Empirical Method for Tunnelling (Q-system):

Site Characterization, Day-to-Day follow-up, Input for Numerical Discontinuum Modelling

CONTENT of LECTURE

1. What we need: a quantitative description of the rock mass and its variation.
2. How to use this? Within an empirical (support) method if good enough.
3. Why the Q-system? Because the big numerical range is fundamentally correct.
4. Why the Q-system? Because it has a proven case record / track record.
5. Why the Q-system? Can be used on exposures, when core-logging, day-to-day.
6. Why the Q-system? Gives simple tunnel and cavern support recommendations.
7. Why the Q-system? Relative (tunnelling) *cost* and *time* are both related to Q.
8. Why the Q-system? Because Q or Q_c relate to V_p, E_{mass}, shear strength.
9. Why not RMR or GSI? Too small numerical scales. Both poor on 'geology'.

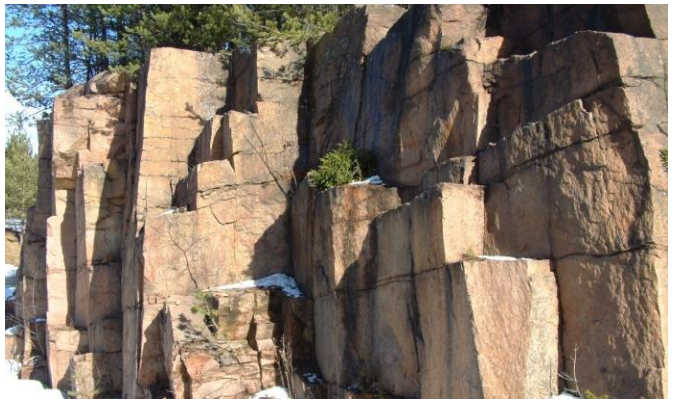
SLIDE NUMBER EXPECTATIONS

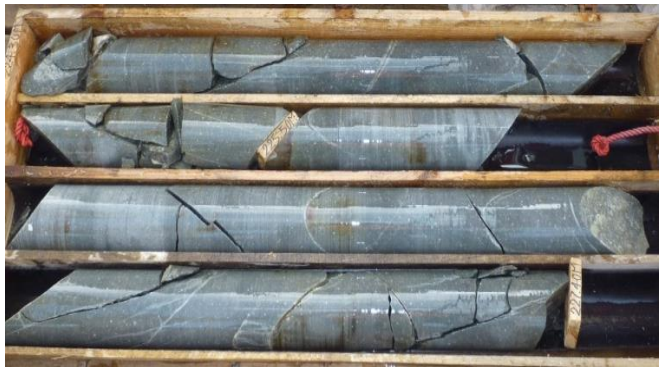
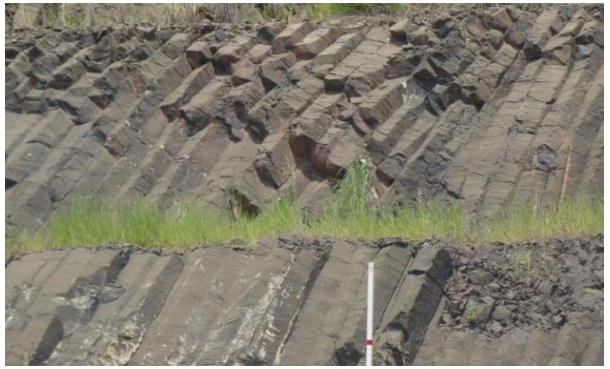
- 1 to 16 CHARACTERIZATION (Q-examples)
- 17 to 25 TUNNEL SUPPORT COMPONENTS, RRS, LG-CRITIQUE
- 26 to 31 Q-LINKS TO COST, TIME, ‘delta’, Vp, E_{mas}
- 32 to 38 BRIEF CRITIQUE OF H-B, CONTINUUM MODELLING

BRIDGE DESIGN – KNOWN MATERIALS

TUNNEL DESIGN – *UNKNOWN* MATERIALS

(Tangential stress and radial stress – make the bridge/tunnel stable - with help, if low Q)



NORWAY
CHINA
BRAZIL

KASHMIR
IRAN
BRAZIL

HONG KONG
PANAMA
BRAZIL

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

Q saves us from impossible sizes of *in situ* rock mass testing.

- **THOUSANDS OF PHOTOGRAPHS**
- **HUNDREDS OF PROJECTS – MANY TUNNELS**
- **FORTY COUNTRIES – AND COUNTING**

- **ONE PROBLEM:**
- ***ALL THE PHOTOGRAPHS/ROCK MASSES ARE DIFFERENT***
- **SO 'DAY-TO-DAY' TREATMENT IS (ALSO) NECESSARY**

A GOOD EXAMPLE OF VARIABILITY OVER SHORT DISTANCES

ALL SOLUTIONS ARE GOING TO BE APPROXIMATE

(not fish-eye camera!)

THE ‘Q-system’ ?

Q used here!

As a briefest introduction:

Q means *<u>rock</u> mass quality*.

Q consists of *ratings for six parameters*.

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

= (Block size) x (friction) x (‘active stress’)

Q = 1000 (or better)
(Q ≈ 100/0.5 x 4/0.75 x 1/1)

Q = 0.001 (or worse)
(Q ≈ 10/20 x 1/8 x 0.5/20)

***WIDE NUMERICAL RANGE OF Q REALISTICALLY* REFLECTS HUGE POTENTIAL DIFFERENCES IN *ROCKMASS* PROPERTIES**

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

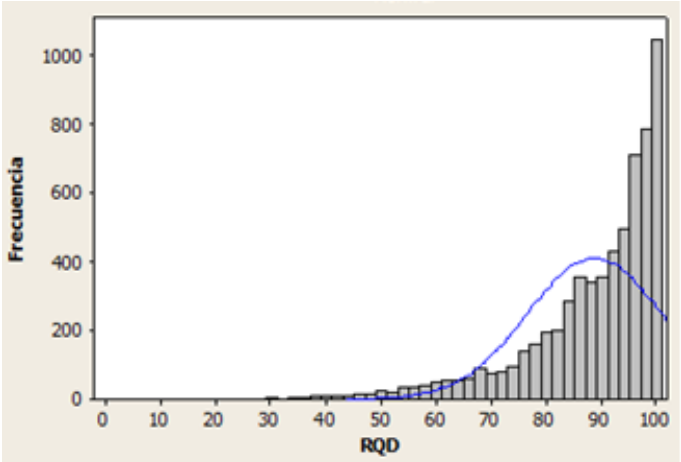
INITIAL 200+ CASE RECORDS..... from 1974.....

50 rock types

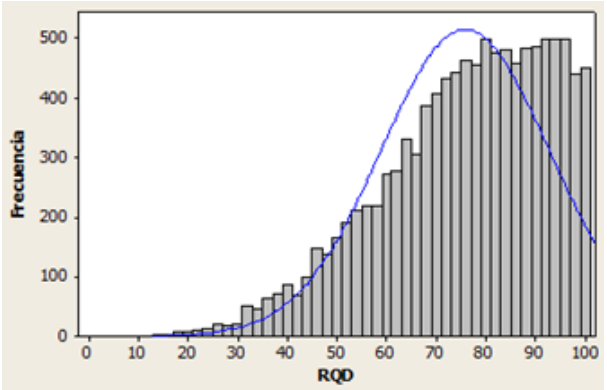
Now > 2,000 case records re tunnel support measures

1. EXAMPLES OF RQD STATISTICS (40km of core)

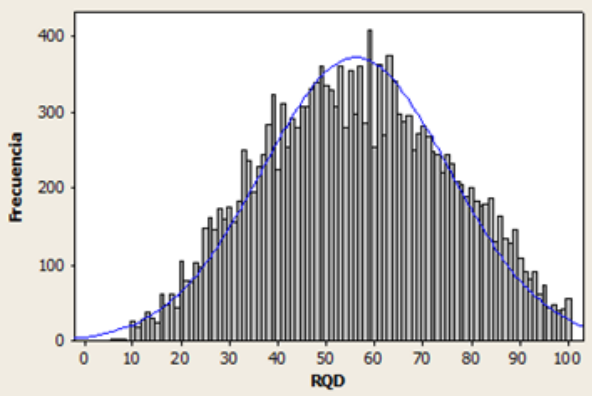
WITHIN RESPECTIVE Q-RANGES 0.1-1, *1-4*, 4-10, 10-40



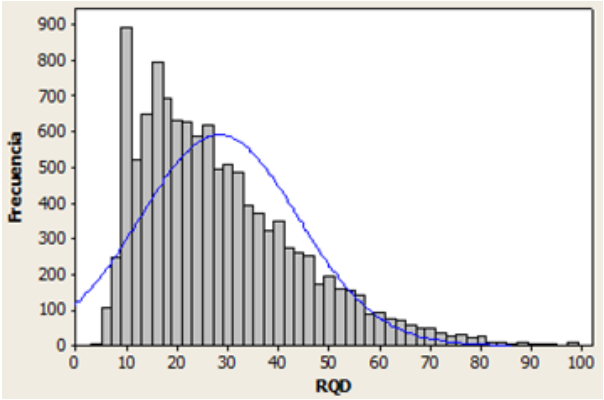
Q = 10-40 ('good')



Q = 4-10 ('fair')



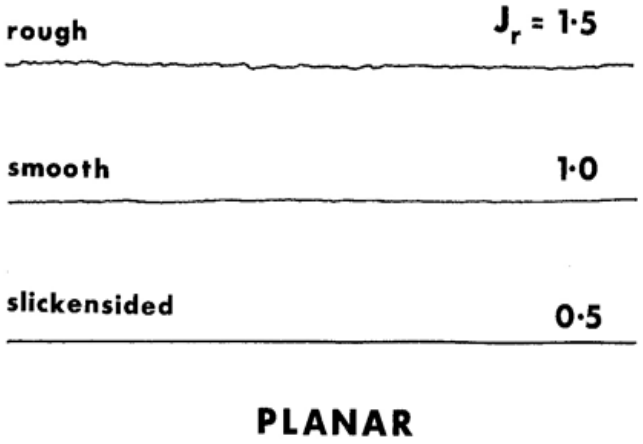
Q = 1-4 ('poor')

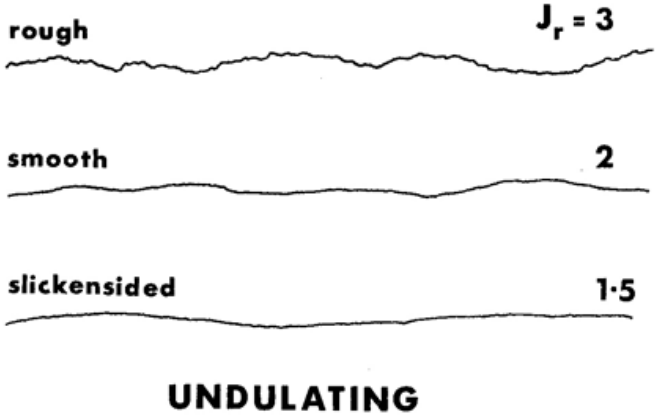


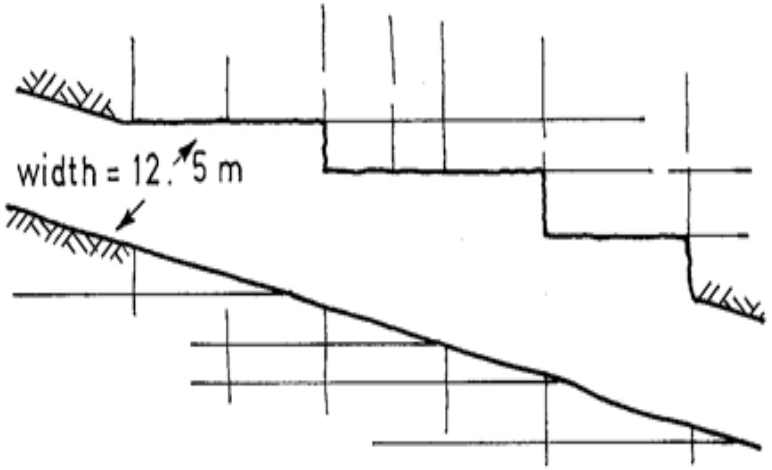
Q = 0.1-1 ('very poor')

RQD USED FOR NEARLY 60 YEARS. WILL CONTINUE TO BE USED!

