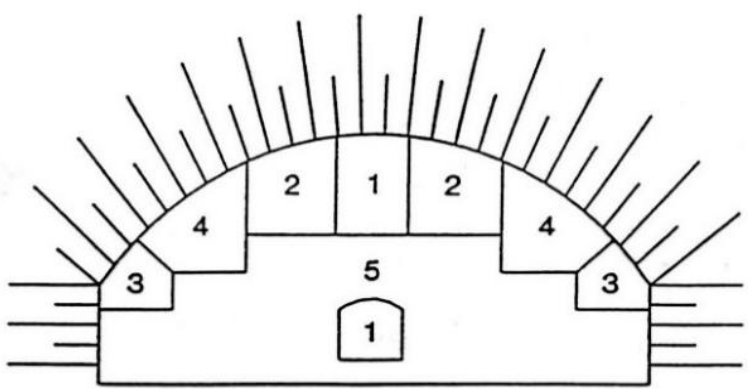
Gjøvik Olympic Sports Cavern



MPBX locations (three rows), excavation week number in 1991 (June to December). 140,000m3

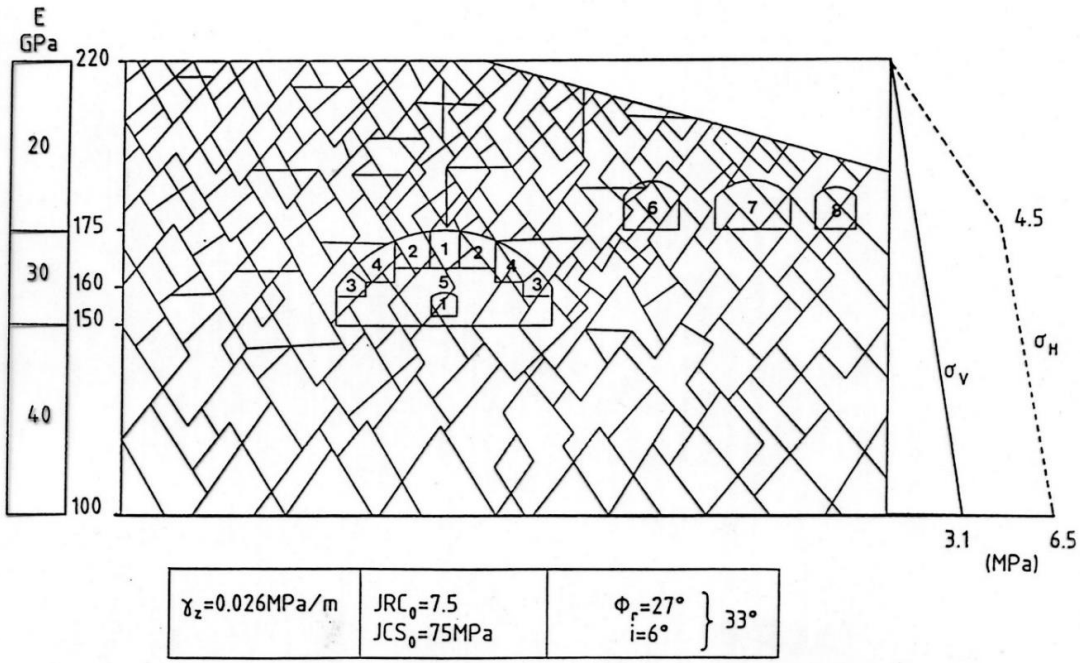


Central deformation 8 mm, ends 7.0 and 7.5 mm
UDEC-BB models: 7 to 9 mm.

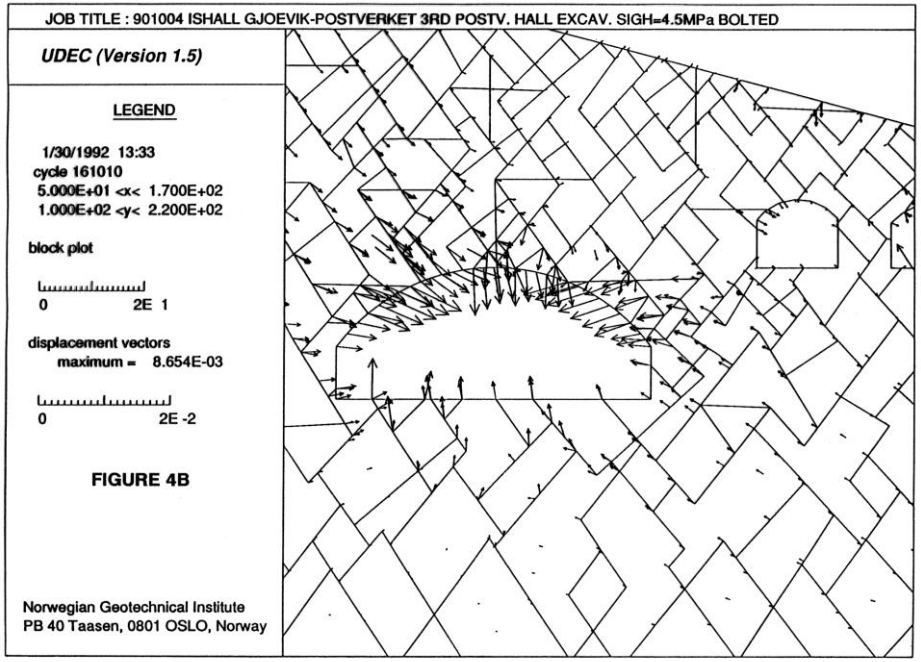


Bolts: L = 2.5 m c/c, S(fr) 10 cm, cable-anchors (temporary) L = 12 m, 2 x 16 mm.

Early rounds of Olympic ice hockey. Cavern has 5,400 persons seating capacity for concerts.



V_P and E_{mass} *INCREASE* with STRESS or DEPTH.



Note discontinuous jointing.

