

THE NEXT HALF- CENTURY OF RQD FROM A DRILL-QUALITY AND *Q-SYSTEMS* PERSPECTIVE

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CONTENT

- Some words about Bieniawski
- RMR and Q have their differences, but NB-ZTB, 2008
- Some words about Deere
- In defence of RQD (contra Jv of Palmstrøm)
- Cecil (1970), RQD, number of joint sets in Q development
- Q-histograms and 'central place' of RQD
- Q_{TBM} Q_{slope} Q_{H2O} in brief (all contain RQD)
- RQD and Vp (Sjøgren et al. 1979)
- Competition for GSI ? (includes RQD)

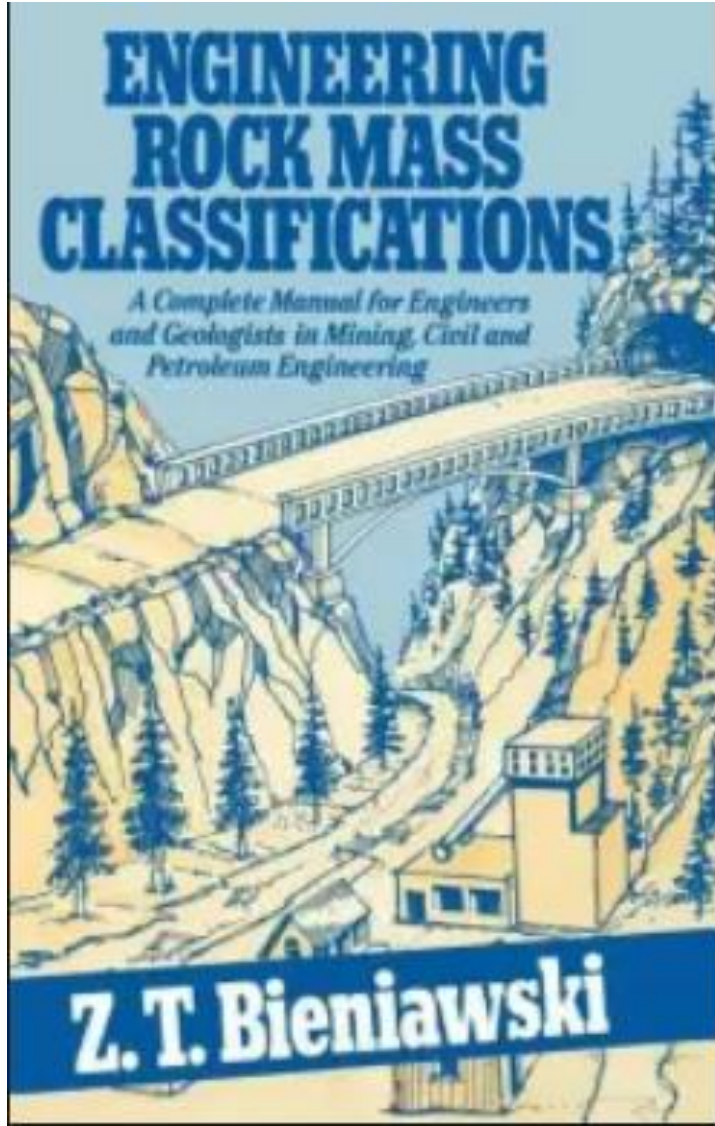
RMR and Q - Setting records straight

The RMR and Q rock mass classifications were independent developments in 1973 and 1974, whose common purpose was to quantify rock mass characteristics previously based on qualitative geological descriptions. They were originally developed for assisting with the rock engineering design of tunnels.

The value of thorough geological exploration was never disputed, indeed it was always emphasised. In addition, it was

After 35 years of use throughout the tunnelling world, the RMR and Q classifications have proved themselves on numerous projects. They still face misconceptions however, as reflected in recent articles in T&T International. Here, Nick Barton, of Nick Barton & Associates, Norway, and ZT Bieniawski, of Bieniawski Design Enterprises, USA, clear common misunderstandings and provide the “ten commandments” for proper use of these rock mass classification systems

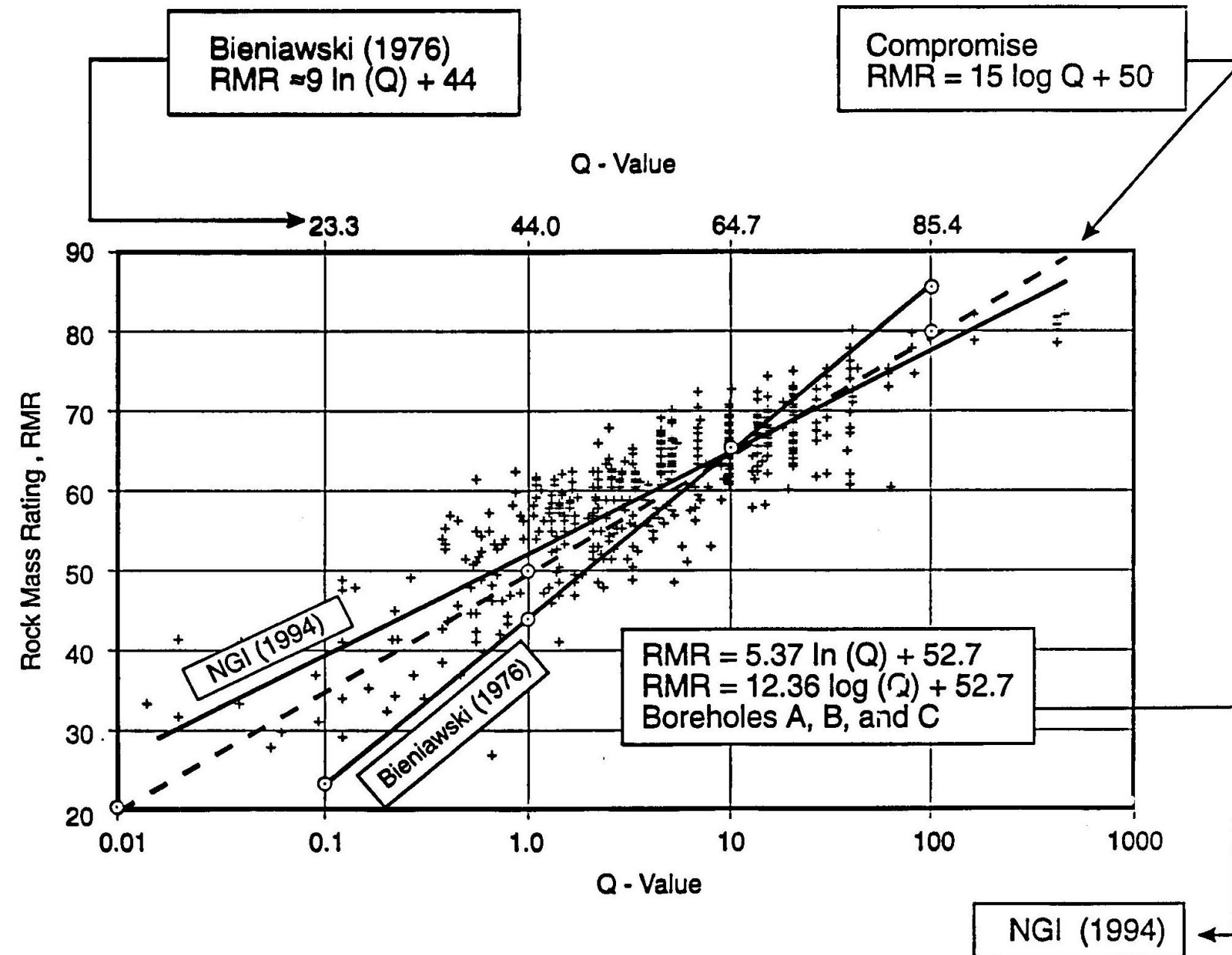
- A 2008 cooperation with Dick Bieniawski – finally! Mainly to address misplaced critical discussion from ‘beam-theorist’ Pells in Australia, and from Schubert/Reidmuller of Austria (as told in Goodman TTI article) about rock mass classification for tunnels.
- **A 2016 article in a Canadian journal by the same Pells of Australia has proposed ‘putting RQD to rest’.**
- In fact these authors, which strangely had Bieniawski as a co-author, **recommended using GSI to estimate RQD.** This really does not sound like Bieniawski!



‘For Q-system see Bieniawski, 1989’....! (Hudson and Harrison)

ALSO - A FOND MEMORY OF DICK – FROM ISTANBUL..... ‘close encounter of the third kind’ with a belly-dancer!

And from TEHRAN (ARMS)... ‘this is the last lecture of my career’ (2008).....thanks to the Brazilians and ITA it was not!

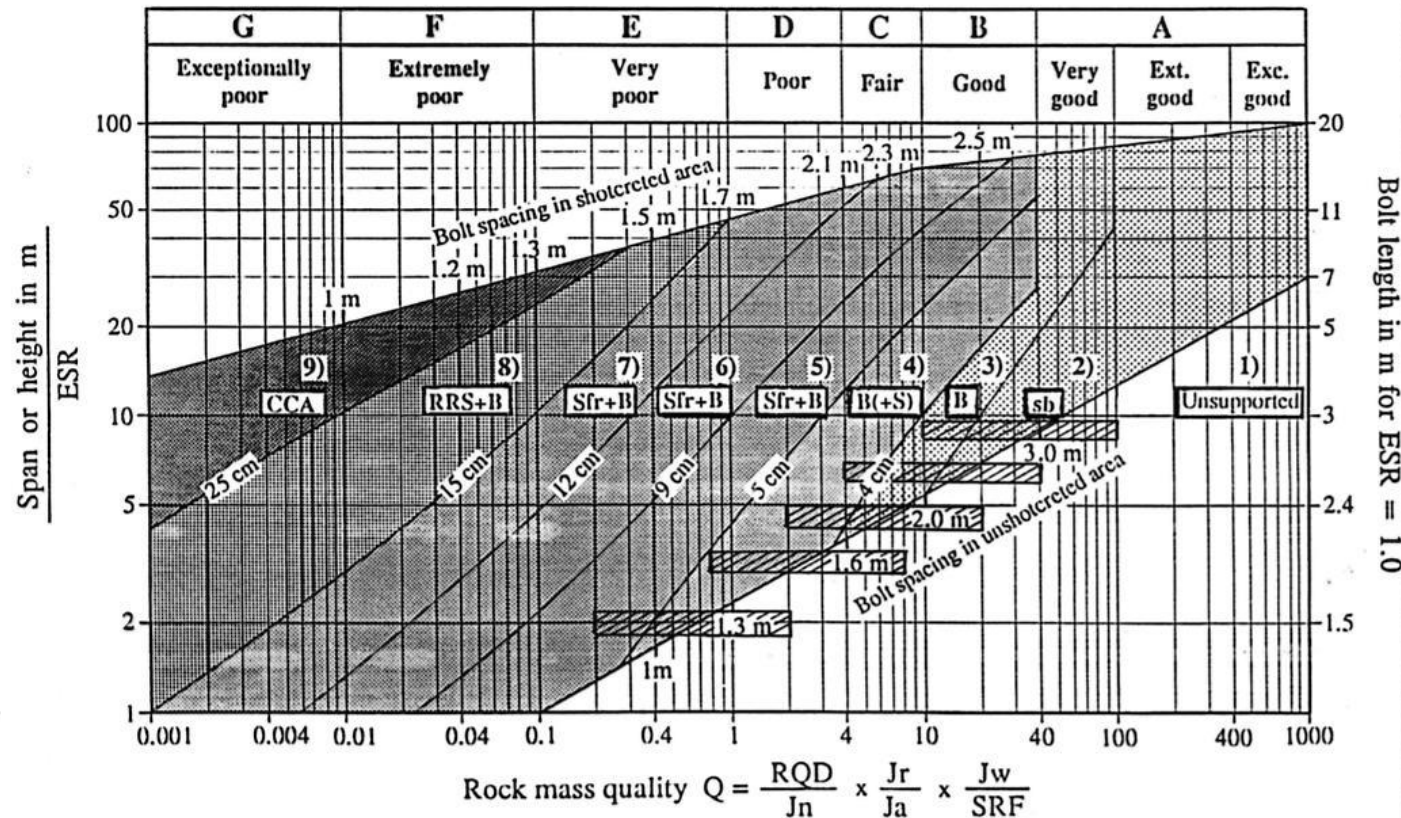


‘Proof’ that RMR and Q are different, though may ‘correlate’ in central areas of quality.