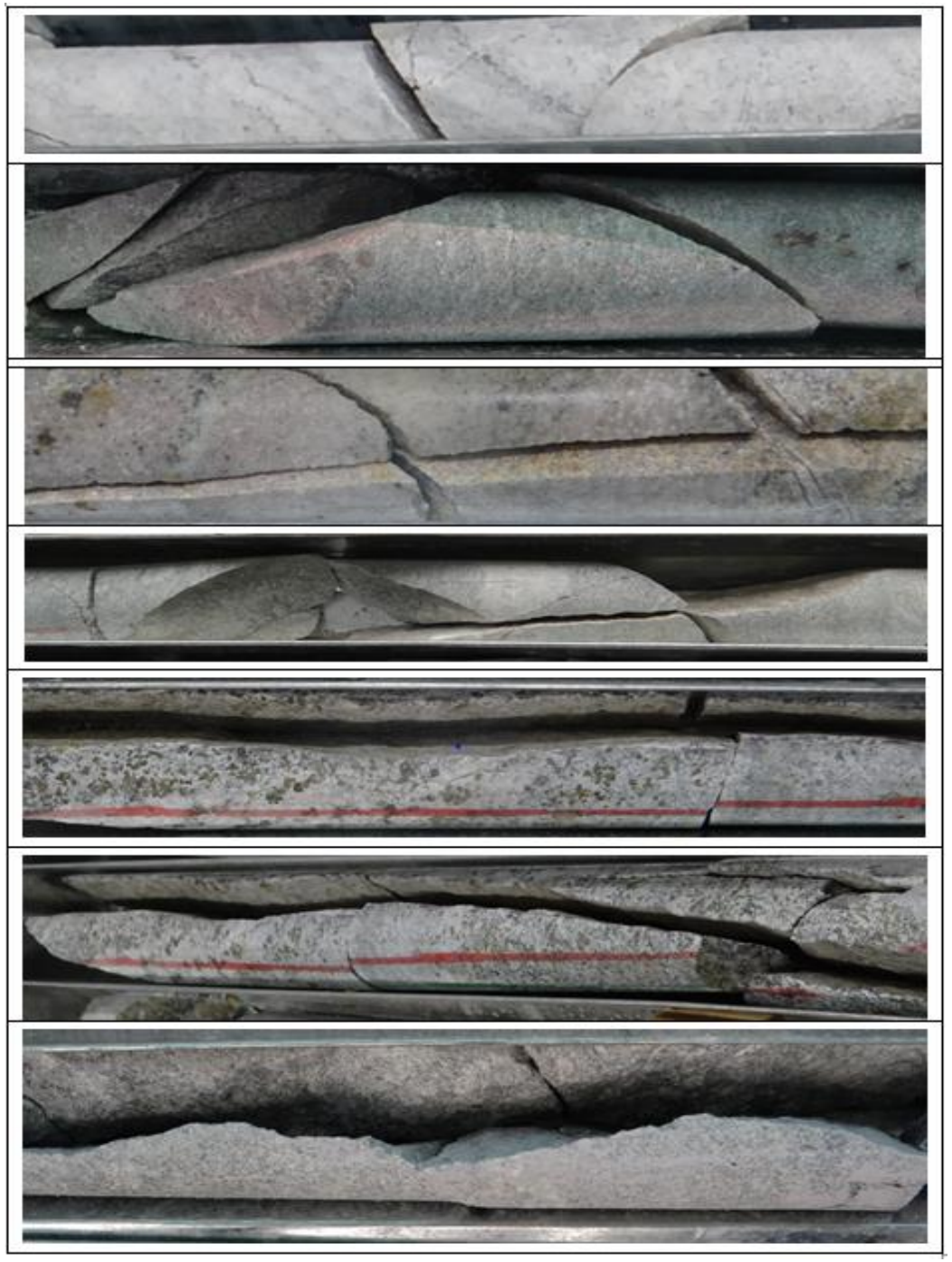
2, 3. THE DUAL ROLES OF Jn (number of sets) and Jr (roughness)







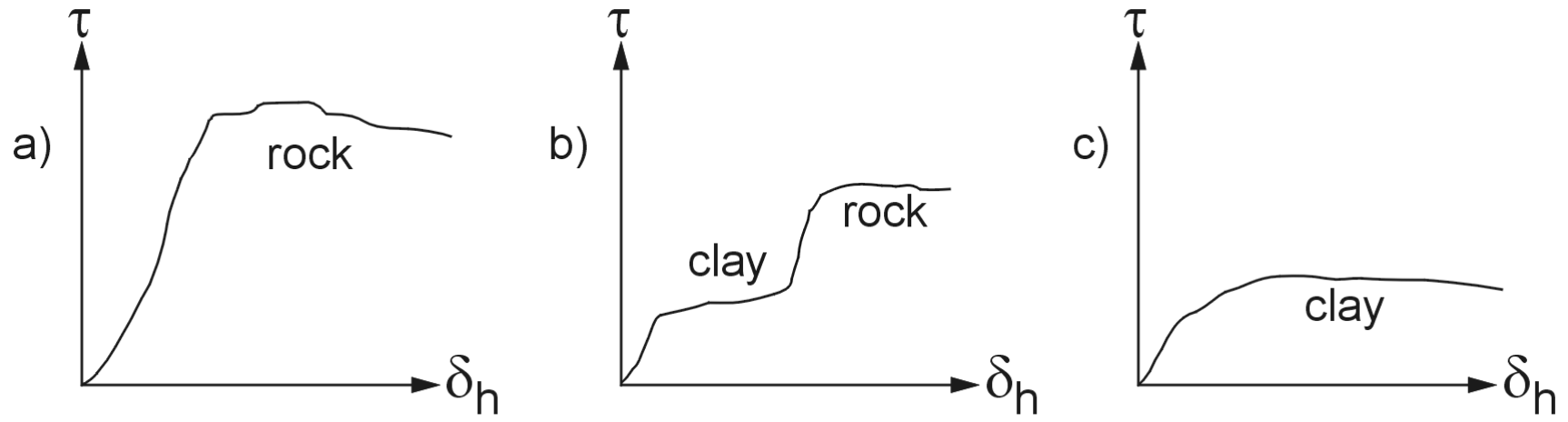
4/2, 6/2, 9/2, 9/3, 12/3, 15/3…….6/1, 9/1.5, 12/2, 15/2 (Jn/Jr ≥ 6)



3. Photos of core with the following approximate Jr values:

Jr = 1.0
Jr = 1.5
Jr = 1.5
Jr = 2.0
Jr = 2.5
Jr = 3.5

Jr determines dilation angles, stability – or over-break, even failure.



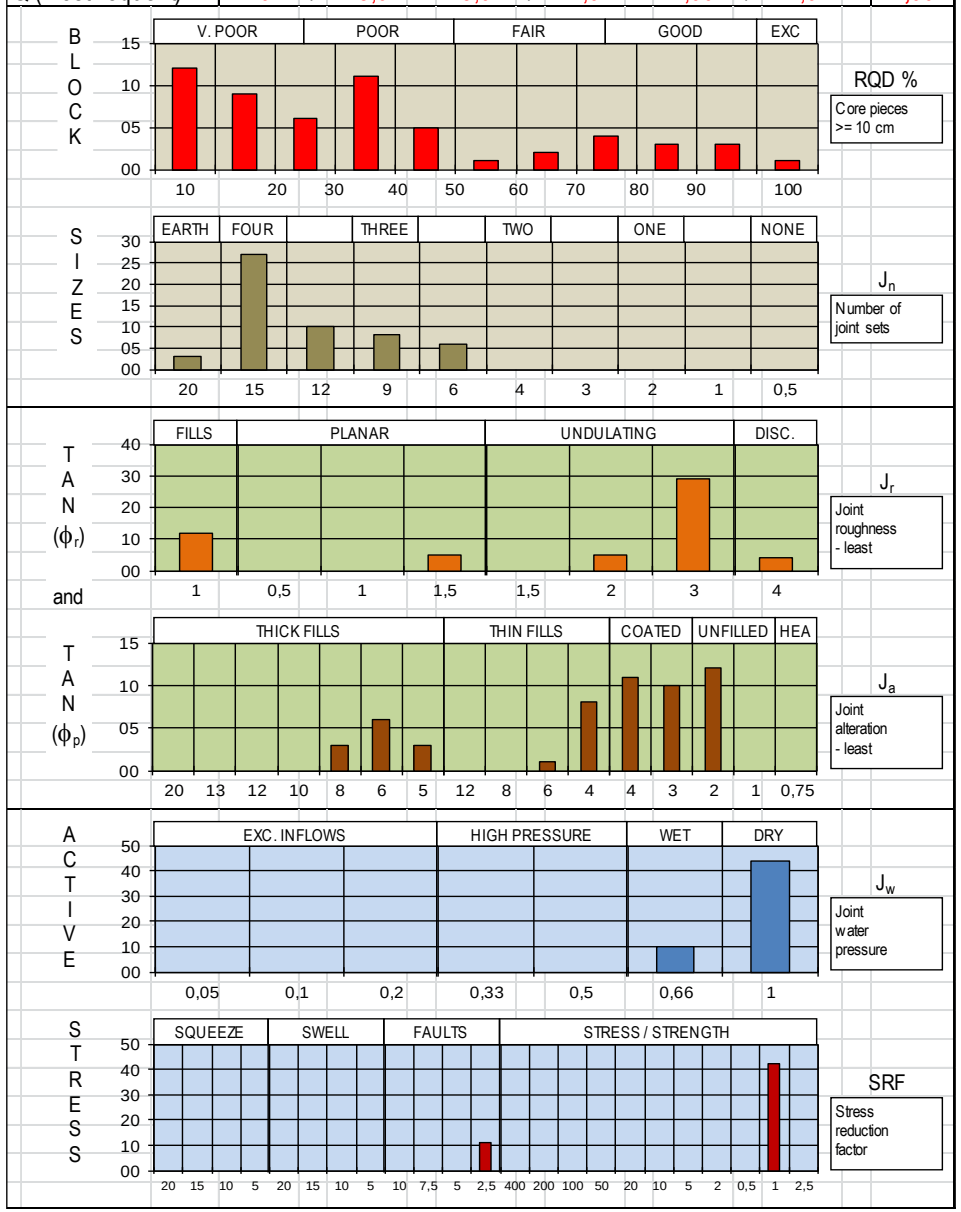
(a) Rock wall contact

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

Ja - clay

3, 4. Jr/Ja *(for least favourable joints)* is like a 'friction coefficient',
$\tan^{-1}$ (Jr/Ja) is like a friction angle.

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**



Q IS ONLY PART OF A ROCK MASS DESCRIPTION EXERCISE.

BUT Q MUCH BETTER THAN RMR, MUCH, MUCH BETTER THAN GSI.

I ROCK MASS STRUCTURE

1	RQD	Deere et al., 1967)	block size	Q
2	J_n	= joint set number		Q
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)		

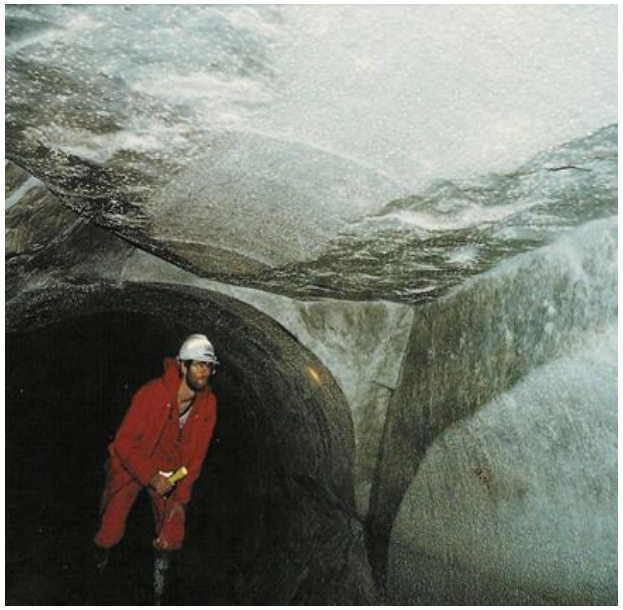
II JOINT CHARACTER

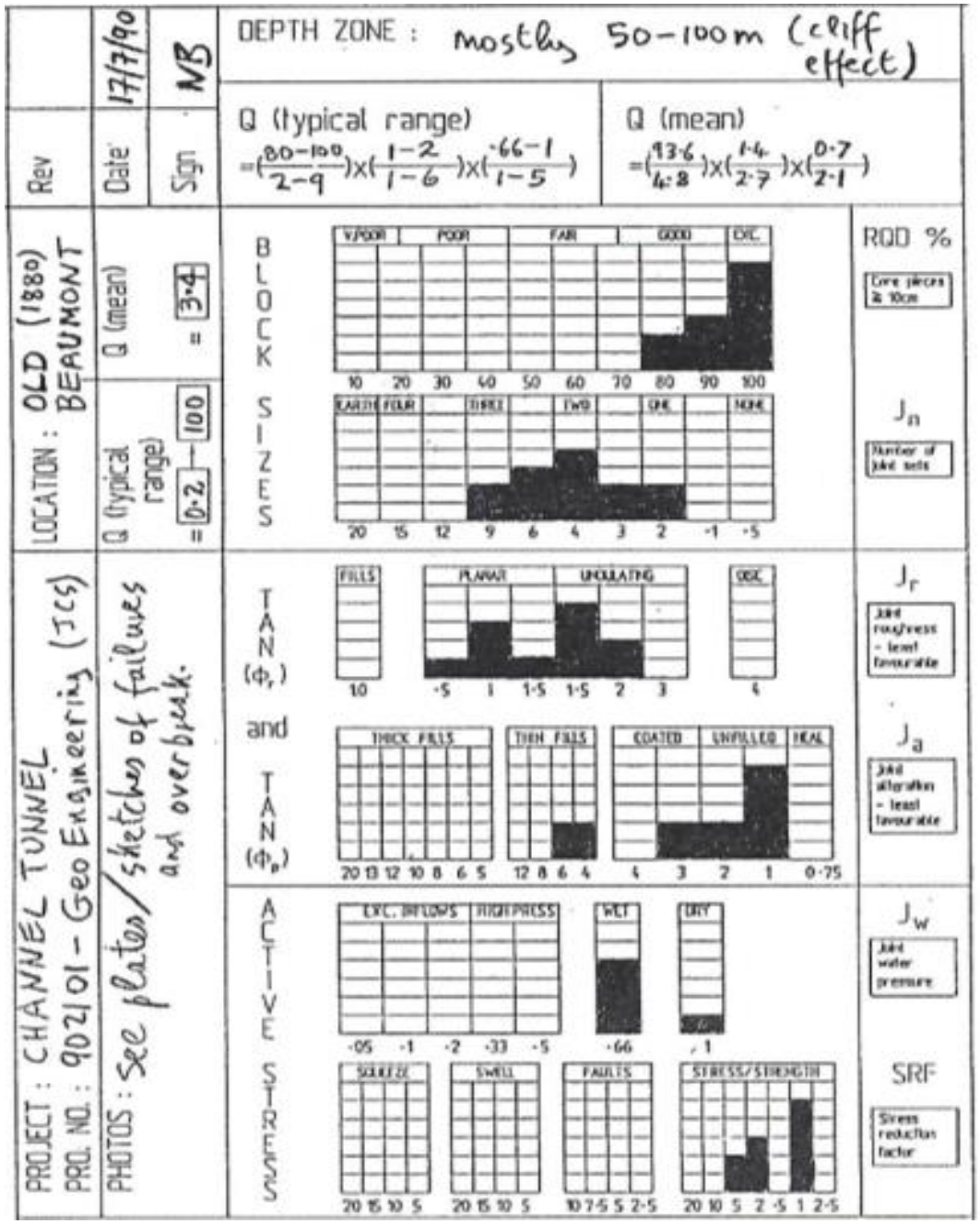
9	J_r	= joint roughness number	shear strength	Q
10	J_a	= joint alteration number		Q
11	JRC	= joint roughness coefficient		
12	a/L	= roughness amplitude of asperities per unit length (mm/m)		
13	JCS	= joint wall compressive strength		
14	ϕ_r	= residual friction angle		
15	r,R	= Schmidt rebound values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