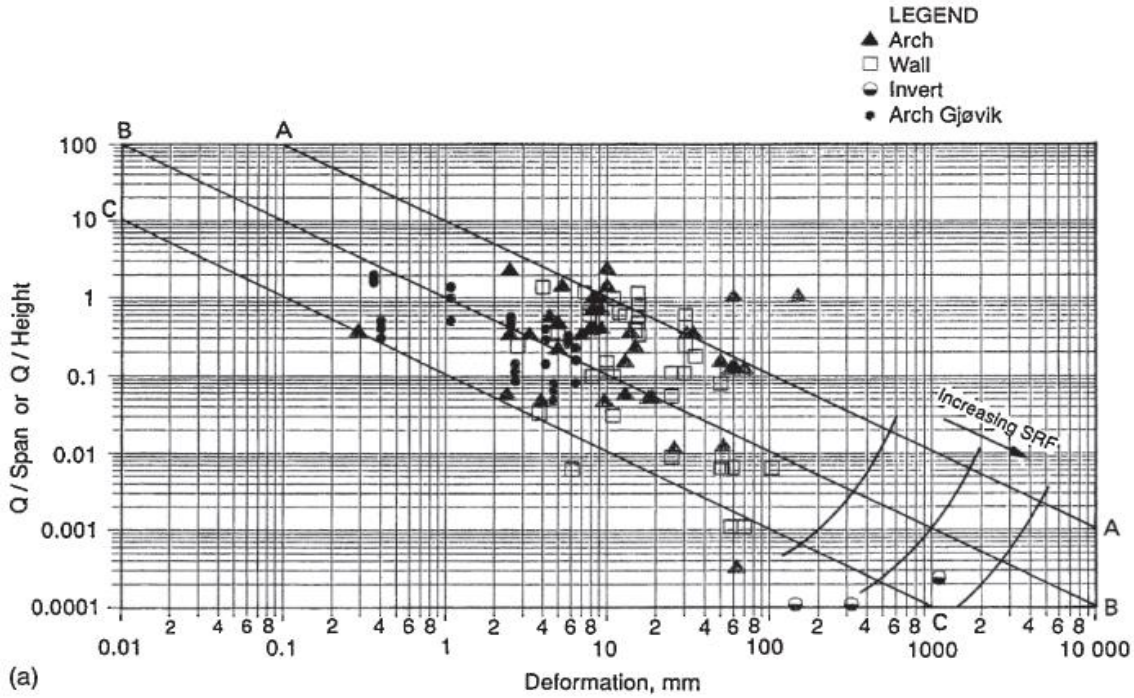
(Δv max 8.7mm)

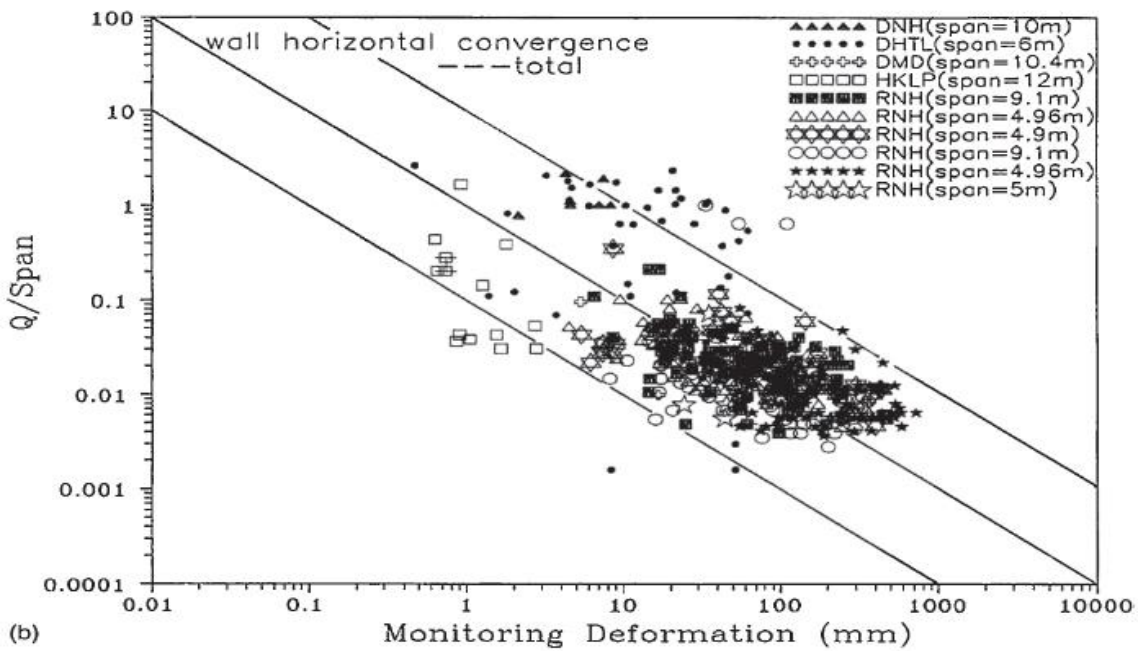
10. ESTIMATING TUNNEL OR CAVERN DEFORMATION

ONE SHOULD CHECK FOR THE REALISM OF 'MODELLED' DEFORMATION.

REALITY MAY BE DIFFERENT FROM WHAT ONE ASSUMES IS CORRECT in COLOURFUL MODELS

(maybe with too continuous jointing in UDEC)