$$\text{RMR} \approx 9 \ln Q + 44 \quad (\text{Bieniawski, 1989}) \quad Q \approx e^{\frac{(\text{RMR}-44)}{9}} \quad [1]$$

$$\text{RMR} \approx 15 \log Q + 50 \quad (\text{Barton, 1995}) \quad Q \approx 10^{\frac{(\text{RMR}-50)}{15}} \quad [2]$$

[1] RMR ≈ -182	2.6	23.3	44	56.5	64.7	77.2	85.4	97.9	106.2
[2] RMR ≈ 5	V	IV	III	II	I				
	20	35	50	59	65	74	80	89	95



These two equations (there are dozens) are in 'good agreement' when $\text{RMR}_{89} = 65$, and $Q = 10$.

Maybe avoidance of zero and negative RMR is a good reason for choosing the \log_{10} version?

The Rock Quality Designation (RQD) Index in Practice

REFERENCE: Deere, D. U. and Deere, D. W., "The Rock Quality Designation (RQD) Index in Practice," *Rock Classification Systems for Engineering Purposes*, ASTM STP 984, Louis Kirkaldie, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 91-101.

ABSTRACT: The Rock Quality Designation (RQD) index was introduced 20 years ago at a time when rock quality information was usually available only from geologists' descriptions and the percent of core recovery. The RQD is a modified core recovery percentage in which unrecovered core, fragments and small pieces of rock, and altered rock are not counted so as to downgrade the quality designation of rock containing these features. Although originally developed for predicting tunneling conditions and support requirements, its application was extended to correlation with *in situ* rock mechanical properties and, in the 1970s, to forming a basic element of several classification systems. Its greatest value, however, remains as an exploratory tool where it serves as a red flag to identify low-RQD zones which deserve greater scrutiny and which may require additional borings or other exploratory work. Case history experience shows that the RQD red flag and subsequent investigations often have resulted in the deepening of foundation levels and the reorientation or complete relocation of proposed engineering structures, including dam foundations, tunnel portals, underground caverns, and power facilities.

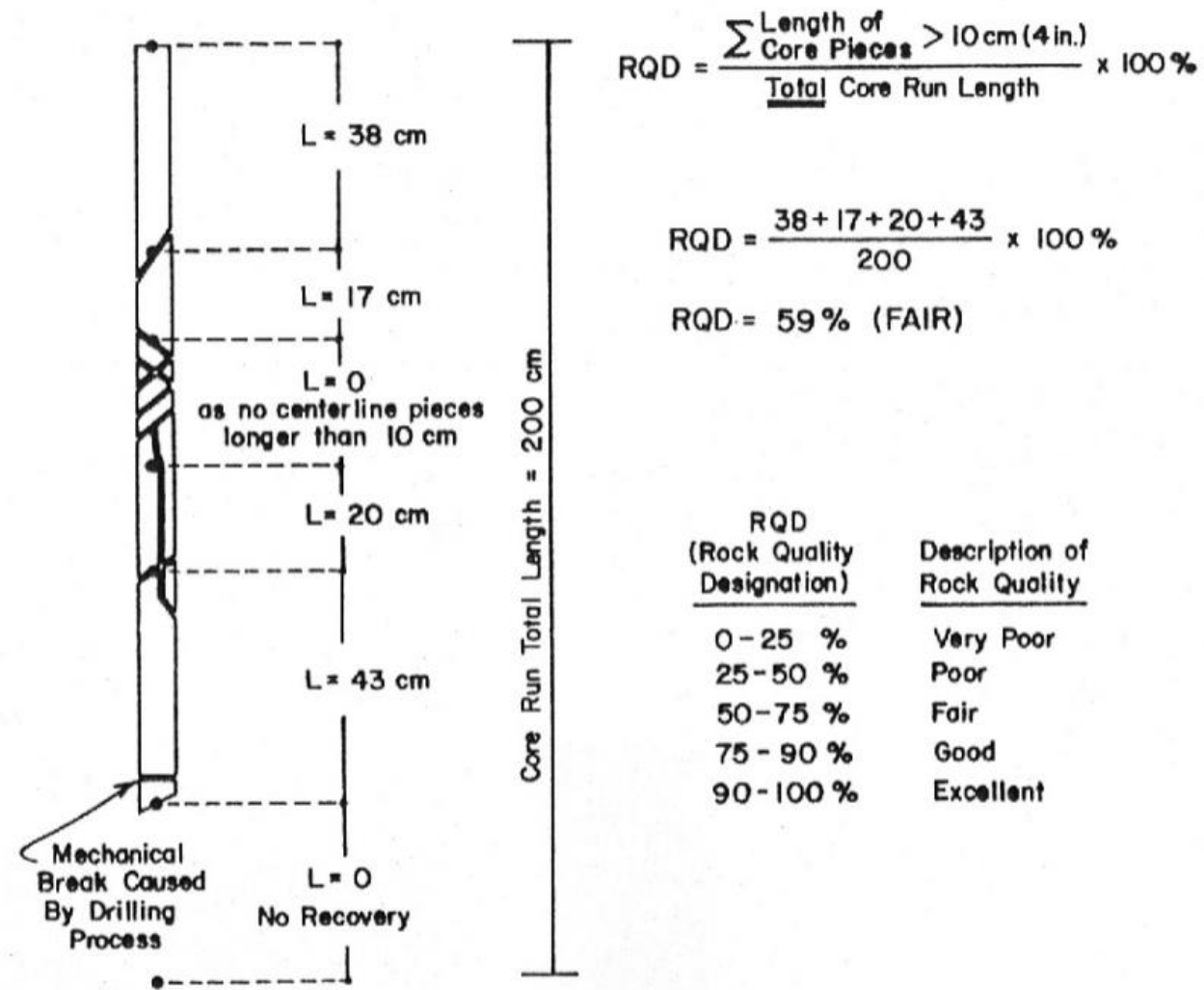
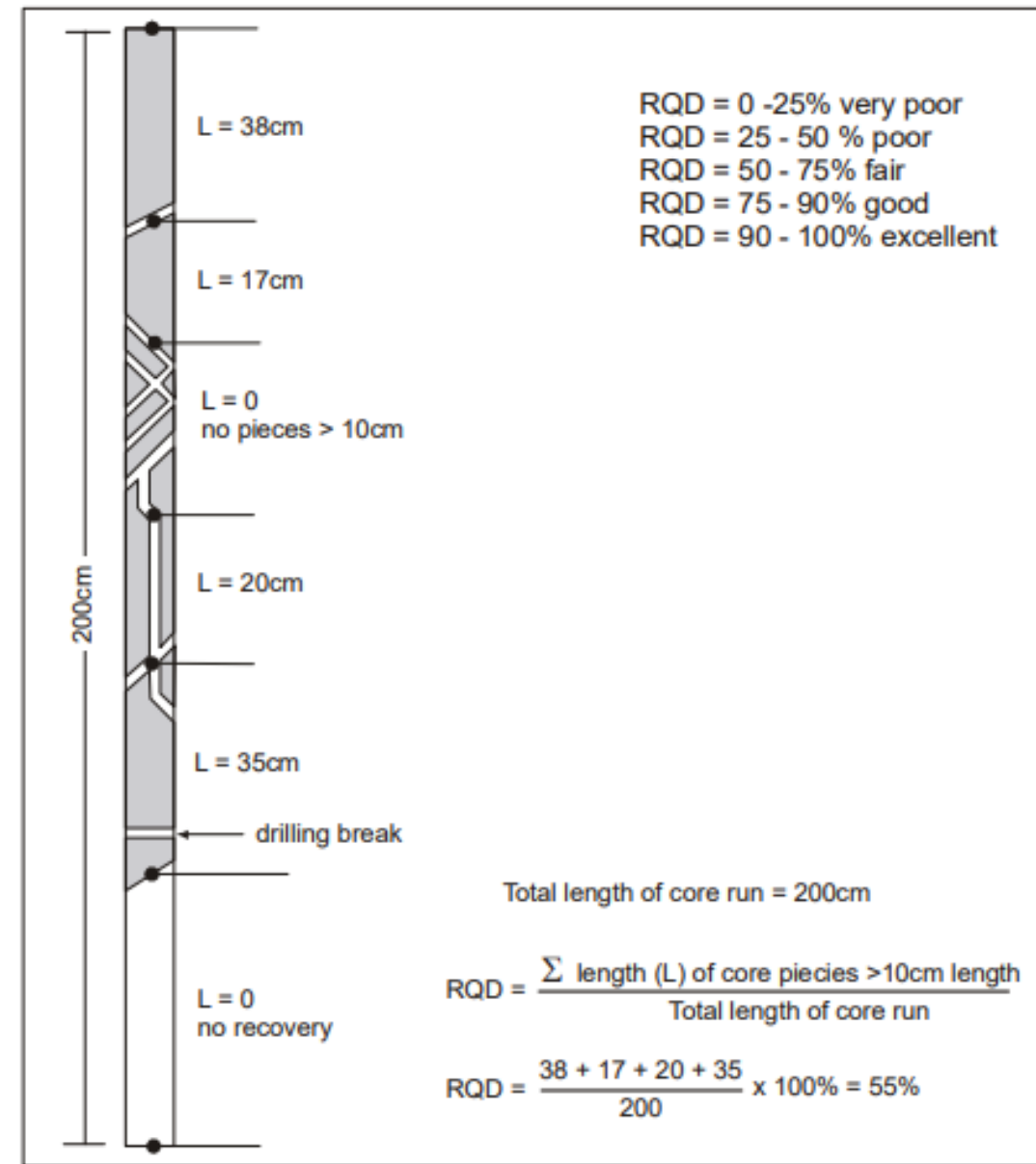


FIG. 1—Procedure for measurement and calculation of RQD.



Redrawn in Palmstrøm, 2005

From Deere and Deere, 1988

for measuring RQD is illustrated in Fig. 1. The RQD index is an index of rock quality in that problematic rock that is highly weathered, soft, fractured, sheared, and jointed is counted against the rock mass. Thus it is simply a measurement of the percentage of “good” rock recovered from an interval of a borehole.