III WATER, STRESS, STRENGTH

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

Q with low UCS?? THE WEAK CHALK MARL OF THE UK CHANNEL TUNNEL *WAS JOINTED* AND THEREFORE Q-LOGGED (BY TML, later by NB). (When Jn = 9, **Jw 0.66, problems with salt H_2O)**

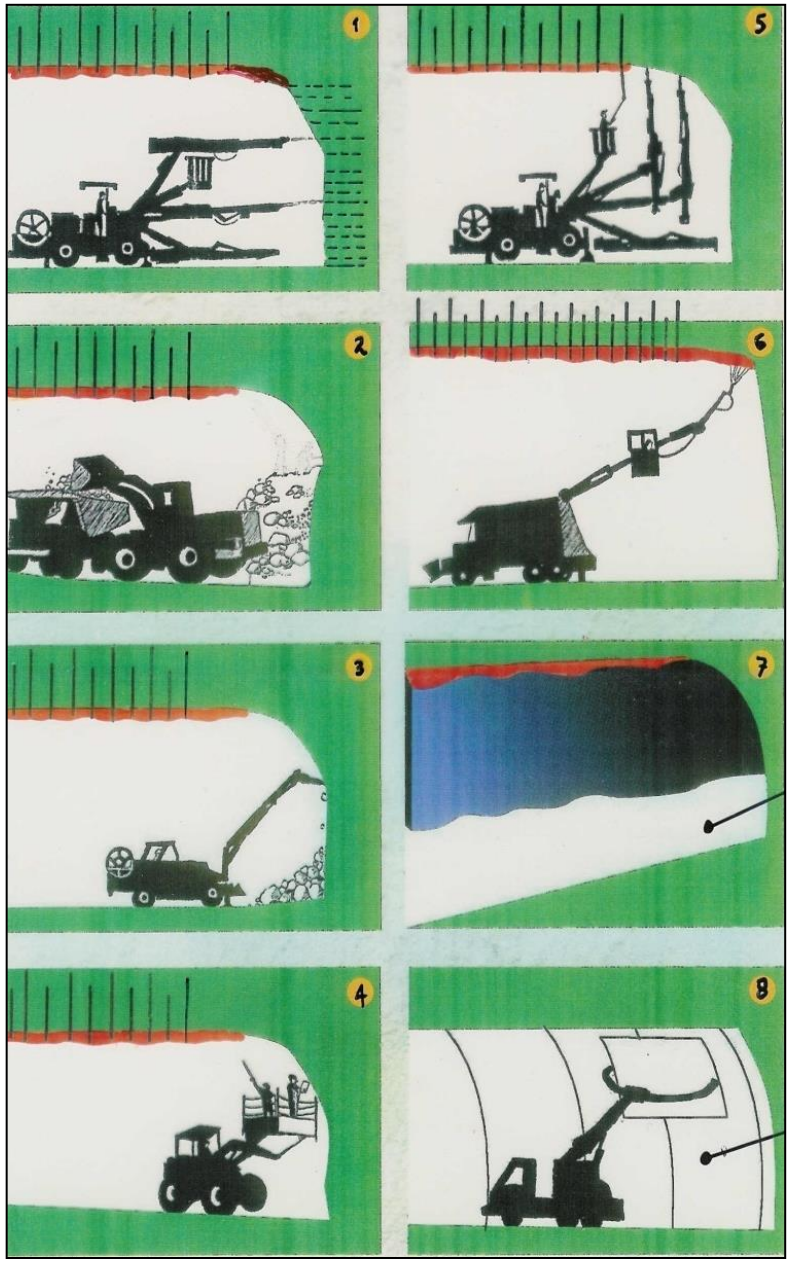


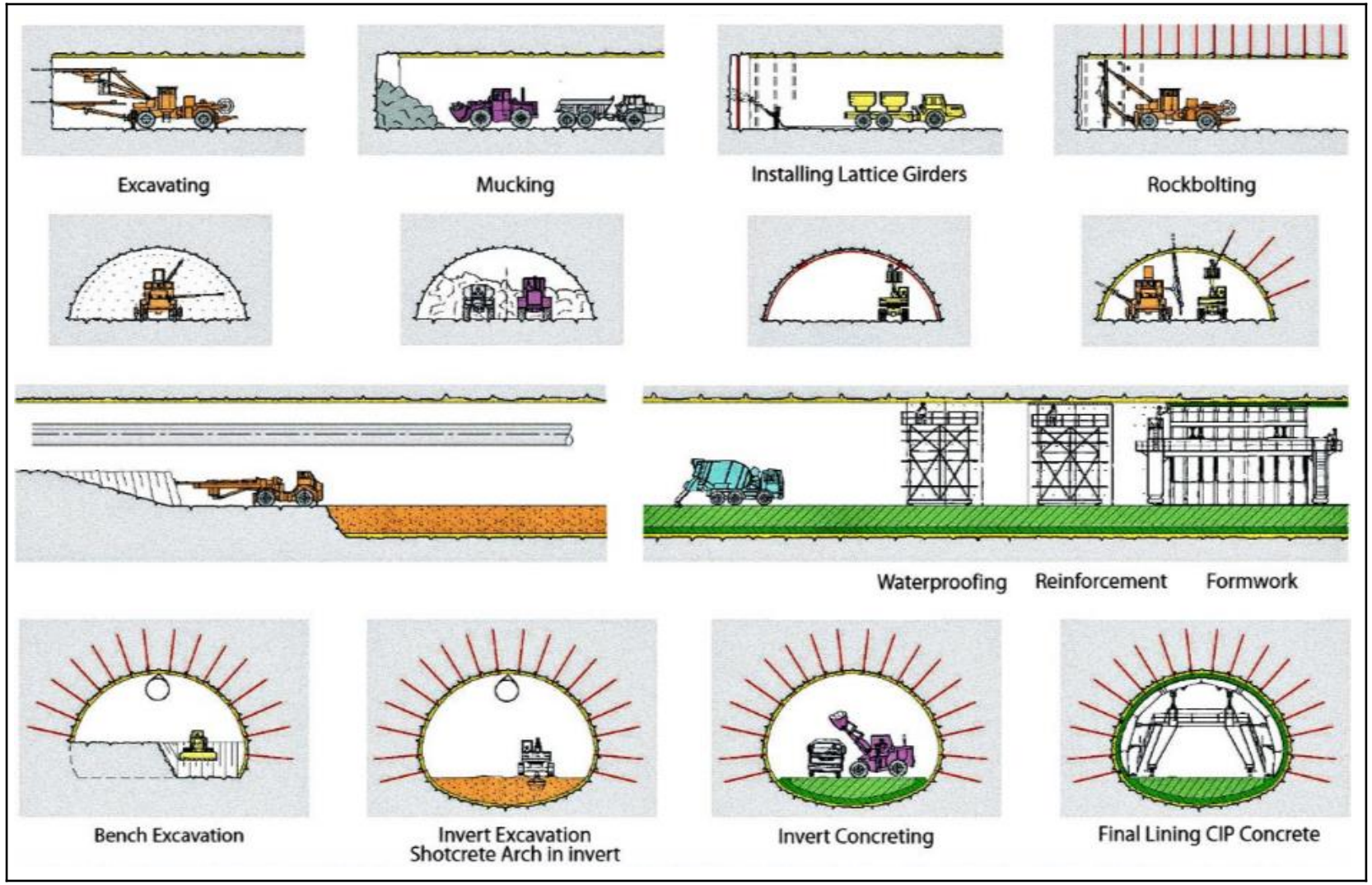


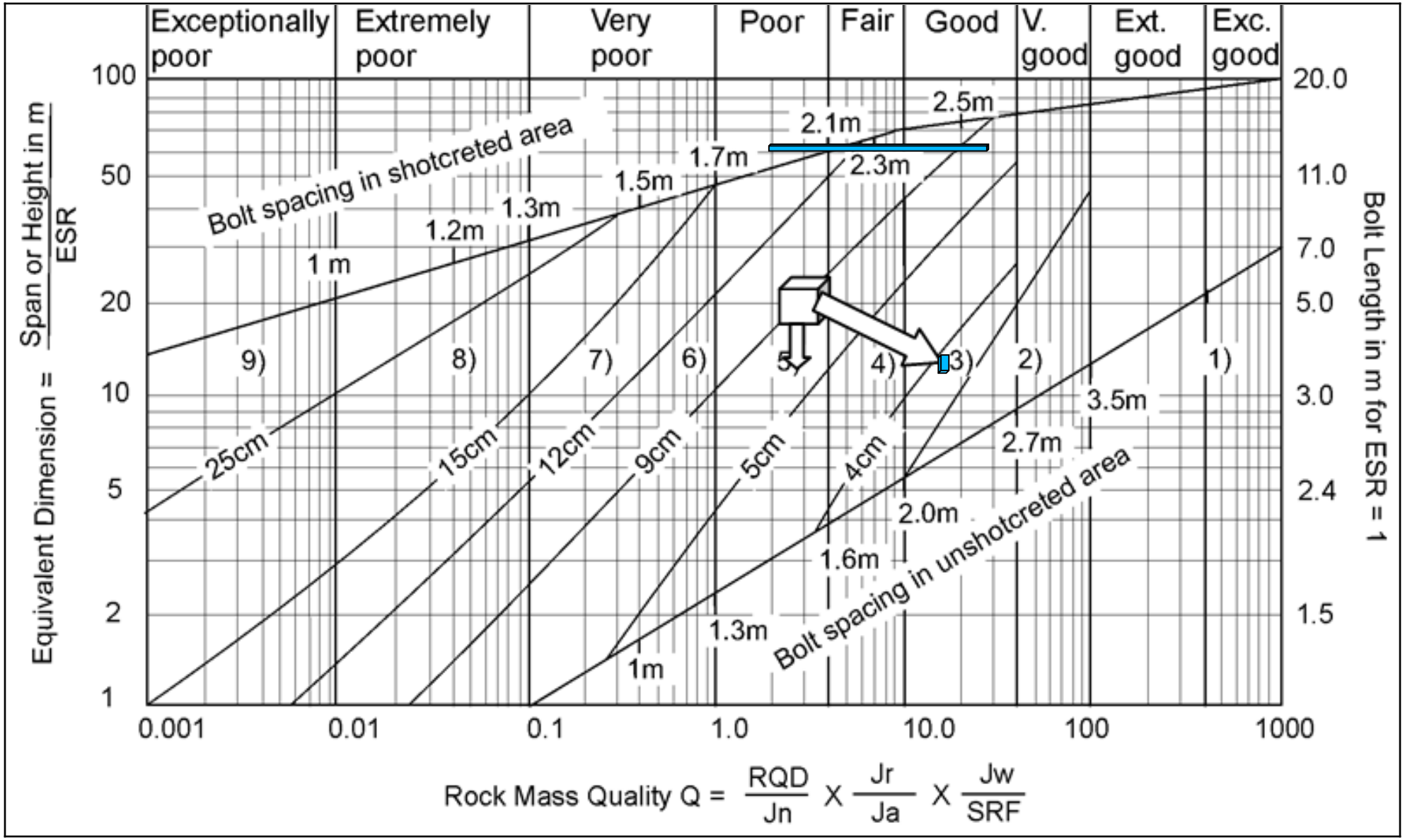
SUPPORT METHODS FOR TUNNELS

- NMT – empirical, monitoring only with large spans
- NATM – semi-empirical, needs careful monitoring

Left: *NMT* in a nut-shell (NMT 1994 brochure)
Right: *NATM* in a nut-shell (AGS, 2010)