$$\Delta = \frac{SPAN}{Q}$$

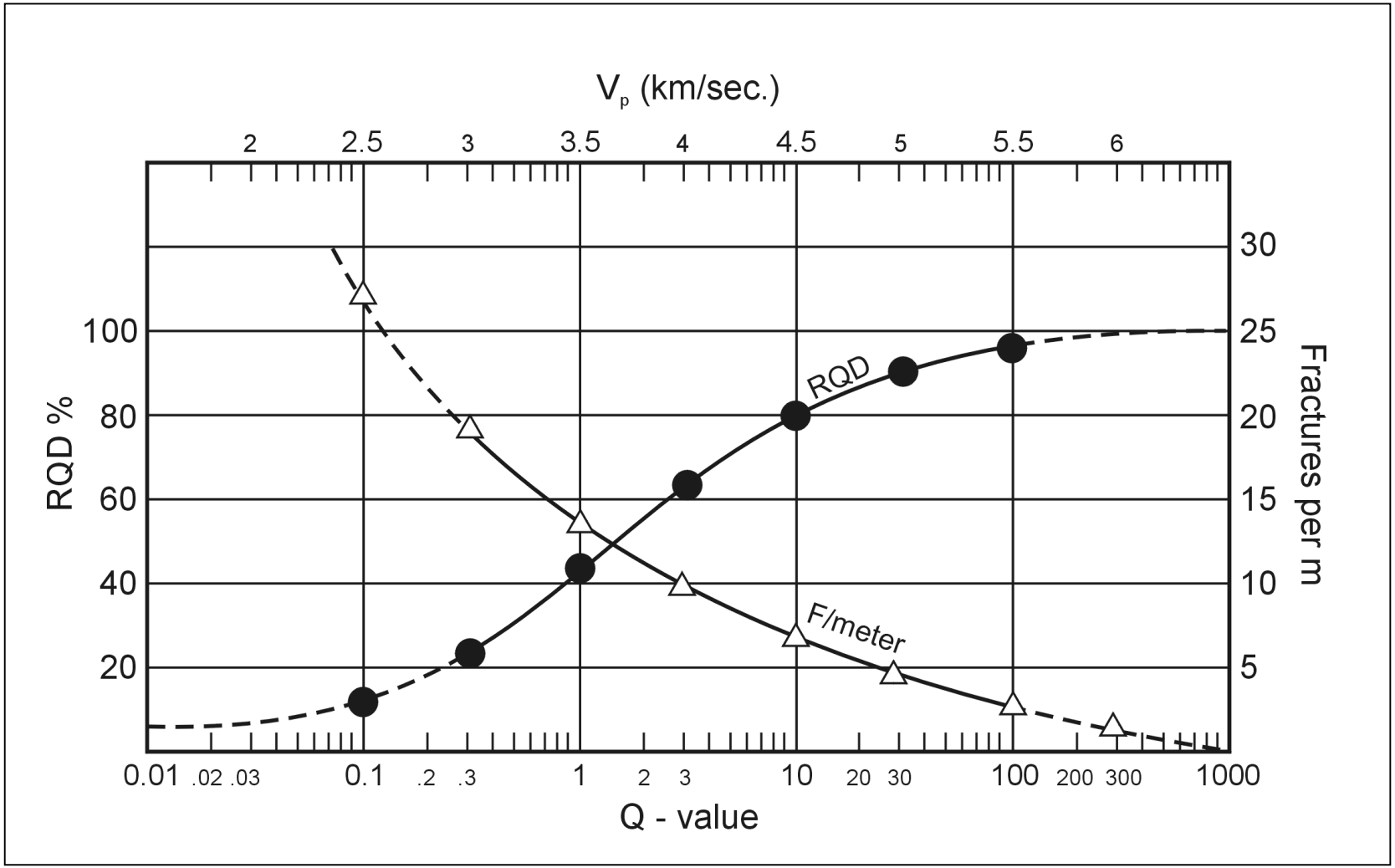
$$\Delta_v = \frac{SPAN}{100\,Q}\sqrt{\frac{\sigma_v}{\sigma_c}}$$

$$\Delta_h = \frac{HEIGHT}{100\,Q}\sqrt{\frac{\sigma_h}{\sigma_c}}$$

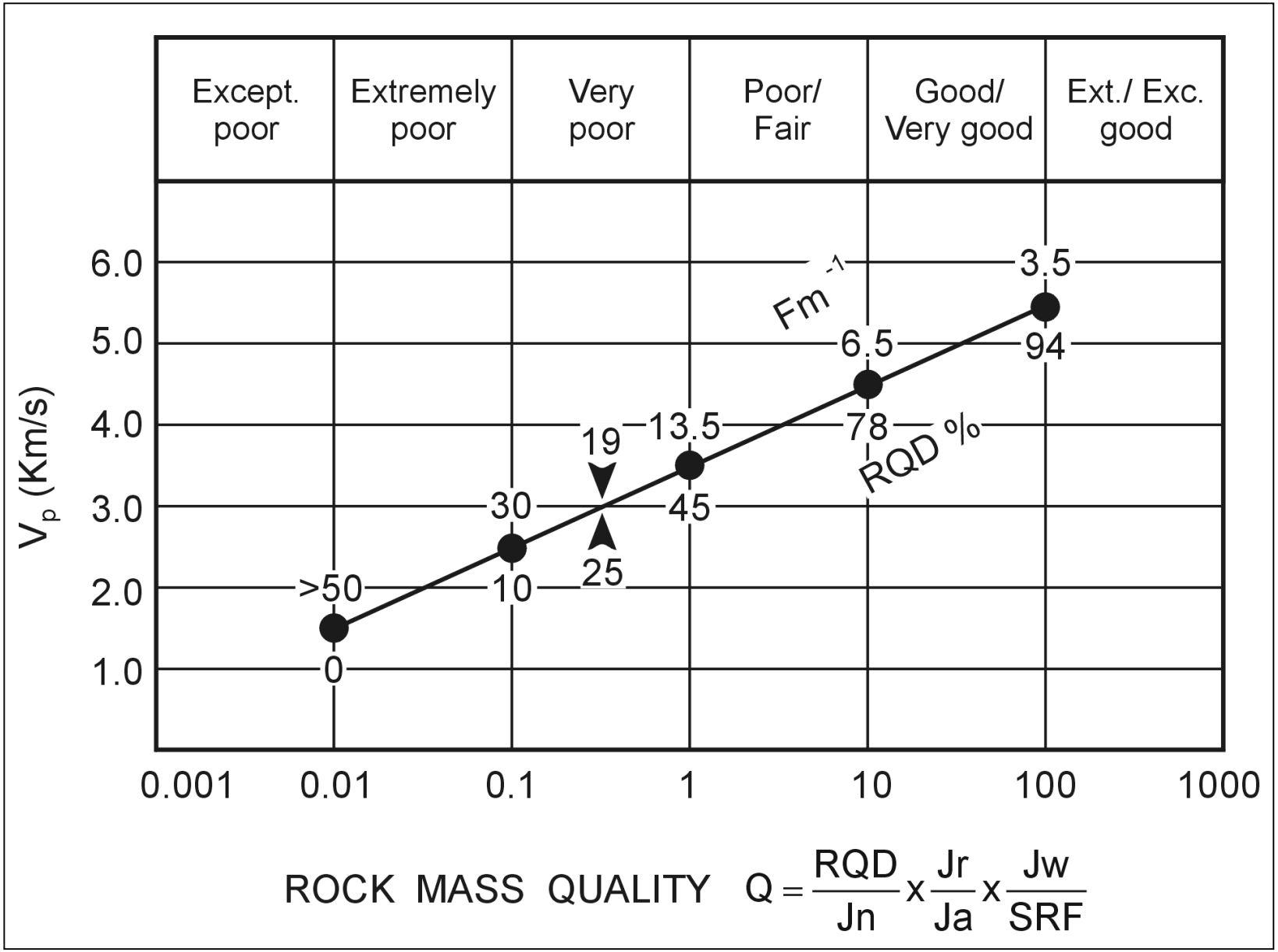
$$k_o = \left(\frac{SPAN}{HEIGHT}\right)^2\left(\frac{\Delta_h}{\Delta_v}\right)^2$$

11. CORRELATING Q WITH V_P, DEFORMATION MODULUS

The Sjøgren et al., 1979 data: from 120 km of seismic profiles, from 2.8 km of core (hard-rock Scandinavian sites with little weathering).