‘counted against’.....i.e. *discounted*

‘serves as a red flag to identify low RQD zones
which deserve greater scrutiny’



Do not
penalise a
core
because it
has a
parallel
joint
causing
break-up



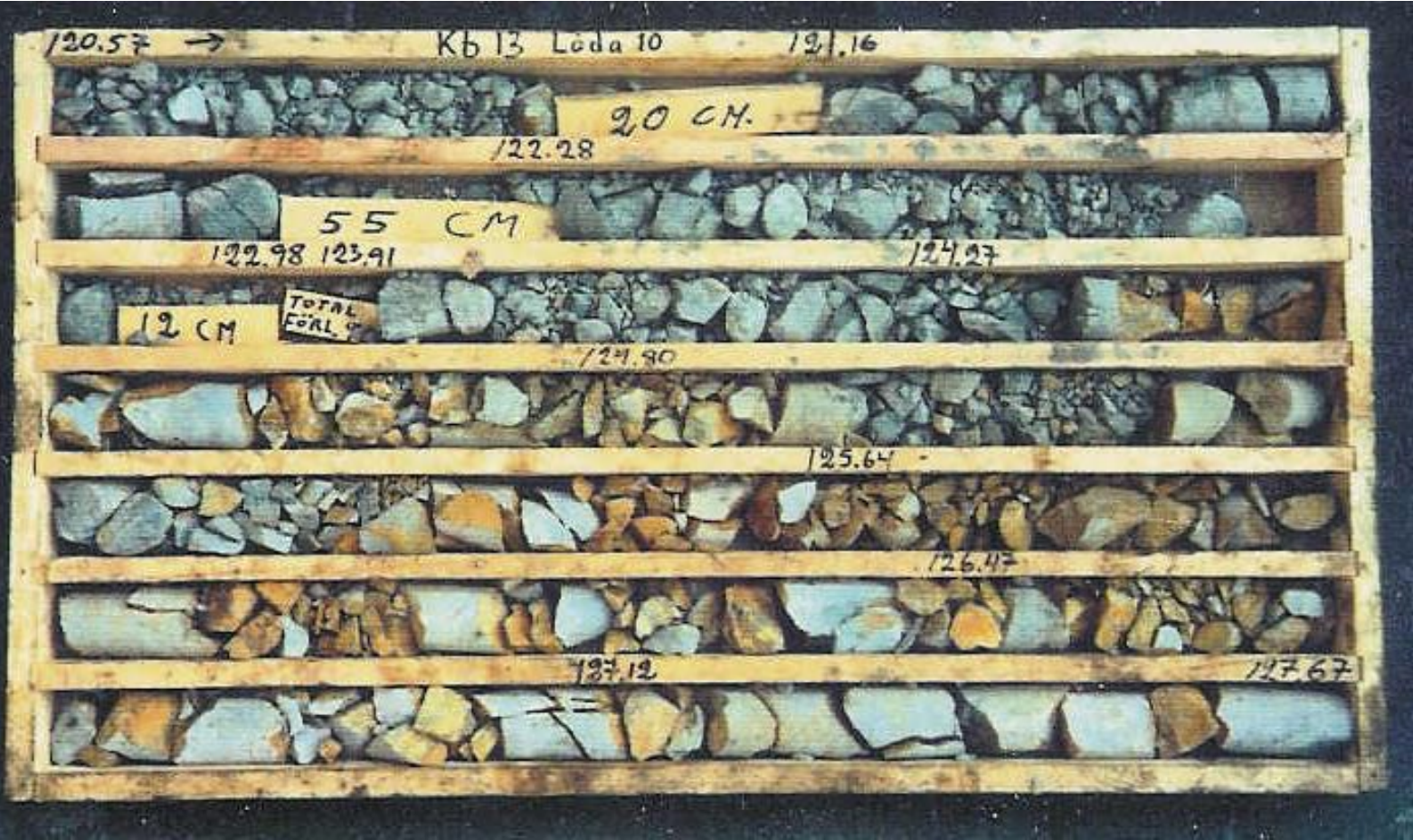
107m (with another core box) of definitively zero RQD.

Maybe:

$$Q = 10/20 \times 1/4 \times 0.5/5 \approx 0.01$$



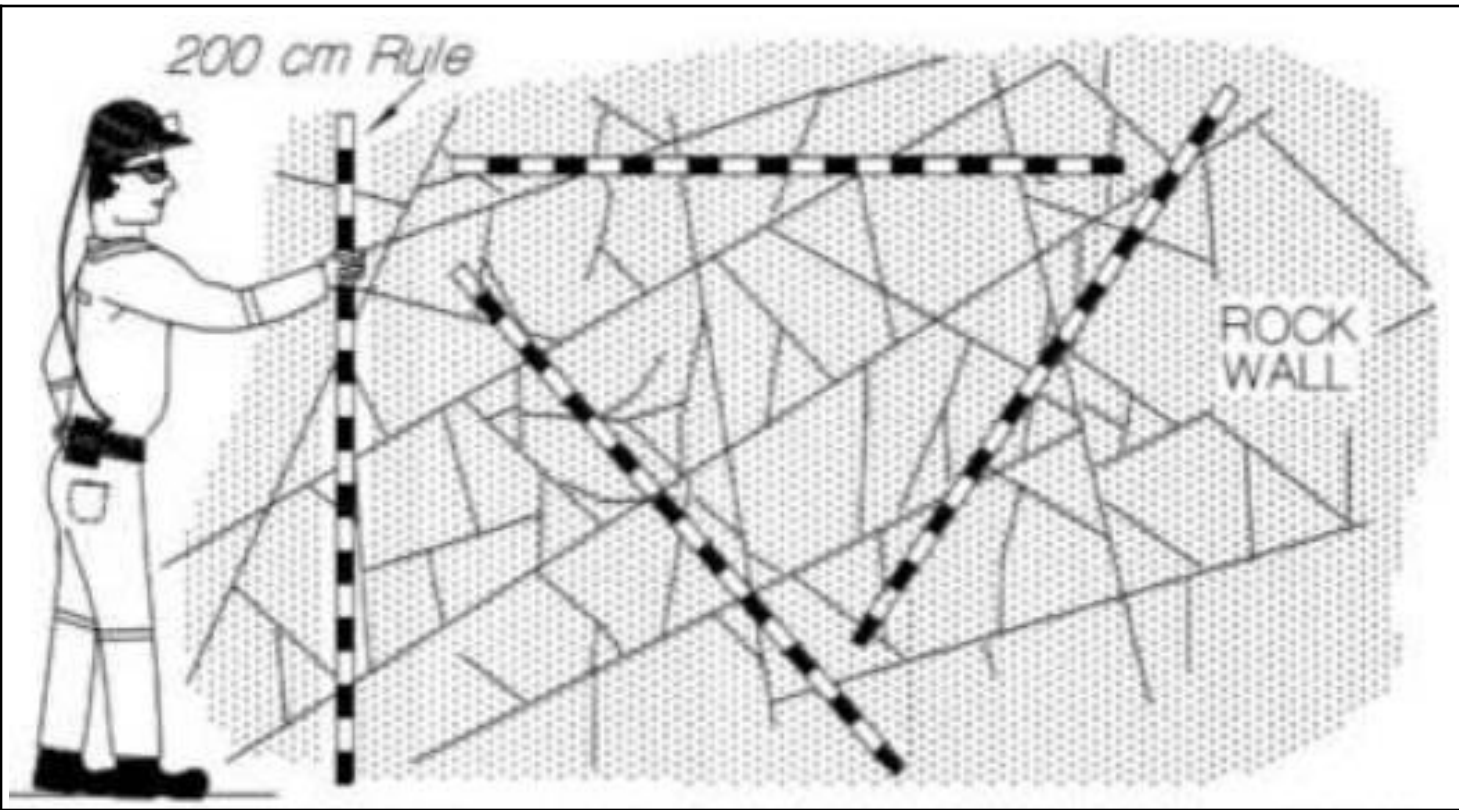




$RQD = 0 \text{ or } 100\%$

(the '100' value is a nice demonstration of the importance of hole orientationactually three joint sets in this Hong Kong granite)

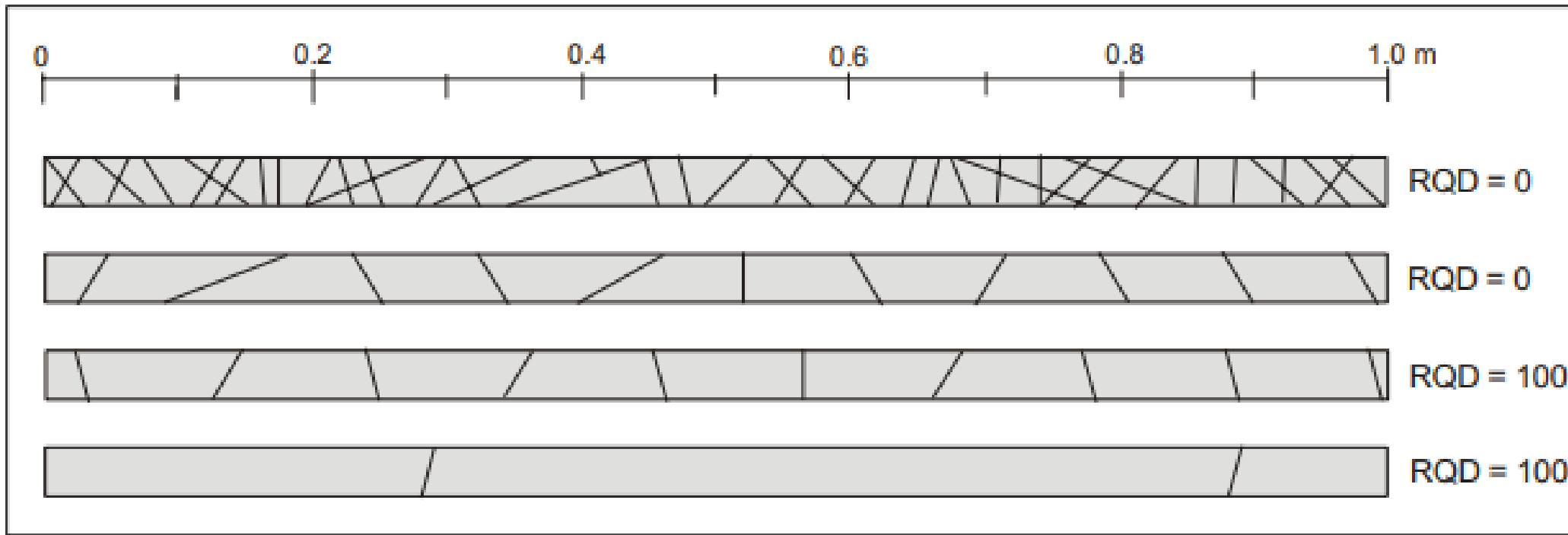




YouTube
figure

'Take RQD_w as the average of many measurements'

(OR WE CAN UTILIZE RQD AS AN ANISOTROPIC PARAMETER)