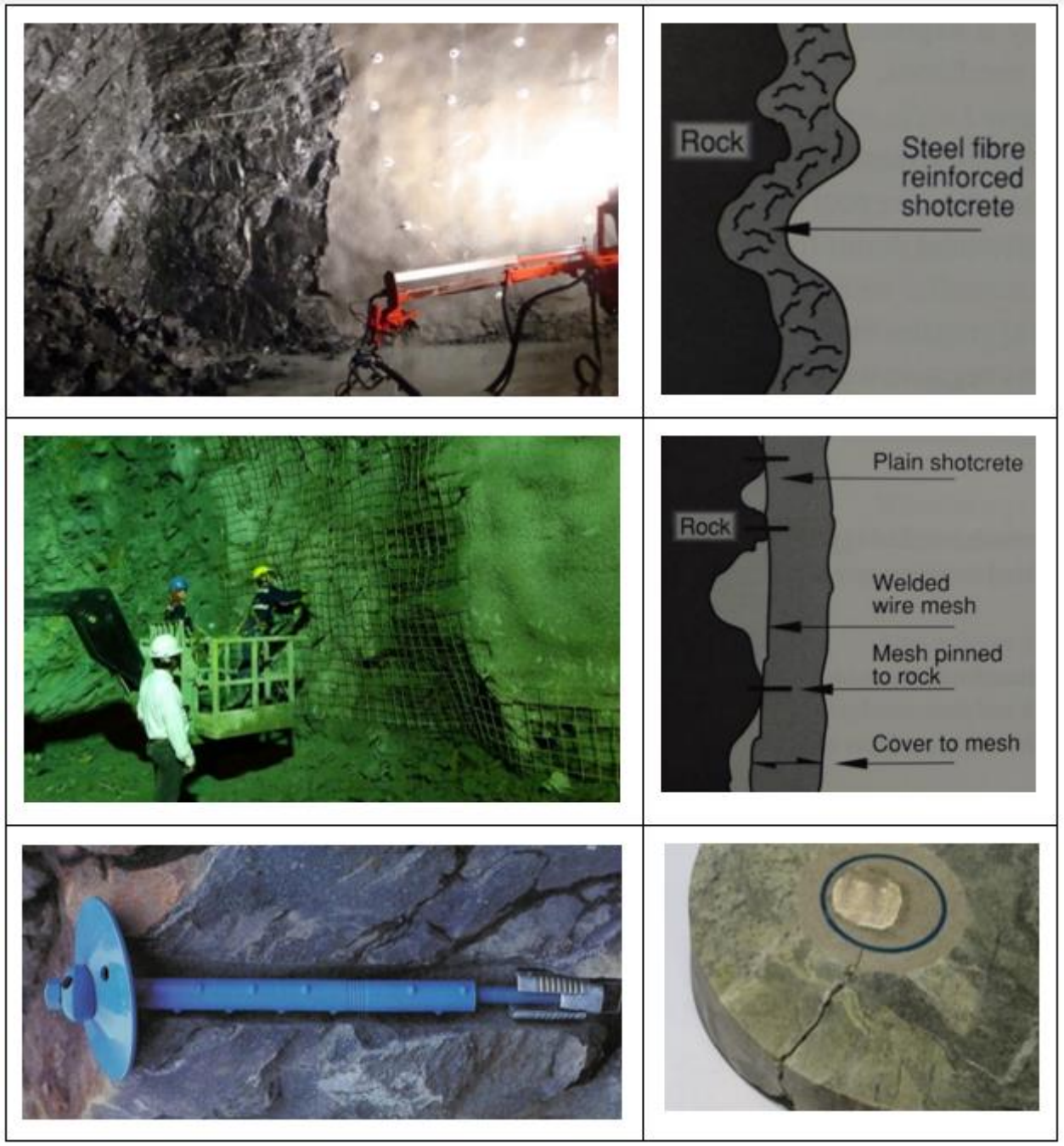


CO_2 FRIENDLY B + S(fr)

CAN USE Q FOR TEMPORARY SUPPORT SELECTION….IF NATM IS PLANNED

(5Q + 1.5 x ESR)

(Grimstad and Barton, 1993)



B + S(fr)

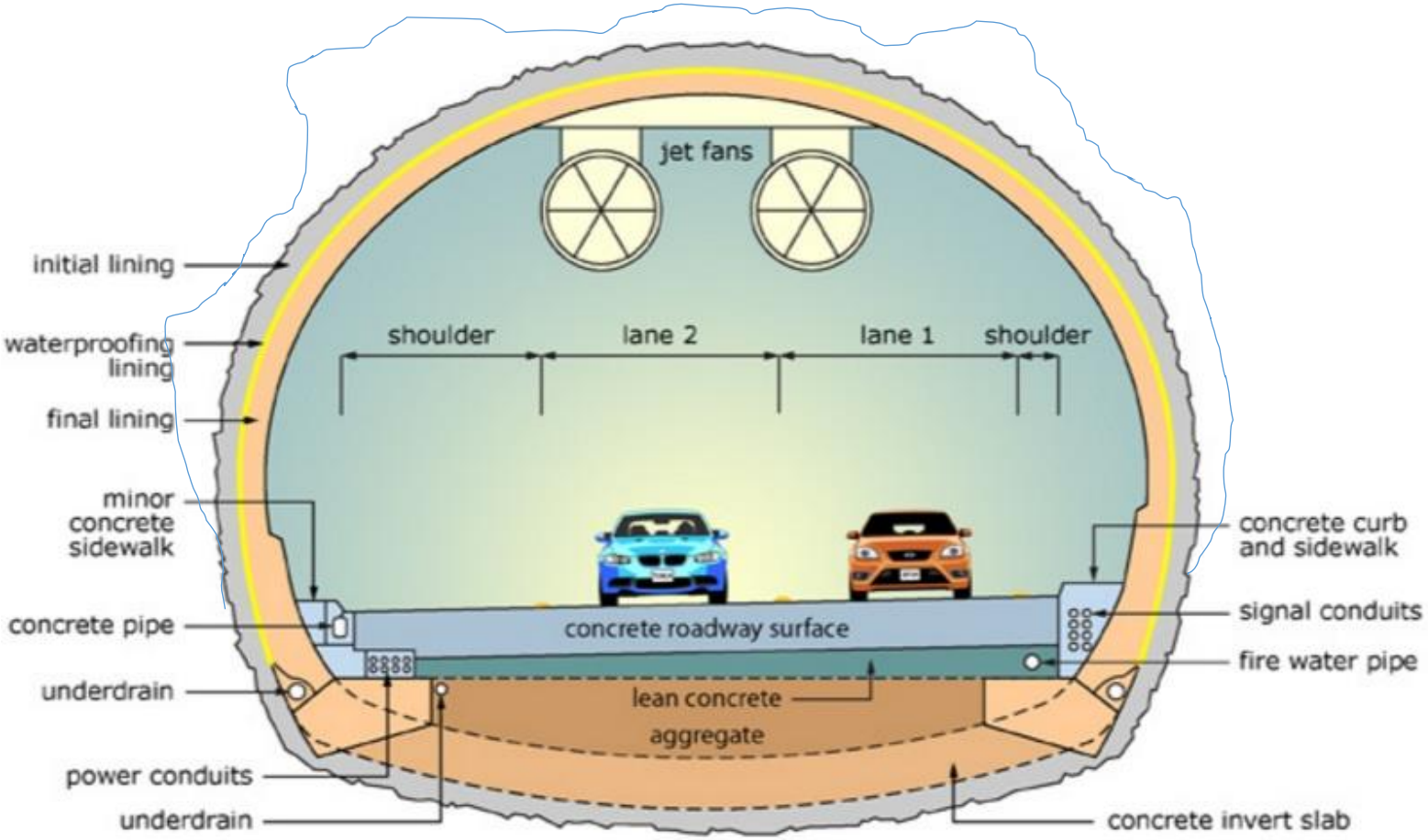
.....is preferred to

B + S(mr)

CT-bolts (4 x corrosion protection)

(Drawings from Vandevall, 1991)

Over-break ignored in drawings, stability, volumes?

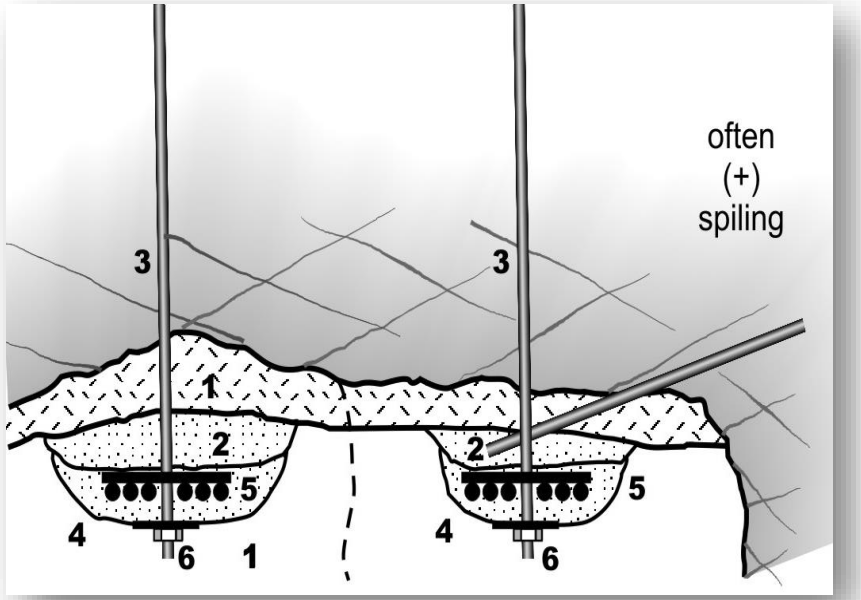


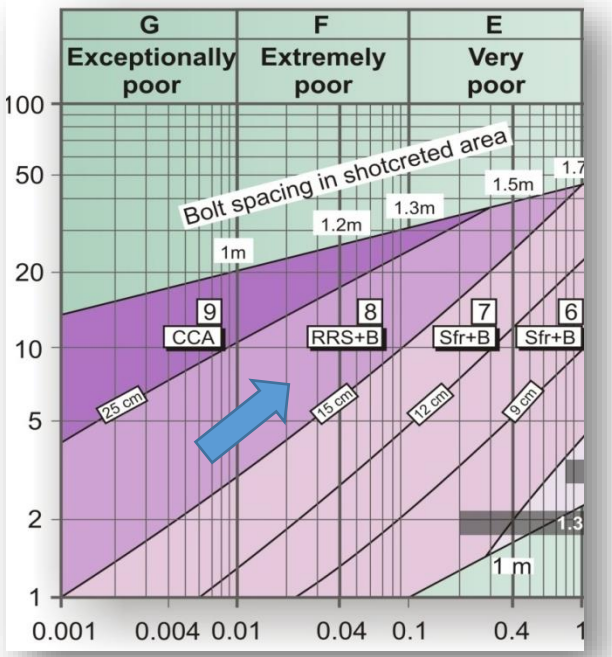
A Botniabanen tunnel, Sweden.

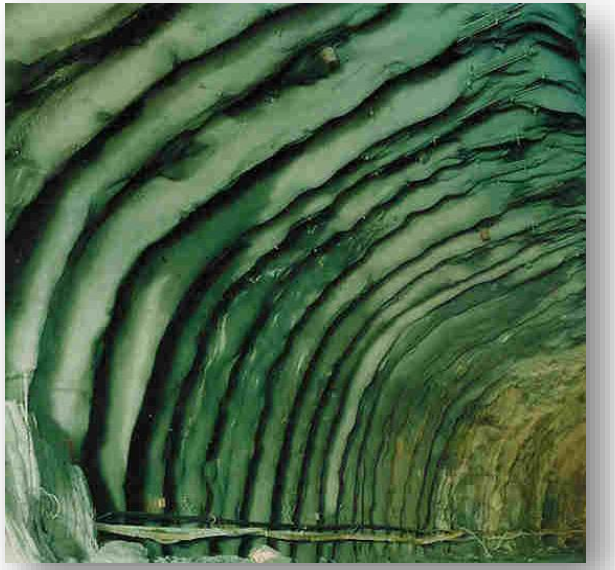
Over-break not an issue. B+Sfr solves it: IMPROVED economy.

May need pre-injection.

Empirical design for this too.

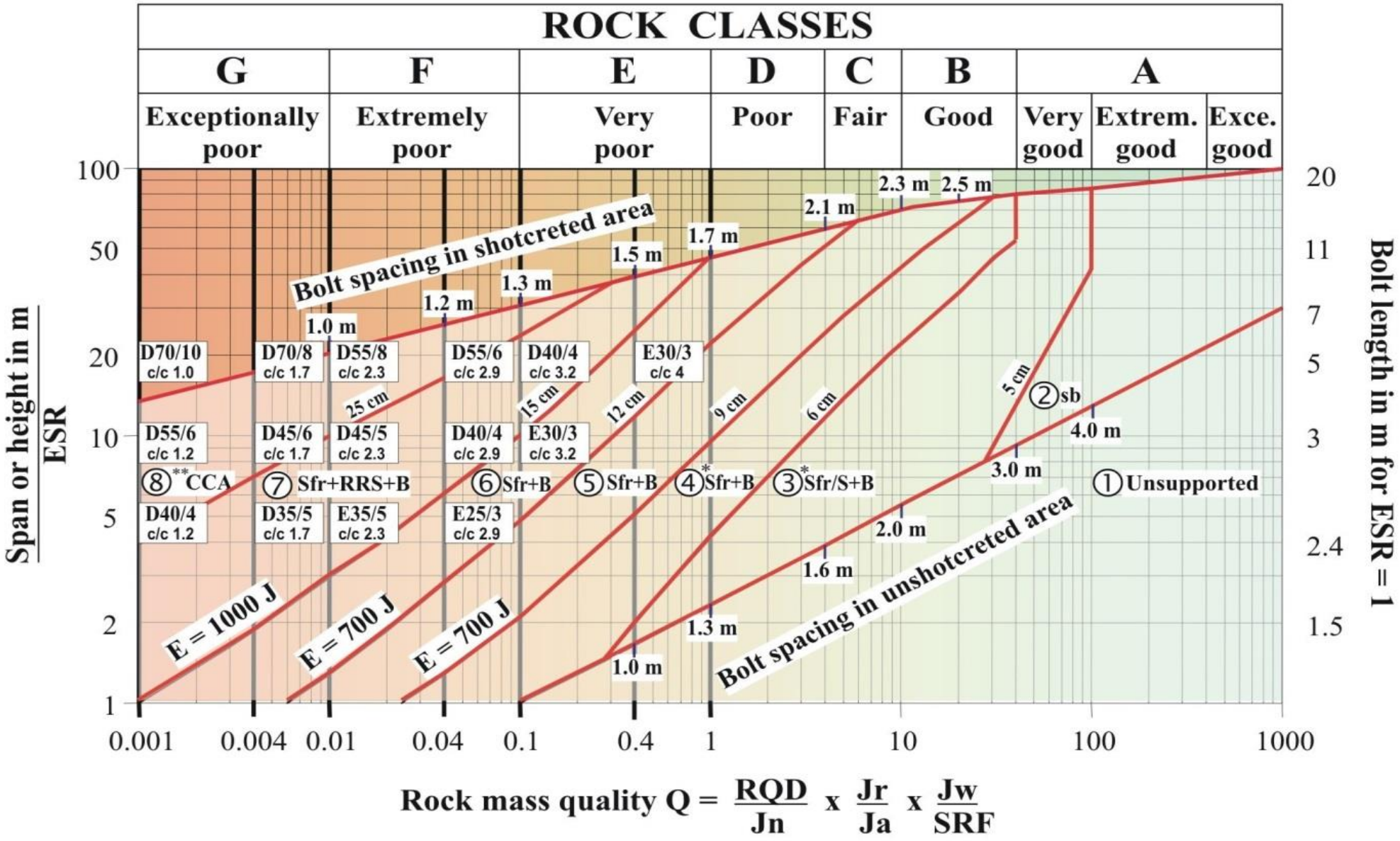






RRS is a flexible (until bolted) 'lattice' girder used in NMT.