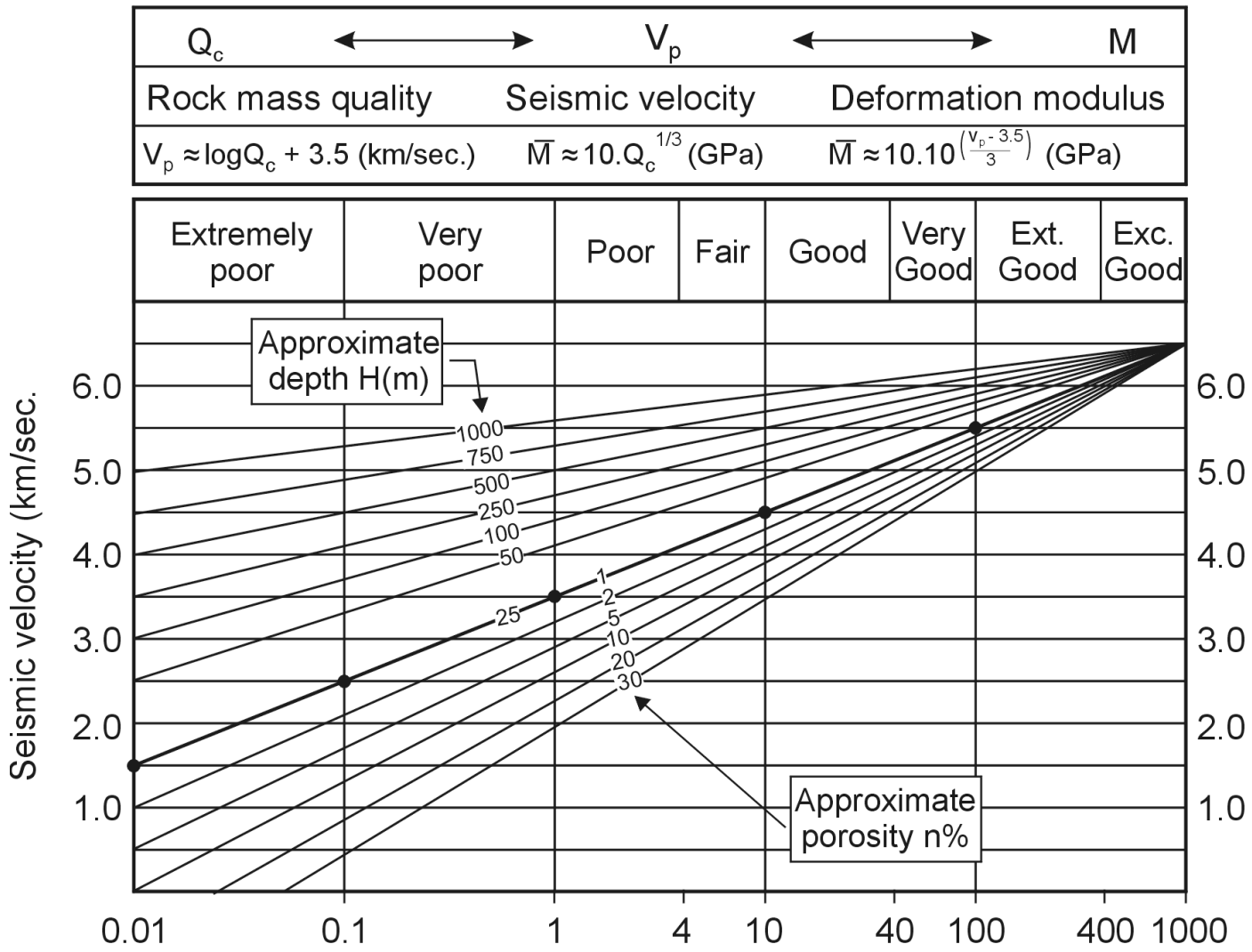


(After Sjøgren et al. 1979, with Barton, 1995 addition of Q)



(As with all Sjøgren data: hard rock, low porosity, near-surface)

AN INTEGRATED MODEL: Q_c – V_p – E_{mass} – P_r



Approx. range of deform. moduli	
M (Min)	M (Mean)
(GPa)	
100	100
53	68
30	46
17	32
9	22
5	15
3	10
2	7
1	5
0.5	3
0.3	2
0.2	1.5
0.1	1.0

Approx. range of support pressures	
P_r	
MPa	tnf/m²
0.01	1
0.02	2
0.05	5
0.1	10
0.2	20
0.5	50
1.0	100

