THE MANY FACES OF Q – ROCK MASS CHARACTERIZATION FOR TUNNELS, CAVERNS, SLOPES, TBM PROGNOSIS, DEFORMABILITY, SHEAR STRENGTH, SEISMIC VELOCITY, PERMEABILITY

BGA · THE BRITISH · GEOTECHNICAL ASSOCIATION

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Institution of Civils, London 2020

ENGINEERING GROUP · Wm. Smith 1769-1839 · 1963

CONTENTS of LECTURE

1. INTRODUCTION TO Q-PARAMETERS, CORE LOGGING, UNEXPECTED ERROR IN A GEOLOGIC INVESTIGATION

2. NMT – NATM CONTRASTED, SHOTCRETE, BOLTS, RRS, LATTICE GIRDERS, OVER-BREAK AND CONSEQUENCES

3. TUNNEL AND CAVERN DEFORMATION, RELATIVE COST AND TIME

4. SEISMIC VELOCITY, DEFORMATION MODULUS, DEPTH

5. LIMITATIONS OF SHEAR STRENGTH MODELS, MODELLING

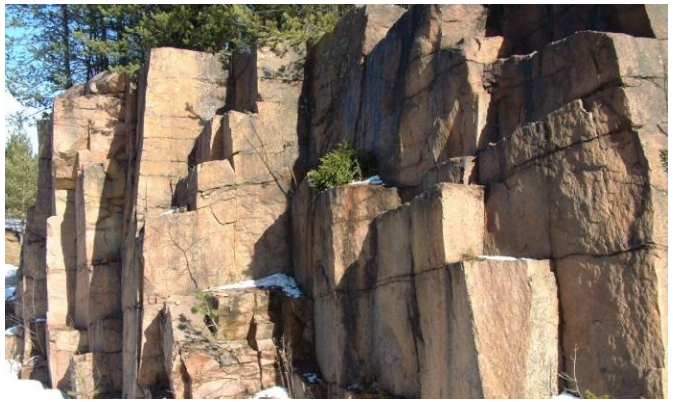
6. WATER CONTROL, WATER TRANSFER, PERMEABILITY (Q_{H_2O})

7. TBM PROGNOSIS, TBM TUNNEL DELAYS IN FAULT ZONES, (Q_{TBM})

8. SAFE ROCK SLOPE ANGLES (Q_{SLOPE})

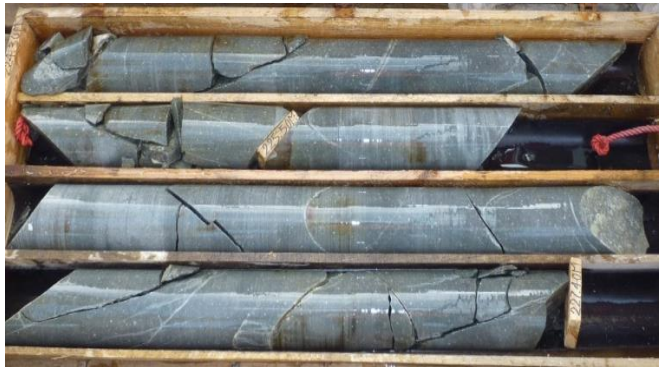
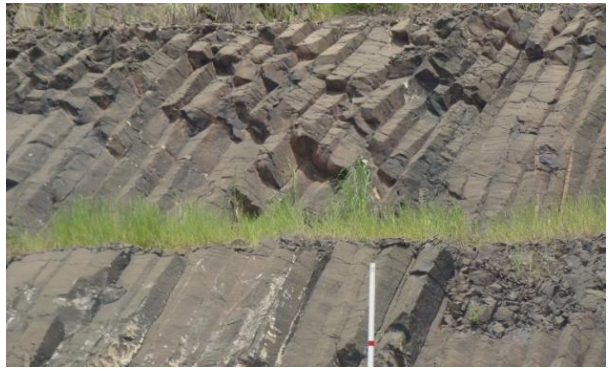
Eystein Grimstad: A key contributor to *tunnel case records* and the introduction of S(fr) into the Q-system support recommendations.

Neil Bar: A key contributor to an overwhelming majority of *Q-slope case records*.



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 having to perform impossible sizes of *in situ* rock mass testing.

THE ‘Q-system’ ?

Q used here!

As a briefest introduction:

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

Q consists of *ratings for six parameters*.

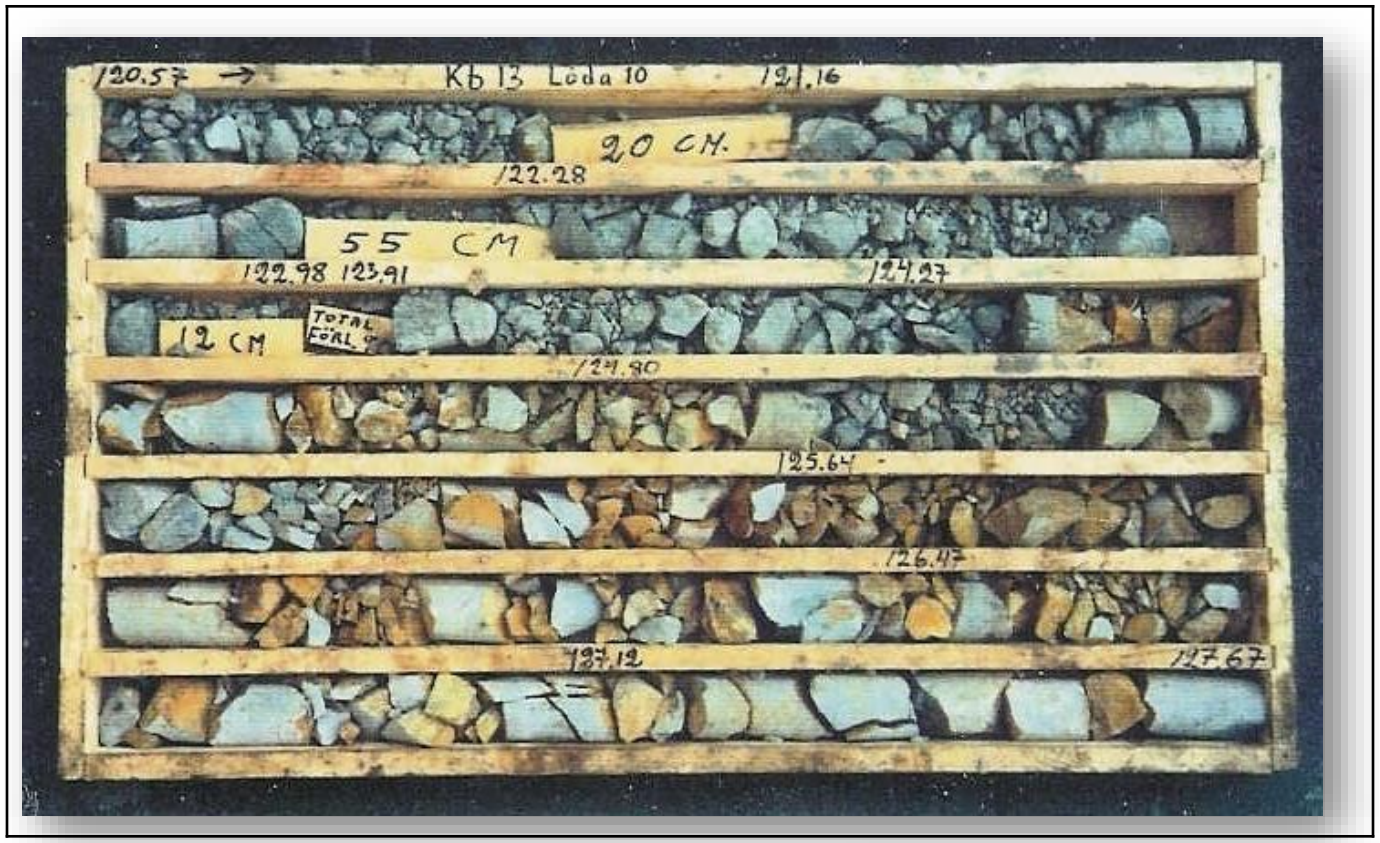
$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$ = **(Block size) x (friction) x (‘active stress’)**

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)

BESIDES LARGE SCALE, *WIDE NUMERICAL RANGE OF Q REALISTICALLY* REFLECTS HUGE POTENTIAL DIFFERENCES IN *ROCKMASS* PROPERTIES

Q = 0.001 and 1000, or RMR = 5 and 95 ?



REGIONAL SHEAR ZONE, S.W. SWEDEN. *VERY LOW Q!*
(HALLANDSÅS RAIL TUNNELS)

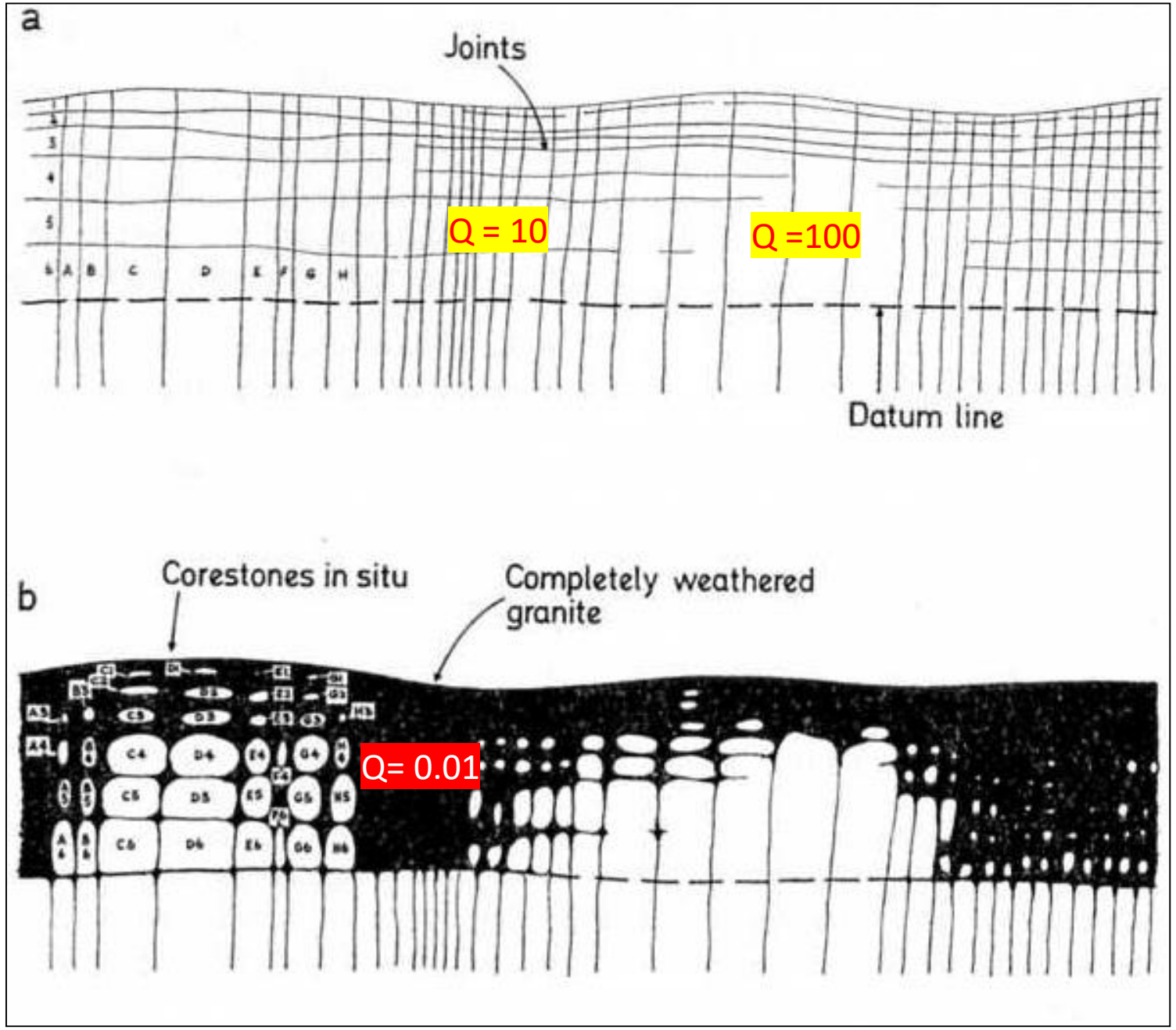
VERTICAL HOLE, ADMIRALTY, HK
(MISSED SUB-VERTICAL JOINT SETS)
APPARENT HIGH Q

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

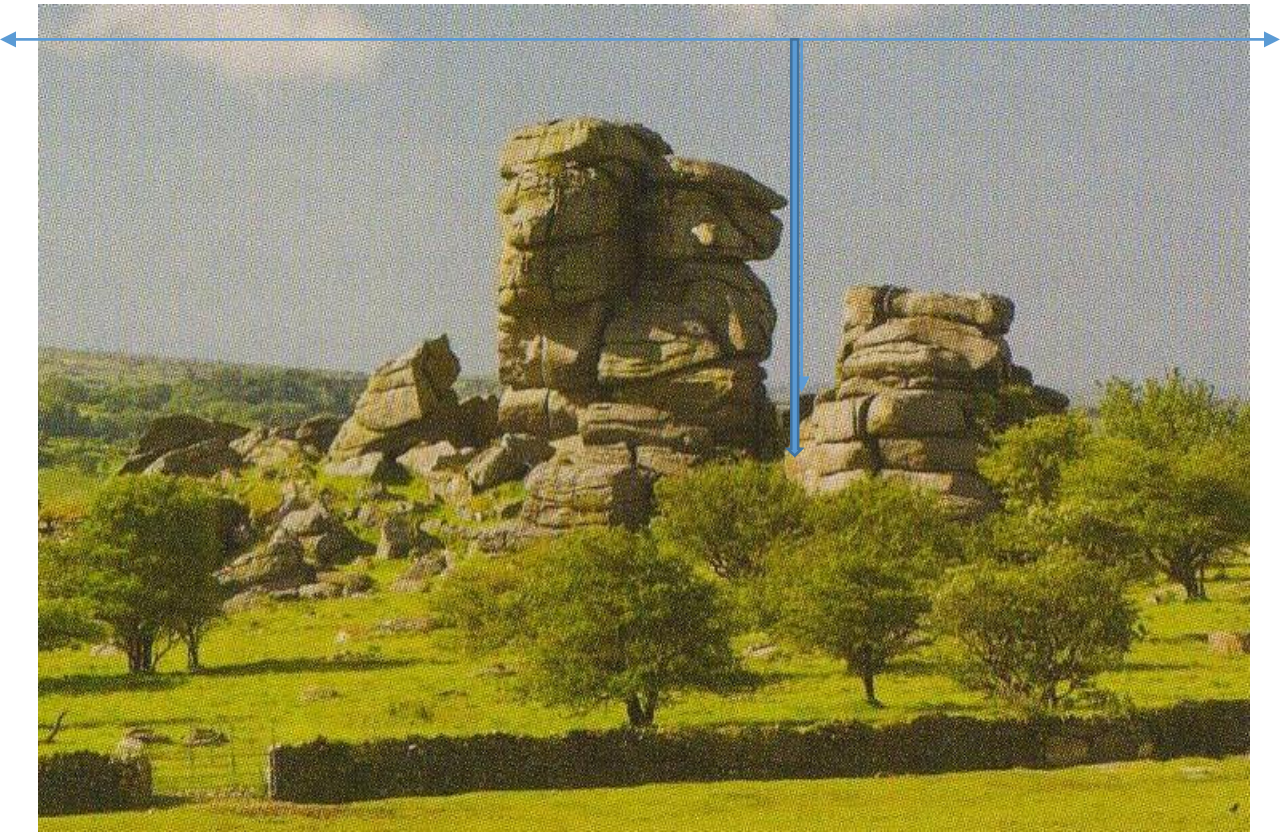
Now > 2,000 case records re tunnel support measures



JOINT SPACING VARIATIONS, SAPROLITE.

(Q = 0.01 -100)

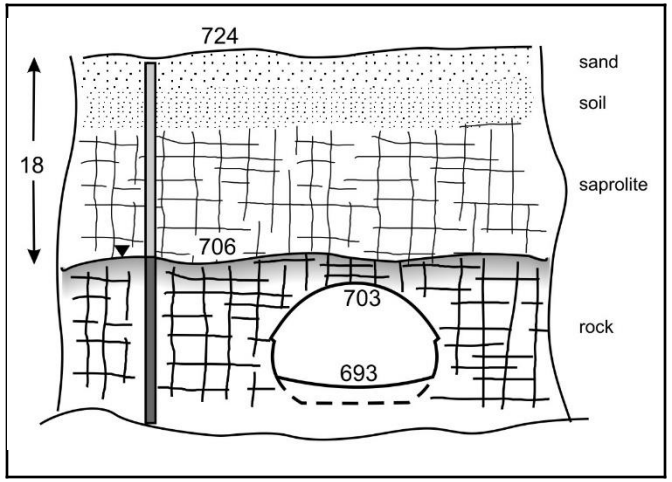
Linton, 1955

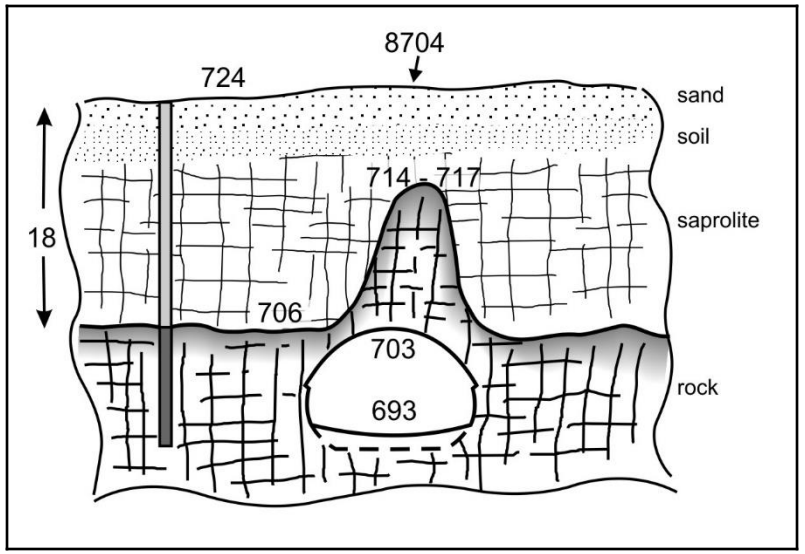


ANY CONNECTION??

LEFT: ‘TORS’ FROM DARTMOOR, S.W. ENGLAND.
PREVIOUSLY SURROUNDED BY SAPROLITE

RIGHT: PINHEIROS CAVERN COLLAPSE: RIDGE-OF-ROCK LOADING





1. MEAN EXPECTATION

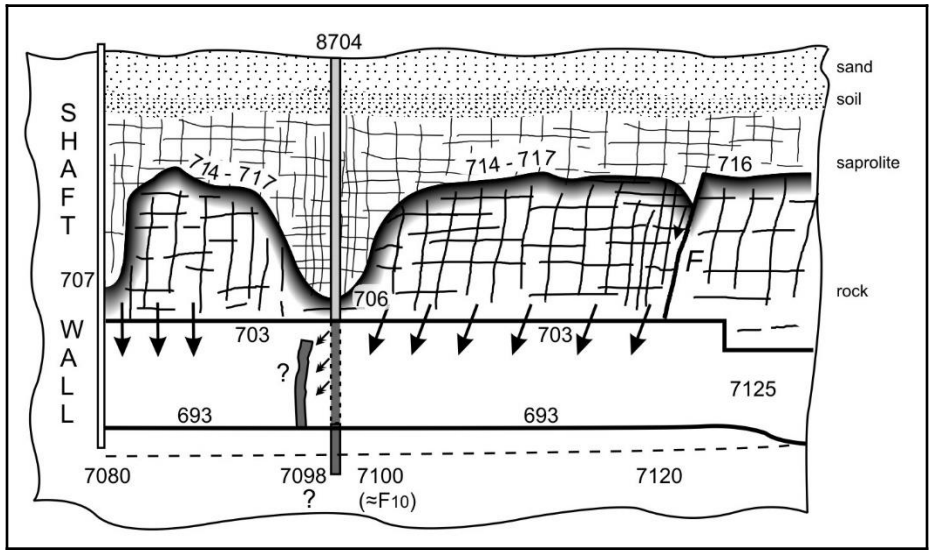
Five holes drilled from 723-724 m, rock at elev. 706-708 m (??)

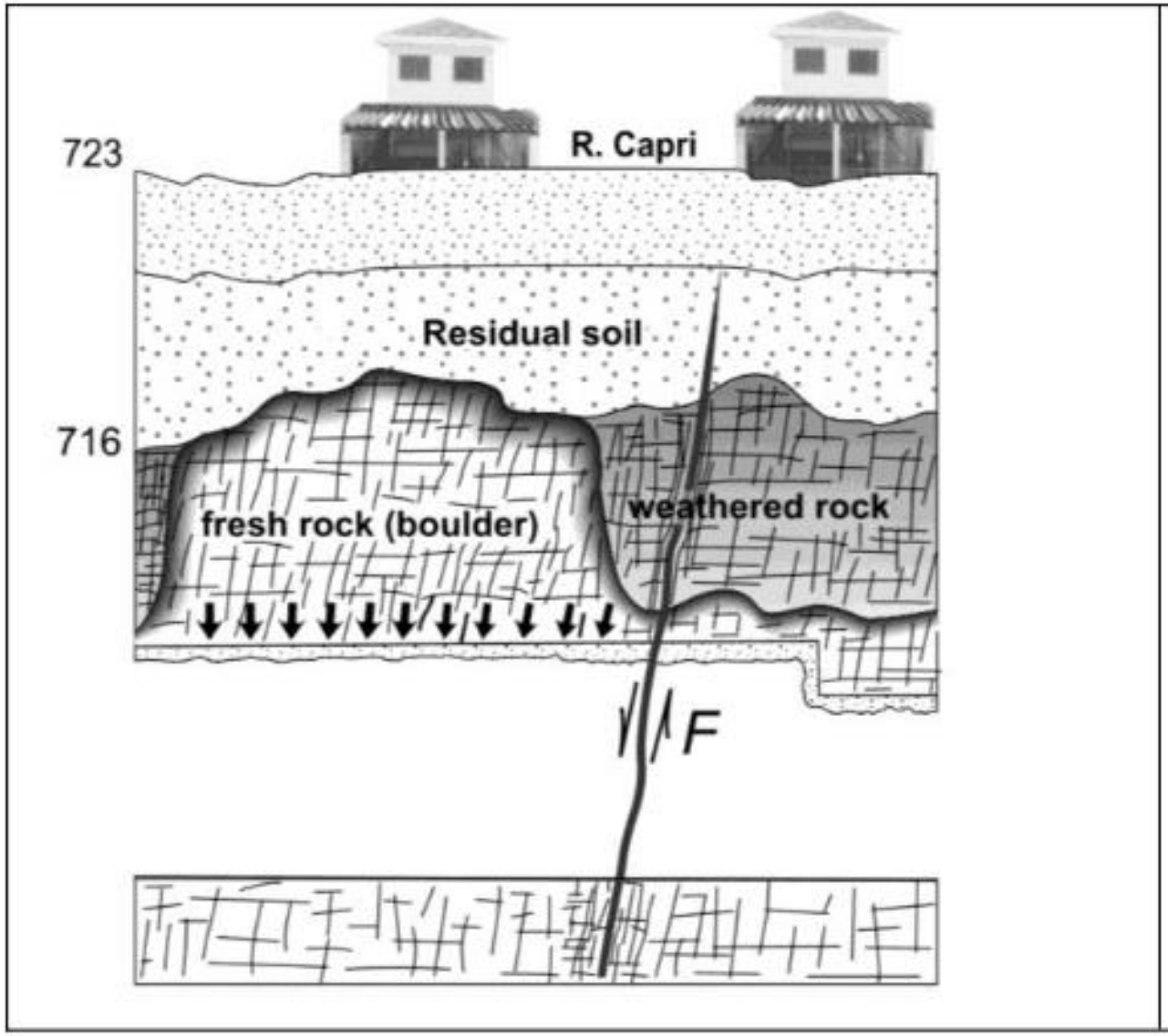
2. POSSIBLE REALITY

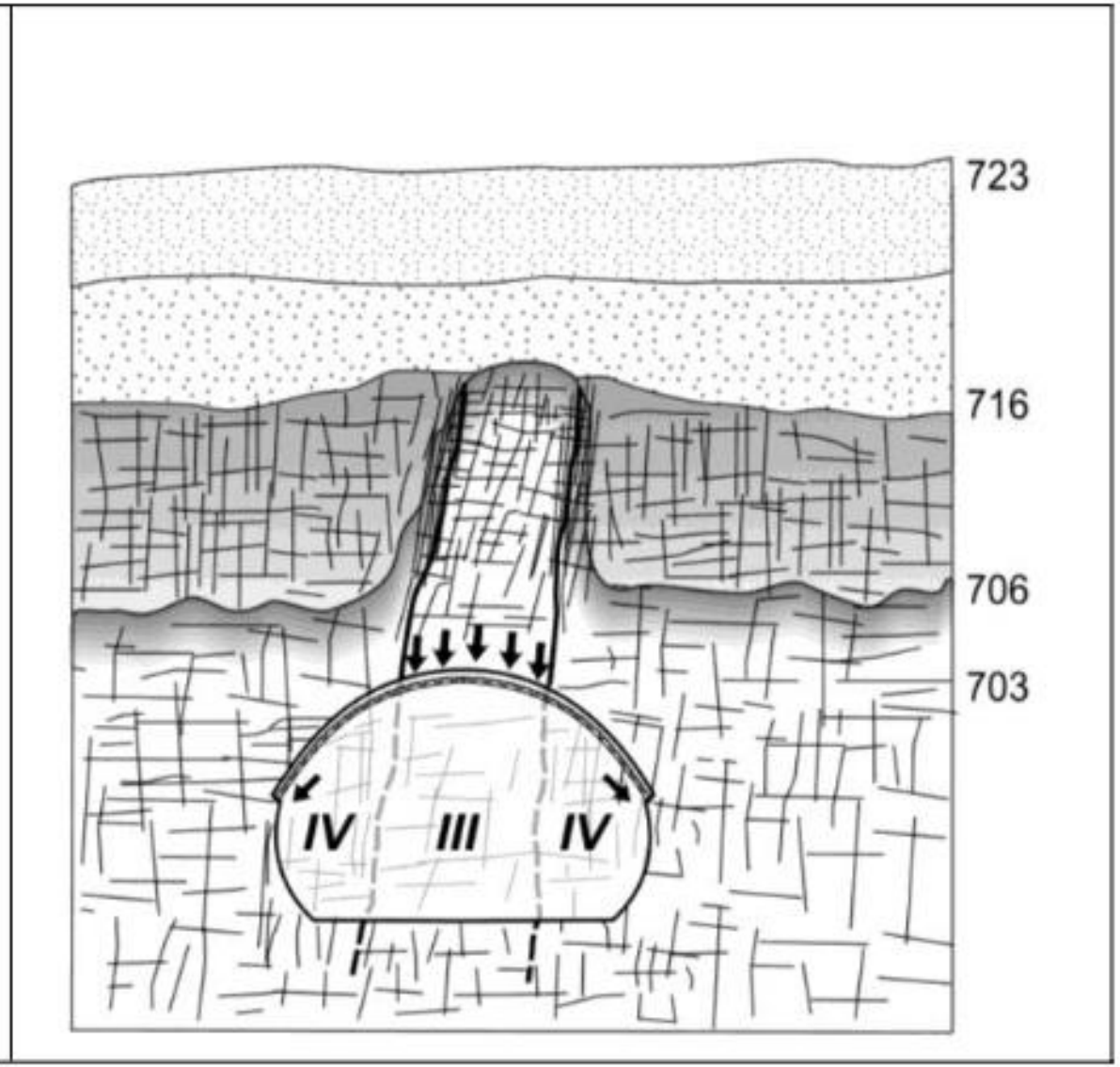
most of collapsed rock fell 10 m to 704-707 m (i.e. 8 to 11m error?)

3. FATED BOREHOLE 8704

(drilled mid-cavern, also reached rock at mean elev. 706 m.




723
R. Capri
Residual soil
716
fresh rock (boulder)
weathered rock
F


723
716
706
703
IV
III
IV

THE FIRST TWO PAIRS OF PARAMETERS HAVE DIRECT PHYSICAL MEANING:

RQD / Jn = relative block size

Jr / Ja = Closely resembles the friction coefficient (between-blocks)

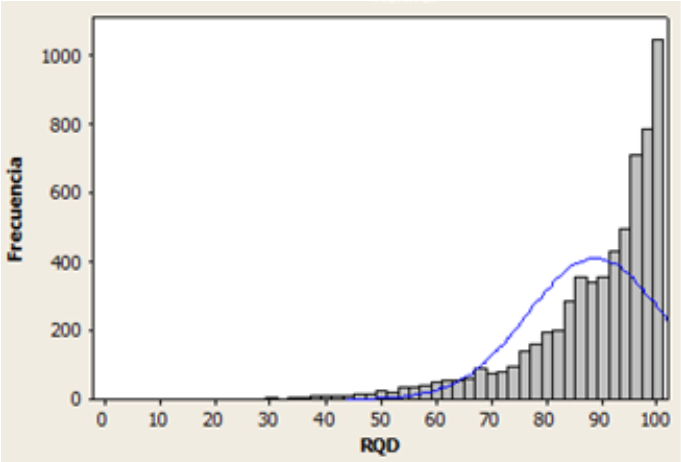
Jw / SRF = relative effects of water, faulting, strength/stress ratio

In the following, several of these Q-parameters will be illustrated **by photographs or figures.**

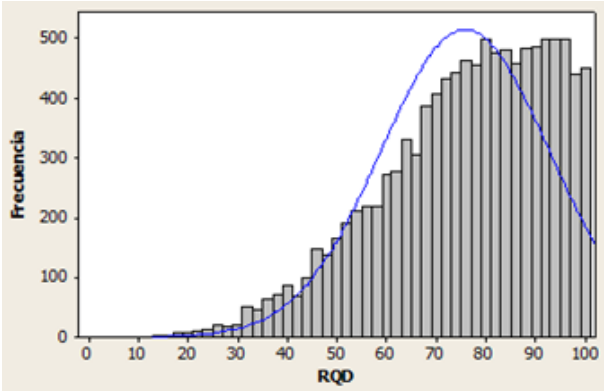
(Note: Q' = first four parameters used in mining)

EXAMPLES OF RQD STATISTICS (40km of core)

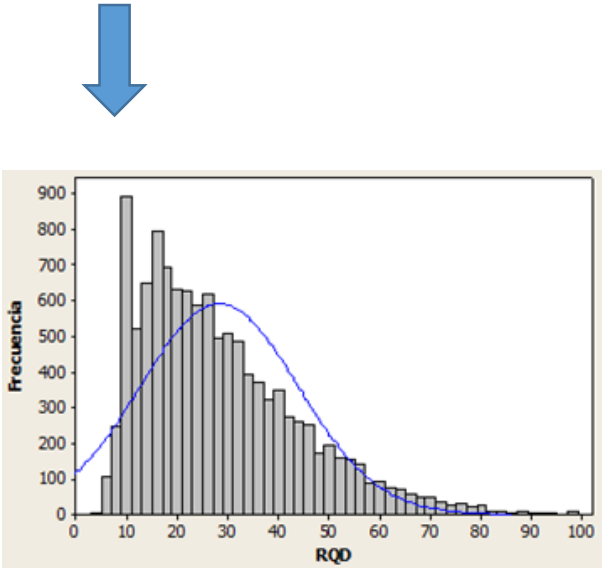
WITHIN RESPECTIVE Q-RANGES 0.1-1, *1-4*, 4-10, 10-40



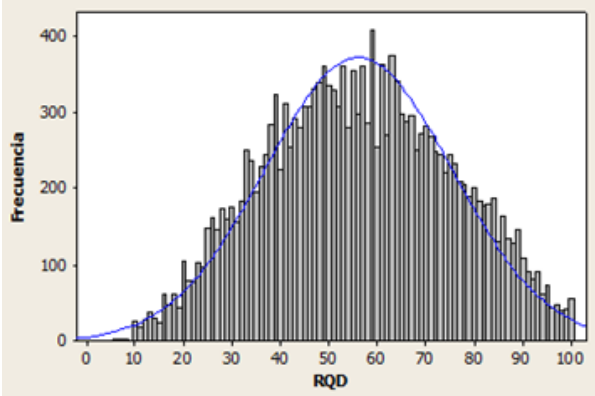
Q = 10-40 ('good')



Q = 4-10 ('fair')



Q = 0.1-1 ('very poor')



Q = 1-4 ('poor')

NO ONE WITH HANDS UP? **HOW CAN YOU HAVE A POSITIVE Q-VALUE IF RQD IS ZERO?**

GOOD QUESTION: DISCOUNT ALL RQD < 10%, CALL THEM 10%.