3D effect because of S(fr) arches.

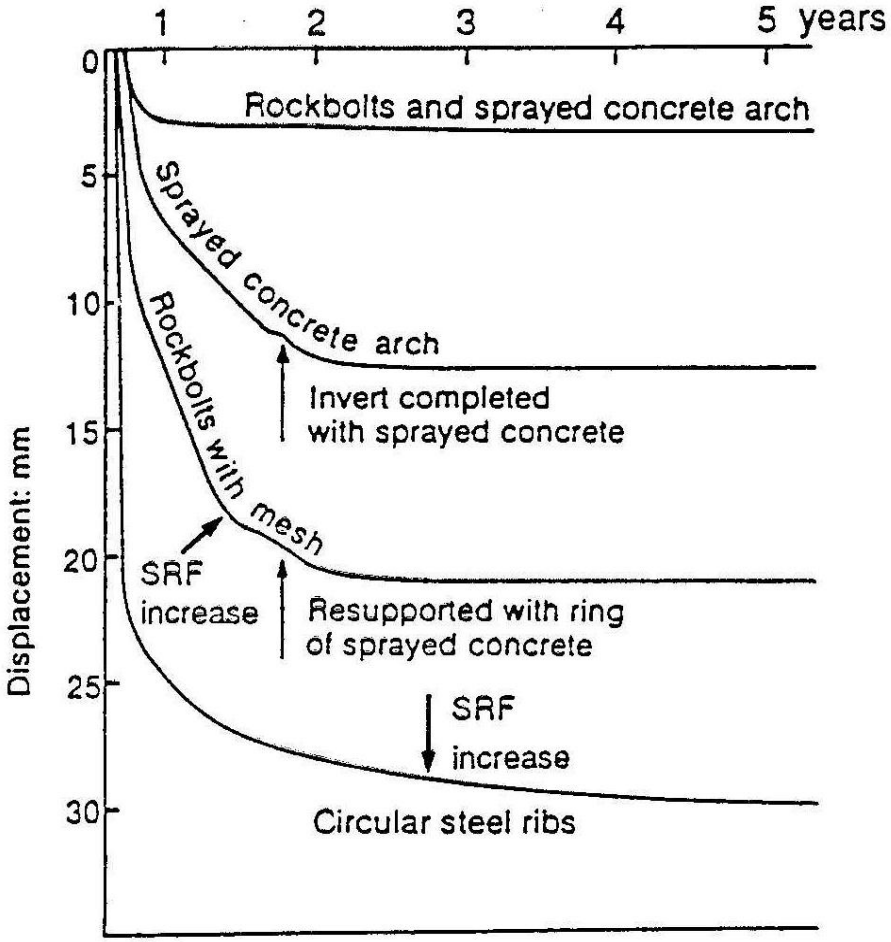


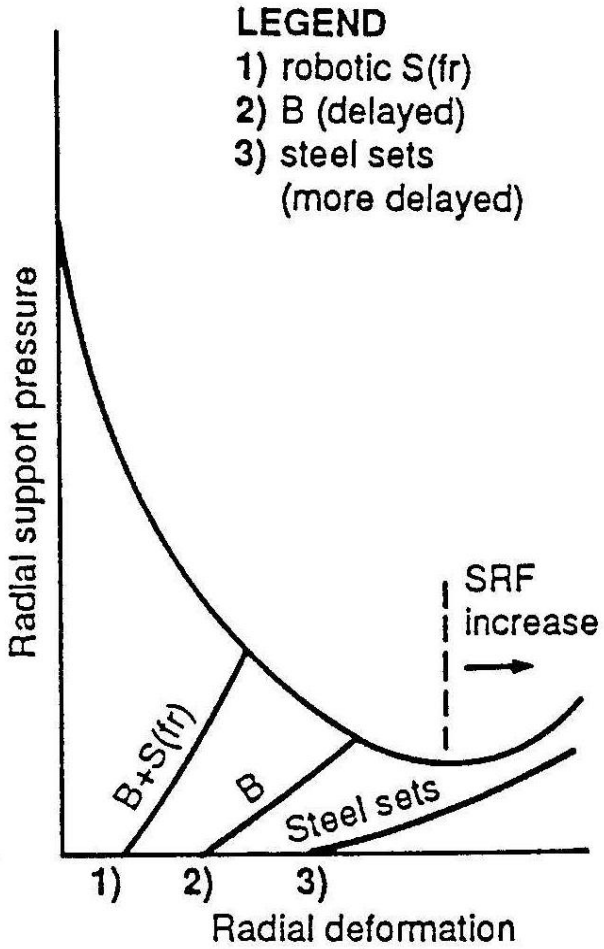
Grimstad et al. 2002

RRS details

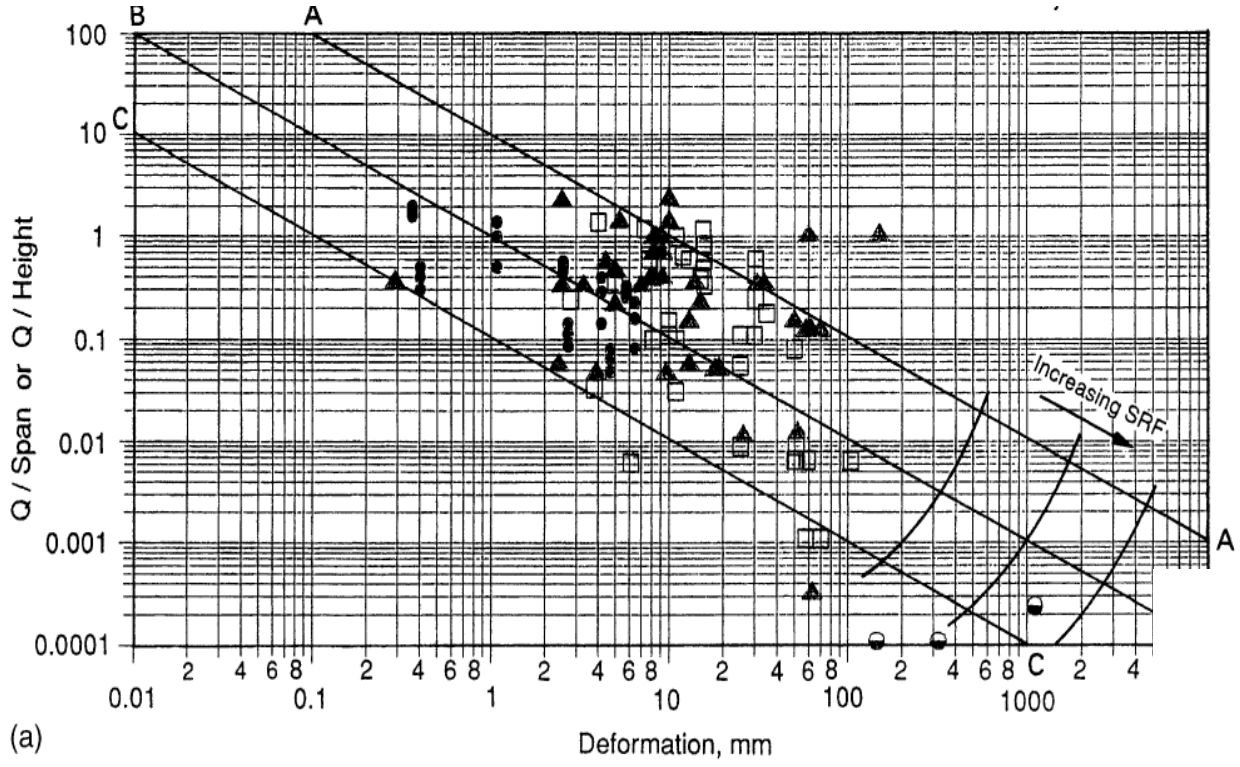
STEEL ARCHES or LATTICE GIRDERS

CONSEQUENCES OF LOOSENING ROCK – SRF ?





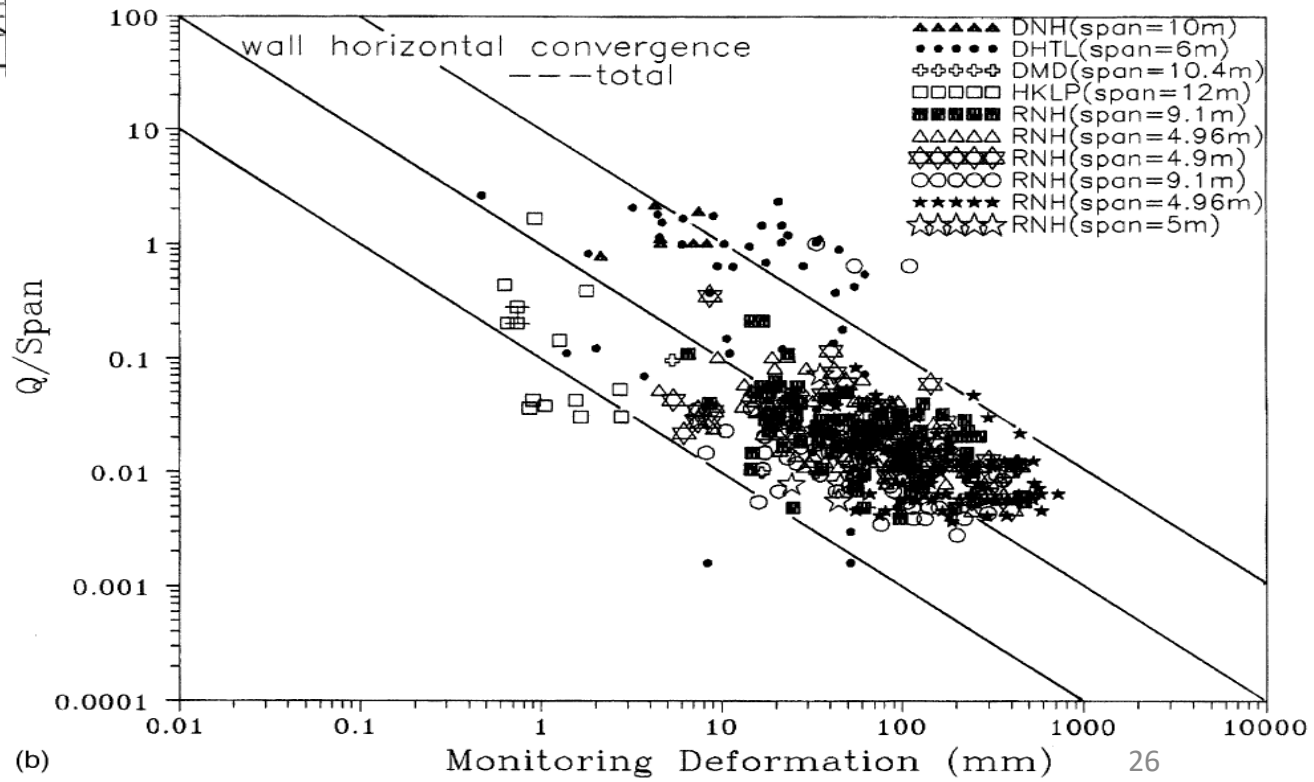
WARD ET AL. 1983: KEILDER TUNNEL, BARTON AND GRIMSTAD, 1994



Barton et al. 1994 and later priv. comm. from Taiwan (Chen and Guo, 1996).