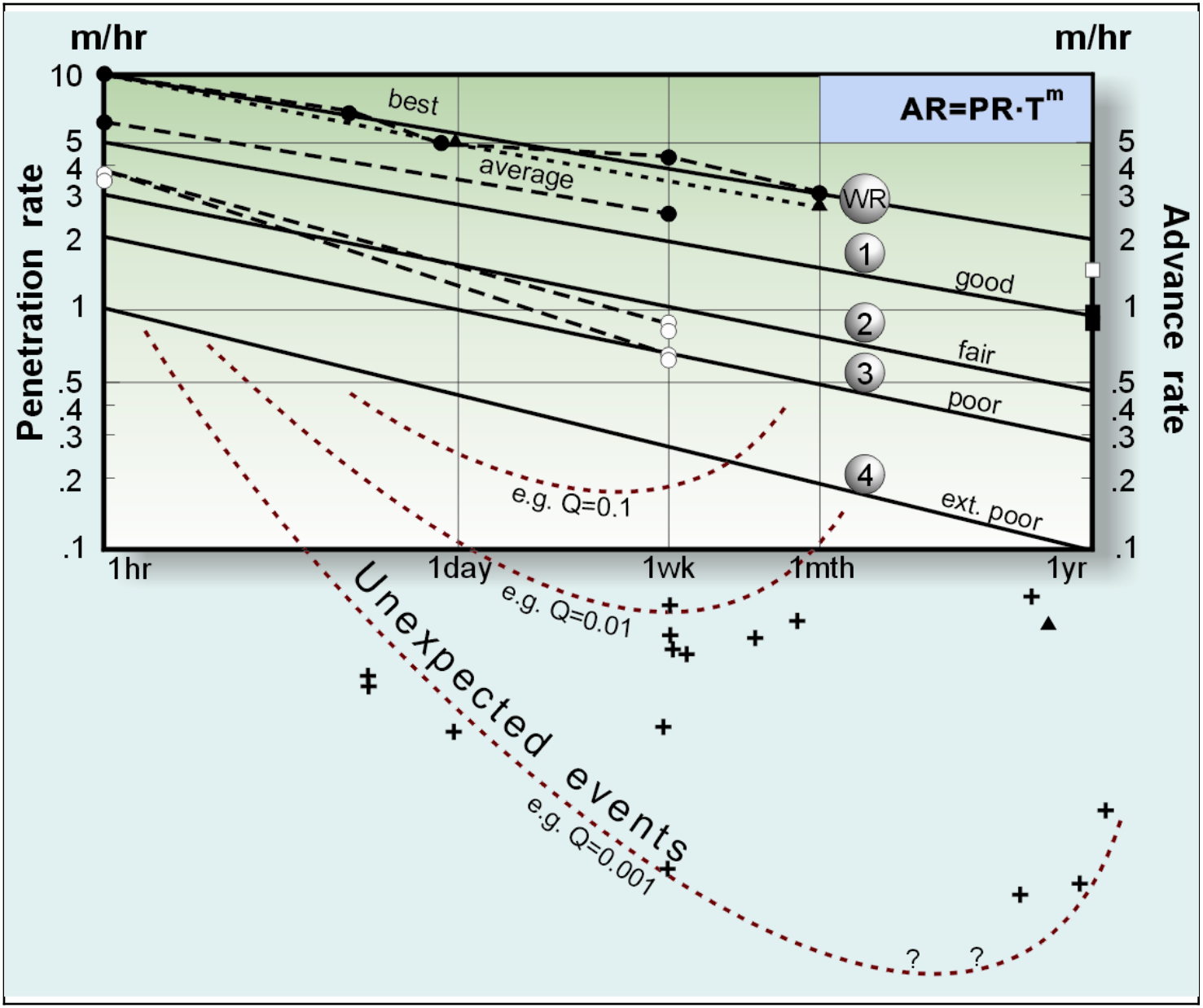
$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right] \frac{\sigma_c}{100}$$

$$E_{mass} \approx 10\, Q_c^{1/3} \text{ (GPa)}$$

$$E_{mass} \approx 10^{(V_p - 2.5 + \log \sigma_c)/3}$$

V_p (km/s)	2.5	3.5	4.5	5.5
σ_c (MPa)	10	100	100	150
E_{mass} (GPa)	2.2	10.0	21.5	53.1

