EMPIRICISM, THEORY, AND PROBLEM SOLVING IN ROCK ENGINEERING

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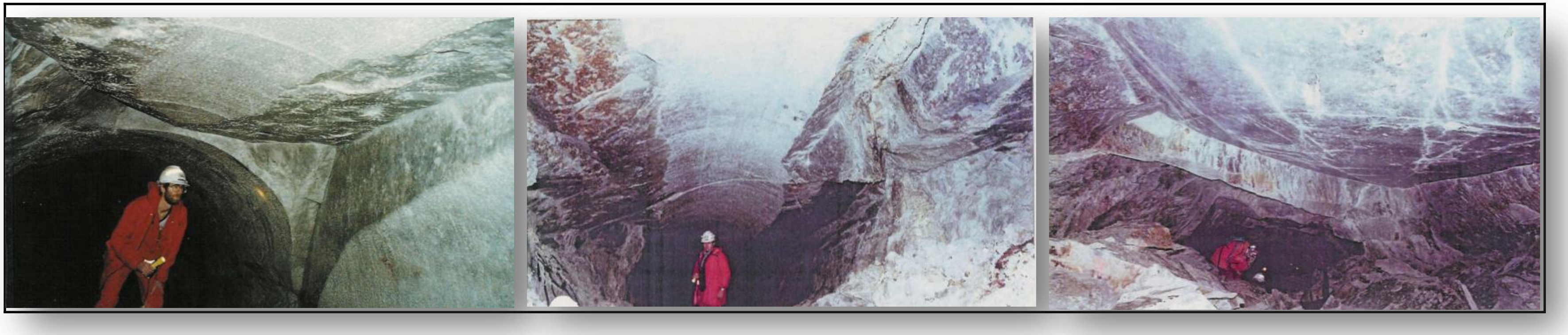
6th Leopold Müller Lecture, with additions

GSL – HONG KONG October 2013



Beaumont TBM Tunnel, 1880 : wedge-failure, stress-failure, tidal influence. Three photos separated by 150 m.

WHY THE 'OVER-BREAK'/ POTENTIAL INSTABILITY?

Because of adverse Jn, Jr, Ja (JRC, JCS, ϕr), Jw, SRF

……and dip/dip direction, gravity, density.

The origin and *numerous* applications of these parameters (J_n, J_r, J_a, JRC, JCS, ϕ_r, J_w, SRF, Q) will be (part of) the subject of this lecture.

ACTUAL EMPIRICAL BEHAVIOUR or ASSUMED BEHAVIOUR ??

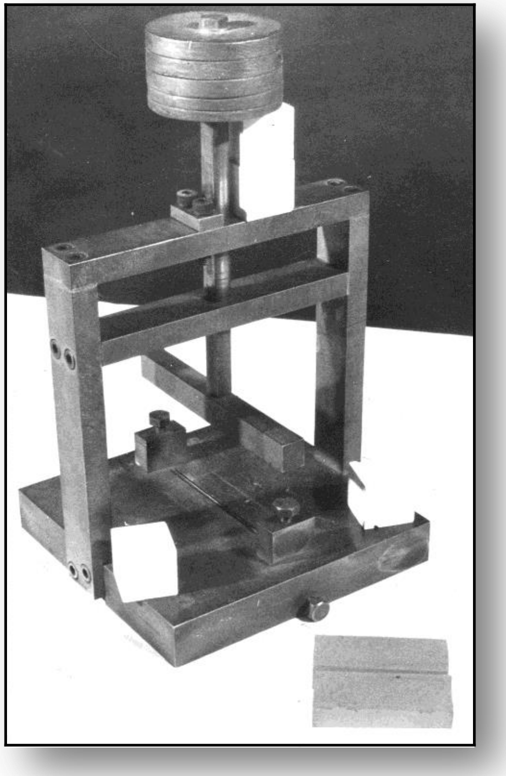
Empiricism: *a posteriori* *(= behaviour based on experience)* is better than *a priori* (= 'behaviour' (?) based on assumptions).

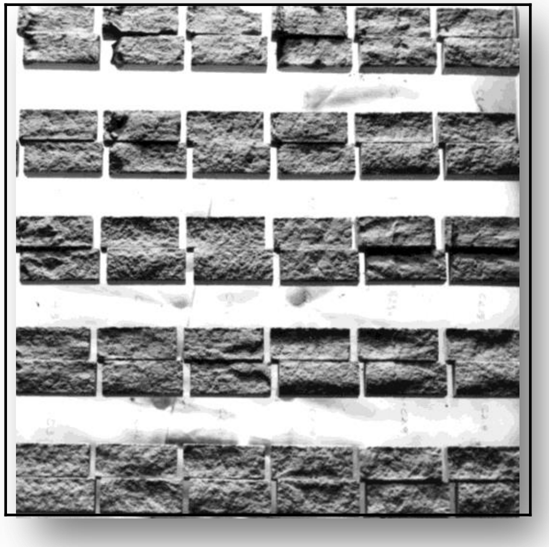
There are too many *a priori* assumptions *(clothed in some amazing algebra)* which are used by many of us these days….e.g. GSI/Phase 2?

PART 1

A DISCONTINUOUS *(and idealized)* *EXPERIMENTAL/EMPIRICAL* START IN 1966

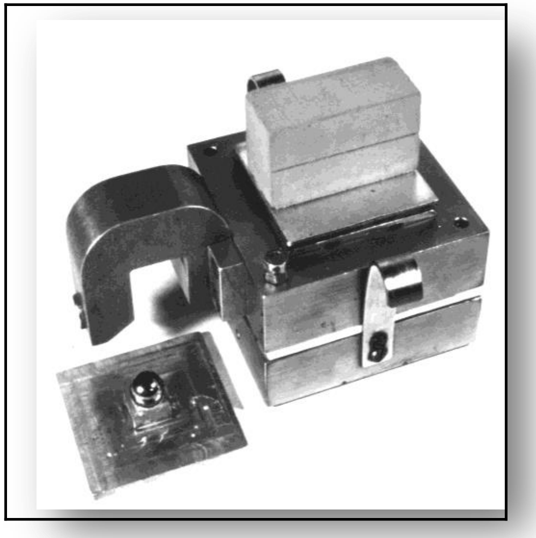
at Imperial (‘*Empirical*’) College, London

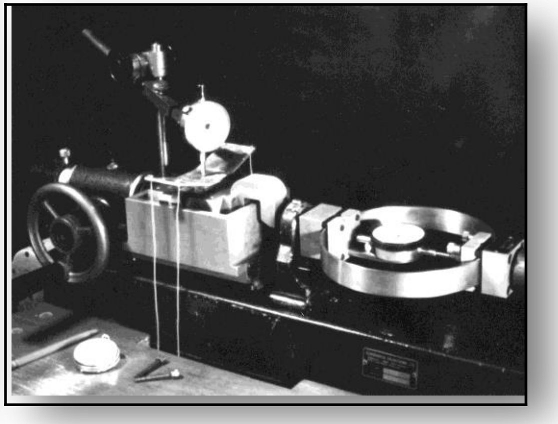


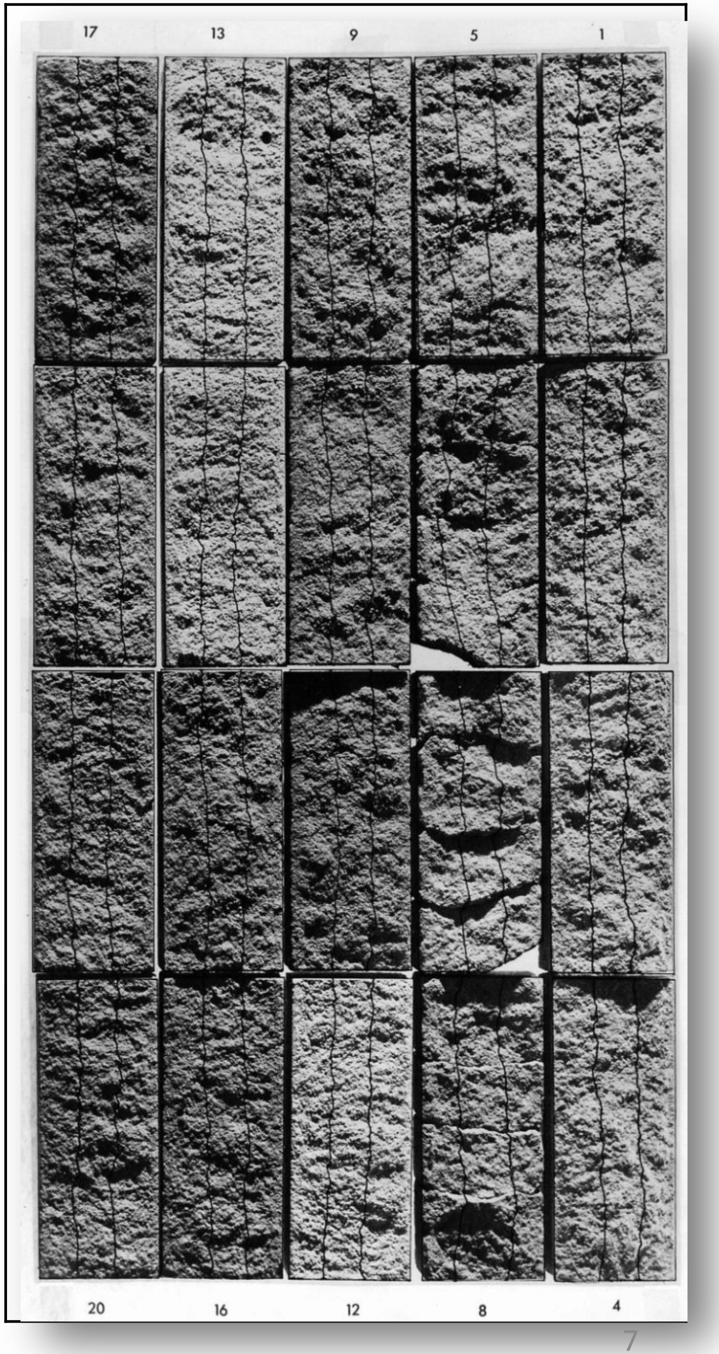


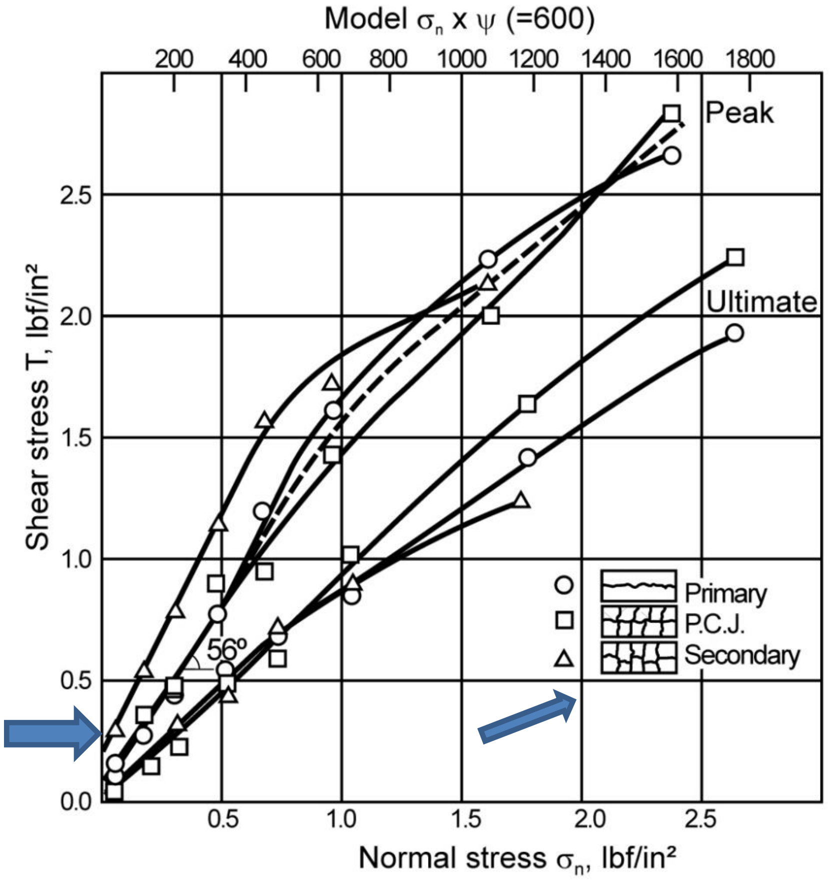
DST on 200 artificial tension fractures in a variety of brittle model materials

(Barton, 1971)

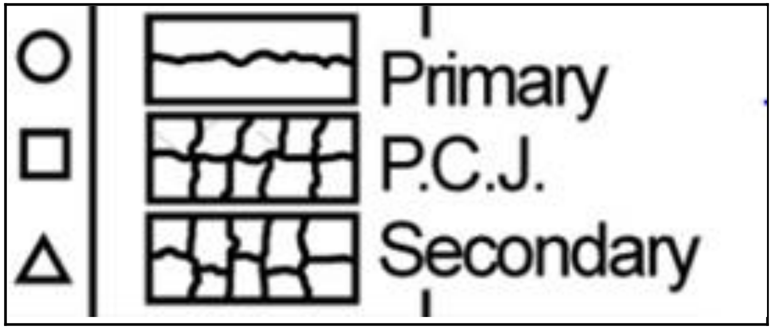


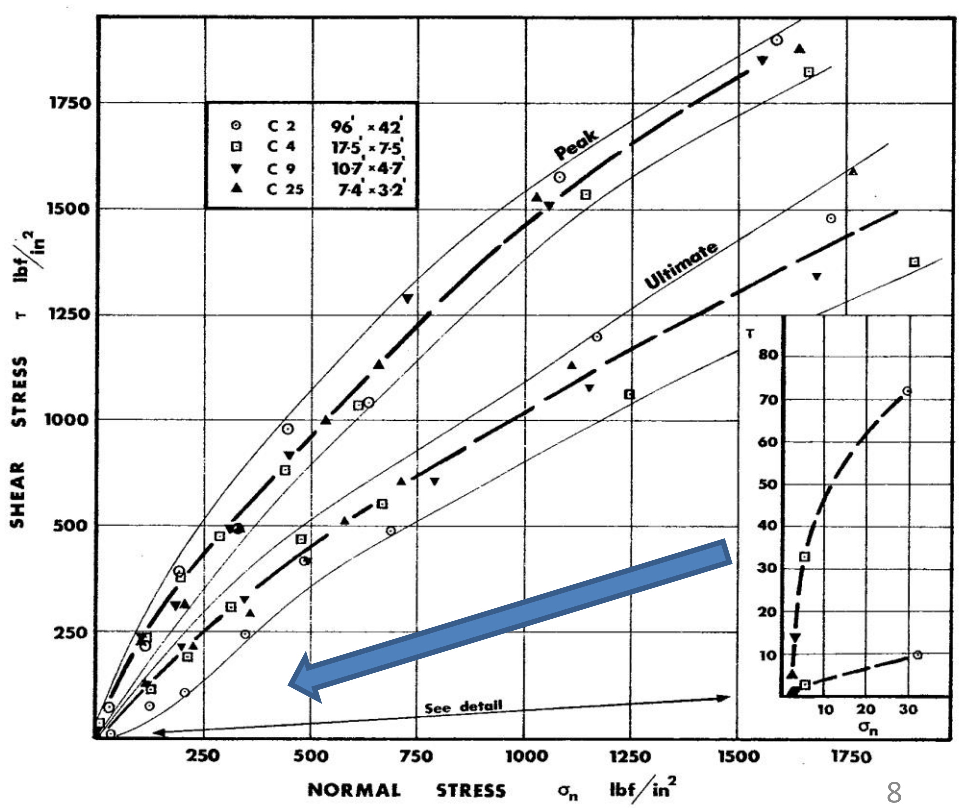






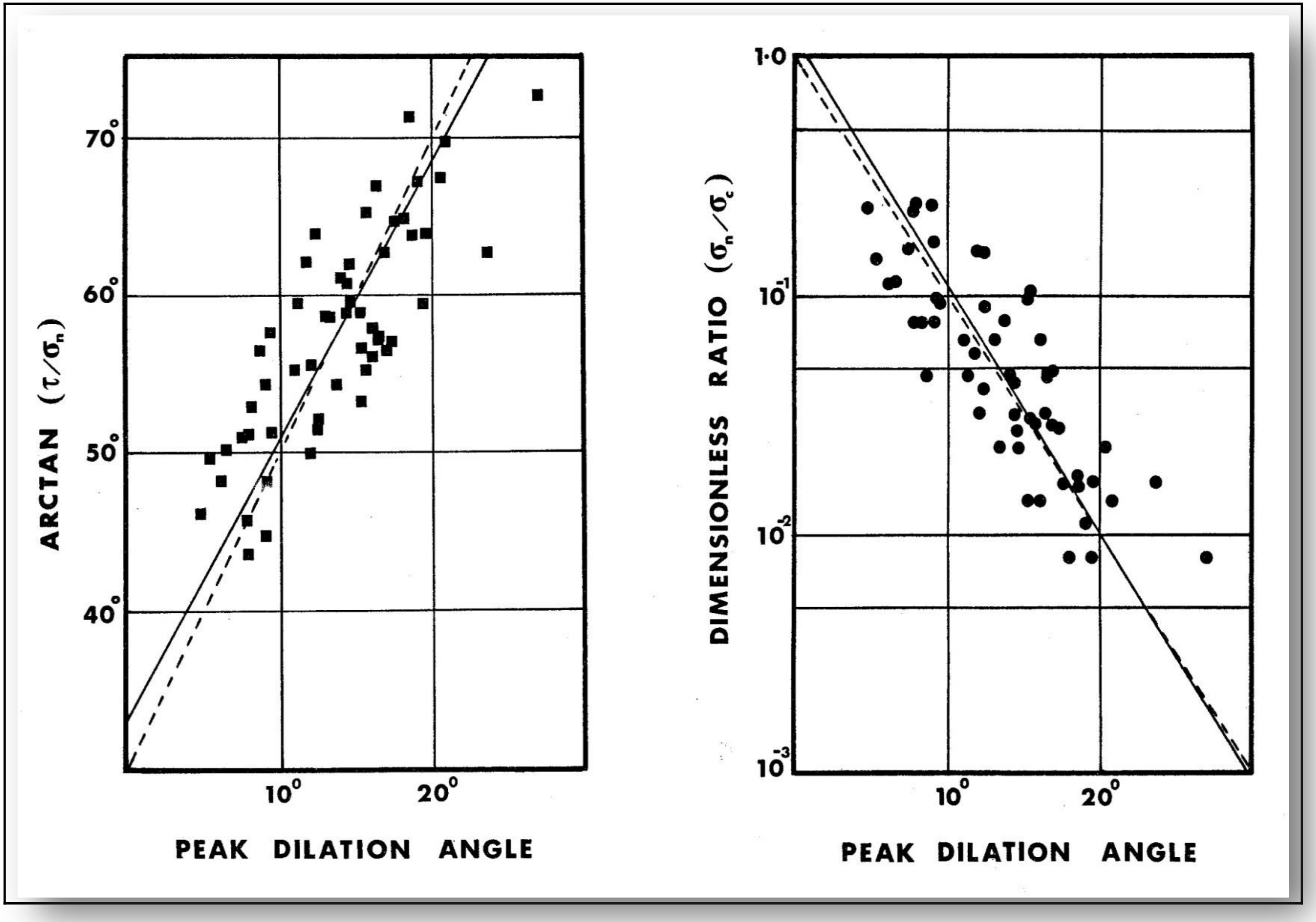
NOTE LACK OF ACTUAL COHESION *UNLESS* STEPPED (“secondary”) FRACTURES ARE TESTED





(------ = no decimal places)

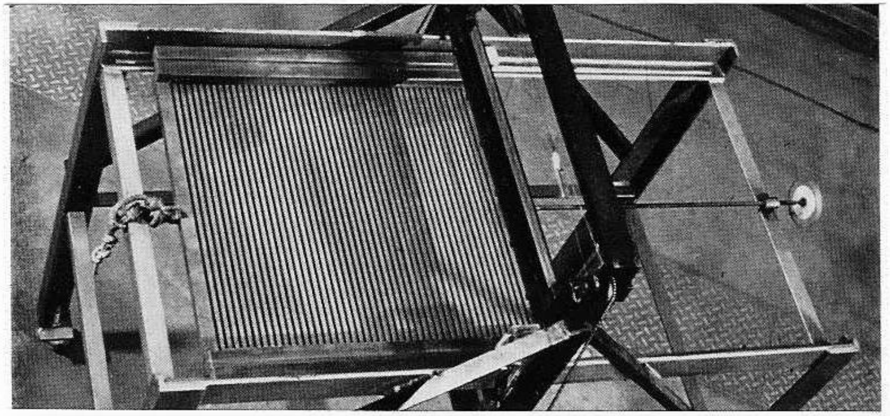
$$\tau = \sigma_n \,.\, \tan\left[\, 20.\log(\,UCS/\sigma_n\,) + 30^{\circ} \,\right]$$

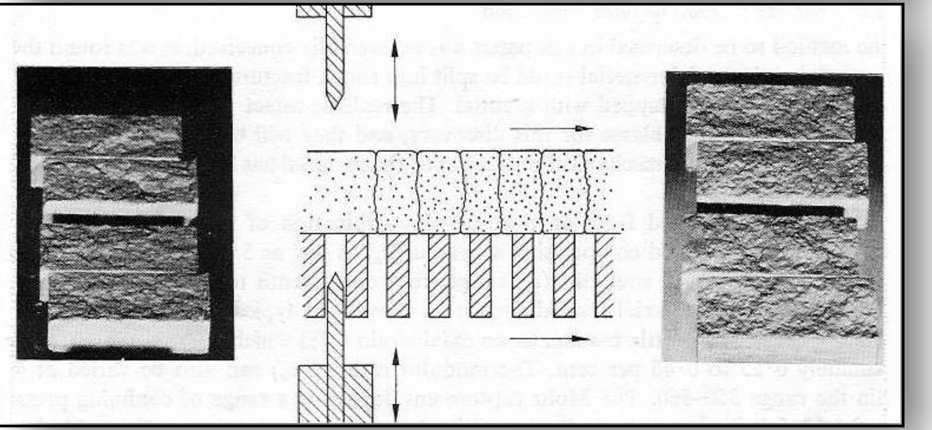


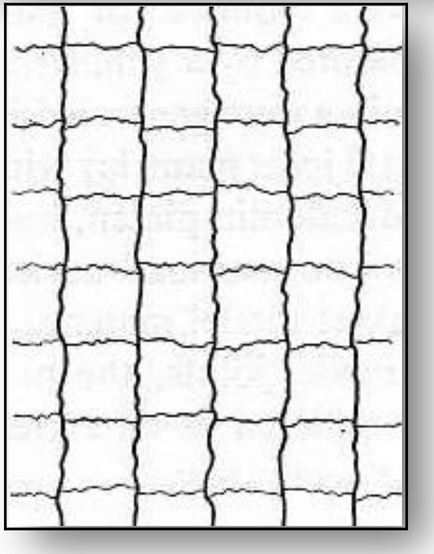
2D JOINTED "ROCK-MASS"

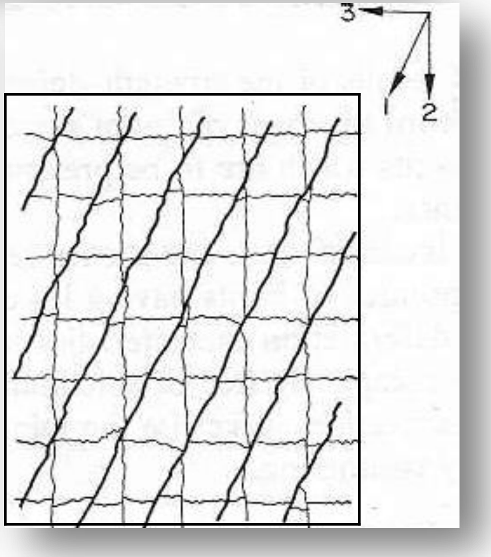
Tension-fracture models used for '*rock slope' studies* (at Imperial College) 1968-1969.

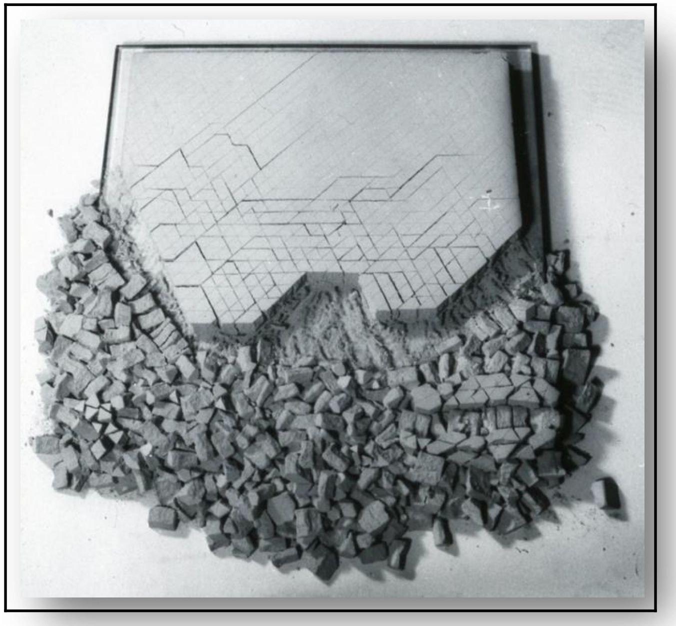
'Nuclear power plant' *rock cavern* investigations (50m) (at NGI) 1977-1978 (pre-UDEC)







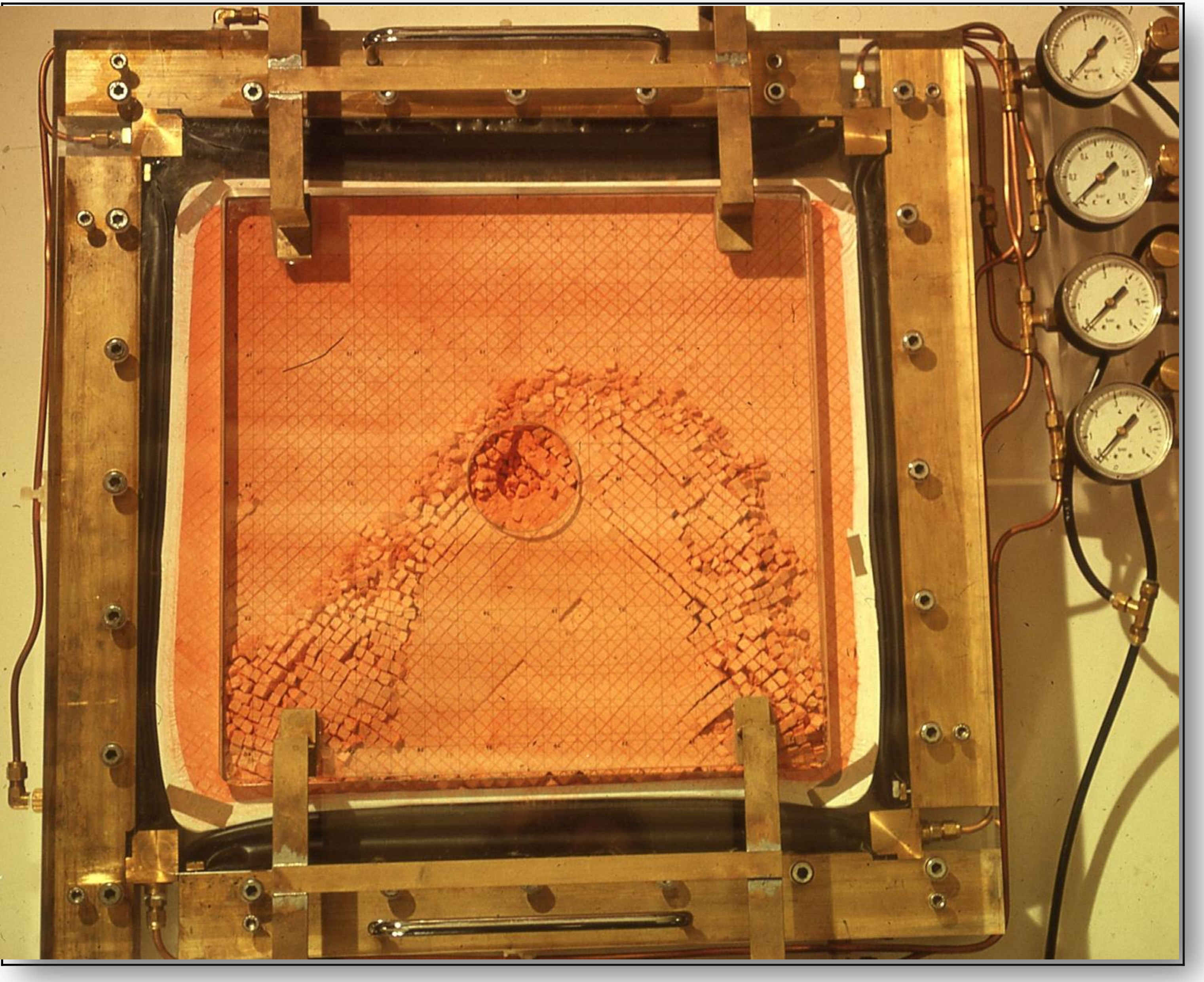




2D ‘rock mass’ research conducted in the laboratory

Physical (1977) models **(this colour)** follow here which ***pre-date*** **UDEC**:

- ☐ Artificial, but some useful lessons
- ☐ They are physical, not conceptual
- ☐ *They are ‘a posteriori’, not ‘a priori’ !*

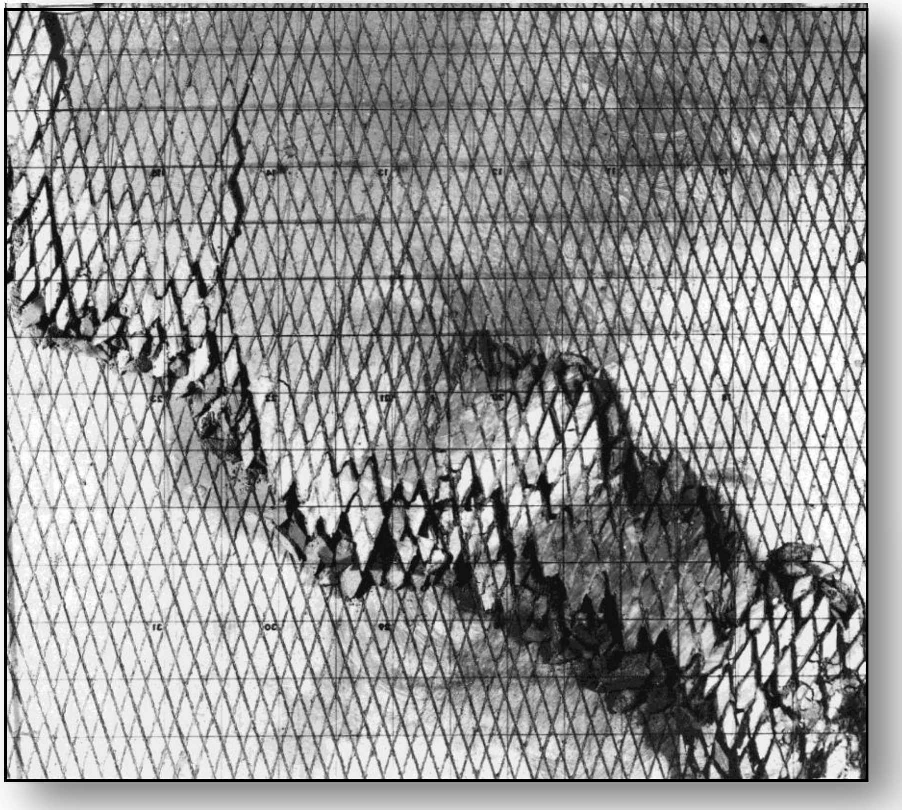


BIAXIAL LOADING

Scale-effect investigations

250, 1000, or 4000 blocks.

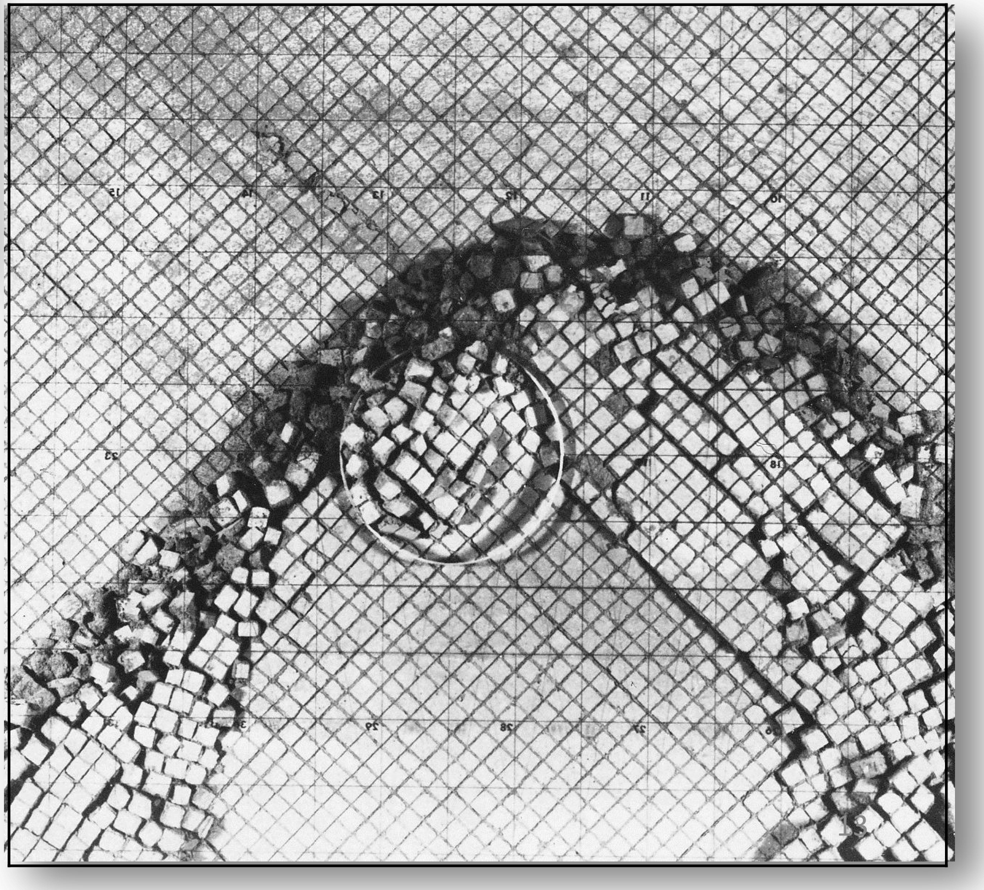
"Always" got rotational failures with small blocks!



BIAXIAL LOADING TESTS WITH HIGHLY ANISOTROPIC STRESS APPLICATION

(as under a big rock slide?)

Shearing by ***rotation of individual blocks***, following local **‘kinking’** within the mass?



APPROPOS: ***LARGE DEBRIS and ROCK SLIDES*** ***(Front cover: eds. J.Clague, D. Stead)***

FRANK SLIDE (Wikipedia)

TRAVEL DISTANCE VARIABILITY

- SAY ***0.5 to 1 km*** TRAVEL DISTANCE EXPECTED
- WITH ‘AIR-CUSHION’ (Chinese research) ***2km***

- REALITY (sometimes) is > ***20 km***
- **SLIDE MASSES TOO HOT FOR RESCUE PARTIES**

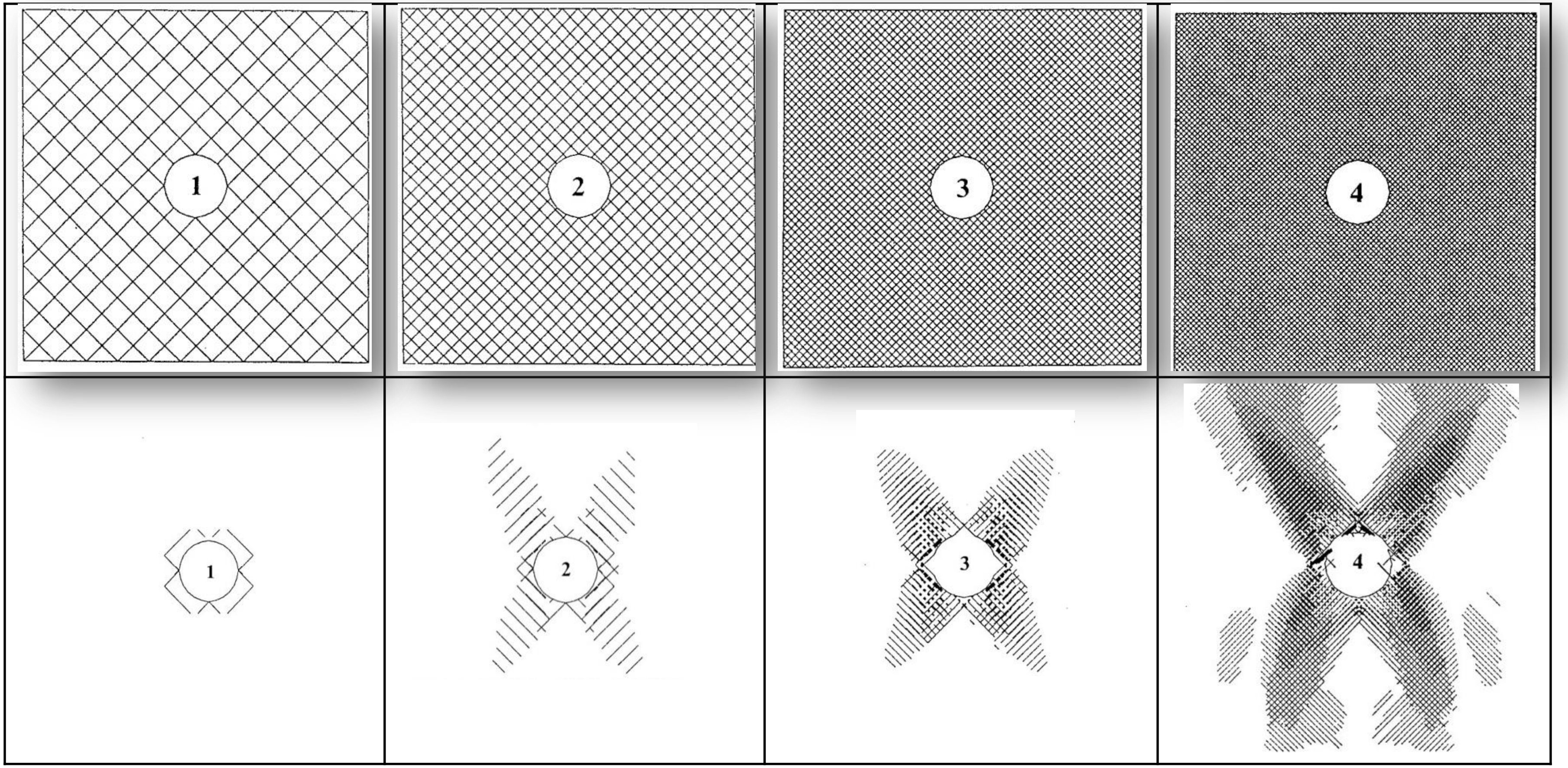
WHY?: Rotational friction, block crushing, extreme heating, ground water converted to steam, ‘steam-cushioned slides’ due to ‘gas’ pressure?

($V_2/V_1 = 1{,}400{:}1$)

SUCCESSIVE HALVING OF THE BLOCK SIZE – HAS DRAMATIC ROTATIONAL (degree-of-freedom) EFFECTS, *ALSO* WITH *UDEC-MC.*

(helps to explain the drama of fault zones: worse with clay and water)

Shen, B. & Barton, N. 1997. The disturbed zone around tunnels in jointed rock masses.



ROCK JOINTS :

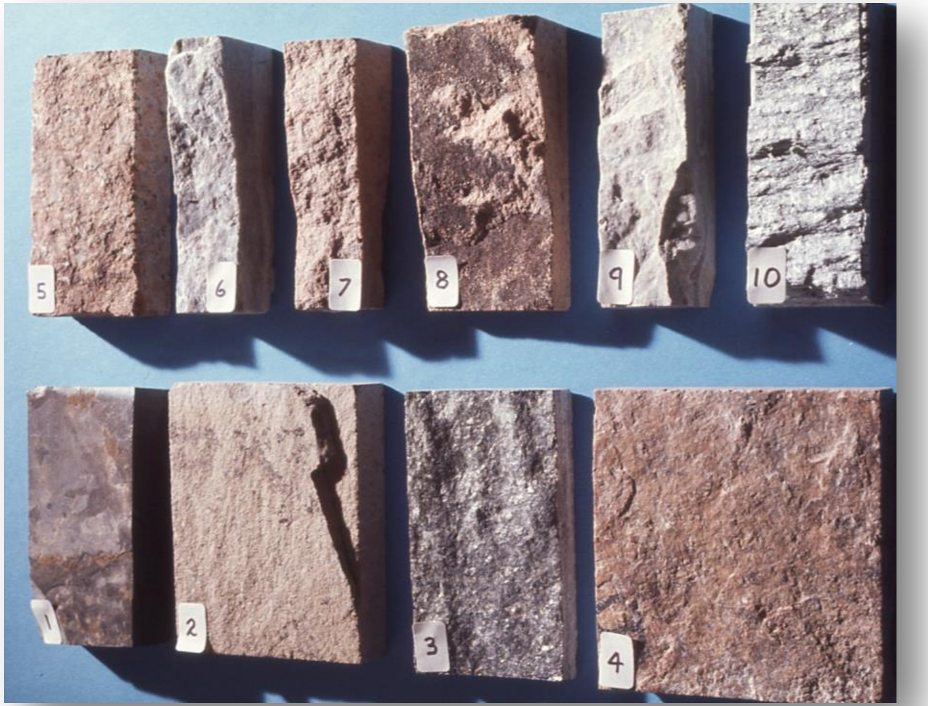
THEY (ALSO) SHOWED

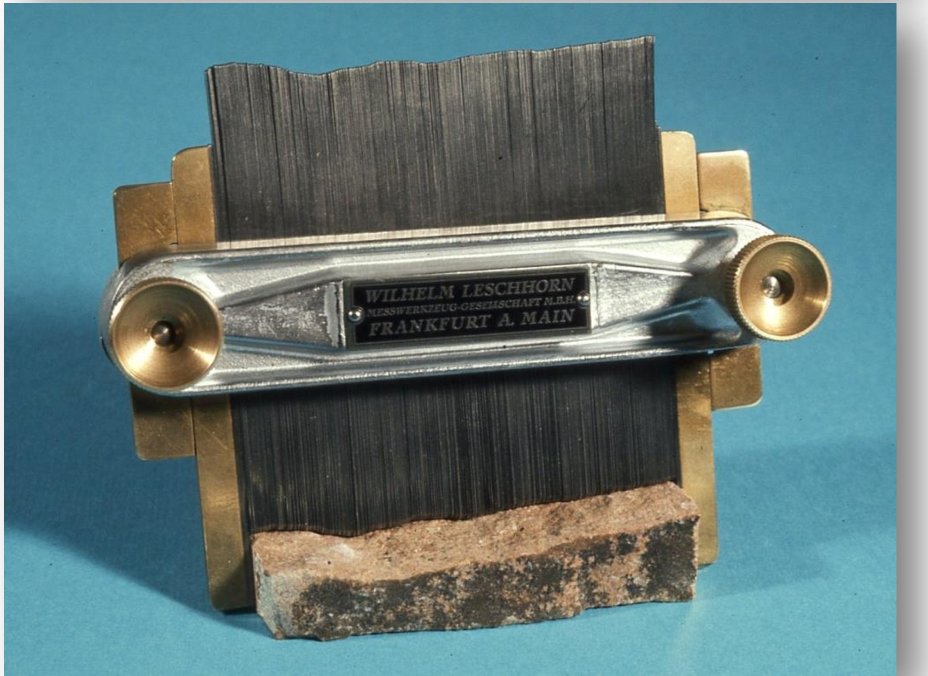
NON-LINEAR SHEAR STRENGTH

(and no cohesion!)