Palmstrøm, 2001....CRITIQUE OF RQDALSO AS A WAY OF SUPPORTING HIS J_v

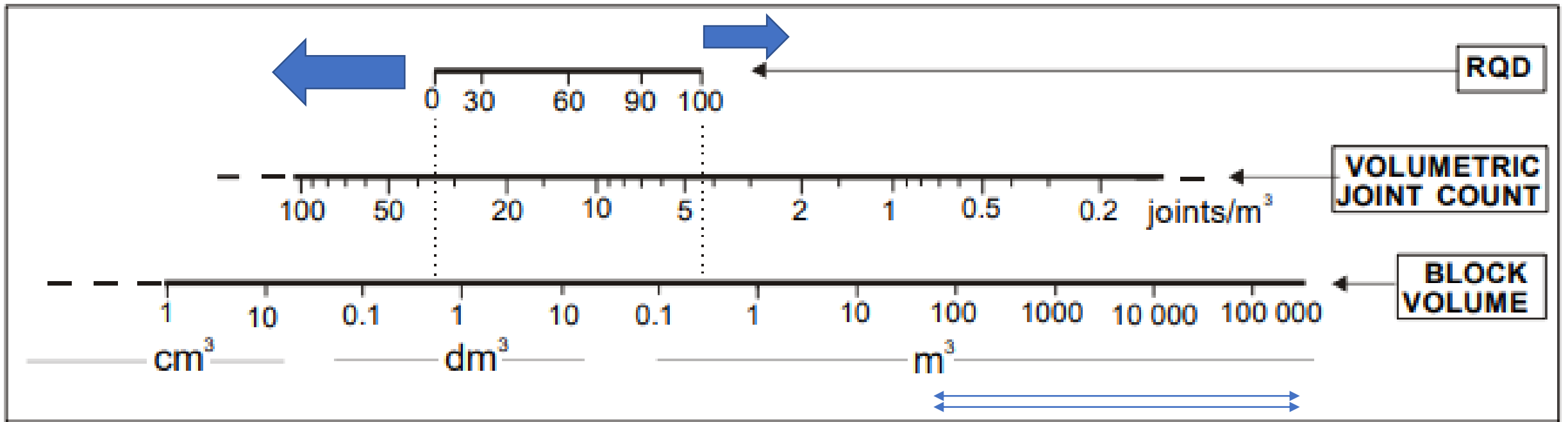
$$10/15 \times 1/2 \times 0.5/2.5 = 0.07$$

$$10/9 \times 1.5/1 \times 0.66/1 = 1.1$$

$$100/6 \times 1.5/1 \times 1/1 = 10$$

$$100/2 \times 2/1 \times 1/1 = 100$$

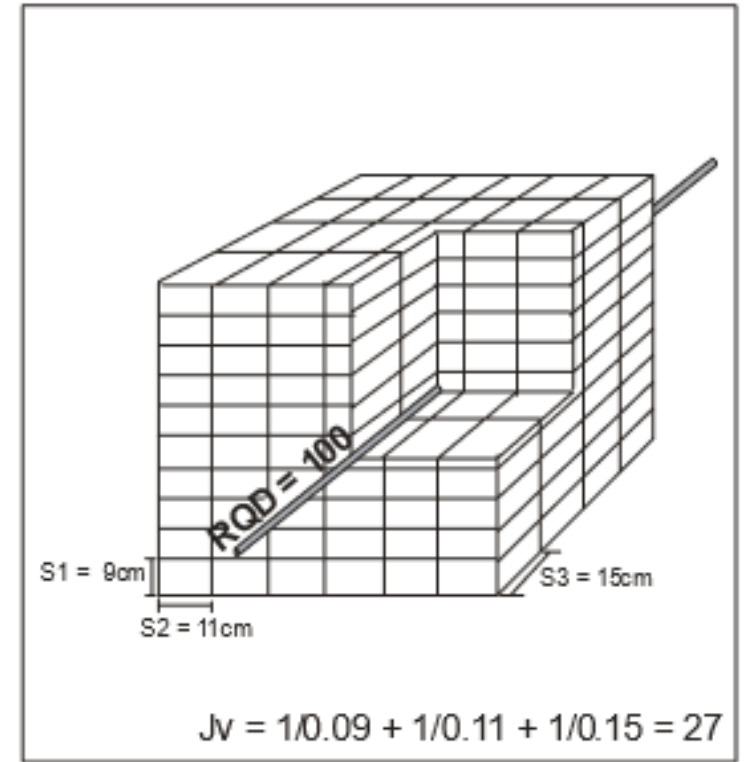
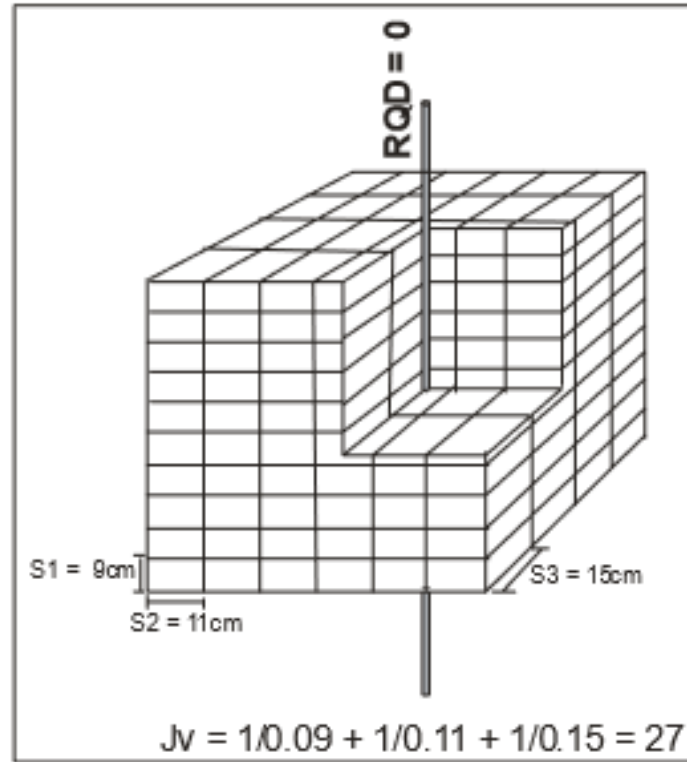
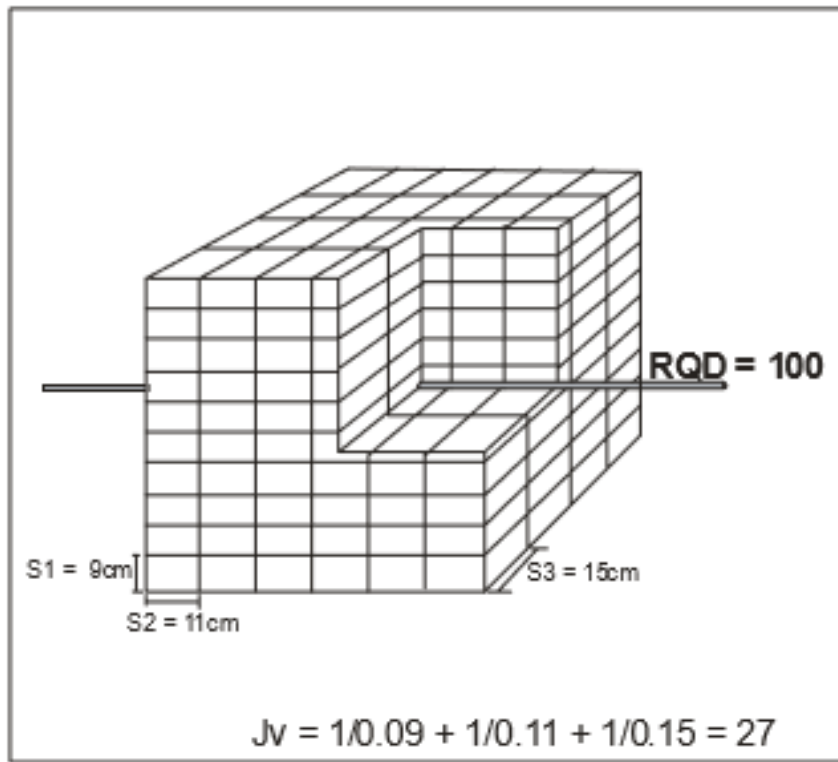
POSSIBLE Q-VALUE
ESTIMATES



**WHO IS INTERESTED IN ROCK
THAT IS THIS MASSIVE?**

Palmstrøm, 2001 critique of RQD. Due to his ignoring the number of joints in different orientations, his poor opinion of RQD is misplaced.

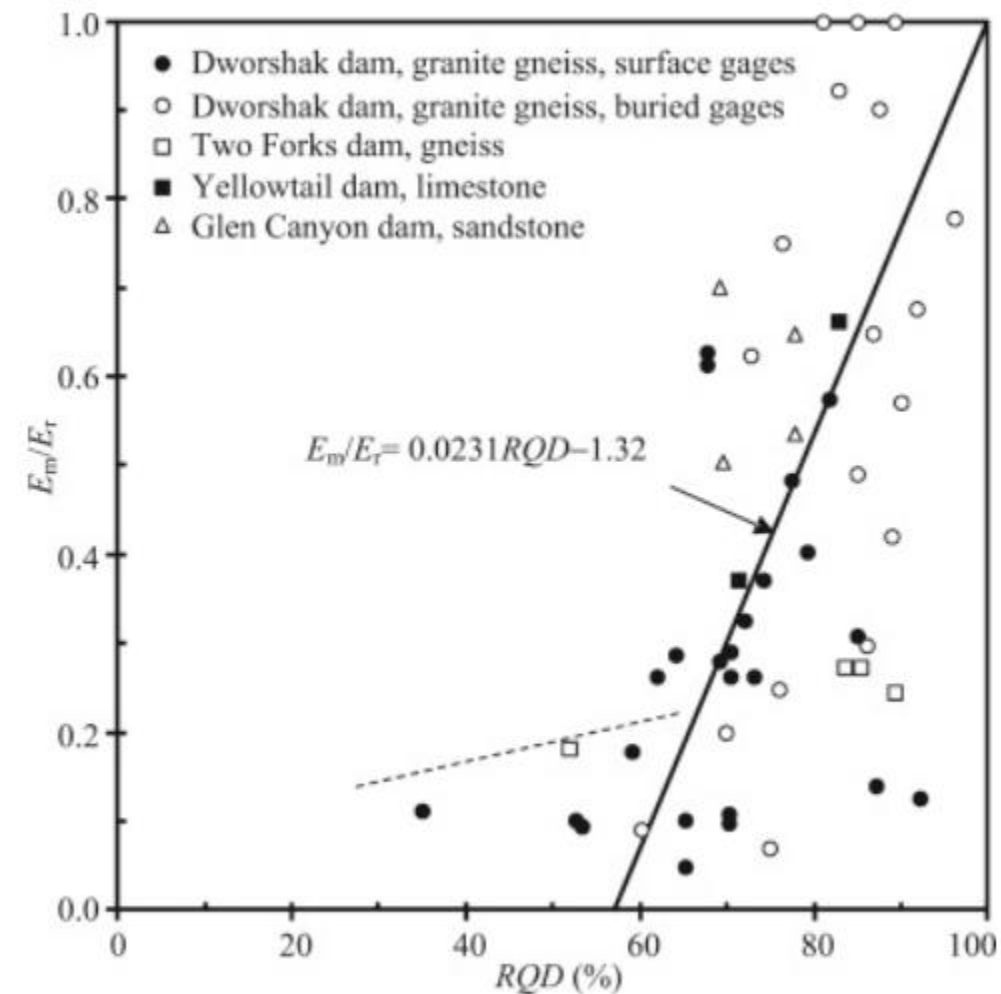
(Is his focus on dimension-stone quarries? where 10m joint spacing is so liked?)