12. Q-VALUE APPLIED TO TBM PERFORMANCE PROGNOSIS VIA Q_{TBM}

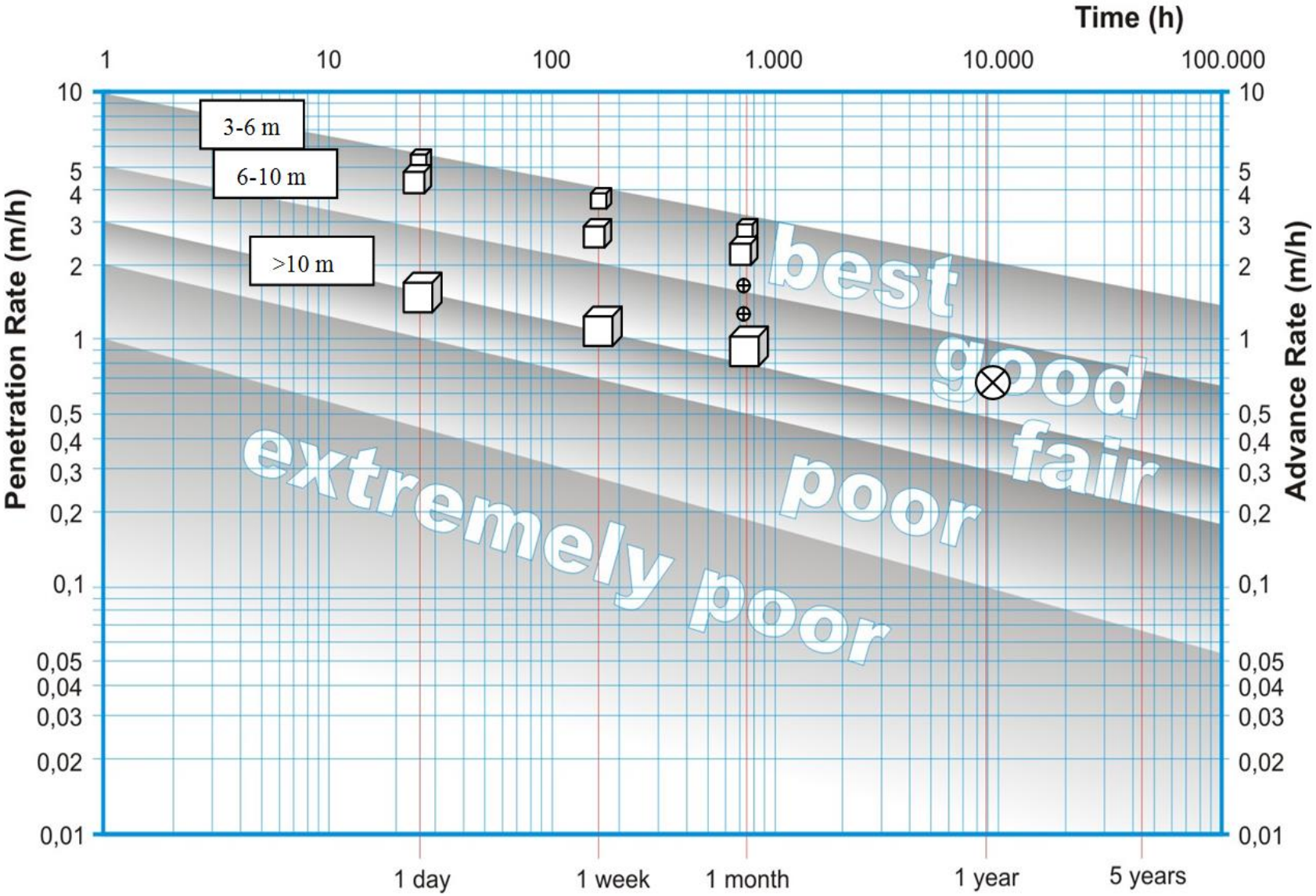


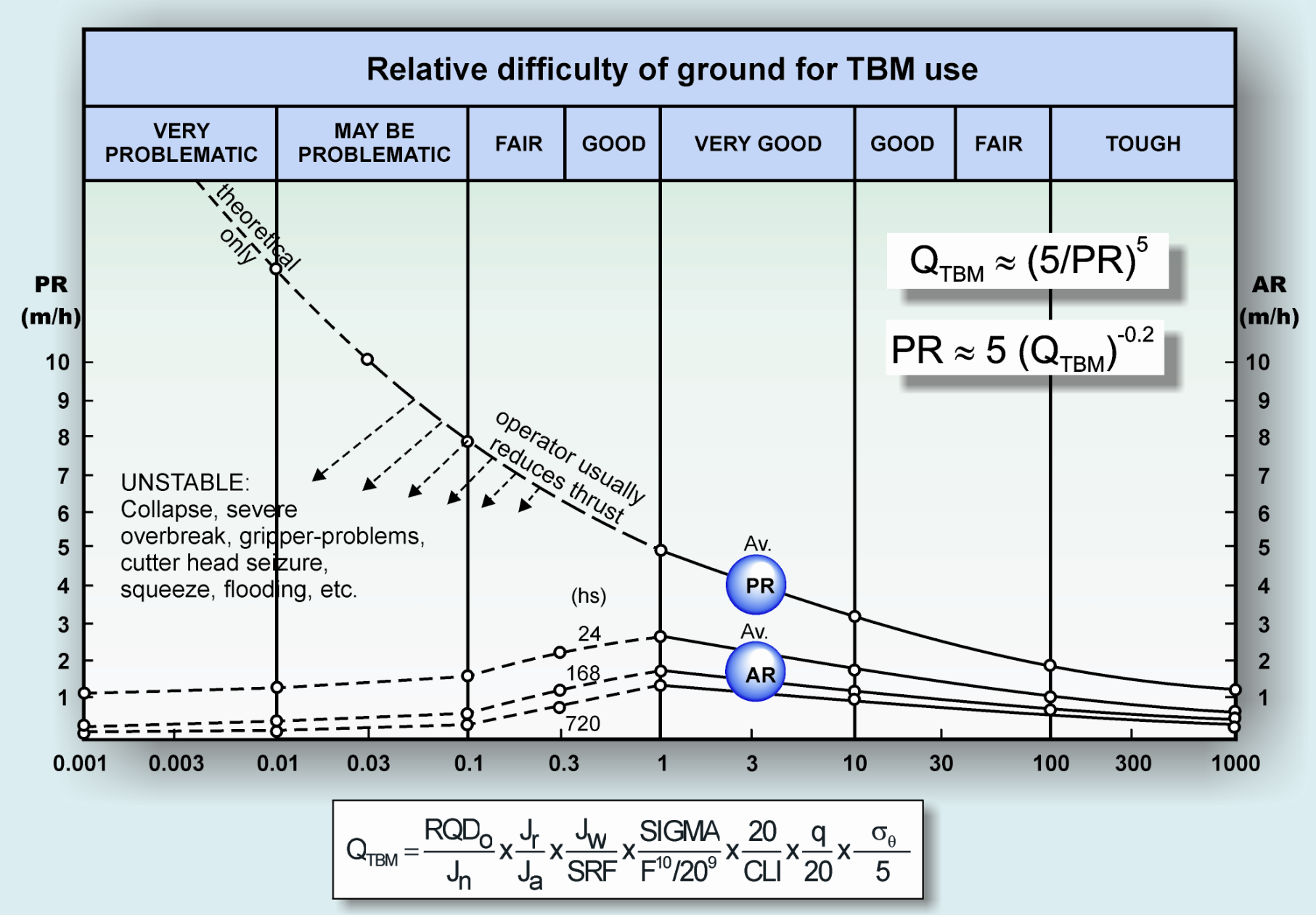
CASE RECORD EVIDENCE OF DECELERATION from 145 cases representing 1000 km of open gripper TBM.

(Low Q-values explain the 'unexpected events').

Conventional equation AR=PR x U

FROM SEVERAL PAGES OF WORLD RECORDS BY TBM – ASSEMBLED BY ROBBINS: *GET FOLLOWING RESULTS WHEN COMBINED TO REDUCE SCATTER*. *Assume 24 hrs/day, 168 hrs/week, 720 hrs/month*





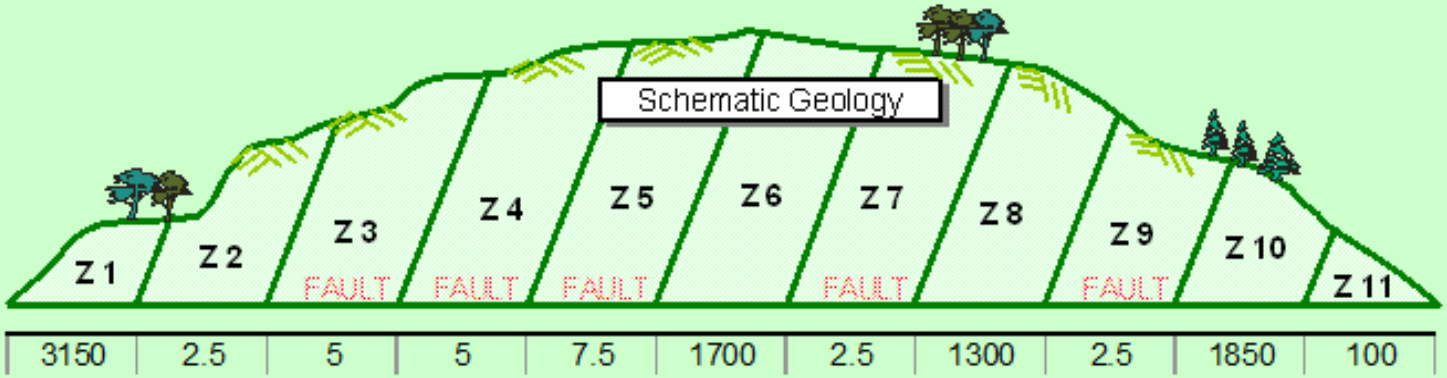
$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