CENTRAL TREND (hundreds of tunnel data):

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



$\Delta = \frac{SPAN}{Q}$	**Cavern X** **Δ = 22.5/20.5 ≈ 1 mm**	**Cavern Y** **Δ = 23/7 ≈ 3 mm**
$\Delta_v = \frac{SPAN}{100\,Q}\sqrt{\frac{\sigma_v}{\sigma_c}}$	Δ_v = (22500/(100 x20.5) x √(1.25/125) = 22500/(2050 x 10) **≈ 1 mm**	Δ_v = (23000/100 x7) x √(1.5/150) = 23000/(700 x 10) **≈ 3 mm**

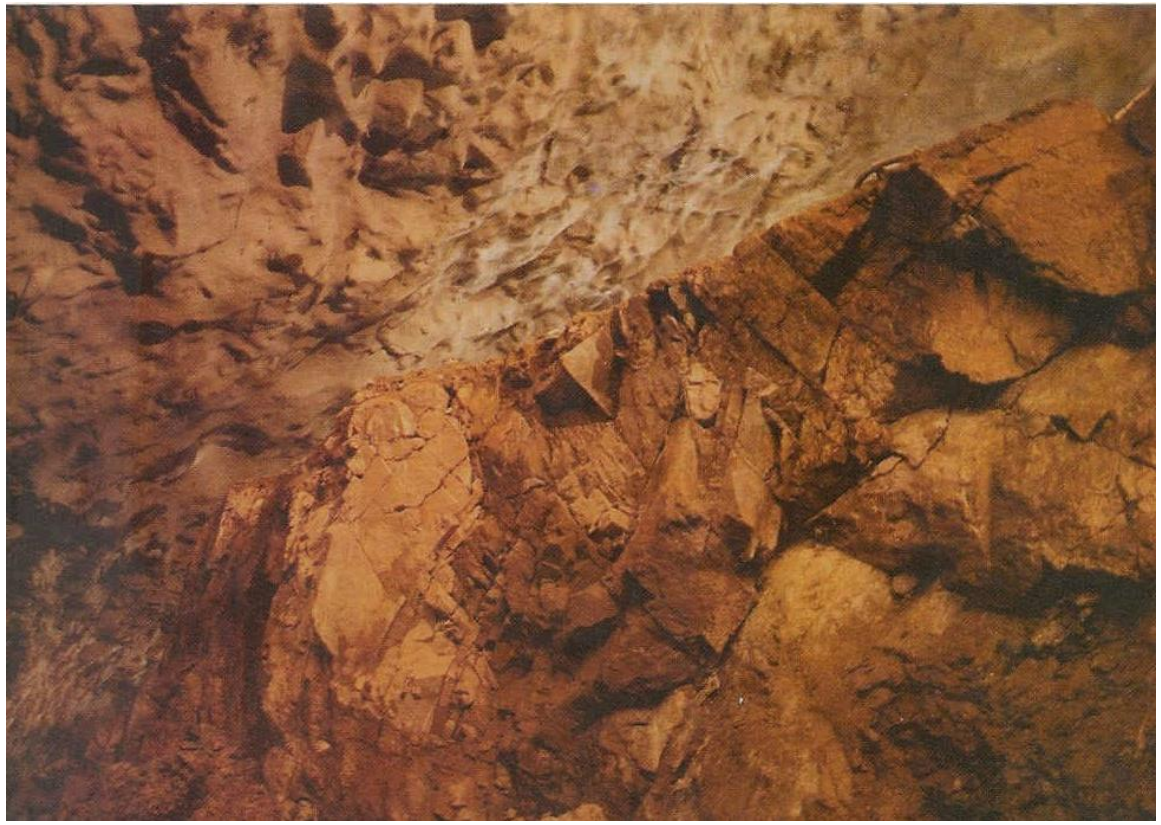
Gjøvik Olympic Cavern

B= 62m, H= 25m, L=90m

(RQD = 60 – 90)

(Q = 1-30)

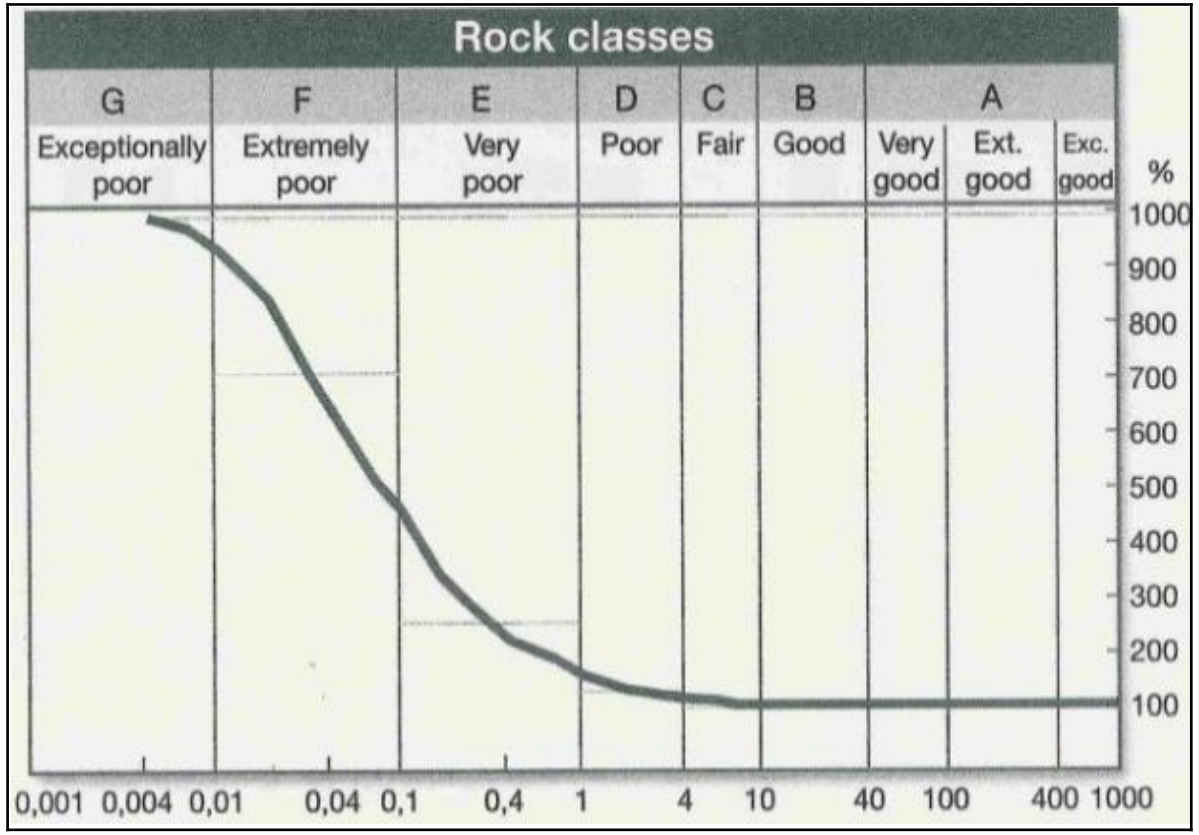
V_P = 3.5-*5.5* km/s

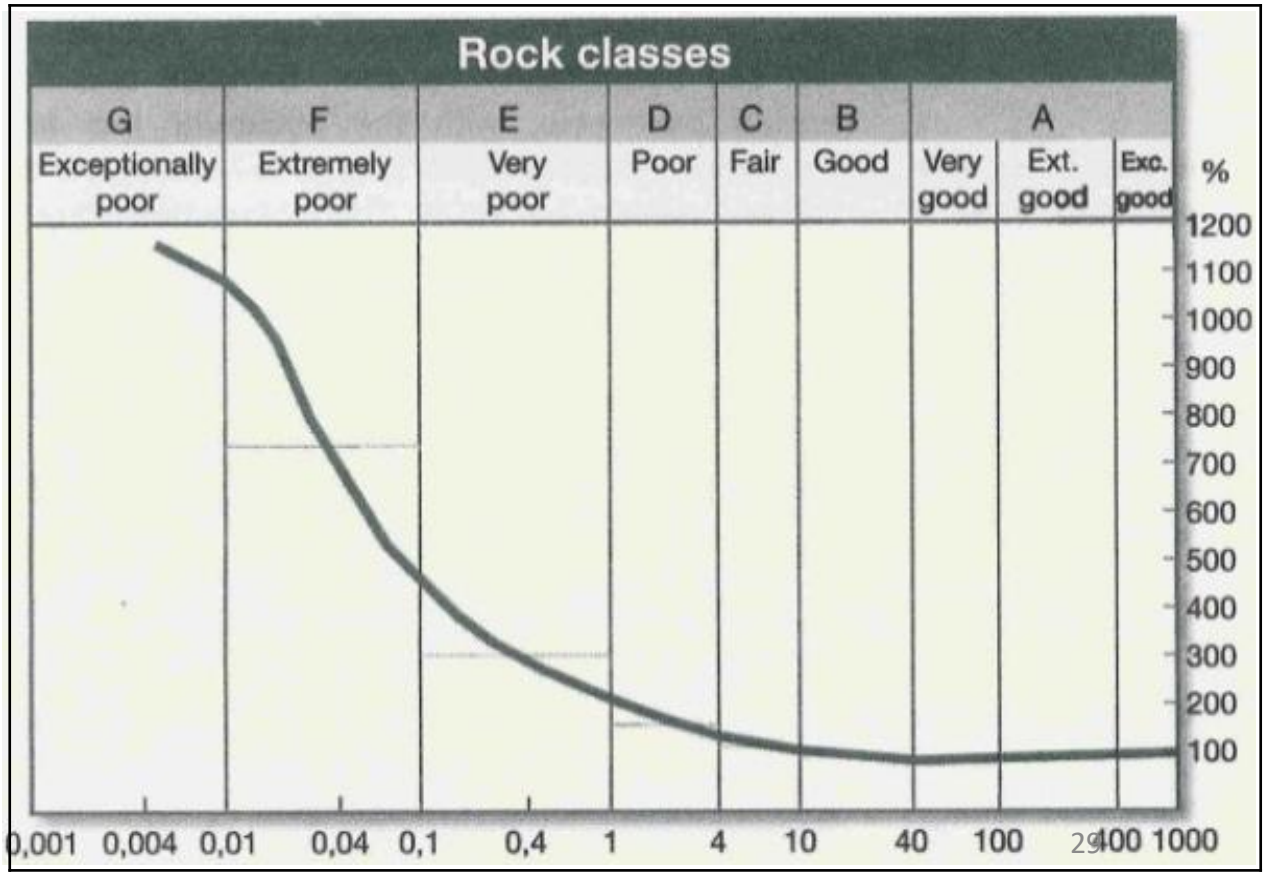


$$\Delta_v = \frac{60{,}000}{100 \times 10} \times (1/75)^{1/2} = 6.9 \text{ mm}$$

(Almost identical to that measured with nine MPBX, and almost identical to UDEC-BB modelling, i.e. 7 to 9 mm range in each case)