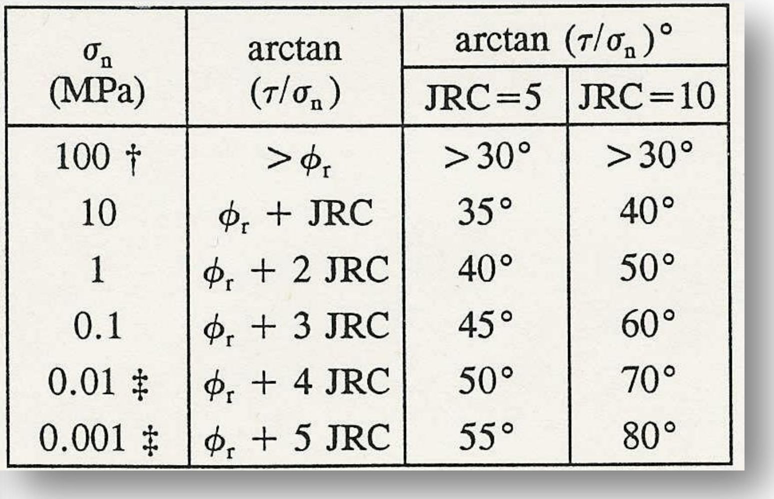
130 joint samples. Roughness measurement and ***tilt test***

(Barton and Choubey, 1977)

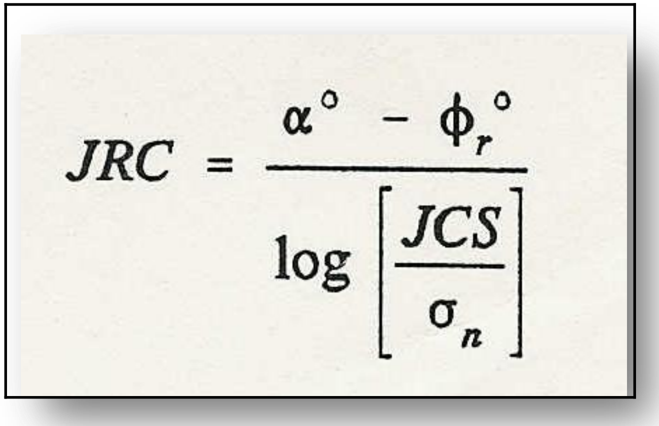




TILT TEST 'THEORY'



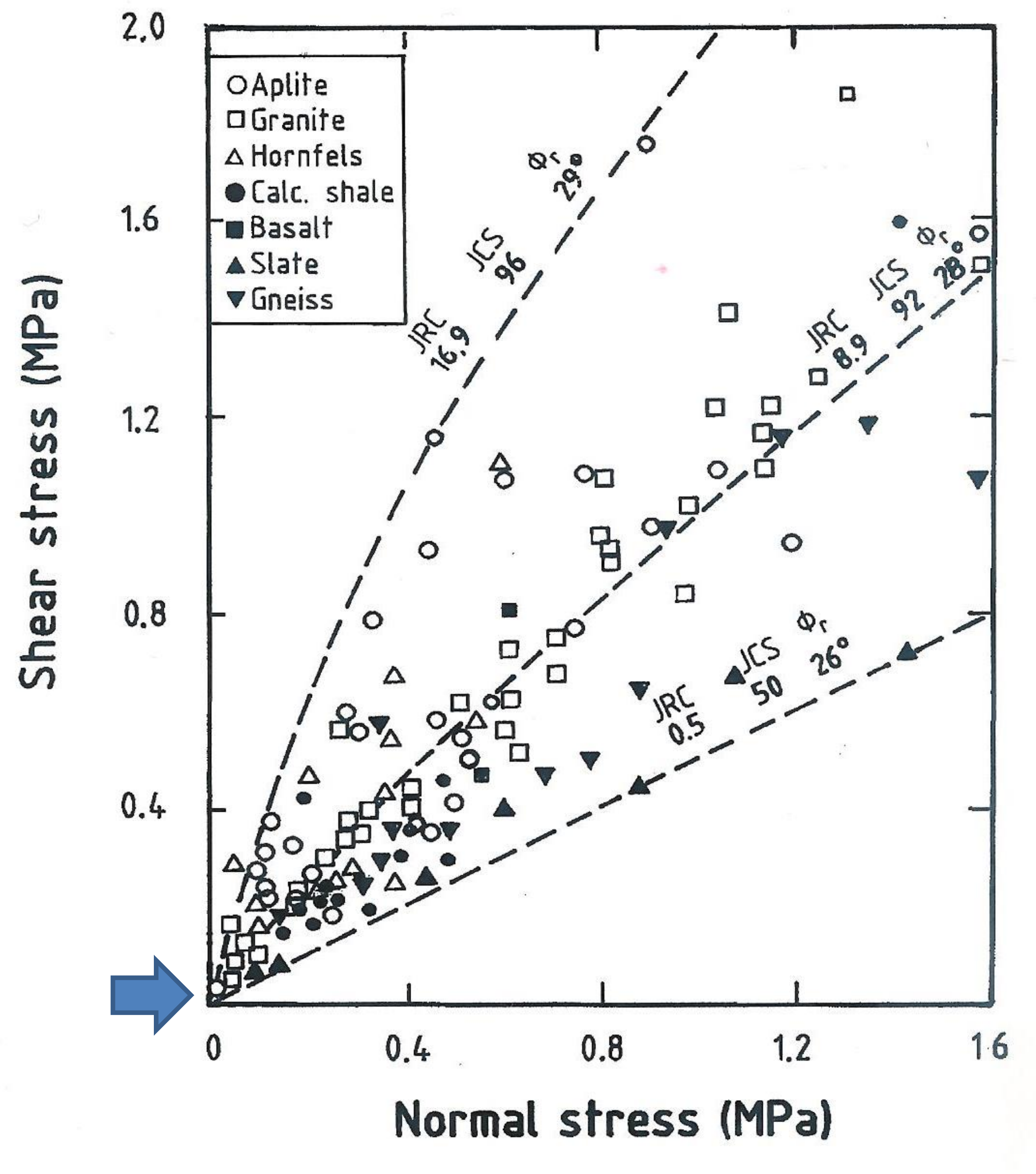
σ_n (MPa)	arctan (τ/σ_n)	arctan $(\tau/\sigma_n)°$ JRC=5	arctan $(\tau/\sigma_n)°$ JRC=10
100 †	$>\phi_r$	>30°	>30°
10	ϕ_r + JRC	35°	40°
1	ϕ_r + 2 JRC	40°	50°
0.1	ϕ_r + 3 JRC	45°	60°
0.01 ‡	ϕ_r + 4 JRC	50°	70°
0.001 ‡	ϕ_r + 5 JRC	55°	80°



$$JRC = \frac{\alpha° - \phi_r°}{\log\left[\frac{JCS}{\sigma_n}\right]}$$

where α° = arctan (τ/σn)

(Barton and Bandis, 1990)



130 rock-joint samples

(Barton and Choubey 1977)

Three curved **peak shear strength** envelopes **and no cohesion!**

1.Maximum strength with JRC = 16.9

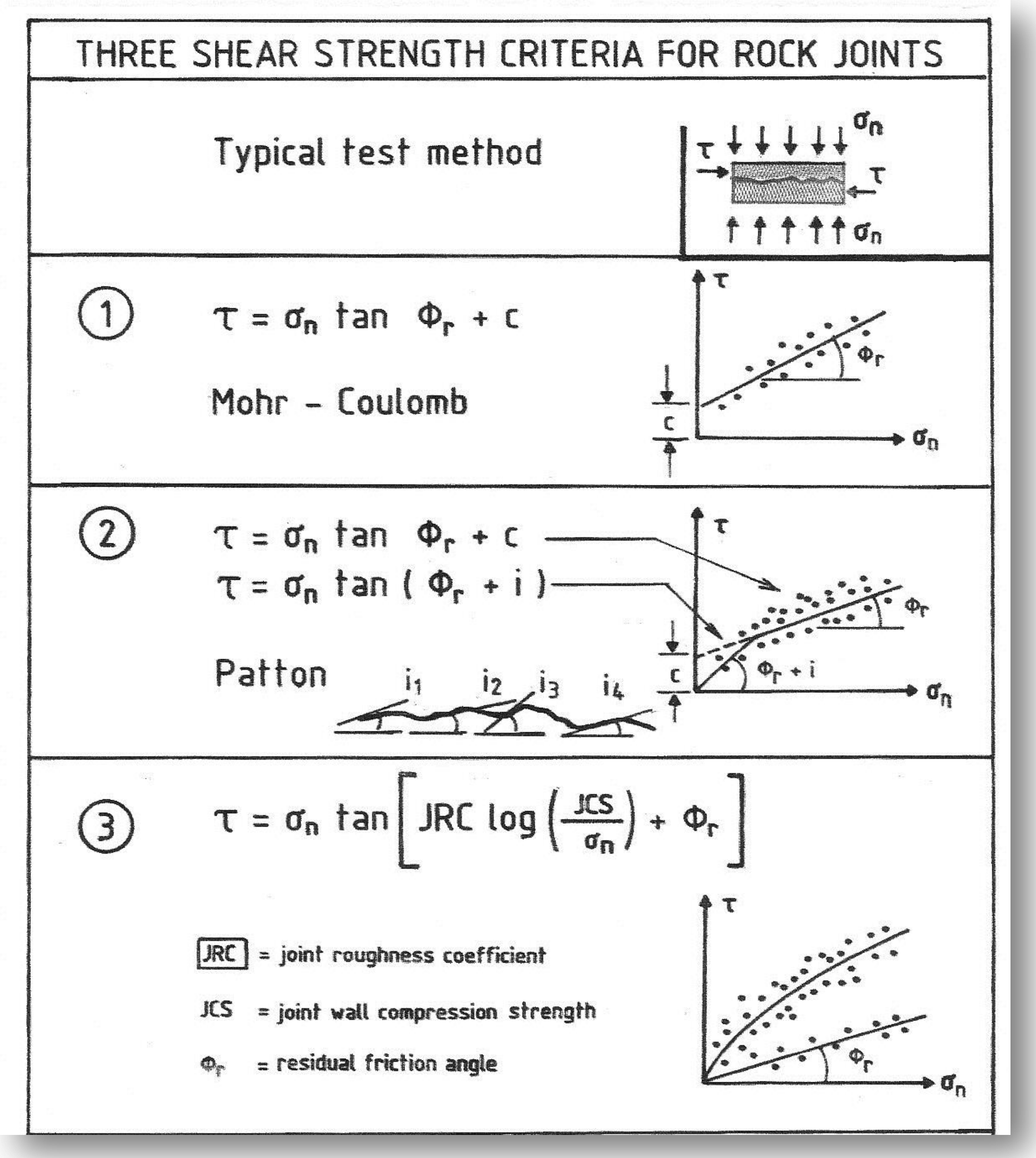
2. Mean parameters

JRC = 8.9

JCS = 92 MPa

ϕ_r = 28°

3. Minimum strength with φ_r = 26º



THREE SHEAR STRENGTH CRITERIA FOR ROCK JOINTS

Typical test method

①

$$\tau = \sigma_n \tan \Phi_r + c$$

Mohr – Coulomb

②

$$\tau = \sigma_n \tan \Phi_r + c$$

$$\tau = \sigma_n \tan (\Phi_r + i)$$

Patton

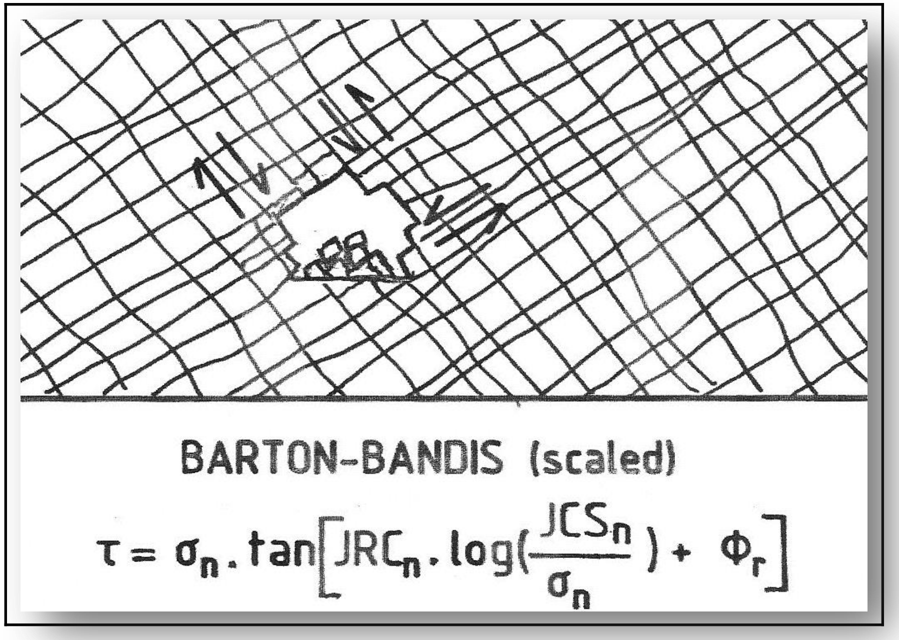
③

$$\tau = \sigma_n \tan \left[\mathrm{JRC} \log \left(\frac{\mathrm{JCS}}{\sigma_n} \right) + \Phi_r \right]$$

JRC = joint roughness coefficient

JCS = joint wall compression strength

Φ_r = residual friction angle



BARTON-BANDIS (scaled)

$$\tau = \sigma_n . \tan\left[JRC_n . \log\left(\frac{JCS_n}{\sigma_n}\right) + \phi_r \right]$$

Note: the original ***tension fracture-based*** equation (1971) was:

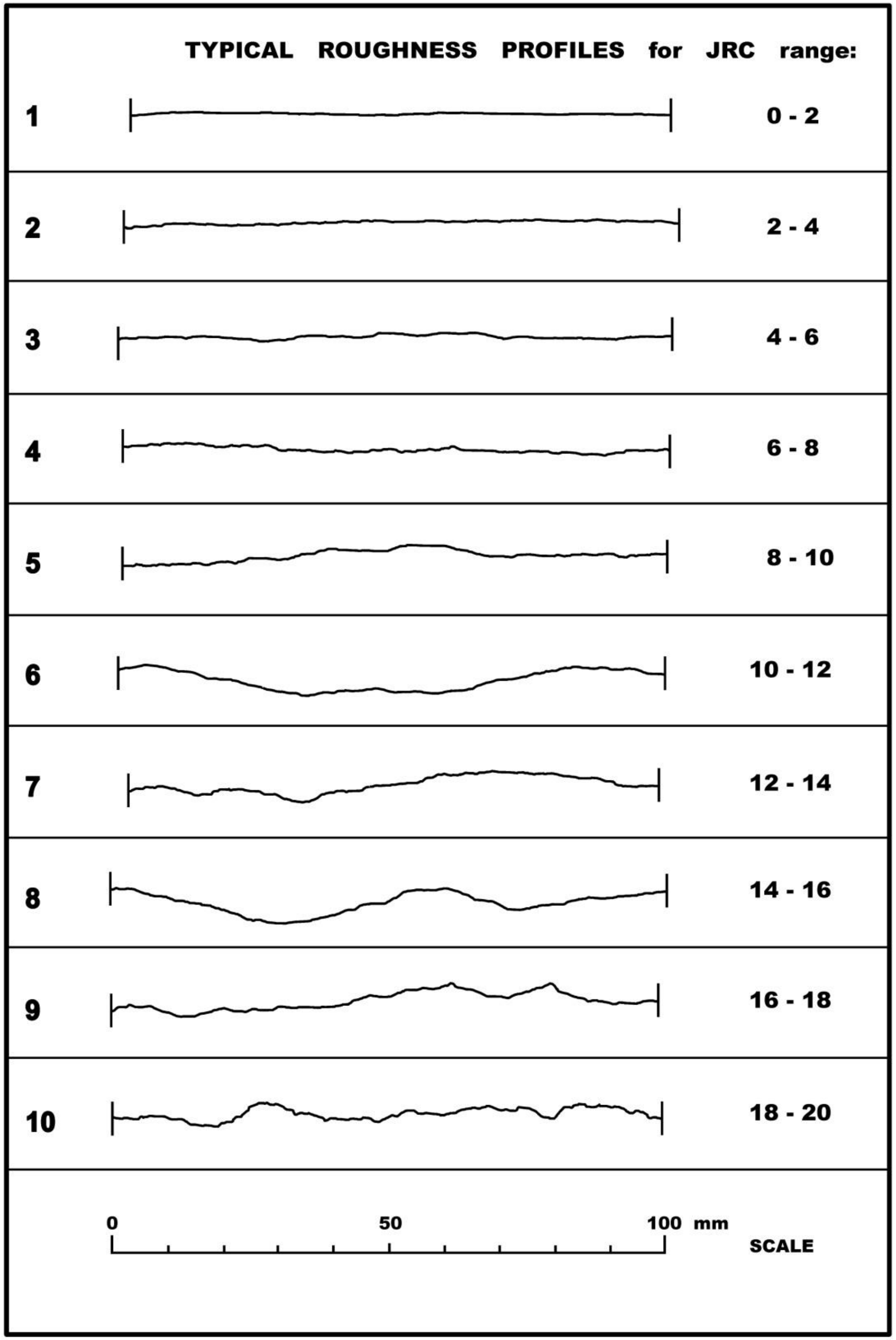
$$\tau = \sigma n \tan [\ 20.\log(UCS/\sigma n\ )+30º]$$

JRC **JCS** **φb (now φr)**

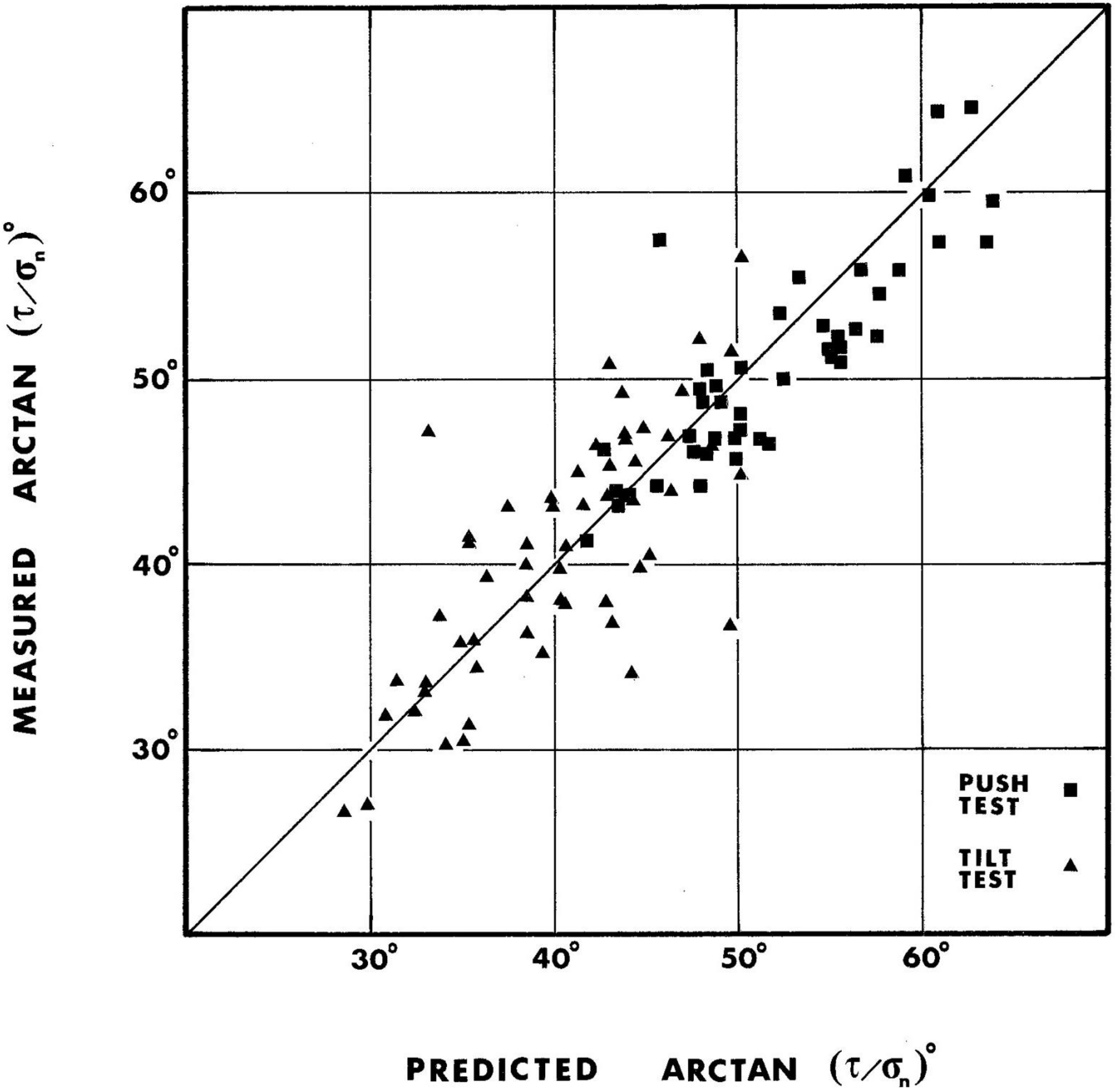
TO THOSE WHO HAVE PERFORMED PH.D.'s AND ARE SELLING SOFTWARE – PLEASE NOTE it is φr since 1977 !

VISUAL MATCHING OF ROUGHNESS – for JRC… **USEFUL BUT HAS LIMITATIONS**

(Barton and Choubey, 1977)



EXAMPLE of ROUGHNESS CONTRAST – BACK-CALCULATED FROM DST (L = 400 mm: Nevada Test Site welded tuff)



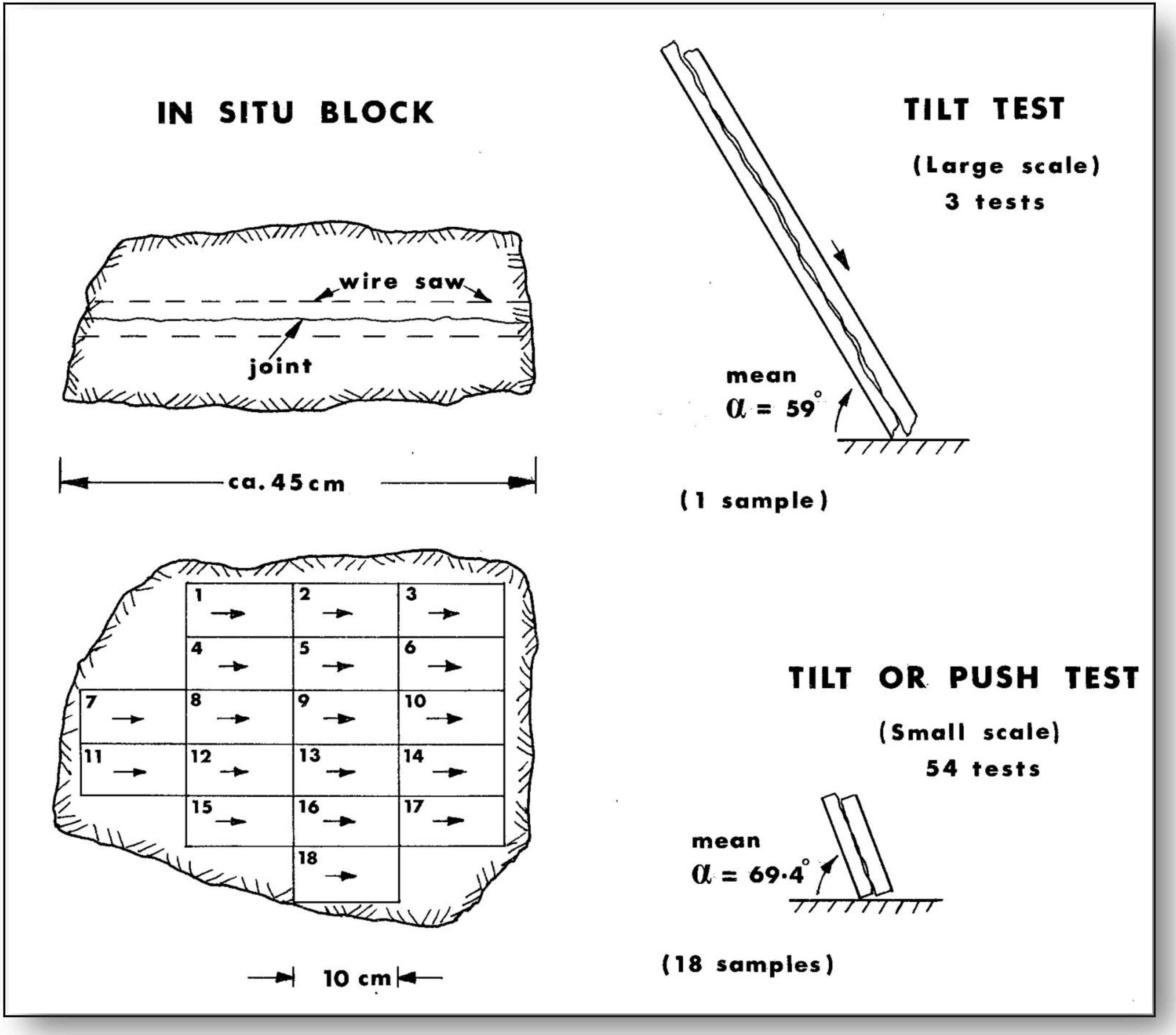
NOTE:
above JRC-JCS strength criterion was developed from tilt and push test correlation with DST

(not from analysing roughness profiles!)

JCS < UCS

JCS > UCS (?)

SCALE EFFECTS FOR INDIVIDUAL JOINTS



Tilt tests repeated at different scale -

there is *almost no damage*.

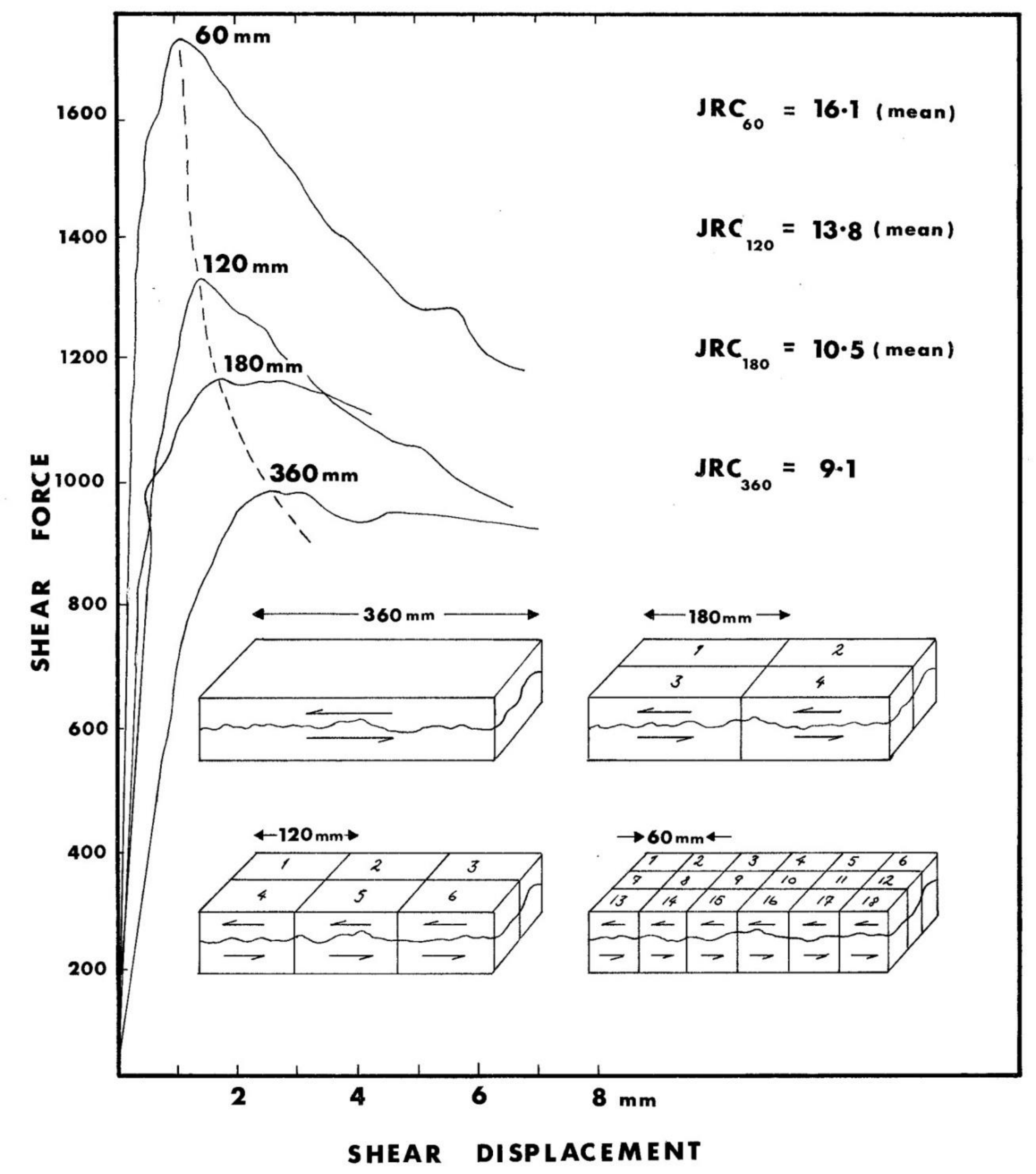
Note:
$JRC_1 < JRC_2$

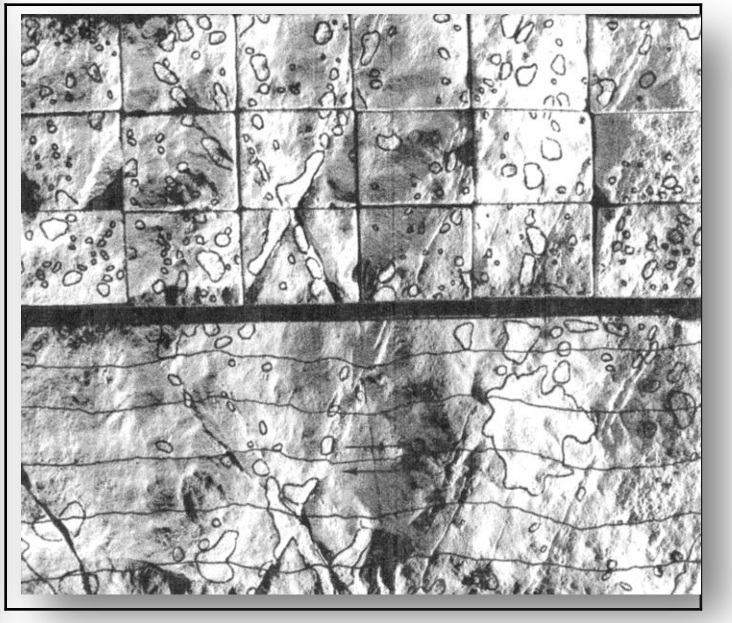
(Barton and Choubey, 1977)

Bandis 1980 Ph.D.

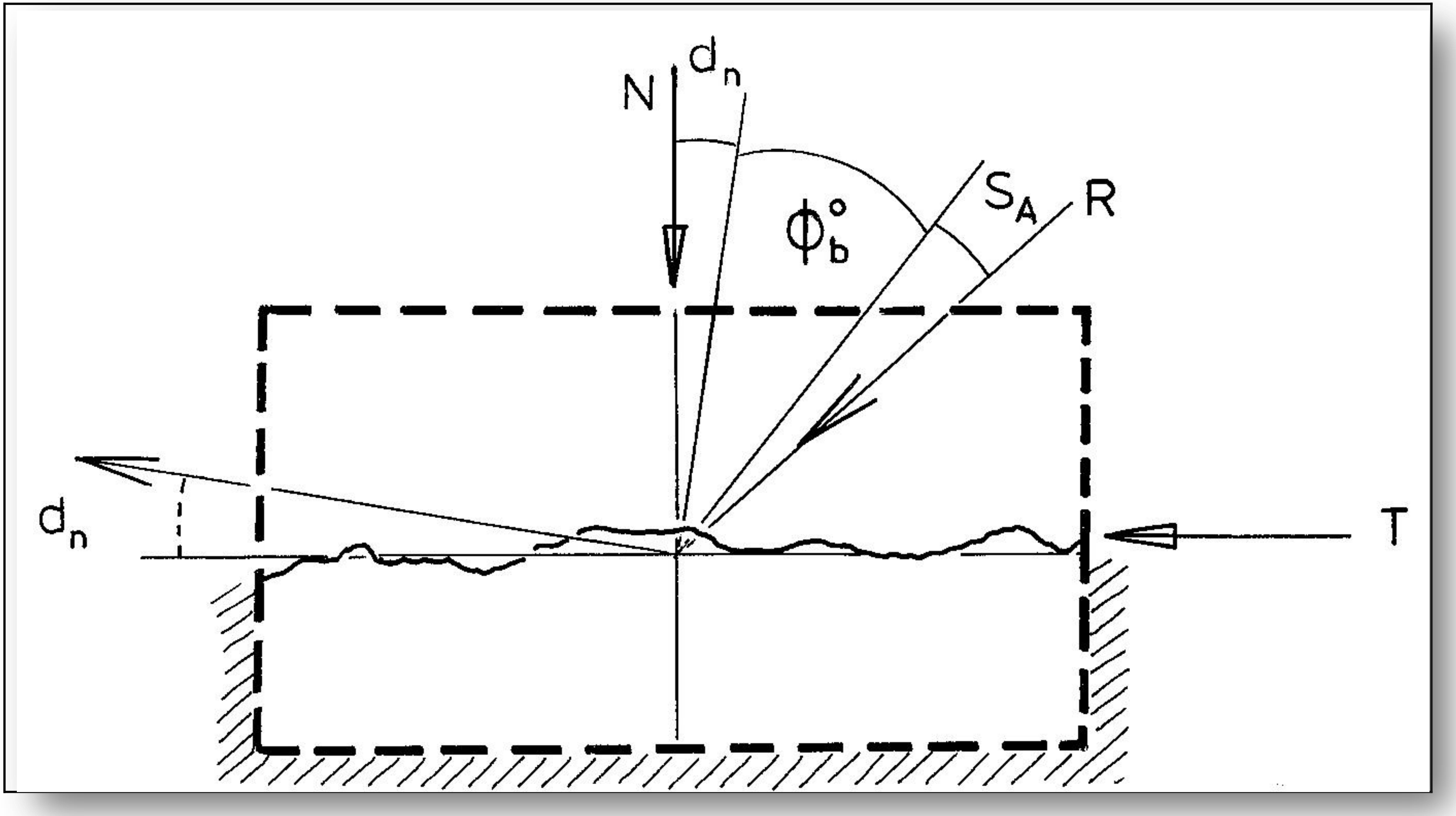
***Ahead-of-their-time* scale-effect investigations.**

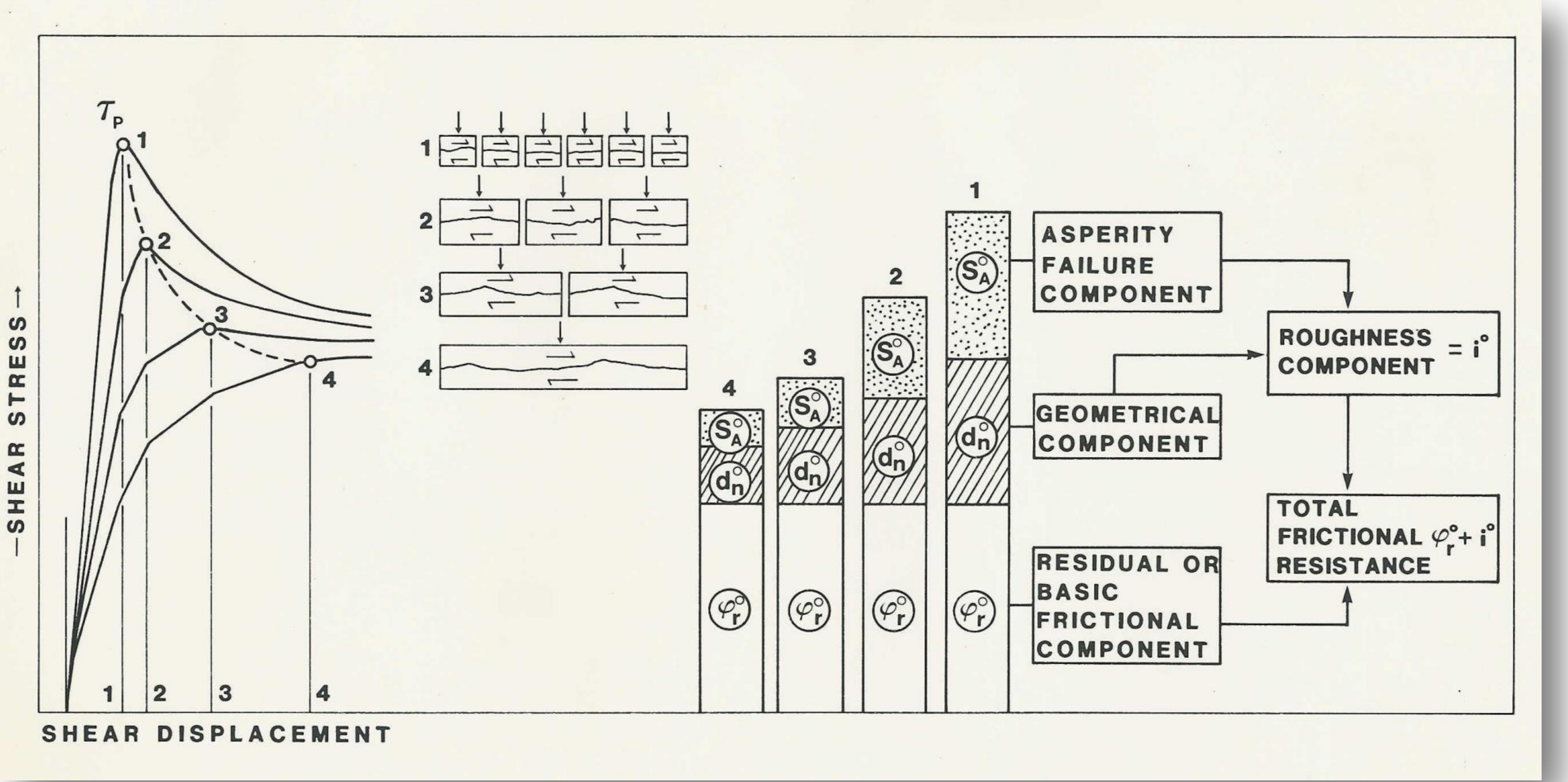
One set of many joint replica tests.





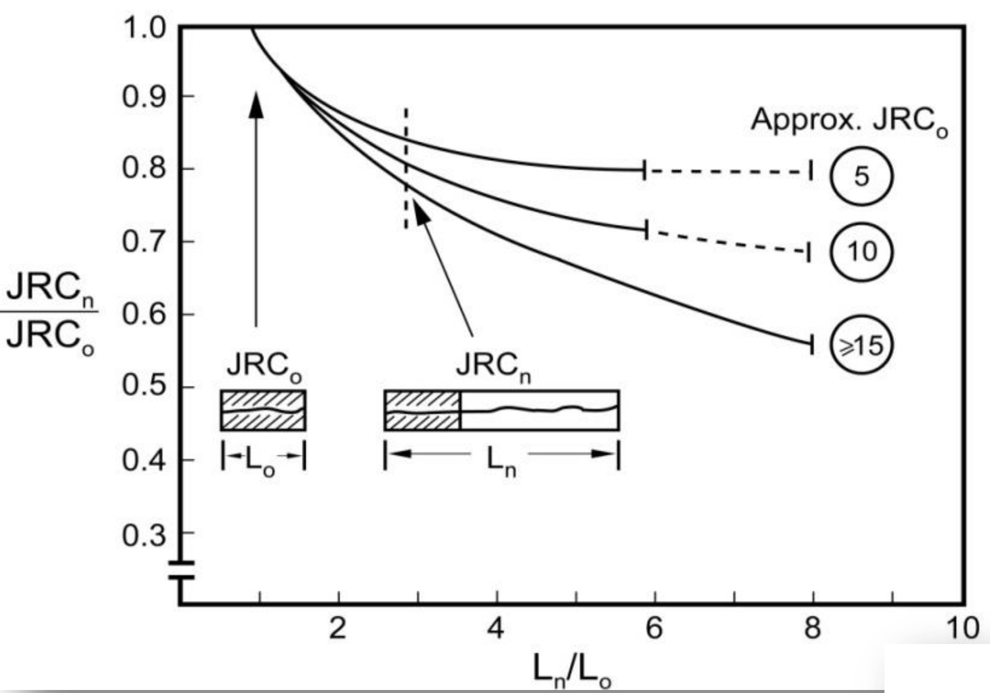
The angular components of ***peak shear strength***, with asperity strength (S_A), and peak dilation angle (d_n) each included. (Barton, 1971)





Asperity component S_A means that *JRC* (or φ_r) cannot be back-calculated *by subtracting dilation (d_n) from peak strength*. Φ_r or Φ_b would then be *dangerously too high (e.g. 40°)* as in some earlier Hong Kong work.