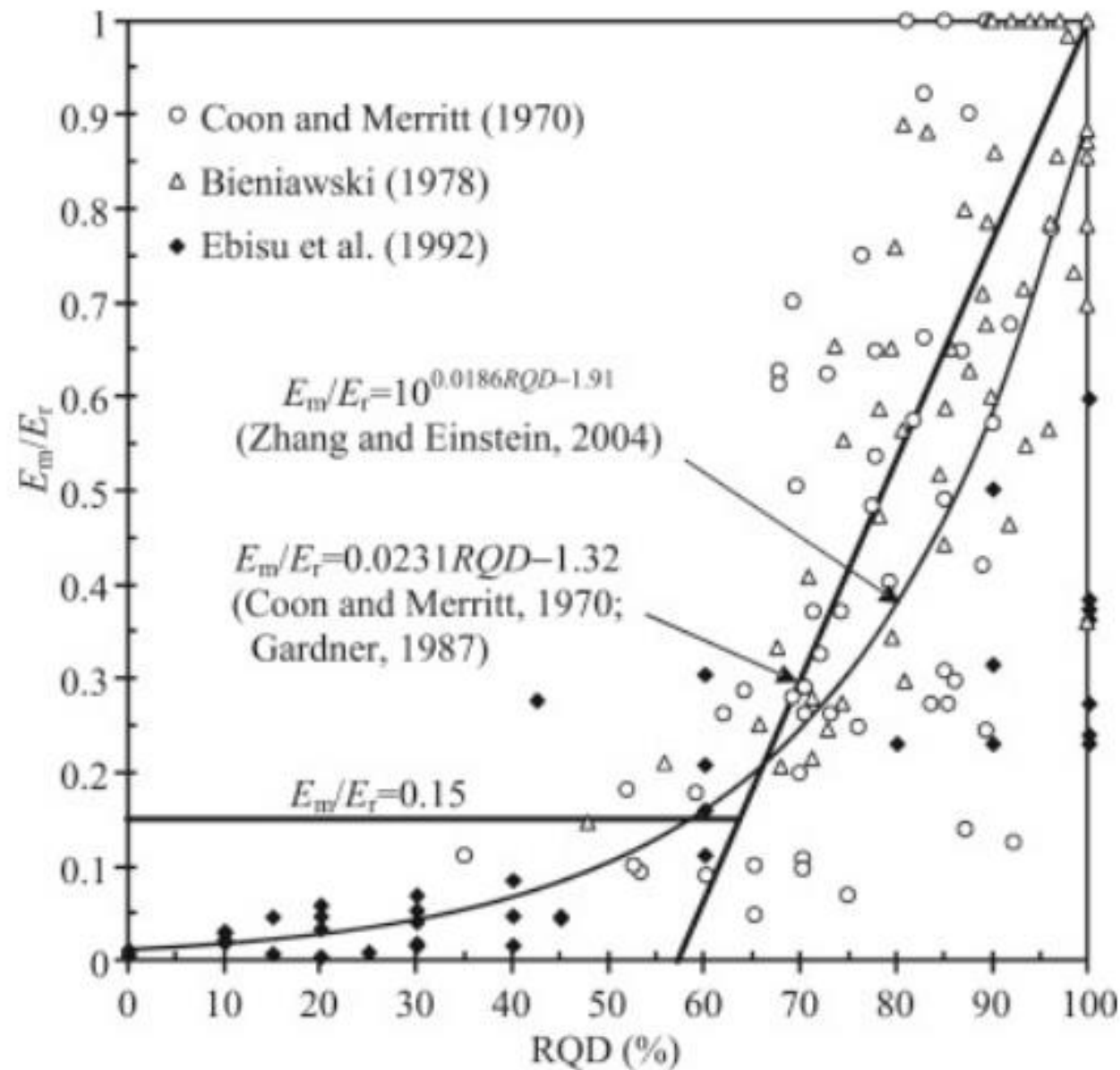
- Another Palmstrøm, 2005 attempt to discredit RQD, and promote his volumetric joint count J_v – which was referenced/supported in Barton et al. 1974.
- Rock masses are seldom so uniform (unless sedimentary).....but treating RQD as an anisotropic parameter has ADVANTAGES compared to J_v ! (For instance, use of tunnel-oriented **RQD_o** is recommended in **Q_{TBM}** prognosis method – where it is essential).

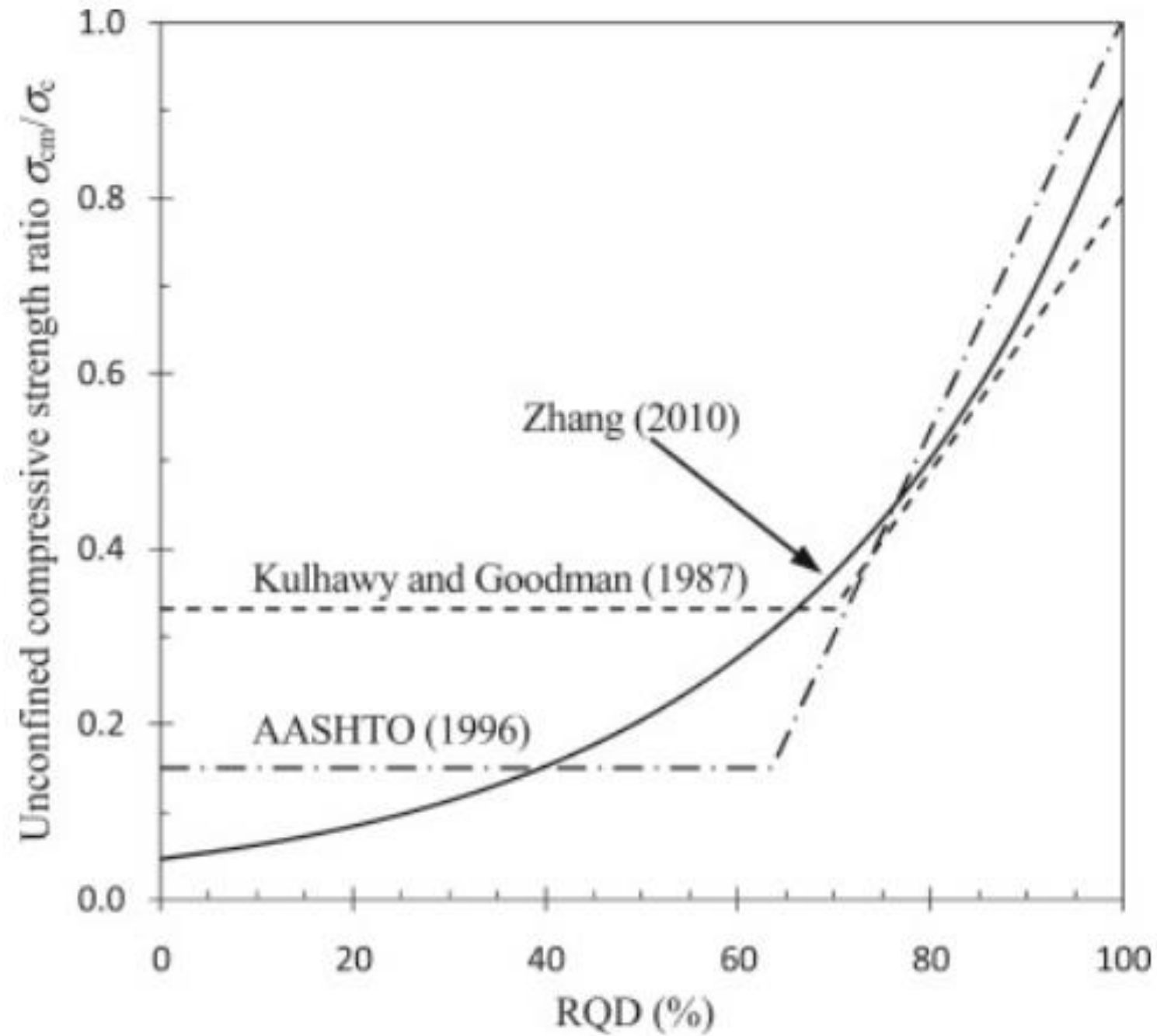
SOME SUGGESTED CORRELATIONS OF RQD
with rock mass deformation modulus
and strength

Zhang and Einstein, 2004



Coon and Merritt, 1970





Zhang, 2010

σ_{cm}/σ_c

DEVELOPMENT OF THE Q-SYSTEM IN 1973

NB was/is INDEBTED TO ONE OF DEERE'S
PH.D. STUDENTS: CECIL, 1970 – for
approx. 90 Norwegian and Swedish case
records.....
AND CECIL'S EMPHASIS THAT *NUMBER
OF JOINT SETS* WAS IMPORTANT....not
just his professor's RQD!

Cecil, 1970 case records

(this selection reproduced in Barton, Lien, Lunde, 1974)