Top left:

granite quarry,

Jn = 9 (= 3 sets)

'cubic' blocks

Isotropic matrix

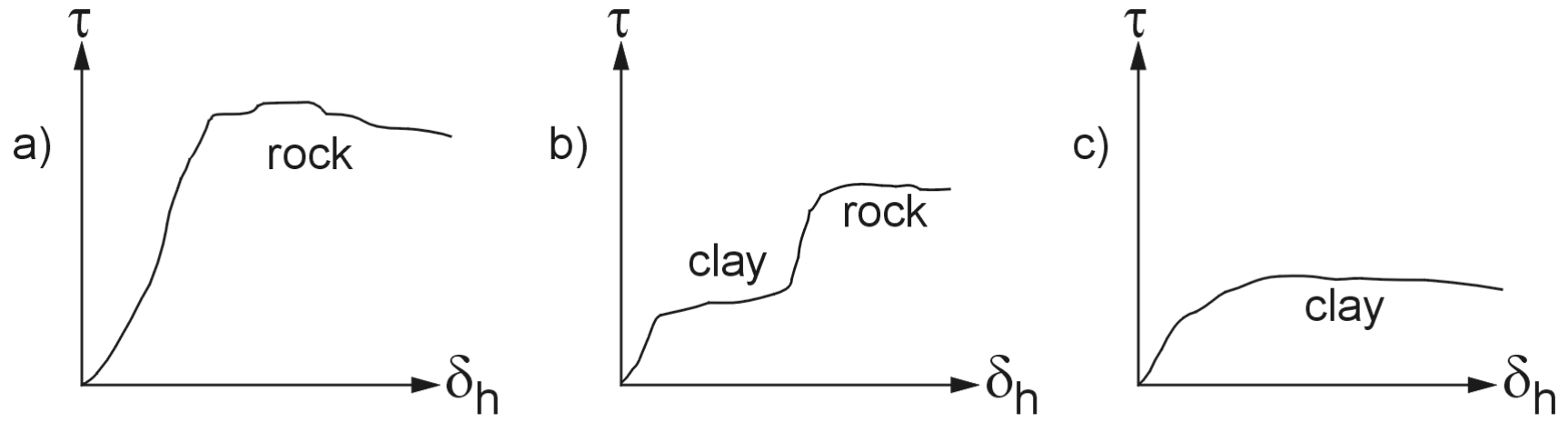
Right and below:

limestone cliffs,

Jn = 9 (= 3 sets)

elongated blocks

BUT wave-action makes balls/spheres as *matrix is isotropic*



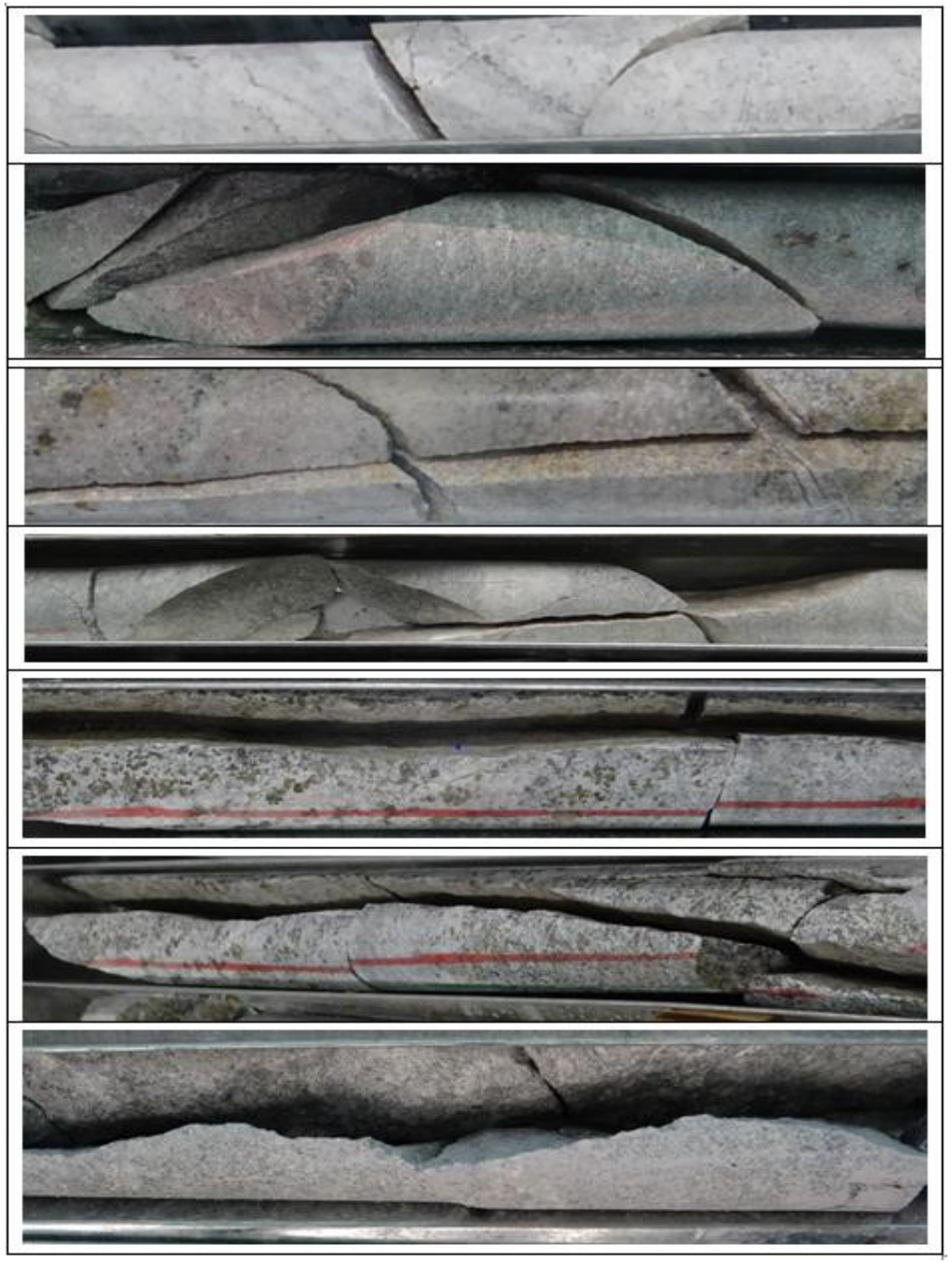
(a) Rock wall contact

(thin coatings)

Ja - clay

	Ja/Jr =	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)°$				
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°

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



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

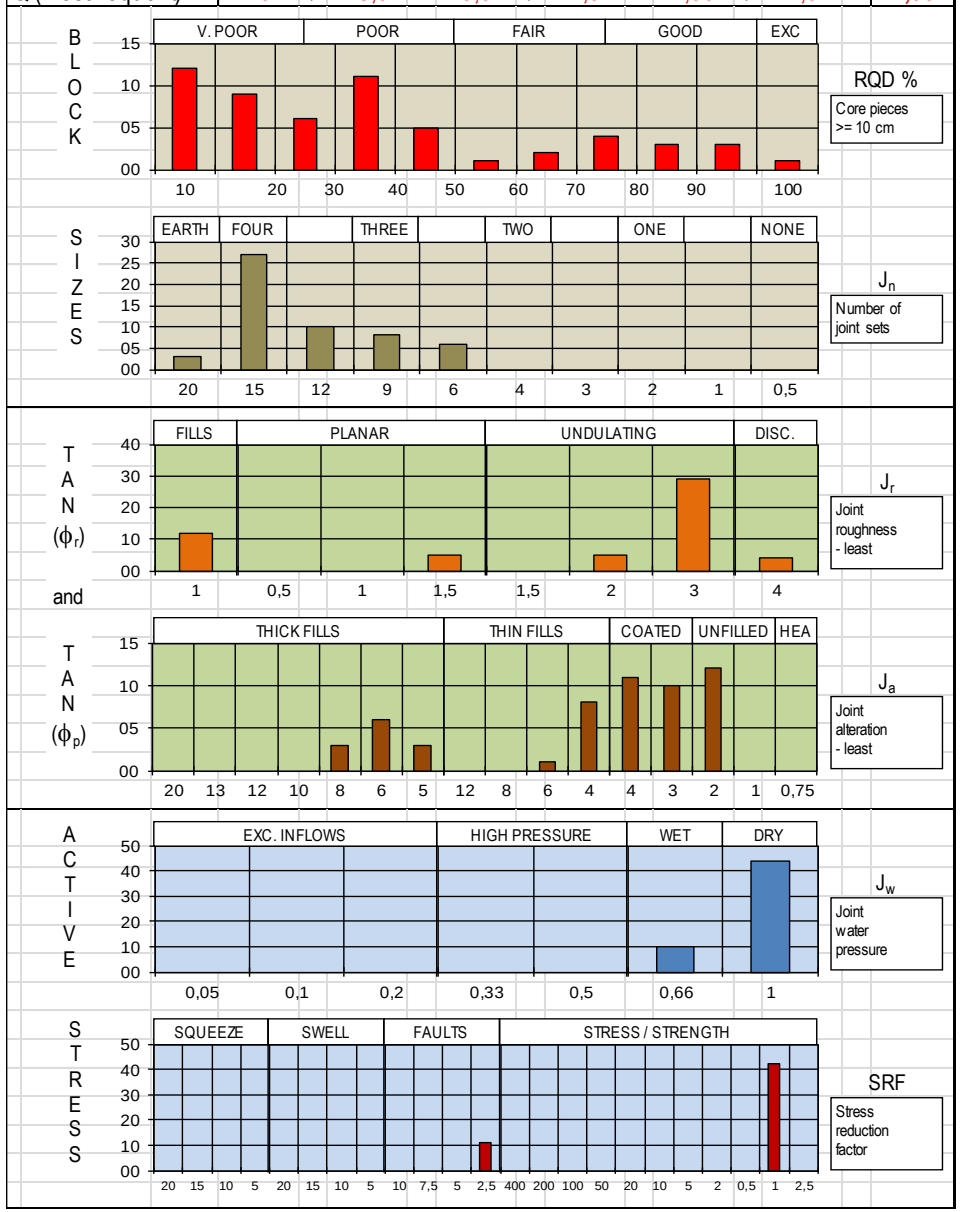
Jr determines dilation angles, stability – or over-break, even failure.

Jr = 0.5 to 1.0 to 1.5

(some slickensides?)

Maybe Ja = 3 (*graphite coatings*)

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



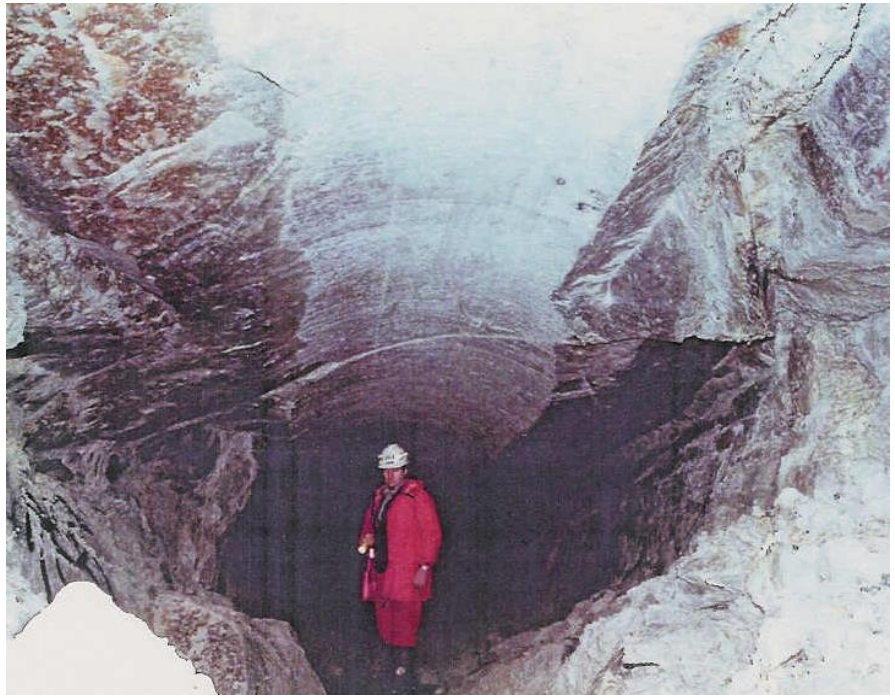
Q IS ONLY PART OF A ROCK MASS DESCRIPTION EXERCISE

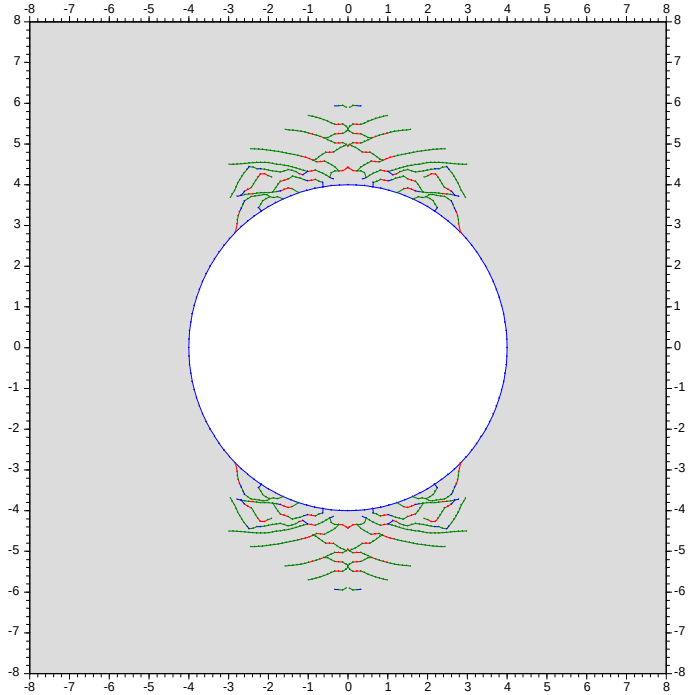
Also Jw and SRF

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		

The 5th Q parameter is Jw

On occasion it is critical !





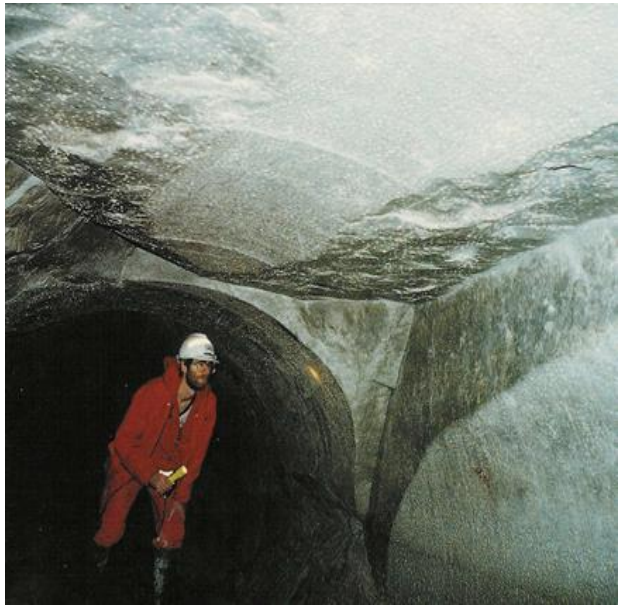
If the stress/strength ratio is > 0.4 x UCS, then elevated values of SRF (***6th parameter***) are used, giving lower Q

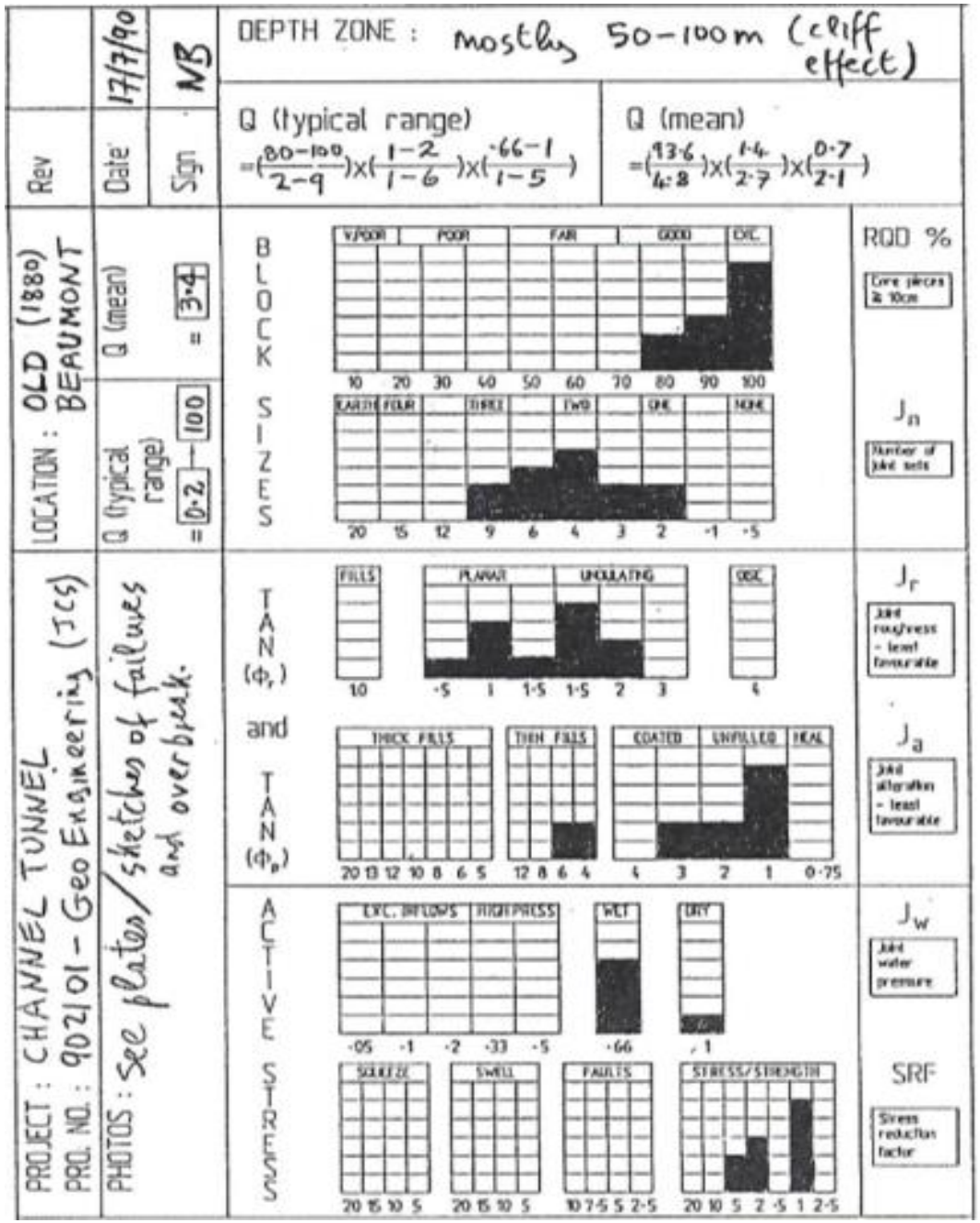
(Recently 0.4 x UCS was equated with **σ_t/ν**)
so actually ***extension failure*** prior to shear failure)

IN SUMMARY

- Q can be used for weak and strong rocks.
- The presence of jointing is a pre-requisite

EVEN THE WEAK CHALK MARL OF THE CHANNEL TUNNEL *WAS JOINTED* AND THEREFORE Q-LOGGED (BY TML, later by NB). **Jw 0.66**





2. NMT – NATM CONTRASTED, SHOTCRETE, BOLTS, OVER-BREAK

FIRST TWO DEFINITIONS:

1. 'SINGLE-SHELL' (NMT)

(PRE-GROUTING?) + B + Sfr + (RRS?)……

NEEDS SMALL WORK FORCE ……(1/10 x NATM?)

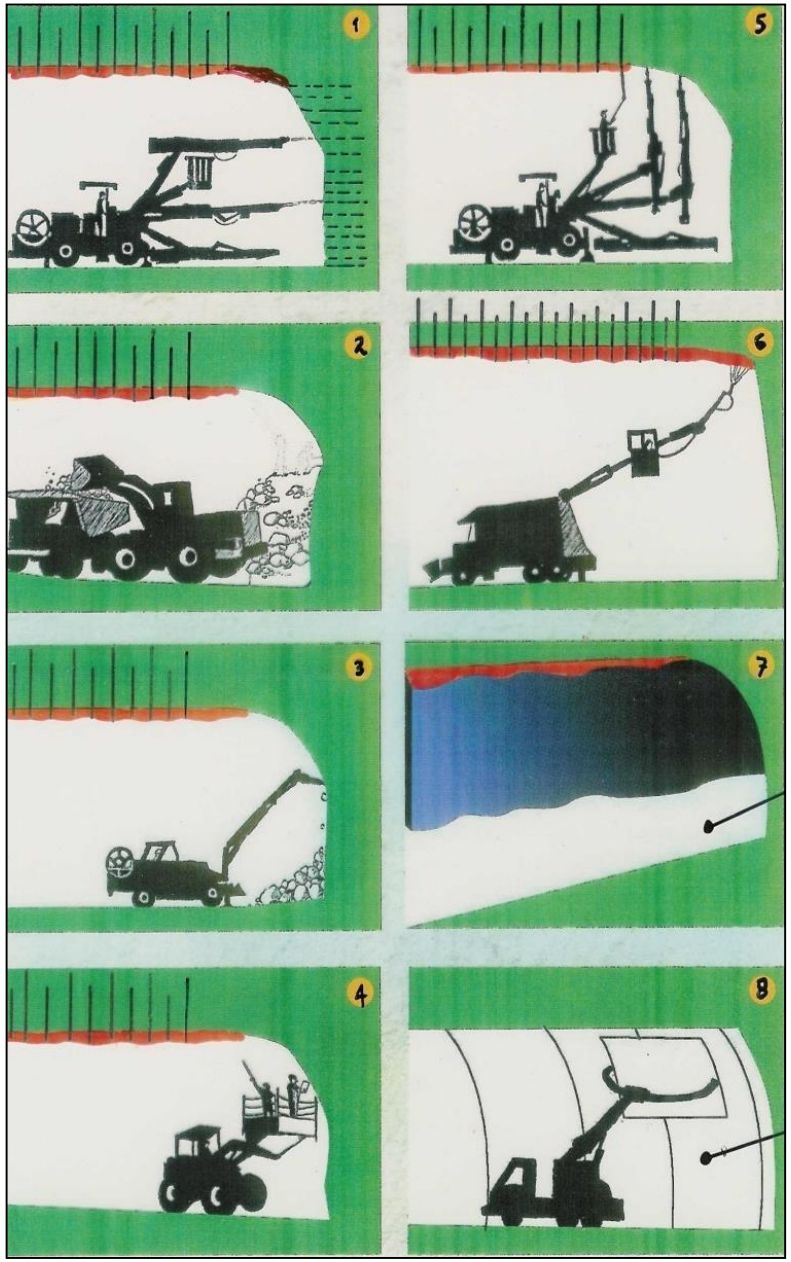
2. 'DOUBLE-SHELL' ('NATM')

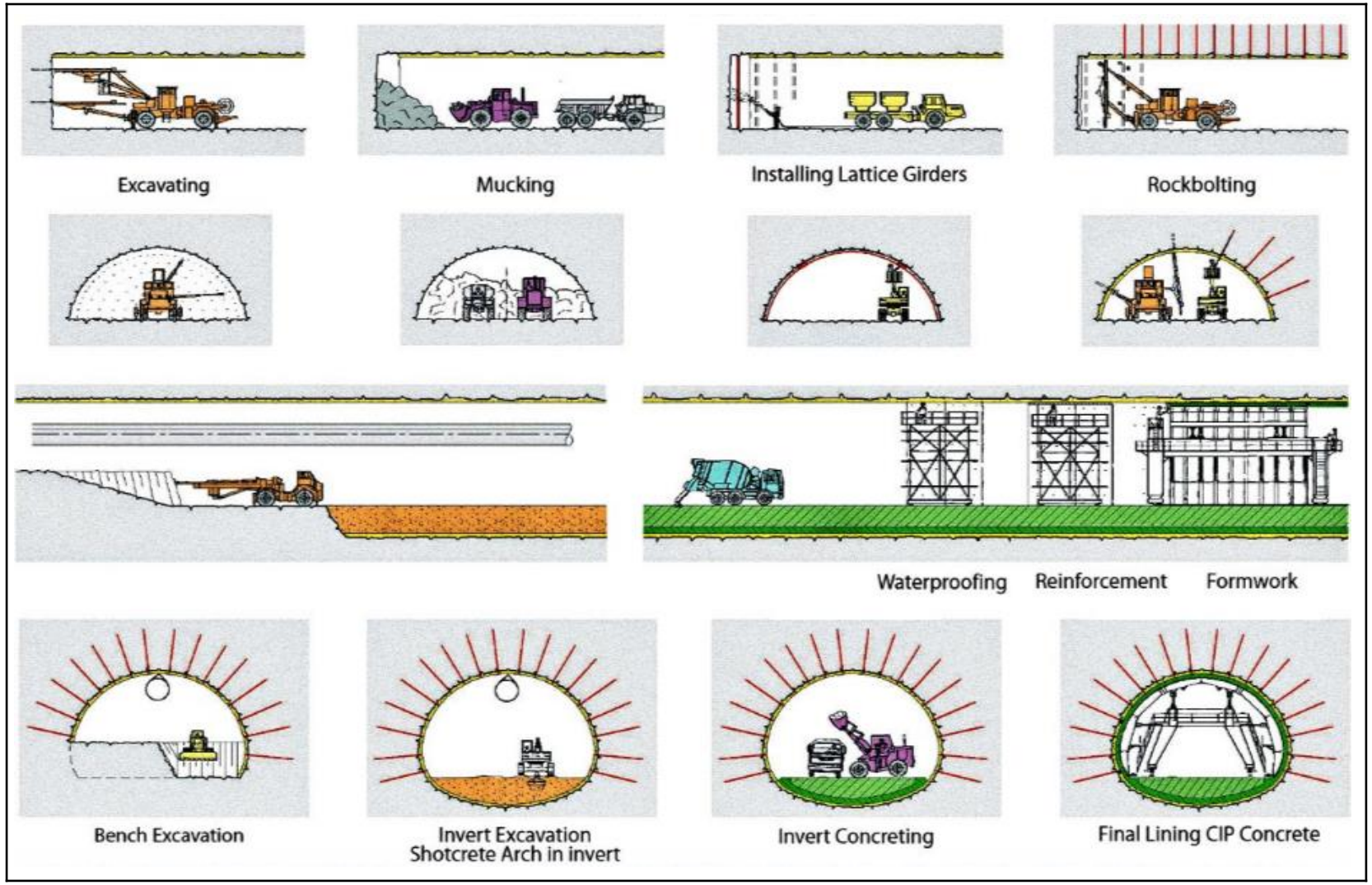
(TEMPORARY: Sfr/Smr, B, STEEL/LATTICE GIRDERS,

PERMANENT: FLEECE, MEMBRANE, CAST CONCRETE

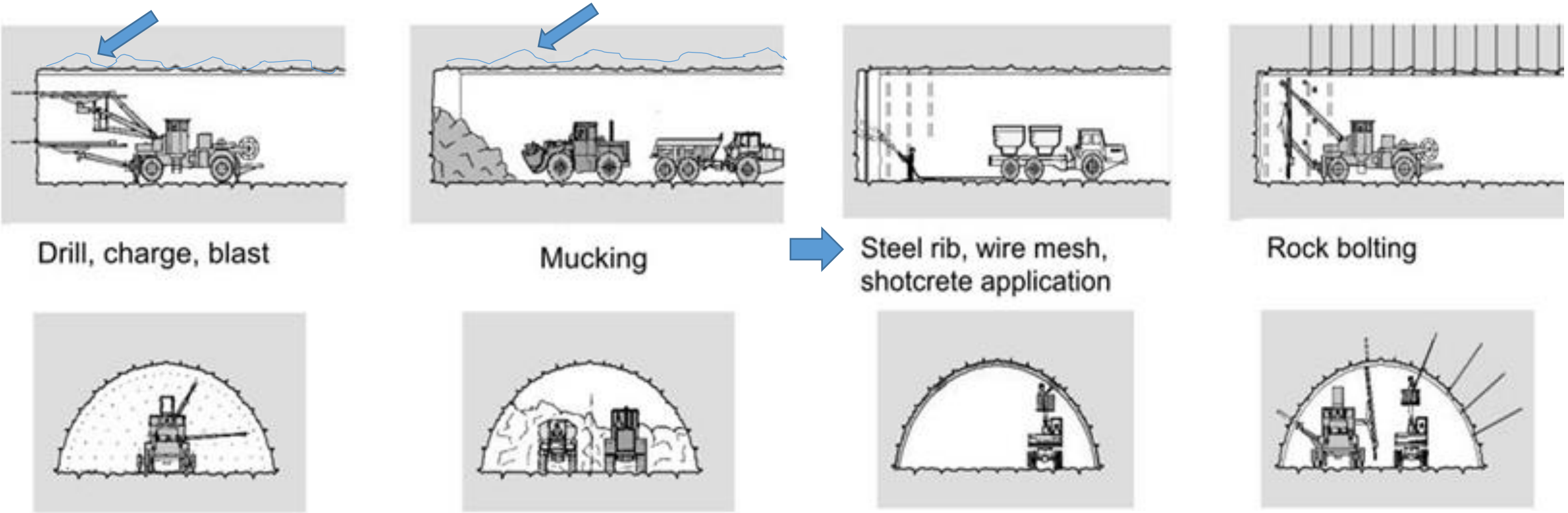
NEEDS LARGE WORK FORCE ……(10 x NMT?)

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





OVER-BREAK MAY EFFECT all OPERATIONS IN NATM

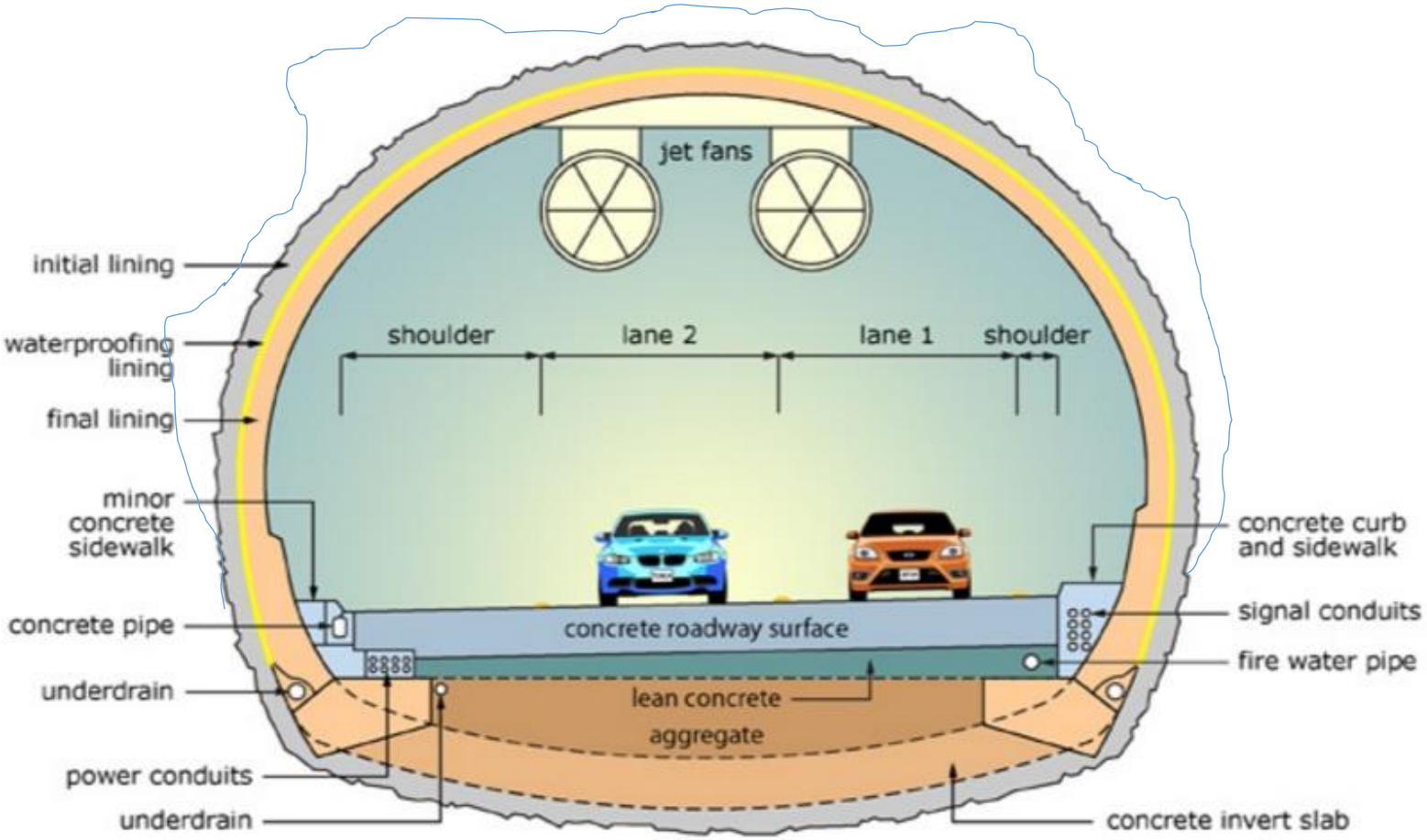


(AGS, 2010. NATM: THE AUSTRIAN PRACTICE OF CONVENTIONAL TUNNELLING)

DRILL-AND-BLAST…..OVER-BREAK…..LATTICE GIRDERS (AND WIRE-MESH) ARE LESS EFFECTIVE…. GREATER VOLUME OF SHOTCRETE/CONCRETE.

(THESE PROBLEMS HAVE MUCH LESS EFFECT ON NMT).

Over-break ignored in drawings, stability, volumes?



A Botniabanen tunnel, Sweden.

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

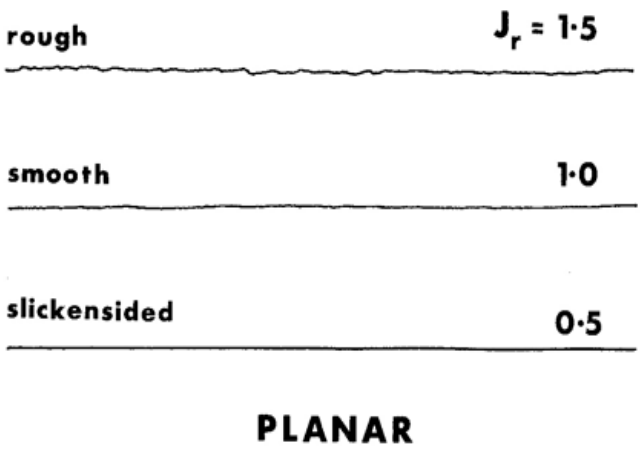
WATER-PROOF MEMBRANE PHASE in NATM. DIFFICULT ('3D') WHEN SIGNIFICANT OVER-BREAK.

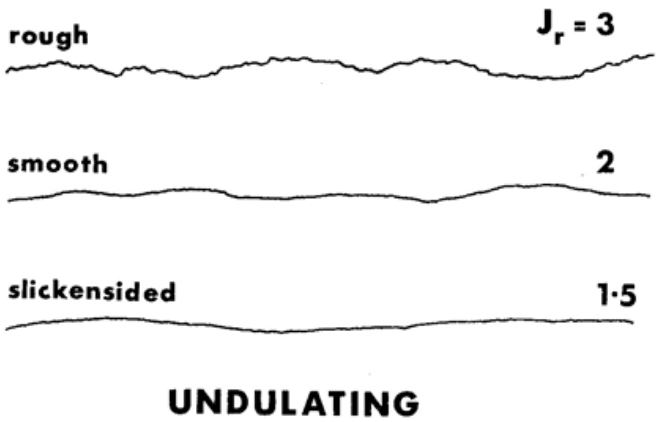
APPROX. <u>12-15km OF MEMBRANE WELDS</u> PER 1km OF (DOUBLE-TRACK) RAIL TUNNEL !

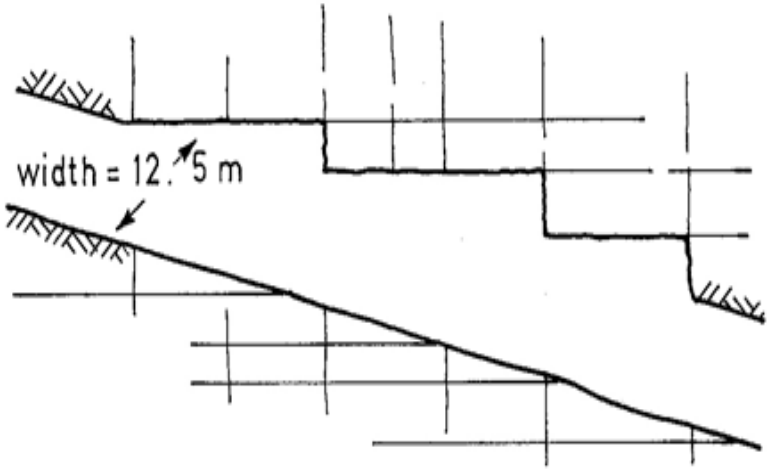
…IF LEAKAGE (through concrete?):

WHERE DOES THE LEAK ORIGINATE?