(JRC would also be incorrect).



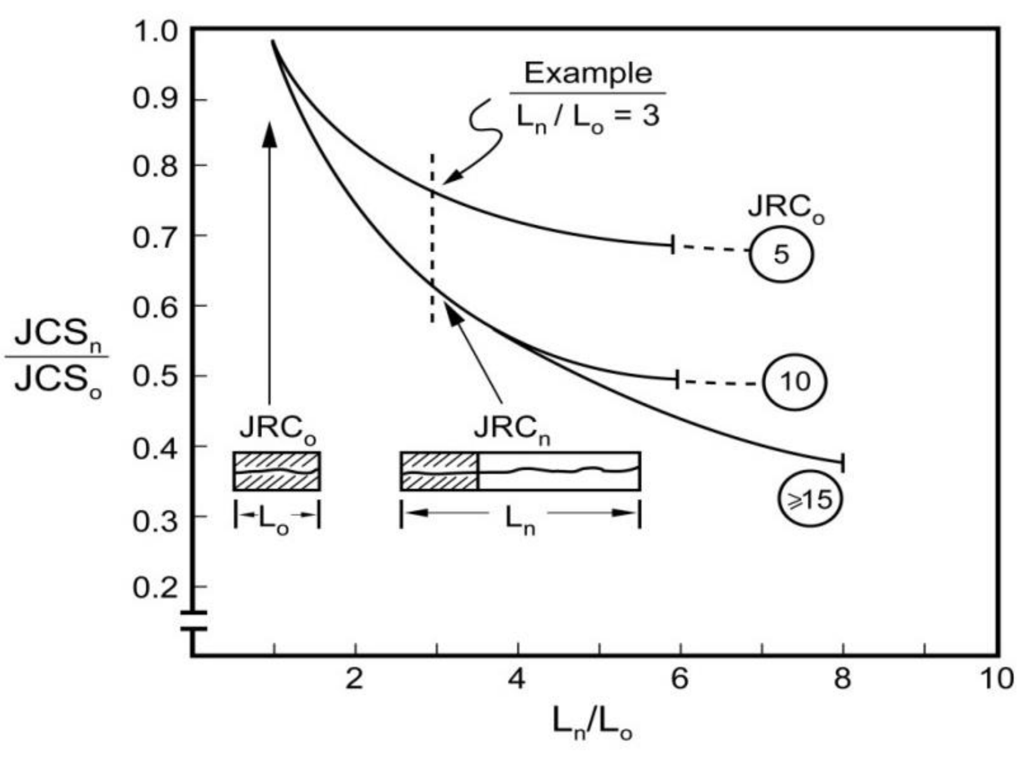
SCALE-EFFECTS

REDUCTION OF of JRC and JCS with block-size

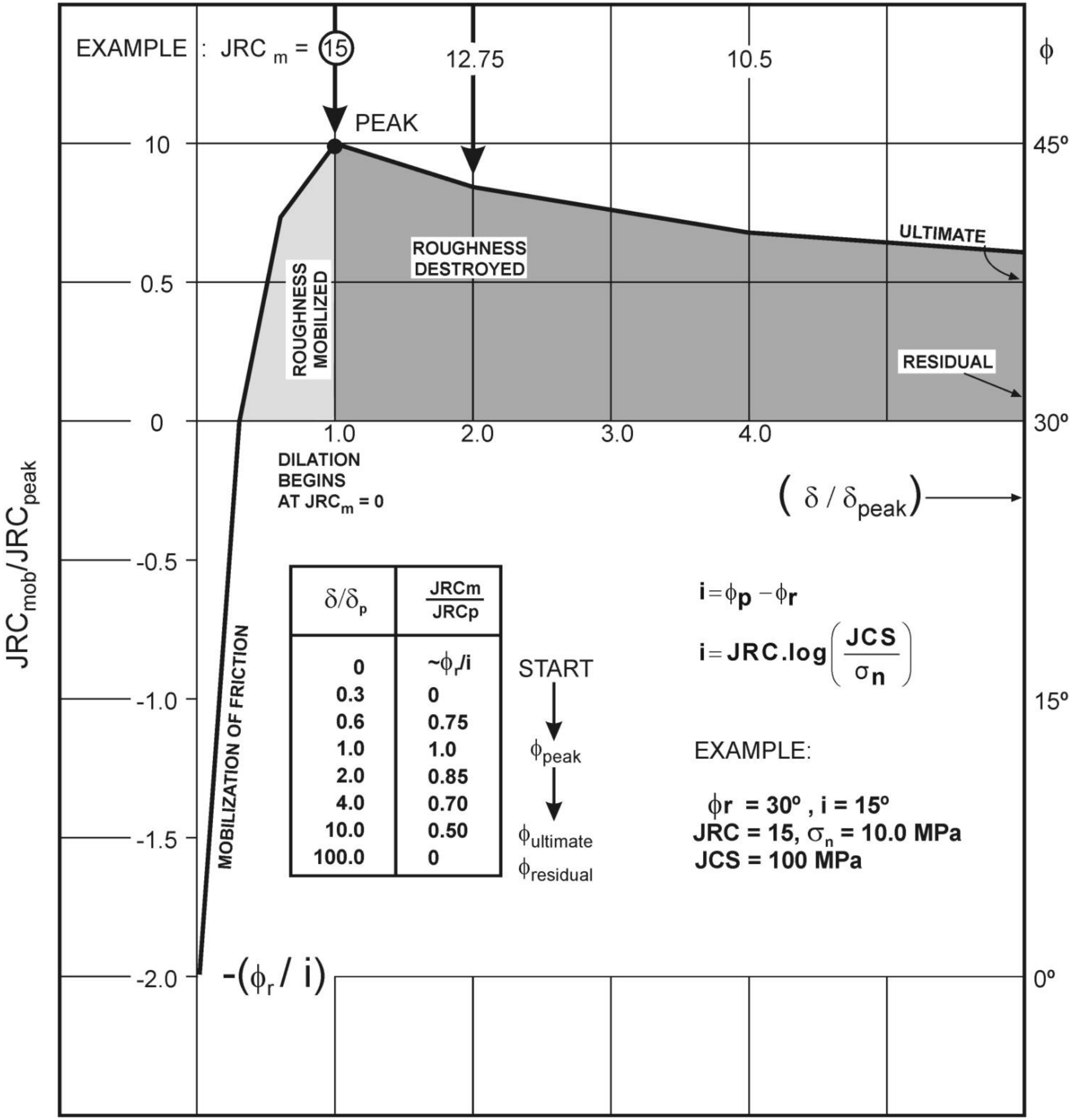
Ln > L0

$$JRC_n \approx JRC_o \left[\frac{L_n}{L_o} \right]^{-0.02\,JRC_o}$$

$$JCS_h \approx JCS_o \left[\frac{L_n}{L_o} \right]^{-0.03\,JRC_o}$$



(Bandis, Dearman, Barton, 1981)



δ/δ_p	$\frac{JRCm}{JRCp}$
0	$\sim\phi_r/i$
0.3	0
0.6	0.75
1.0	1.0
2.0	0.85
4.0	0.70
10.0	0.50
100.0	0

$$i = \phi p - \phi r$$

$$i = JRC.\log\left(\frac{JCS}{\sigma n}\right)$$

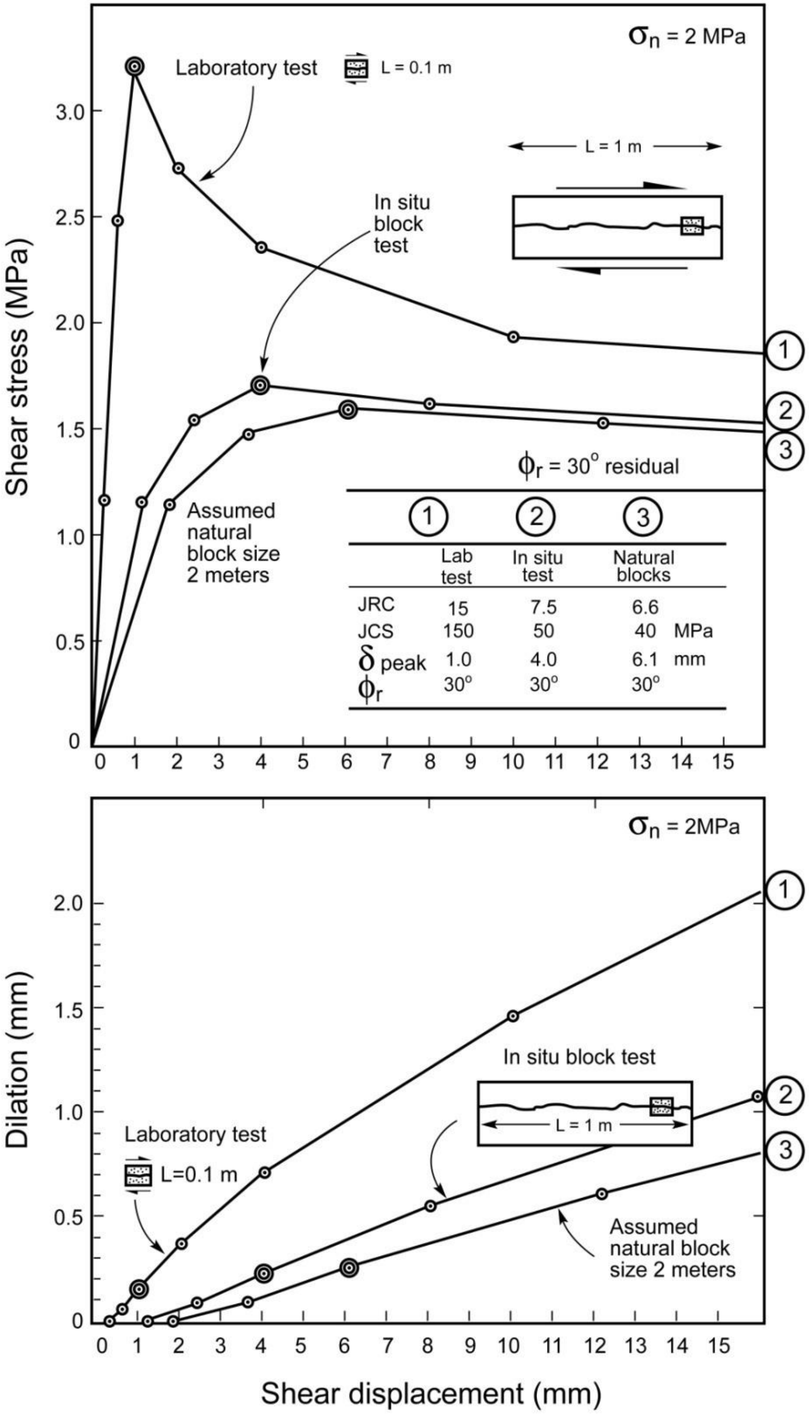
EXAMPLE:

$\phi r = 30^\circ$, $i = 15^\circ$
JRC = 15, $\sigma_n = 10.0$ MPa
JCS = 100 MPa

$JRC_{mobilized}$ defined

(also with dimensionless displacement)

Barton, 1978, 1982



Then possible to predict/model *shear stress-displacement and dilation-displacement behaviour.*

(Barton, 1982, with scaling from Bandis et al. 1981).

Note (double) scale effect on shear stiffness (Ks), because it is strongly <u>scale-and-stress-dependent</u>.

(Ks usually < 1 MPa/mm, 0.1 MPa/mm if large blocks)

Well-jointed wedge.

Remains in place because of the *higher shear strength* of the *smaller component blocks* ?

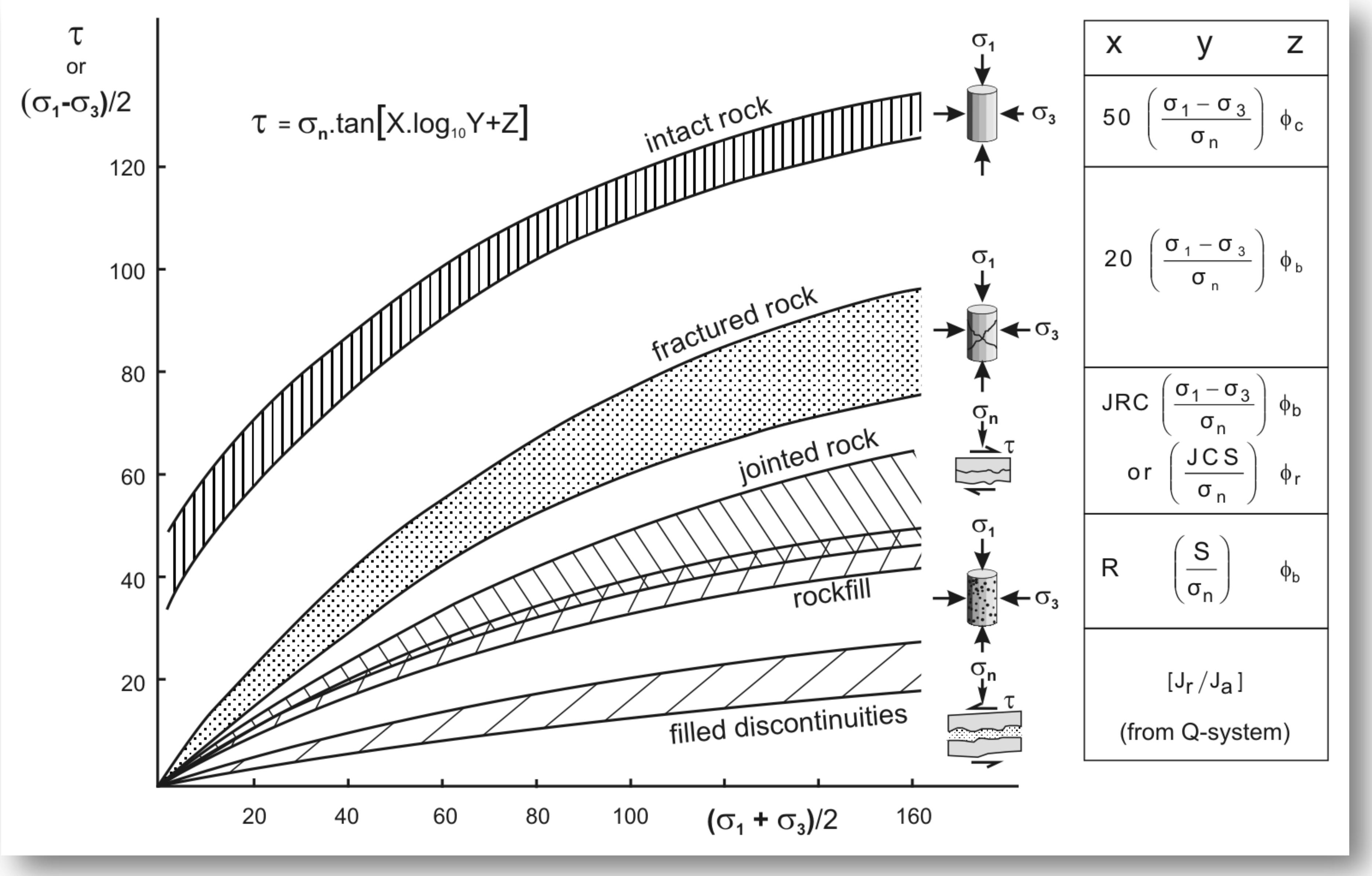
$$\tau = \sigma_n \tan\left[JRC_n \log\left(\frac{JCS_n}{\sigma_n}\right) + \phi_r\right]$$

Larger blocks defining wedge

(failure at much shallower angle of dip)

Before leaving shear strength envelopes:

When a rock mass fails: 1st, 2nd, 3rd (and 5th) envelopes are mobilized at different strains - not like H-B / GSI estimation (Barton, 1976, 1999, 2006)



x	y	z
50	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$	ϕ_c
20	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$	ϕ_b
JRC	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$	ϕ_b
or	$\left(\frac{JCS}{\sigma_n}\right)$	ϕ_r
R	$\left(\frac{S}{\sigma_n}\right)$	ϕ_b
	$[J_r / J_a]$ (from Q-system)	

INTO THE FIELD !!

CHARACTERIZATION OF JOINTING, DEFORMABILITY, AT MAJOR DAM SITES

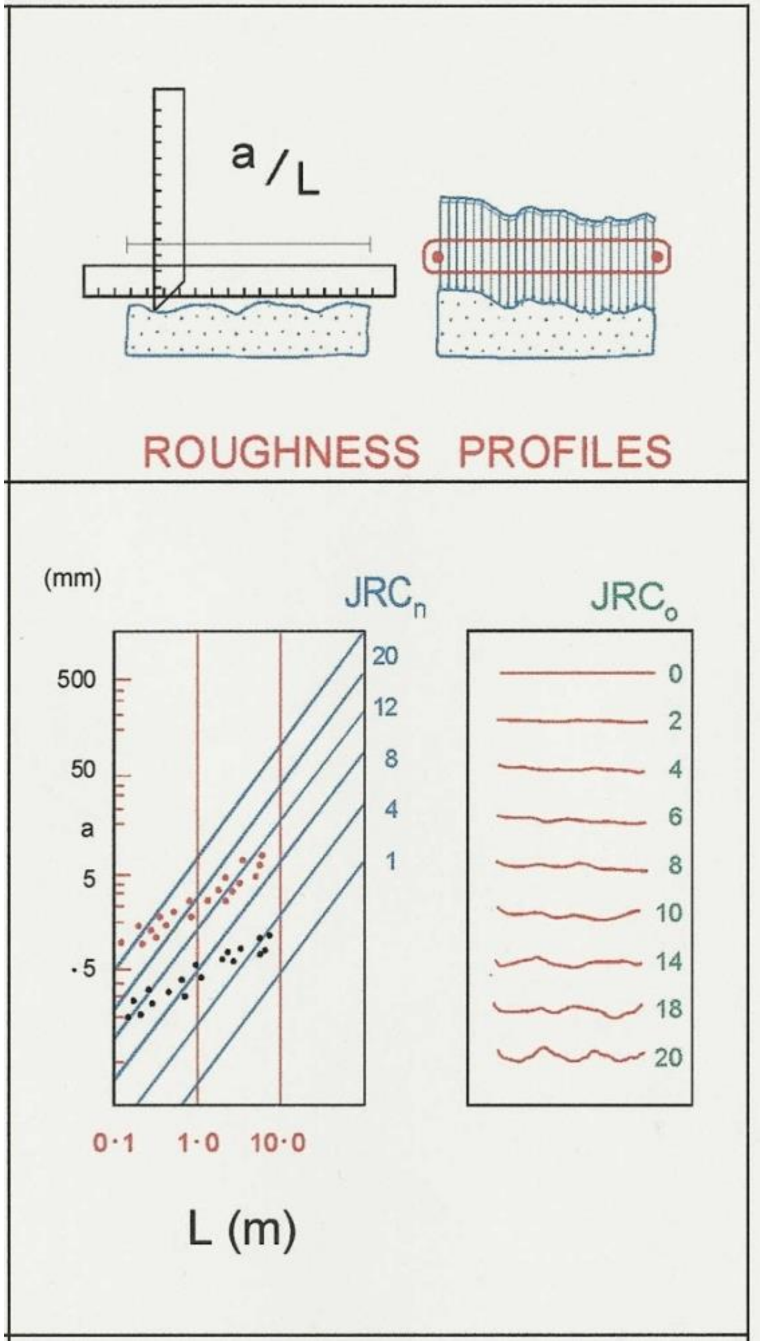
- IRAN: **KARUN IV** 230 m
- IRAN: **BAKHTIARY** 325 m
- CHINA: **BAIHETAN** 283 m (2 x 8,000 MW)

"You need to hire a *rock-climbing-engineering-geology* group to characterise the major joint planes that define the two major wedges that your company are worried about"

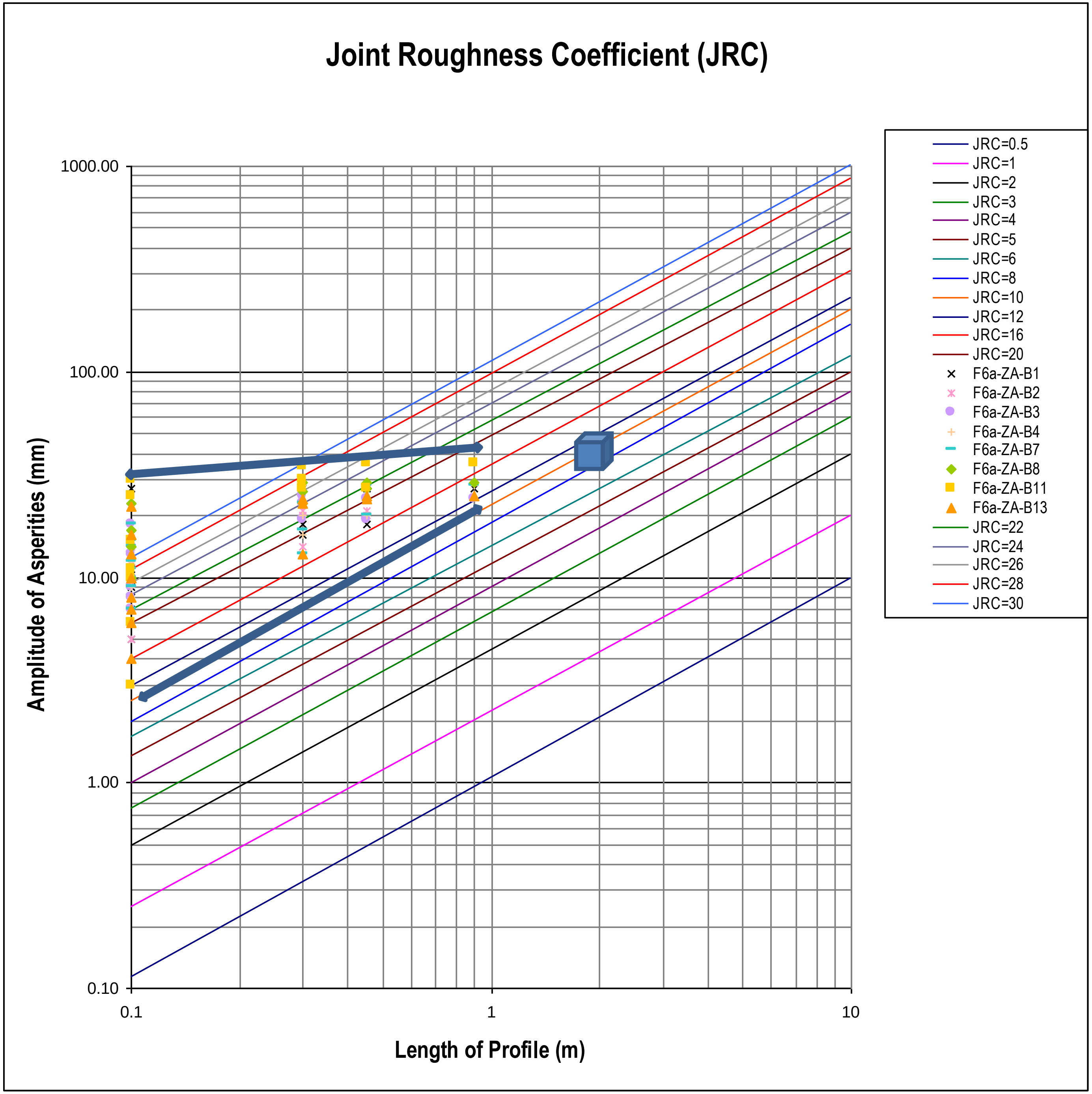
*Some kilos lighter, **and not telling his wife the reason***, Iranian colleague M.Zargari is profiling major-joint MJ-67, **Karun IV Dam, Iran**

Schmidt rebound *(R) on intact rock* (> r on joint plane)

Karun IV Dam site canyon, Iran



The a/L method for *roughness* is used when JRC is TOO LARGE



For the very rough bedding plane, had to use **“a/L”** method

Mean

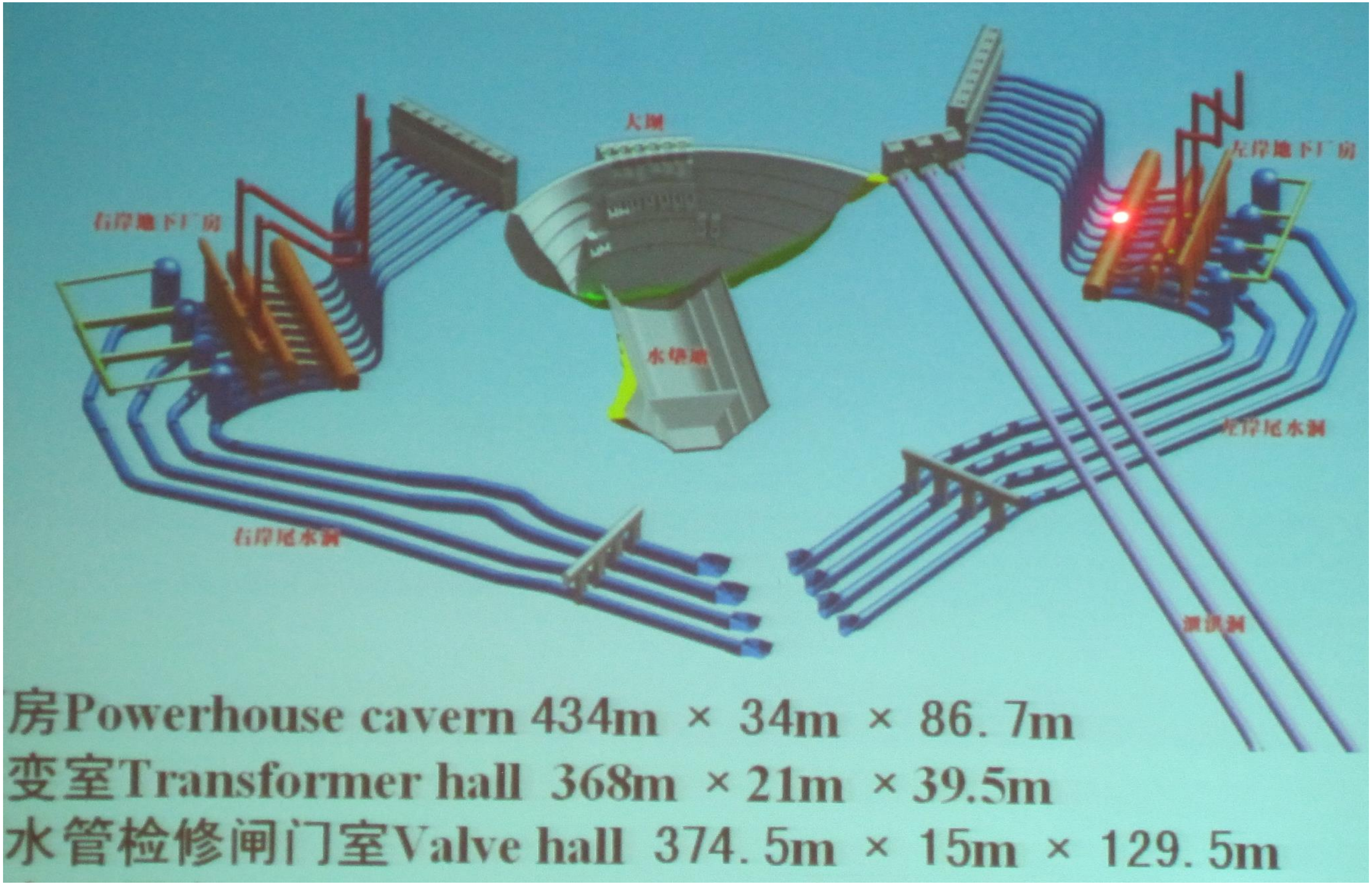
JRC_n = 11

(for 2m block size)

COLUMNAR JOINTING AT A MAJOR DAM SITE IN CHINA

(Baihetan, 283m, 2 x 8000 MW)

BAIHETAN DAM and POWER GENERATION: 2 X 8,000 MW
HydroChina/ECIDI



房Powerhouse cavern 434m × 34m × 86. 7m
变室Transformer hall 368m ×21m ×39.5m
水管检修闸门室Valve hall 374. 5m × 15m × 129. 5m

RECORDING OF ROUGHNESS FOR ***JRC*** ESTIMATION, *70 to 140 m into the canyon walls*.

(May need stripping to this competent-rock depth)

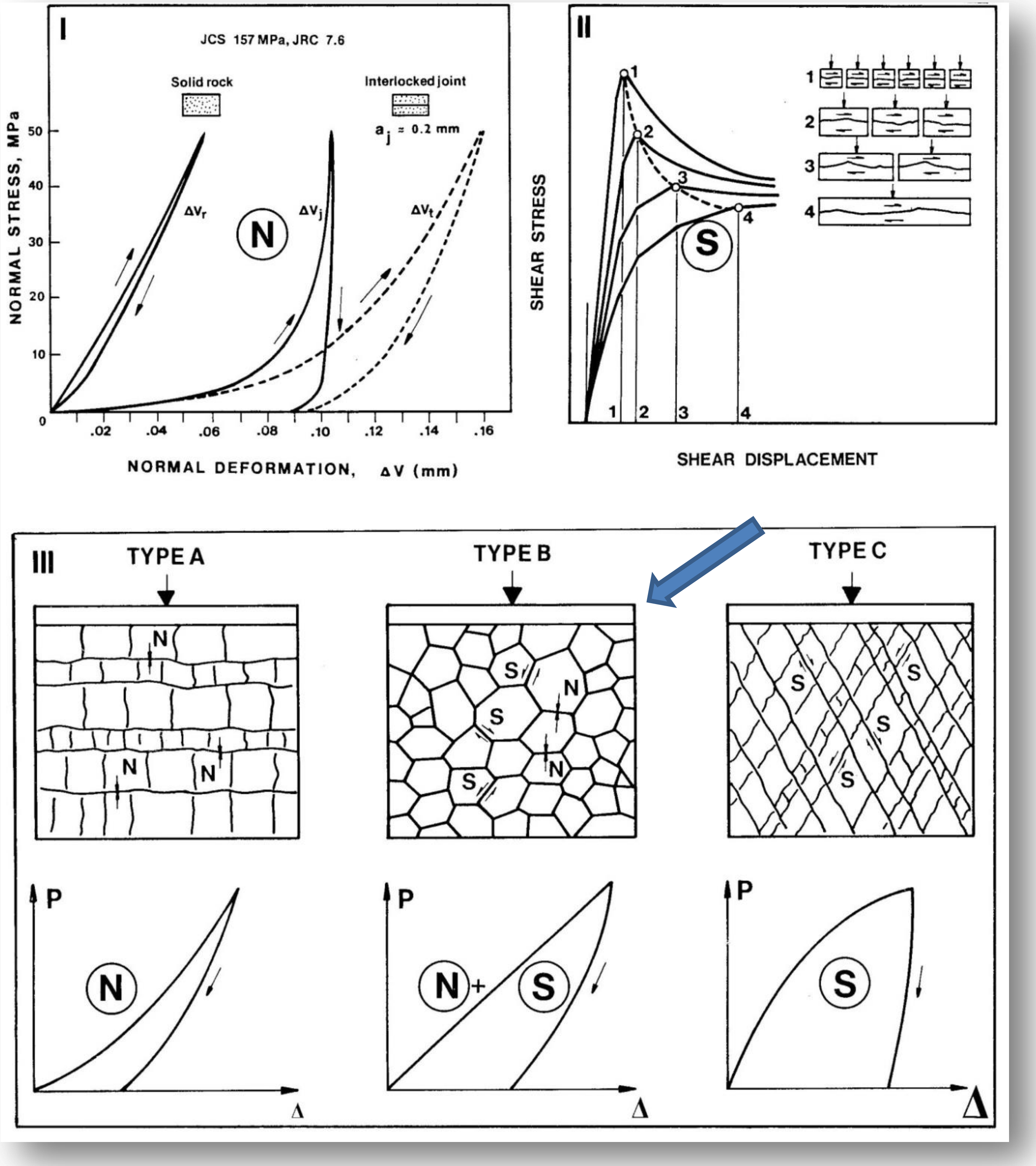
RECORDING OF SCHMIDT-HAMMER REBOUND FOR ***JCS*** ESTIMATION

APPLICATION OF ***JRC*** and ***JCS*** to ROCK MASS DEFORMABILITY

and to

MODELLING with UDEC-BB

(see columnar basalt behaviour)

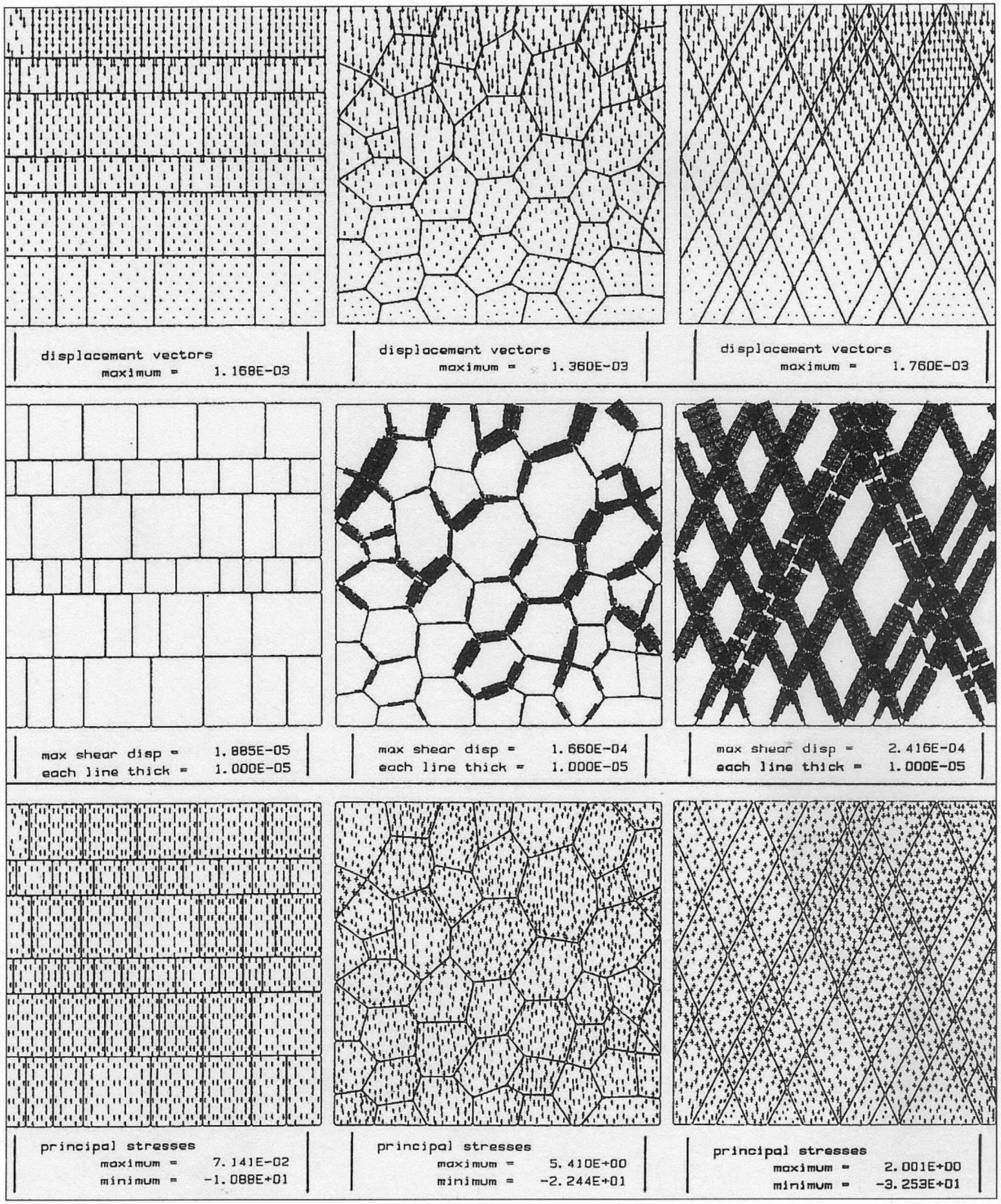


Stress-closure and scale-effect shear tests. (Bandis et al. 1981 and 1983)

The N, S components in rock mass *load-deformation* mechanisms.

(Barton, 1986)

There is plate-load / block-test evidence for these three P-Δ type-curves.



UDEC-BB simulations

(Chryssanthakis, NGI)

EMPHASISES WHY *DISCONTINUUM ANALYSES GIVE MORE EXCITEMENT/INTEREST/ VALUE/REALISM than analyses without joints!*

PART 2

Q-SYSTEM

❑ SINCE 1974 Q HAS ACTUALLY BECOME “A SYSTEM”, SINCE THERE ARE NOW SEVERAL COMPONENTS.

❑ (***50 rock types in first 210 cases***, 1250 case records)

❑ Q rockmass classification, **Q-histograms**

❑ Q for ***‘single shell’*** **NMT support (B + Sfr, RRS)**

❑ Q_c (= *Q x UCS/100*) for correlating with $\mathbf{V_P}$ **and** $\mathbf{E_{MASS}}$

❑ Q as part of Q_{TBM} for TBM prognosis

❑ Q_{SLOPE} for selecting safe slope angles (in progress)

❑ **Qc split into CC and FC** (***if*** ‘continuum’ modelling)

EXAMPLE OF SLOPE ANGLE MATCHED TO GEOTECHNICAL PROPERTIES

(*or to local* ***Q-slope*** *= 0.1, 1.0, 10*).

(Panama expansion project, 2011. PCA photo)

Why/how was Q developed?

Because of a question to NGI in 1973:

"Why are Norwegian underground power houses showing such a variety of deformations"?

(from Norwegian State Power Board/ STATKRAFT)

Question passed to NB. Answer given after 6 months of *Q-system development!*

VARIABLES: Rock mass quality, support type/quantity, span/height, depth, stress.

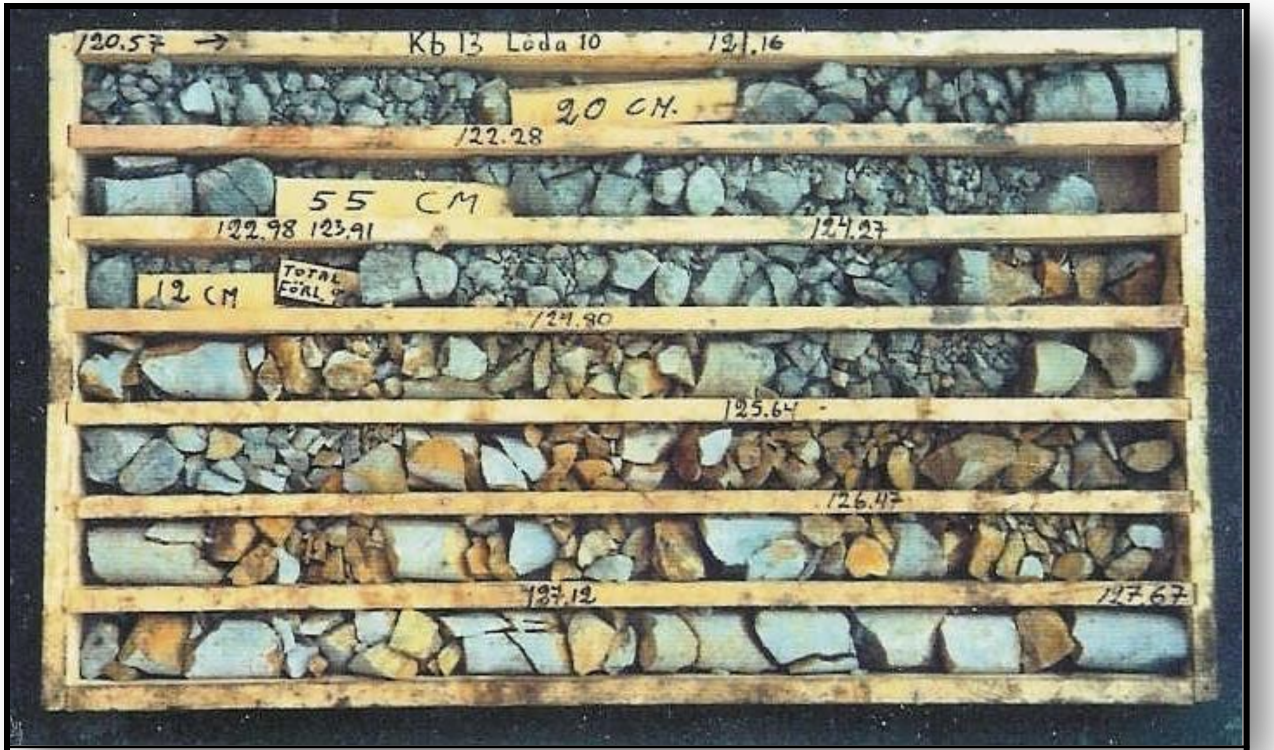
212 case records used. B, S(mr), B+S(mr), CCA.