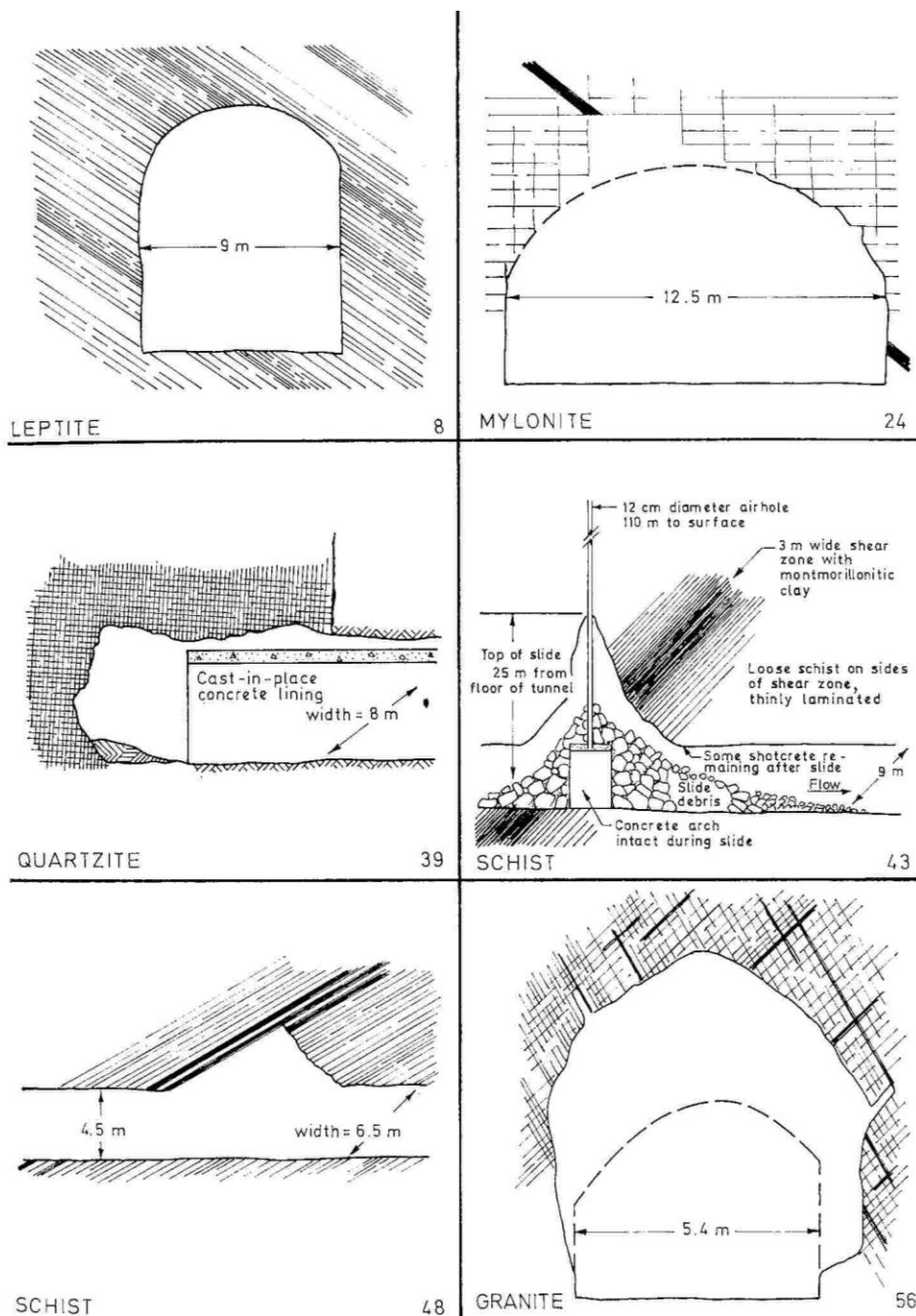
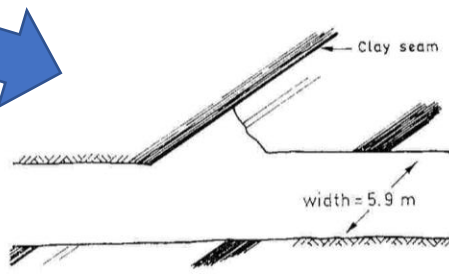
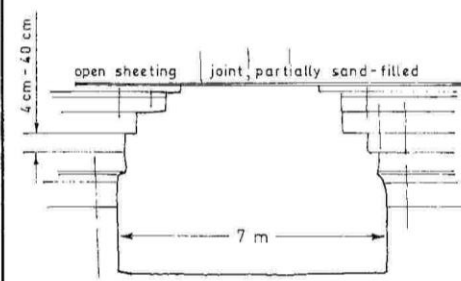


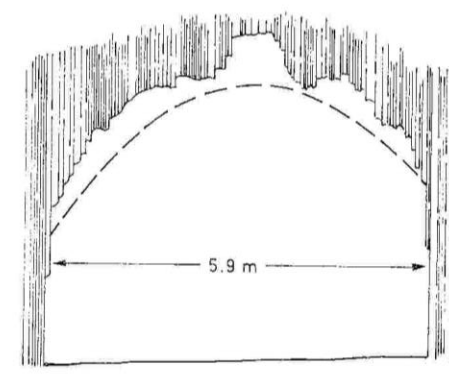
Fig. 7. Sketches of the six case records described in Table 8, after Cecil (1970)



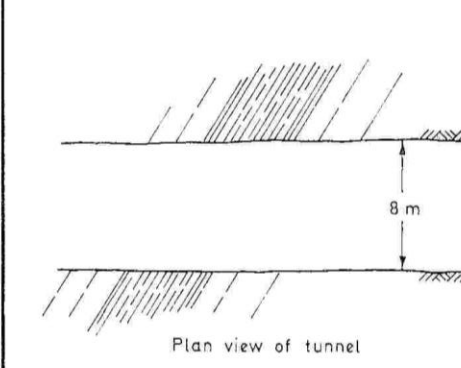
GRANITE 60



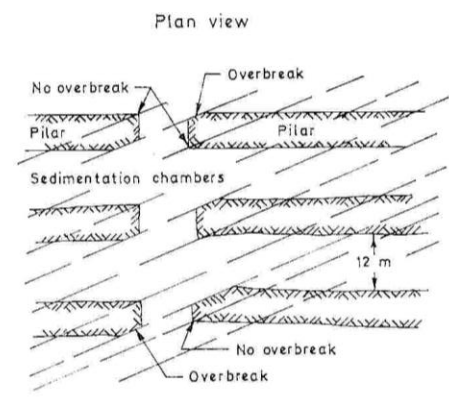
GRANITE 66



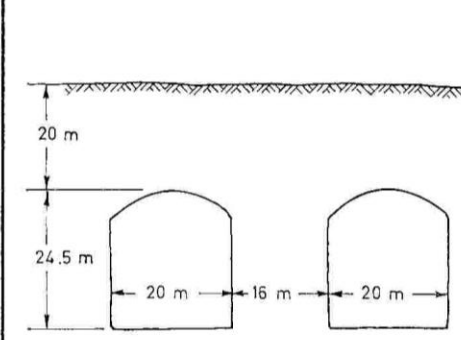
SCHISTOSE METAGREYWACKE 67



GRANITE 70



GRANITE 74, 75



GNEISS 77

Cecil, 1970 case records

(this selection reproduced in Barton, Lien, Lunde, 1974)

Fig. 8. Sketches of the six case records described in Table 9, after Cecil (1970)

Case No.	1. DESCRIPTION OF ROCK MASS	SPAN m	Height m	Depth m	Support used	RQD J _n	J _r J _a	J _w SRF	Q	ESR	SPAN/ ESR m	Roof Support Recommendation
8	1. 50 m length of closely spaced, tight diagonal joints in leptyte. Planar, smooth joints. 1 joint set, 5–30 cm, spacing. No water present. 2. Minor overbreak when blasting. 3. Tailrace tunnel, Seitevare Hydro, N. Sweden (ref. Cecil 1970).	9	9	140	None	70 2	1.0 1.0	1.0 1.0				Category 0
24	1. 60 m length, including a 1 m wide shear zone in mylonite. Crushed mylonite and non-softening clay seams and joint fillings. Intersecting joint set. 2 joint sets plus random, 5–30 cm spacing. Minor water inflows (<31/min). 2. Wedge shaped roof fall. 3. Headrace tunnel, Vietas Hydro, N. Sweden (ref. Cecil 1970).	12.5	6.5	60	Rock bolts, wire mesh and shotcrete	60 6	1.0 6	1.0 2.5		35 1.6 5.6		Category 22 = B 1 m + S (mr) 2.5–5 cm
39	1. 50 m length, shear zone in quartzite, "sugar cube" rock structure. Planar, smooth, unaltered joints. 3 joint sets, <5 cm, spacing. 5–10 l/min water inflow. 2. Major roof falls, progressive formation of dome- and vault-shaped crown. Also falls from the face. 3. Headrace tunnel, Rendal Hydro, Norway (ref. Cecil 1970).	8	6	200	Cast concrete arch, immediately after mucking out	20 15	1.0 1.0	0.66 5		1.3 1.6 7.8		Category 31 = CCA 20–30cm + B 1 m
43	1. 25 m length, 3 m wide shear zone in thinly laminated schist, swelling montmorillonitic clay seam in shear zone, some chlorite joint coatings. Planar slickensided joint walls. 1 joint set, 5–30 cm spacing. Ground water seepage along cased de-air hole may have contributed to swelling process. 2. Complete collapse of tunnel during operation of power plant. Vault-shaped crown opening. 3. Tailrace tunnel, Sällsjö Hydro, N. Sweden (ref. Cecil 1970).	9	8	110	Original 6–8 cm shotcrete failed. Permanent support after failure with cast concrete arches	20 2	0.5 12	1.0 2.5		0.18 1.6 5.0		Category 31 = CCA (sr) 30 cm + B 1 m
48	1. 15 m length, overthrust shear zone in schist, in which there was a 3 cm thick clay (non softening) and graphite seam. Shear zone was 50–100 cm wide and contained smooth, slickensided graphite-coated joint surfaces, 1 joint set, 5–30 cm spacing. Insignificant water inflow. 2. Wedge-shaped roof fall. 3. Tailrace tunnel, Bergvattnet Hydro, N. Sweden (ref. Cecil 1970).	6.5	4.5	50	Rock bolts, wire mesh and two shotcrete applications	10 2	1.0 10	1.0 5		0.17 1.6 5.6		Category 31 = B 1 m + S (mr) 5 cm
56	1. 20 m length, 10 m wide vertical shear zone in granite. Rock crushed and frequently altered to earthy-gravel. Some remnant joint surfaces coated with clay (non-softening). Rock adjacent to zone blocky and loose. Irregular slickensided joint surfaces, 5–30 cm spacing. Large water inflows after blasting carried fault zone debris into tunnel, left open voids up to 1 m wide. Note: Tunnel located within 10 km of a major overthrust sheet, locally vertical and low angle shear zones occur. 2. Progressive roof fall-out to form a large vault-shaped opening. 3. Headrace tunnel, Stensjöfallet Hydro, N. Sweden (ref. Cecil 1970).	5.9	4.3	100	No support immediately after blasting. Eventually two shotcrete applications	10 20	1.5 6	0.33 2.5		0.10 1.6 4.1		Category 34 = S (mr) 7.5 cm

Note: Right-hand column "Roof Support Recommendation" is obtained from Tables 11, 12, 13, and 14

Key: S = shotcrete, B = systematic bolting, sb = spot bolting, CCA = cast concrete arches, mr = mesh reinforced, sr = steel reinforced, clm = chain link mesh.

Bolt spacing is given in metres. — Shotcrete or concrete thickness is given in centimeters.