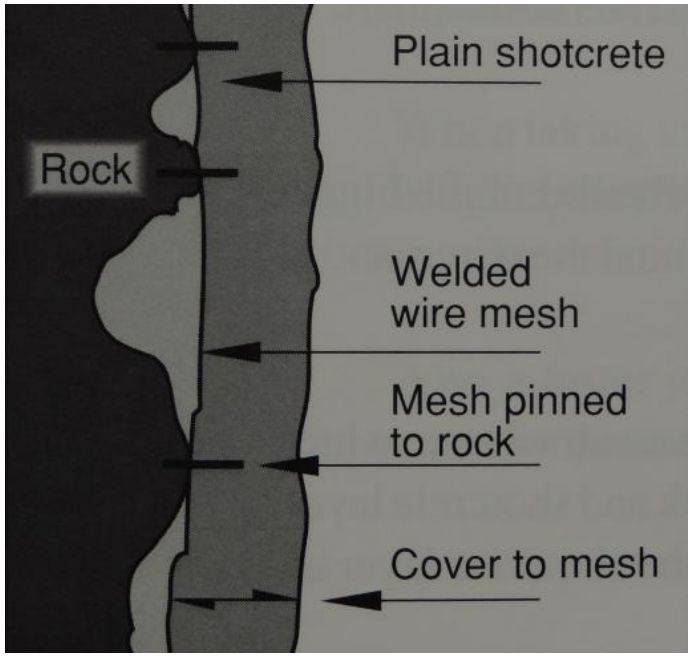
THE DUAL ROLES OF Jn (number of sets) and Jr (roughness)

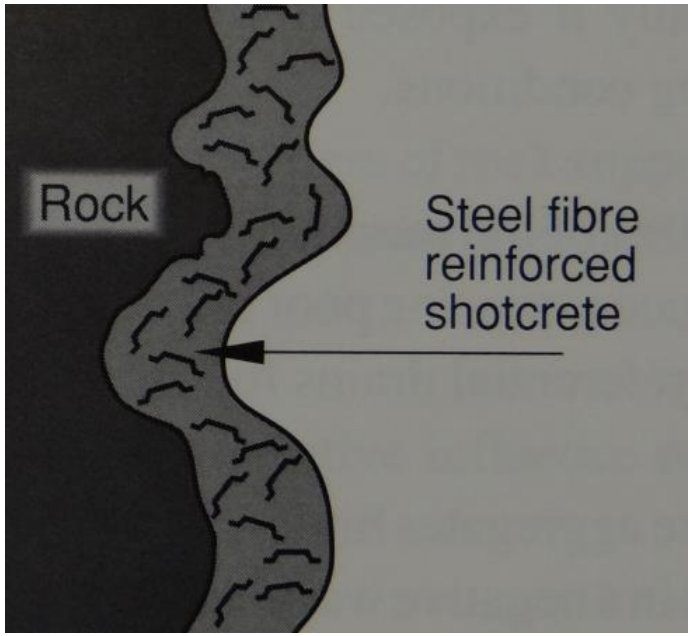






4/2, 6/2, 9/2, 9/3, 12/3, 15/3…….6/1, 9/1.5, 12/2, 15/2 (Jn/Jr ≥ 6)





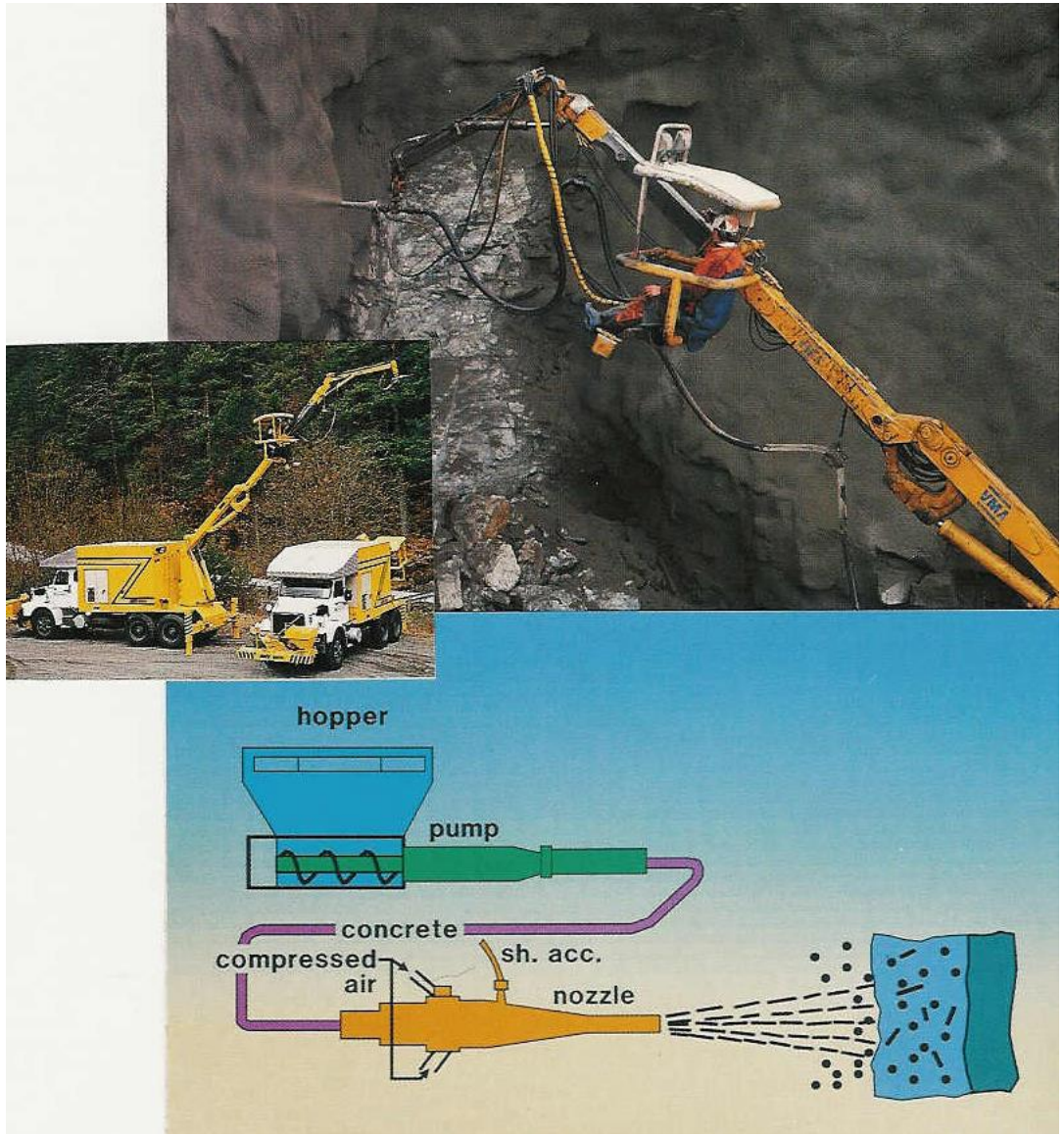
PERU: HEP

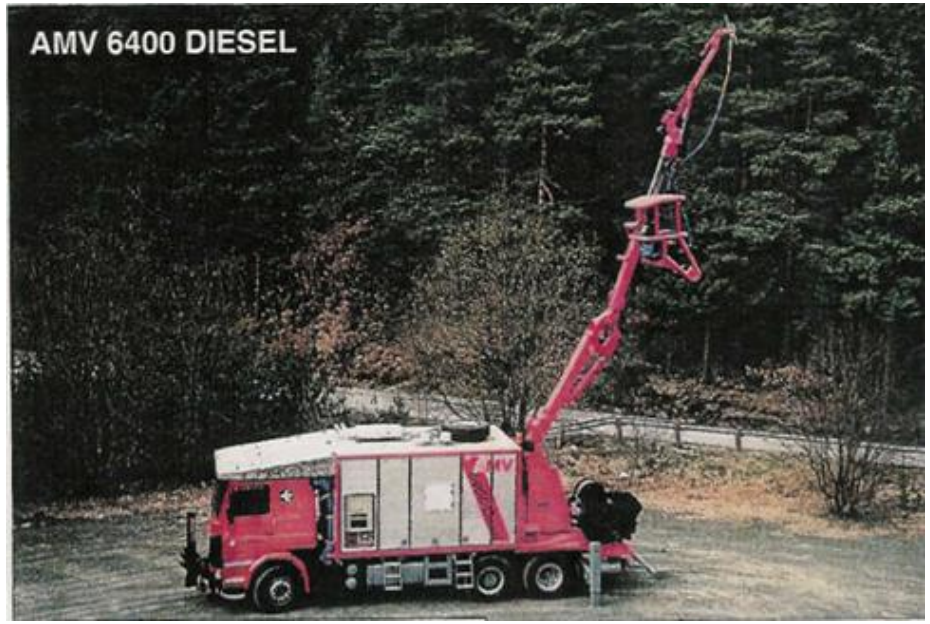
NORWAY: RAIL

REVOLUTIONARY CHANGE FROM S(mr) TO S(fr):

FIRST USED 1979, LAST S(mr) 1983 (IN NORWAY).

Drawings from Vandevall, 1998.

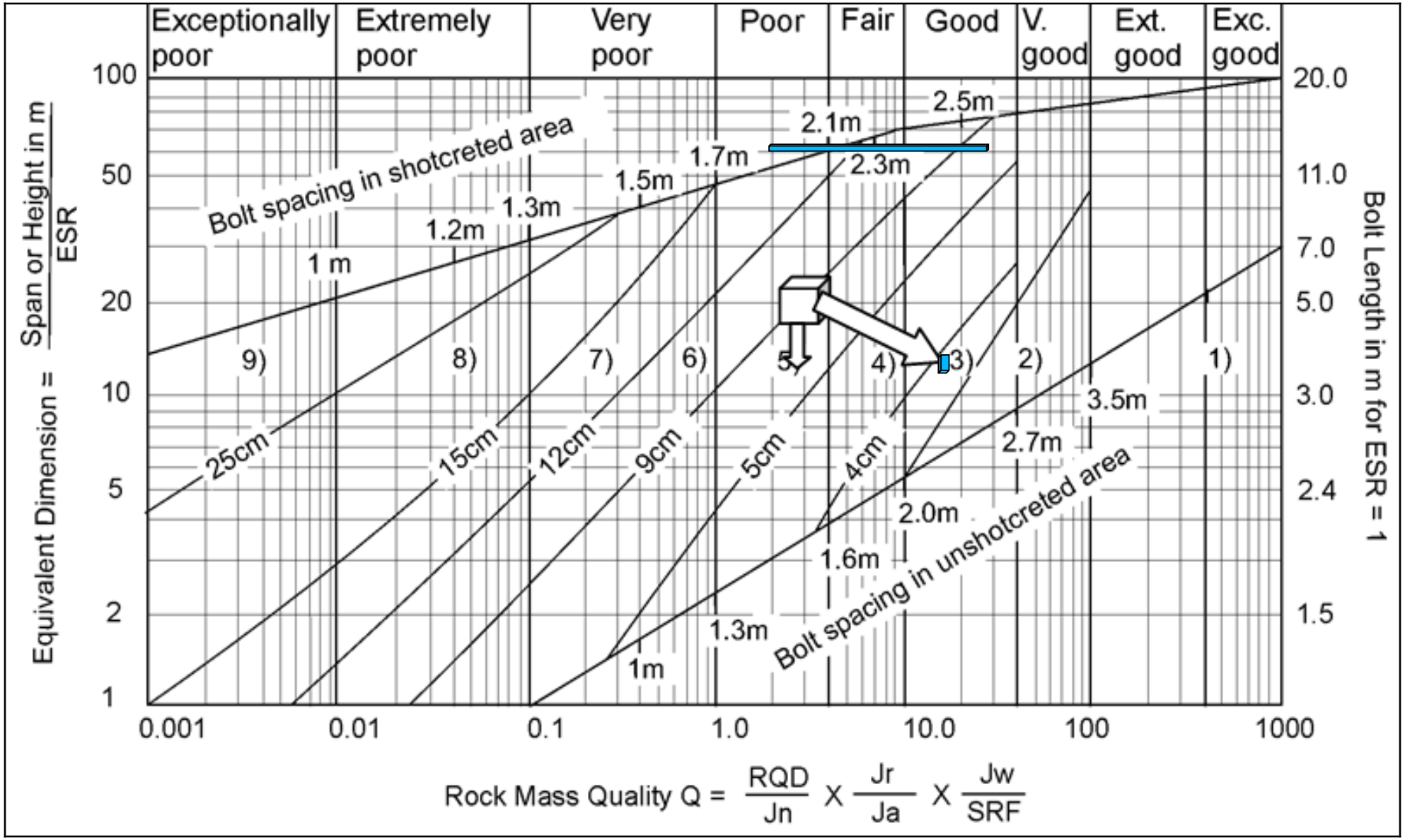




Portland cement (c)	450 – 550 kg/m³
Silica fume (s)	3 – 10 % of cement weight
Aggregate	0 – 10 mm
Plasticizer	0.3 – 1.0 % of cement weight
Superplasticizer	0.3 – 1.0 % of cement weight
Steel fibre	50 kg/m³ (dependent on toughness requirements)
Water/(c+s)	0.40 – 0.45
Slump	15 – 18 cm
Air content	< 4%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

DETAILS of S(fr) and robots from 1990's contractor brochure.

Nowdays 25-35kg of steel fibre, or 6-8kg of PP fibre.



THOSE WHO PREFER NATM – CAN USE Q FOR TEMPORARY SUPPORT SELECTION....

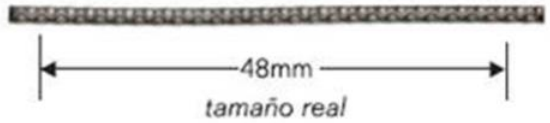
5Q + 1.5 x ESR

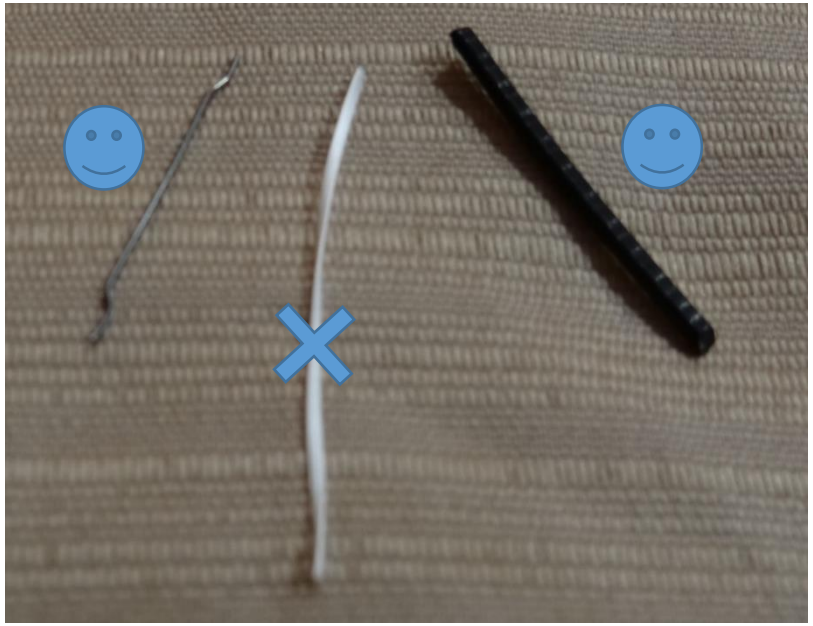
25 YEARS USE IN HK ROAD TUNNELS AND METRO TUNNELS

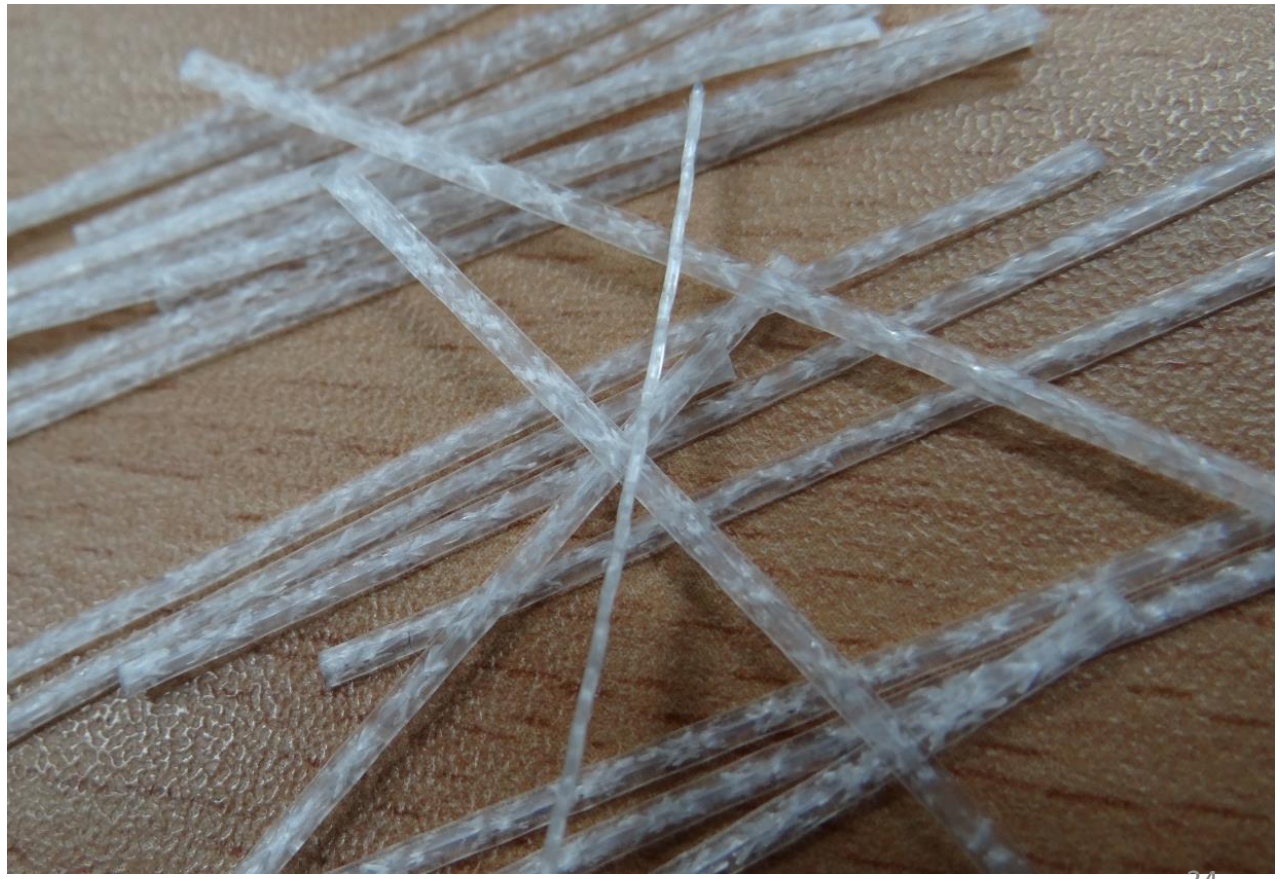
ANCHORAGE WHEN SO SMOOTH??

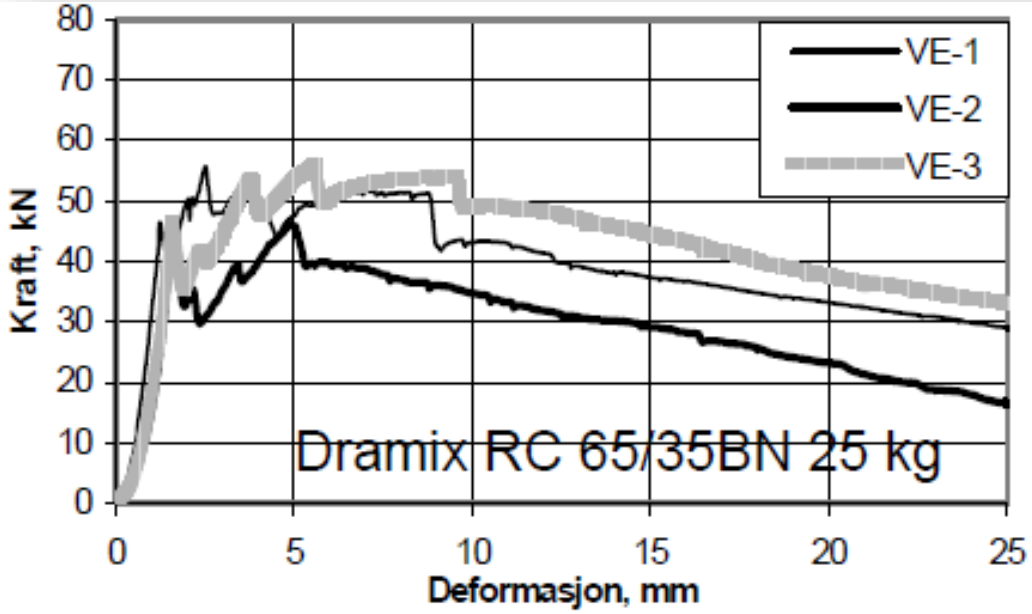
NO! – ‘OPTICAL ILLUSION’ PRODUCT IS USED IN CONCRETE FLOORS.

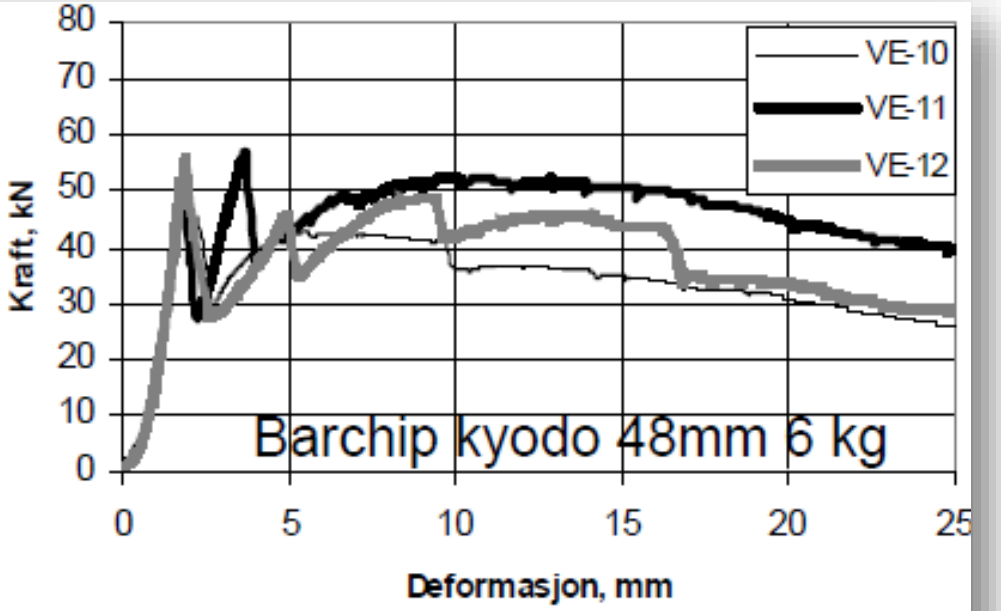
DO NOT USE IN TUNNELS / MINES ! (Probably responsible for a collapse).

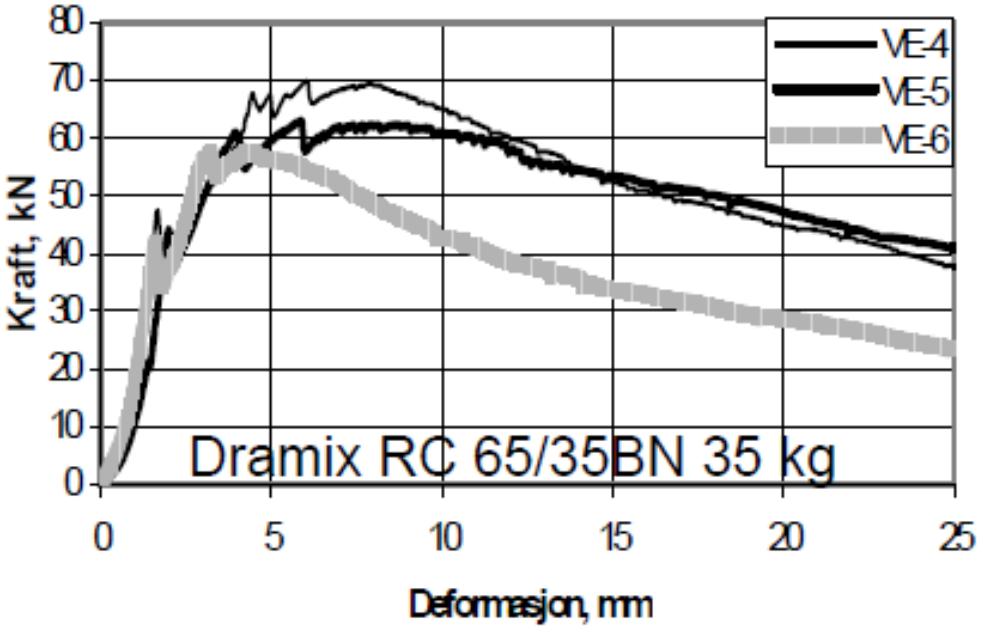


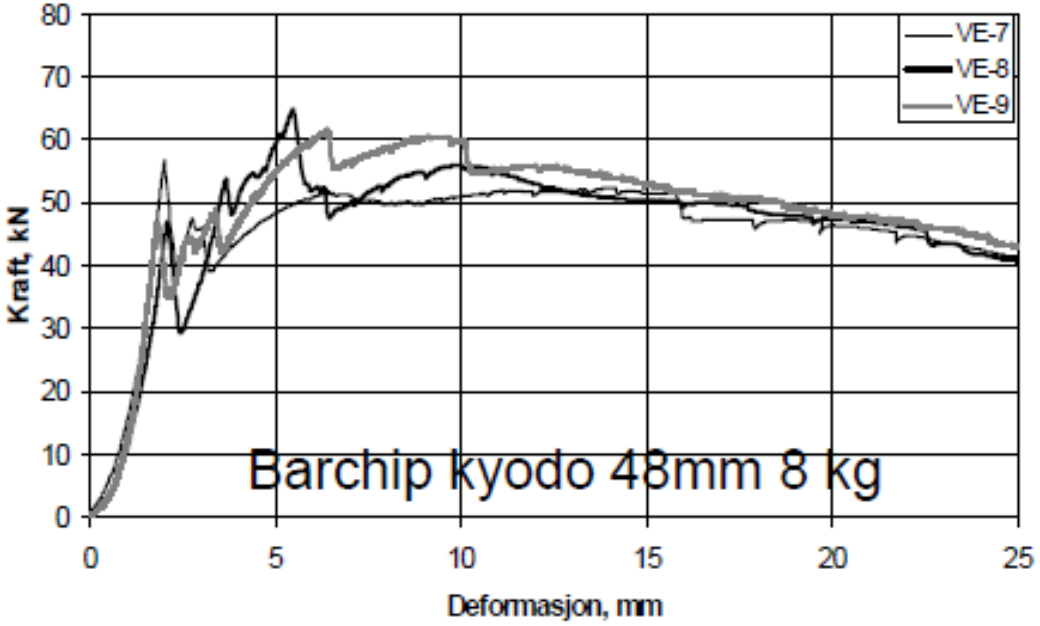












Norwegian Tunnelling Society

Steel or PP fibre.

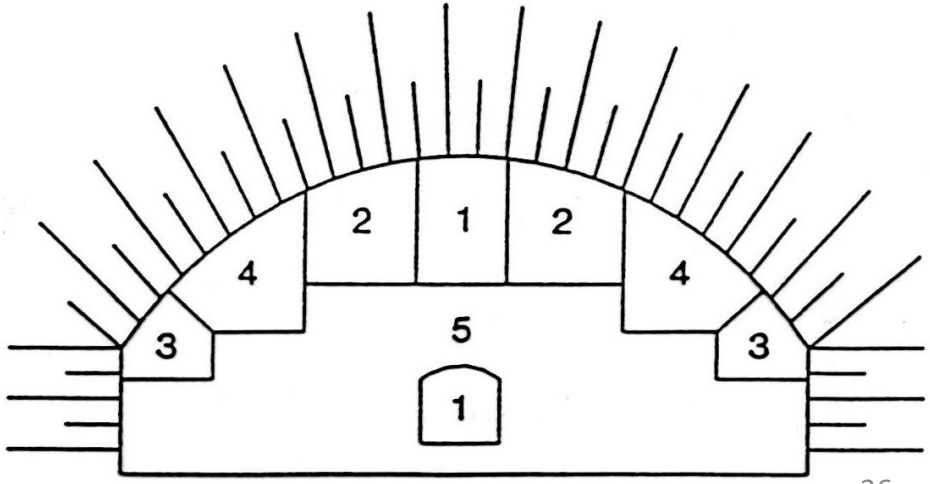
Fracture energy

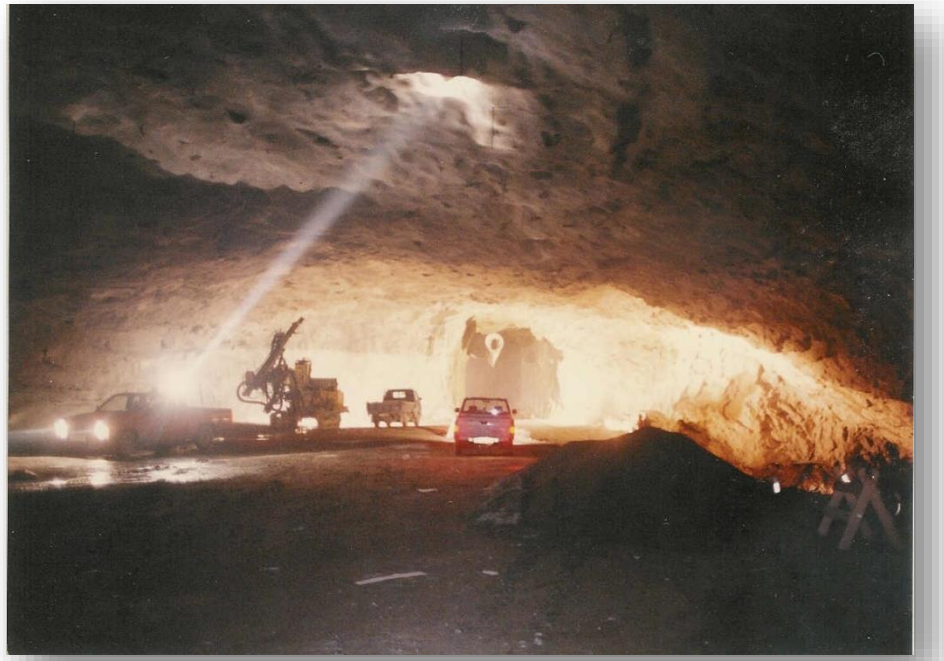
NMT: B+S(fr) in GJØVIK CAVERN

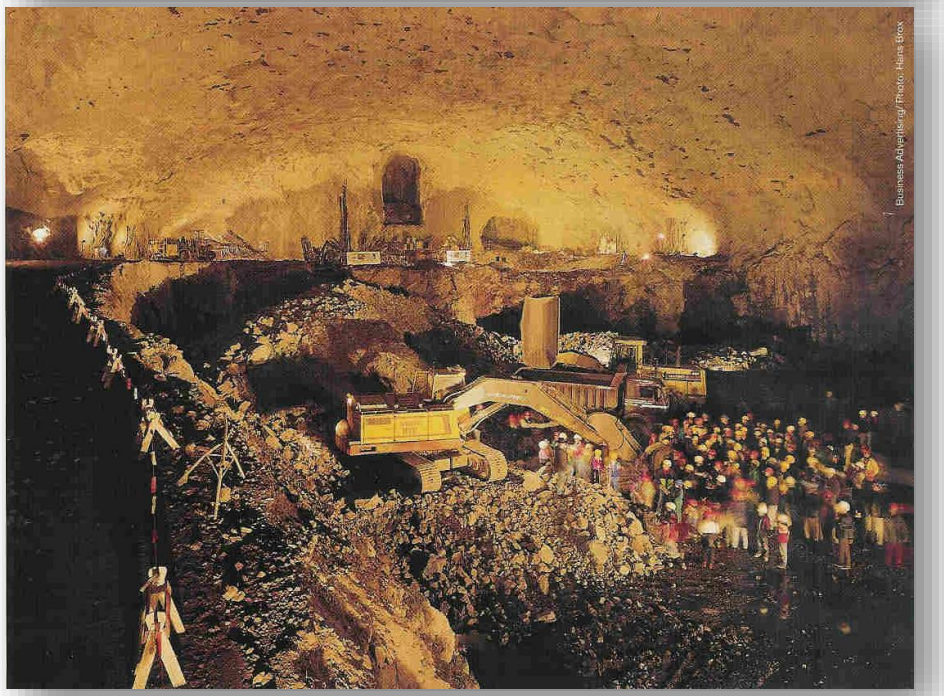
(Note: limited 'Terzaghi scale effect'. Same B c/c but thicker *S(fr)* for 60m cavern if same Q-value as 10m tunnel)

B 2.5 m c/c, L = 6 m, + S(fr) 10 cm

(and temporary anchors of 12m length)



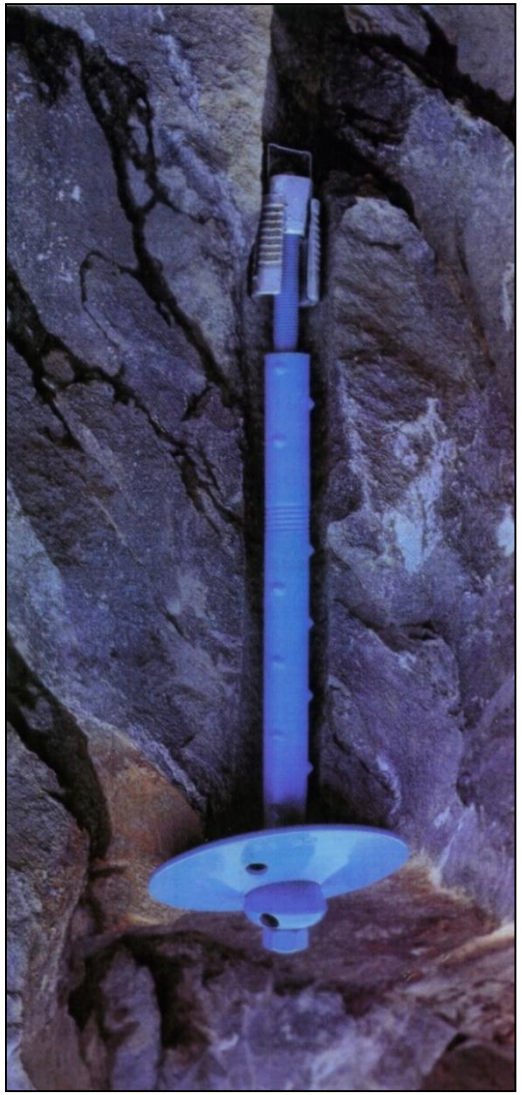


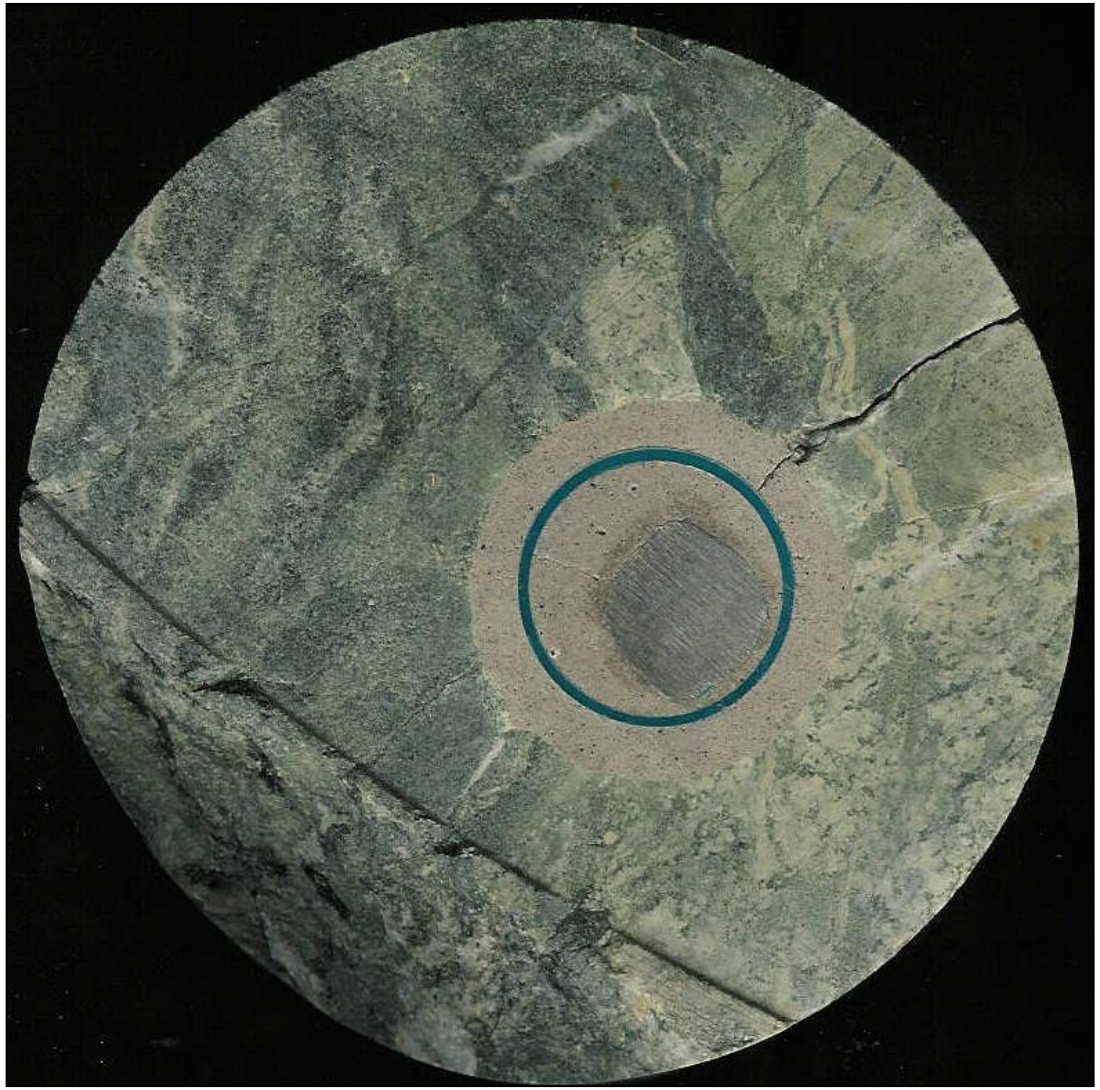


NMT: S(fr)+B

(since 1980)

Note up to 1m over-break (where Jn/Jr > 6)





CT BOLT

OVER-CORED BOLT.