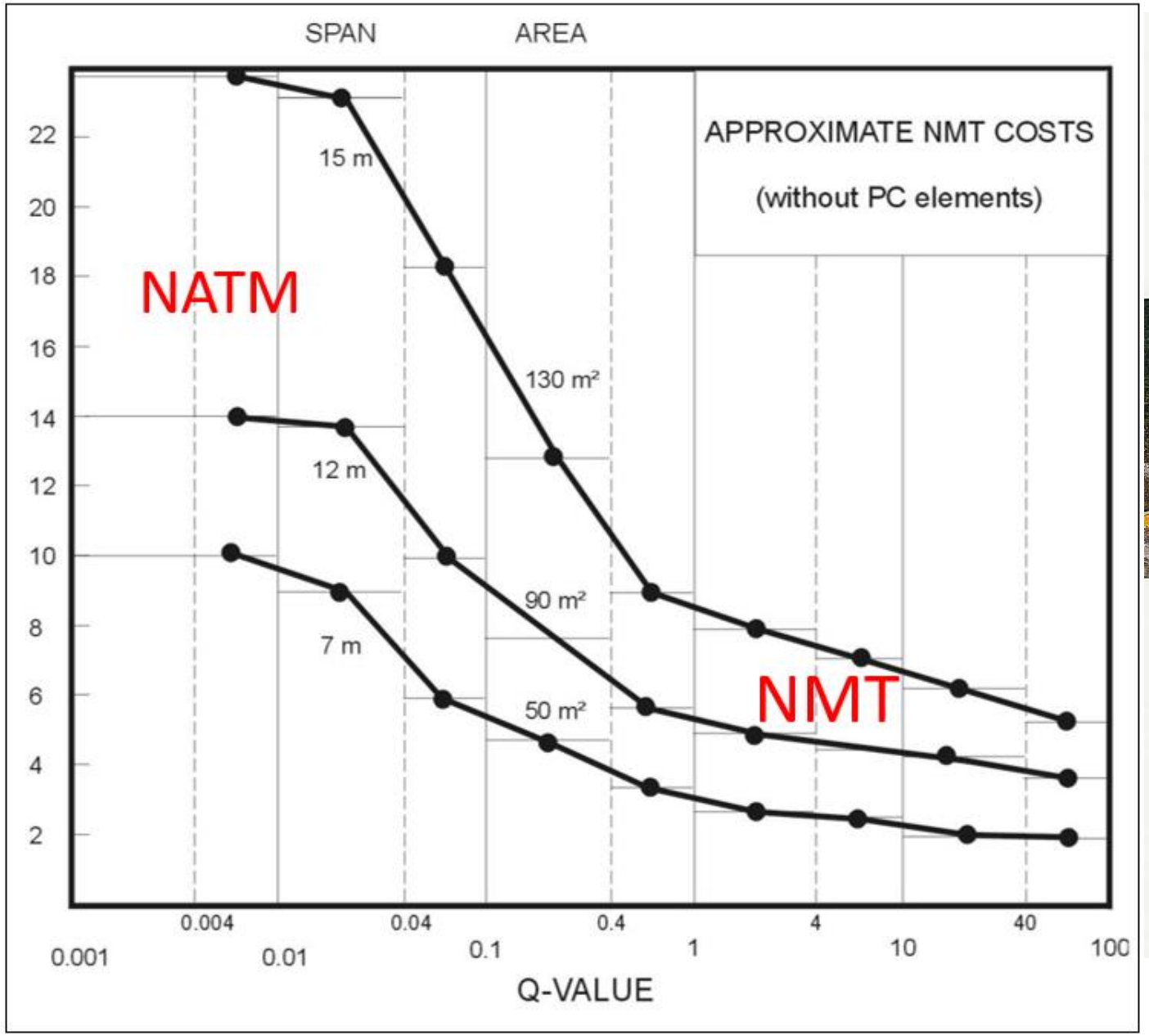
RELATIVE *TIME* AND *COST* IN RELATION TO Q-VALUE

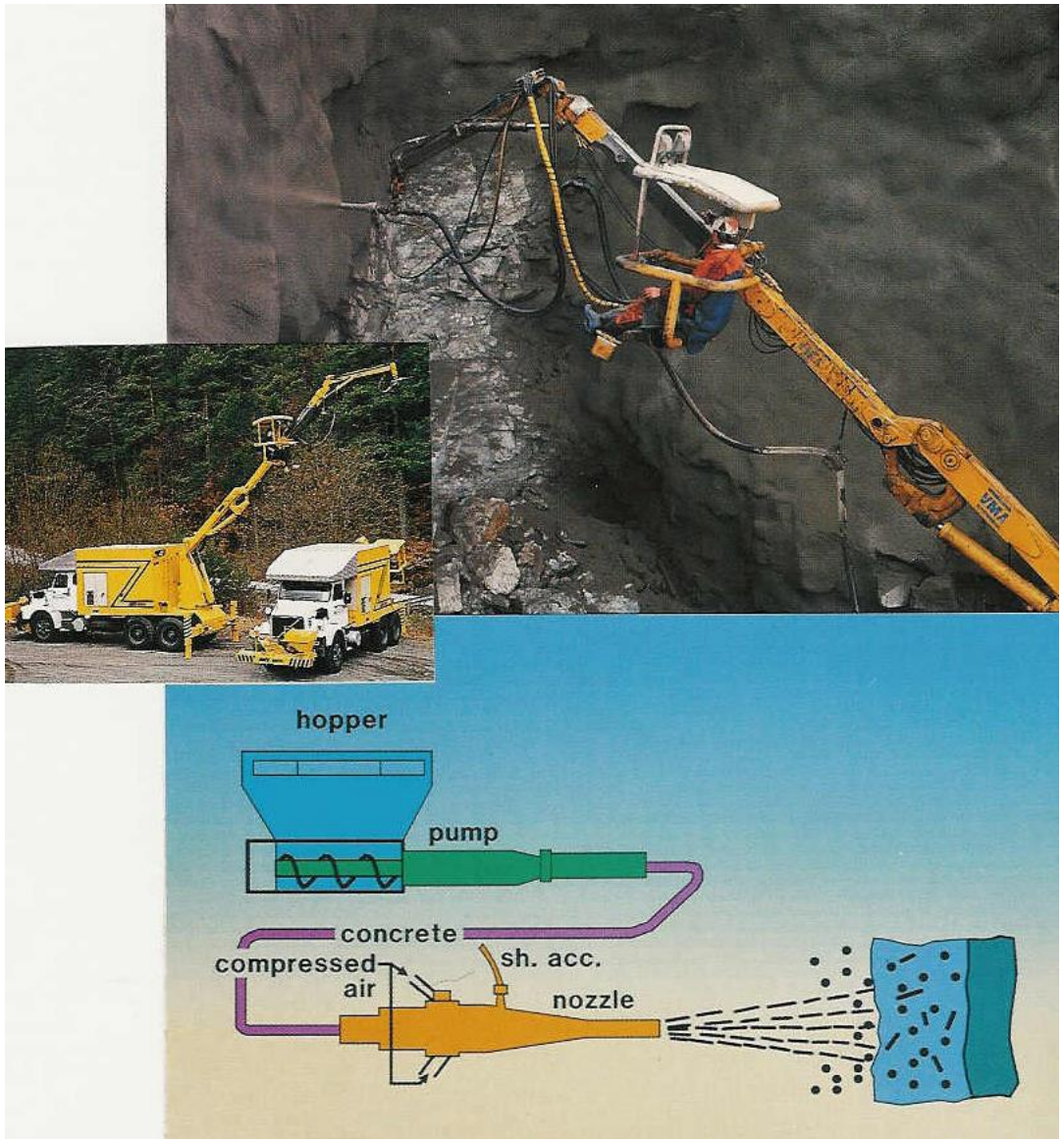




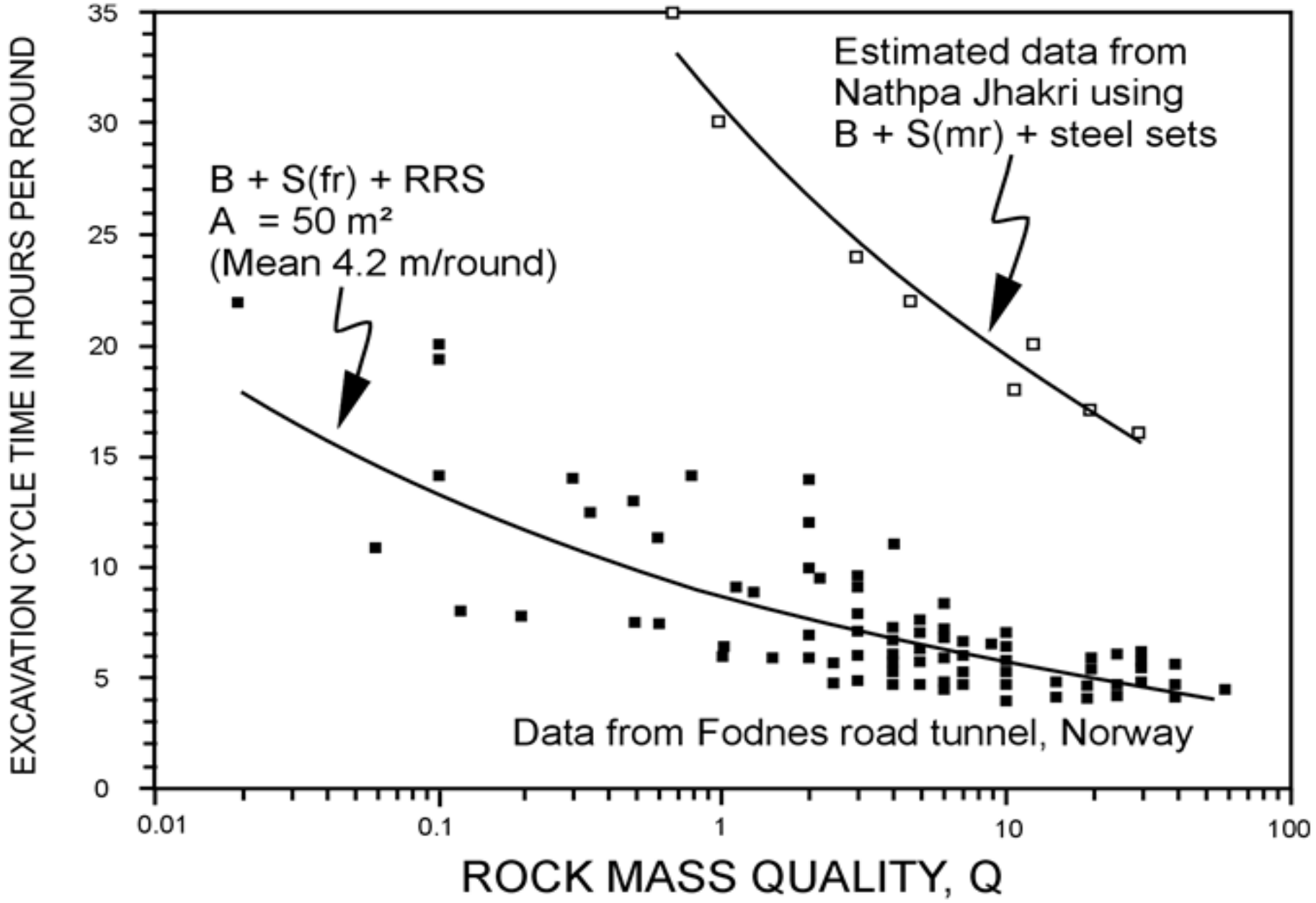
ACCORDING TO A SURVEY OF 50km OF TUNNELS CARRIED OUT BY ROALD, PUBLISHED AS:

Barton, Buen and *Roald,* 2001.