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Case No.	1. DESCRIPTION OF ROCK MASS	SPAN m	Height m	Depth m	Support used	RQD J _n	J _r J _a	J _w SRF	Q	ESR	SPAN/ ESR m	Roof support recommendation
60	1. 20 m length, 1 m wide zone of sheared granite with clay seams (non-softening) slide boundary is a thin (<1 cm) clay seam and thinly sheared material that lie in contact with massive rock. Planar, slickensided joints. 1 joint set, 5–30 cm spacing. Insignificant inflow of water. See note, case 56. 2. Wedge-shaped roof fall. 3. Headrace tunnel, Stensjöfallet Hydro, N. Sweden (ref. Cecil 1970).	5.9	4.3	85	Rock bolts, and shotcrete	80 2	0.5 6	1.0 2.5				Category 21 = B 1 m + S 2.5 cm
66	1. 80 m length, open horizontal sheeting joints in granite, partially filled with sand sized material. Planar, rough surfaced joints. 2 joint sets, 5–30 cm spacing. Insignificant water inflow. See note, case 56. 2. Overbreak above springline. 3. Access tunnel, Stensjöfallet Hydro, N. Sweden (ref. Cecil 1970).	7	4.5	15–20	Rock bolts and shotcrete	70 4	1.5 2	1.0 5		1.3 1.6 3.7		Category 21 = B 1 m + S 2.5 cm
67	1. 50 m length, close vertical jointing cutting across schistose rock structure in schistose metagreywacke. Sandy, gravelly joint fillings. Planar smooth surface joints. 1 joint set plus random (for schistosity planes), 5–30 cm spacing. Water inflows up 1000 l/min. 2. Large overbreak in intrados, some roof falls. 3. Railrace tunnel, Stensjöfallet Hydro, N. Sweden (ref. Cecil 1970).	5.9	4.8	100	Shotcrete	20 3	1.0 2	0.2 1.0		2.6 1.3 5.4		Category 21 = S 2.5 cm
70	1. 10 m length, strongly sheared granite, very tight vertical structure. Planar, rough surfaced, unaltered joints. 1 joint set, 5–30 cm spacing. Insignificant water inflow. 2. Stable, minor overbreak, no roof falls. 3. Collector tunnel, Mo i Rana Hydro, N. Norway (ref. Cecil 1970).	8	5.7	15	None	40 2	1.5 1.0	1.0 2.5		1.7 1.6 3.7		Category 0 Note: Very tight structure may imply higher stress, i. e. SRF=1.0 Hence Q=30
74 75	1. Approx. 2 km length, massive granite, widely spaced, tight, vertical joints. Planar, smooth-surfaced unaltered joints. 1 joint set, 1–3 m spacing. Insignificant water inflow. 2. No overbreak in chambers, but overbreak at intersections. 3. Waste water treatment plant, Källpala, Sweden (ref. Cecil 1970).	12	12.5	≤100	None in chambers	100 2	1.0 1.0	1.0 1.0	50	1.3 9.2		Category 0,9 = NONE or sb
77	1. 300 m length, massive gneiss, few joints. Planar, rough-surfaced, unaltered joints, >3 m spacing. Insignificant water inflow. 2. Minor overbreak, no falls or slides. 3. Wine and liquor storage rooms. Stockholm (ref. Cecil 1970).	20	24.5	18	Bolts at intersections 50 spot bolts in about 300 m of chamber	100 2×3	1.0 1.0	1.0 1.0	16.7	1.0 12.0		Category 14 = B 1.5–2 m + clm Category 0,5 = None or sb

Note: Right-hand column "Roof Support Recommendation" is obtained from Tables 11, 12, 13, and 14.

Key: S = shotcrete, B = systematic bolting, sb = spot bolting, CCA = cast concrete arches, mr = mesh reinforced, sr = steel reinforced, clm = chain link mesh.

Bolt spacing is given in metres. — Shotcrete or concrete thickness is given in centimeters.

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N. Barton, R. Lien, and J. Lunde:

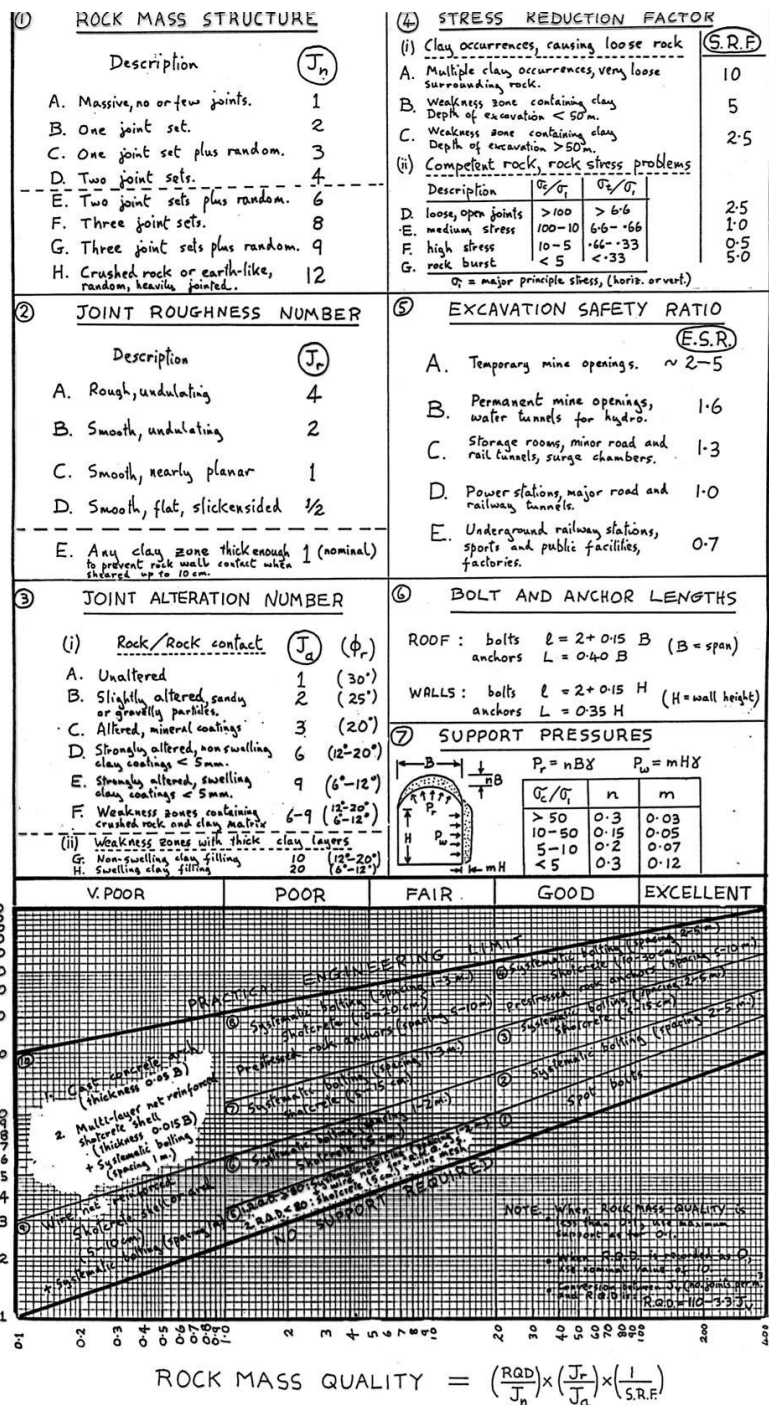
Engineering Classification of Rock Masses for the Design of Tunnel Support 219



Table 9. Classification and Prediction of Support for Six of the Case Records Described by Cecil (1970)

Case No.	1. DESCRIPTION OF ROCK MASS 2. Nature of instability 3. Purpose of excavation, location, reference	SPAN m	Height m	Depth m	Support used	RQD J_n	J_r J_a	J_w SRF	Q	ESR	SPAN/ ESR m	Roof support recommendation
60	1. 20 m length, 1 m wide zone of sheared granite with clay seams (non-softening) slide boundary is a thin (< 1 cm) clay seam and thinly sheared material that lie in contact with massive rock. Planar, slicken-sided joints. 1 joint set, 5—30 cm spacing. Insignificant inflow of water. See note, case 56. 2. Wedge-shaped roof fall. 3. Headrace tunnel. Stensjöfallet Hydro. N. Sweden (ref. Cecil 1970).	5.9	4.3	85	Rock bolts, and shotcrete	80 2	0.5 6	1.0 2.5				Category 21 = B 1 m + S 2.5 cm
									1.3	1.6	3.7	

SUMMARIZED DETAIL OF ONE OF CECIL, 1970 CASE RECORDS – AND Q-SYSTEM INTERPRETATION

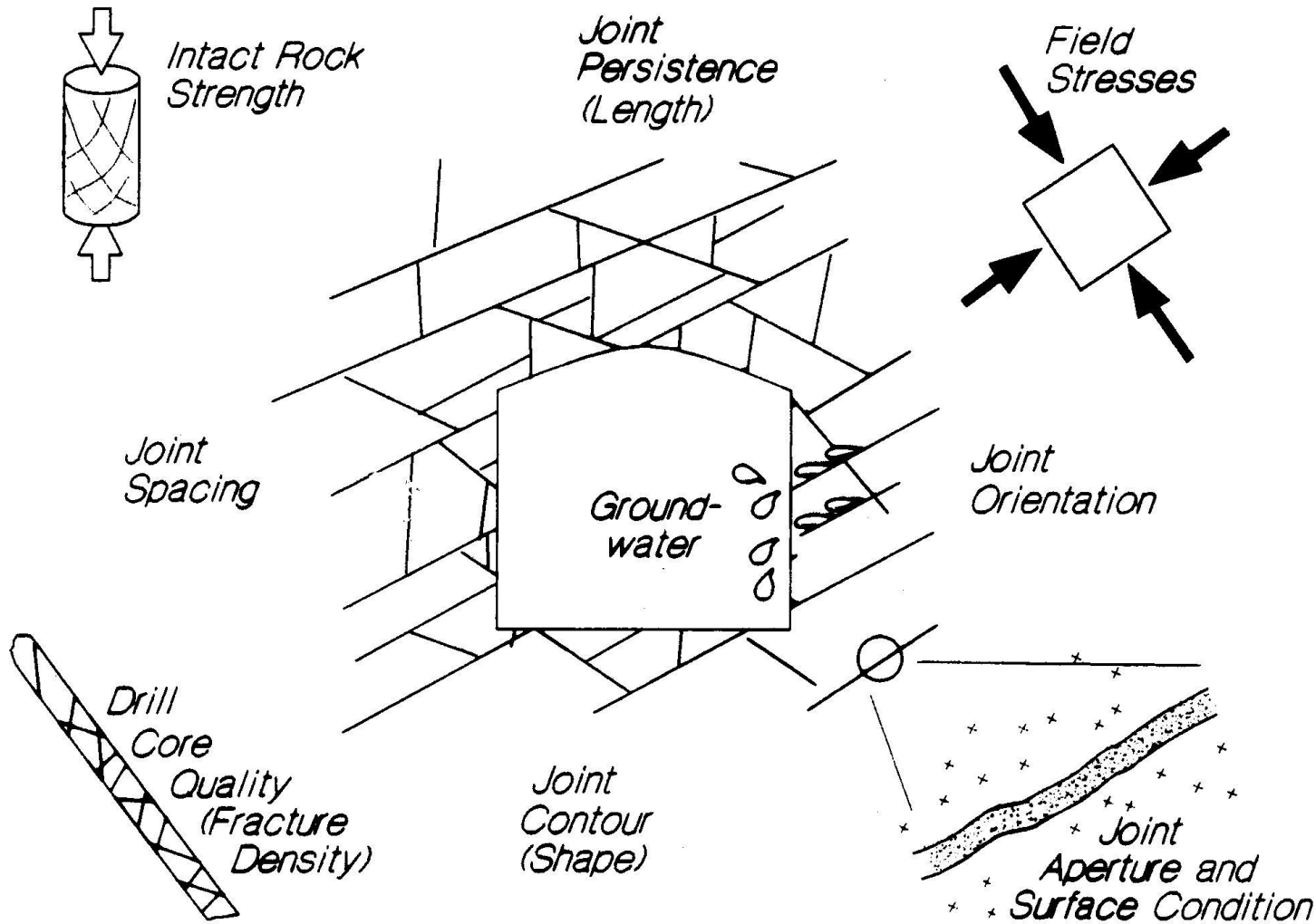


An early version of 'Q' in 1973
(Note: RQD assumed – obviously)

RQD HAS A PERMANENT ROLE IN
 Q , Q_{TBM} , Q_{slope} , Q_{H2O}

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

Hutchinson
and
Diederichs,
1996



SO WHAT IS THE 'Q-system' ?