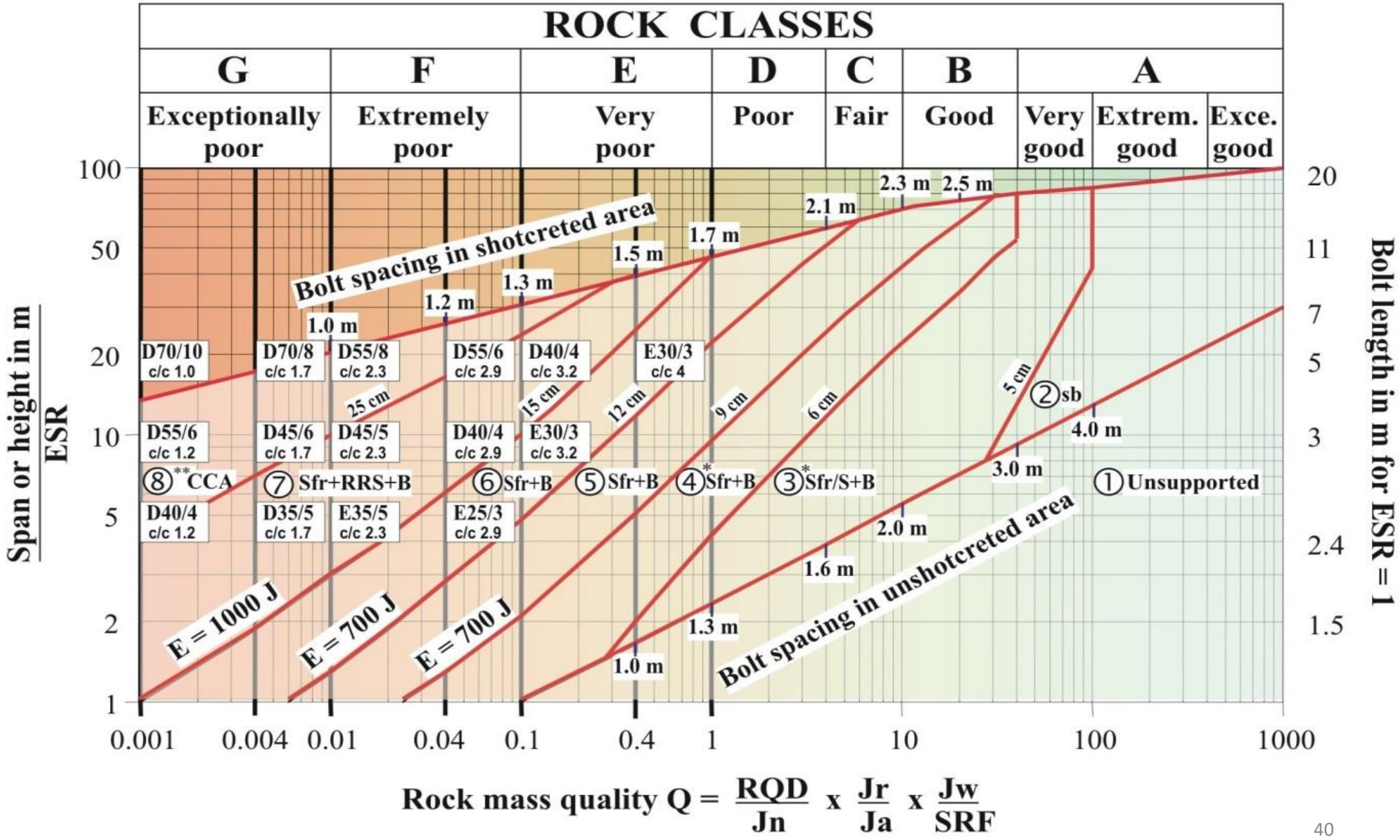
CRACK (JOINT) PENETRATION TO OUTER LAYER OF GROUT.

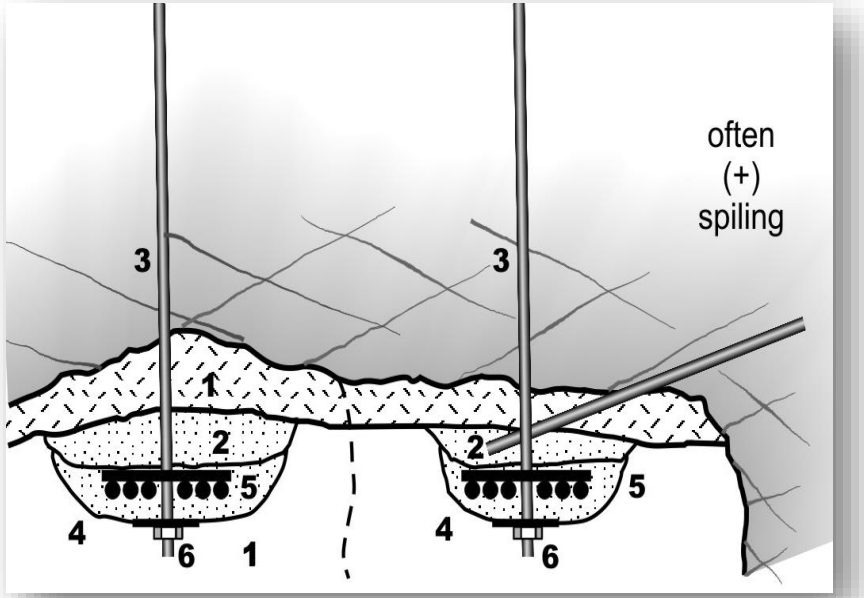
USUAL COMMENCEMENT OF CORROSION.

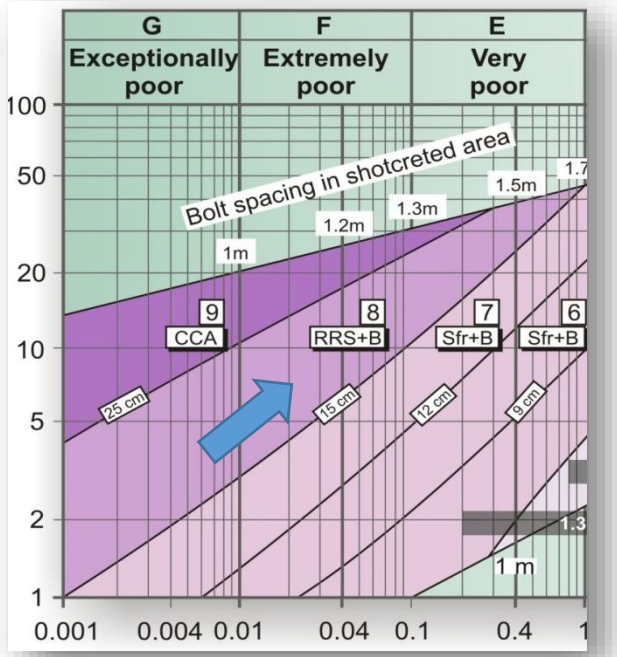
FOUR LAYERS OF CORROSION PROTECTION REMAIN, EVEN WITH THE JOINT/CRACK.

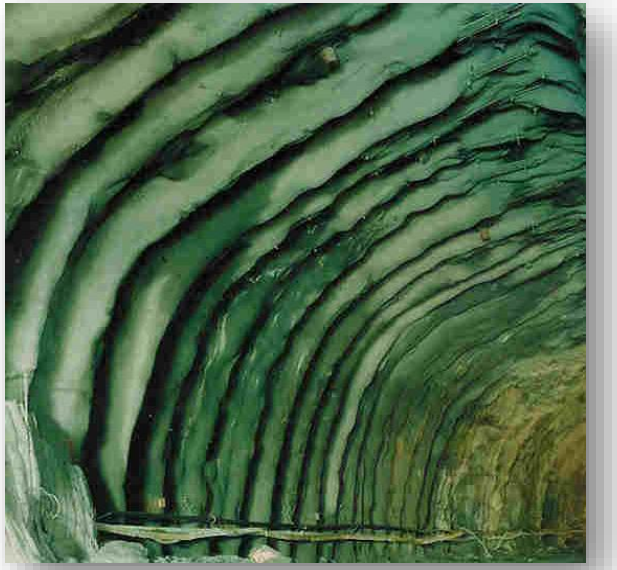
B + S(fr) for twin-track high-speed rail tunnel.

(7 of the 9 people are visitors!)


ROCK CLASSES
G
F
E
D
C
B
A
Exceptionally poor
Extremely poor
Very poor
Poor
Fair
Good
Very good
Extrem. good
Exce. good
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
Span or height in m / ESR
Bolt length in m for ESR = 1
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

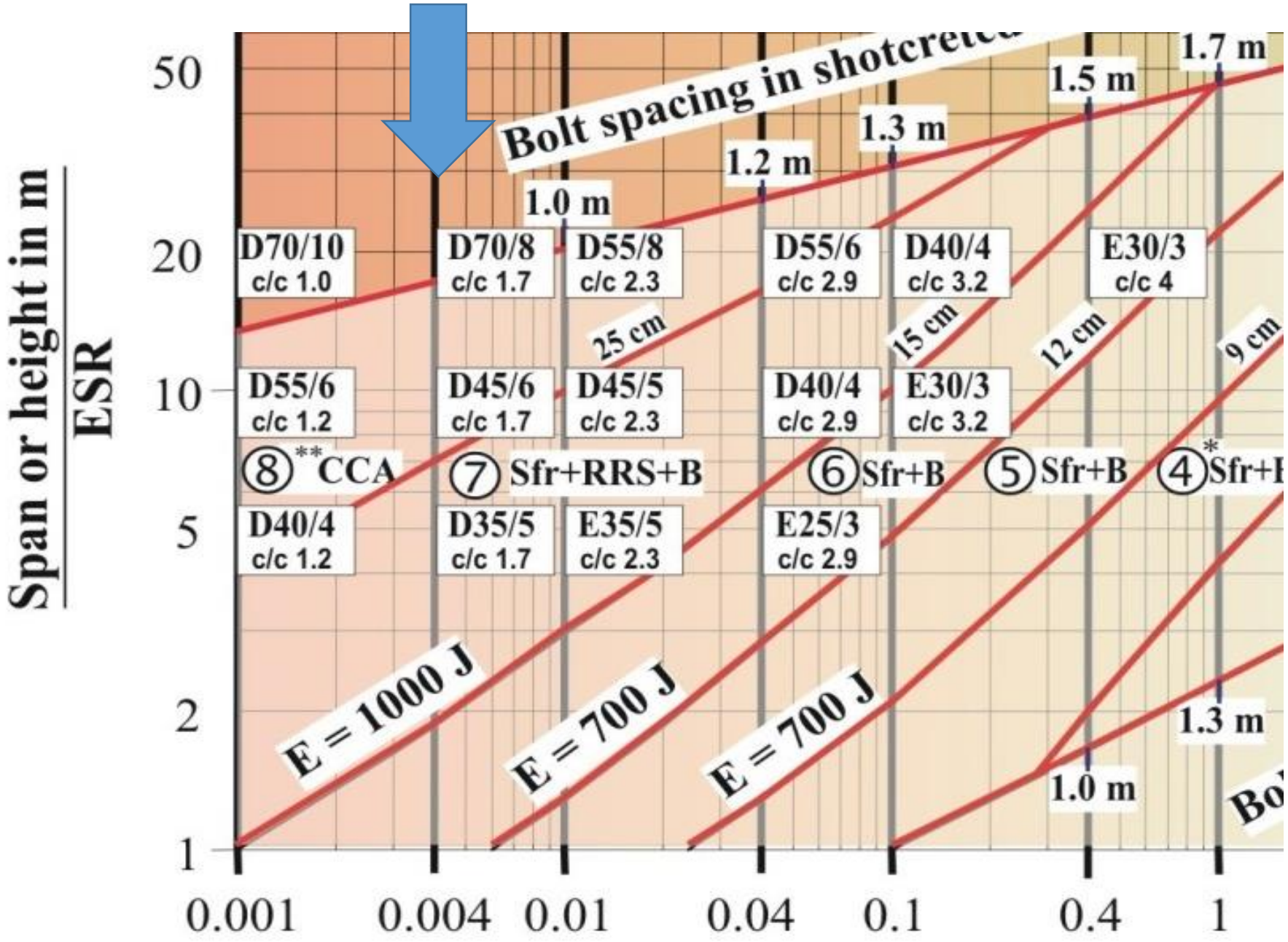






RRS is a flexible (until bolted) 'lattice' girder used in NMT.

3D effect because of S(fr) arches.

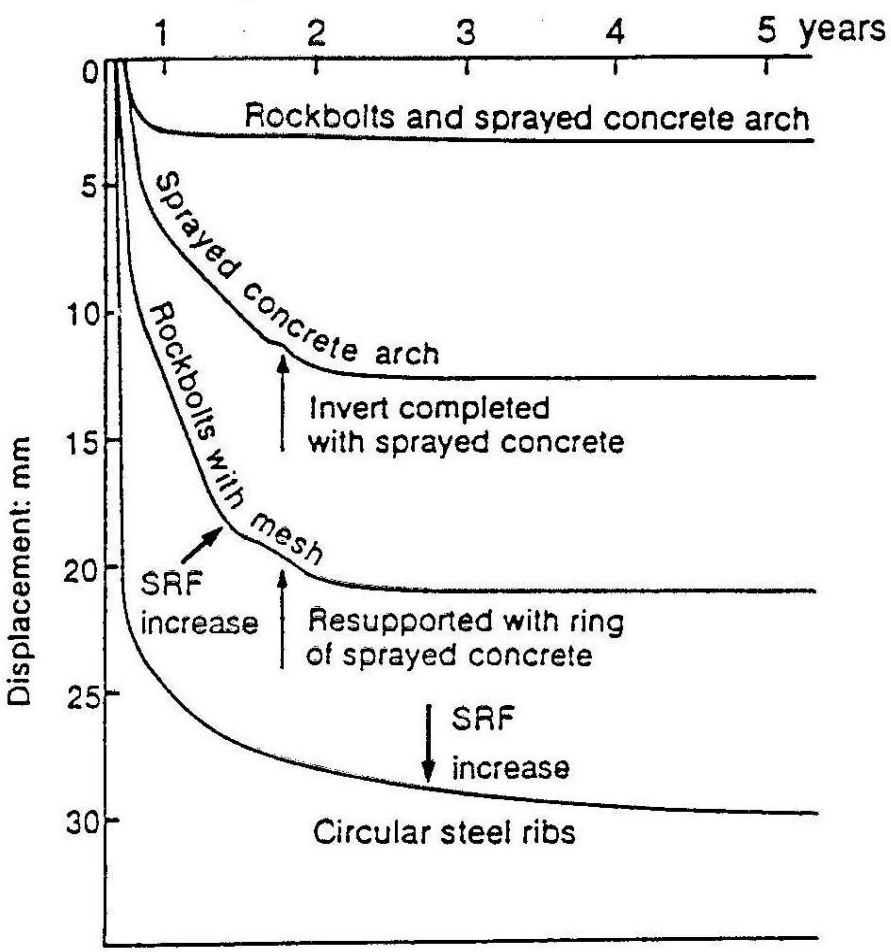


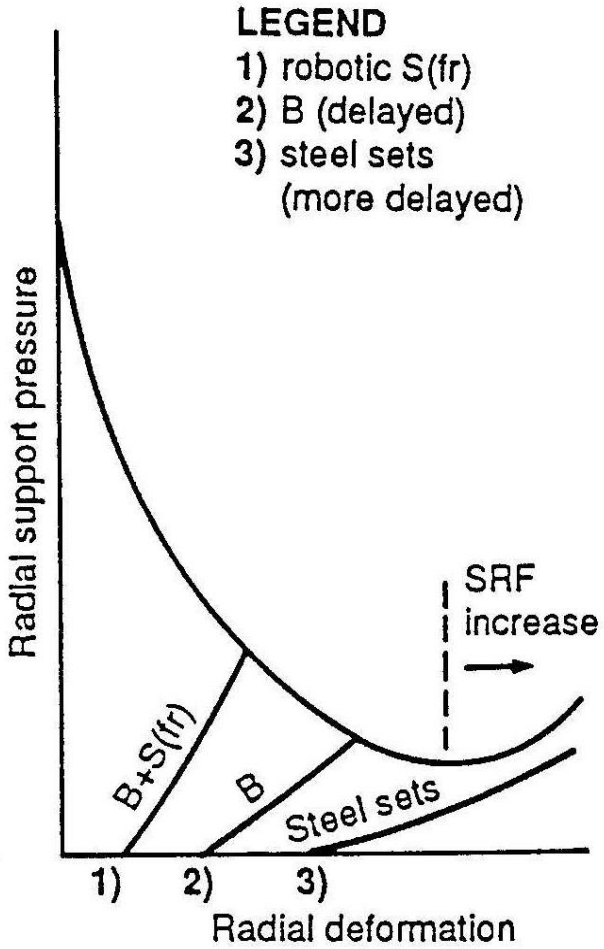
Details of the RRS

LEFT SIDE OF EACH BOX ON RELEVANT Q-VALUE

STEEL ARCHES or LATTICE GIRDERS

CONSEQUENCES OF LOOSENING ROCK – SRF ?





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

Lattice Girders (unbolted) are the ‘softest’ tunnel support yet invented.

Of course LG is ‘convenient’....

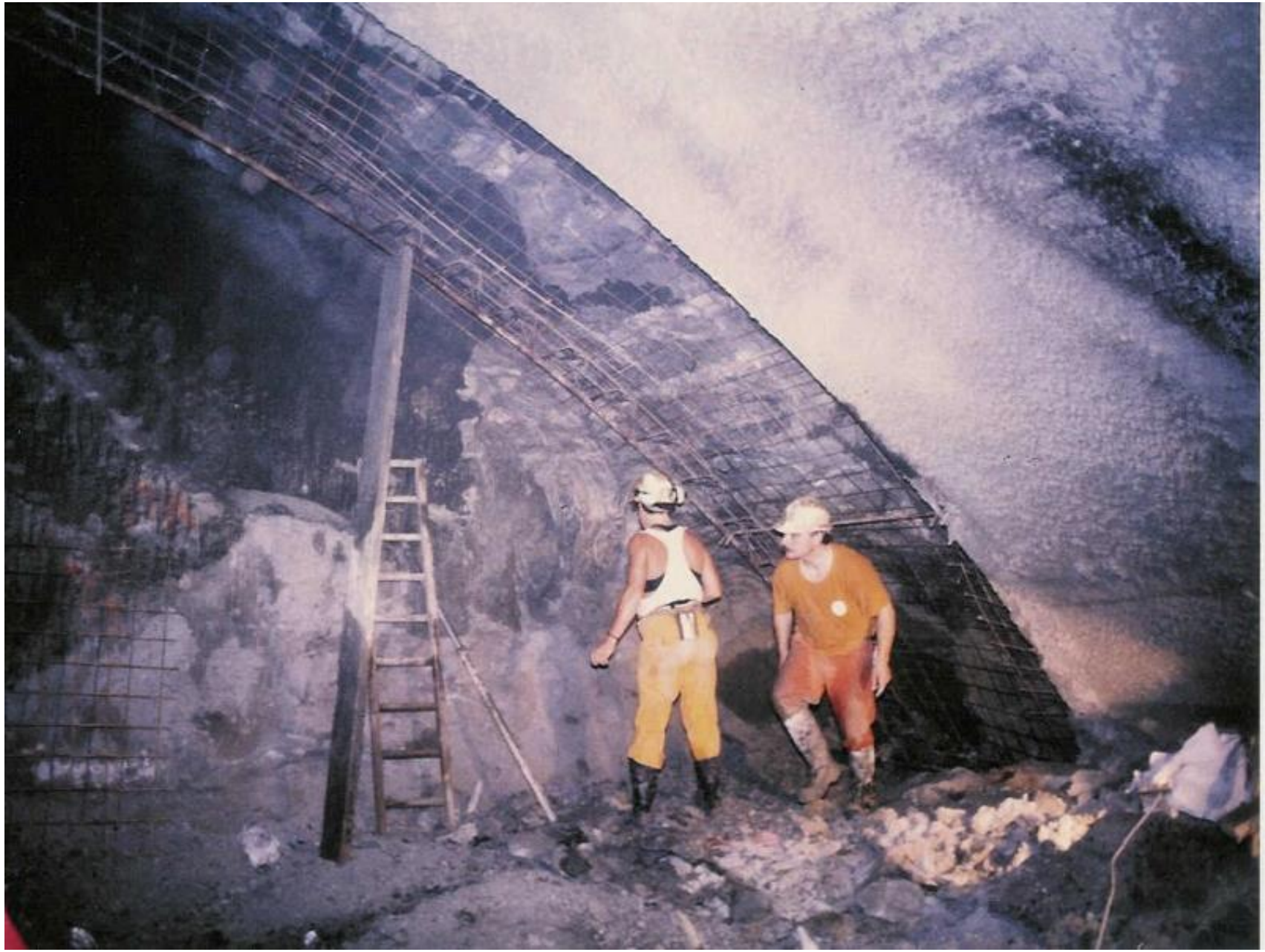
and not usually so over-loaded.

SOMEWHERE ELSE IN SOUTH AMERICA

140 m collapsed first, then 140m in parallel tube. No casualties.

INCORRECT
(NOT ADJUSTED TO CONDITIONS)
REINFORCEMENT AND SUPPORT TECHNIQUES.

OVER LOADED STEEL SETS CAUSED BY SHEAR ZONE IN THE ARCH



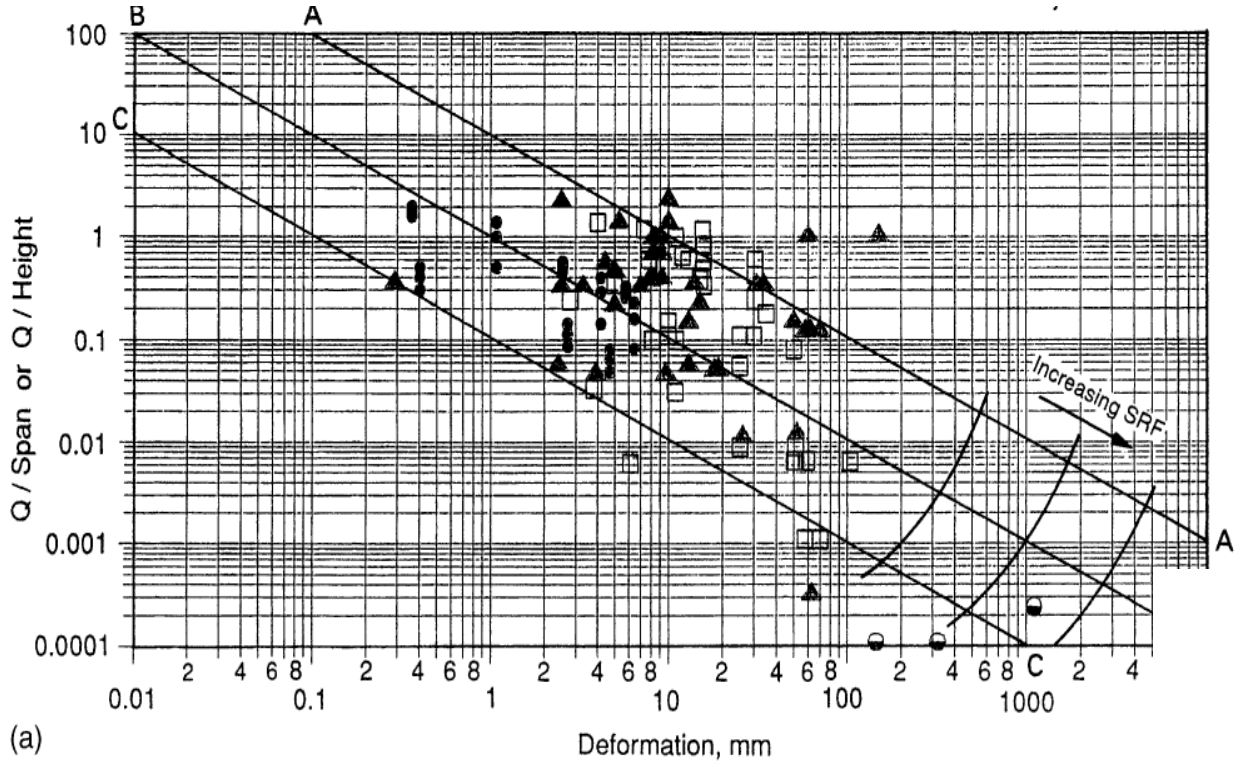
The temporary support phase of NATM (if including lattice girders) is not PARTICULARLY STABLE. Where is the stiffness? And no bolting.

EUROTUNNEL:

SUB-SEA CROSS-OVER CAVERN

FINAL CCA STABLE – OF COURSE (INTERNET PHOTO).

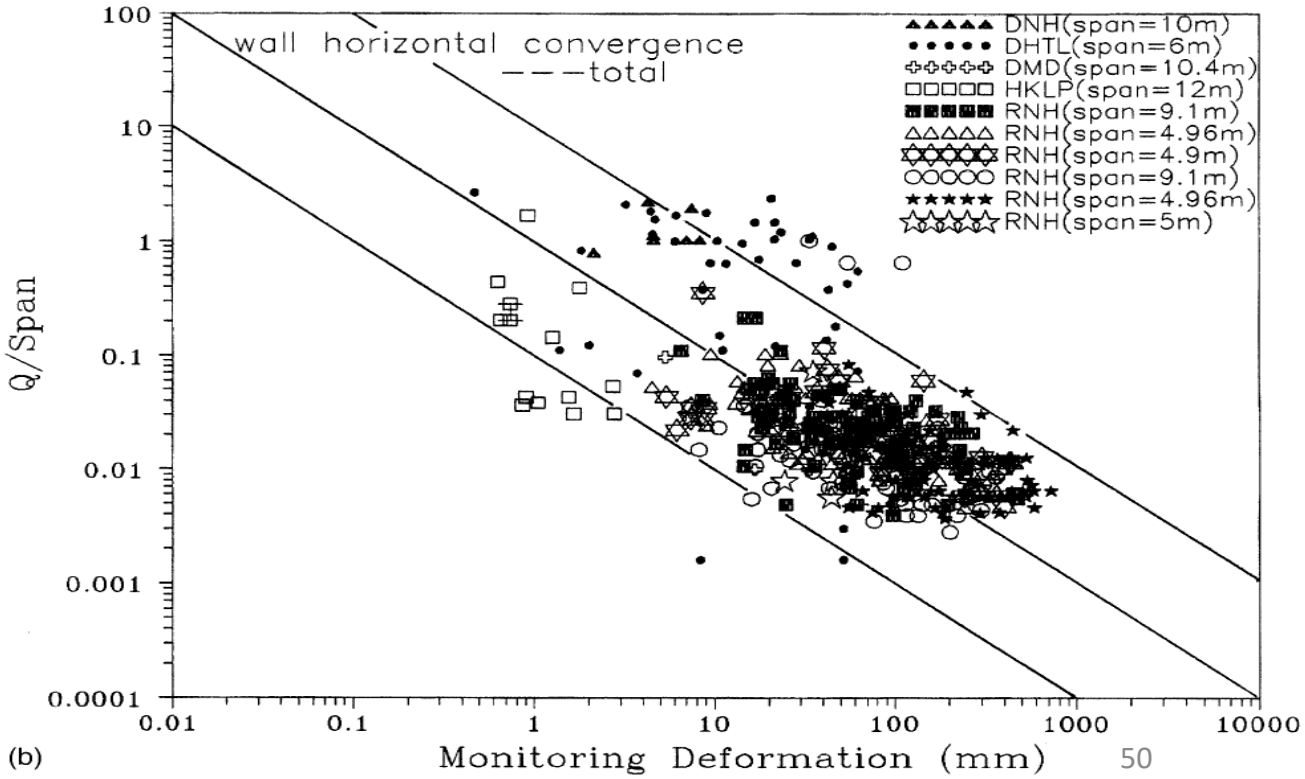
3. TUNNEL AND CAVERN DEFORMATION, RELATIVE COST AND TIME RELATED TO Q



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

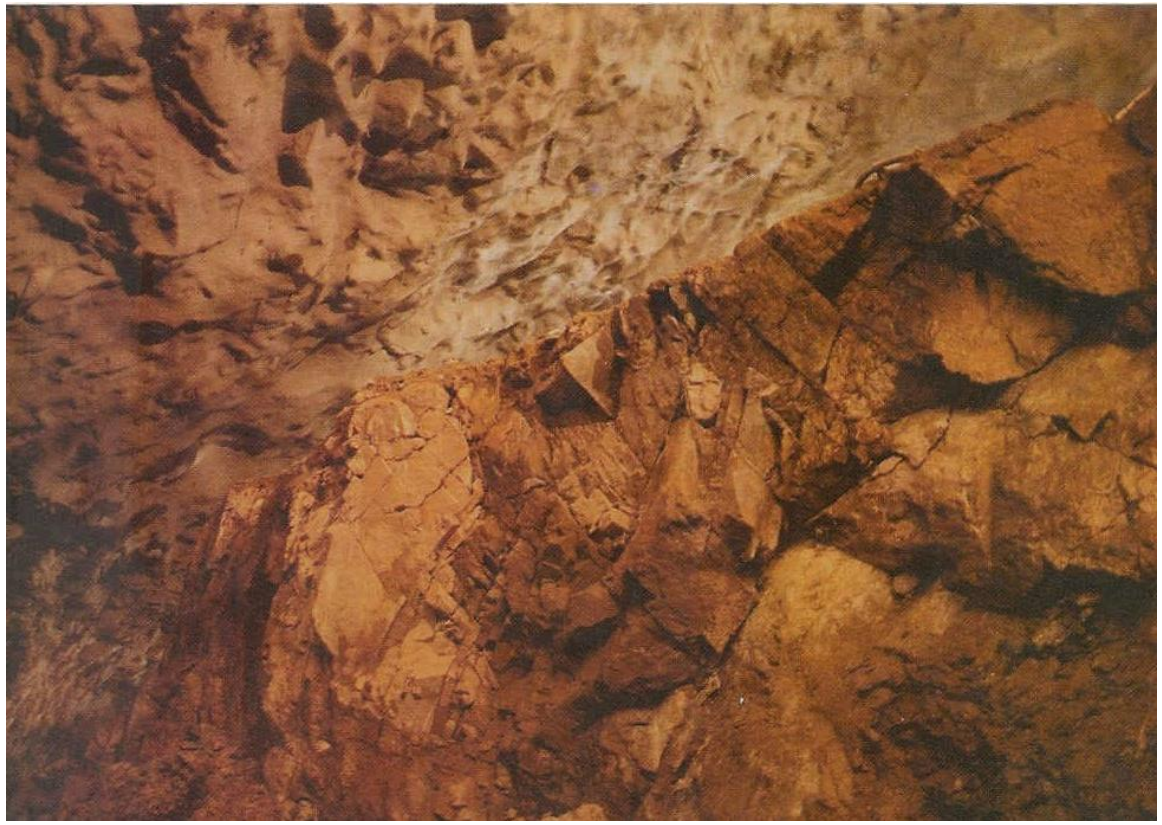
Gjøvik Olympic Cavern

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

(RQD = 60 – 90)

(Q = 1-30)