VARIABLE WORLD NEEDS *BROAD-REACH CHARACTERIZATION* METHOD

VARIABLE WORLD **CANNOT ALWAYS BE COMPUTER MODELLED – BUT IT CAN BE CHARACTERIZED**

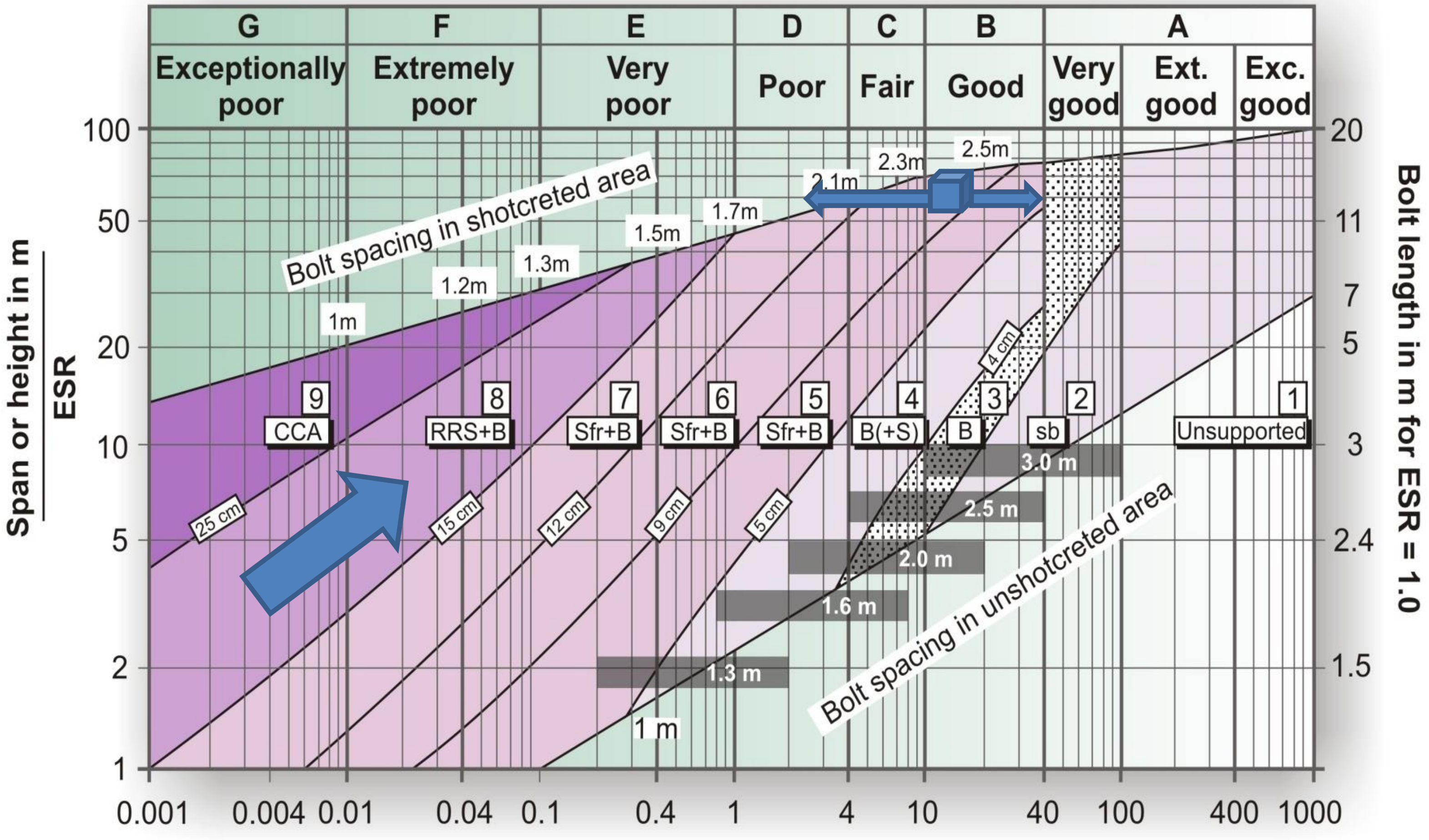
Strength contrast, modulus contrast, constructability contrast (15 years/1 year)!

0.001→1000, or 5→95, or F7→F1 ???



A GLIMSE OF NMT (SINGLE-SHELL TUNNELLING)

for which the Q-system was actually designed



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

Grimstad and Barton, 1993

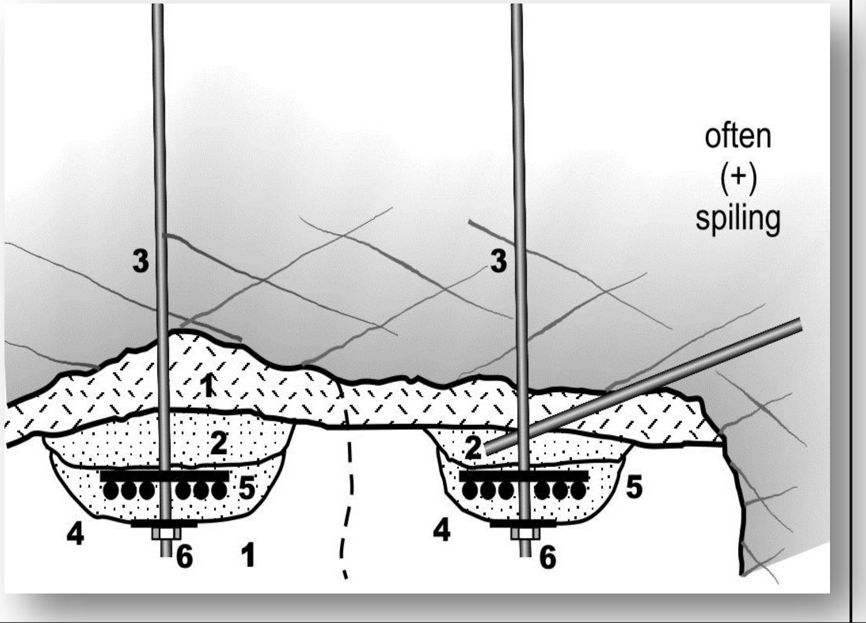
(Norwegian conference),

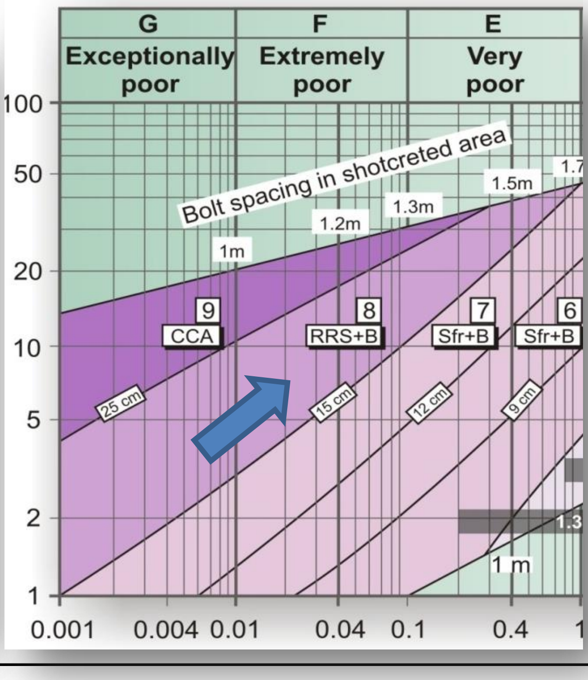
Barton and Grimstad, 1994

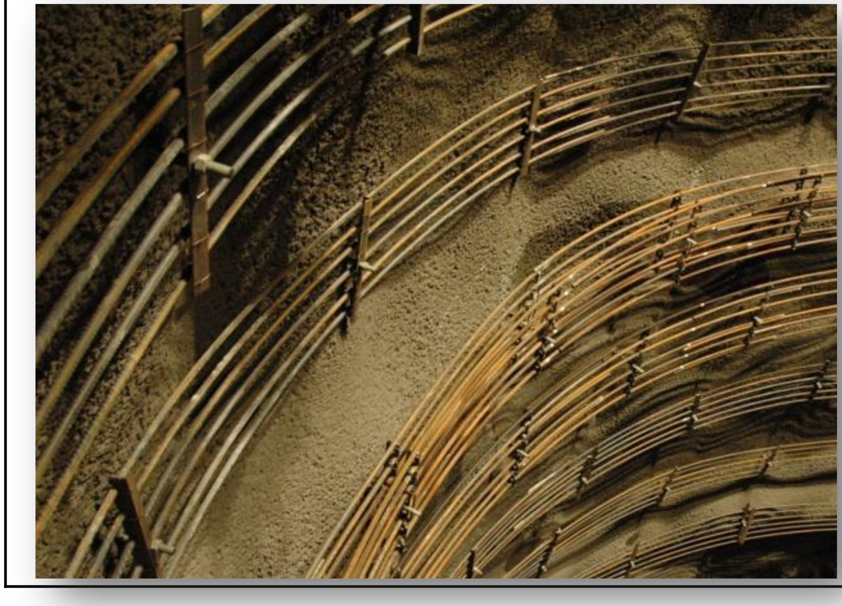
(Austrian conference).

The Q-system is most strongly associated with ‘single shell’ solutions :

(B+Sfr + water control) (= NMT= Norwegian Method of Tunnelling) in *mostly* better rock, costs about 1/5 x ‘double-shell’ NATM, e.g. 20,000 US $/m compared to 100,000 US $/m (Costs from many countries).







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

3D effect because of S(fr) arches.

QUESTION:

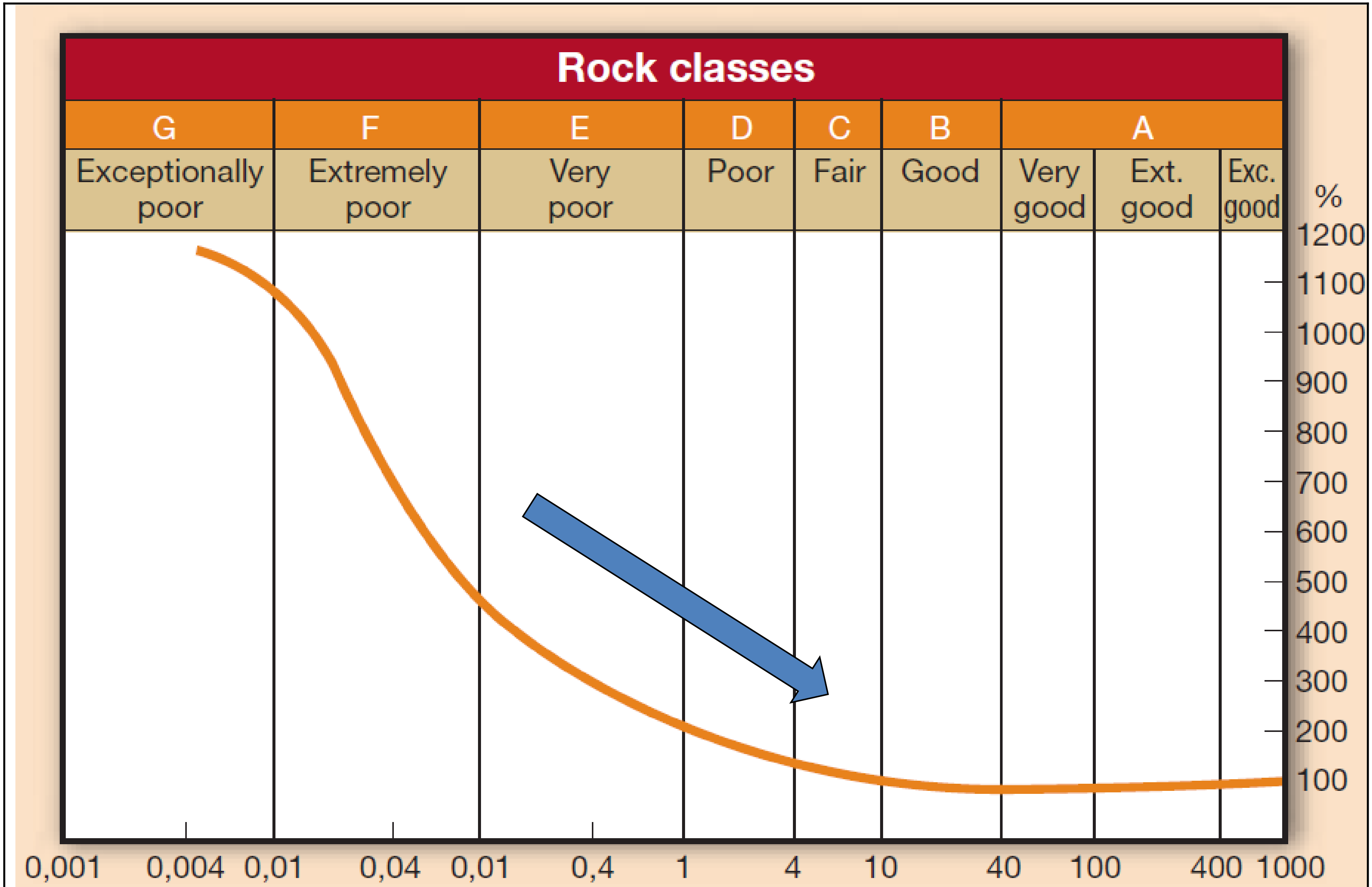
SHALLOW METRO or DEEP METRO?

- MIXED-FACE OR ROCK?
- 5 m PER WEEK OR 20 m PER WEEK?
- COST DIFFERENCE MAY BE 5:1 (at least)

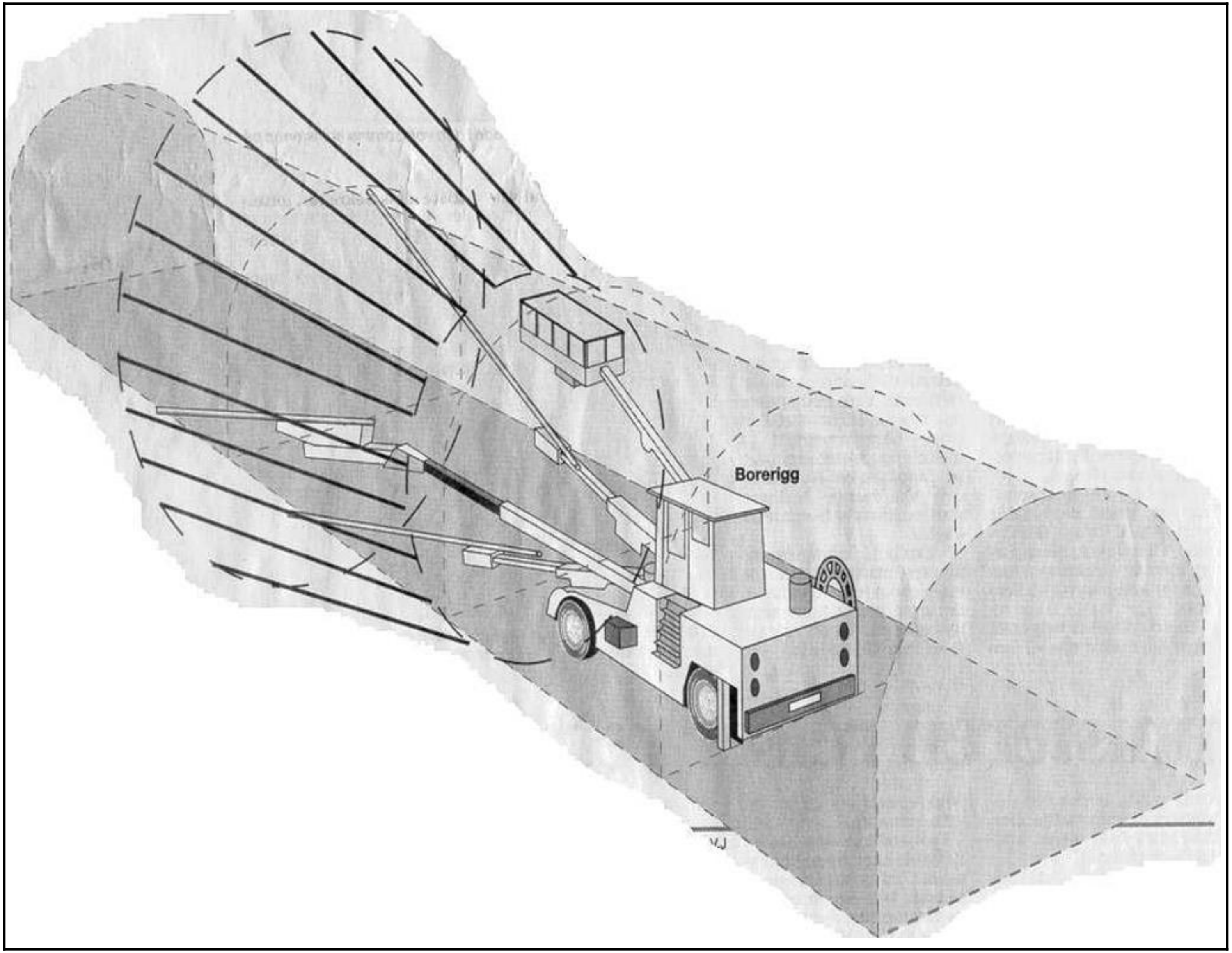
RELATIVE ***COST*** FOR TUNNEL EXCAVATION AND SUPPORT

(Barton, Roald, Buen, 2001)

……..potential benefits of pre-grouting, especially if Q ≈ 0.1



Pre-injection screen 30-70 holes, 20-30m long, 0.5-1.0 m c/c (Hognestad and Frogner, 2005….. and Garshol (ICE/HK, 2010)

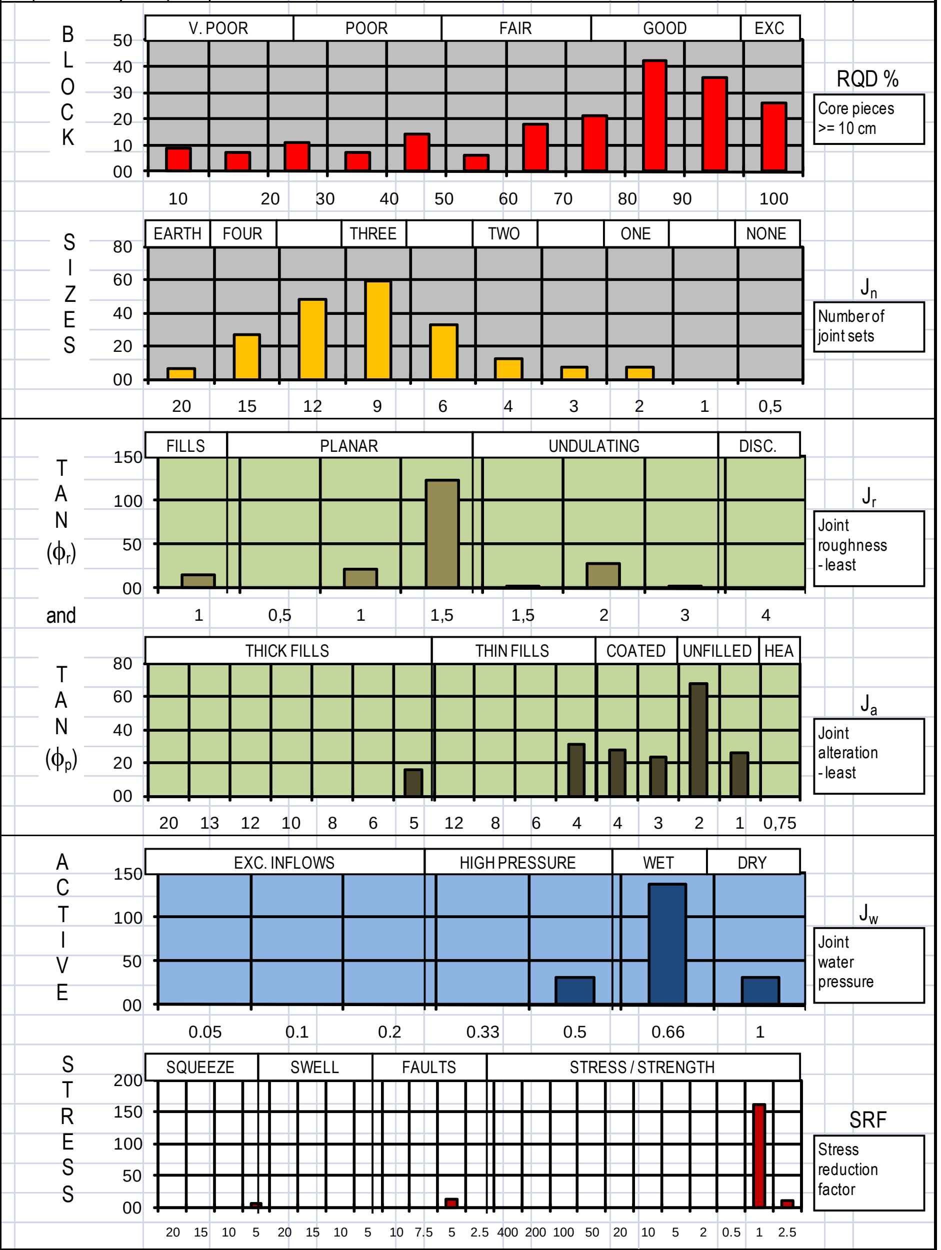


BÆRUM TUNNEL RAIL TUNNEL. Pre-injection in progress. Truck mounted grout storage and mixing. Note up to 70 holes for dry 110m2 tunnel in shales and limestones. *Packered injection 'lances' are chained for safety. 24-30 hours CYCLE time. Cost of finished NMT tunnel: < 25,000/m*

Q-HISTOGRAM METHOD
of logging

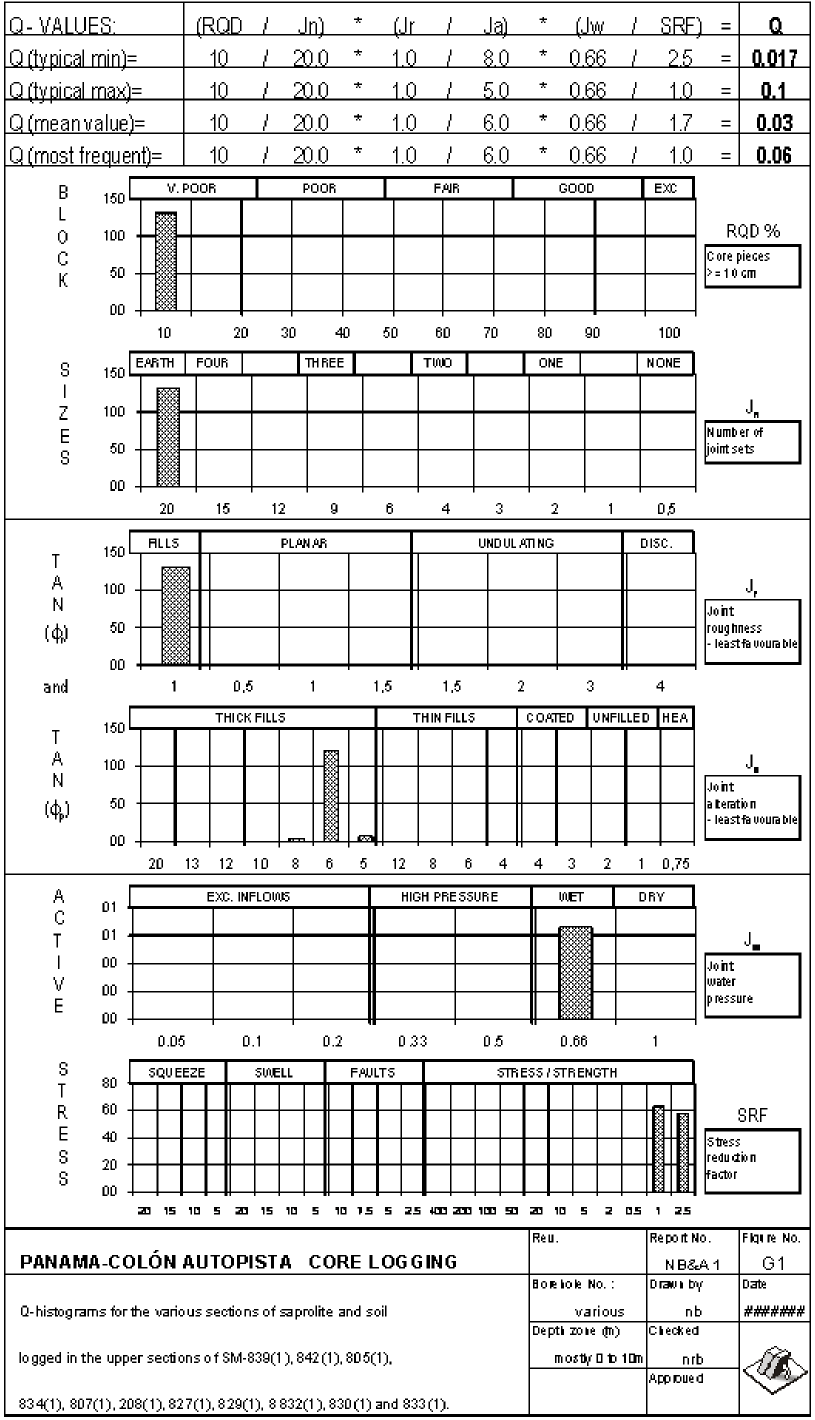
THE RESULT OF Q-HISTOGRAM LOGGING OF ***SIX CORES*** AT A PLANNED METRO PROJECT IN HONG KONG. DEVIATED HOLES.

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	5.0	*	0.50	/	5.0	=	**0.010**
Q (typical max)=	100	/	2.0	*	2.0	/	1.0	*	1.00	/	1.0	=	**100.0**
Q (mean value)=	71	/	9.6	*	1.5	/	2.8	*	0.69	/	1.5	=	**1.78**
Q (most frequent)=	85	/	9.0	*	1.5	/	2.0	*	0.66	/	1.0	=	**4.68**



How do the Q-parameter histograms change, as depth is increased in the same rock type?

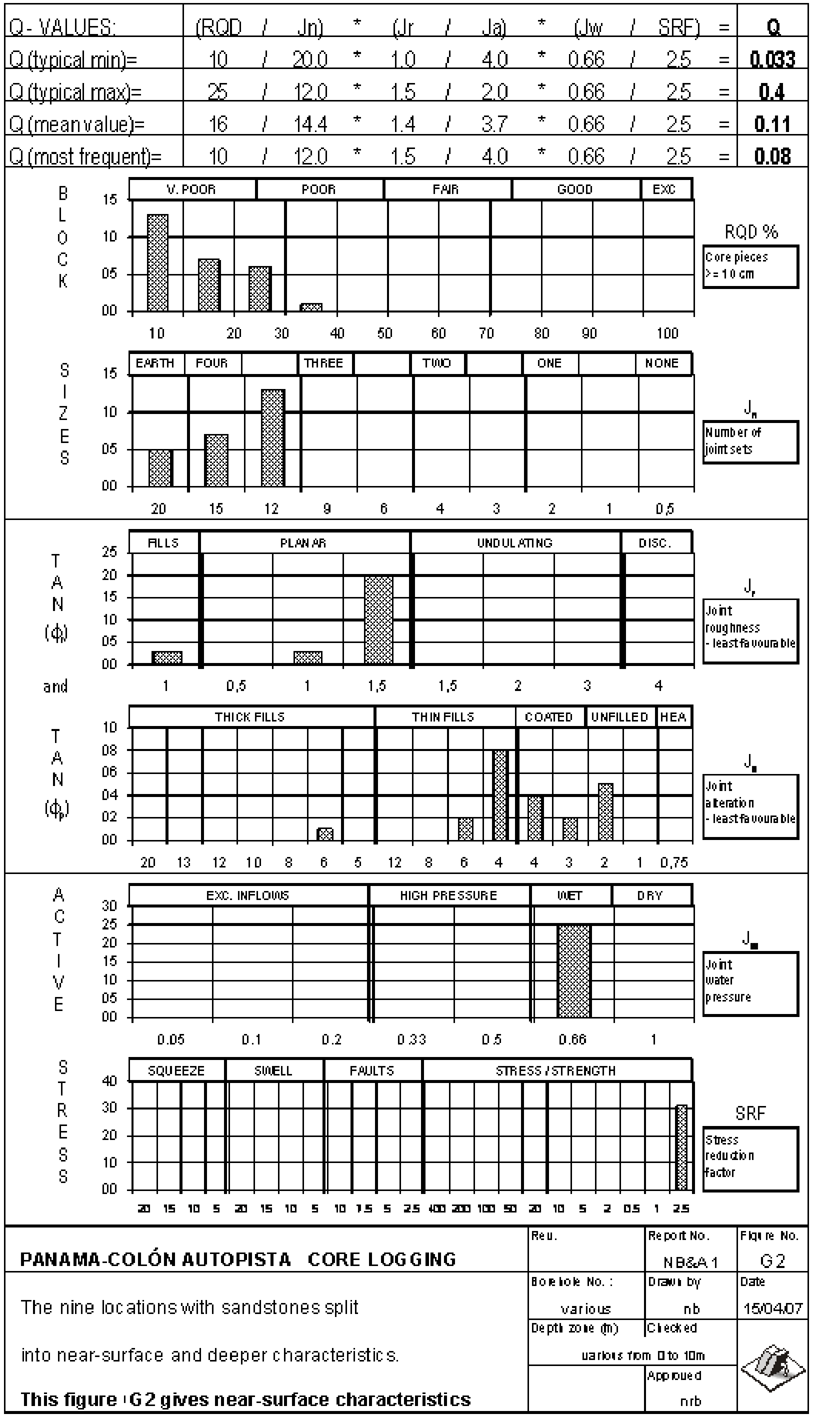
CHARACTER OF SAPROLITE AND SOIL



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	8.0	*	0.66	/	2.5	=	**0.017**
Q (typical max)=	10	/	20.0	*	1.0	/	5.0	*	0.66	/	1.0	=	**0.1**
Q (mean value)=	10	/	20.0	*	1.0	/	6.0	*	0.66	/	1.7	=	**0.03**
Q (most frequent)=	10	/	20.0	*	1.0	/	6.0	*	0.66	/	1.0	=	**0.06**

PANAMA-COLÓN AUTOPISTA CORE LOGGING	Rev. 	Report No. NB&A 1	Figure No. G1
Q-histograms for the various sections of saprolite and soil logged in the upper sections of SM-839(1), 842(1), 805(1), 834(1), 807(1), 208(1), 827(1), 829(1), 8 832(1), 830(1) and 833(1).	Borehole No. : various Depth zone (m) mostly 0 to 10m	Drawn by nb Checked nrb Approved	Date #######

LOGGED CHARACTER OF NEAR-SURFACE SANDSTONES



Q- VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	4.0	*	0.66	/	2.5	=	**0.033**
Q (typical max)=	25	/	12.0	*	1.5	/	2.0	*	0.66	/	2.5	=	**0.4**
Q (mean value)=	16	/	14.4	*	1.4	/	3.7	*	0.66	/	2.5	=	**0.11**
Q (most frequent)=	10	/	12.0	*	1.5	/	4.0	*	0.66	/	2.5	=	**0.08**

PANAMA-COLÓN AUTOPISTA CORE LOGGING

The nine locations with sandstones split

into near-surface and deeper characteristics.

This figure G2 gives near-surface characteristics

Rev.

Report No. NB&A1

Figure No. G2

Borehole No.: various

Drawn by nb

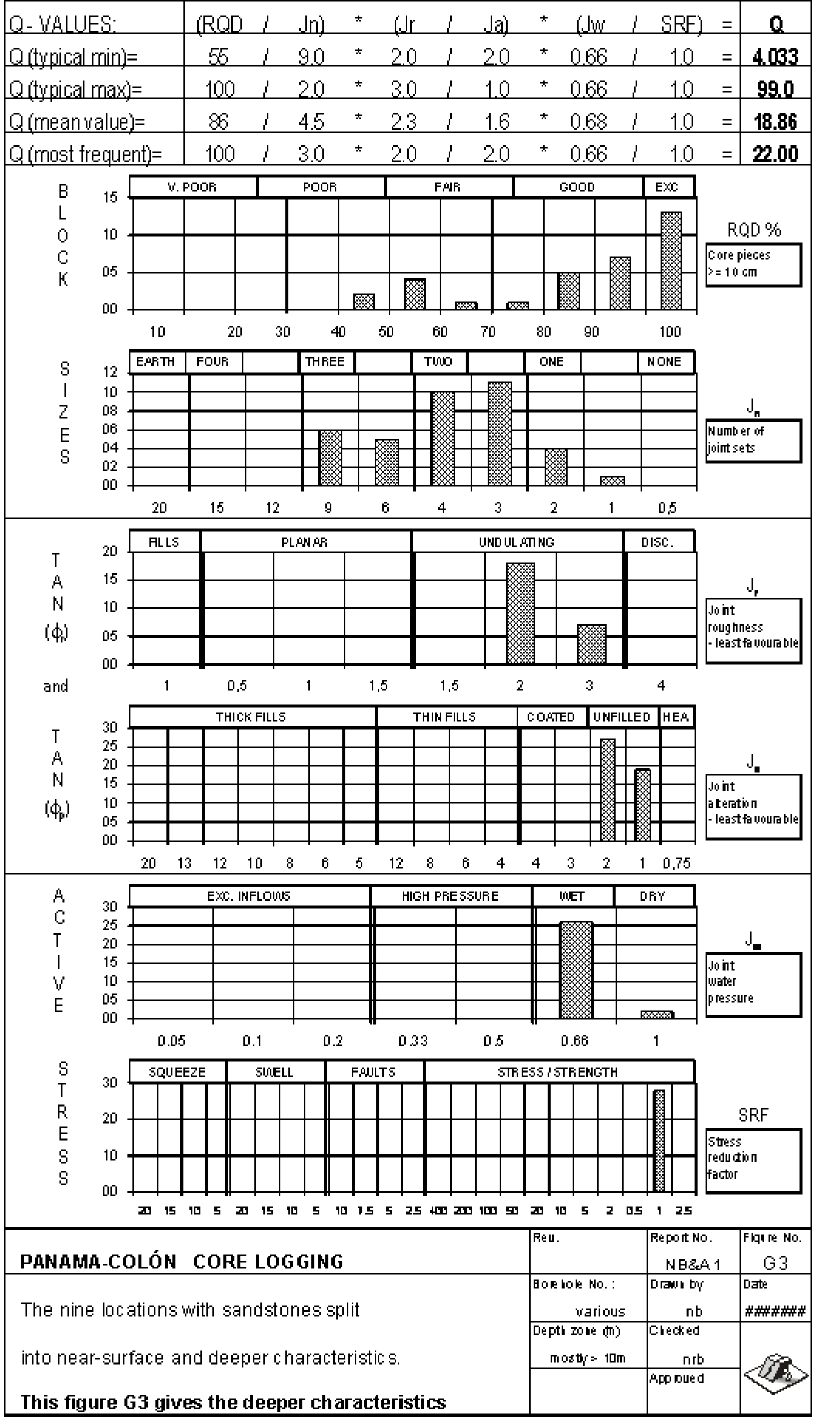
Date 15/04/07

Depth zone (m) various from 0 to 10m

Checked

Approved nrb

LOGGED CHARACTER OF DEEPER SANDSTONES



Q- VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	55	/	9.0	*	2.0	/	2.0	*	0.66	/	1.0	=	**4.033**
Q (typical max)=	100	/	2.0	*	3.0	/	1.0	*	0.66	/	1.0	=	**99.0**
Q (mean value)=	86	/	4.5	*	2.3	/	1.6	*	0.68	/	1.0	=	**18.86**
Q (most frequent)=	100	/	3.0	*	2.0	/	2.0	*	0.66	/	1.0	=	**22.00**

PANAMA-COLÓN CORE LOGGING

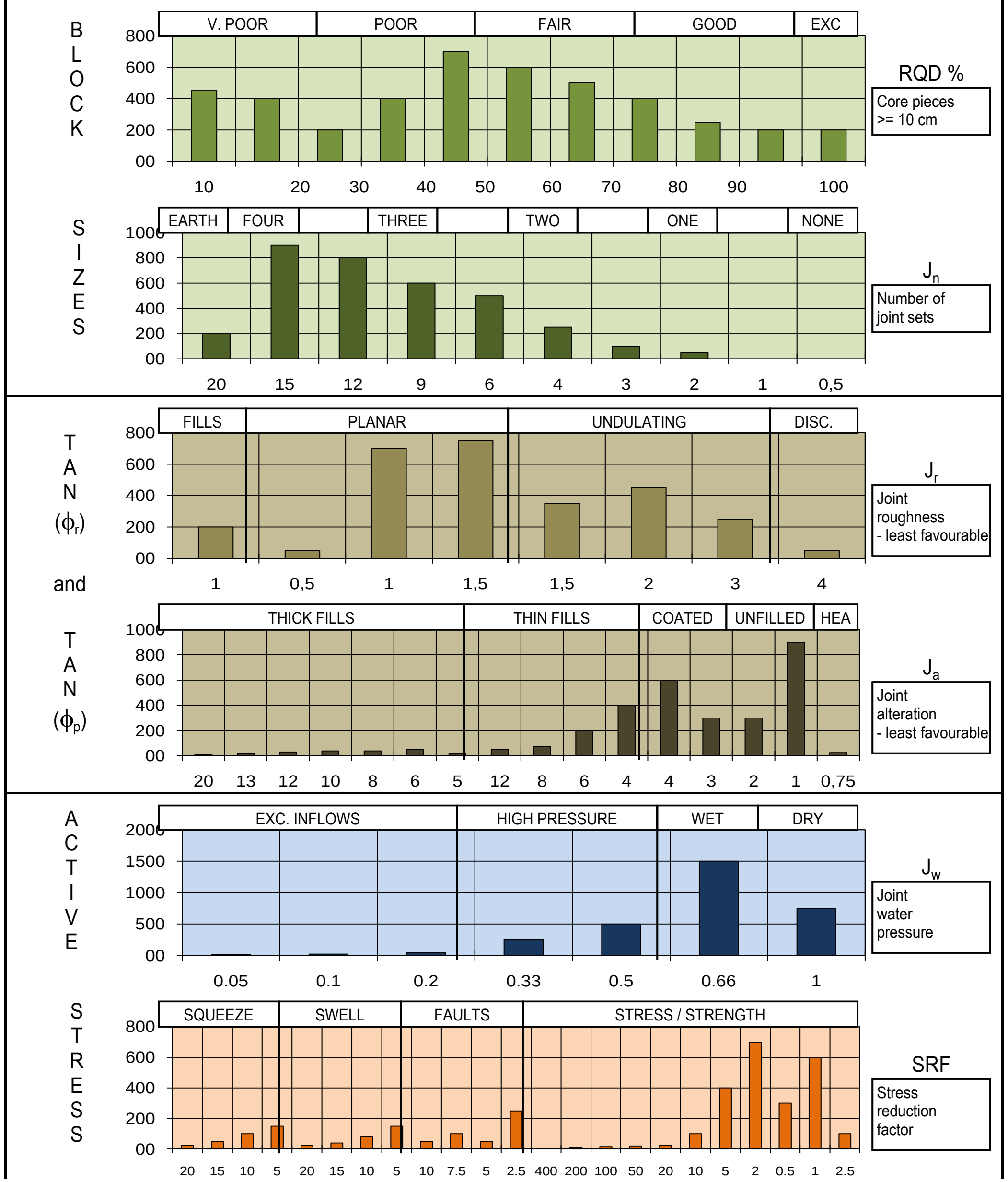
The nine locations with sandstones split

into near-surface and deeper characteristics.