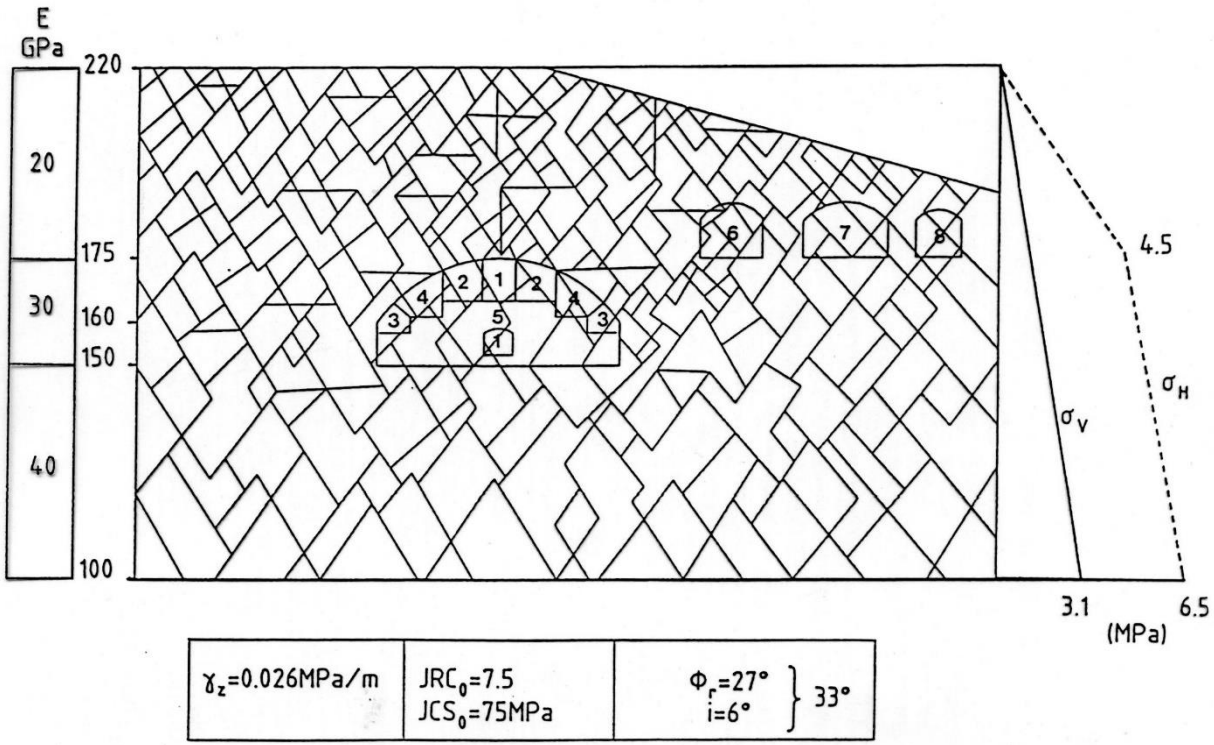
From 1994 NMT brochure



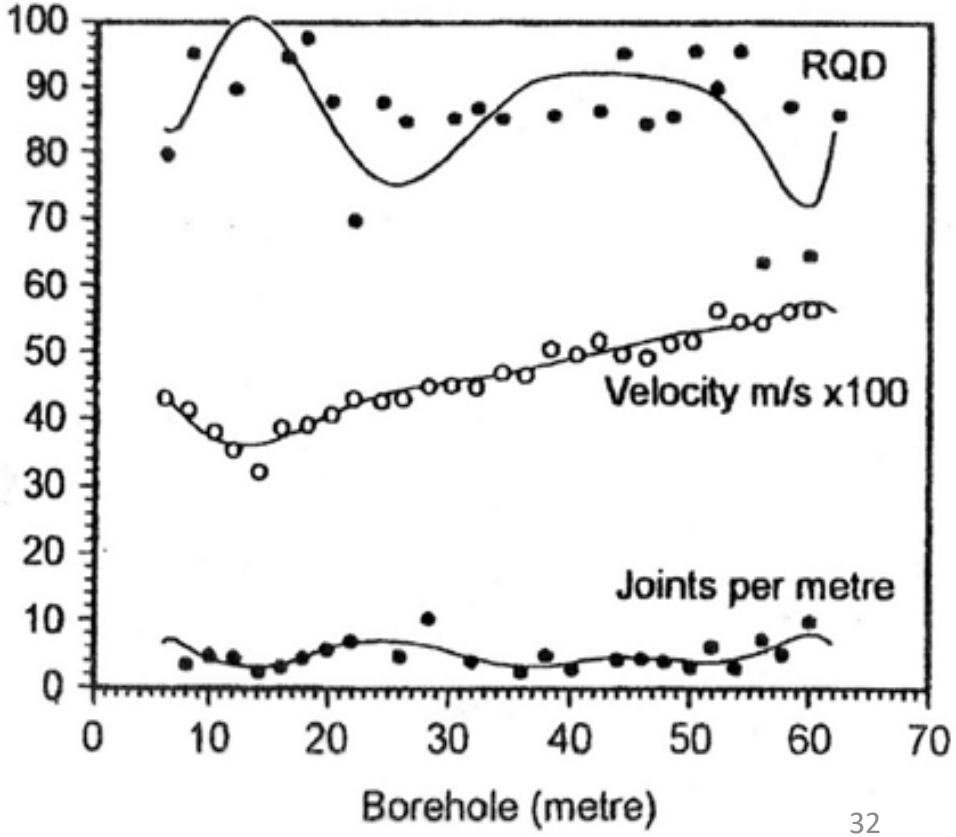
'cycle time' =

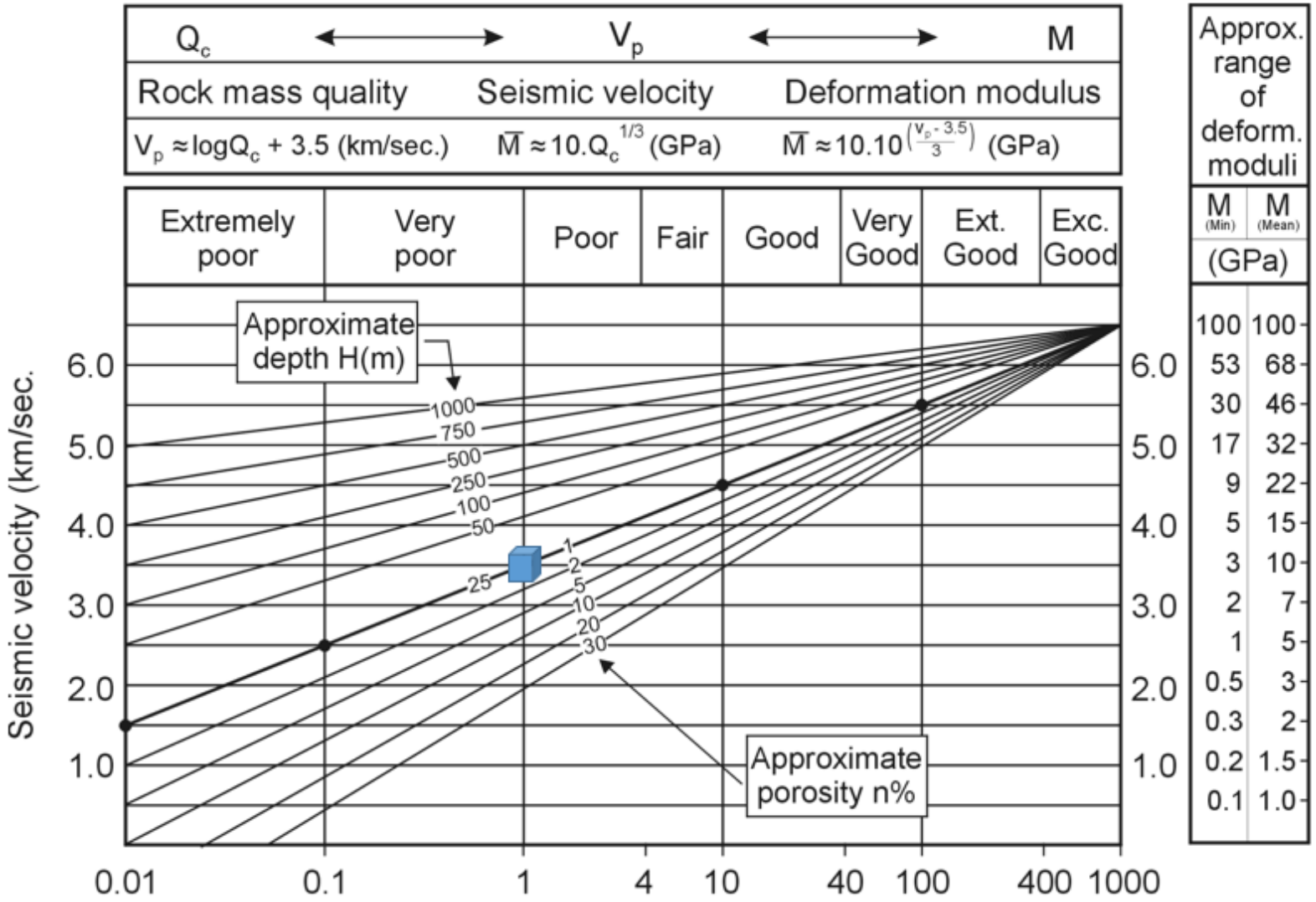
drilling blast holes, charging, blasting, waiting for gasses to clear, scaling, mucking, geologic and Q-logging, eventual B + S(fr).....

Grimstad, 1998 pers. comm.



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





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

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

(Q_c is the Q-value normalized by UCS/100)

$$E_{mass} \approx 10\, Q_c^{(Vp - 0.5)/3}\ \text{GPa}$$

$$E_{mass} \approx 10^{(Vp - 2.5 + \log \sigma c)/3}\ \text{GPa}$$

DEPTH-DEPENDENCE MUST NOT BE IGNORED!

FINALLY - CRITIQUE !

(OF SOME ‘MODERN’ TRENDS)

WHY ARE WE USING H-B EQUATIONS IN ROCK MECHANICS MODELLING? WHY CONTINUUM?

$$c' = \frac{\sigma_{ci}\left[(1+2a)s+(1-a)m_b\sigma'_{3n}\right]\left(s+m_b\sigma'_{3n}\right)^{a-1}}{(1+a)(2+a)\sqrt{1+\left(6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}\right)/(1+a)(2+a)}}$$

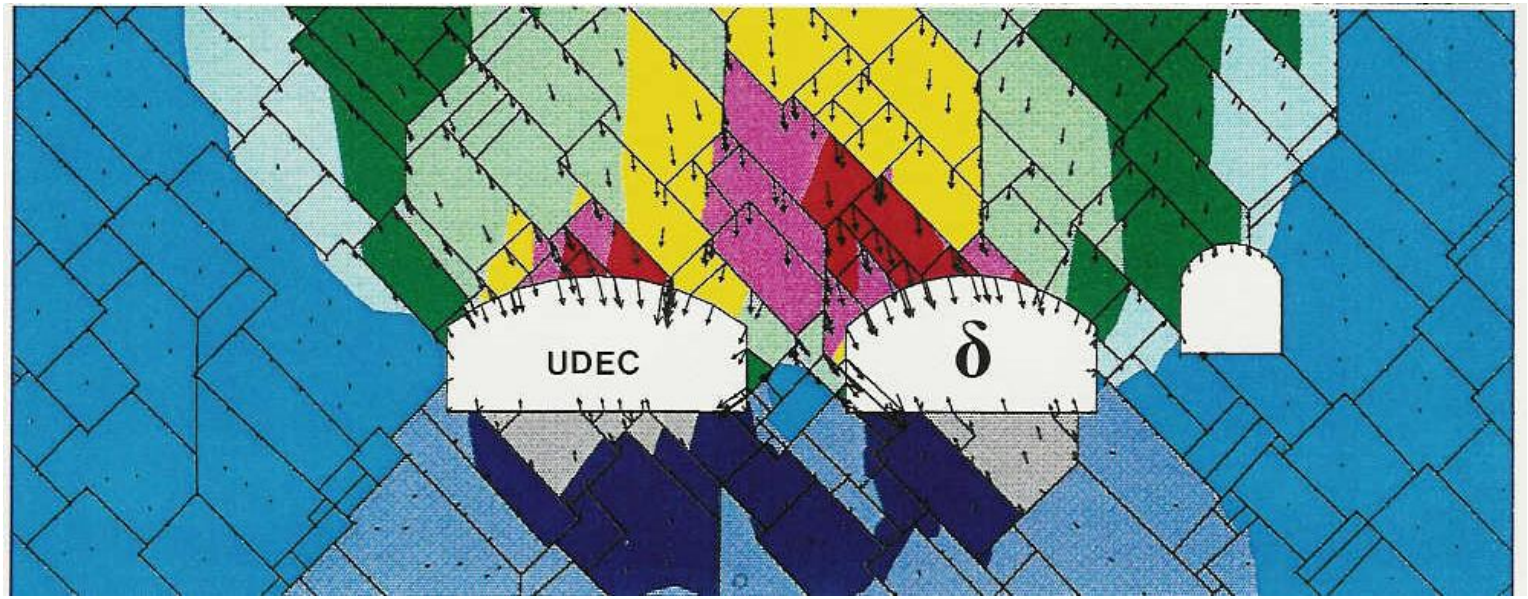
$$\phi' = \sin^{-1}\left[\frac{6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}{2(1+a)(2+a)+6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}\right]$$

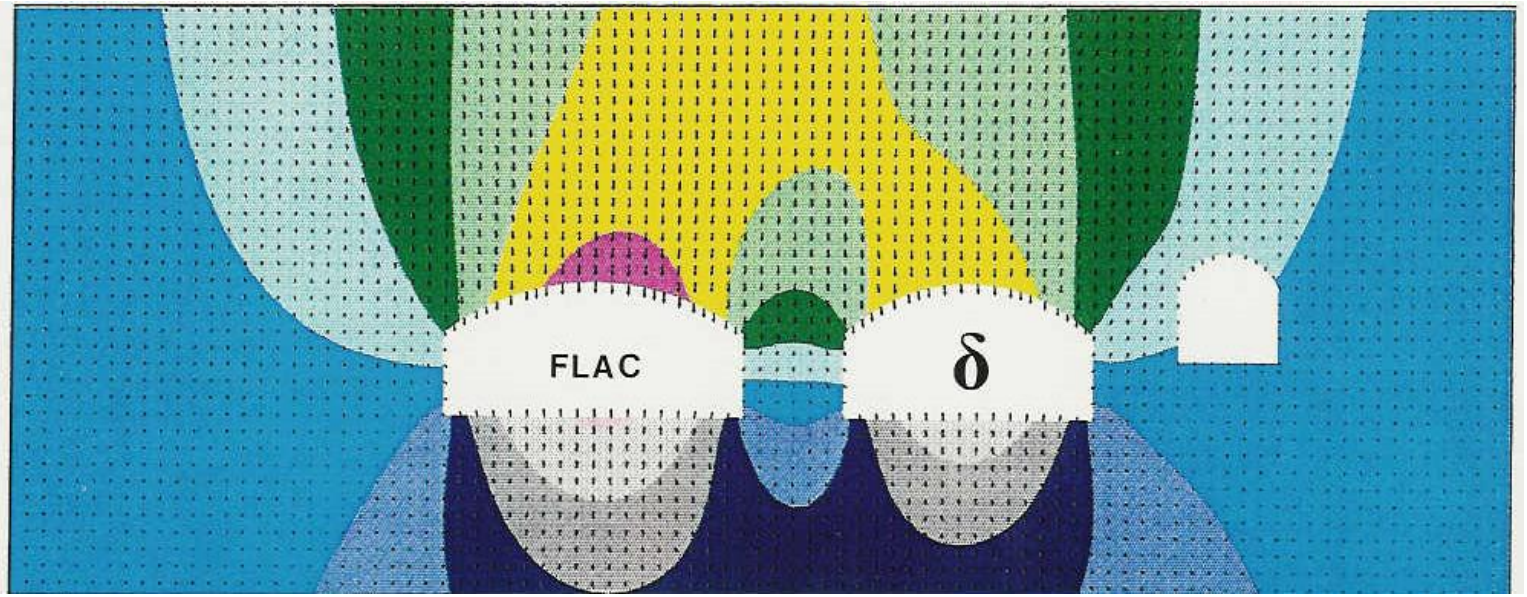
$$m_b = m_i \exp\left(\frac{GSI-100}{28-14D}\right)$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right)$$

$$a = \frac{1}{2}+\frac{1}{6}\left(e^{-\frac{GSI}{15}}-e^{-\frac{20}{3}}\right)$$

16 X ‘GSI’ in equation for ‘c’
12 X ‘GSI’ in equation for ‘ϕ’
GSI is not ‘geological’ nor easily quantified. D is a ‘joker’ – any result.

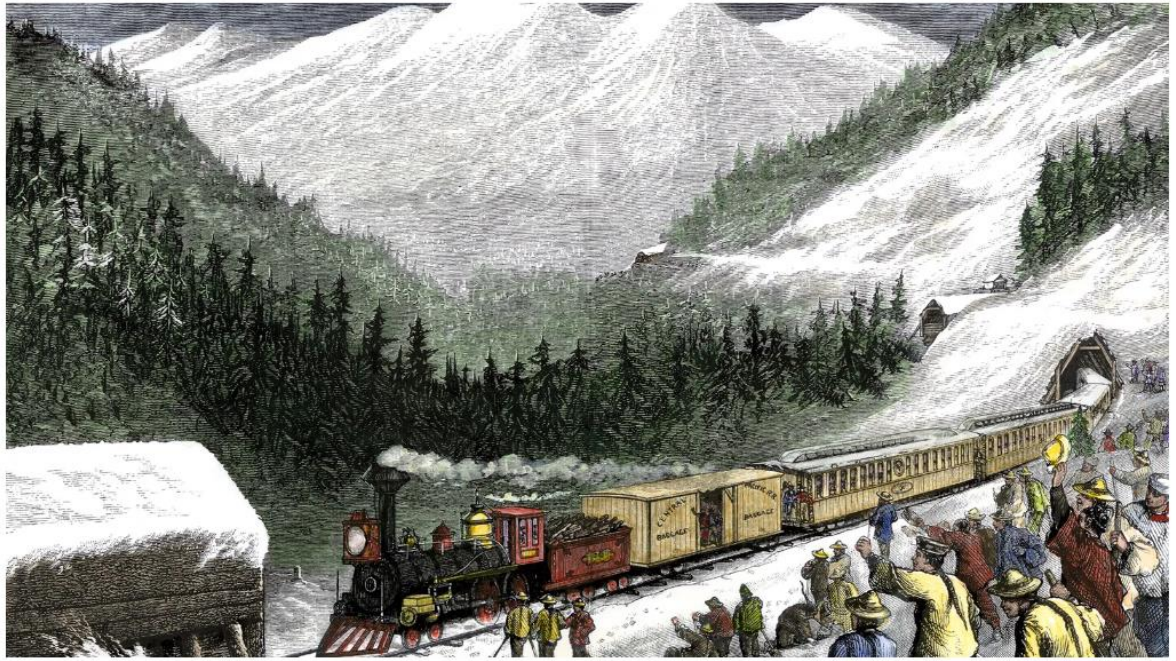




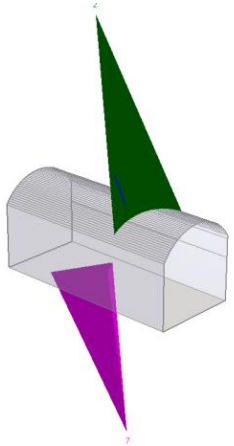
The *aposteriori empiricism behind* *discontinuous analyses*, is preferred to the *apriori* assumptions of continuum analyses.

(Lise Backer, pers. comm.)

No **UnWedge** in CPRR 1880 rail tunnels.



Chinese labourers made up 90% of the CPRR's workforce (Credit: North Wind Picture Archives/Alamy)



It took Chinese workers more than two years to hand-chisel the 1,700ft-long tunnel at Donner Summit (Credit: yhelfman/Getty Images)

Pre-grouted NMT.

Inflow 1 to 2 litres/min/ 100m, or better, 5 km.

Lugeon range
<0.1L to 368L

CONCLUSIONS

1. EMPIRICAL-BASED 'DESIGN' *(SELECTION of SUPPORT CLASSES)* IS URGENTLY NEEDED – ON A BLAST-BY-BLAST BASIS - AS THE ROCK MASS IS UNKNOWN.

2. Q-SYSTEM CHARACTERIZATION FOR TUNNEL SUPPORT SELECTION IS EMPIRICAL AND THEREFORE WORKS.

3. GSI AND HOEK-BROWN EQUATIONS (FOR ROCK MASSES) ARE NOT EMPIRICAL, AND ARE HIGHLY SUSPECT AS REPRESENTATIONS OF 'GEOLOGY'.