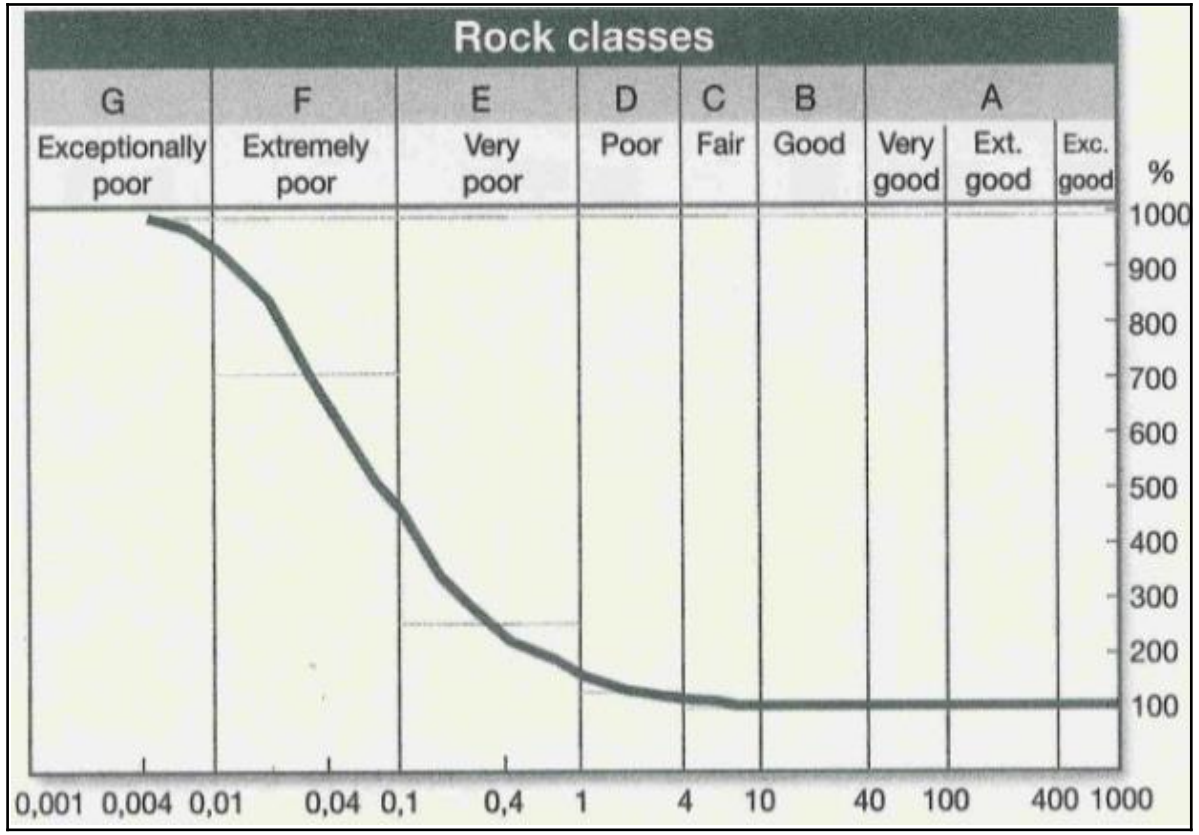
V_P = 3.5-*5.5* km/s

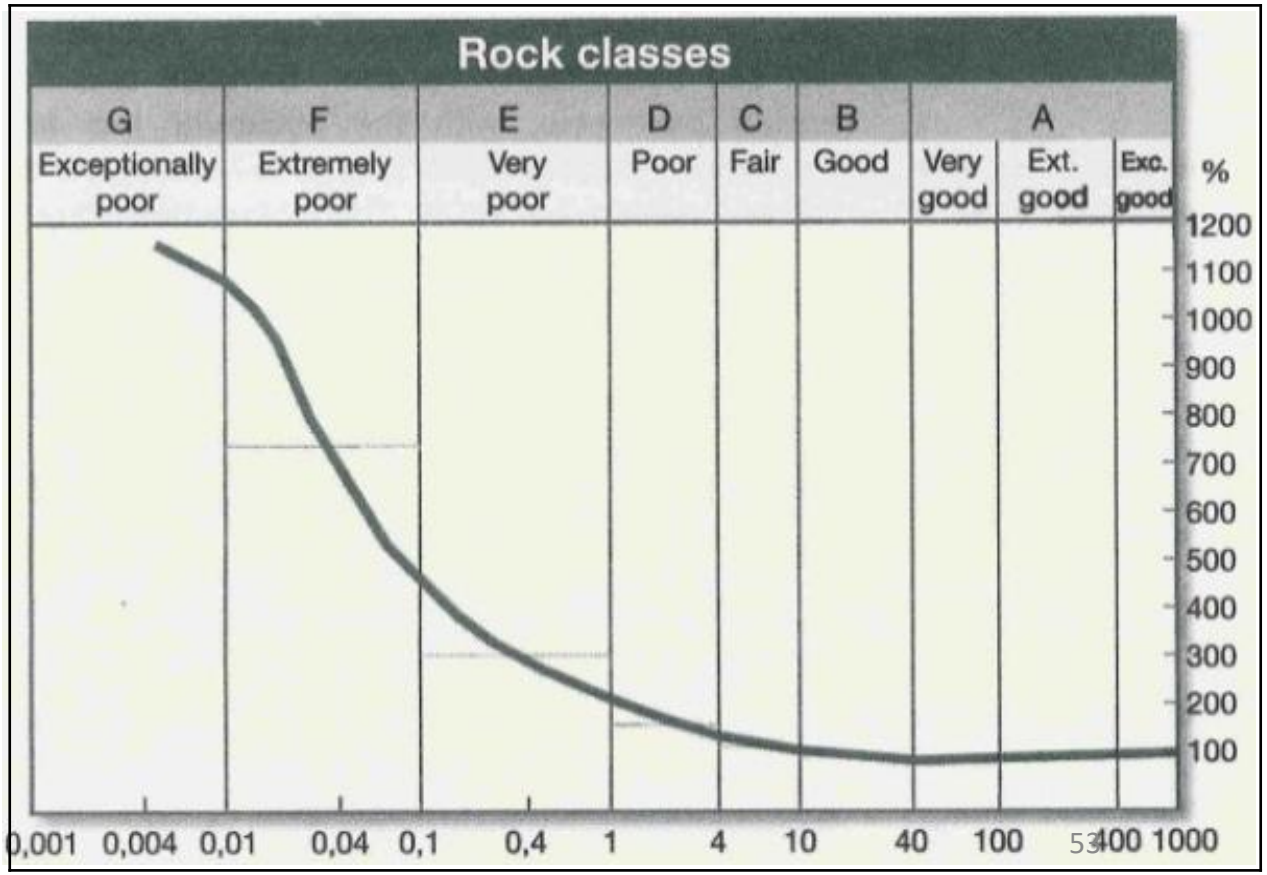


$$\Delta_v = \frac{60{,}000}{100 \times 10} \times (1/75)^{1/2} = 6.9 \text{ mm}$$

(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)

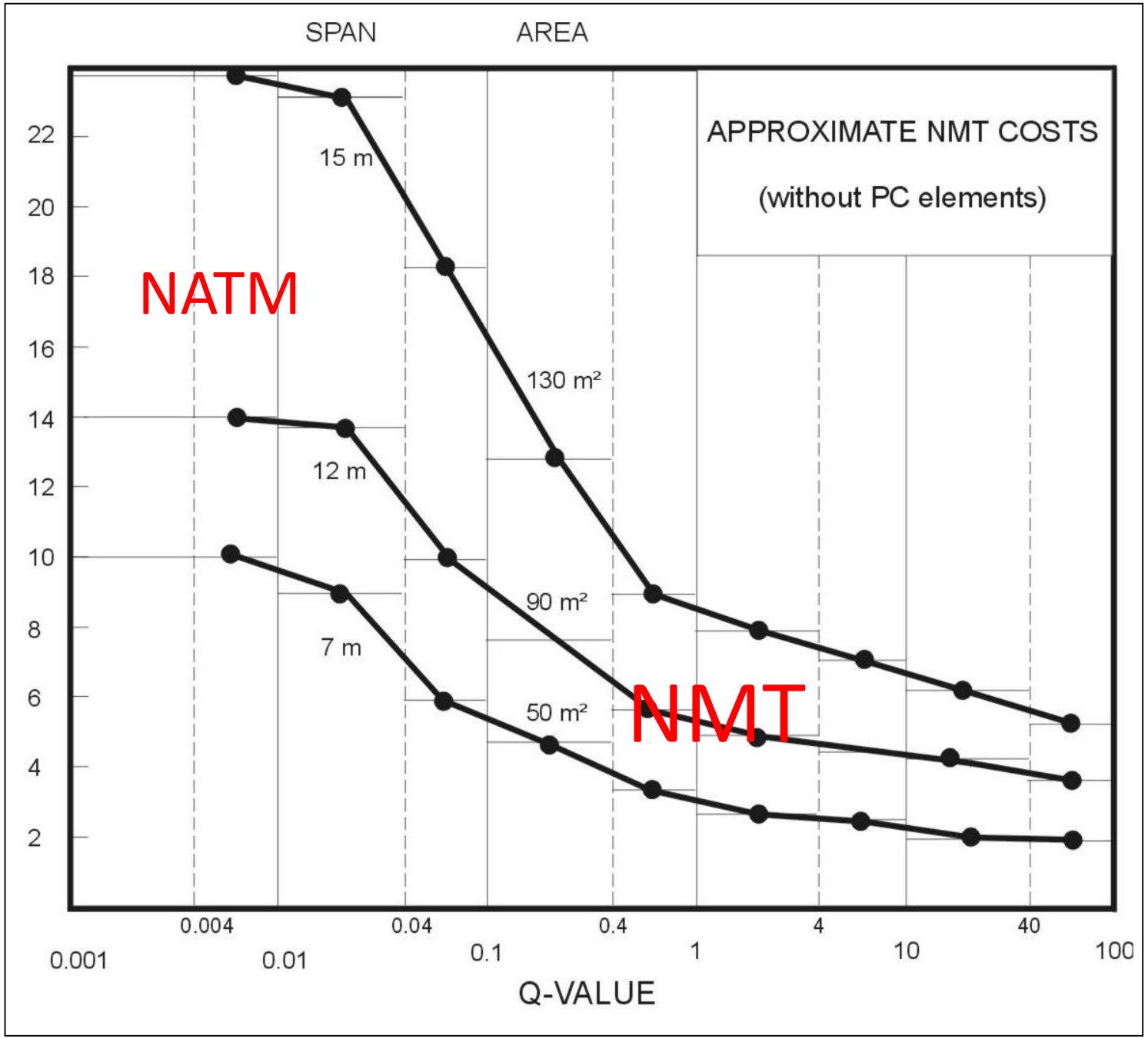
RELATIVE *TIME* AND *COST* IN RELATION TO Q-VALUE





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

Barton, Buen and Roald, 2001.



RELATIVE COST-VERSUS-Q CURVES

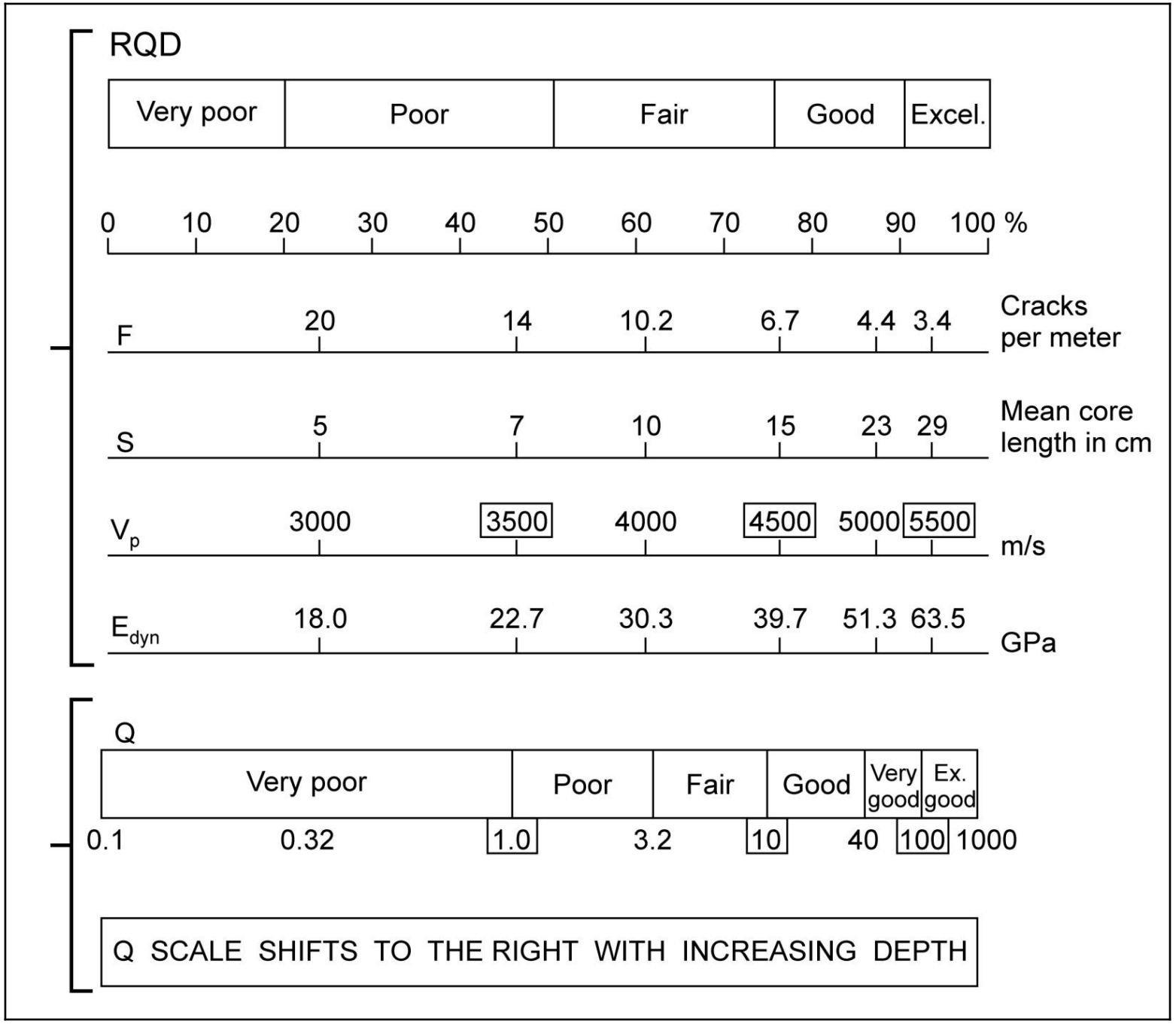
PART 1: Conventional applications of Q

0----------54

PART 2: More recent applications of Q

56----------108

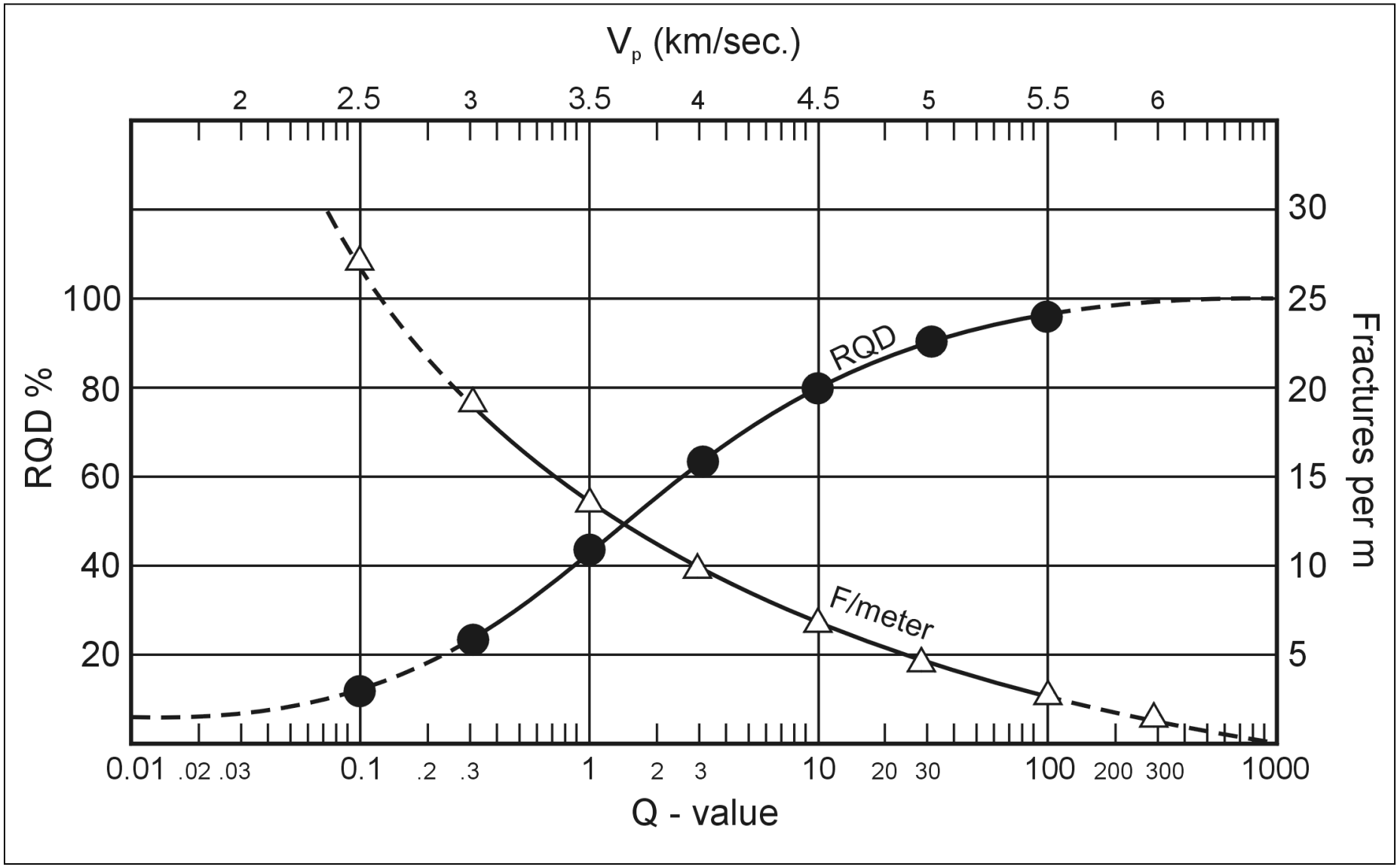
4. SEISMIC VELOCITY, DEFORMATION MODULUS, INFLUENCE OF DEPTH or STRESS



HARD ROCK DATA

Sjøgren et al. 1979, using 120km seismic profiles, 2.8km core.

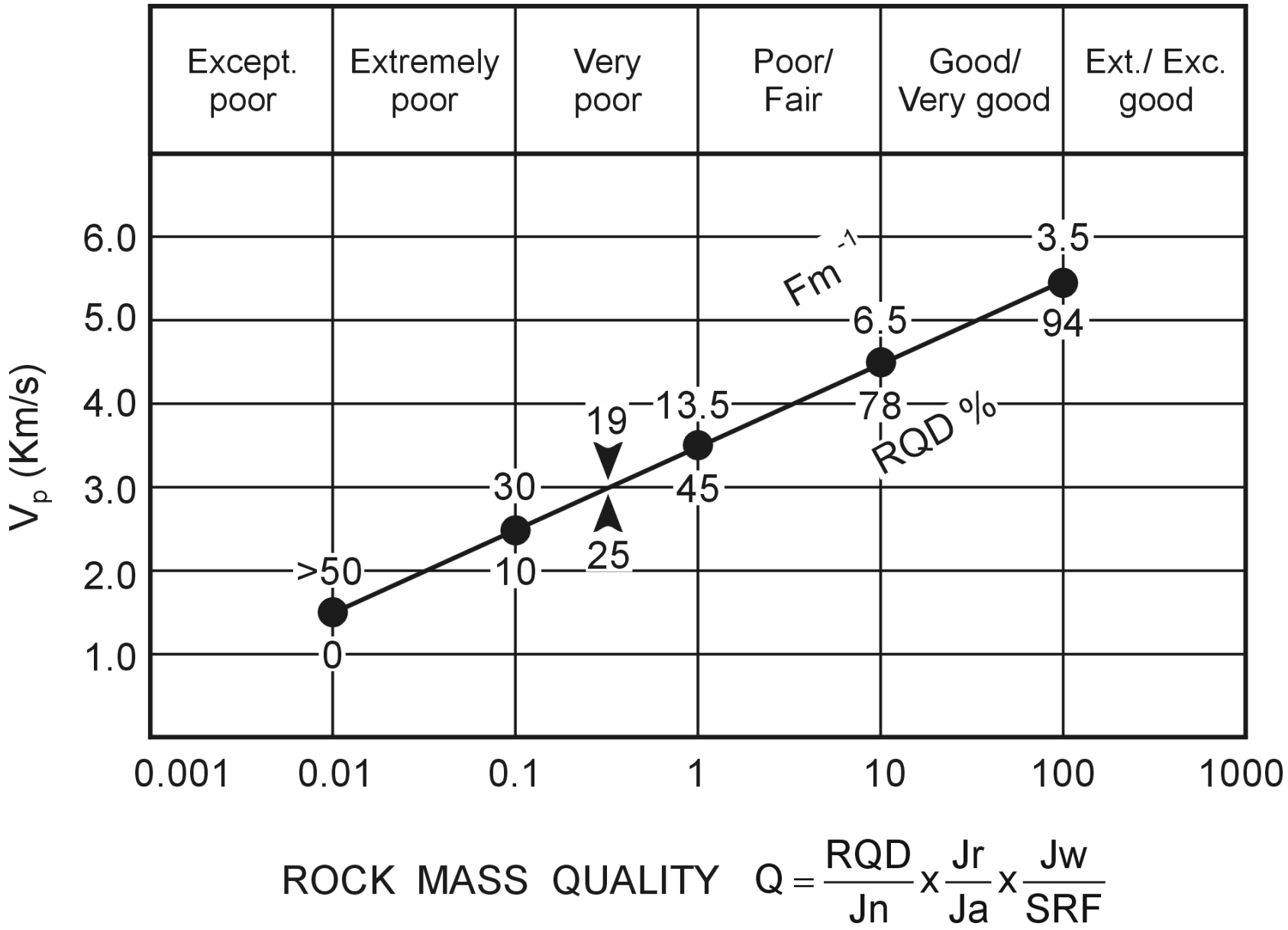
Q-scale added by Barton, 1995/2006.



The starting point from 120 km of seismic profiles, 2.8 km core.

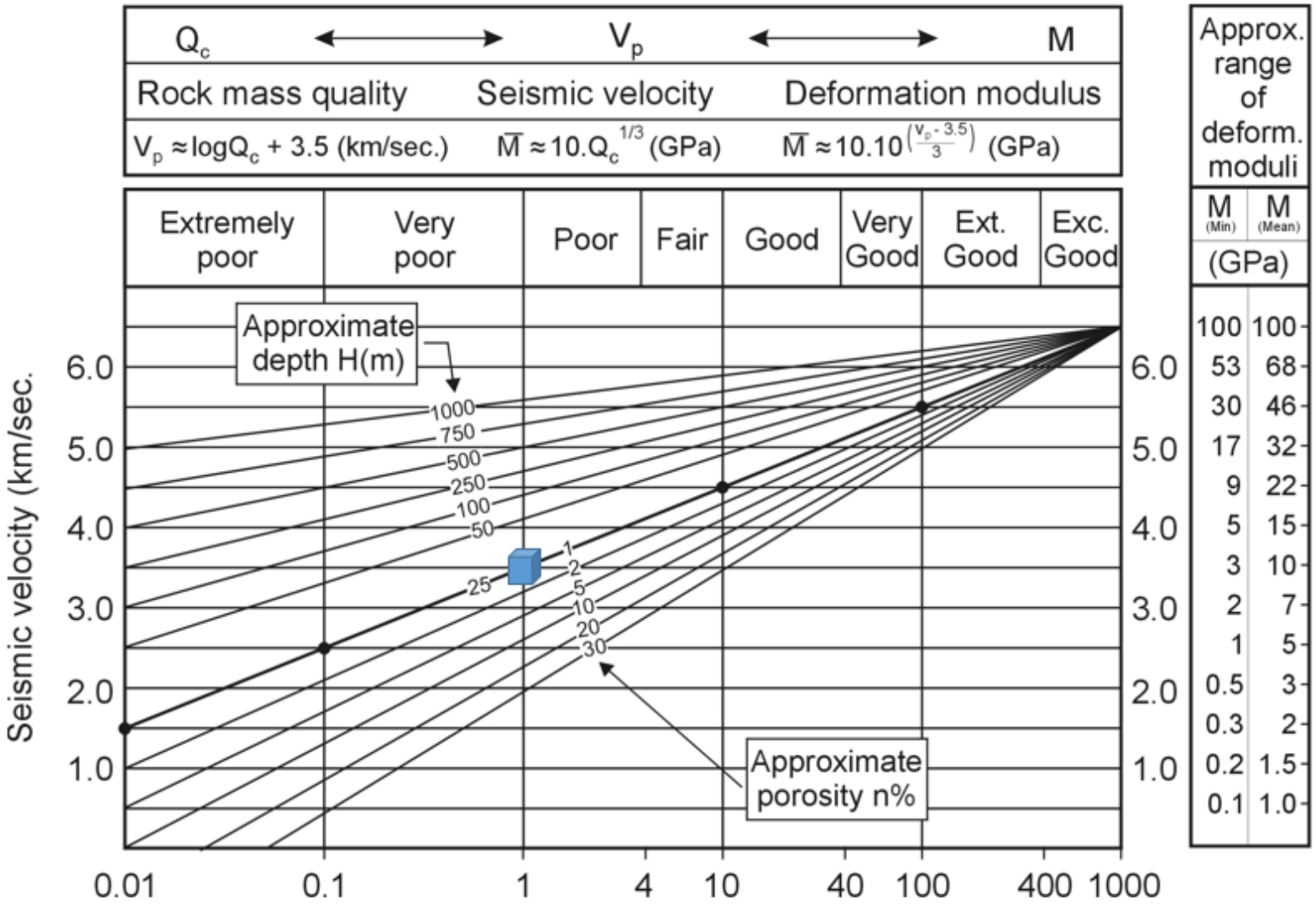
Hard rock

(After Sjøgren et al. 1979, with Barton, 1995 addition of Q – and dotted trends)



Sjøgren et al. 1979 data: hard rock, near-surface.

Q-scale from Barton, 1995.



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

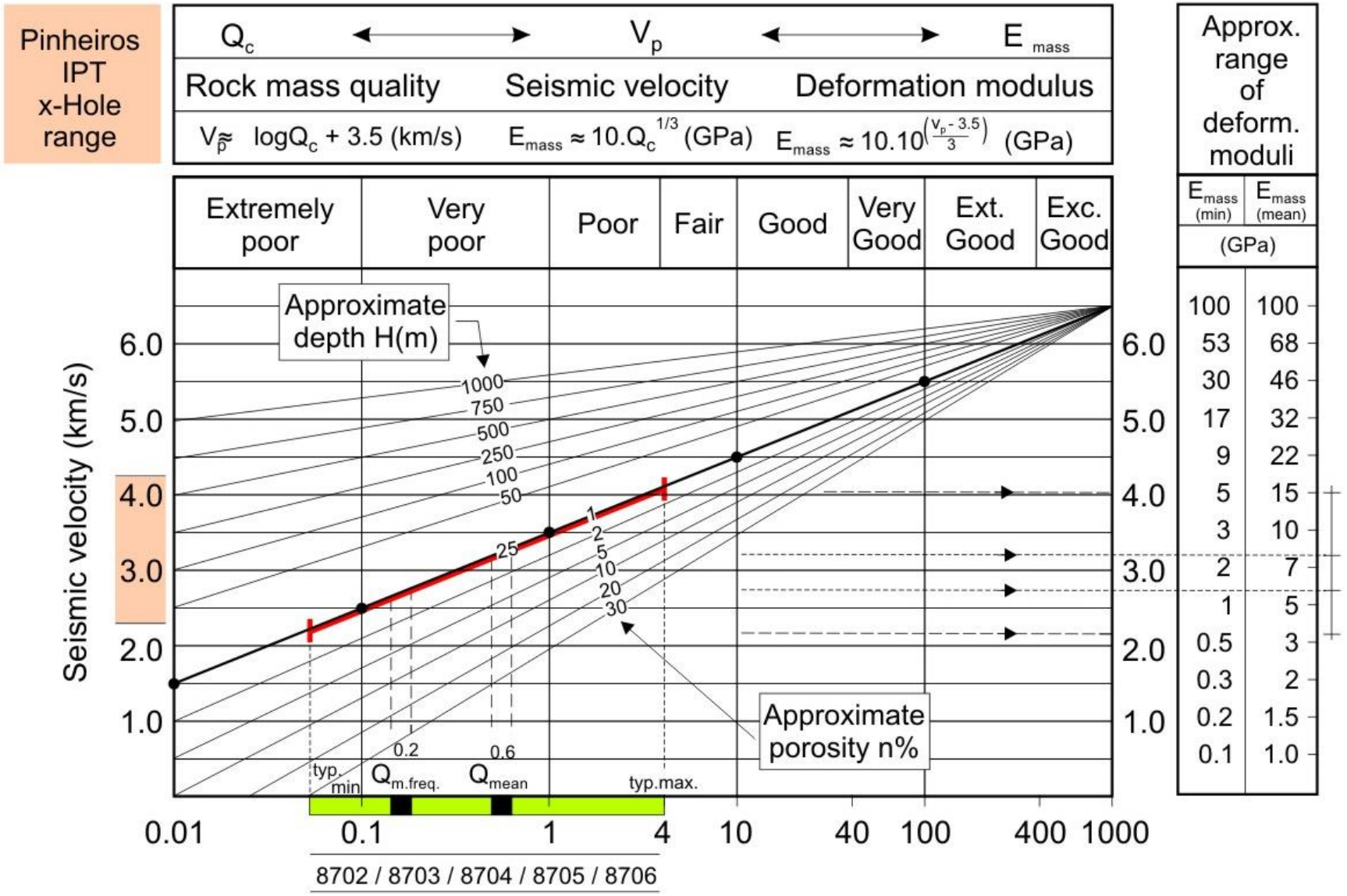
An empirical model for interpreting depth effects. Some of the data is X-hole tomography from Sellafield tuffs/ignimbrites at 1,000m depth.

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

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

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

Note need for higher modulus at greater depth, where Vp will also probably be higher.