This figure G3 gives the deeper characteristics

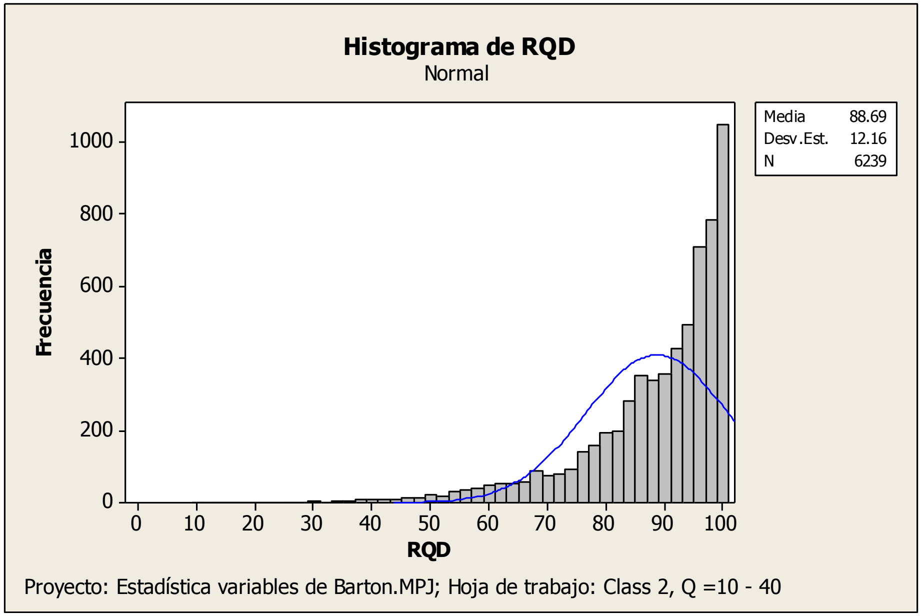
Rev.	Report No. NB&A 1	Figure No. G3
Bore hole No.: various	Drawn by nb	Date #######
Depth zone (m) mostly > 10m	Checked nrb	
	Approved	

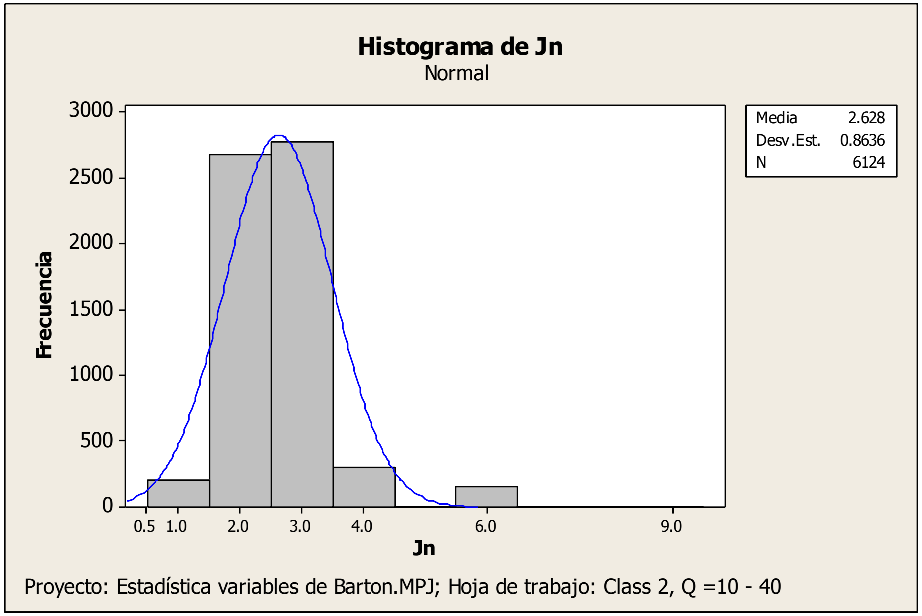
Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	12.0	*	0.20	/	20.0	=	**0.000**
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	0.5	=	**200.0**
Q (mean value)=	50	/	10.9	*	1.6	/	3.5	*	0.68	/	5.4	=	**0.26**
Q (most frequent)=	45	/	15.0	*	1.5	/	1.0	*	0.66	/	2.0	=	**1.49**

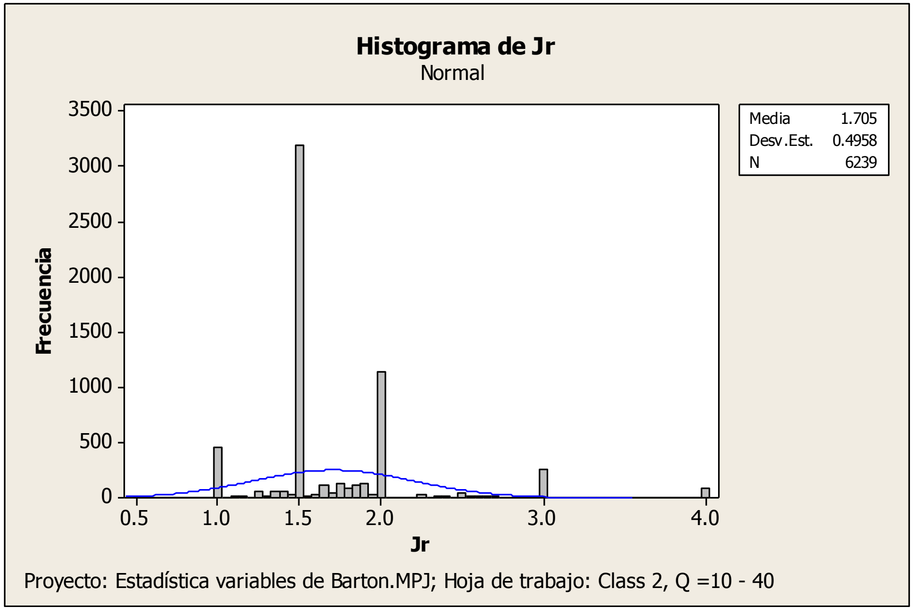


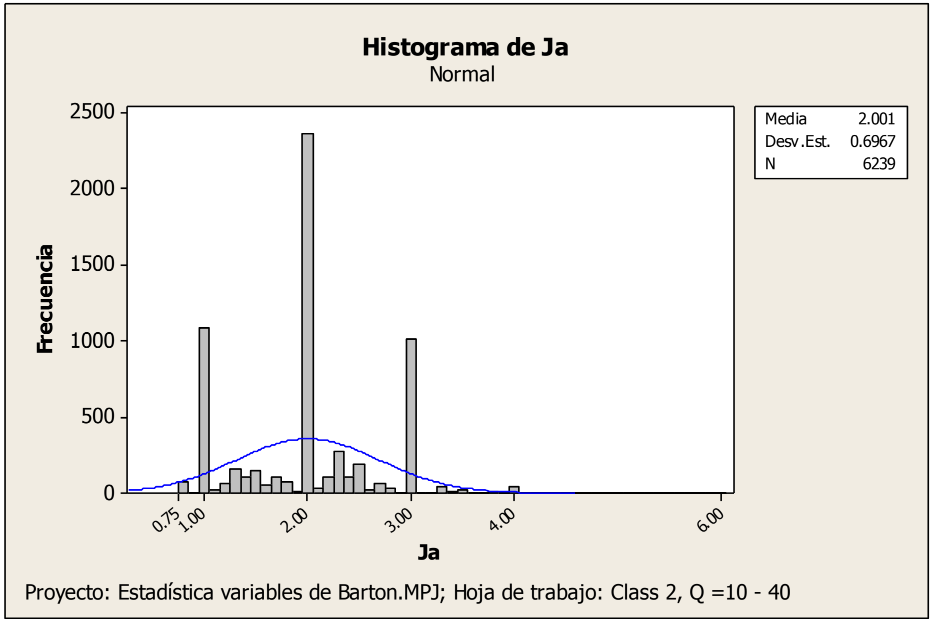
J & K rail-link, Kashmir.
Here 12m/2 years.

Class 2: Q = 10 to 40

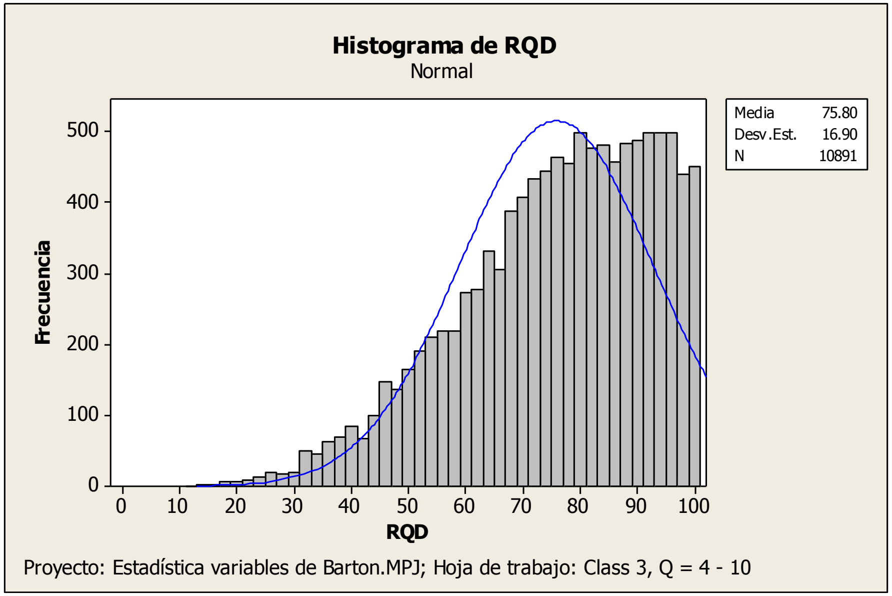




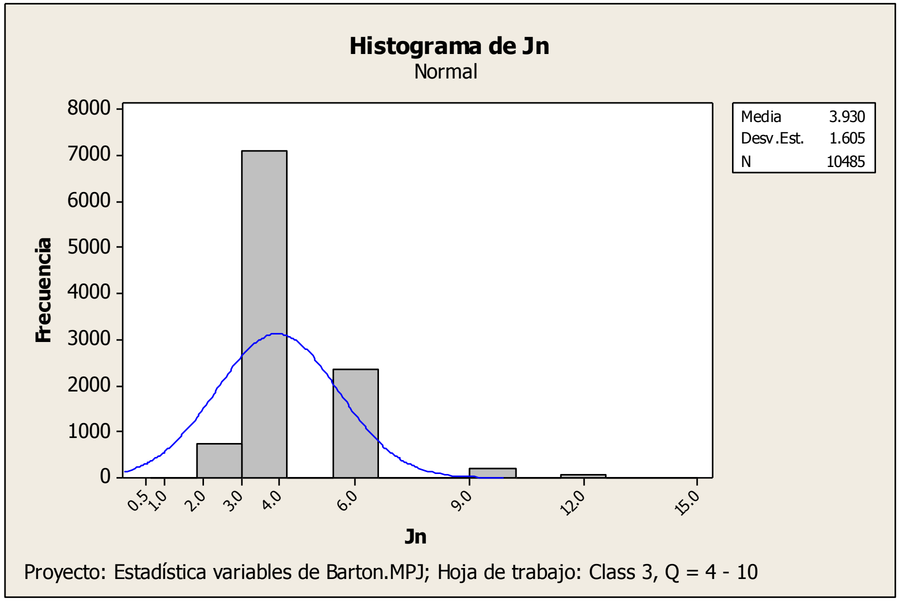




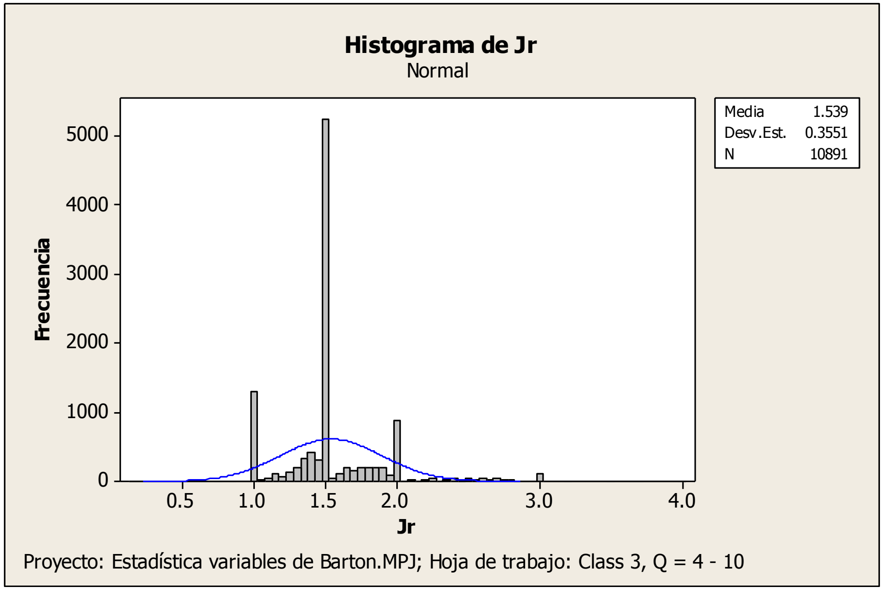
Class 3: Q = 4 to 10



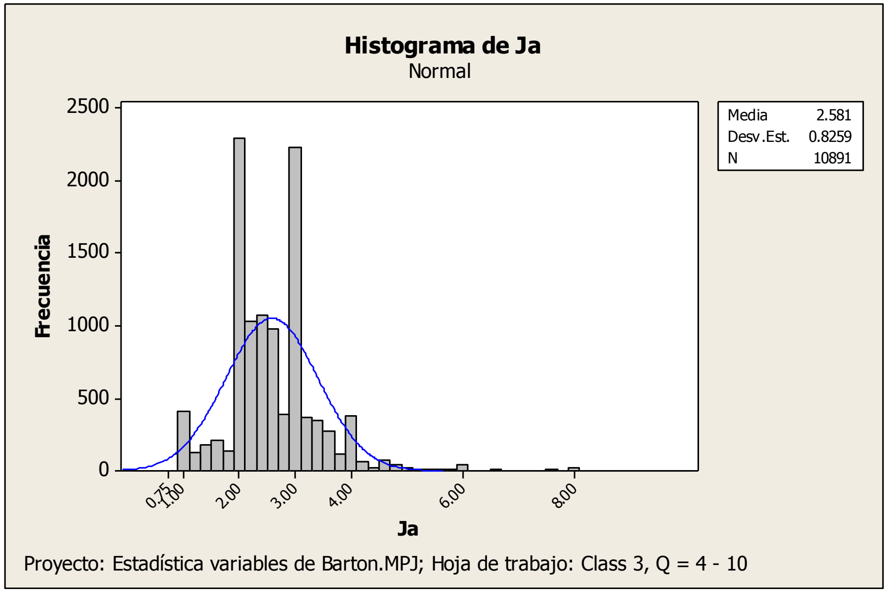
Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 3, Q = 4 - 10



Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 3, Q = 4 - 10

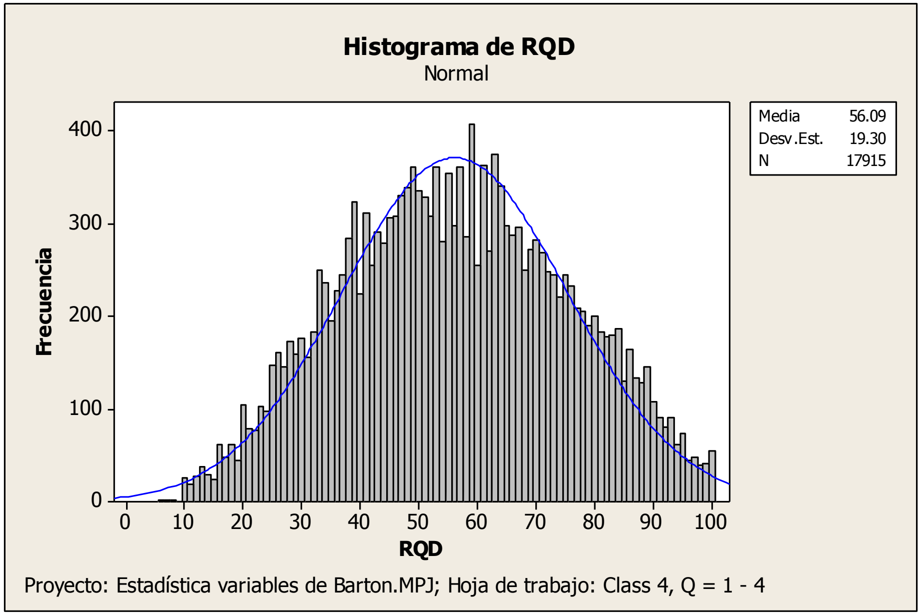


Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 3, Q = 4 - 10

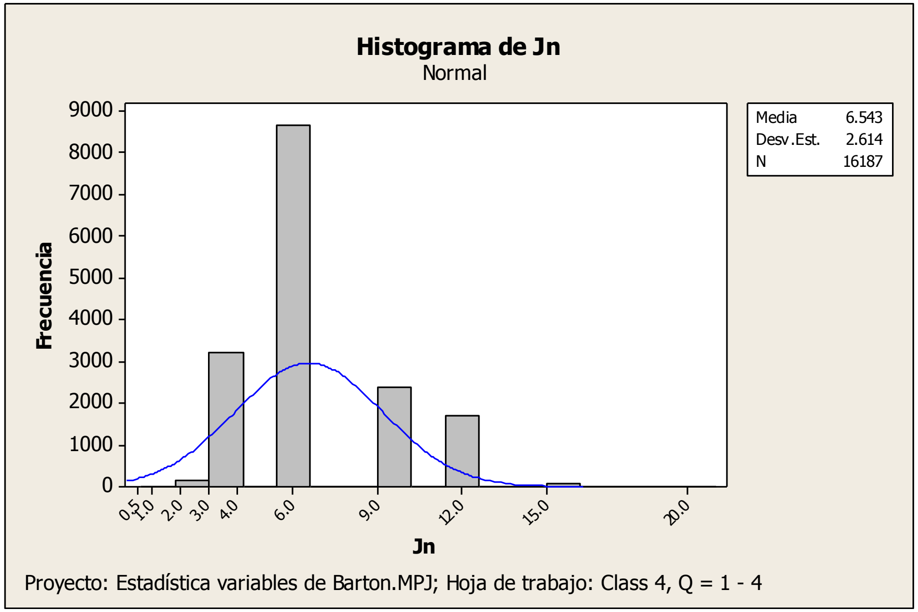


Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 3, Q = 4 - 10

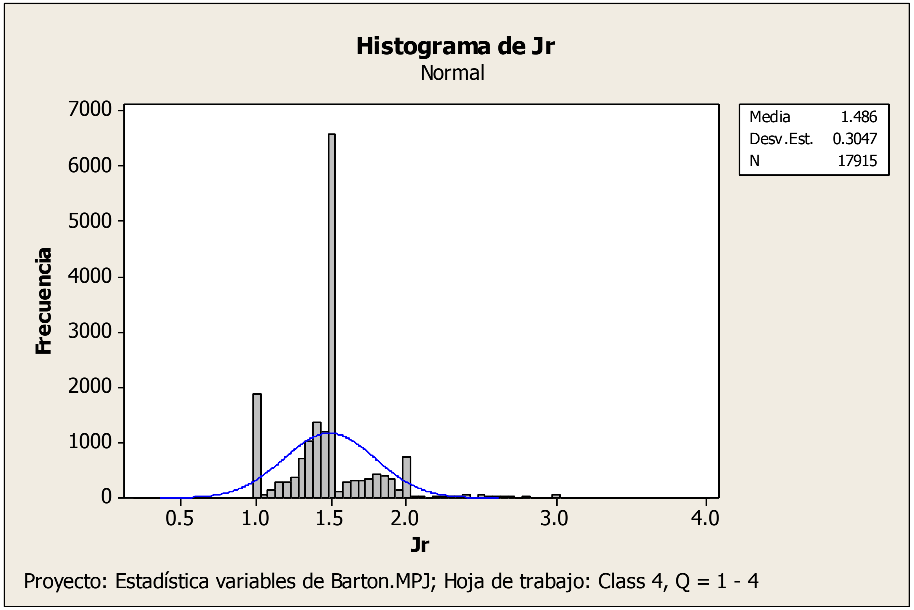
Class 4: Q = 1 to 4



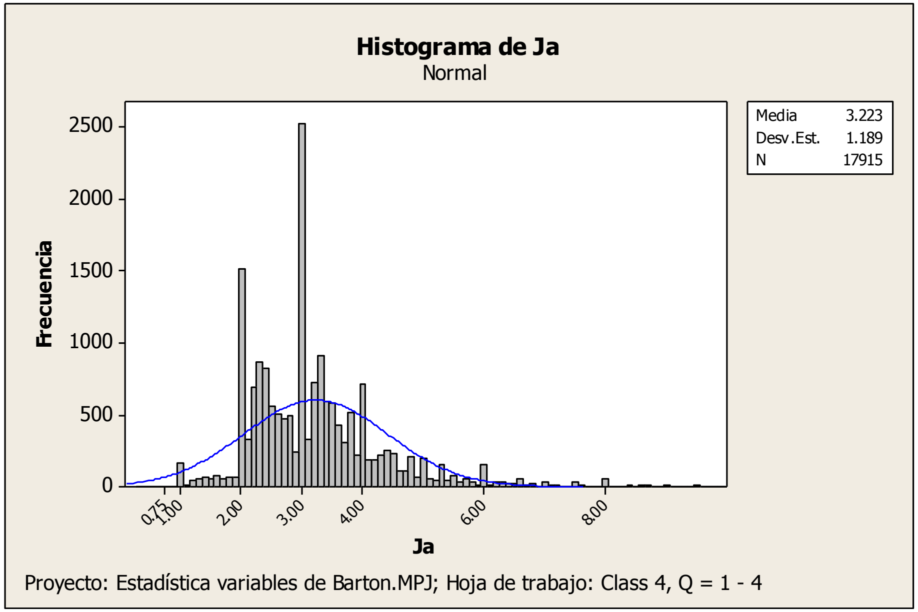
Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 4, Q = 1 - 4



Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 4, Q = 1 - 4

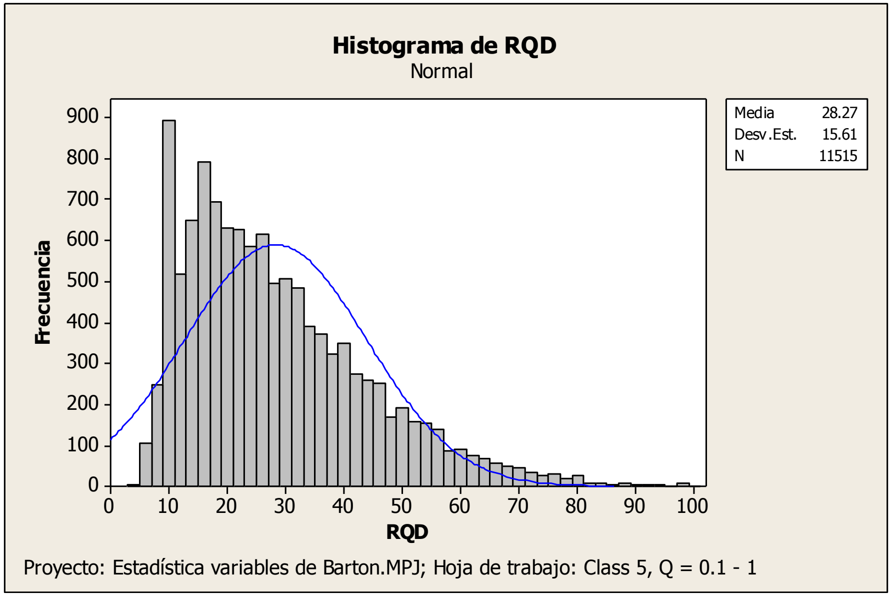


Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 4, Q = 1 - 4

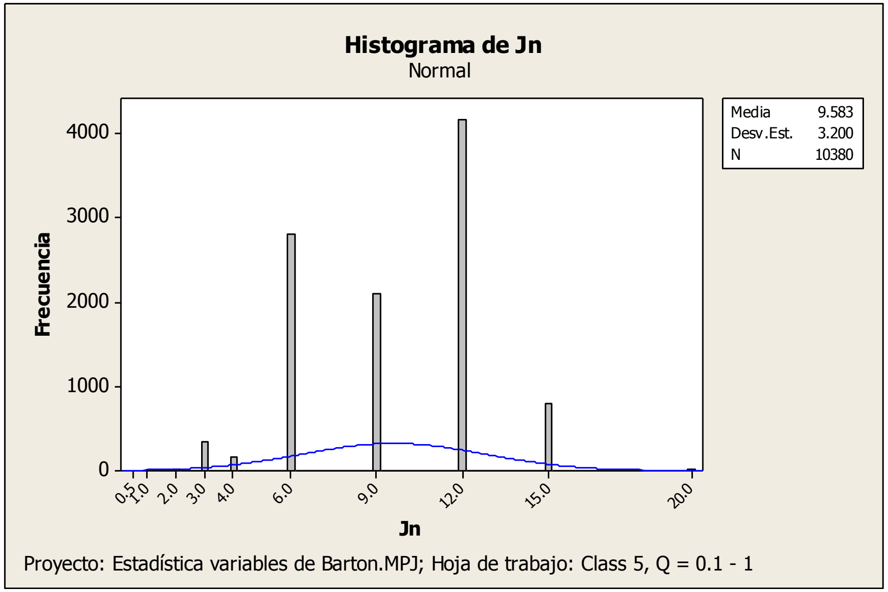


Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 4, Q = 1 - 4

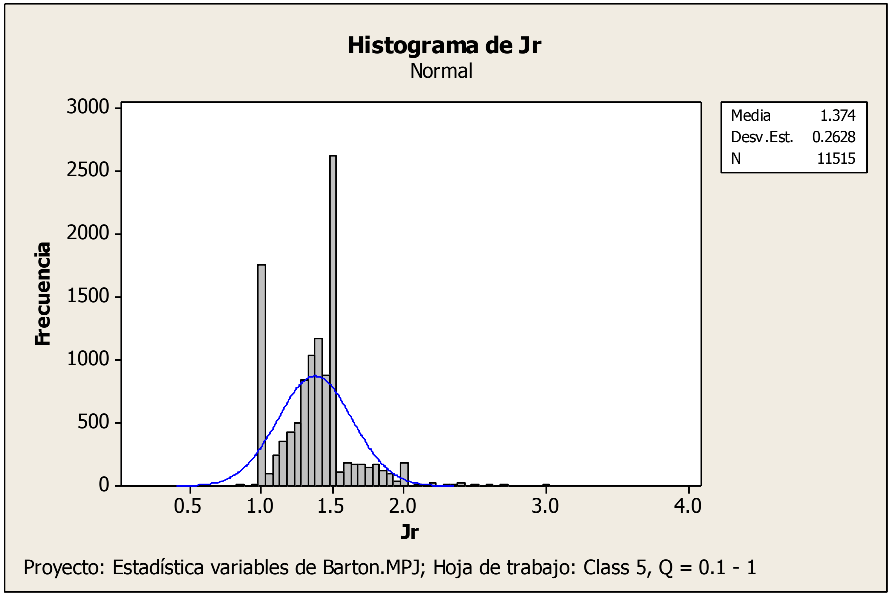
Class 5: Q = 0.1 to 1



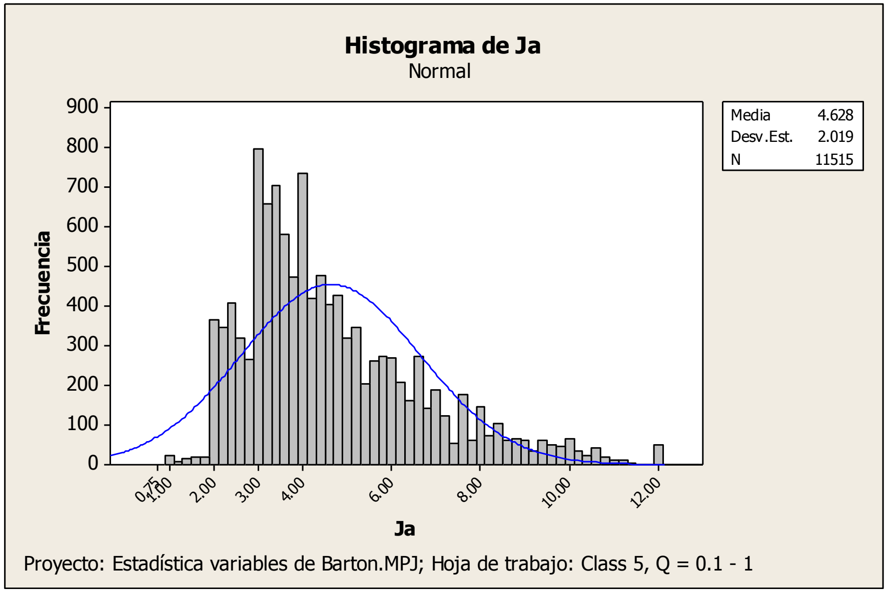
Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 5, Q = 0.1 - 1



Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 5, Q = 0.1 - 1



Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 5, Q = 0.1 - 1



Proyecto: Estadística variables de Barton.MPJ; Hoja de trabajo: Class 5, Q = 0.1 - 1

VELOCITY-MODULUS-PERMEABILITY-Q-VALUE CHALLENGES,

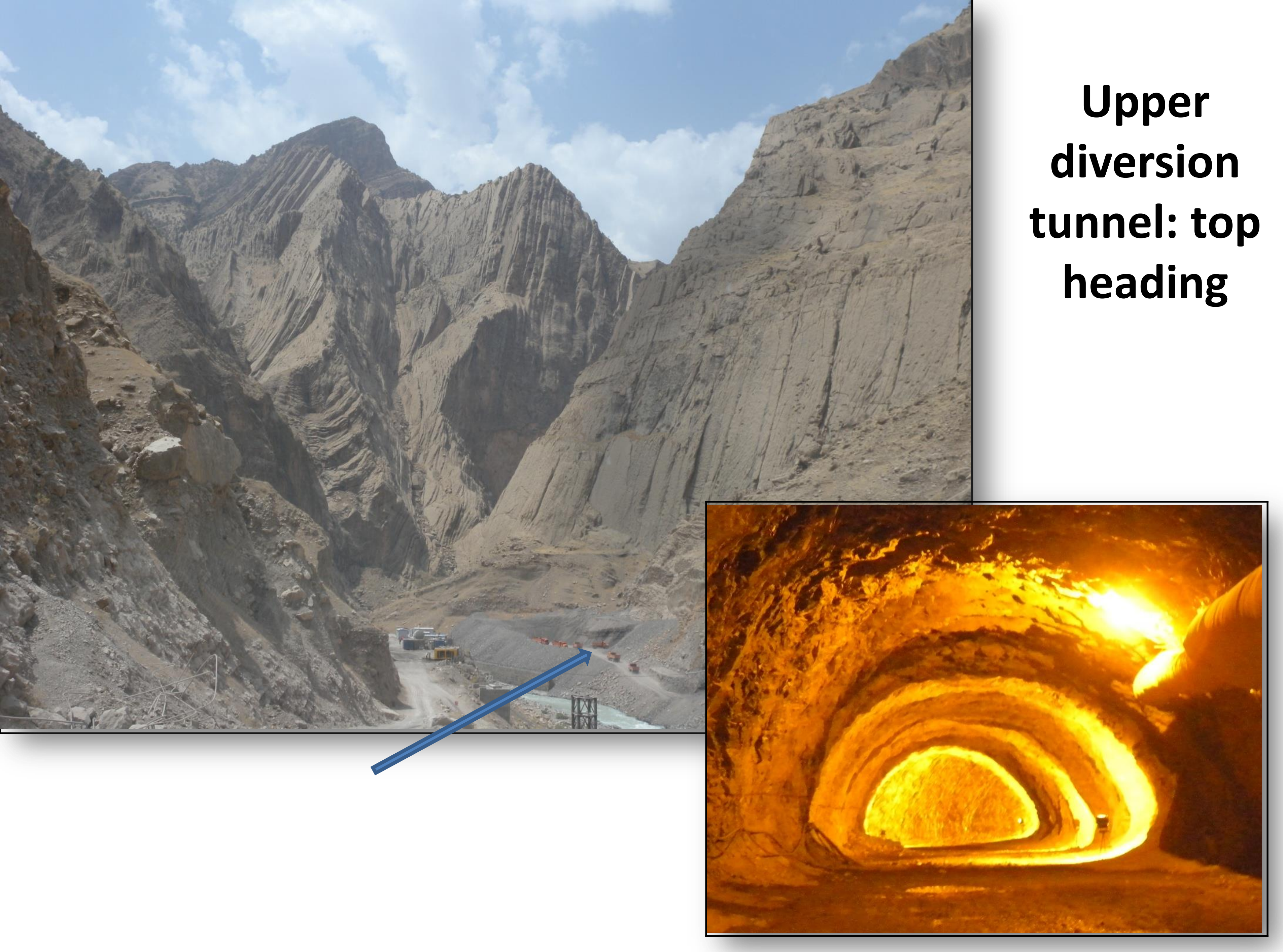
AT BAKHTIARY DAM SITE, IRAN

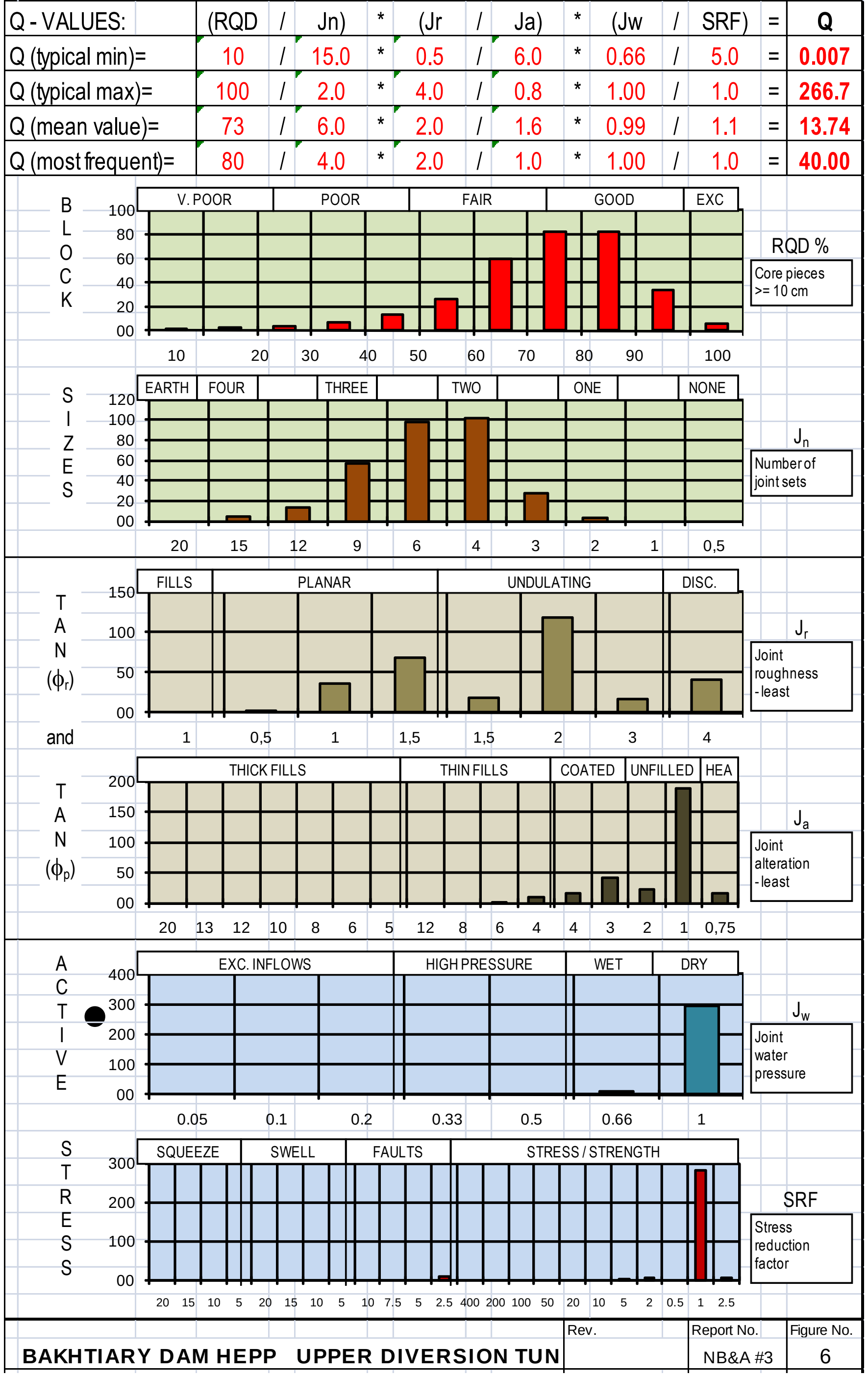
(325 m)

How to characterize voids?

Velocity-modulus-permeability-Q-value correlation difficulties.

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. NB&A #3	Figure No. 6

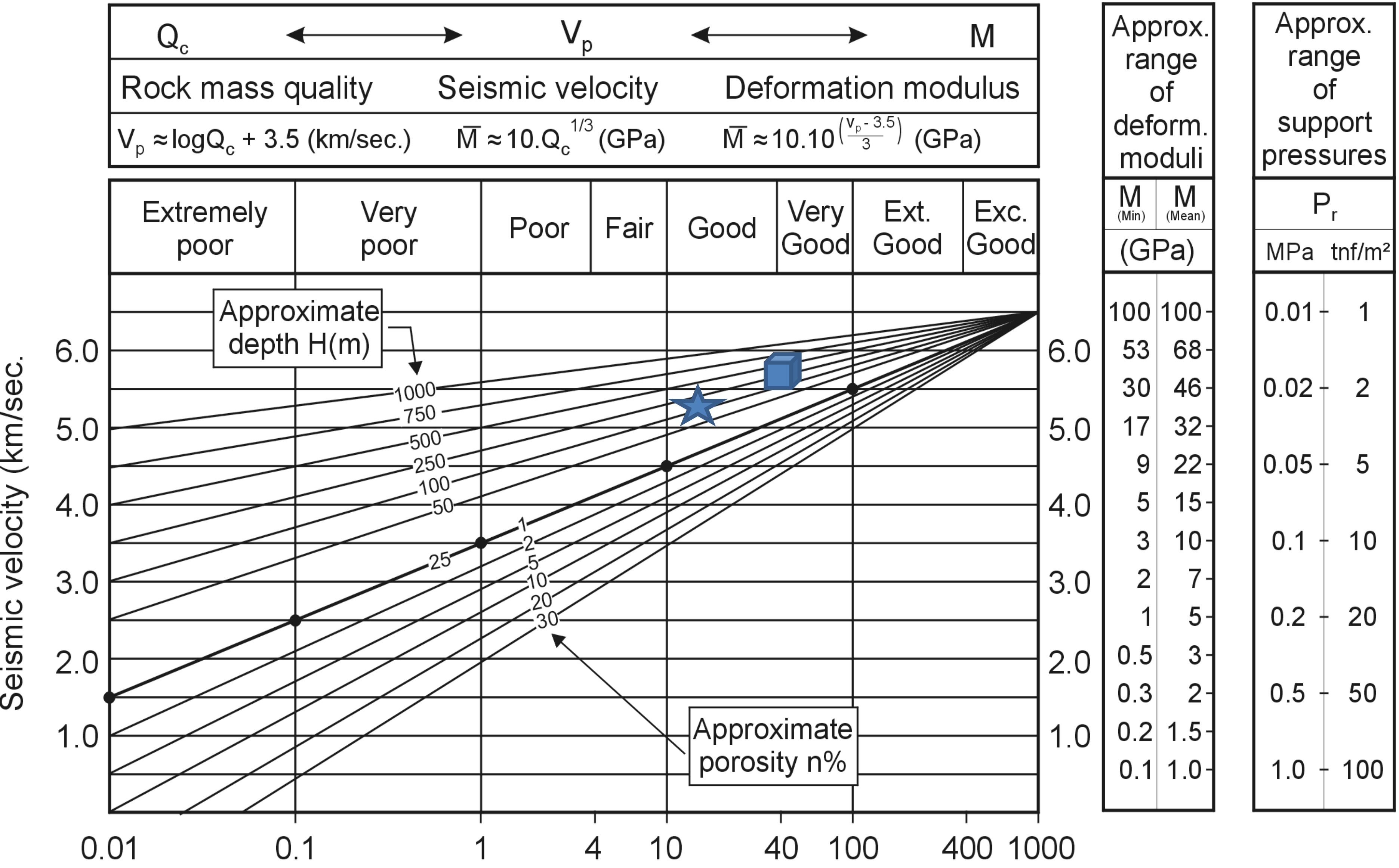
In diversion tunnel

$Q_{m.f.} = 40$

$Q_{mean} = 14$

Next steps:

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

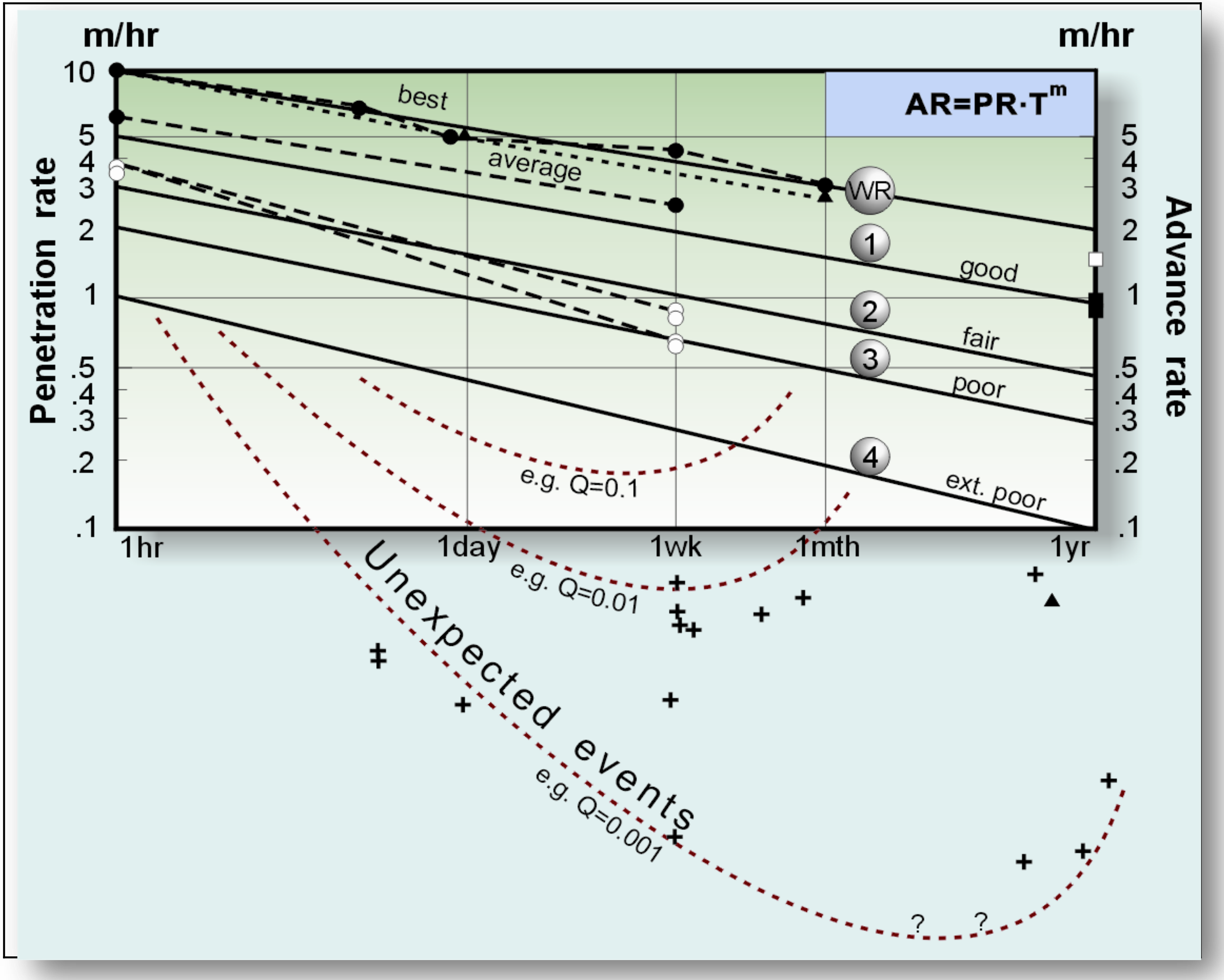


$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right] \frac{\sigma_C}{100}$$

TBM prognosis and comparing with drill-and-blast

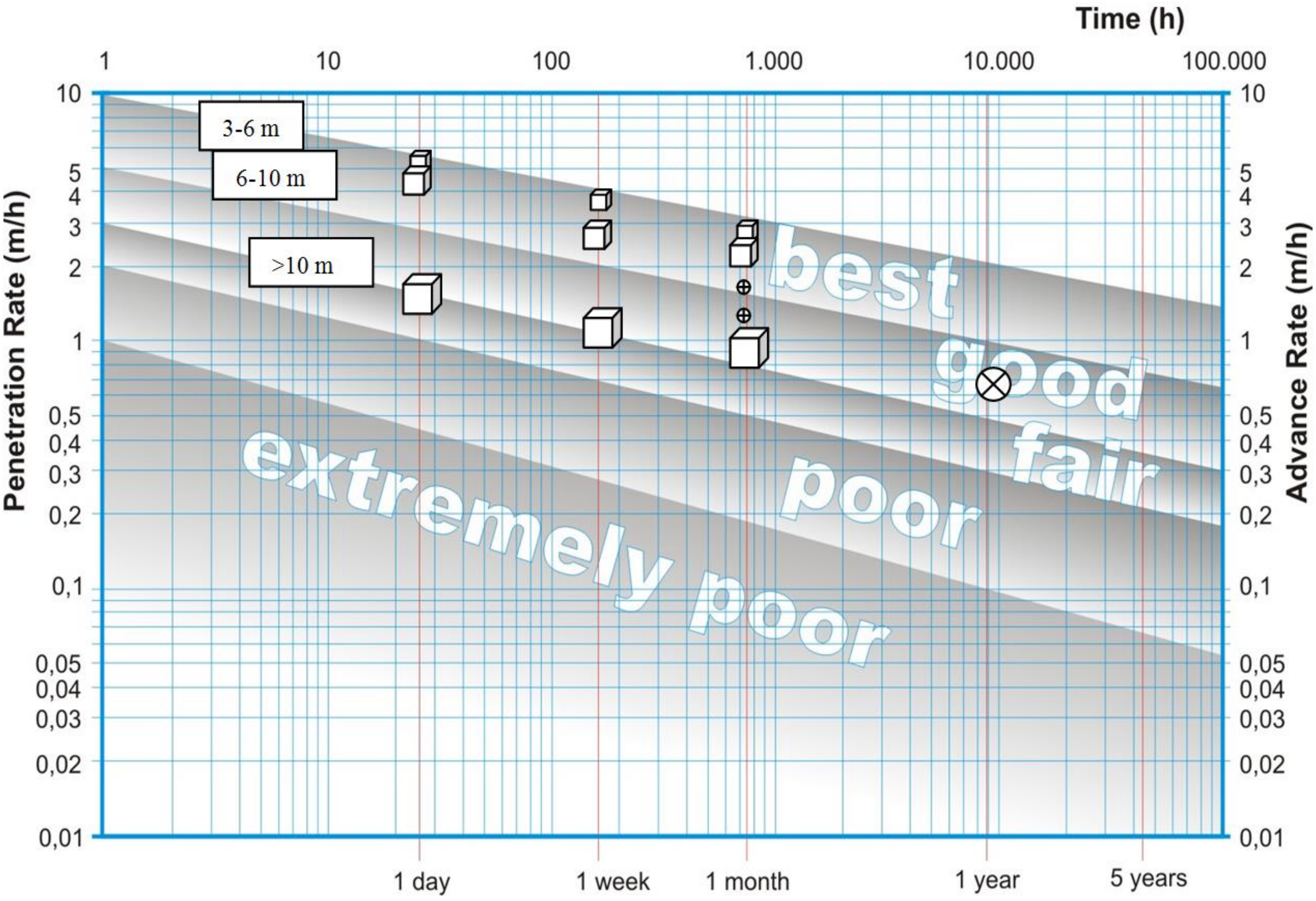
Q_{TBM}

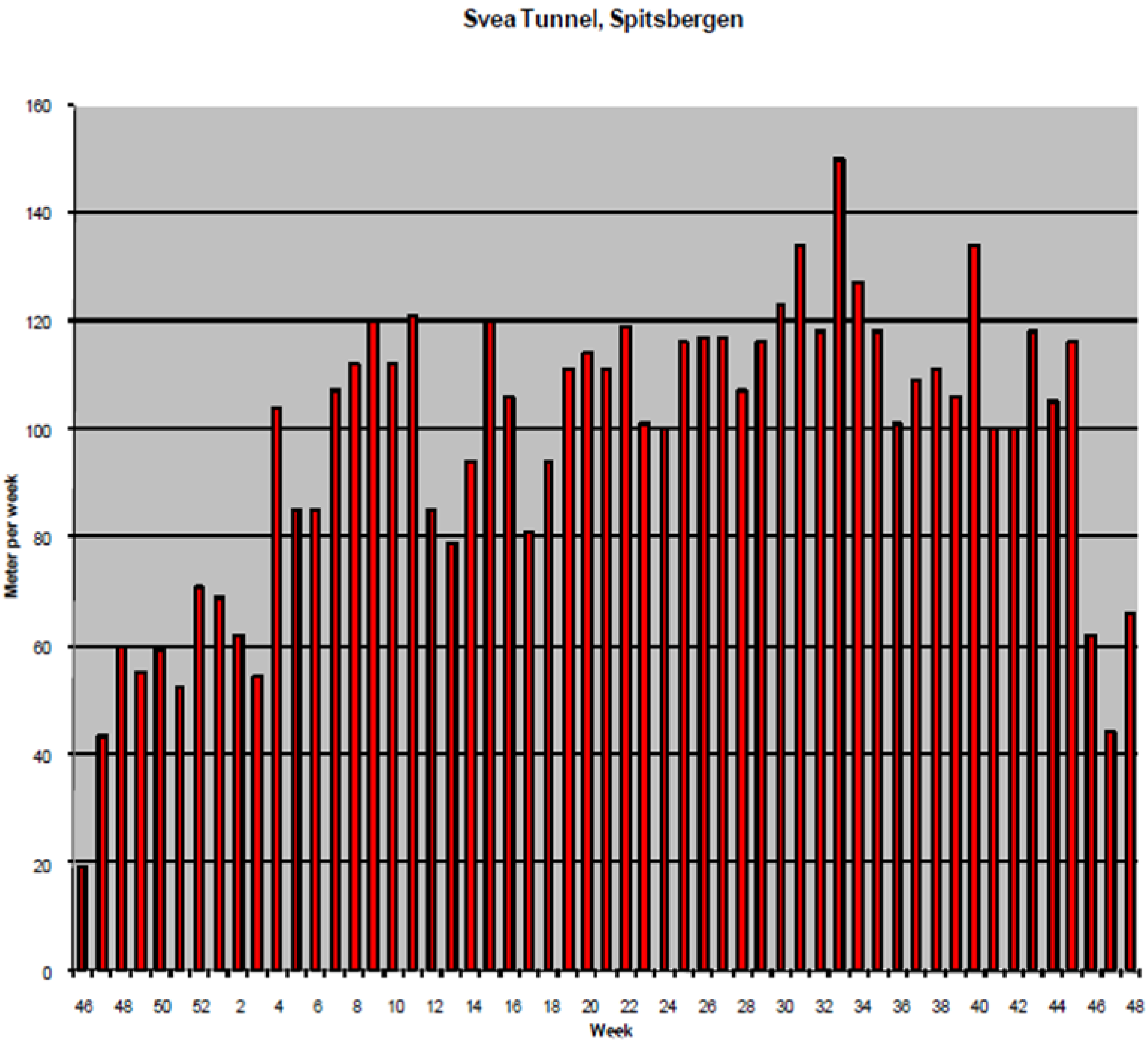
145 cases, ≈ 1000 km, open-gripper trends (Barton, 2000).