THE Q_{TBM} EQUATION WAS DEVELOPED BY TRIAL AND ERROR. MOST ADDITIONS TO Q-PARAMETERS ARE 'NORMALIZED BY CENTRAL VALUES'

EXAMPLE OF INPUT DATA SCREEN

Nick Barton & Associates

Q TBM



ZONE	11	LITHOLOGY	BRECHA-CLORITA/-BIOTITA	ZONE LENGTH	100

INPUT DATA

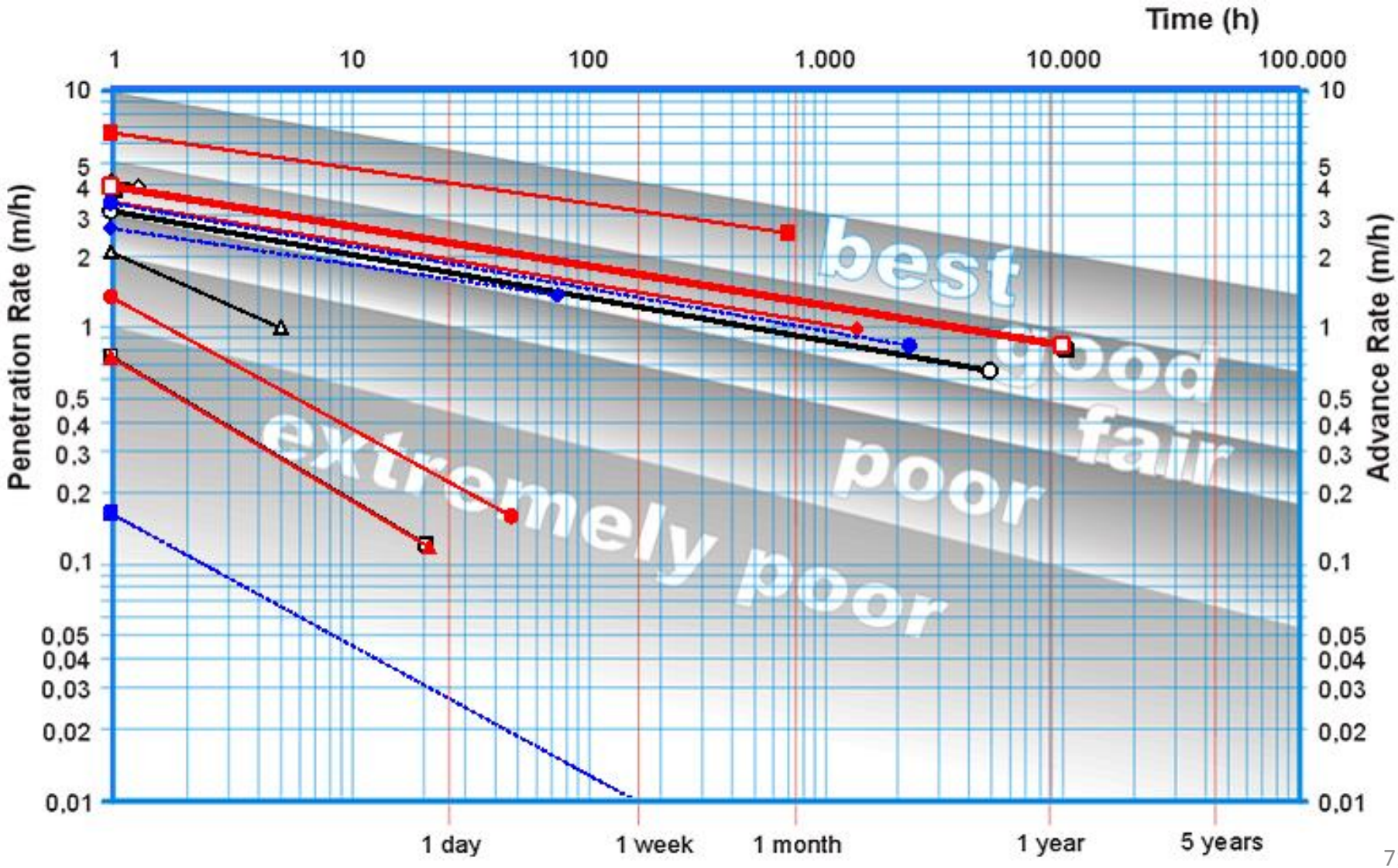
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)
100.0	4.0	1.5	3.0	1.00	1.0	-0.17	100.0	2.8

V_P (km/s)

β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
60.0	100.0	3.0	20.0	25.0	10.0	20.0	4.5	2.0

EXAMPLES OF Q_{TBM} GRAPHIC RESULTS

(8km tunnel predicted to take approx. 10,000 hours)



Q-manual
(1974-2014)

(44 pages, 79 figs/photos)