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

Assume σ_c= 100 MPa

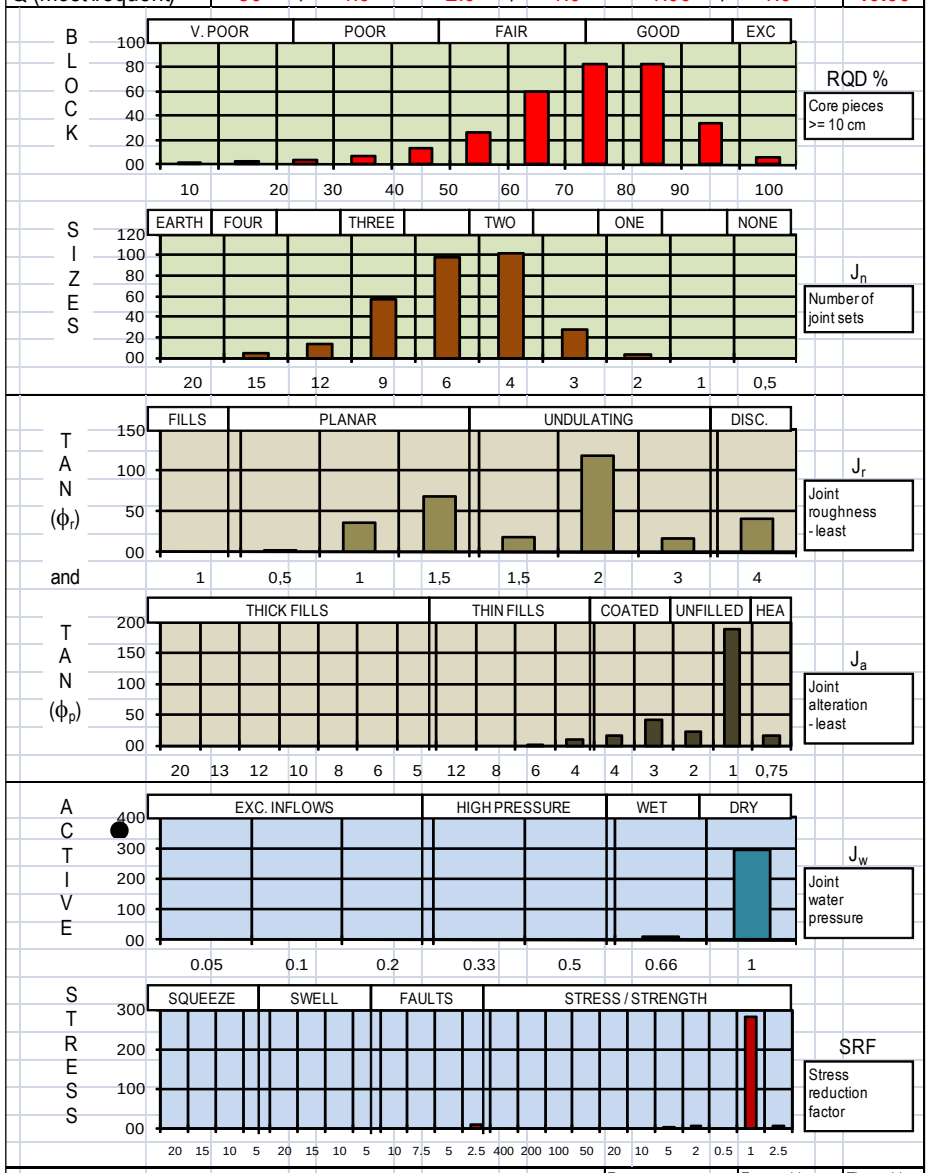
Approximate correspondence between **cross-hole seismic Vp,** and **Q-logging results** for five boreholes –

AN EXAMPLE from SAO PAULO, BRAZIL

Bakhtiary Dam, Iran

Upper diversion tunnel: top heading

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15.0	*	0.5	/	6.0	*	0.66	/	5.0	=	0.007
Q (typical max)=	100	/	2.0	*	4.0	/	0.8	*	1.00	/	1.0	=	266.7
Q (mean value)=	73	/	6.0	*	2.0	/	1.6	*	0.99	/	1.1	=	13.74
Q (most frequent)=	80	/	4.0	*	2.0	/	1.0	*	1.00	/	1.0	=	40.00



BAKHTIARY DAM HEPP UPPER DIVERSION TUN	Rev.	Report No.	Figure No.
		NB&A #3	6

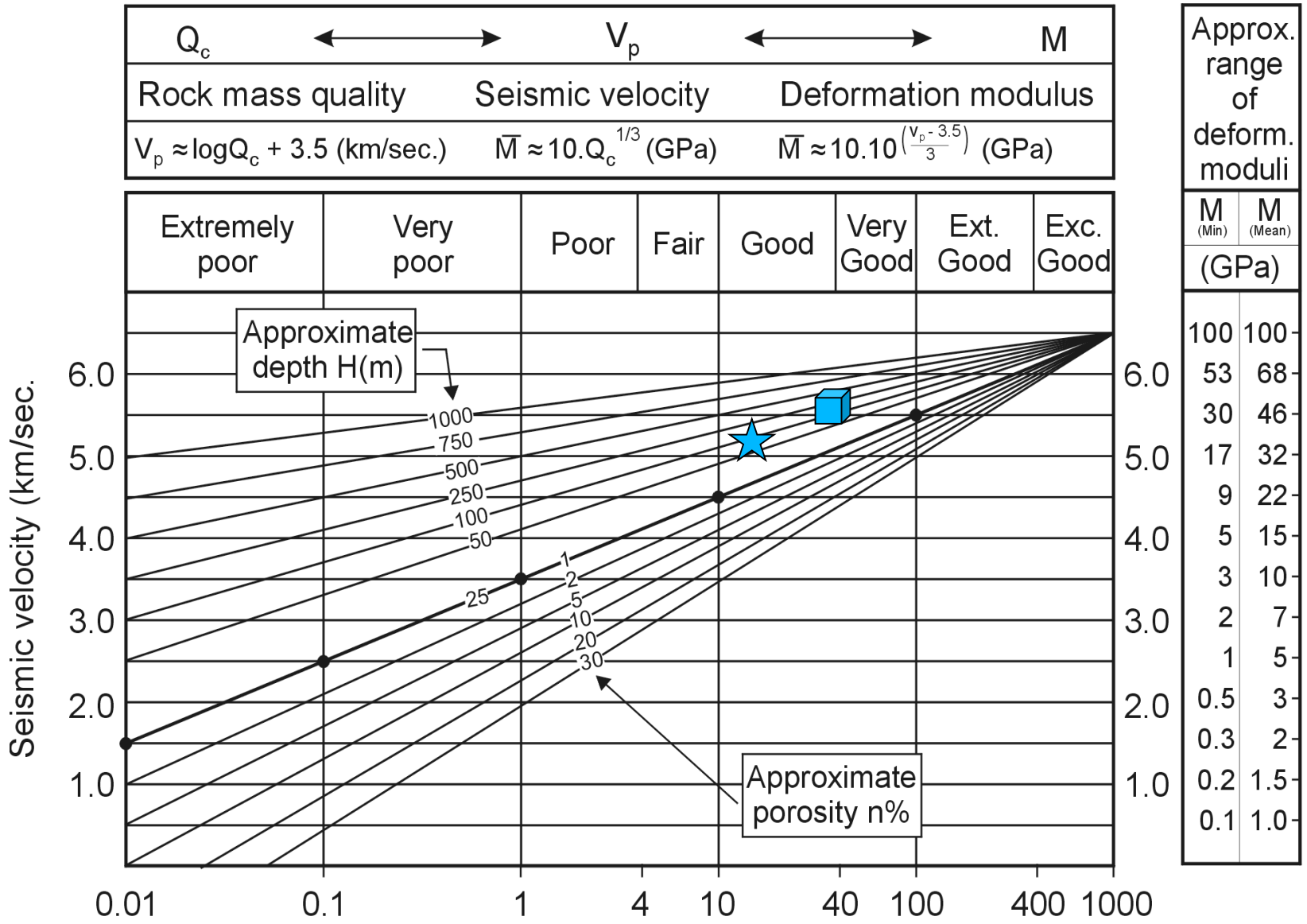
In diversion tunnel

$Q_{m.f.} = 40$

$Q_{mean} = 14$

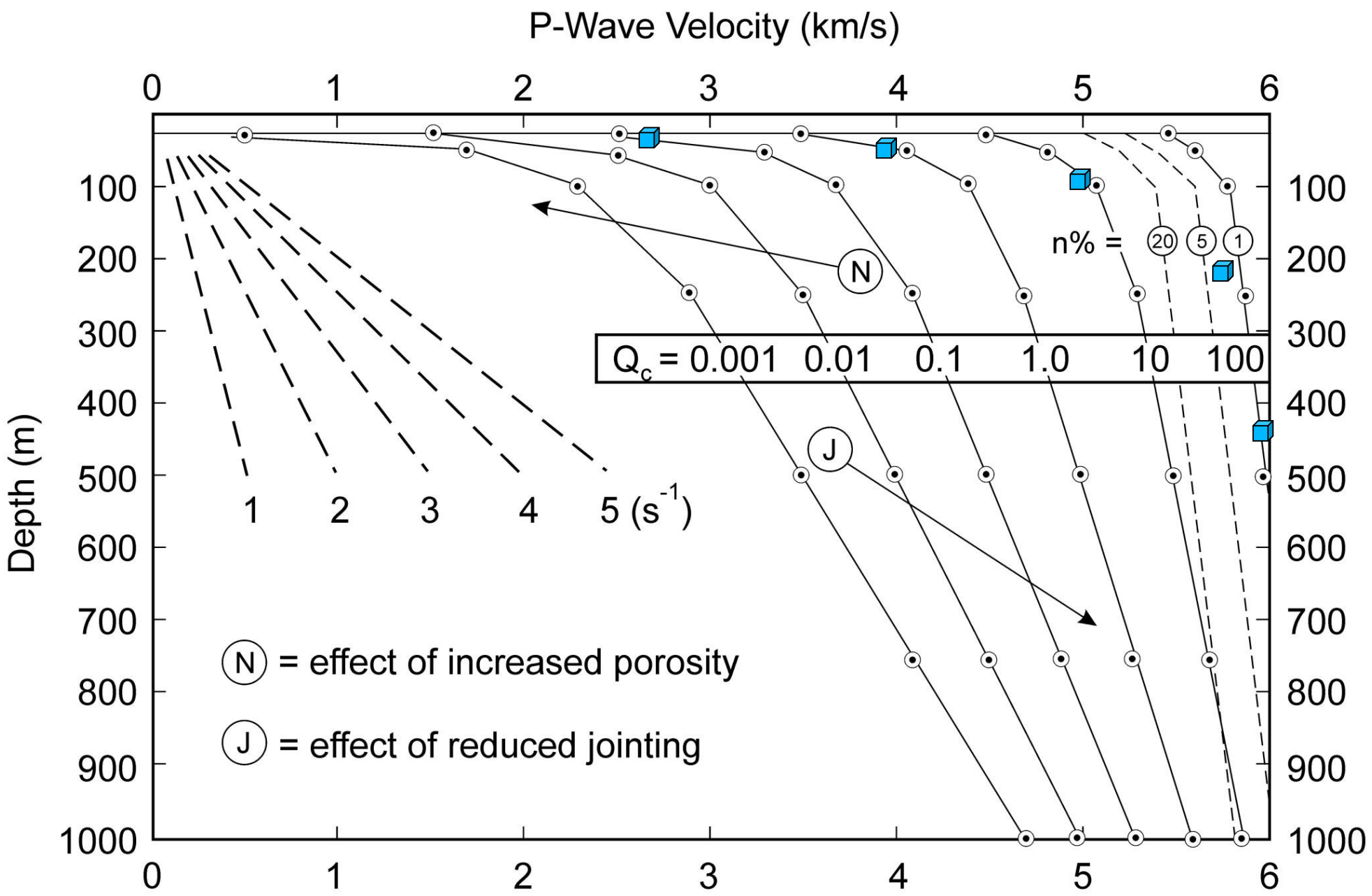
Next steps:

1. Convert Q to Qc
(What UCS?)
2. Convert to V_p
3. Convert to E_{mass}



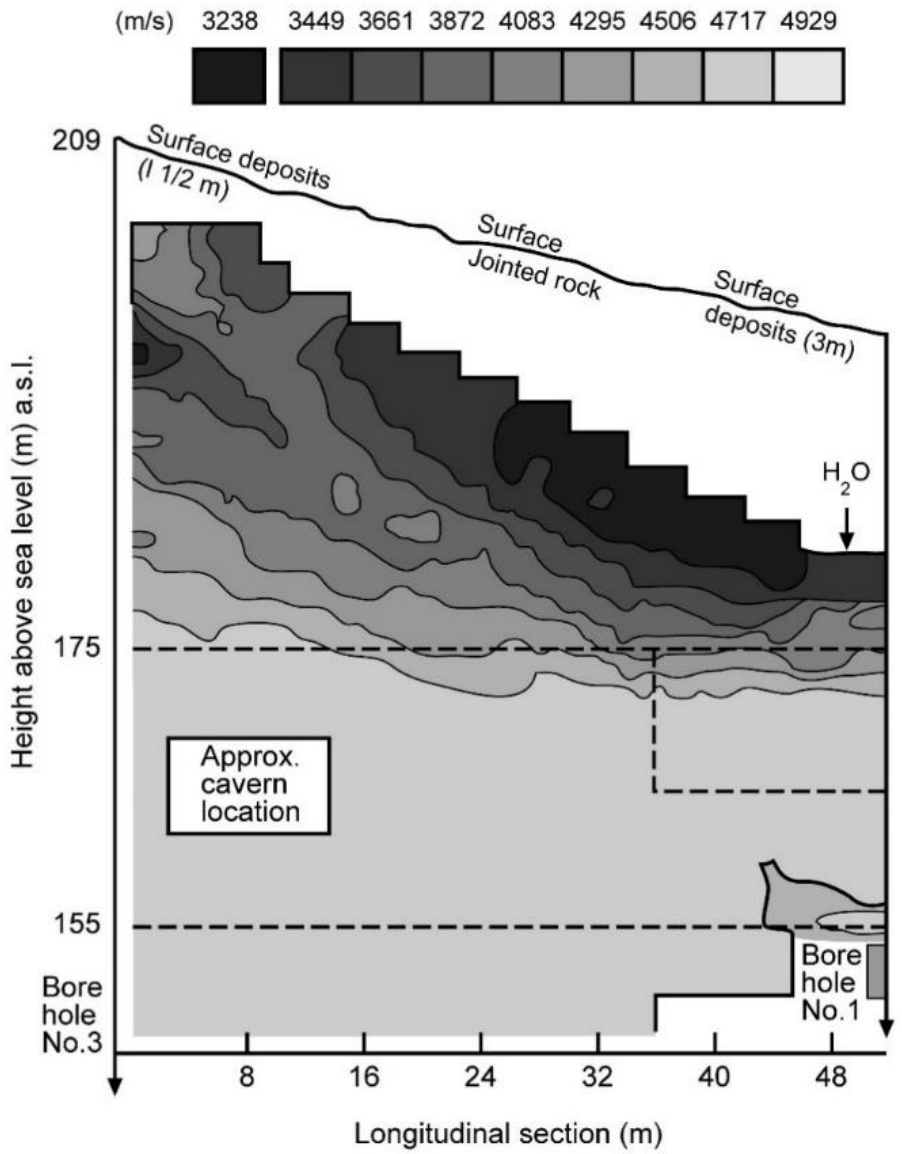
Approx. range of deform. moduli	
M (Min)	M (Mean)
(GPa)	
100	100
53	68
30	46
17	32
9	22
5	15
3	10
2	7
1	5
0.5	3
0.3	2
0.2	1.5
0.1	1.0

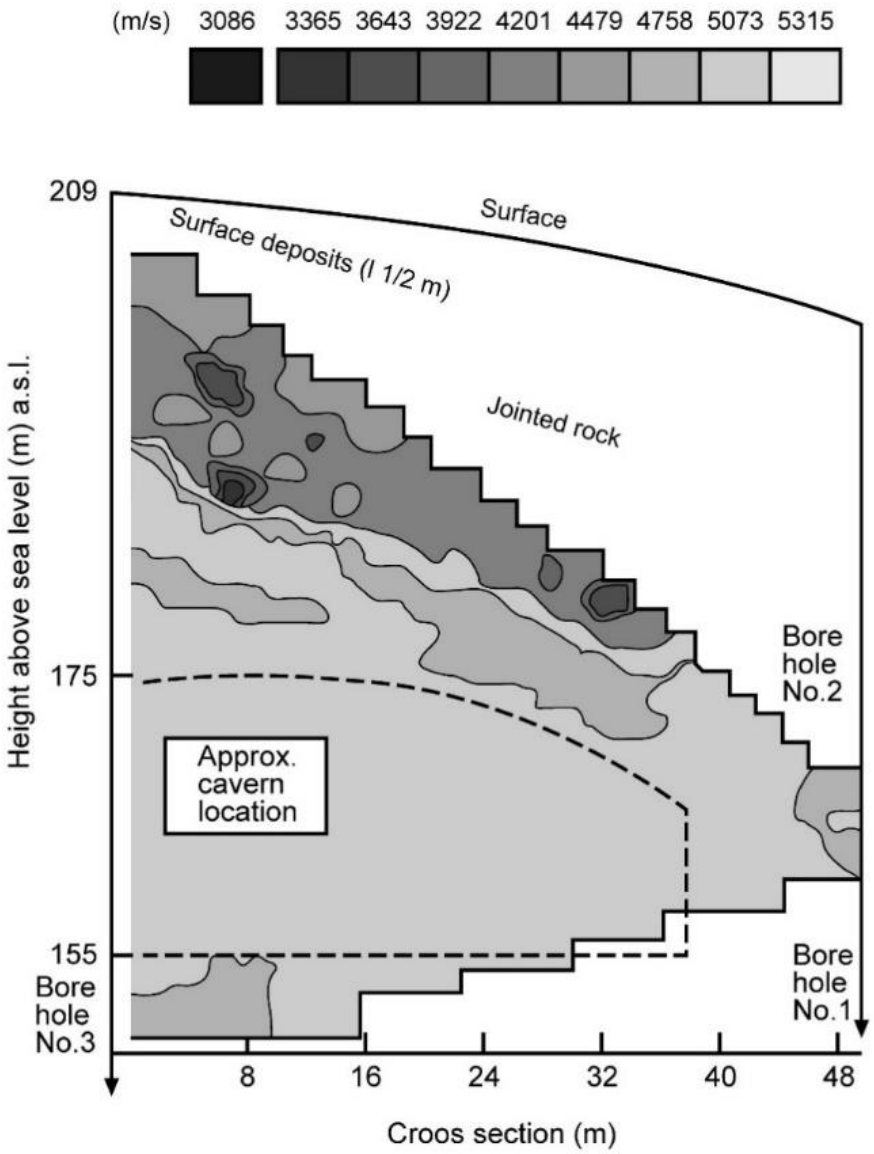
$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}\right] \frac{\sigma_c}{100}$$



IN THE NEAR-SURFACE – P-WAVE VELOCITY CHANGES RAPIDLY.

('Q-JUMPING')…. DUE TO IMPROVED Q-VALUE (LESS WEATHERING) AND INCREASED STRESS.

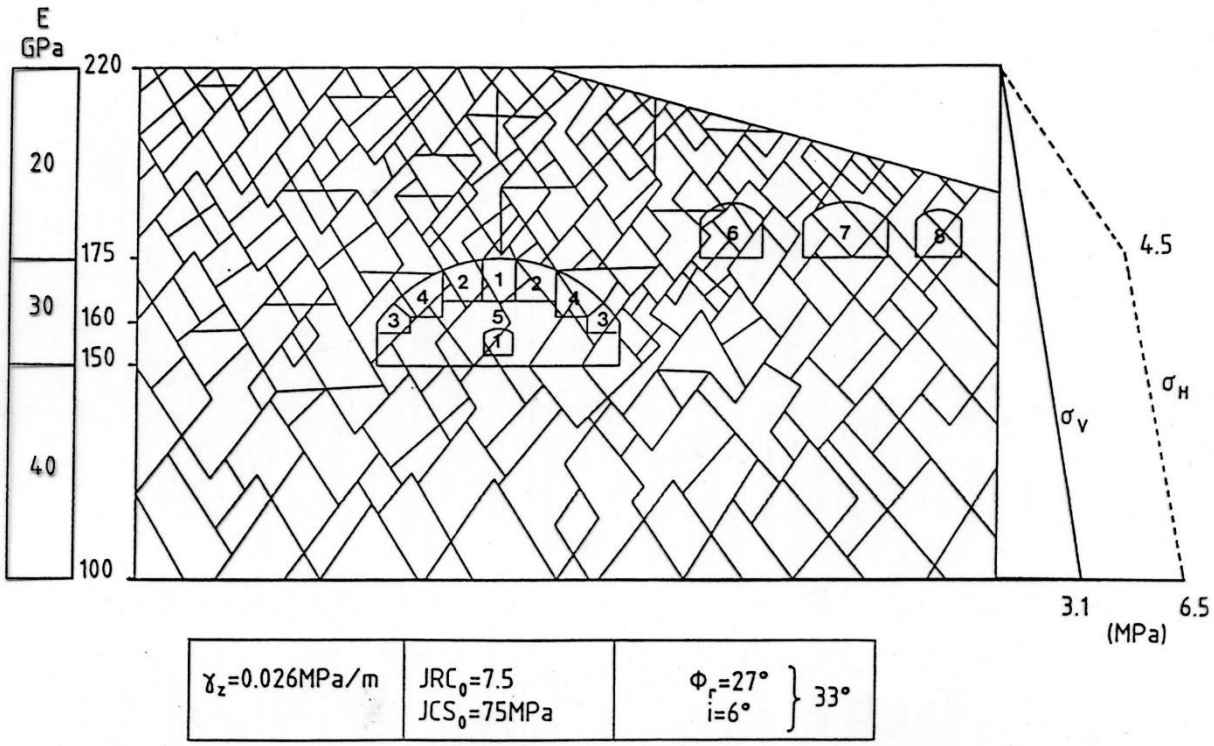




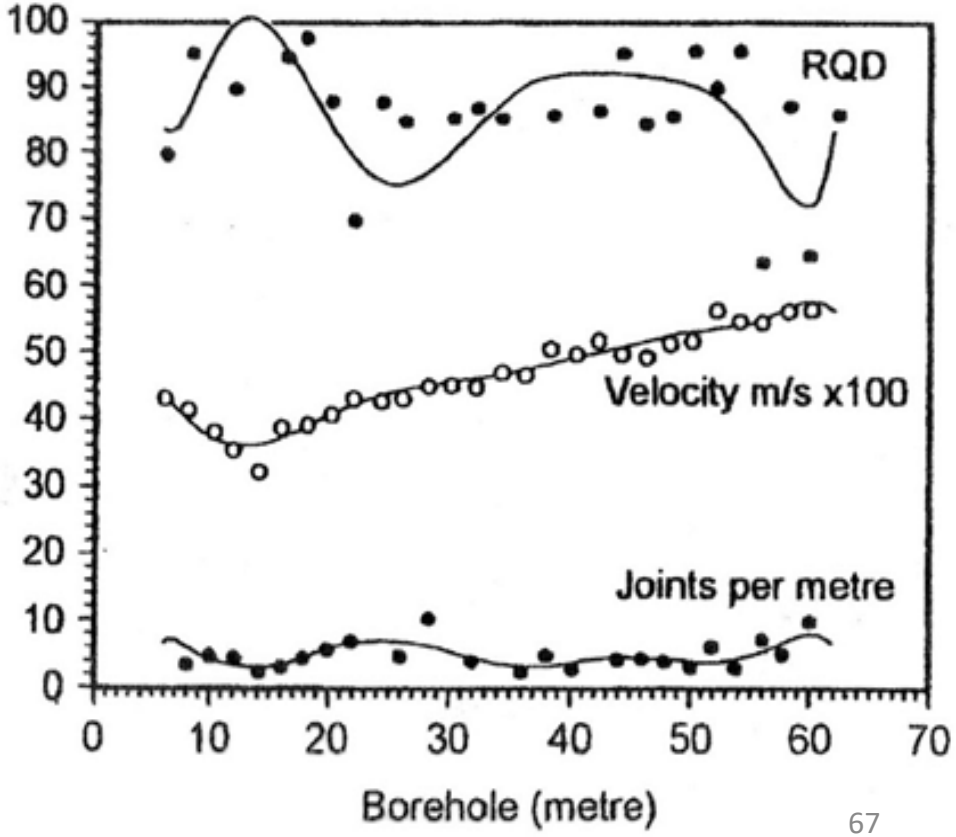
GJØVIK OLYMPIC CAVERN: 62M SPAN.

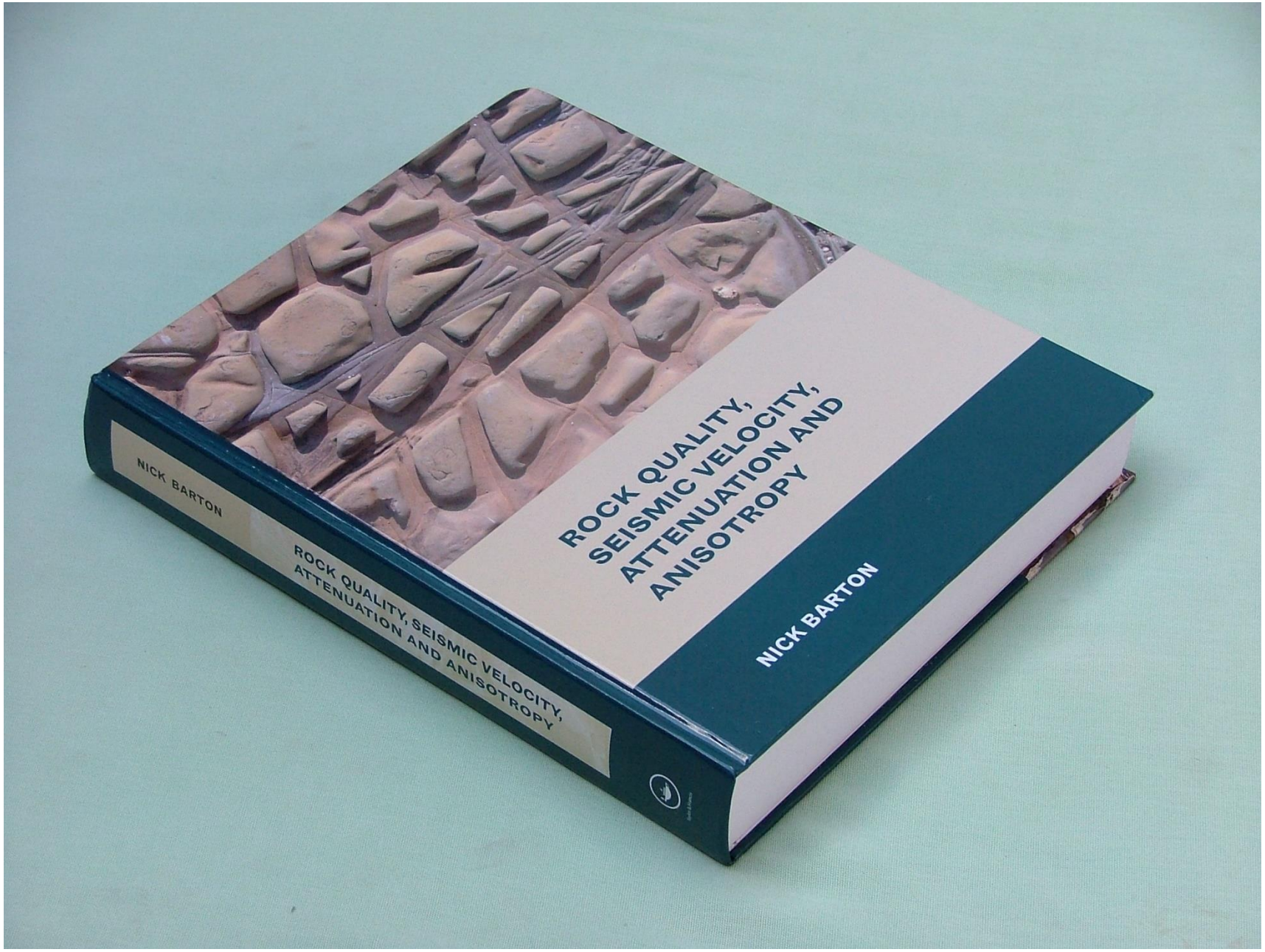
CROSS-HOLE SEISMIC HELPED WITH OPTIMAL CAVERN LOCATION.

Barton et al. 1994 (Westerdahl)



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

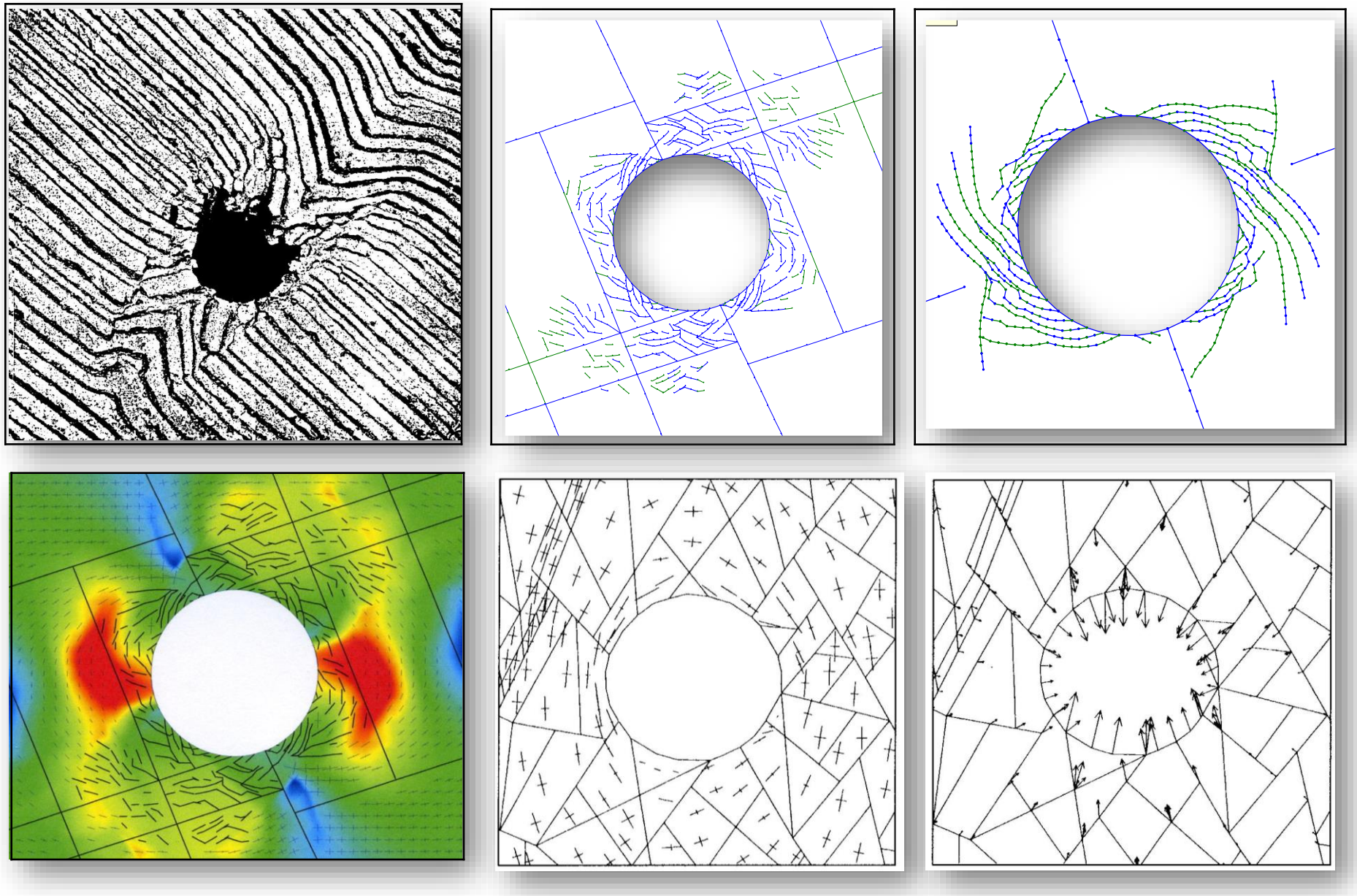




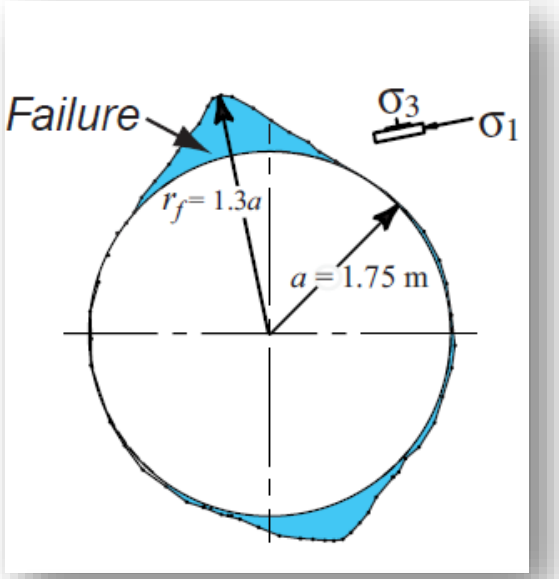
A LOT OF LINKS BETWEEN GEOPHYSICS and ROCK QUALITY (including Q)

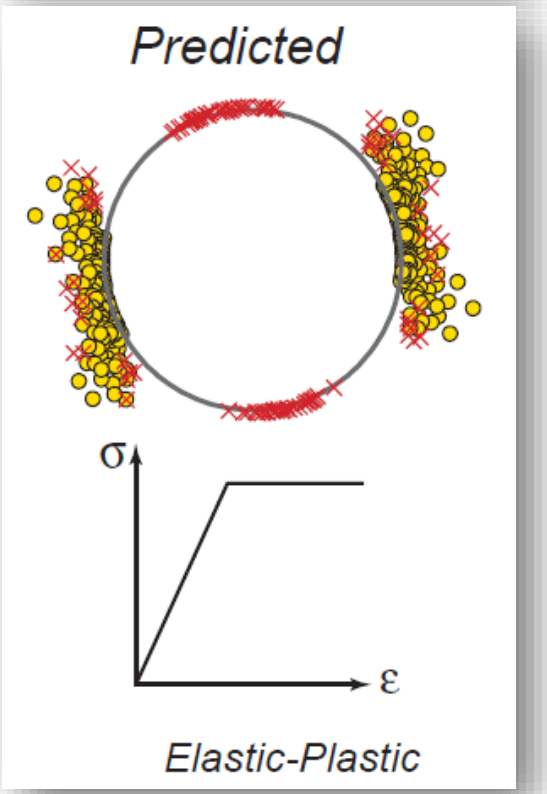
5. SHEAR STRENGTH

We need input for numerical modelling. But are we discontinuum or continuum modellers?



Physical model: layered, by Bandis 1987, three **FRACOD** models by Baotang Shen, 2004, two **UDEC-BB** models, Hansteen, NGI, 1991.





COMPARED TO

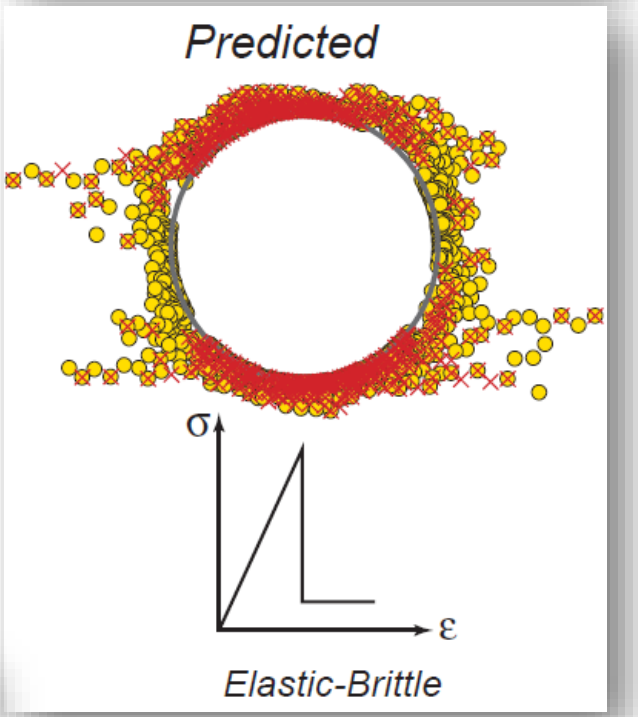
CONVENTIONAL continuum modelling methods.

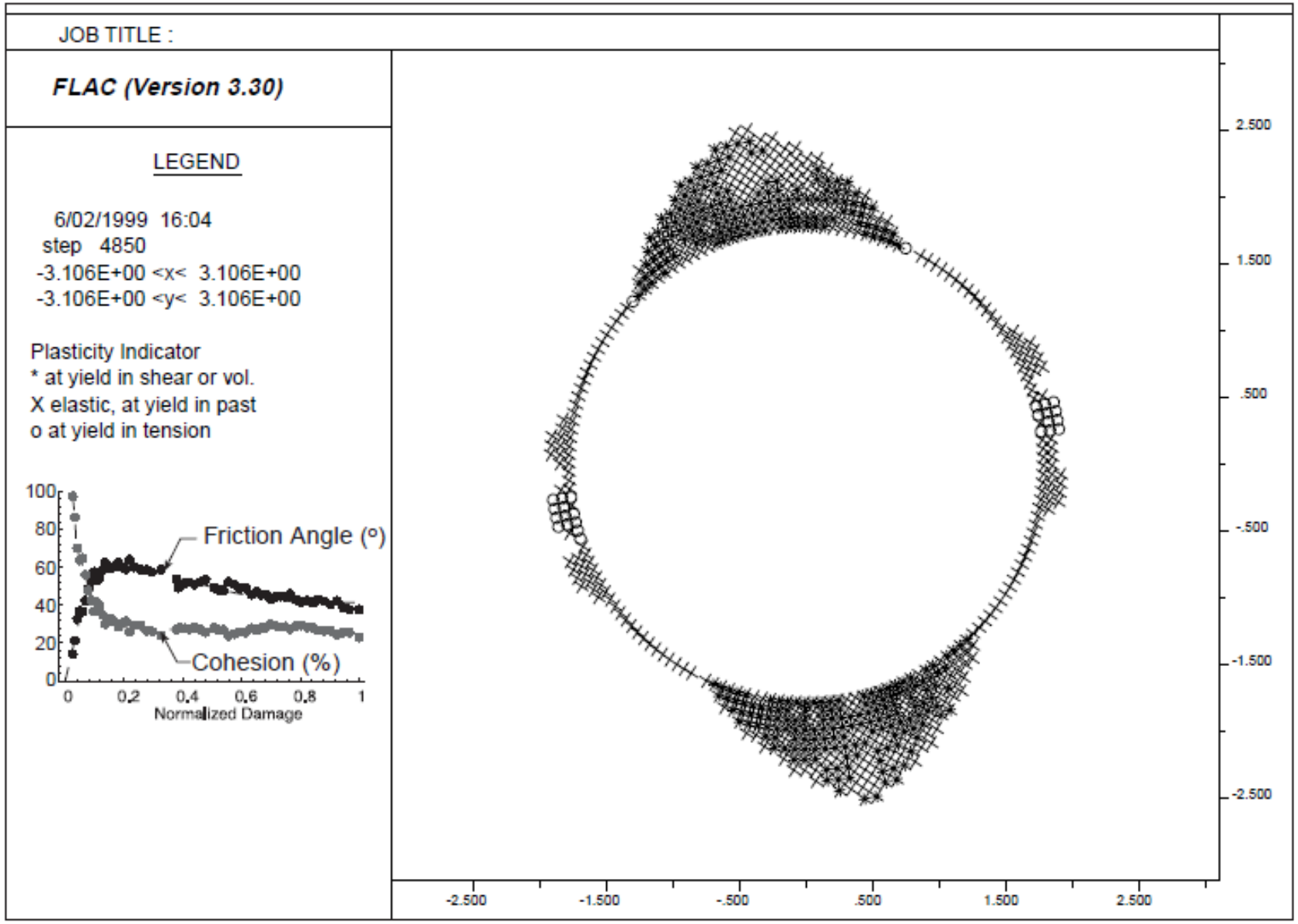
Poor simulation with Mohr Coulomb or Hoek and Brown strength criteria.