SEVERAL PAGES OF WORLD RECORDS BY TBM – ASSEMBLED BY ROBBINS, GIVE THE FOLLOWING RESULTS WHEN COMBINED

Assume 24 hrs/day, 168 hrs/week, 720 hrs/month





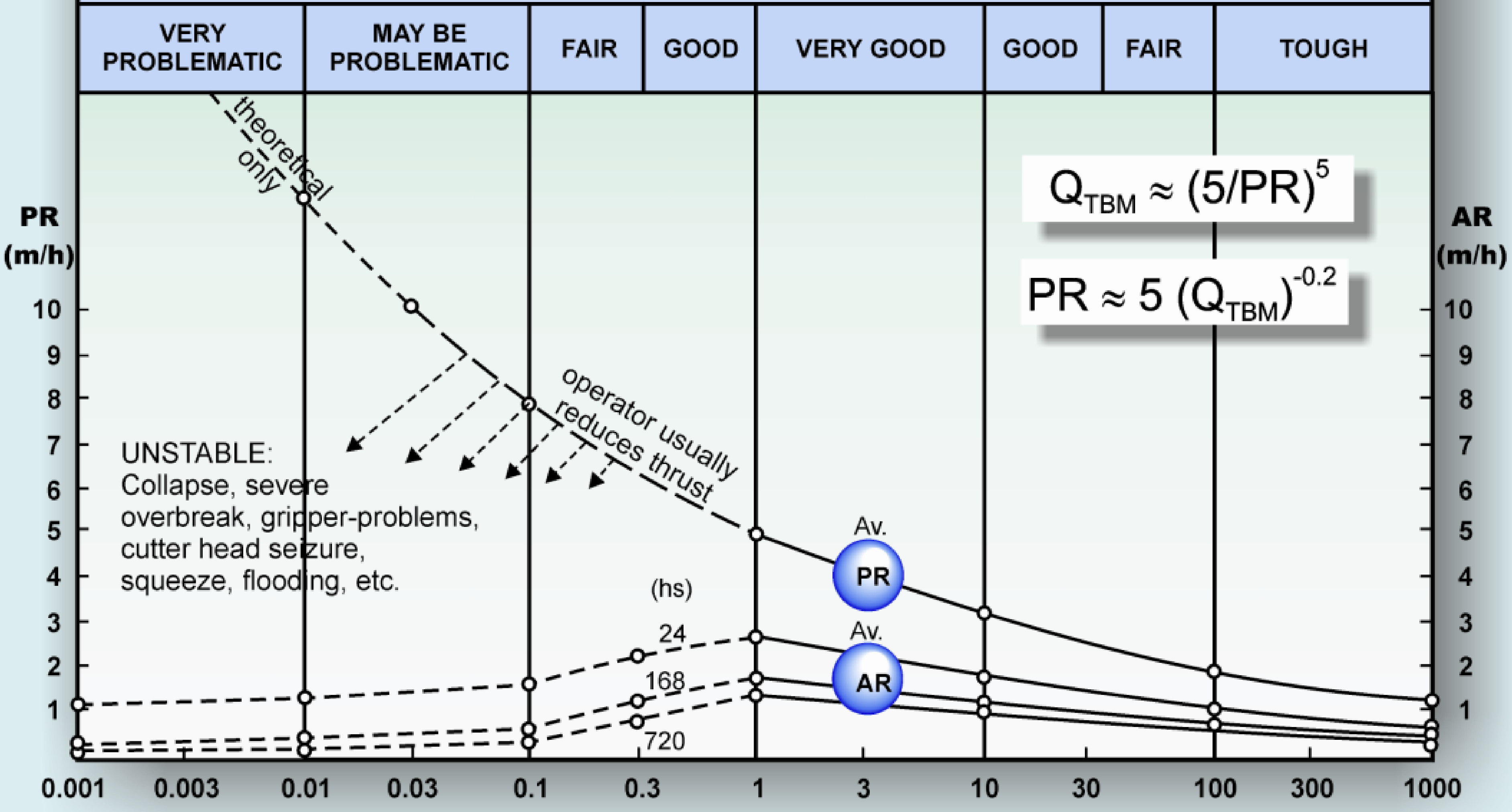
LNS (Northern Norway contractor)

Leonhard Nilsen & Sonner A/S

32 weeks >100m/week

(Drill-and-blast mine access tunnel, one face)

Relative difficulty of ground for TBM use



$$Q_{TBM} \approx (5/PR)^5$$

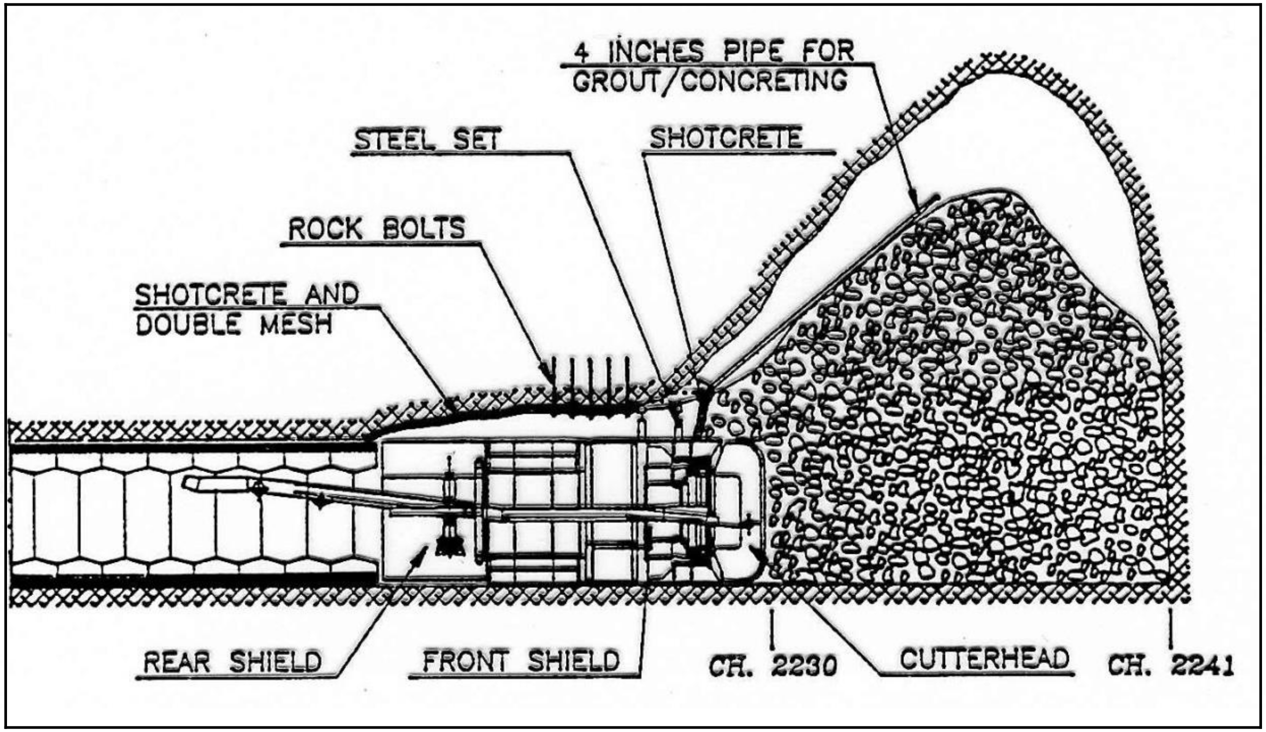
$$PR \approx 5\,(Q_{TBM})^{-0.2}$$

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

WHY TBM DELAYS IN FAULT ZONES ?

“Theo-empirical” reasons

Lack of belief gets paid for!



‘THEO – EMPIRICAL’ REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM – THREE BASIC EQUATIONS:

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

2. $U = T^{m}$ **(due to the decelerating advance rate with time)**

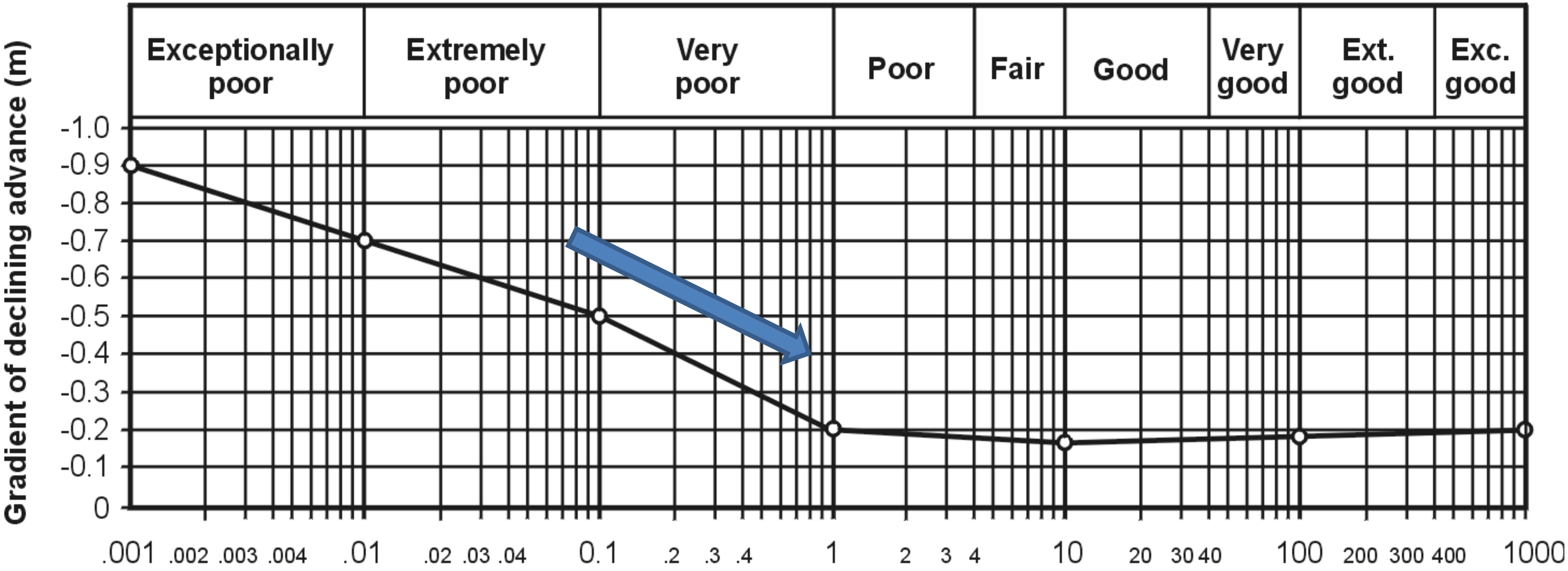
3. $T = L / AR$ **(obviously time for length L must be proportional to 1/AR)**

4. $\underline{T = (L / PR)^{(1/(1+m))}}$ (from #1, #2 and #3)

5. This is VERY important for TBM……since ***(-)m*** is strongly related to Q-values …..in FAULT ZONES.

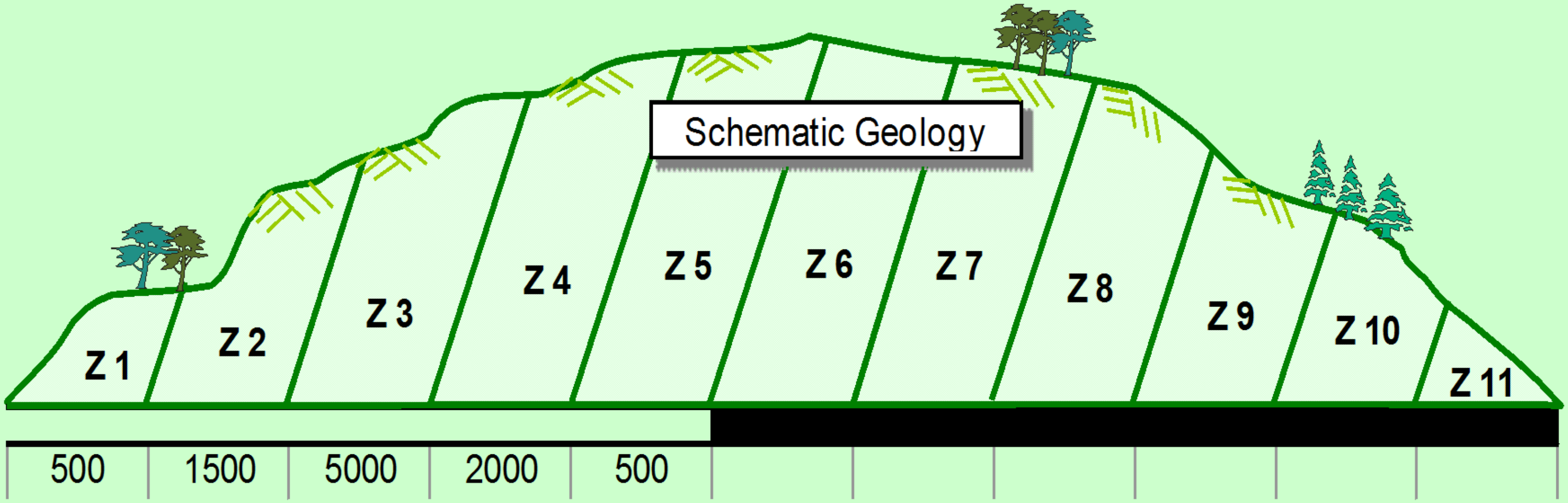
6. It is important because very ***negative (-)m*** values make ***1/(1+m)*** TOO BIG – ***giving ‘huge delays’ (T in months or years)***

BUT…Q CAN BE IMPROVED BY PRE-GROUTING !
(IMPROVE –m.....to less negative value)



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

RAIL TUNNEL PROGNOSIS – OSLO-SKI / FOLLO-BANEN

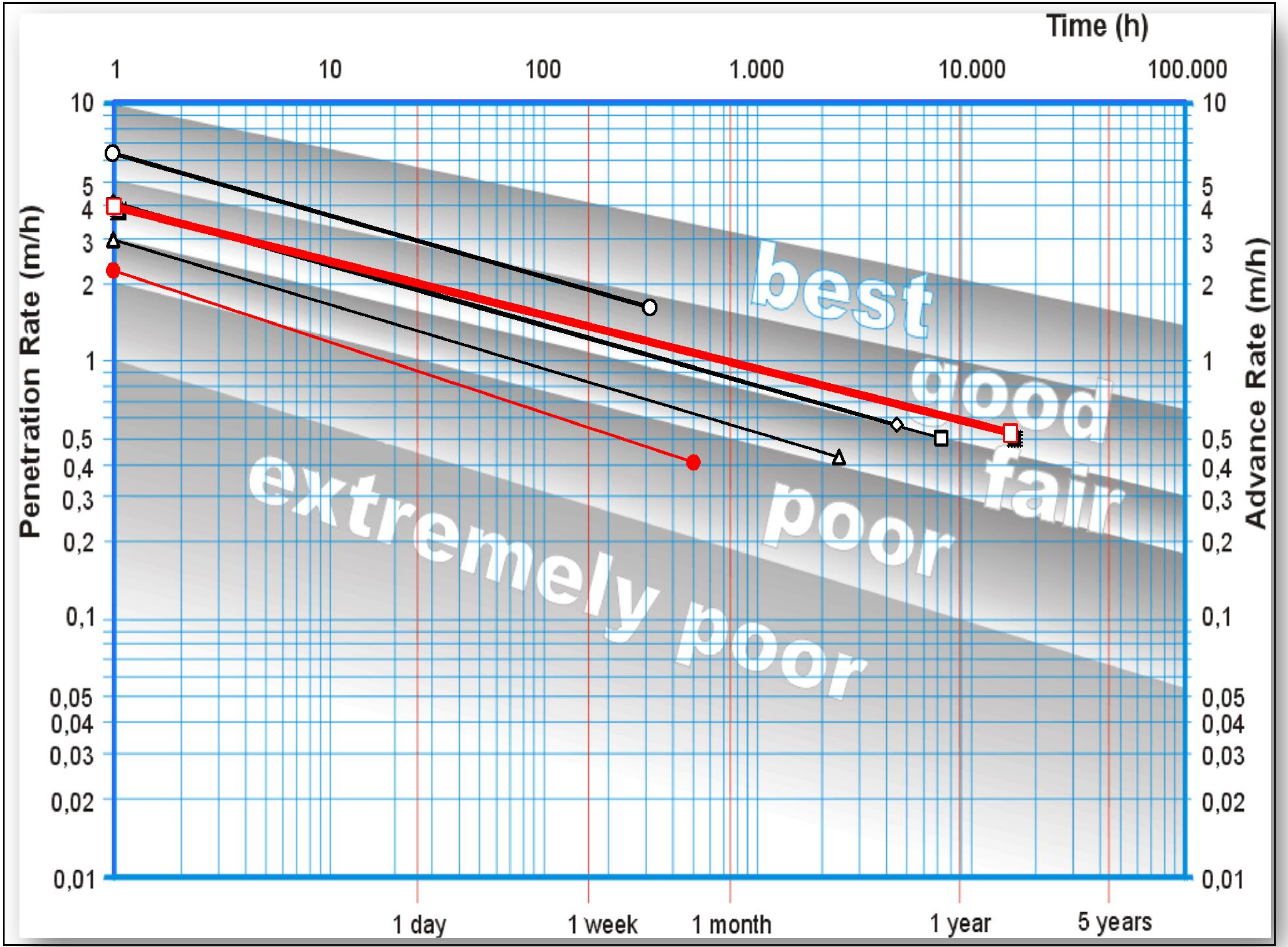


5	LITHOLOGY	*Class 1 granitic gneiss*	ZONE LENGTH	*500*

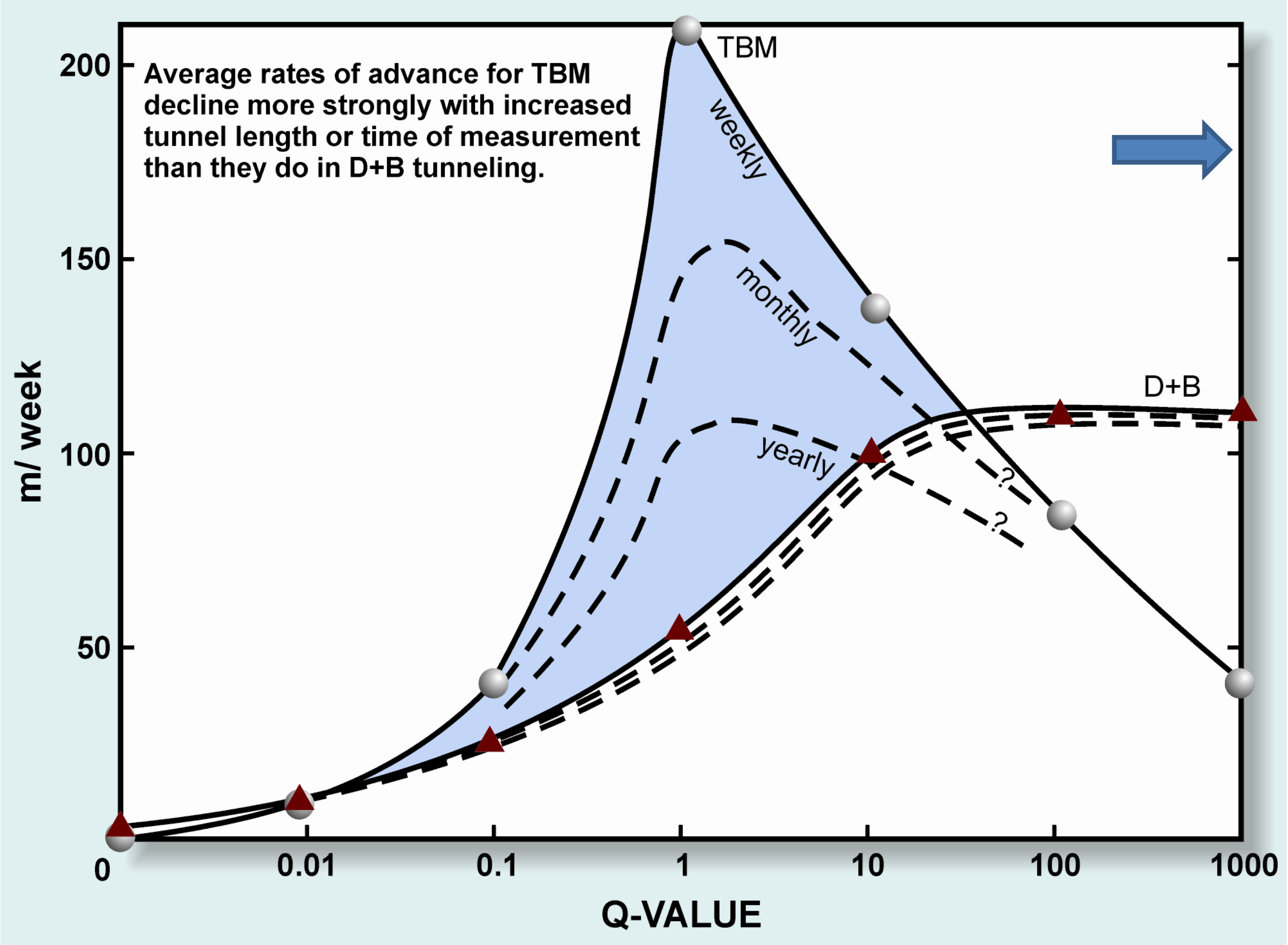
INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)	V_P (km/s)
100.0	2.0	3.0	1.0	1.00	1.0	-0.19	100.0	2.8	

β°	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	250.0		32.0	5.0	35.0	8.0	10.0	1.0


Time (h)
1
10
100
1.000
10.000
100.000
Penetration Rate (m/h)
Advance Rate (m/h)
10
5
4
3
2
1
0,5
0,4
0,3
0,2
0,1
0,05
0,04
0,03
0,02
0,01
best
good
fair
poor
extremely poor
1 day
1 week
1 month
1 year
5 years

CENTRAL Q-VALUES AND Q_{TBM} VALUES ARE BEST FOR GOOD TBM PROGRESS. *TAIL-DISTRIBUTIONS 'BETTER' WITH D+B !*



Note records for *drill-and-blast:*

176m/one face in 168 hours (7x24) week.

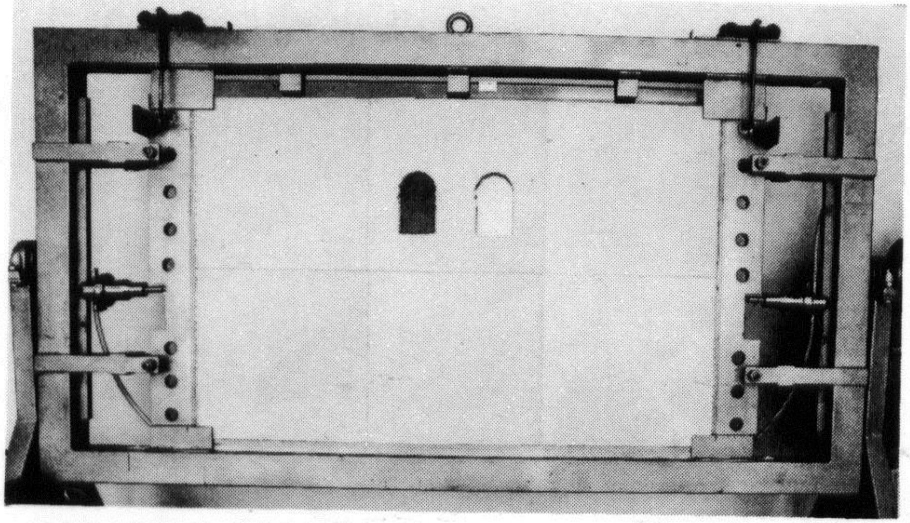
Whole project 104 m/week average

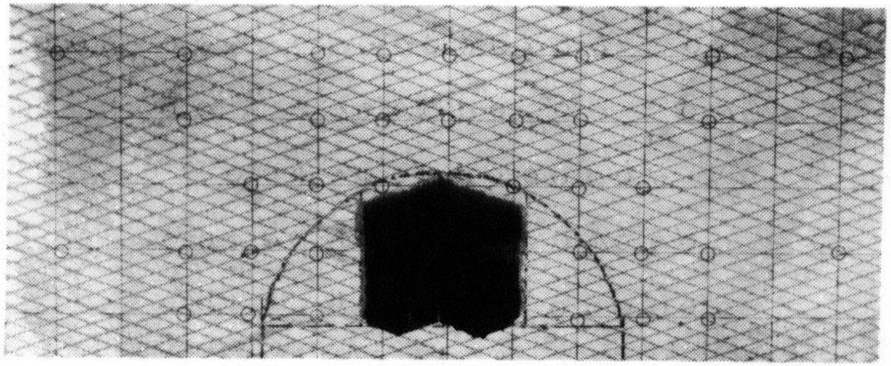
– IN COAL-MEASURE ROCKS needing B+S(fr).

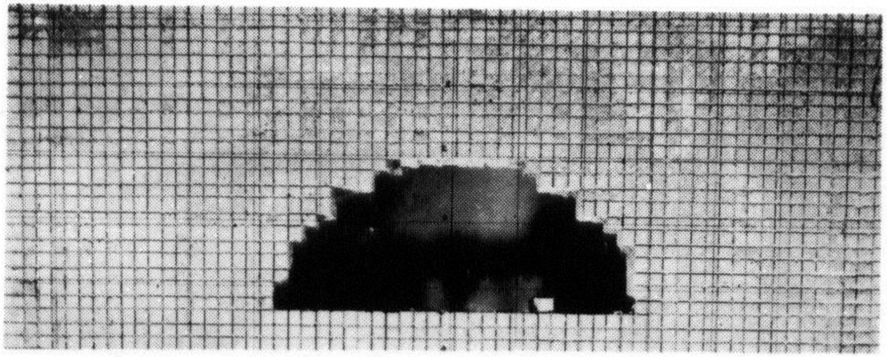
LNS Norway

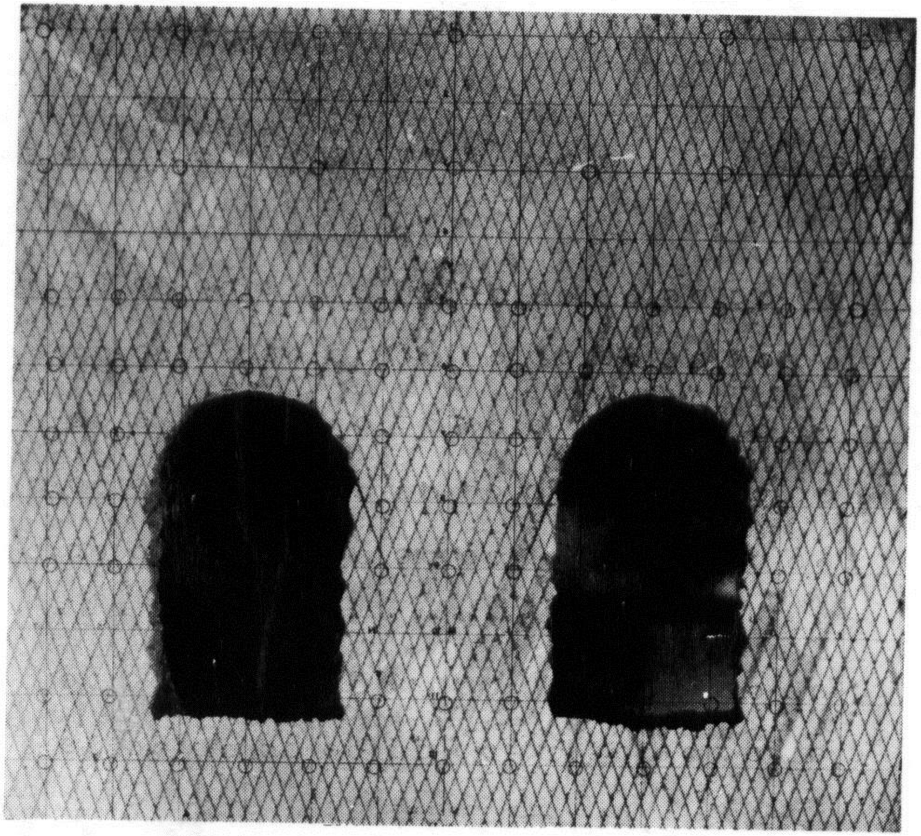
PHYSICAL (2D) MODELS of ROCK CAVERNS, AS FORE-RUNNER TO *UDEC-BB* FLEXIBILITY

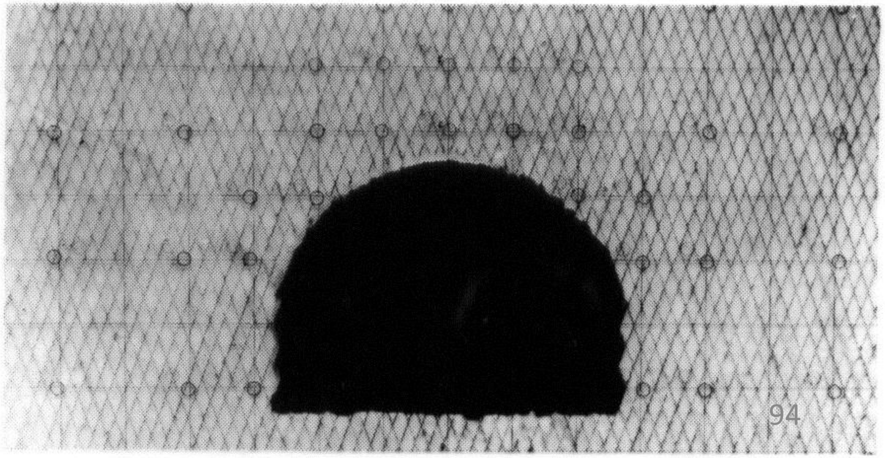
(1977-1978)





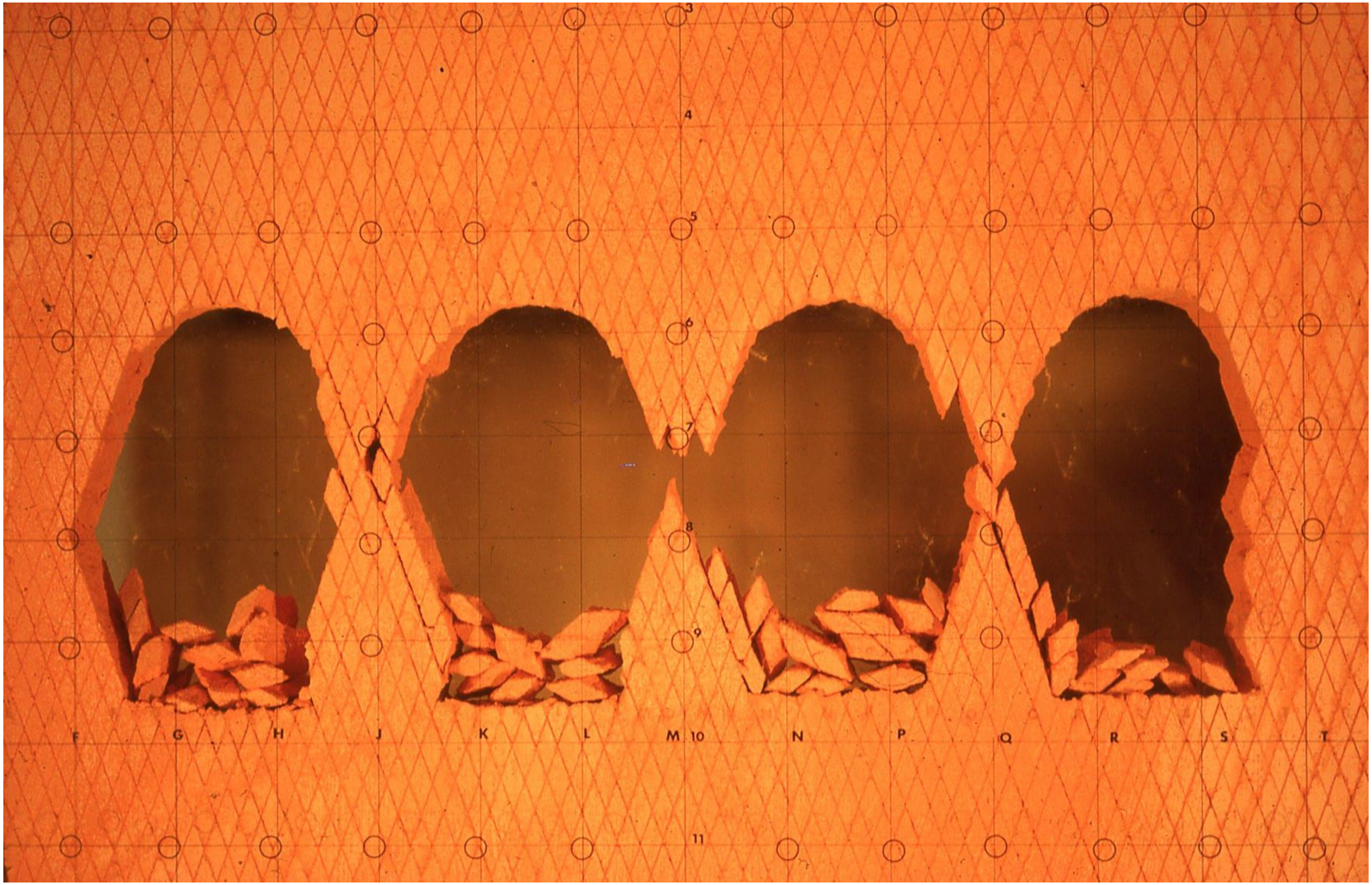


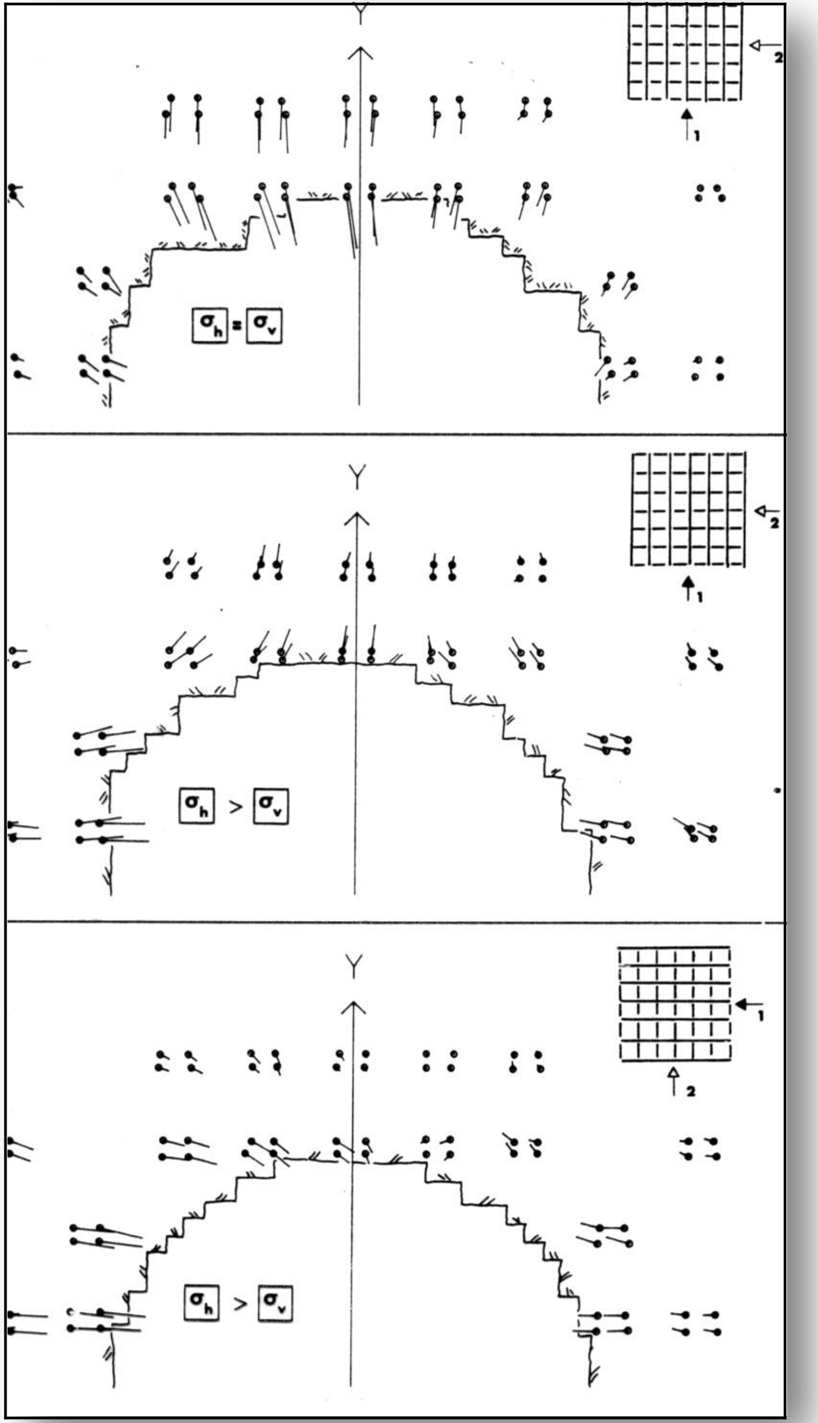




THE ‘jointed’ NATURE OF THE MODELLING MATERIAL

(Post- ‘seismic’ loading result, following 0.2 to 0.5 g)





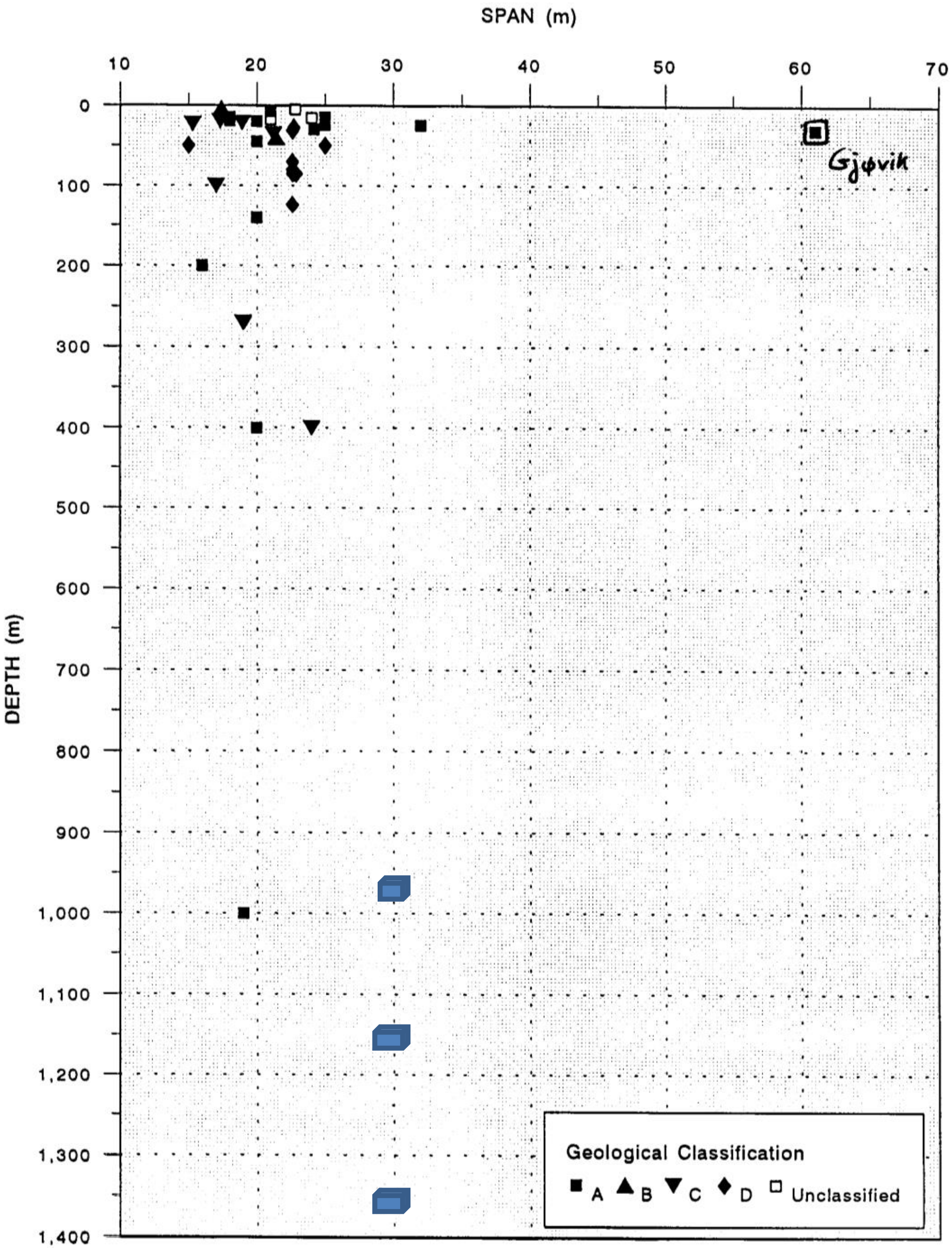
Physical and FEM modelling (Barton and Hansteen, 1979) suggested possible ‘heave’ resulting from large-cavern construction near the surface……..