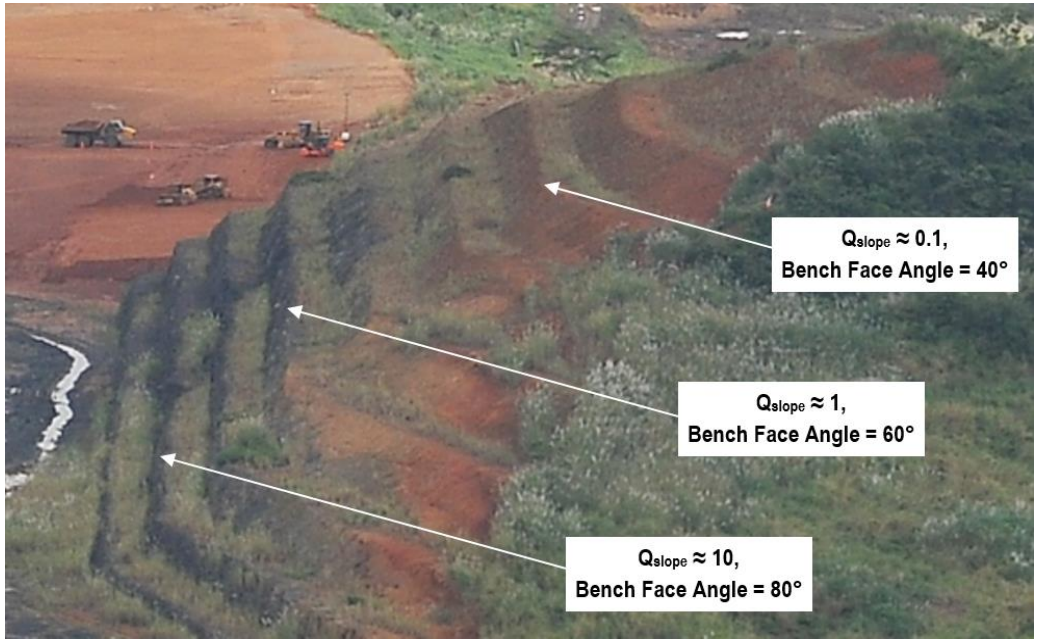
See www.nickbarton.com

(p.4 of downloads)

AN ILLUSTRATED GUIDE TO THE Q-SYSTEM

N. Barton and E. Grimstad

www.nickbarton.com



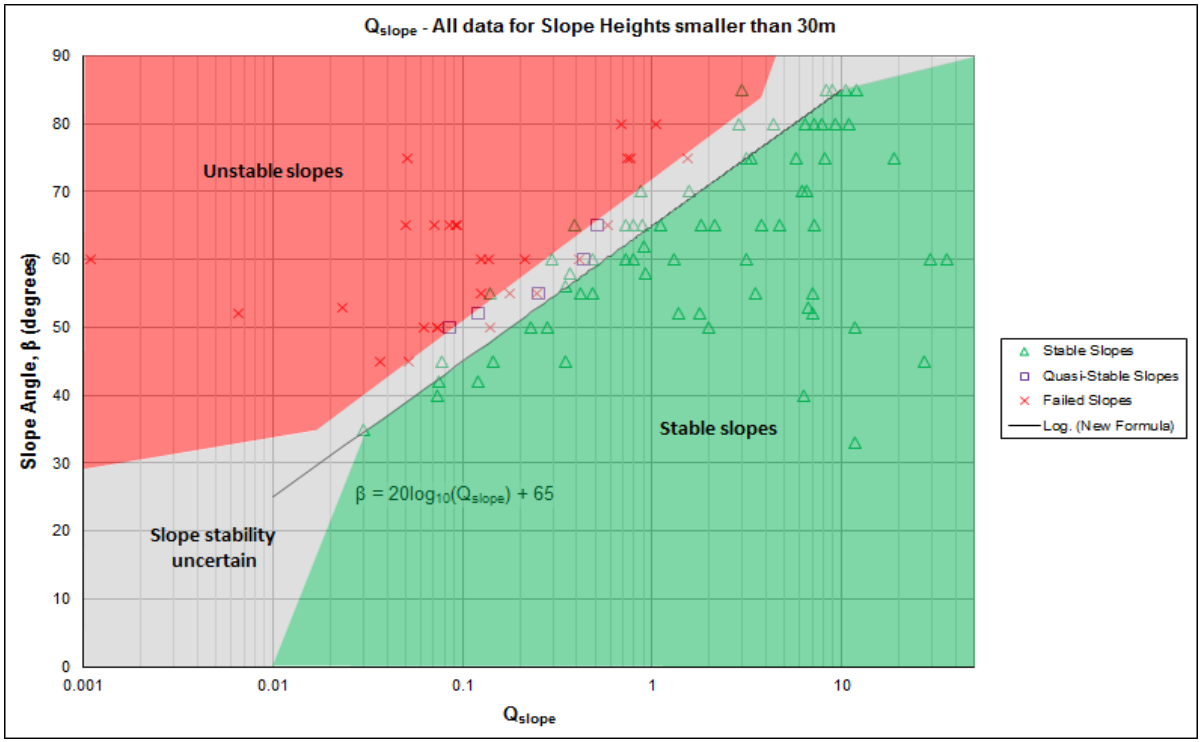
Q-SLOPE METHOD

(Barton and Bar, 2015)

Q-slope = 0.01 : slope angle ≈ 25°
Q-slope = 0.1 : slope angle 45°
Q-slope = 1.0 : slope angle 65°
Q-slope = 10 : slope angle 85°

$$Q_{slope} = \frac{RQD}{J_n} x \left(\frac{J_r}{J_a}\right)_0 x \frac{J_{wice}}{SRF_{slope}}$$

$$\beta = 20\, log_{10}\, Q_{slope} + 65°$$



SINGLE-SHELL NMT – Q-BASED SUPPORT SELECTION

CONCLUSIONS

1. **The Q-system has had application in thousands of civil and mining engineering projects in a large number of countries during the last four decades. It is most strongly linked to single-shell permanent tunnel support and non-entry mining stopes (Q' = RQD/Jn x Jr/Ja).**

2. **In relation to 'competing methods' such as RMR it appears to have the advantage of a logarithmic quality scale. Why? Because nature varies by many many orders of magnitude, as opposed to just 'one' in RMR and GSI.**

3. **Q has some important parameters like number of joint sets (Jn) and inter-block friction (Jr/Ja) and ways to evaluate the stress/strength ratio (SRF) which seem to be absent elsewhere. Orientation is there too (RQD is oriented and the least favourable Jr/Ja is oriented).**

4. **The Q-value and its statistical variation has an important role in site investigation, core-logging, seismic velocity interpretation, and later for deciding on 'support class' and suitable support during tunneling. This cannot be done by 'finite element modelling' at 80 m/week.**

5. **Do not assume that *a priori* methods like GSI-HB give more reliable results than empirical *a posteriori* methods like Q. FEM with these shear strength assumptions has the effect of accentuating plastic zones, as shown in a formal court case, and as seen on many other occasions more recently.**