(Hajiabdolmajid, Martin and Kaiser, 2000 "Modelling brittle failure", NARMS.)

So why performed by so many consultants?

× Shear failure ○ Tensile failure





Degrade cohesion, mobilize friction: excellent match.

(Hajiabdolmajid, Martin and Kaiser, 2000)

CC and FC from Qc = Q x σ_c /100 :

Qc = RQD/Jn x Jr/Ja x Jw /SRF x σ_c /100)

CC = cohesive strength (the component of the rock mass requiring shotcrete)

FC = frictional strength (the component of the rock mass requiring bolting).

Cut Q_c into two halves → 'c' and 'φ'

$$CC = \frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100}$$

$$FC = \tan^{-1}\left(\frac{Jr}{Ja} \times Jw\right)$$

	$$c' = \frac{\sigma_{ci}\left[(1+2a)s+(1-a)m_b\sigma'_{3n}\right]\left(s+m_b\sigma'_{3n}\right)^{a-1}}{(1+u)(2+a)\sqrt{1+\left(6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}\right)\Big/\left((1+a)(2+a)\right)}}$$
CC	$$"c" \approx \left(\frac{RQD}{J_n}\times\frac{1}{SRF}\times\frac{\sigma_c}{100}\right)$$
	$$\phi' = \operatorname{asin}\left[\frac{6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}{2(1+a)(2+a)+6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}\right]$$
FC	$$"\phi" \approx \tan^{-1}\left(\frac{J_r}{J_a}\times\frac{J_w}{1}\right)$$

GSI-BASED ALGEBRA FOR **'c'** AND **'Φ'**

CONTRASTED WITH **Q-BASED 'EMPIRICISM'**

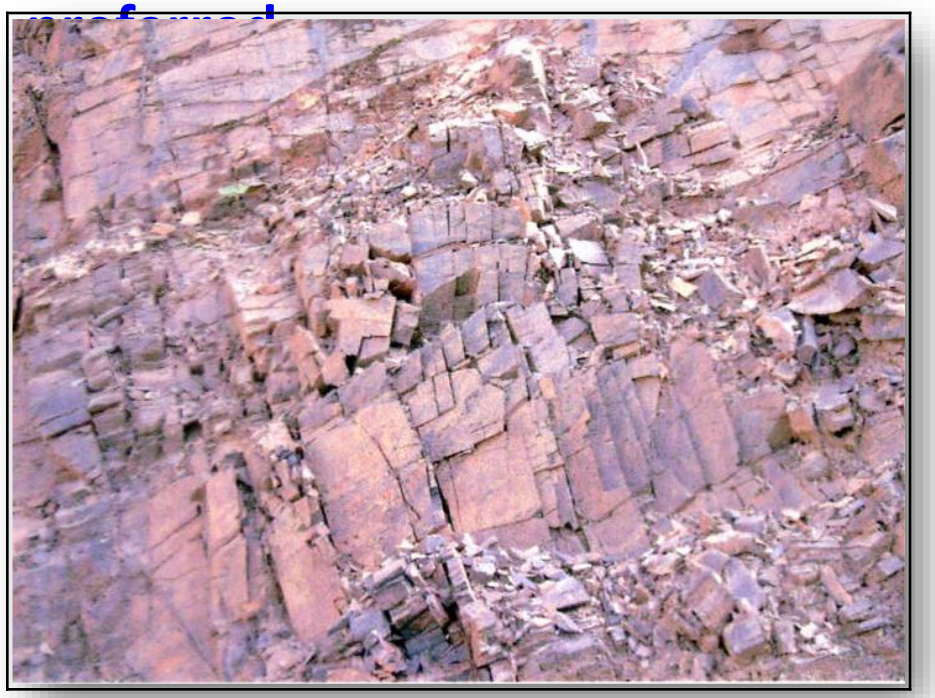
SHOTCRETE NEEDED WHEN LOW CC.

BOLTING NEEDED WHEN LOW FC.

RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	*FC°*	*CC* MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5

Four rock masses with successively reducing character: more joints, more weathering, lower UCS, more clay.

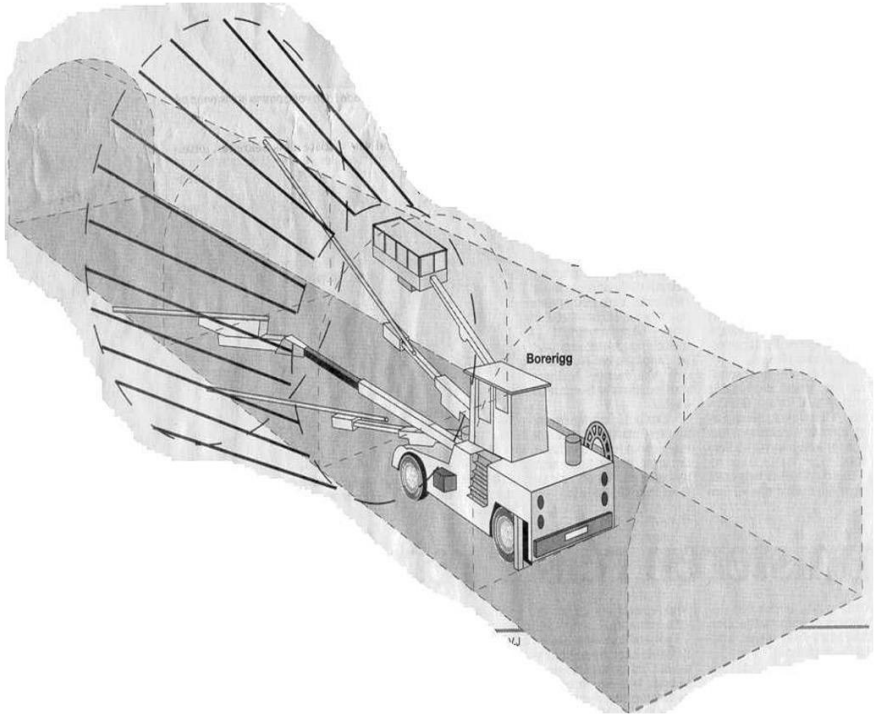
Low CC –shotcrete preferred



Low FC – bolting

6. PERMEABILITY (Q_{H_2O})

PRE-INJECTION (for NMT)
RIVER DIVERSION WARNING!



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**

BÆRUM TUNNEL

(shales, limestones, intrusive dikes)

TWIN-TRACK RAIL TUNNEL, 5km

Systematically pre-injected at high pressure.

RIVER DIVERSION TUNNELS – warning!

***Q-SYSTEM CASE RECORDS* INVOLVING HYDROELECTRIC PROJECTS:**

≈ 60% OF ORIGINAL CASE RECORDS OF 1974 WERE FOR HEADRACE TUNNELS WITH TYPICAL 1.5 TO 2.5m/s (LAMINAR, PARABOLIC) FLOW VELOCITIES. NO TRANSPORT OF FALLEN BLOCKS.

B + S(mr) AND THE MORE MODERN B + S(fr) TACKLE 1-3m/s VERY WELL.

DO NOT DESIGN *RIVER DIVERSION TUNNELS* WITH HIGH VELOCITIES WITHOUT 'BEEFING-UP' THE B+S(fr) – *INCLUDING ALL THE WALLS, AND CONCRETE INVERTS.*

A HYDRAULIC/EROSION/COLLAPSE DRAMA OF RARE PROPORTIONS. WHY? RIVER DIVERSION ROUND A SHARP BEND AT 10m/s (36km/hr) WITH ‘LIGHT’ Q-SYSTEM SUPPORT DESIGNED FOR 2.5m/s MAX.

Q and V_P and LUGEON/permeability ?

(IS THERE A CONNECTION?)

Q-value	0.1	1	10	100
Lugeon	10	1	0.1	0.01
K ≈ m/sec	10^{-6}	10^{-7}	10^{-8}	10^{-9}
V_p km/s	2.5	3.5	4.5	5.5

USEFUL APPROXIMATIONS.

STRONG LACK-OF-FIT WOULD SUGGEST CLAY-FILLED JOINTS. USE Q_{H2O}

No clay present:

$L \approx 1/Q_c$

For hard, jointed, clay-free, rock masses)

(1 Lugeon $\approx 10^{-7}$ m/s $\approx 10^{-14}$ m^2 for water at 20ºC)

Q_c = RQD/Jn x **Jr/Ja** x Jw/SRF x σ_c/100

(standard equation, normalized by σ_c/100)

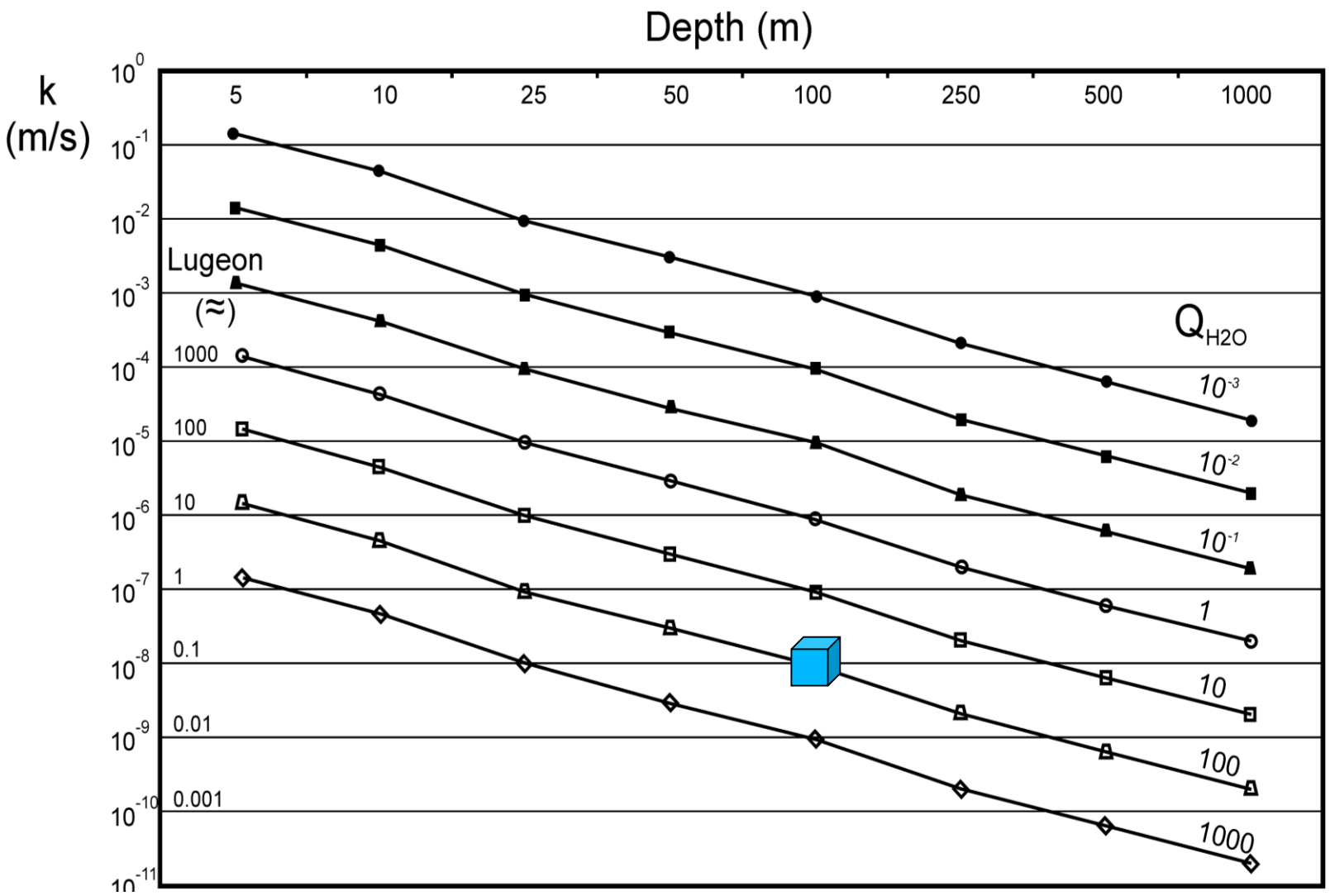
General case, with or without clay, with depth or stress allowance, *and consideration of*

joint wall strength JCS

Q_{H2O} = RQD/Jn x *Ja/Jr* x Jw/SRF x 100/JCS

$K \approx 0.002 /(Q_{H20}\ D^{5/3})$ m/s

(Barton, 2007)



Regular Q-value =

$$\frac{50}{9} \times \frac{1.5}{4} \times \frac{0.66}{1}$$

= 1.4, i.e. 'poor quality'

$$Q_{H_2o} = \frac{50}{9} \times \frac{4}{1.5} \times \frac{0.66}{1} \times \frac{100}{10} = 98$$

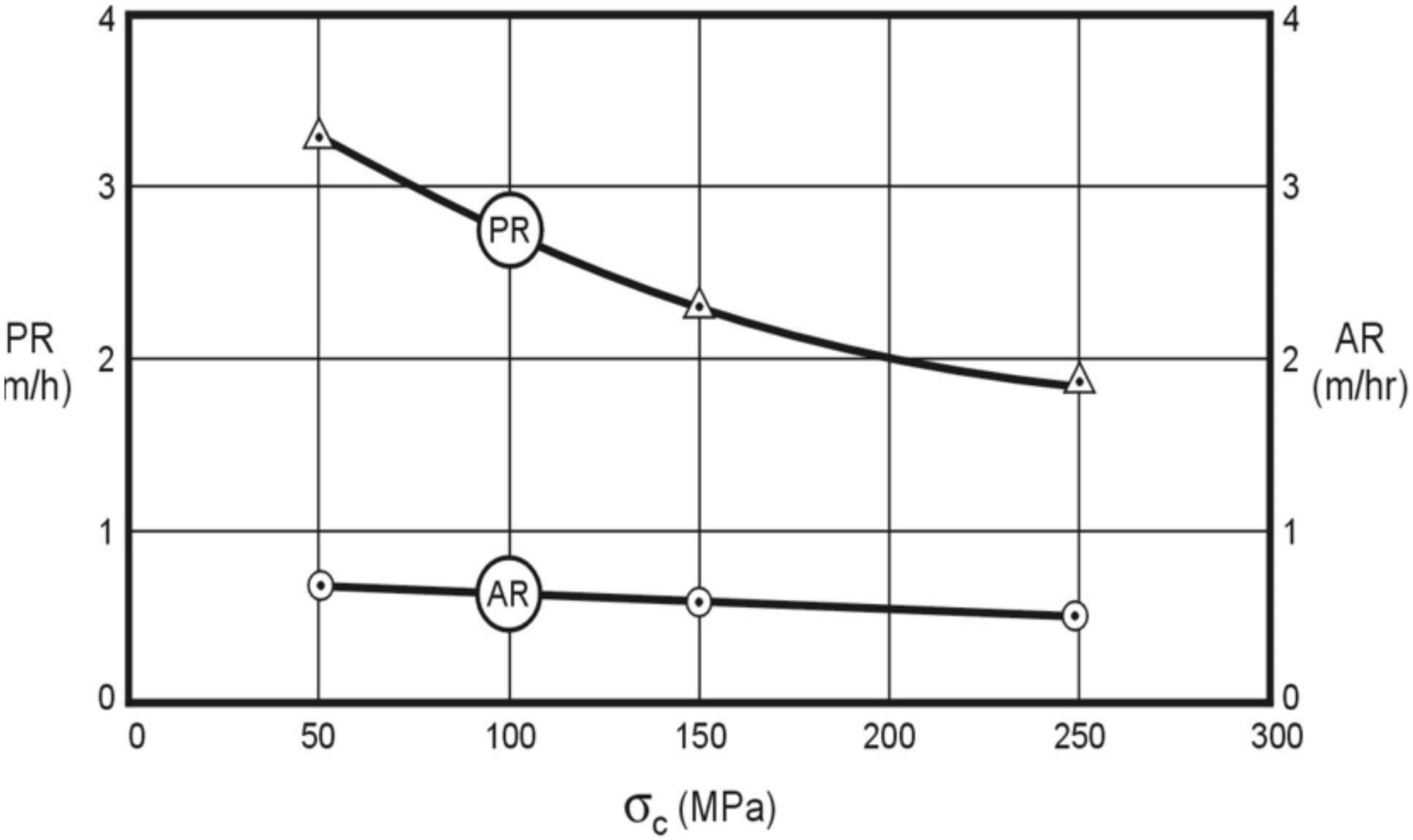
$$K \approx \left(\frac{2}{1000 \times 98 \times 100^{5/3}} \right) = 9 \times 10^{-9} \text{ m/s}$$

7. TBM PERFORMANCE

AR = PR x (U?)

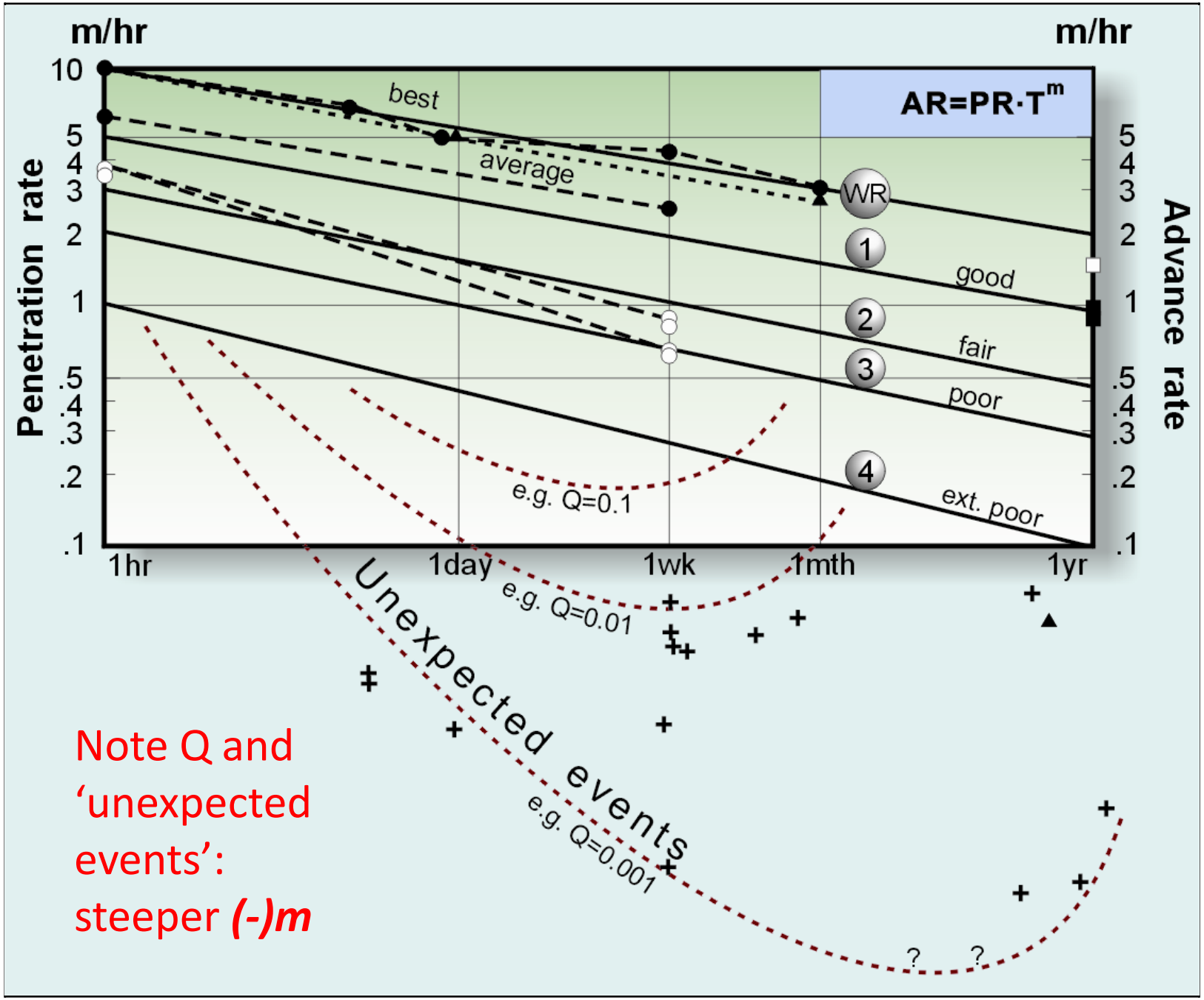
TBM TUNNEL DELAYS IN FAULT ZONES,

Q_{TBM} PROGNOSIS



Data for tunnelling in shale, tillite, sandstone

(Fawcett 1993)



CASE RECORD EVIDENCE OF DECELERATION (gradient –m) from 145 cases representing 1000 km of TBM

(Mostly open-gripper cases)

Conventional equation:

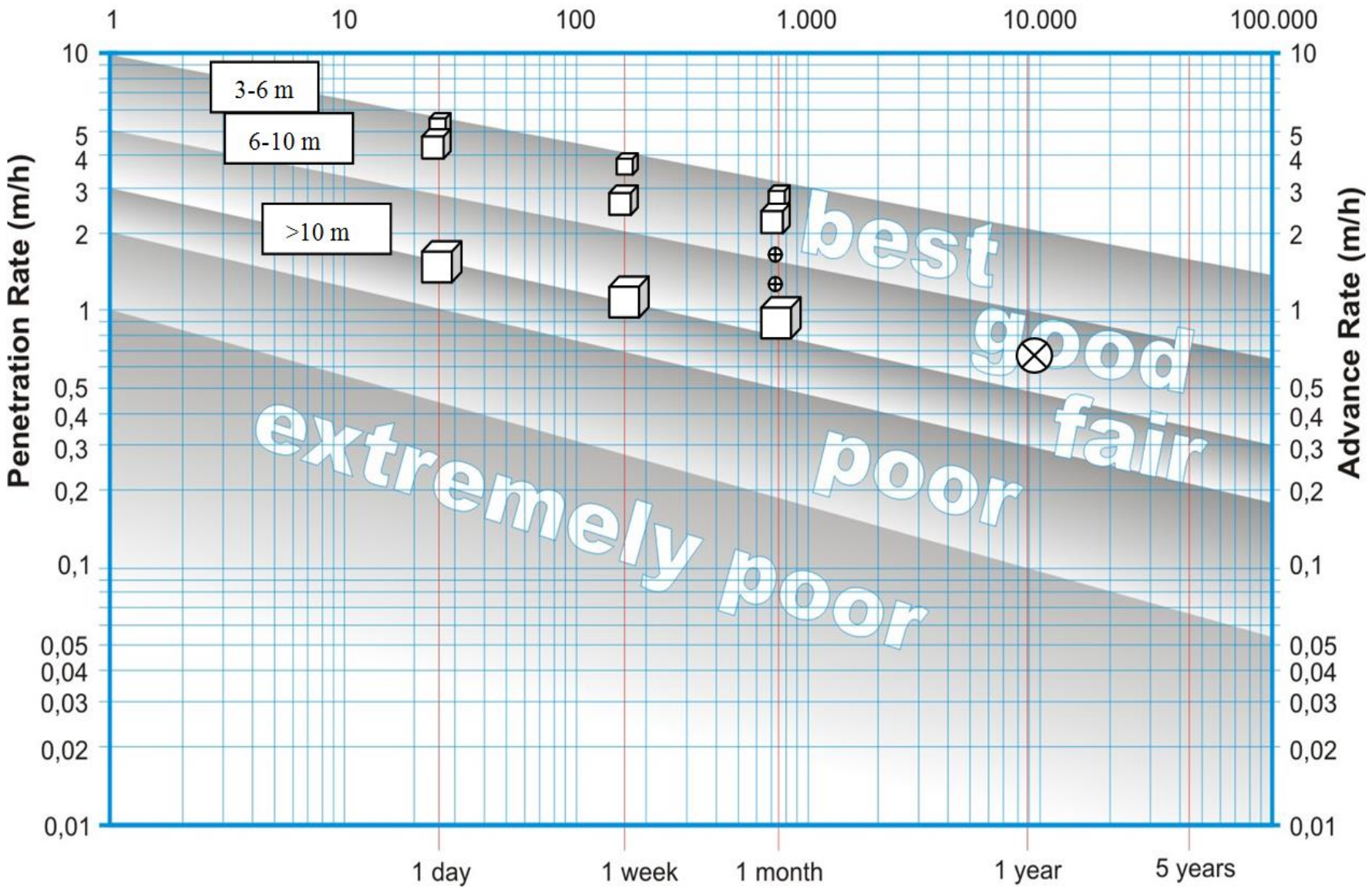
AR = PR x U

but reality is :

$$AR = PR \cdot T^m$$

WORLD RECORDS BY TBM – ASSEMBLED BY ROBBINS: *RESULTS WHEN SIZES ARE COMBINED TO REDUCE SCATTER.*

Assume 24 hrs/day, 168 hrs/week, 720 hrs/month. *(Barton, 2013).*



World record drill-and-blast Svea Tunnel:

5.8 km 54 weeks, from one face.

NOTE:THE WORLD RECORD TBM ALSO SHOW *(-)m* gradient

DIAMETER	7 - 8 m	8 - 9 m
BEST DAY	115 m Robbins Karahnjukar Iceland	75 m Robbins Channel Tunnel UK
BEST WEEK	428 m Robbins Karahnjukar Iceland	428 m Robbins Channel Tunnel UK
BEST MONTH	1482 m Robbins TARP Chicago USA	1719 m Robbins Channel Tunnel UK
MONTHLY AVERAGE FOR PROJECT	770 m Robbins TARP Chicago USA	873 m Robbins Channel Tunnel UK

SOME OF THE WORLD RECORDS ARE FROM THE UK

HALF OF THE CHANNEL TUNNEL (chalk marl)

UCS 4 to 9MPa

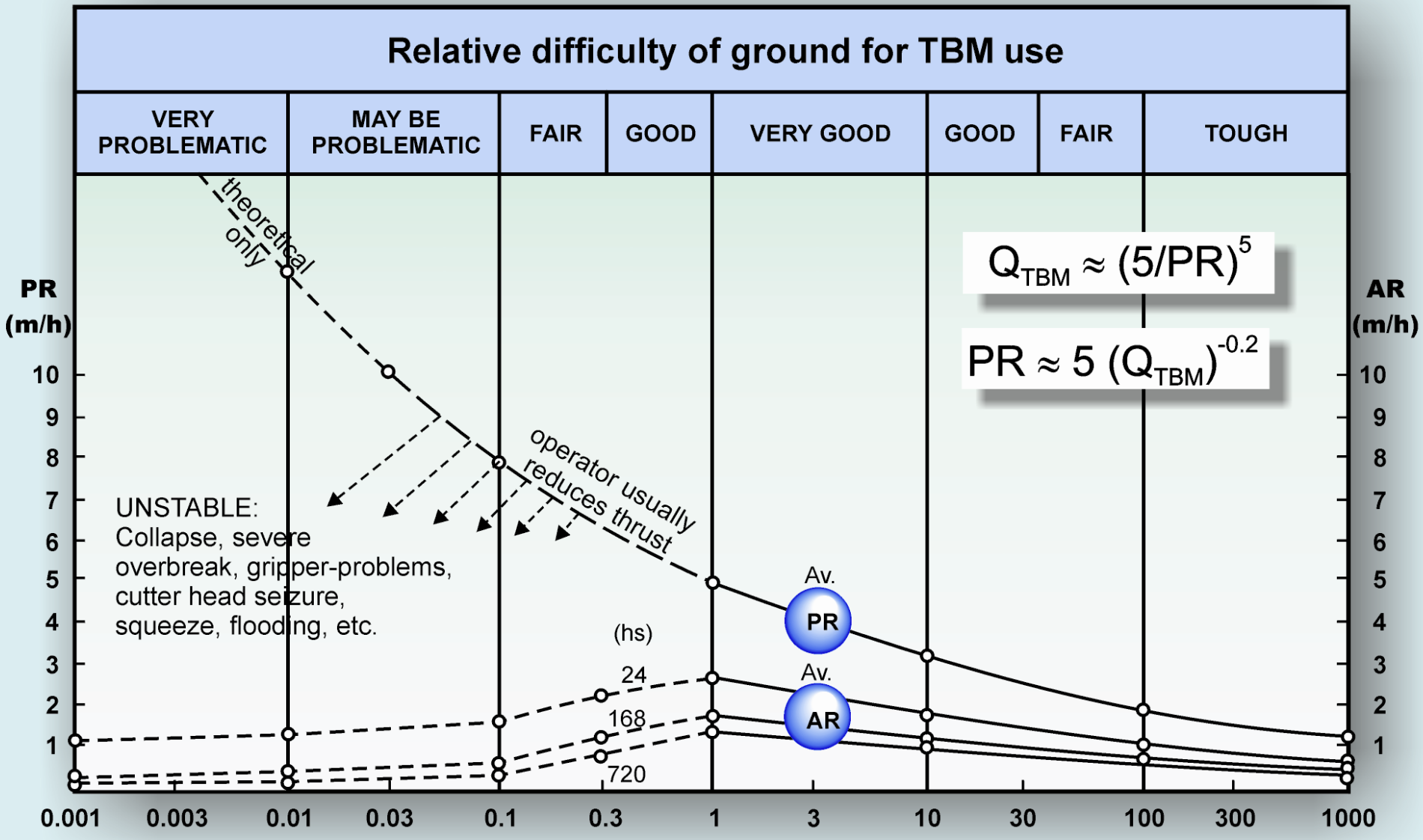
THE Q_{TBM} MODEL FOR TBM PROGNOSIS

involves Q , and machine/rock interaction 'normalizations'

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

$$SIGMA \approx 5\,\gamma\, Q_c^{1/3}$$

$$PR \approx 5\, Q_{TBM}^{-1/5}$$



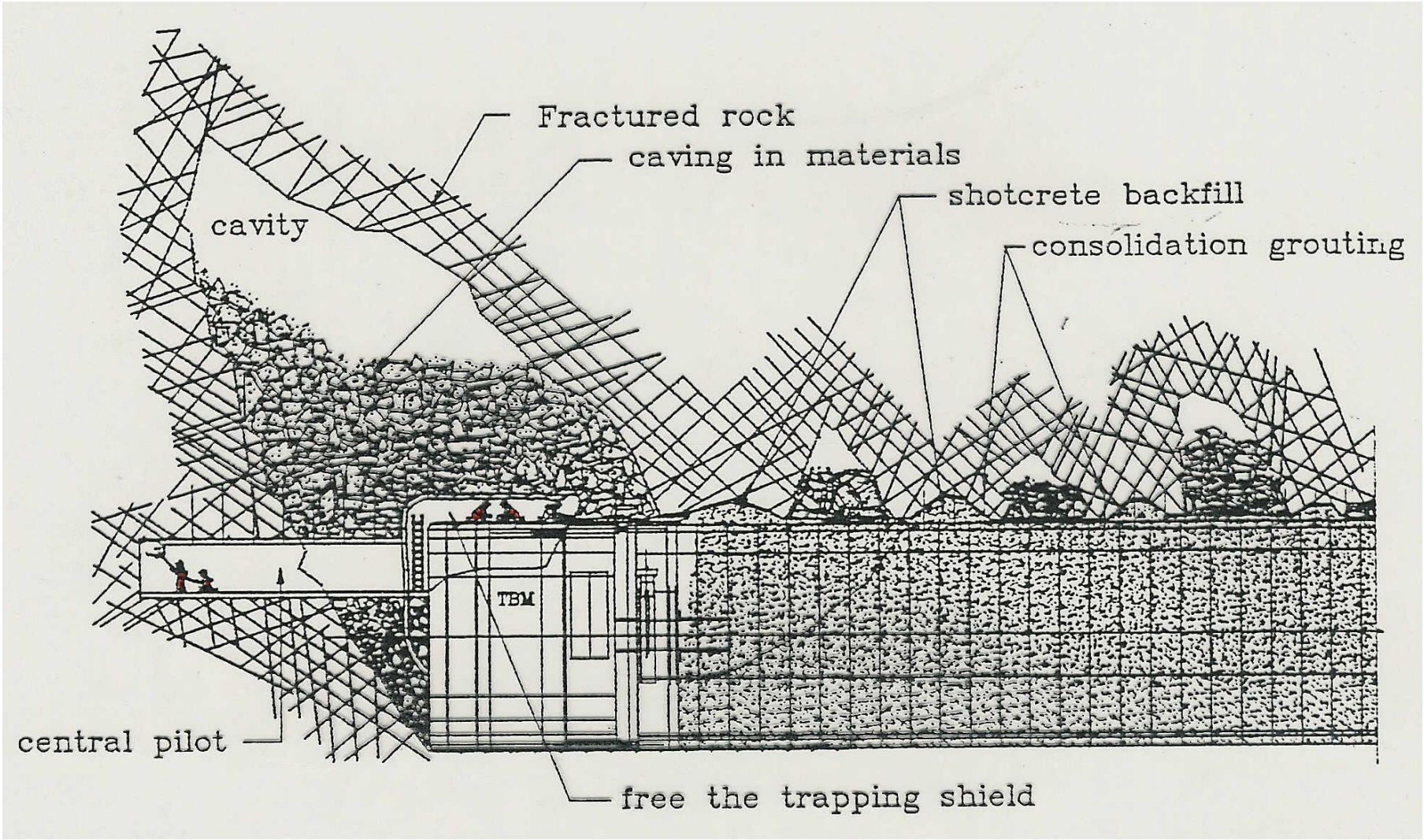
$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

THE Q_{TBM} EQUATION WAS DEVELOPED BY TRIAL AND ERROR.