……….depended on joint pattern and horizontal stress level in the physical models.

GJØVIK CAVERN

INCREASE OF LARGEST CAVERN SPAN BY ALMOST 2 x

(Note also the three deep caverns in a Norwegian road tunnel)



CAVERN PRECEDENT STUDY

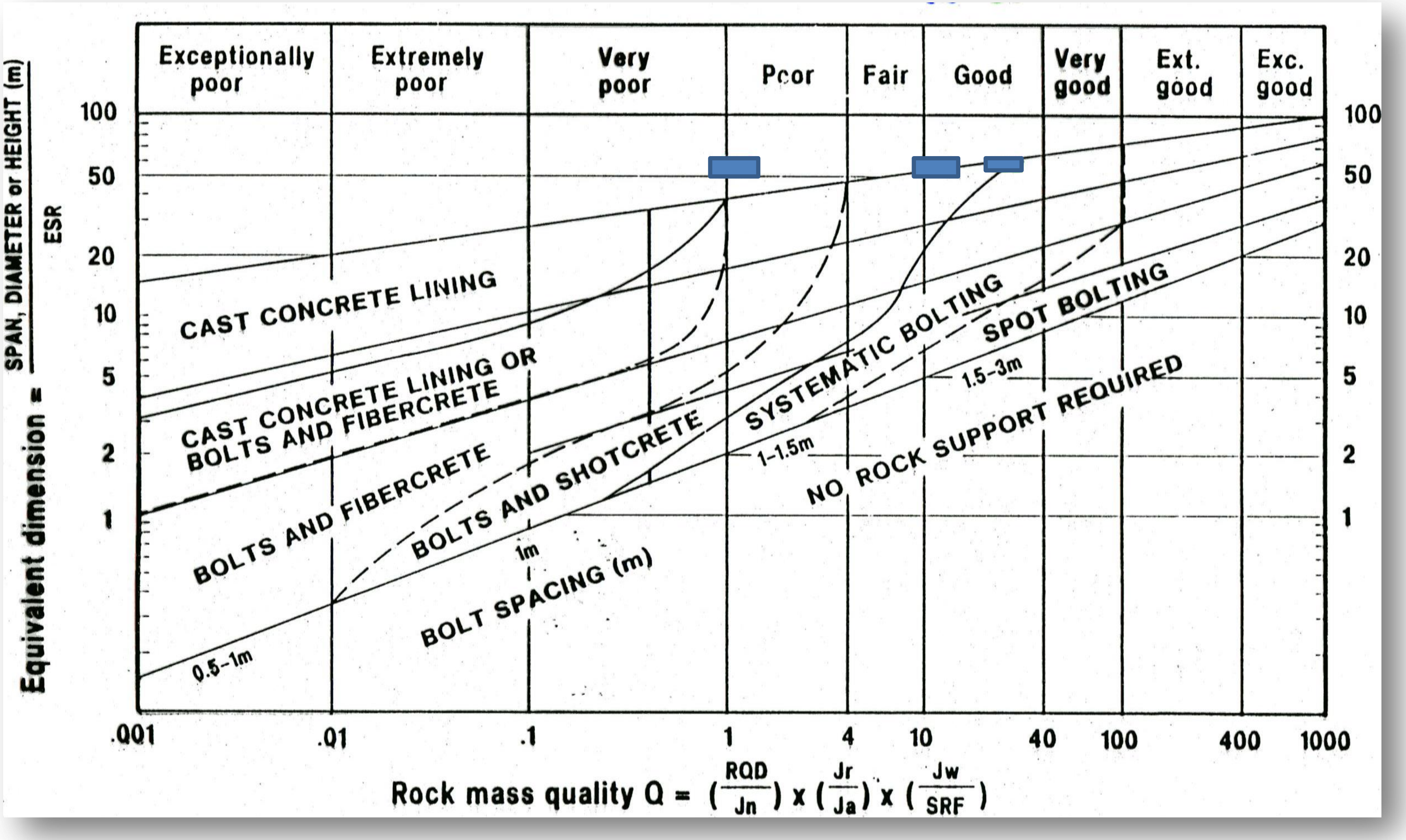
Gjøvik Olympic cavern represented a big jump…….in span and confidence!

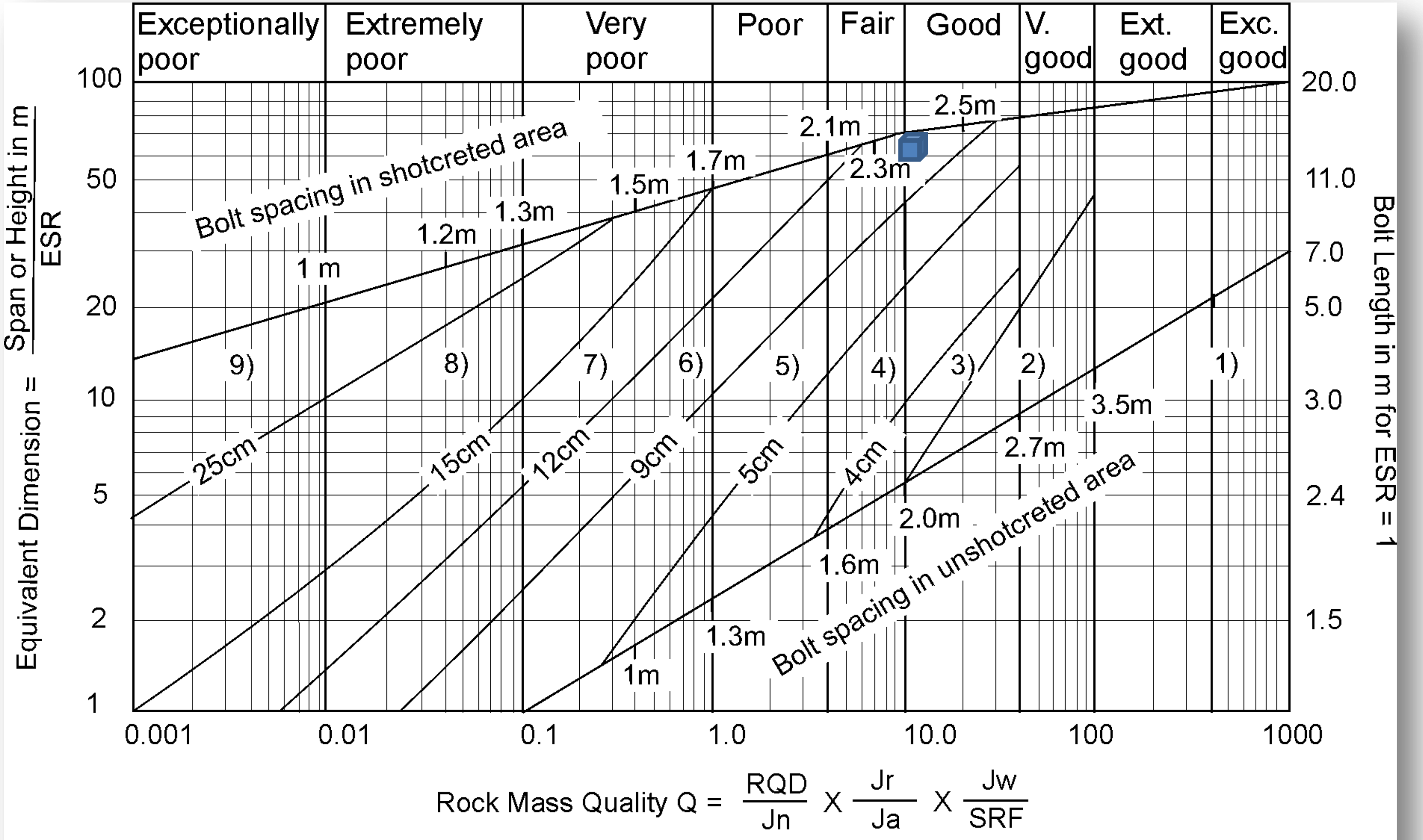
(Figure from Sharp, 1996: UK Nirex study)

BLUE: Lærdal Tunnel (three lorry-turning and *‘wake-up-driver’* caverns in 24.5 km long tunnel)

LÆRDAL TUNNEL lorry-turning caverns (three of them) 30 m span, depths 1,000 to 1,400 m (Photo G.Lotsberg)

Gjøvik cavern : an 'extension' of 1974 Q-system data base.
(Q_{min}, Q_{mean}, and Q_{max} values of **1**, **12**, **30** logged in the cavern)
RQD = 60-90%, UCS = 90 MPa was typical.



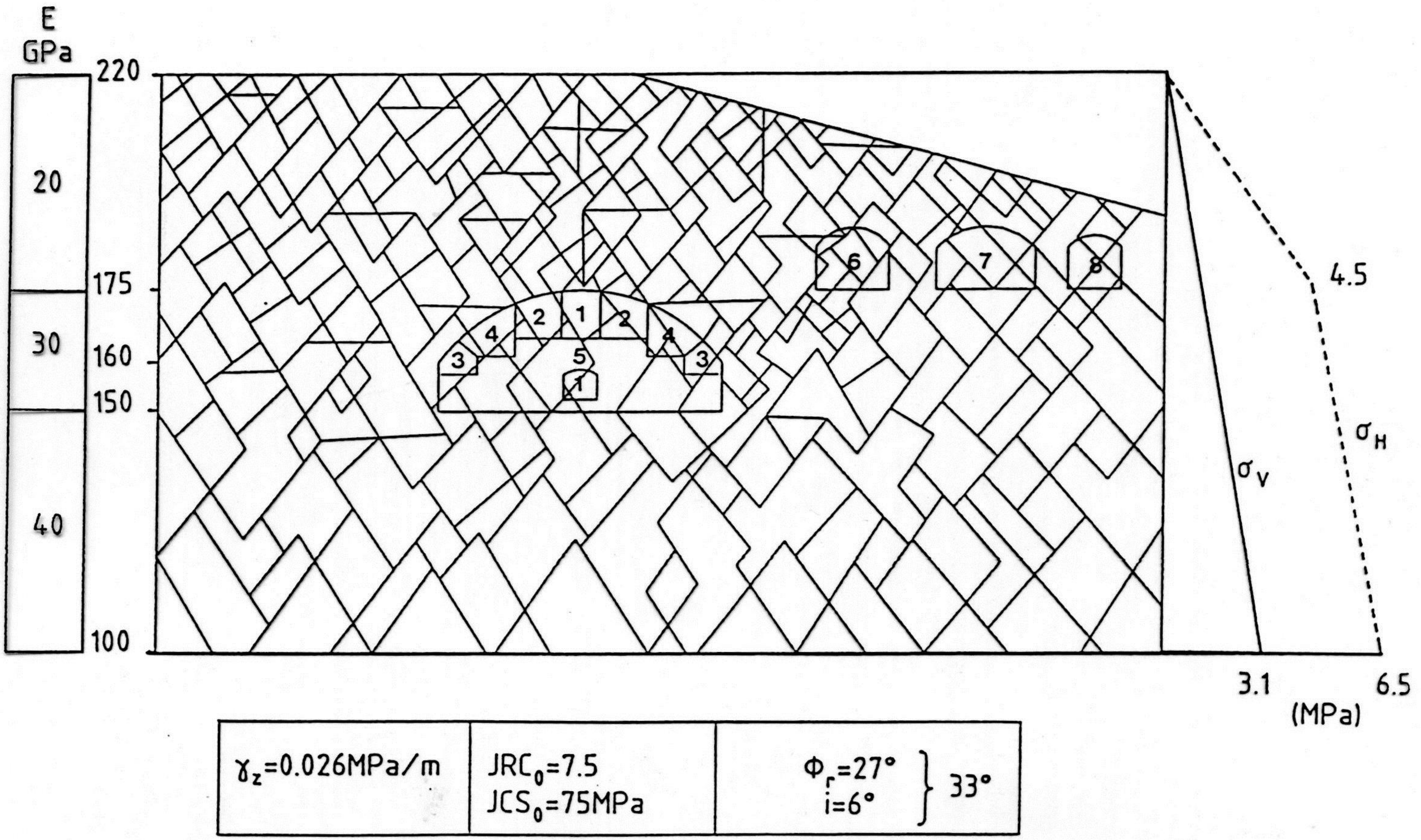


REINFORCEMENT CATEGORIES

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

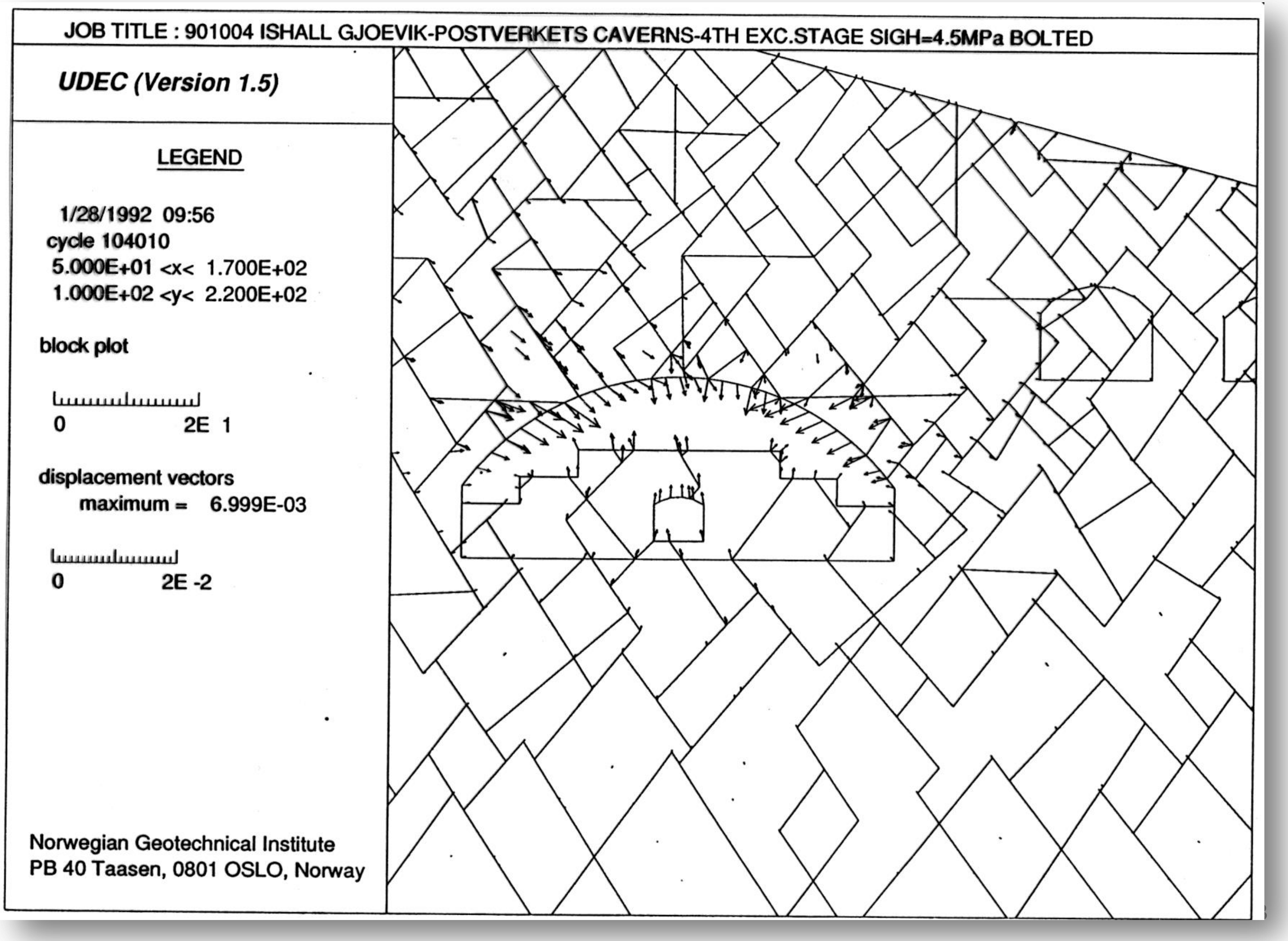
GJØVIK CAVERN JOINT-GEOMETRY ASSUMPTIONS
input data, boundary stresses

Barton, N., By, T.L., Chryssanthakis, P., Tunbridge, L., Kristiansen, J., Løset, F., Bhasin, R.K., Westerdahl, H. & Vik, G. 1994. Predicted and measured performance of the 62m span Norwegian Olympic Ice Hockey Cavern at Gjøvik. Int. J. Rock Mech, Min. Sci. & Geomech. Abstr. 31:6: 617-641. Pergamon.



γ_z=0.026MPa/m	JRC_0=7.5 JCS_0=75MPa	ϕ_r=27° i=6° } 33°

TOP HEADING TOO WIDE TO OBSERVE FROM ONE LOCATION



JOB TITLE : 901004 ISHALL GJOEVIK-POSTVERKETS CAVERNS-4TH EXC.STAGE SIGH=4.5MPa BOLTED

UDEC (Version 1.5)

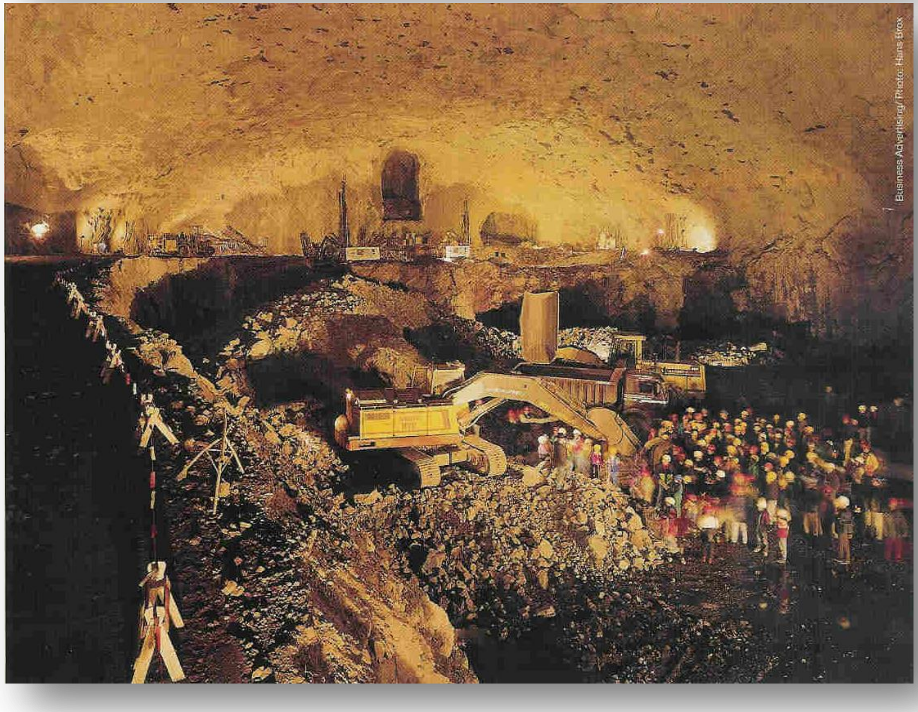
LEGEND

1/28/1992 09:56
cycle 104010
5.000E+01 <x< 1.700E+02
1.000E+02 <y< 2.200E+02

block plot

displacement vectors
maximum = 6.999E-03

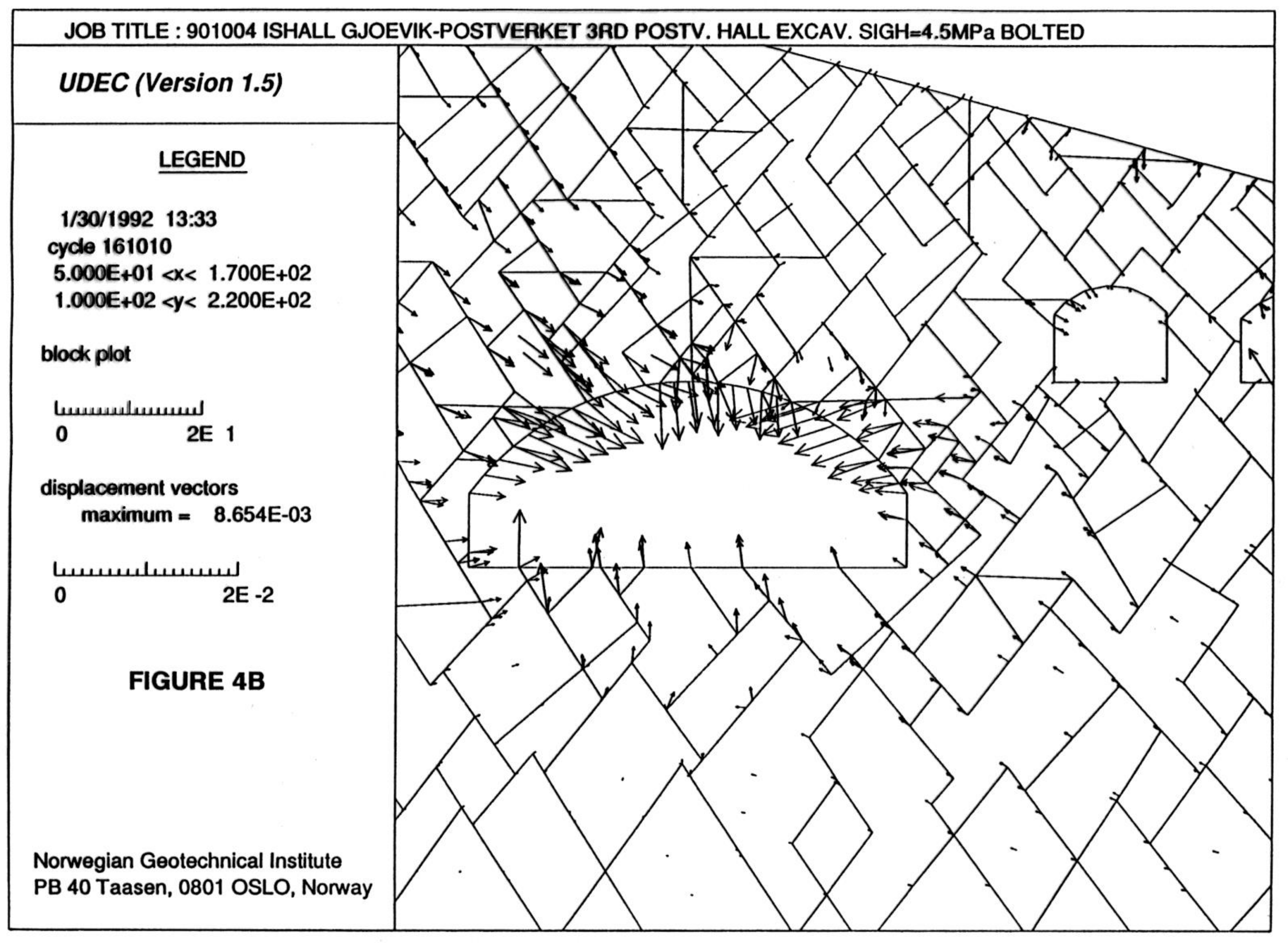
Norwegian Geotechnical Institute
PB 40 Taasen, 0801 OSLO, Norway



Business Advertising / Photo: Hans Brox

The final modelled 7 to 9 mm (downwards directed) deformations matched the unknown (to be measured) result almost perfectly.

(UDEC-BB modelling by Chryssanthakis, NGI)



JOB TITLE : 901004 ISHALL GJOEVIK-POSTVERKET 3RD POSTV. HALL EXCAV. SIGH=4.5MPa BOLTED

UDEC (Version 1.5)

LEGEND

1/30/1992 13:33
cycle 161010
5.000E+01 <x< 1.700E+02
1.000E+02 <y< 2.200E+02

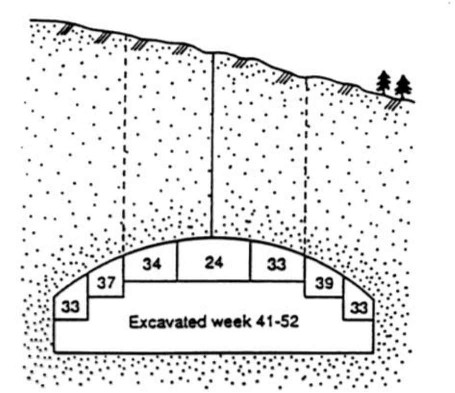
block plot

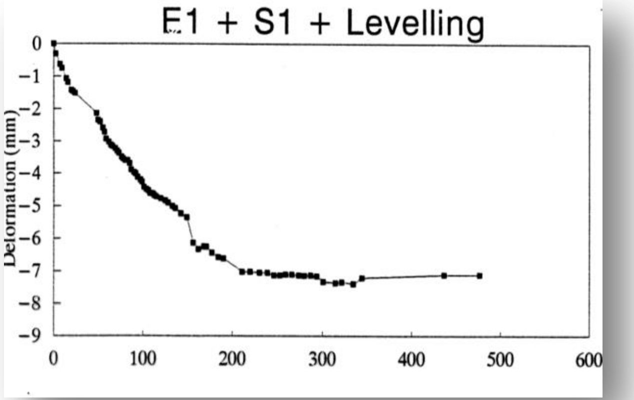
displacement vectors
maximum = 8.654E-03

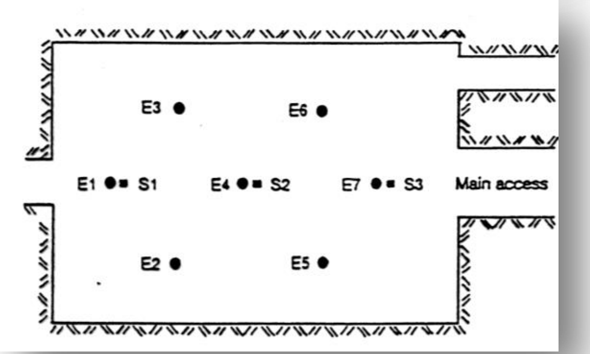
FIGURE 4B

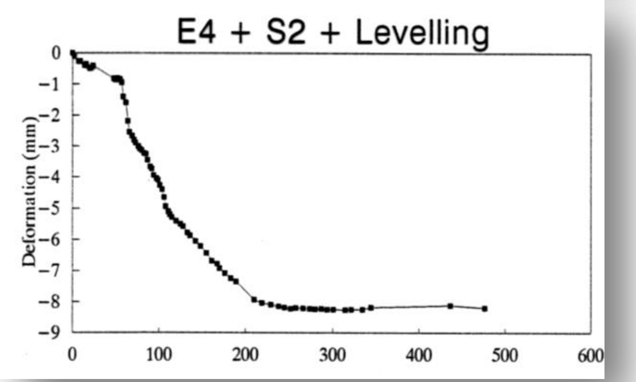
Norwegian Geotechnical Institute
PB 40 Taasen, 0801 OSLO, Norway

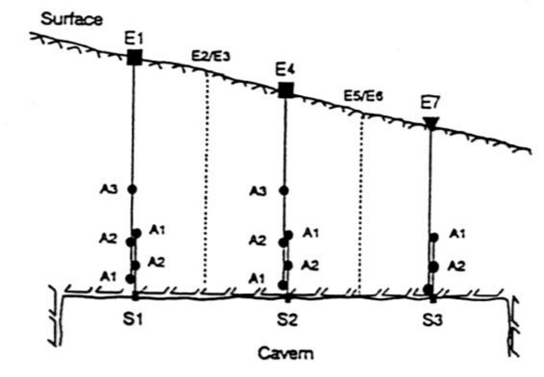
DEFORMATION RECORDS FROM MPBX AND LEVELLING

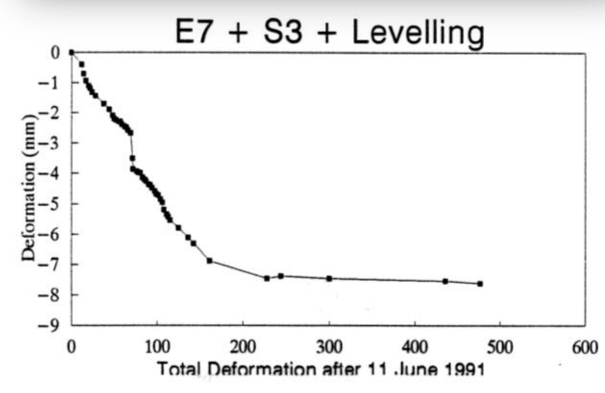












Δ = 7 to 8 mm was typical.

Construction period: week 24 to week 52, following arrival of access tunnels (top and bottom).

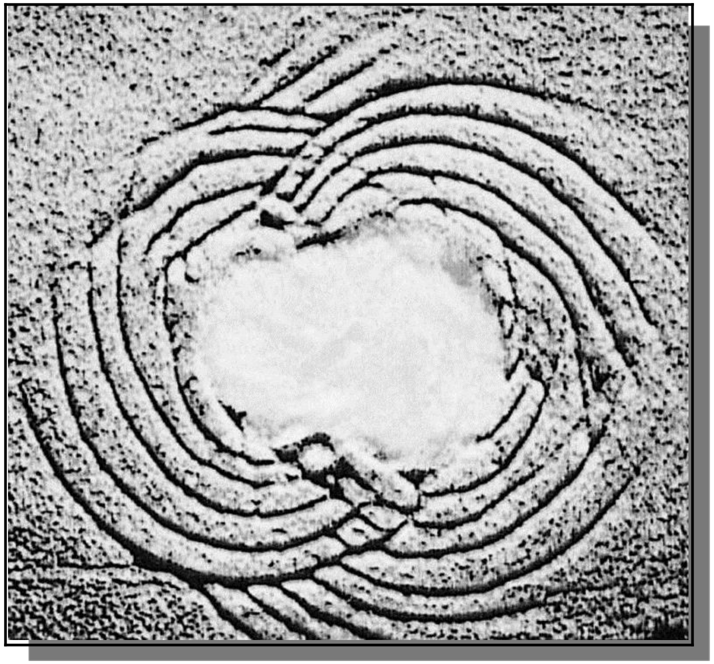
B x H x L
= 62 x 24 x 90
= 140,000 m3

Typical NMT
B + S(fr)
DRAINED

CONTINUUM (??)

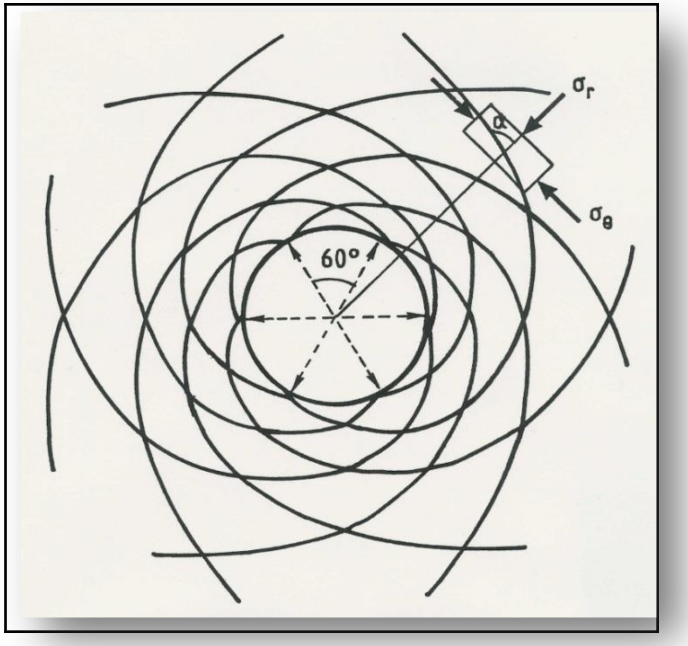
or

DISCONTINUUM MODELLING



Borehole stability studies at NGI

Continuum becomes a discontinuum!