'ADDITIONS' TO Q-PARAMETERS *'NORMALIZED BY CENTRAL VALUES'*

DECELERATION GRADIENTS *(-m)* ARE *Q-VALUE RELATED: WHEN* Q < 1.
BUT *EFFECTIVE Q-VALUE* CAN BE IMPROVED BY PRE-GROUTING !
(improves many Q-parameters, reduces negative –m)

Rock mass quality $$Q = \left(\frac{RQD}{J_n}\right) x \left(\frac{J_r}{J_a}\right) x \left(\frac{J_w}{SRF}\right)$$

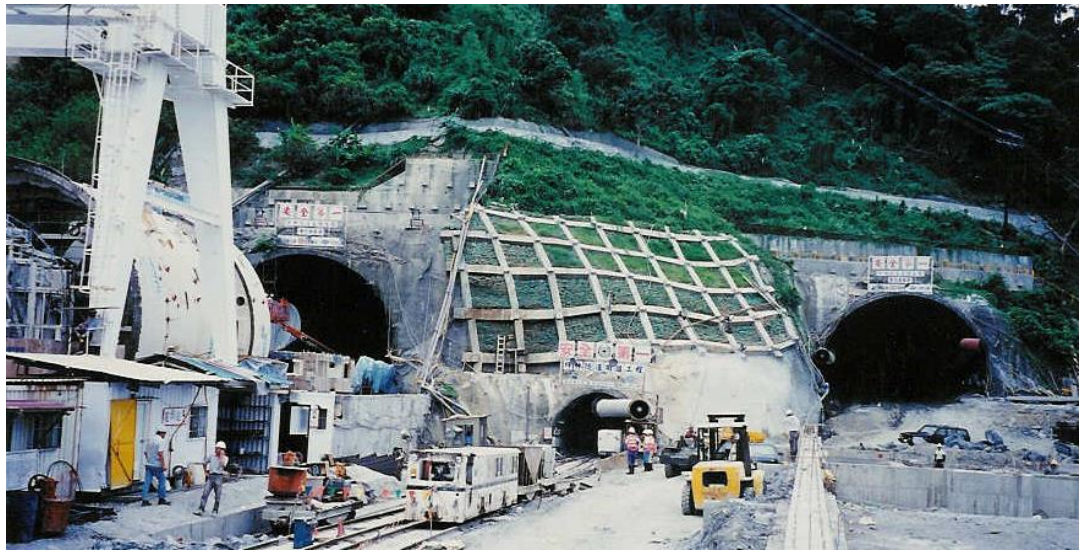


BY-PASS FOR 11.7 m DIA. WIRTH TBM, PINGLIN, TAIWAN

SECOND 11.7m TBM DESTROYED IN A FAULT-ZONE COLLAPSE.

FINALLY, TUNNELS COMPLETED BY DRILL-AND-BLAST.

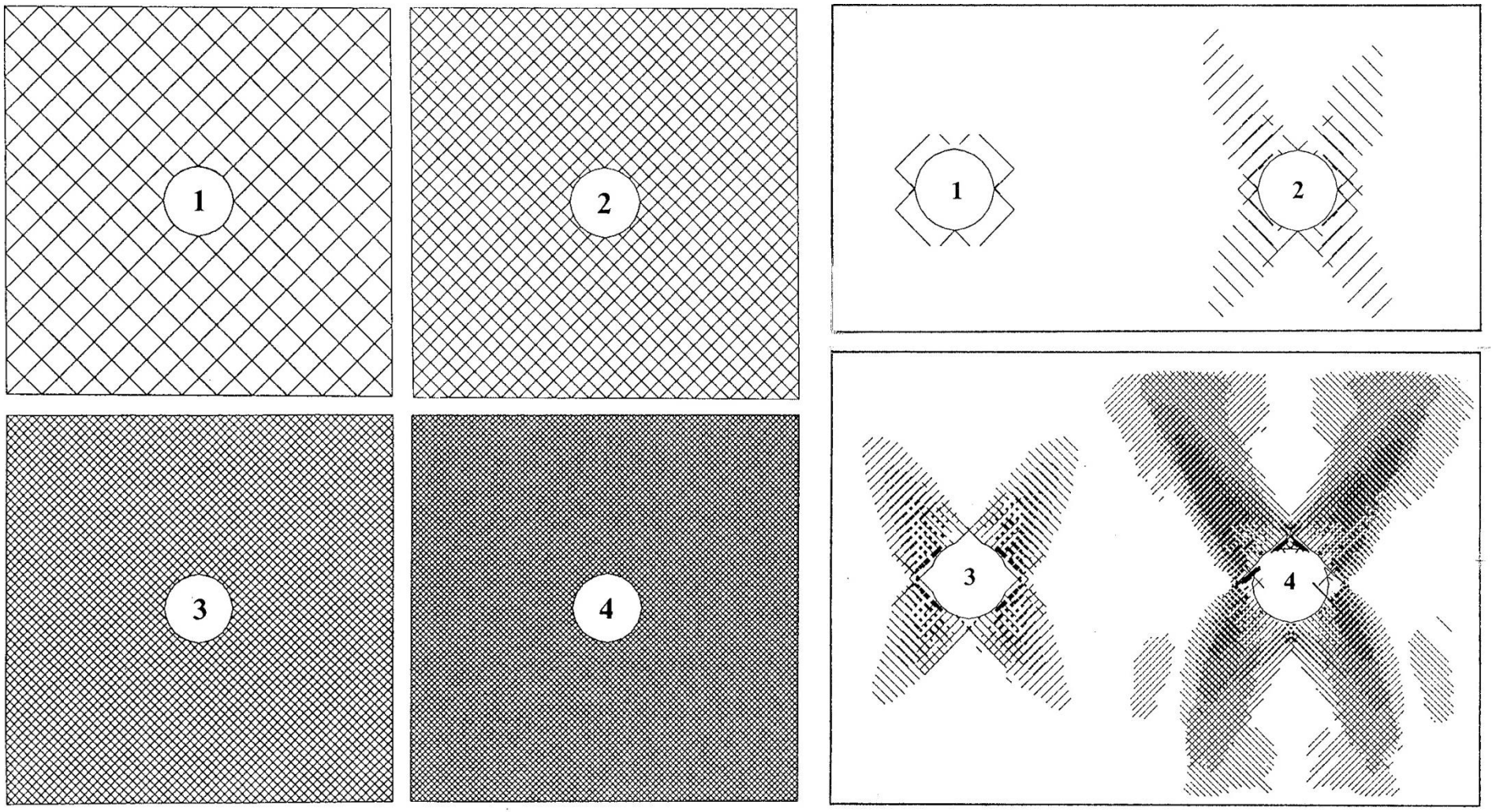
(Shen et al. 1999)



PILOT TBM IN CENTRE. BY-PASSED TO FREE CUTTER-HEAD > 13 TIMES.

FREQUENTLY FAULTED ROCK MASS: META-SANDSTONES, CLAY-COATINGS, WATER.

DIFFICULT TO DRILL (AND INSERT PACKERS) INTO PRE-INJECTION HOLES.



WHY TUNNELS NEED GENEROUS SEPARATION (PILLAR-WIDTH) IN POTENTIALLY FAULTED ROCK!

(Barton and Shen, 1996)

BLOCKED CUTTER-HEAD AND BYPASS TO FREE MACHINES AT TWO DIFFERENT SCALES

(Photo: Chris Fong, Taiwan)

THE META-SANDSTONES WORE OUT THE FACE ARMOUR IN 4 TO 5 km

(Pinglin, Taiwan. Photo NB)

‘THEO – EMPIRICAL’ REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM.

We need three basic equations:

1. $AR = PR \times U$ **(all TBM must follow this)**

2. $U = T^m$ **(*decelerating advance rate* means time-dependent U)**

3. $T = L / AR$ **(time for length L depends on AR.....as when walking)**

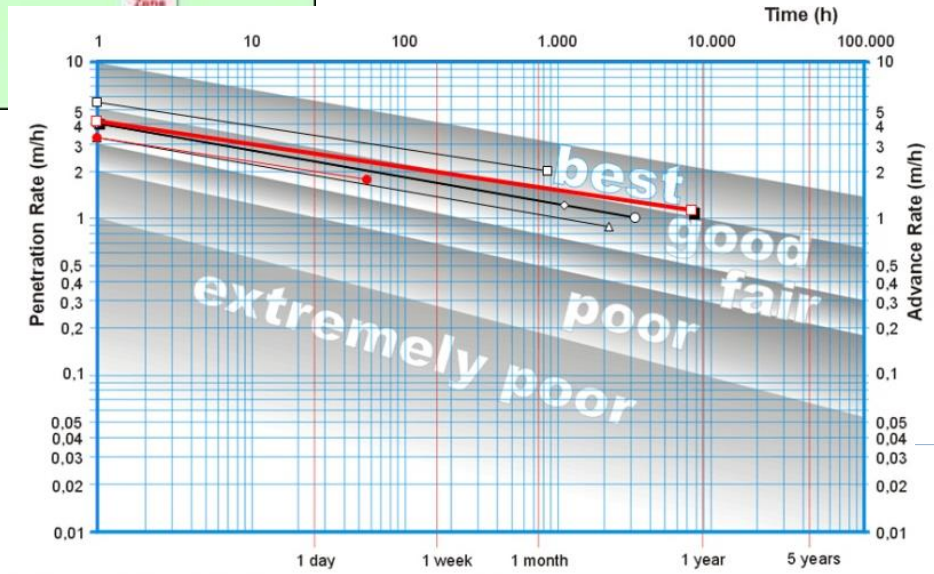
Therefore we have the following:

4. $T = L / (PR \times T^m)$ **(from #1, #2 and #3)**

5. $T = (L / PR)^{(1 / (1+m))}$

VERY important for TBM……because very *negative (-)m* values make the 1/(1+m) *component* TOO LARGE.....time T gets too long (months or years)!

THE THREE QTBM SCREENS
(DETAILS SHOWN next) WERE
DEVELOPED FROM NB EQUATIONS
BY Ricardo Abrahão, RAGeociencias



Nick Barton & Associates

Q TBM

Contract SRK / ANGLO AMERICAN - CHILE
Site LOS BRONCES
Date 19-Oct-07

INPUT DATA

ZONE	LITHOLOGY	RQD	J_n	J_r	J_a	J_w	SRF	m_s	RQD_0	γ	β*	σ_c	I_{50}	F	CLI	q	σ_θ	D	n	L	Vp
1	CUARZOMONZONITA	92.00	6.10	1.70	2.10	0.92	0.90	-0.17	92.00	2.80	60.00	200.00	10.00	27.50	10.00	10.00	15.00	4.50	2.00	3,150.00	0.00
2	ANDESITA	71.00	11.60	1.60	2.60	0.78	1.30	-0.19	71.00	2.80	60.00	150.00	7.70	22.50	55.00	10.00	25.00	4.50	2.00	1,700.00	0.00
3	PORFIDO RIODACITIC	97.00	6.80	1.50	2.30	0.92	1.00	-0.17	97.00	2.80	60.00	200.00	10.00	27.50	10.00	10.00	25.00	4.50	2.00	1,300.00	0.00
4	BRECHA TURMALINA	88.00	5.30	1.70	2.00	0.96	1.20	-0.17	88.00	2.80	60.00	150.00	7.50	25.00	10.00	10.00	20.00	4.50	2.00	1,850.00	0.00
5	BRECHA-CLORITA/-BI	97.00	6.30	1.80	2.10	0.93	1.10	-0.17	97.00	2.80	60.00	125.00	6.25	22.50	25.00	10.00	20.00	4.50	2.00	100.00	0.00
6																				0.00	0.00
7																				0.00	0.00
8																				0.00	0.00
9																				0.00	0.00
10																				0.00	0.00
11																				0.00	0.00

BASIC CALCULATION

ZONE	LITHOLOGY	STABILITY	ORIENTED	ROCK MASS STRENGTH					Q	GRADIENT
		Q	Q0	Qc	QT	$SIGMA_{CH}$	$SIGMA_{TH}$	SIGMA	TBM	m
1	CUARZOMONZONITA	12.48	12.48	24.96	31.20	40.31	44.07	40.31	**3.17**	-0.17
2	ANDESITA	2.26	2.26	3.39	4.35	21.03	22.85	21.03	**0.67**	-0.15
3	PORFIDO RIODACITIC	8.56	8.56	17.12	21.40	35.08	38.87	35.08	**3.20**	-0.17
4	BRECHA TURMALINA	11.23	11.23	16.84	21.17	35.95	38.73	35.95	**0.72**	-0.17
5	BRECHA-CLORITA/-BI	11.16	11.16	13.95	17.43	33.70	36.30	33.70	**3.26**	-0.15
6									**0.00**	0.00
7									**0.00**	0.00
8									**0.00**	0.00
9									**0.00**	0.00
10									**0.00**	0.00
11									**0.00**	0.00

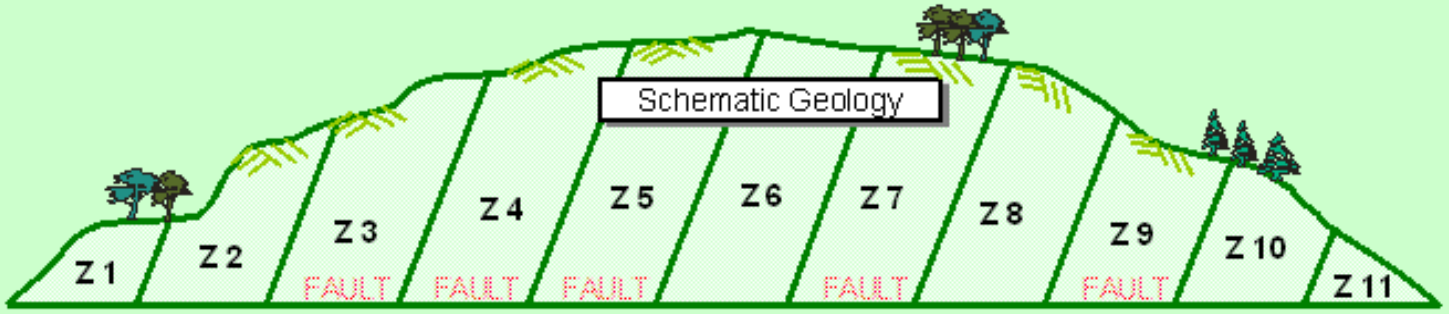
PERFORMANCE

ZONE	LITHOLOGY	PENETRATION		TIME TO ADVANCE		OVERALL PERFORMANCE		
		PR	AR	T	check	ΣL	ΣT	
1	CUARZOMONZONITA	3.97	0.93	3,186.25	3,150.00			PRL(av)
2	ANDESITA	5.42	1.98	858.23	1,700.00			
3	PORFIDO RIODACITIC	3.36	1.19	1,095.75	1,300.00	8,100.00	7,336.26	4.10
4	BRECHA TURMALINA	3.24	0.87	2,138.68	1,850.00	m	h	
5	BRECHA-CLORITA/-BI	3.20	1.74	57.35	100.00			
6		0.00	0.00	0.00	0.00			ART(av)
7		0.00	0.00	0.00	0.00			
8		0.00	0.00	0.00	0.00	8.10	10.19	
3		0.00	0.00	0.00	0.00	km	month	1.10
10		0.00	0.00	0.00	0.00			
11		0.00	0.00	0.00	0.00			

EXAMPLE OF INPUT DATA SCREEN

Nick Barton & Associates

Q TBM



3150	2.5	5	5	7.5	1700	2.5	1300	2.5	1850	100

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

INPUT DATA

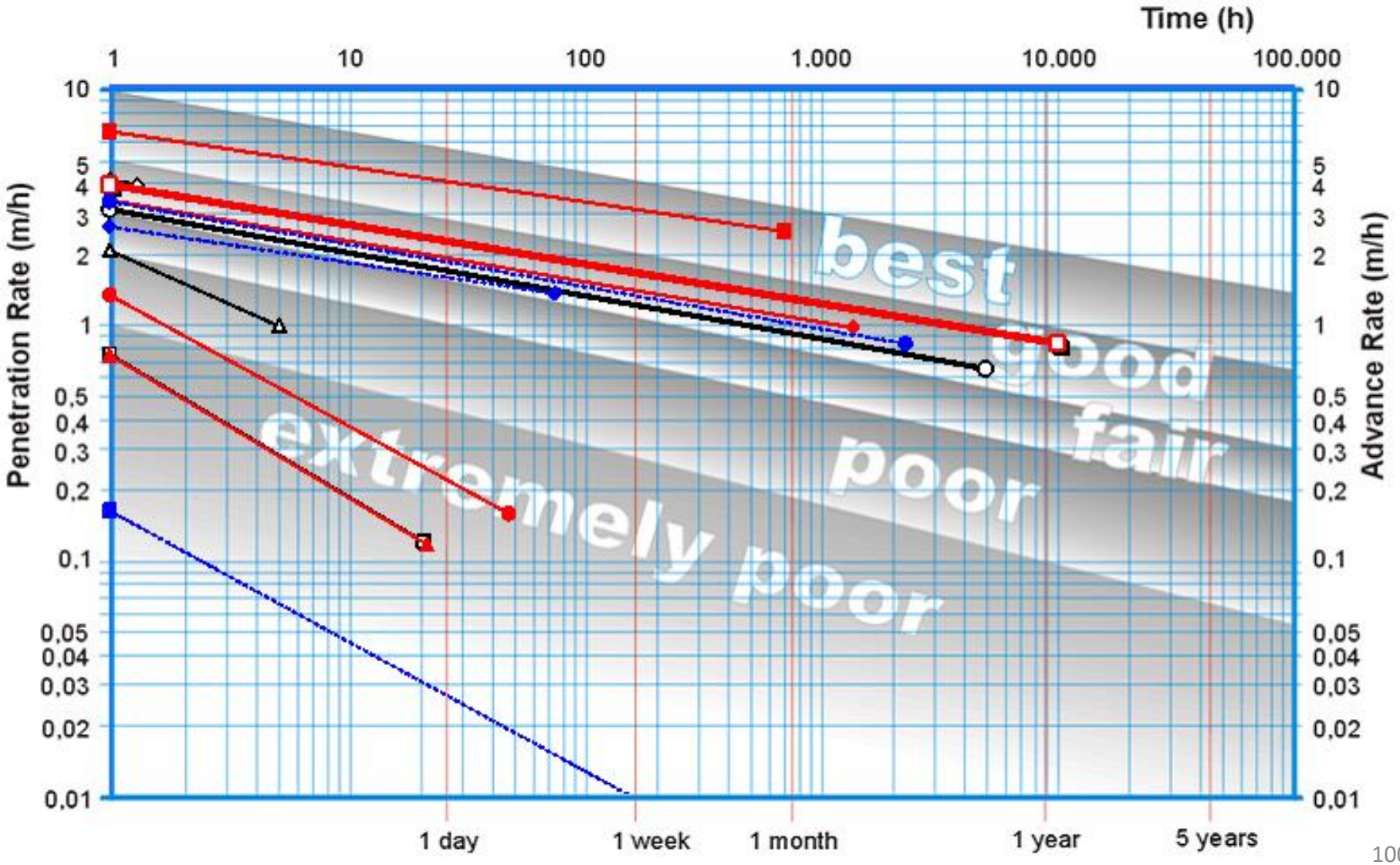
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)
100.0	4.0	1.5	3.0	1.00	1.0	-0.17	100.0	2.8

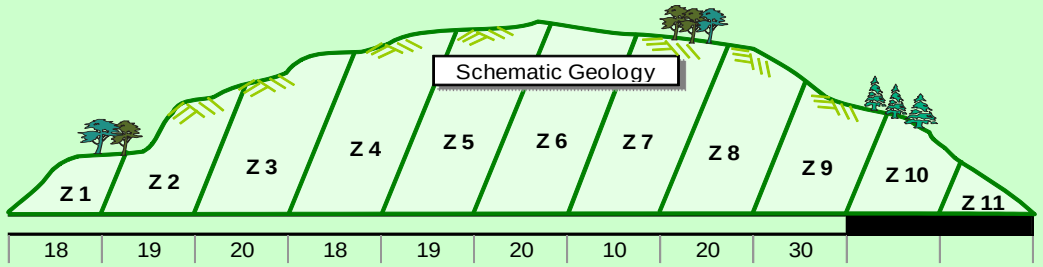
V_P (km/s)

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)





ZONE	9	LITHOLOGY	*Type 3 weakness zone*	ZONE LENGTH	*30*

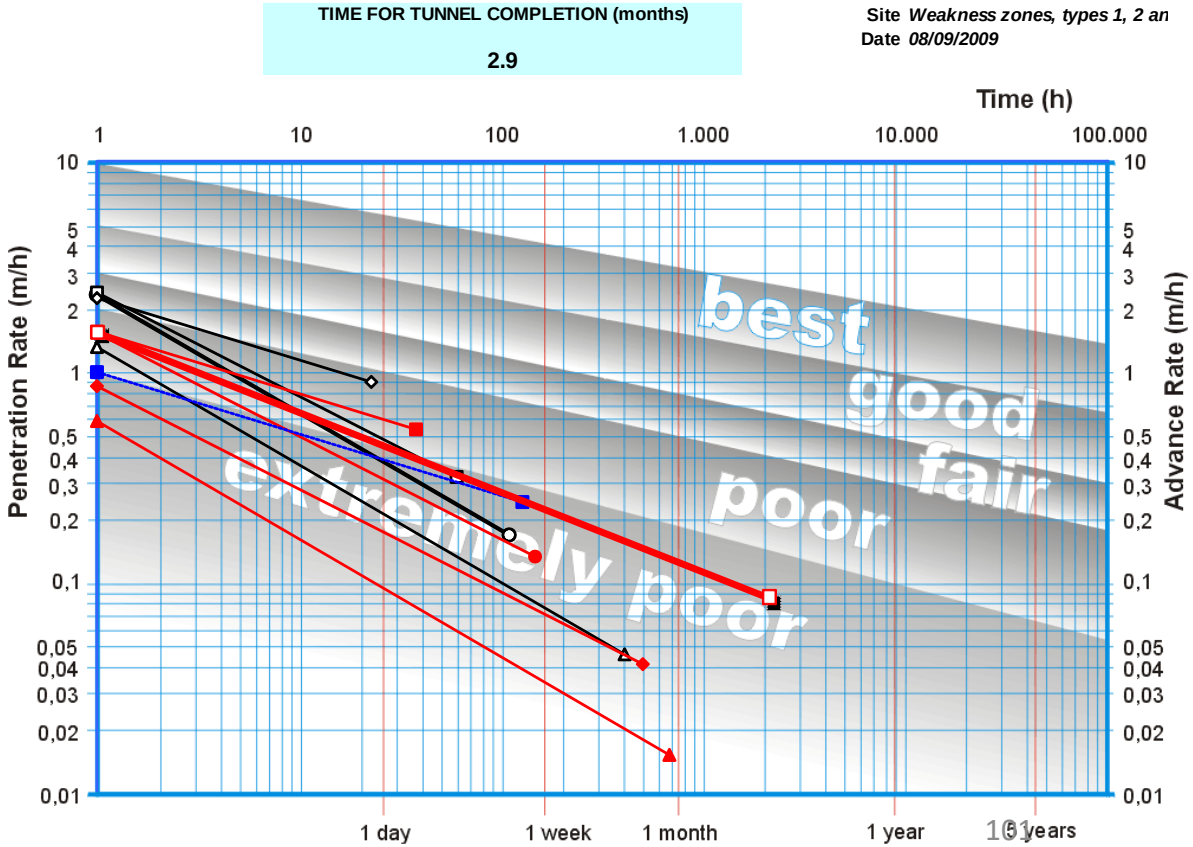
INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)	V_P (km/s)
						-0.25		2.7	3.4

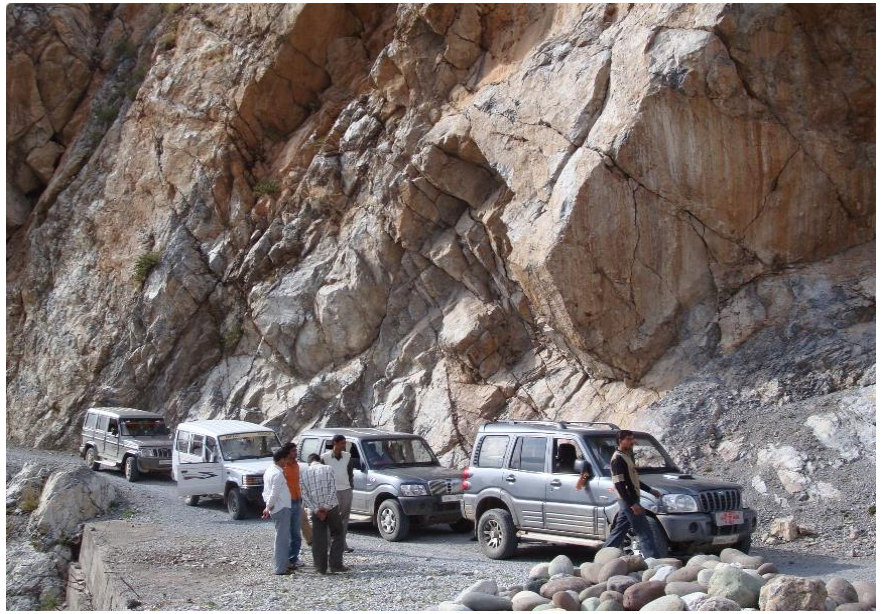
$\beta°$	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	150.0		8.0	20.0	25.0	5.0	10.0	2.0

ACCUMULATED TIME FOR *NINE* SIMULATED WEAKNESS ZONES = 2.9 MONTHS.

NOTE USE OF Vp (for shallow parts of tunnel can use refraction seismic)



8. SAFE ROCK SLOPE ANGLES (Q_{SLOPE})



SKILL, TRUST, STABLE, RECKLESS?

NON-LINEAR SHEAR STRENGTH?

IN OTHER WORDS HIGH TOTAL FRICTION ANGLES DUE TO DILATION.

Q-SLOPE METHOD

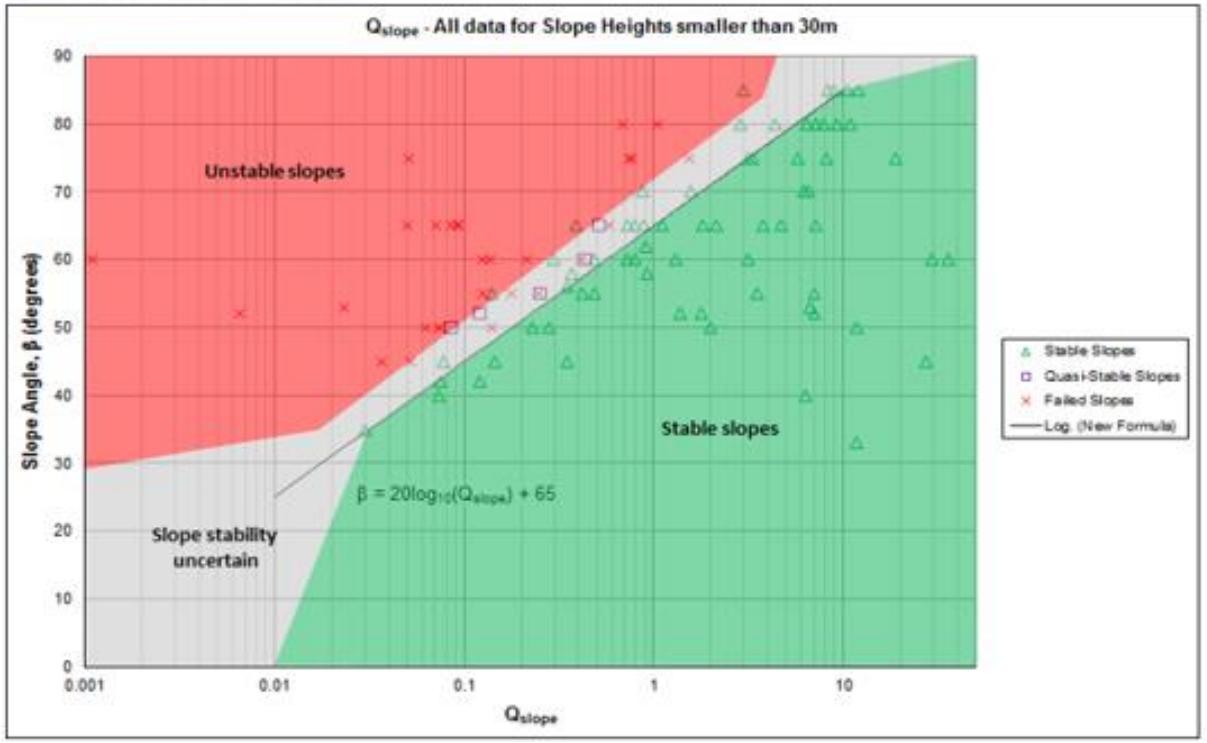
(Barton and Bar, 2015)

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°

Photo (and rock slope design) by *Panama Canal Authority.*

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

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



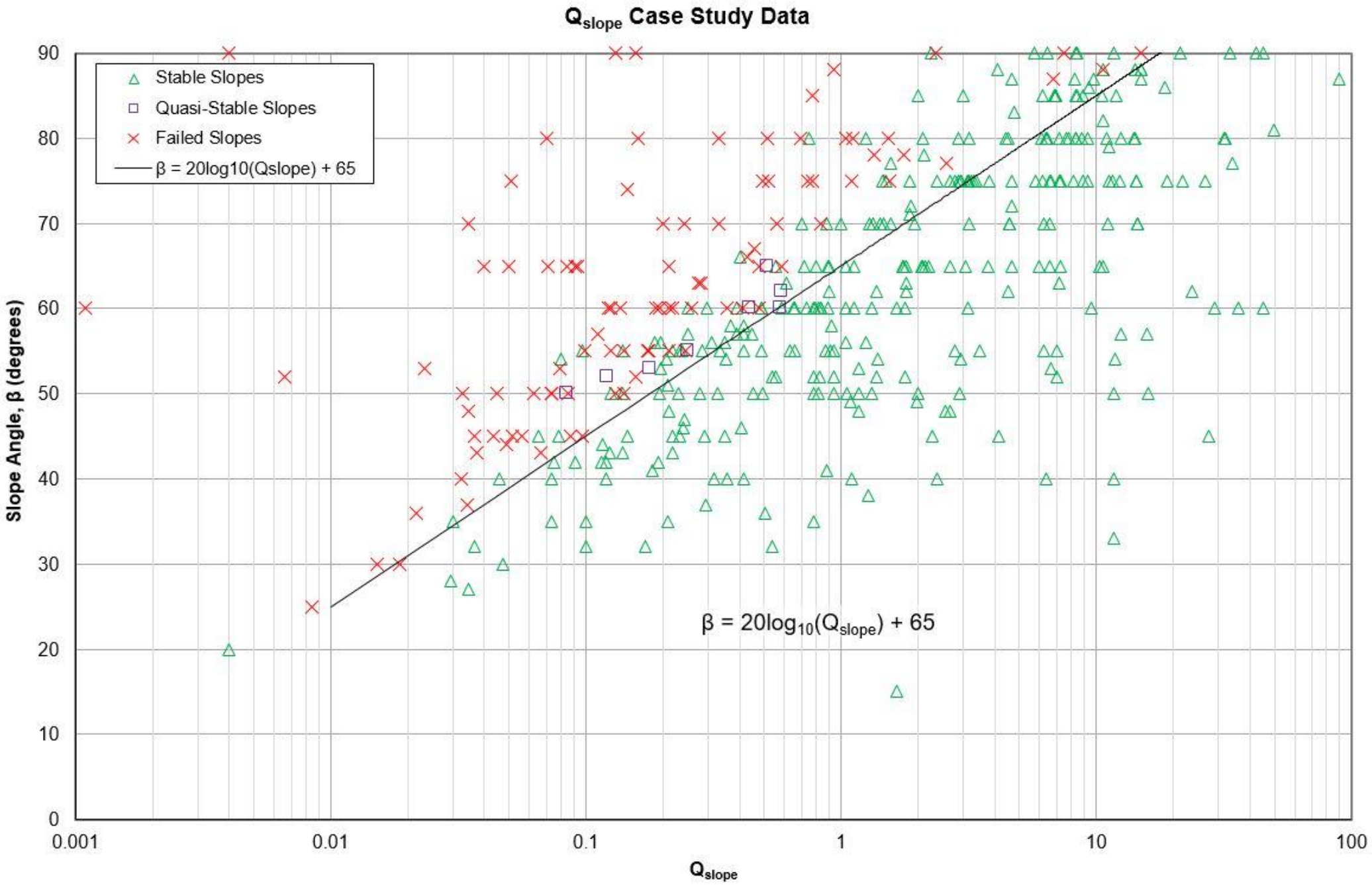
$$Q\ slope = \frac{RQD}{J_n} \ x \left(\frac{J_r}{J_a}\right)_o \ x \ \frac{J_{wice}}{SRF_{slope}}$$

RQD/J_n are unchanged

$(J_r/J_n)_o$ are unchanged, BUT have an orientation, and 'wedge' adjustment

J_w (now J_{wice}) has a new structure for slopes, including ice-effects and *tropical rainfall-effects*

SRF_{slope} has new categories tailored for slopes



The steadily increasing data base: thanks to active work by Neil Bar in Australia

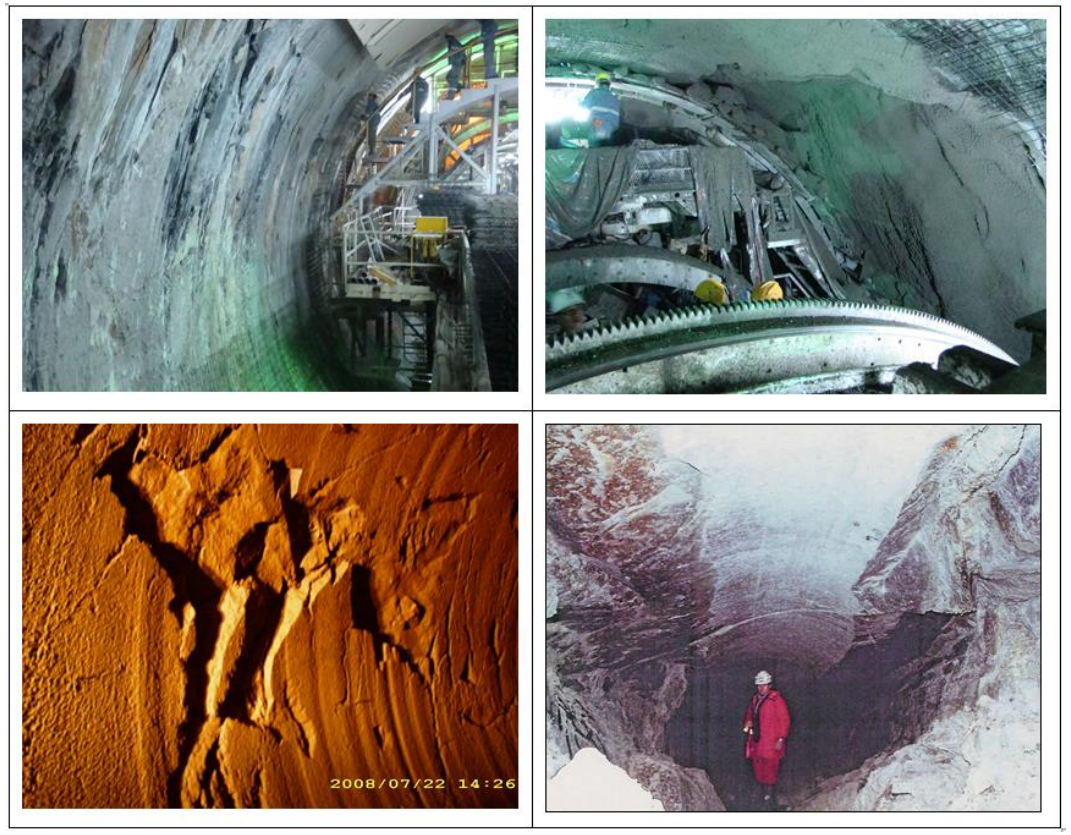
Actual cutting, with Q-slope-based steeper slopes at base (Note: feeder road)

Each car, bus, lorry, had to clear stones that had fallen in last 1 to 2 minutes.

Several drivers in hospital!

Peru, Cerro del Aguila HEP access (5km/200km)

Explain, even avoid, failures with Q !



PRE-INJECTED, SINGLE-SHELL NMT – Q-BASED SUPPORT SELECTION