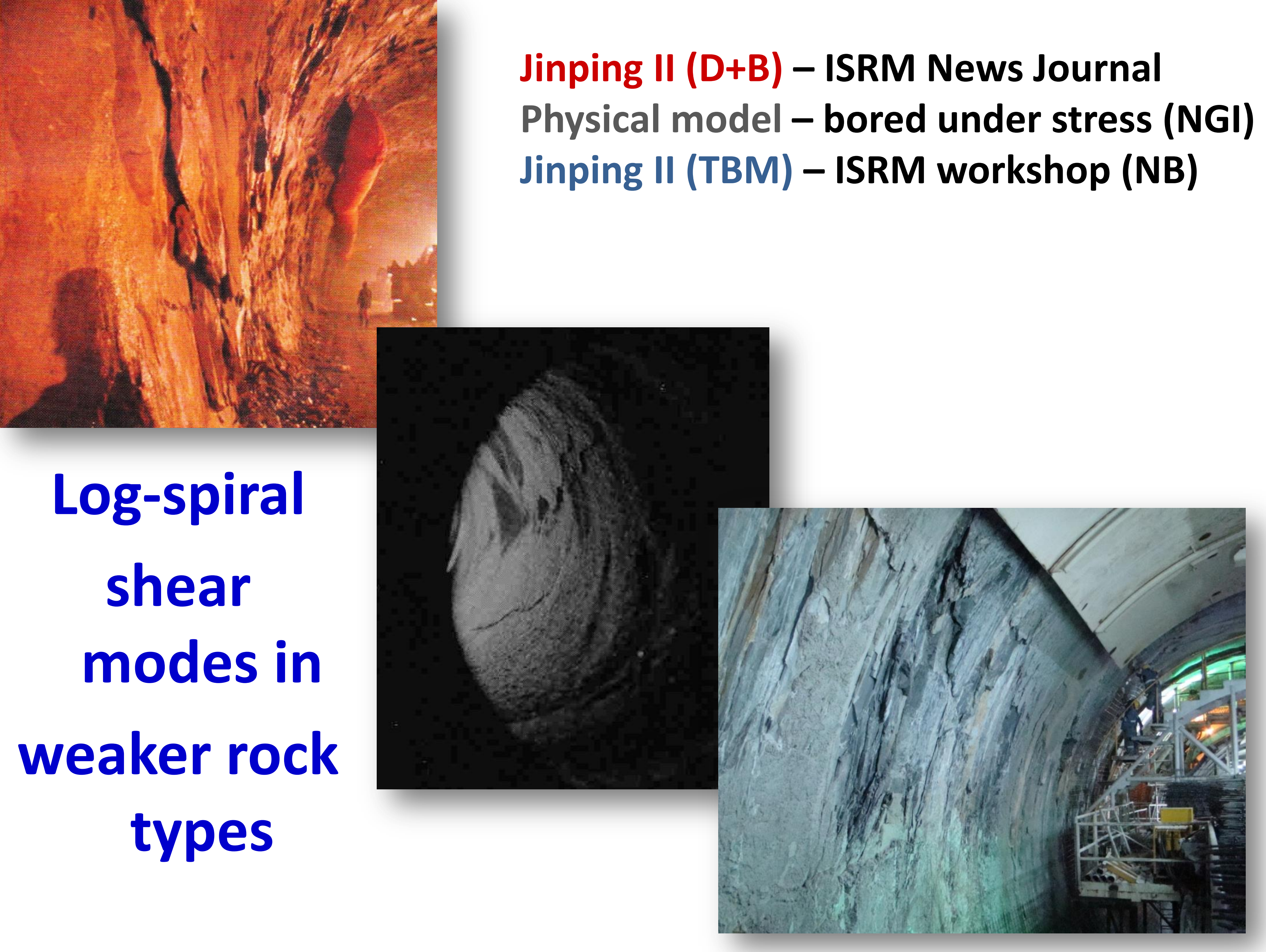


Drilling into $\sigma_1 > \sigma_2 > \sigma_3$ loaded cubes

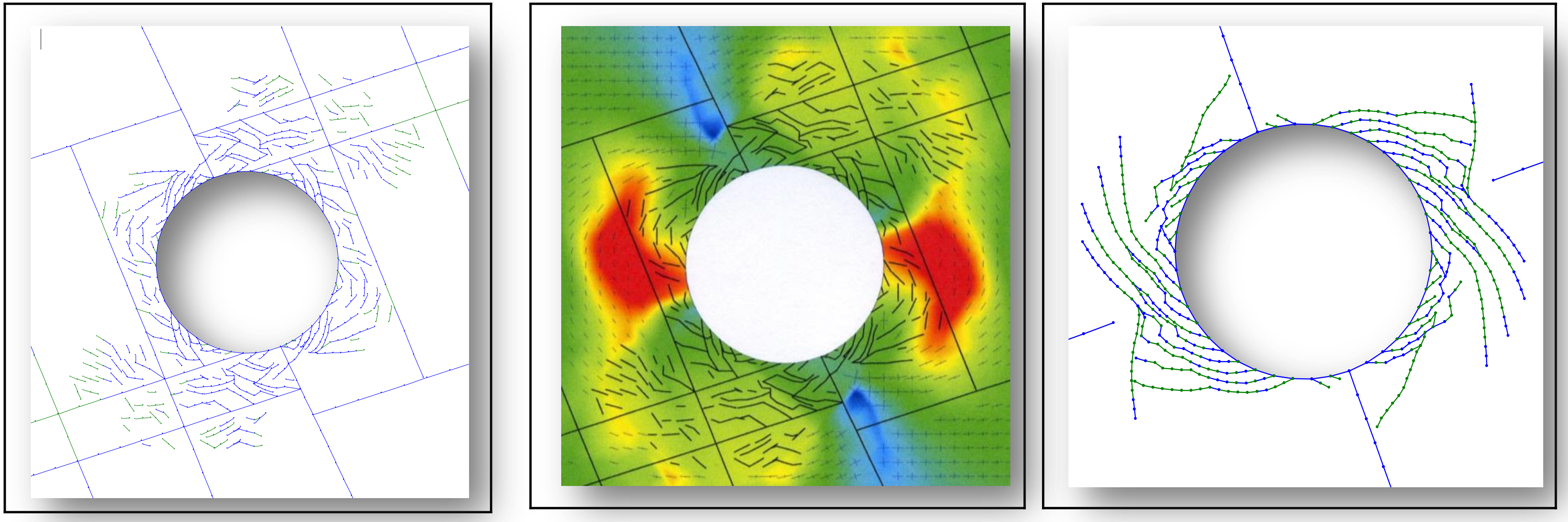
0.5 x 0.5 x 0.5 m

of model sandstone

Jinping II (D+B) – ISRM News Journal
Physical model – bored under stress (NGI)
Jinping II (TBM) – ISRM workshop (NB)



Log-spiral shear modes in weaker rock types

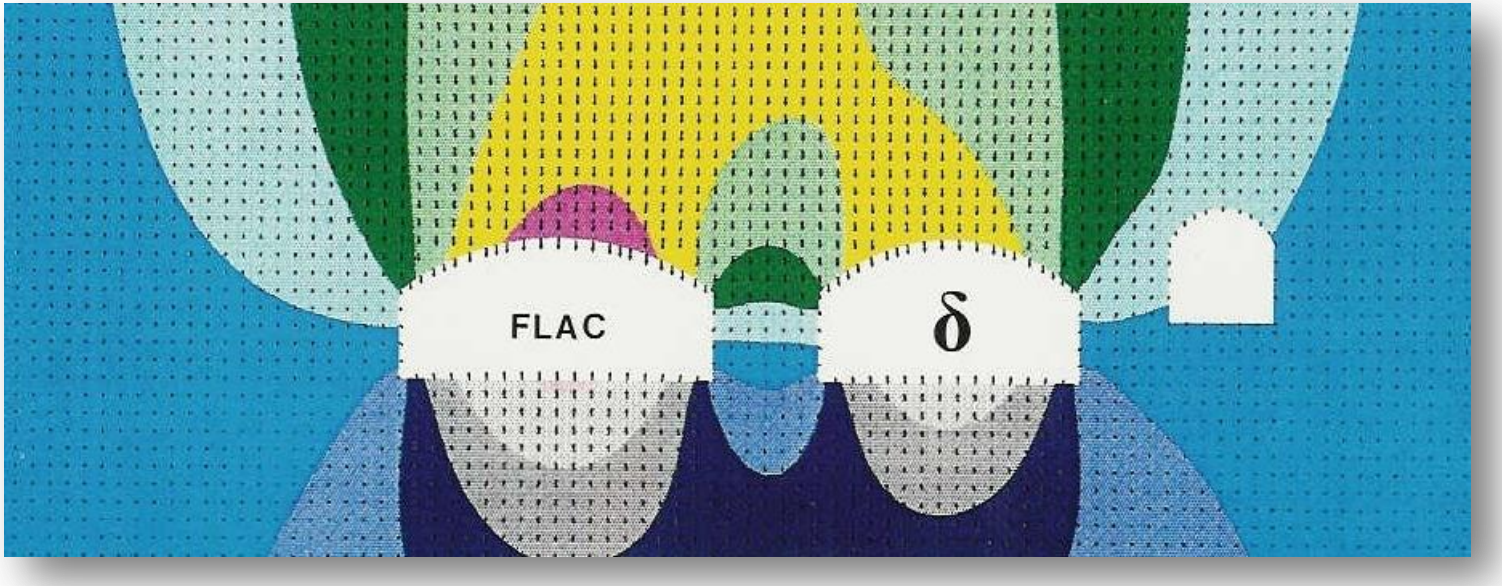


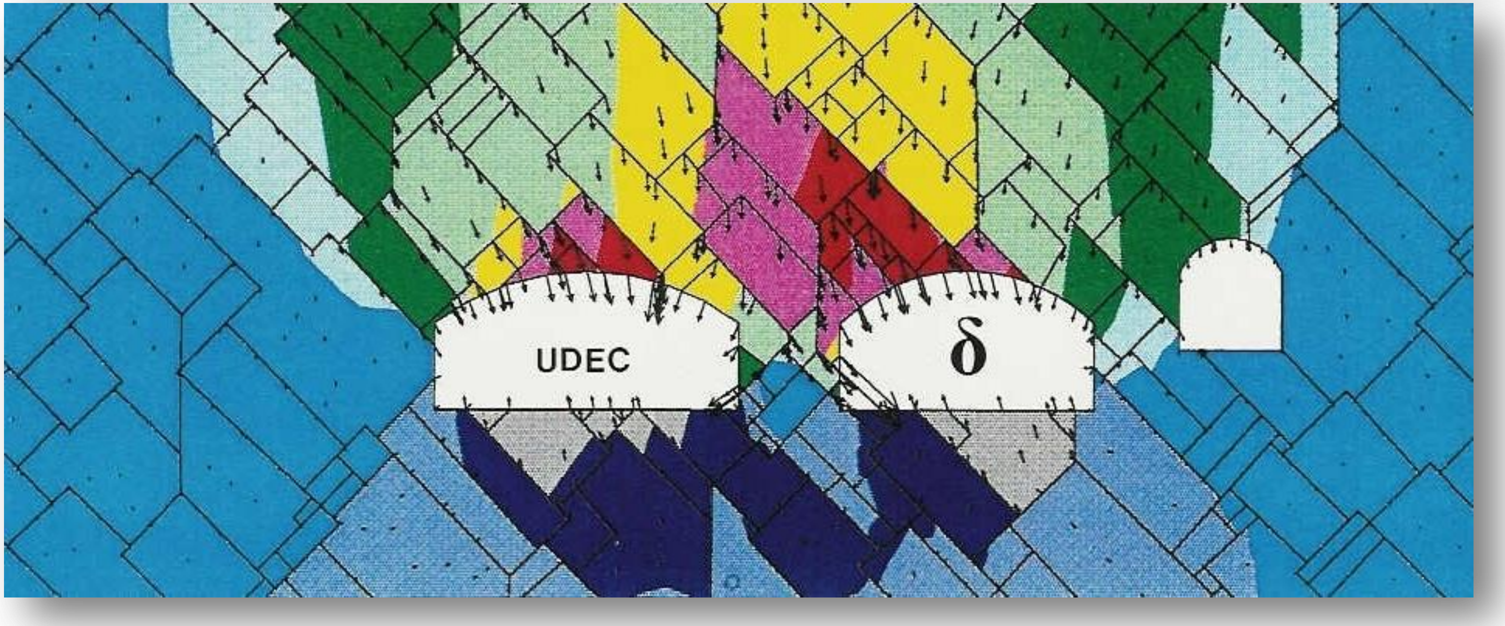
Three FRACOD models showing fracturing development.

Baotang Shen, 2004

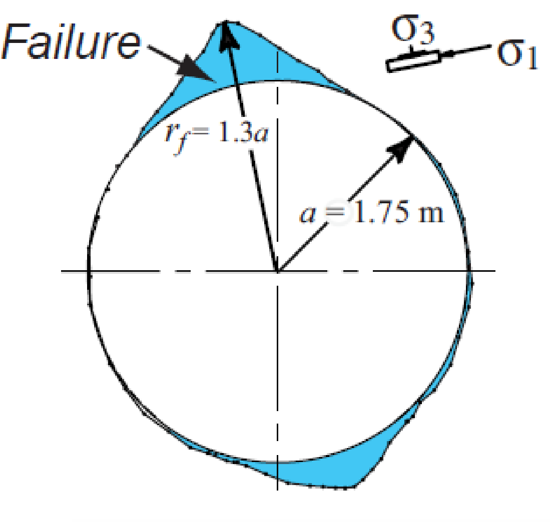
Cundall and Cundall………but the choice is clear!

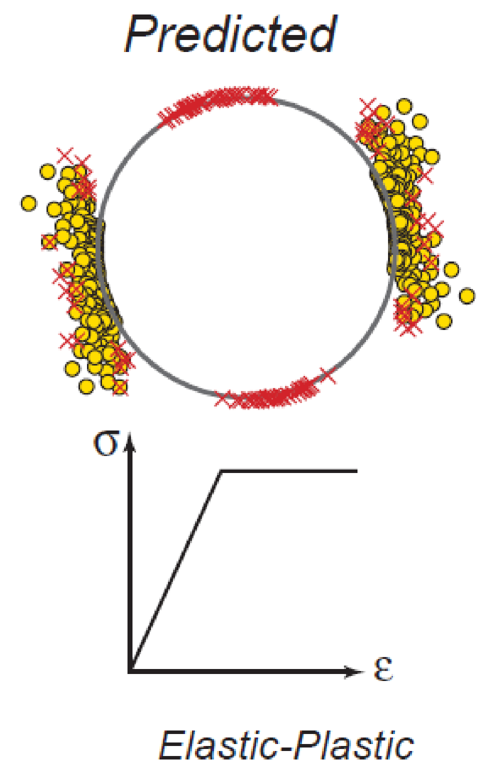
(NGI modelling by Lise Backer)





NEED for CHANGE



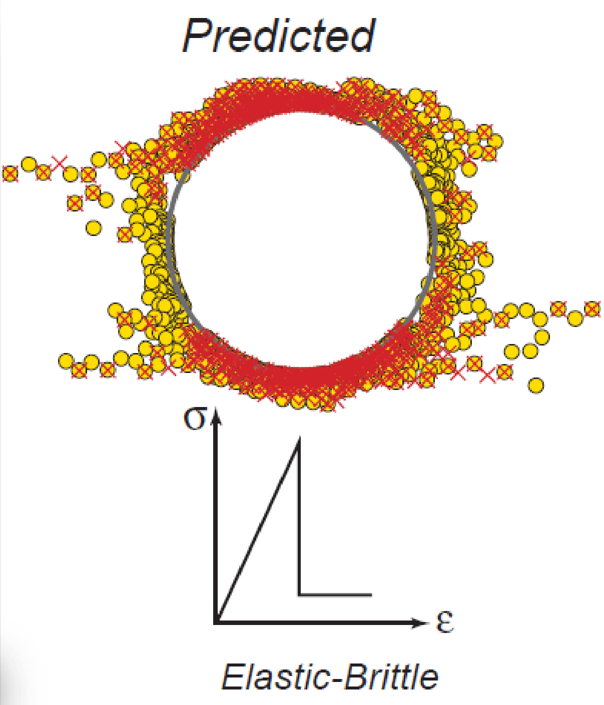


CONVENTIONAL continuum modelling methods are suspect.

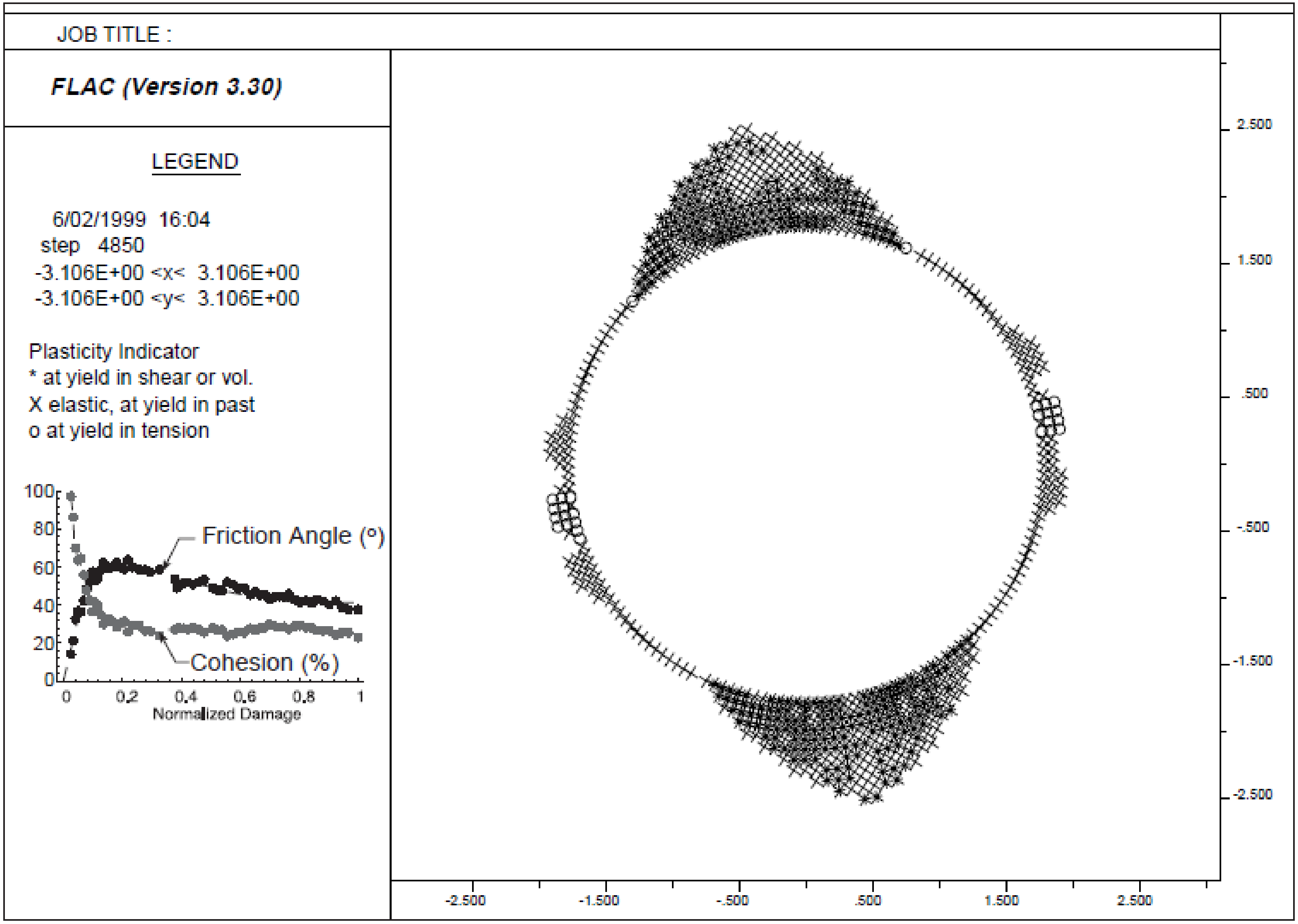
Poor simulation with Mohr Coulomb or Hoek and Brown strength criteria.

(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.

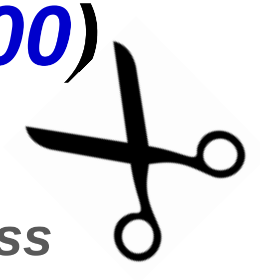
(**Hajiabdolmajid, Martin and Kaiser, 2000** “Modelling brittle failure”, NARMS.)

NOW AN ALTERNATIVE WAY TO ESTIMATE ***‘c’ and ‘φ’*** FOR ROCK MASSES

(but still need to ***degrade c*** at small strain, and ***mobilize φ*** at larger strain)

CC and FC from $Q_c = Q \times \sigma_c /100$:

$Q_c = RQD/Jn \times Jr/Ja \times Jw / SRF \times \sigma_c /100)$



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'

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

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

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

GSI-based algebra for ‘c’ and ‘φ’

contrasted with

Q-based ‘empiricism’

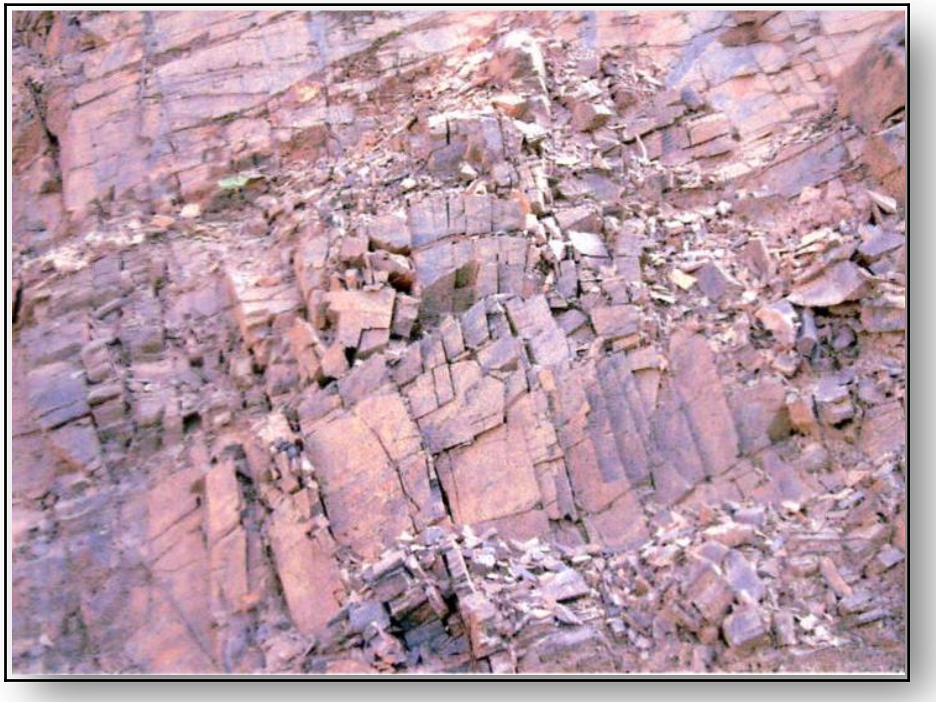
Note: shotcrete needed when low CC, bolting needed when low FC.

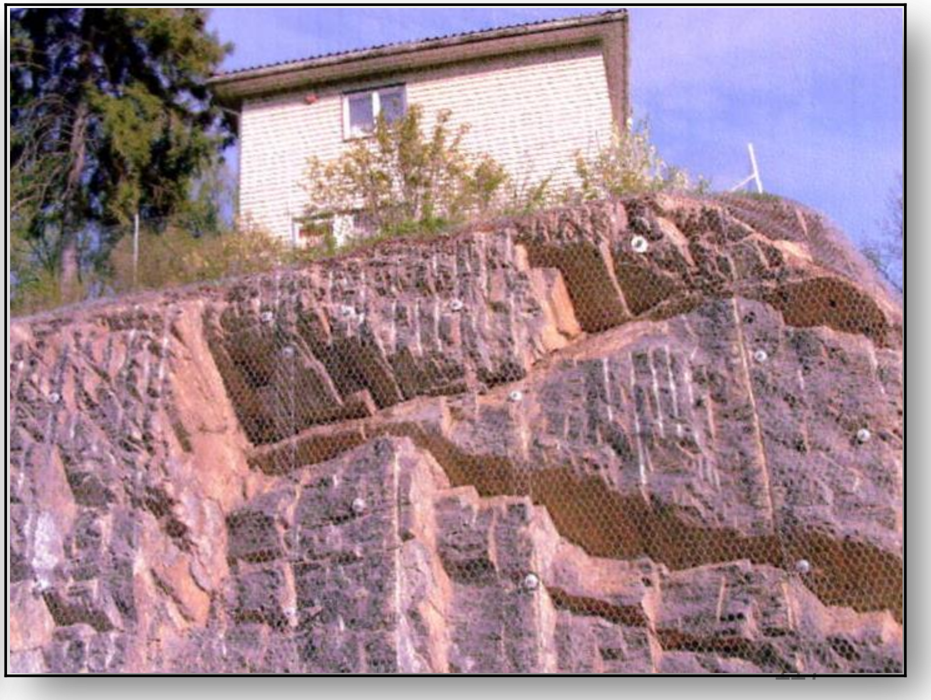
RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	*FC*°	*CC* MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5

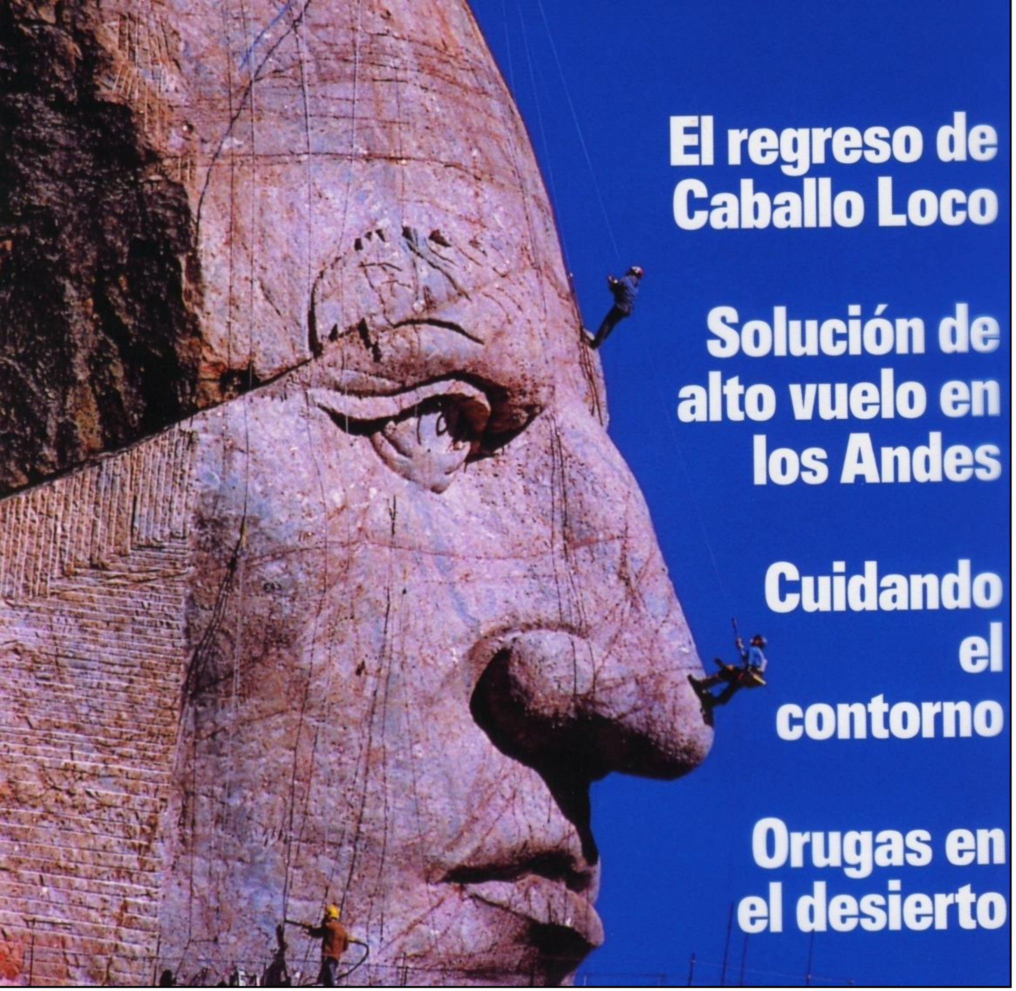
Four rock masses with successively reducing character: more joints, more weathering, lower UCS, more clay.

Low CC –shotcrete preferred

Low FC – bolting preferred







MINING AND CONSTRUCTION MAGAZINE

Picture of the mountain-side rock sculpture of the Indian chief 'Crazy Horse', in North Dakota, USA.

HIGH CC HIGH FC

$Q \approx 100/6 \times 4/0.75 \times 1/5$

(SRF = 5 due
to near-surface)

$CC \approx 100/6 \times 1/5 \times 150/100$
≈ 5 MPa

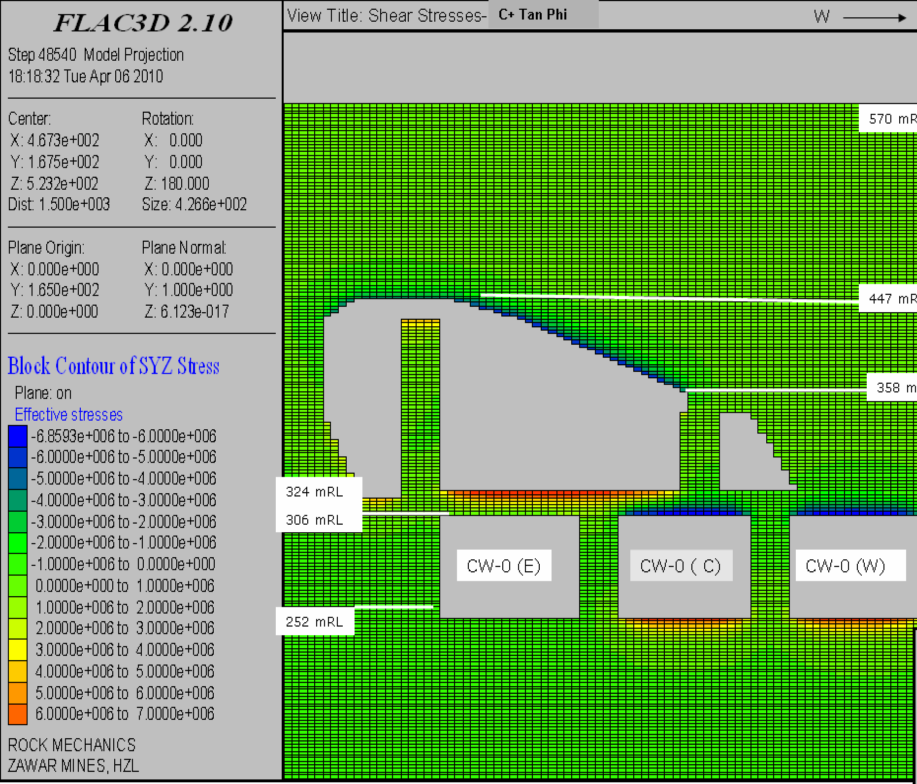
$FC \approx \tan^{-1} (4/0.75 \times 1/1)$
$\approx 79^{\circ}$

FLAC 3D

‘$c + \sigma_n \tan \phi$’ (left)

‘c *then* $\sigma_n \tan \phi$’ (below)

(Barton and Suneet Pandey, 2011)



FLAC3D 2.10

Step 48540 Model Projection
18:18:32 Tue Apr 06 2010

Center:
X: 4.673e+002
Y: 1.675e+002
Z: 5.232e+002
Dist: 1.500e+003

Rotation:
X: 0.000
Y: 0.000
Z: 180.000
Size: 4.266e+002

Plane Origin:
X: 0.000e+000
Y: 1.650e+002
Z: 0.000e+000

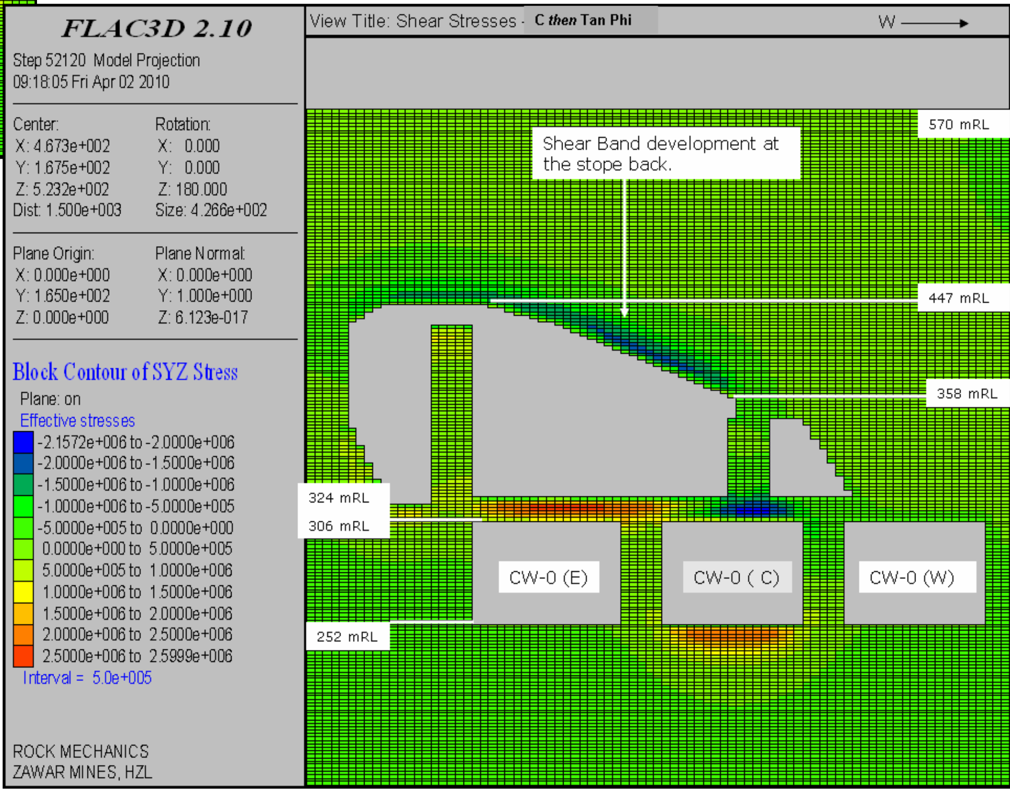
Plane Normal:
X: 0.000e+000
Y: 1.000e+000
Z: 6.123e-017

Block Contour of SYZ Stress
Plane: on
Effective stresses

- -6.8593e+006 to -6.0000e+006
- -6.0000e+006 to -5.0000e+006
- -5.0000e+006 to -4.0000e+006
- -4.0000e+006 to -3.0000e+006
- -3.0000e+006 to -2.0000e+006
- -2.0000e+006 to -1.0000e+006
- -1.0000e+006 to 0.0000e+000
- 0.0000e+000 to 1.0000e+006
- 1.0000e+006 to 2.0000e+006
- 2.0000e+006 to 3.0000e+006
- 3.0000e+006 to 4.0000e+006
- 4.0000e+006 to 5.0000e+006
- 5.0000e+006 to 6.0000e+006
- 6.0000e+006 to 7.0000e+006

ROCK MECHANICS
ZAWAR MINES, HZL

View Title: Shear Stresses- C+ Tan Phi



FLAC3D 2.10

Step 52120 Model Projection
09:18:05 Fri Apr 02 2010

Center:
X: 4.673e+002
Y: 1.675e+002
Z: 5.232e+002
Dist: 1.500e+003

Rotation:
X: 0.000
Y: 0.000
Z: 180.000
Size: 4.266e+002

Plane Origin:
X: 0.000e+000
Y: 1.650e+002
Z: 0.000e+000

Plane Normal:
X: 0.000e+000
Y: 1.000e+000
Z: 6.123e-017

Block Contour of SYZ Stress
Plane: on
Effective stresses

- -2.1572e+006 to -2.0000e+006
- -2.0000e+006 to -1.5000e+006
- -1.5000e+006 to -1.0000e+006
- -1.0000e+006 to -5.0000e+005
- -5.0000e+005 to 0.0000e+000
- 0.0000e+000 to 5.0000e+005
- 5.0000e+005 to 1.0000e+006
- 1.0000e+006 to 1.5000e+006
- 1.5000e+006 to 2.0000e+006
- 2.0000e+006 to 2.5000e+006
- 2.5000e+006 to 2.5999e+006

Interval = 5.0e+005

ROCK MECHANICS
ZAWAR MINES, HZL

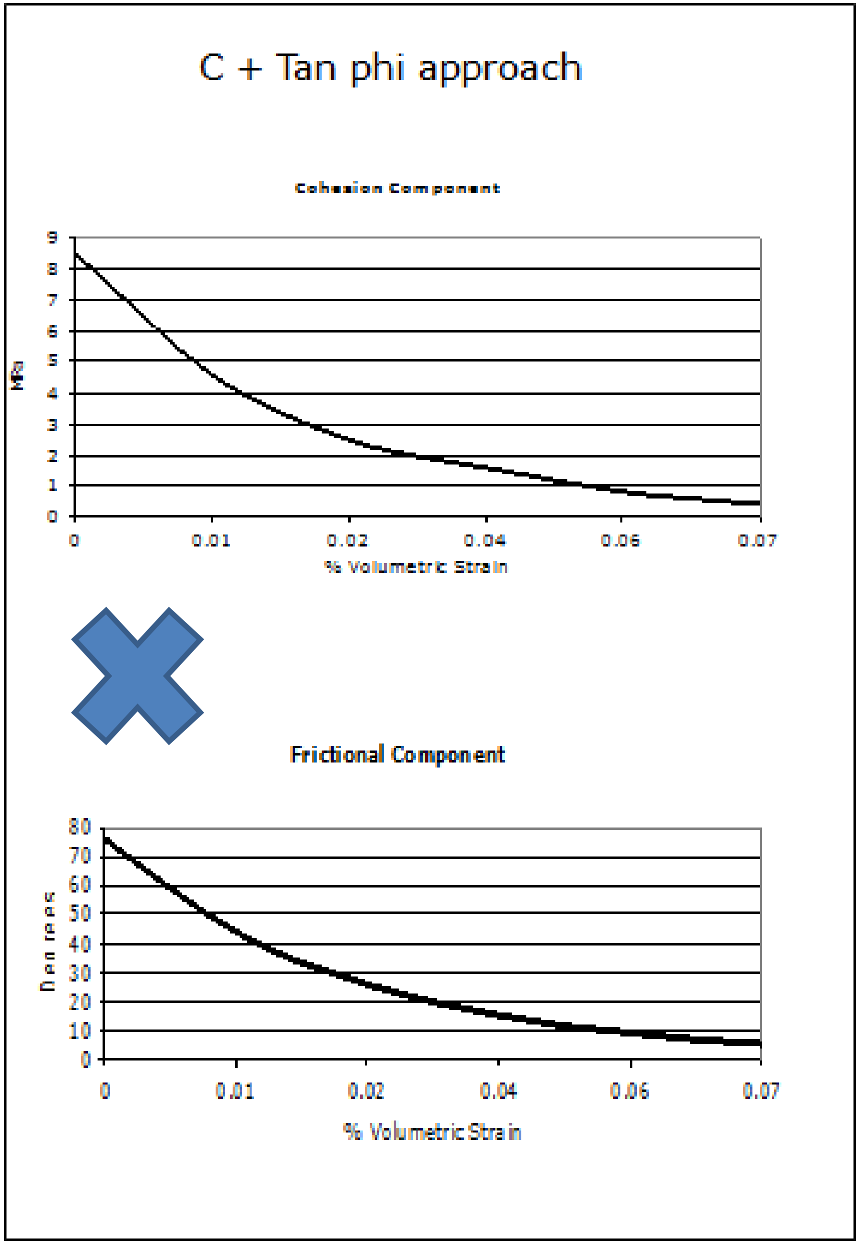
View Title: Shear Stresses - C *then* Tan Phi

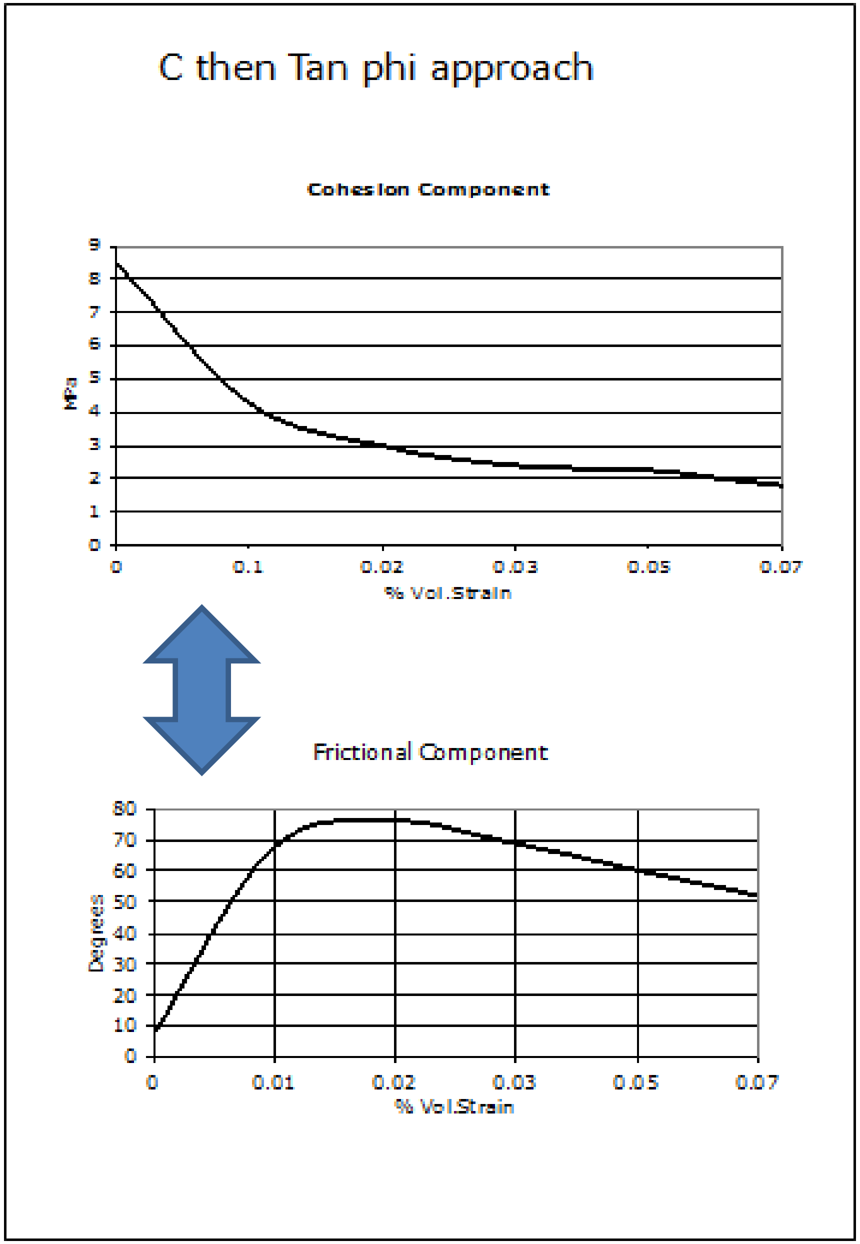
Shear Band development at the stope back.

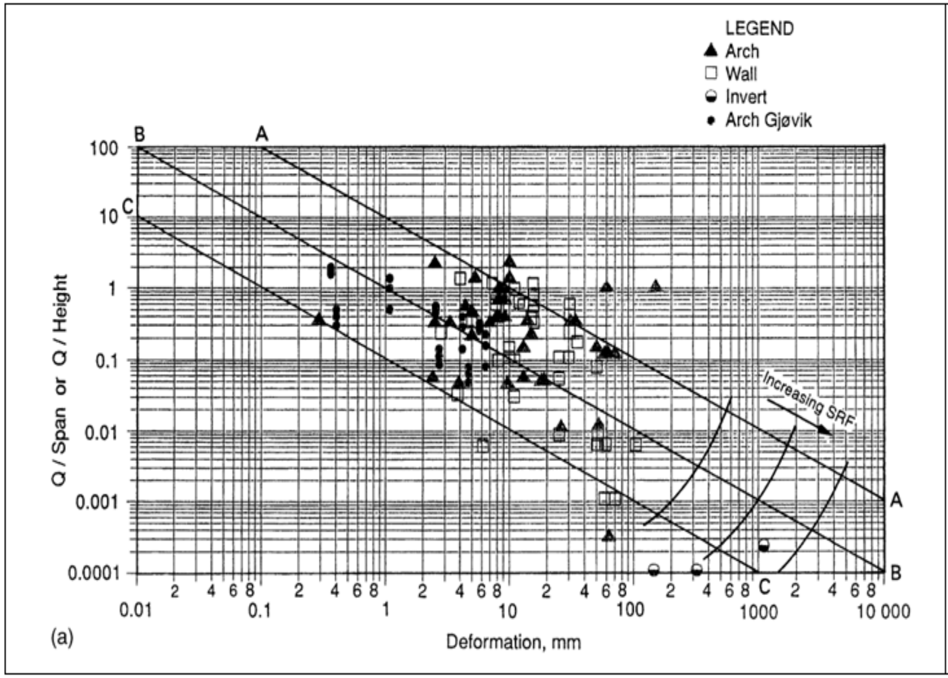
‘New’ approaches:

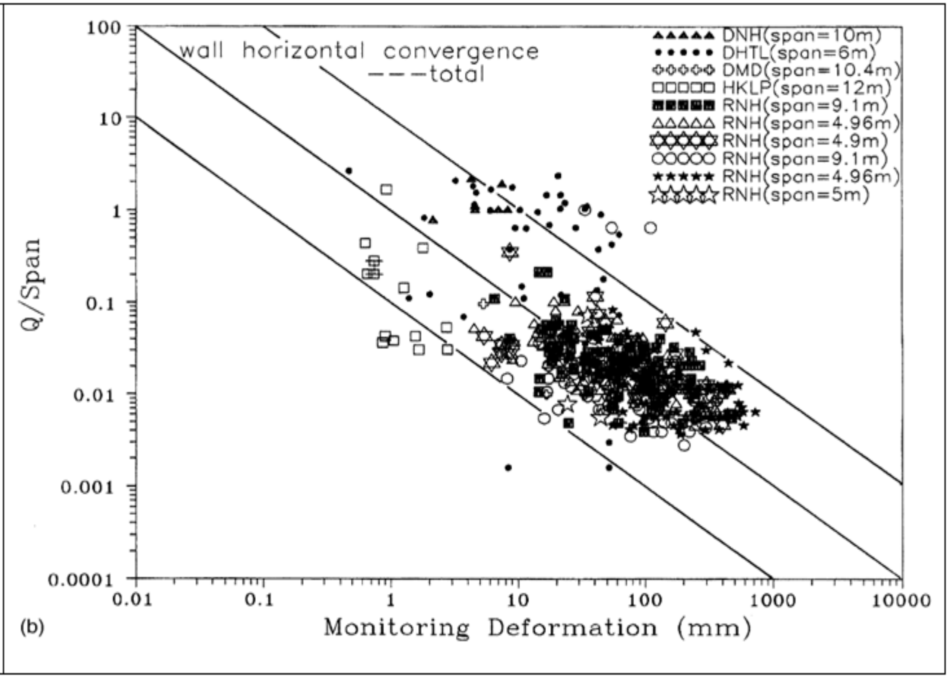
- ☐ **c *then* tan ϕ (not new, but rare!)**
- ☐ **Comparing modelled and measured displacements with pre-installed *MPBX*.**
- ☐ **Back-calculating Q from empirical Δ equations, as well as logged Q.**

‘c *then* $\sigma_n \tan\varphi$’ (as used in Barton and Pandey, 2011)









Original plotting method from Barton et al., 1994	*Data from Chen and Guo (priv. comm.)*

$\Delta = \frac{SPAN}{Q}$	(central trend of all data: approx)	$\Delta_v = \frac{SPAN}{100Q}\sqrt{\frac{\sigma_v}{\sigma_c}}$	(more accurate estimate)

NMT tunnel (= single-shell)

through pre-injected (10 MPa pressure) shales, limestones.