- *Hellenic Society Soil Mech./Geotech.*
- *engineers may not be familiar with 'Q'*



Q used here!

As a briefest introduction:

Q means *rock mass quality*.

Q consists of *ratings for six parameters*.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \text{('Block size')} \times \text{('friction')} \times \text{('active stress')}$$



SUGAR LOAF MOUNTAIN, RIO DE JANEIRO

TOP END OF ROCK MASS QUALITY
SCALE.

$$Q \approx \underline{100}/0.5 \times 4/0.75 \times 1/1$$

i.e. >1000

BRAZILIAN HYDROPOWER PROJECT COLLAPSE IN FAULT

LOWEST END OF THE ROCK
MASS QUALITY SCALE.

$$Q \approx \underline{10}/20 \times 1/8 \times 0.5/20$$

i.e. < 0.001



THE FIRST TWO PAIRS OF PARAMETERS HAVE DIRECT PHYSICAL MEANING:

RQD / J_n = relative block size

J_r / J_a = frictional strength ($\approx \mu$)

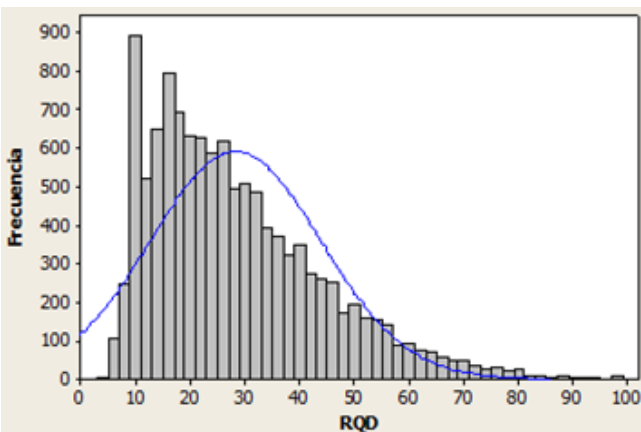
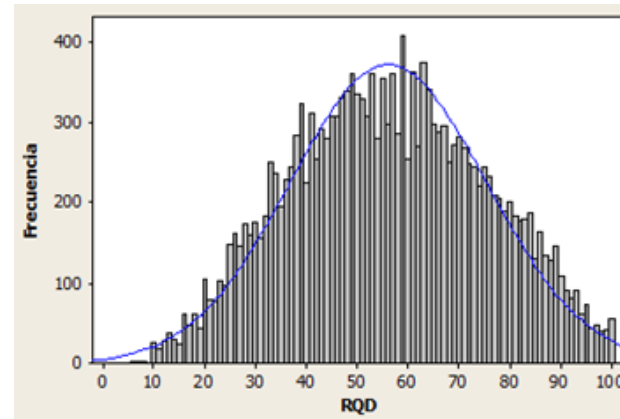
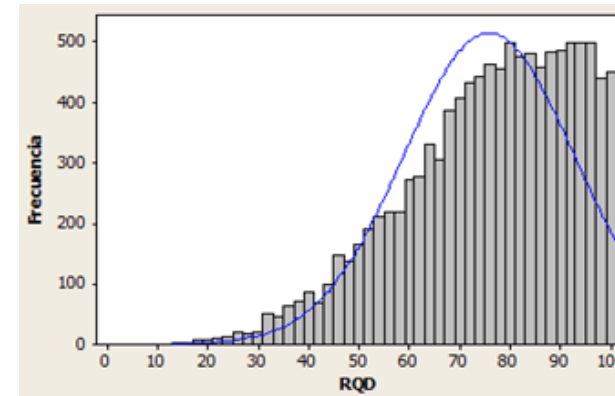
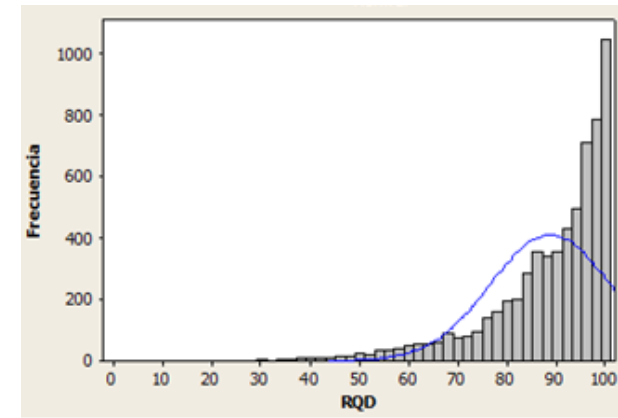
**J_w / SRF = effects of water, faulting,
strength/stress ratio, squeezing or
swelling (an 'active stress' term)**

Q-classes with respective RQD distributions and Q-ranges:

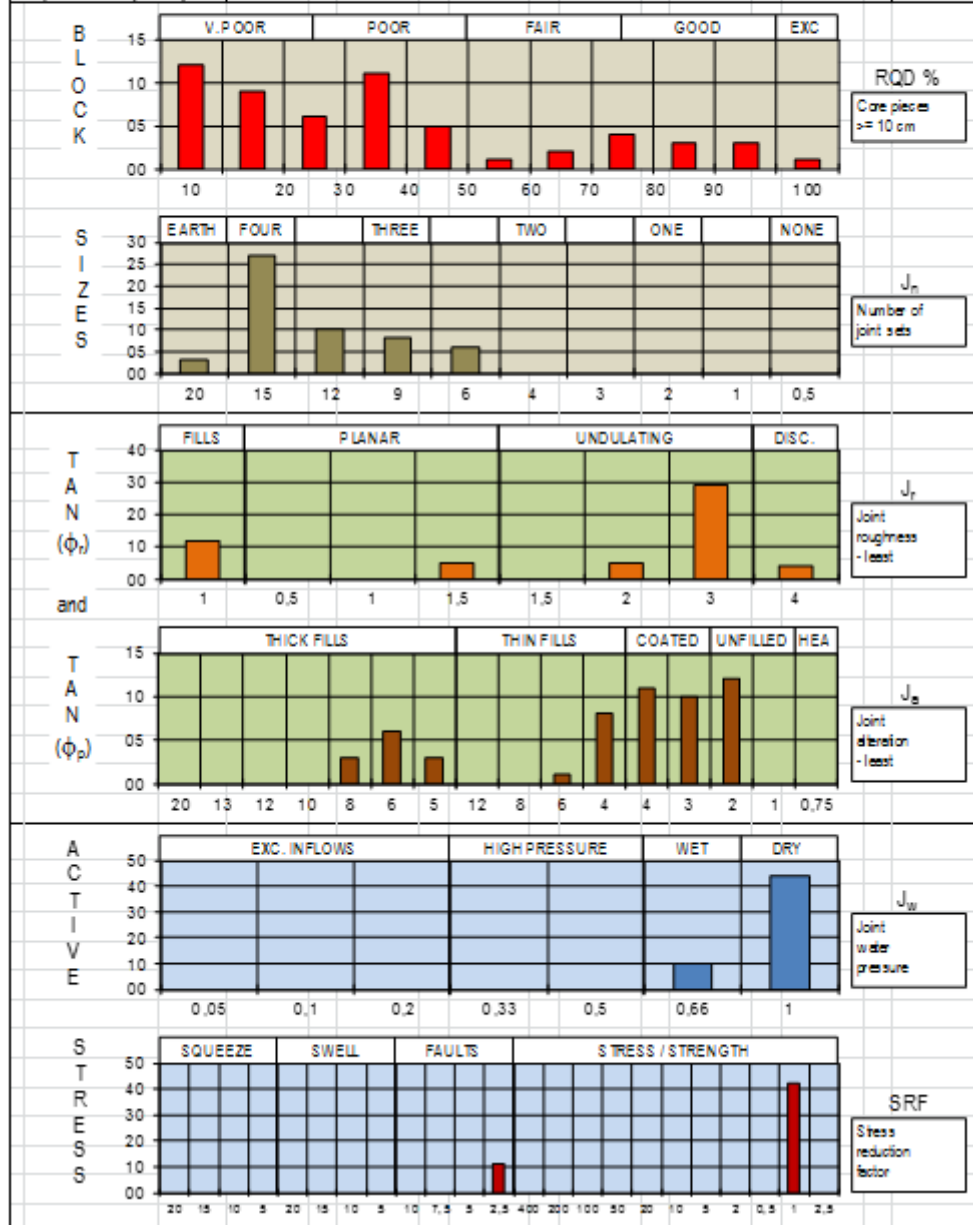
0.1-1, 1-4, 4-10, 10-40

(part of 340 km of core logging at mine, by 12 to 15 engineering geologists)

Demonstrates central role played by RQD in
(> 40 km of core)



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



- ### I ROCK MASS STRUCTURE
- RQD** (Deere et al., 1967) block size { Q
 - J_n** = joint set number
 - F** = joint frequency (per metre)
 - J_v** = volumetric joint count (Palmström, 1982)
 - S** = joint spacing (in metres)
 - L** = joint length (in metres)
 - w** = weathering grade (ISRM, 1978)
 - α/β** = dip/dip direction of joints (Schmidt diagram)
- ### II JOINT CHARACTER
- J_r** = joint roughness number shear strength { Q
 - J_a** = joint alteration number
 - JRC** = joint roughness coefficient
 - a/L** = roughness amplitude of asperities per unit length (mm/m)
 - JCS** = joint wall compressive strength
 - φ_r** = residual friction angle
 - r, R** = Schmidt rebound values for joint and rock surfaces
- ### III WATER, STRESS, STRENGTH
- J_w** = joint water reduction factor active stress { Q
 - SRF** = stress reduction factor
 - K** = rock mass permeability (m/s)
 - σ_c** = compressive strength
 - σ₁** = major principal stress

Q IS ONLY PART OF A ROCK MASS DESCRIPTION EXERCISE

ELEVATION OR DEPTH ZONE : X Y Z (m)

Q (typical range) = $\left(\frac{80-100}{6-9}\right) \times \left(\frac{1-2}{1-2}\right) \times \left(\frac{.66-1}{1}\right)$ Q (mean) = $\left(\frac{82}{8.7}\right) \times \left(\frac{1.6}{1.7}\right) \times \left(\frac{.7}{1.3}\right)$

BLOCK SIZES

RQD %

Core pieces $\geq 10\text{cm}$

J_n

Number of joint sets

J_r

Joint roughness - least favourable

J_a

Joint alteration - least favourable

J_w

Joint water pressure

SRF

Stress reduction factor

ACTIVE STRESS

EXC. INFLOWS HIGH PRESS WET DRY

SQUEEZE SWELL FAULTS STRESS/STRENGTH

Q-histogram
method of
recording
data.

RQD is
frequently
the most
variable
parameter

Location: LYSAKER - PARSELL: SANDVIKA Depth / chainage: BH-2 300-360m Date: 8/6/2005 Page: 24 NR8

Numbers for domains, core boxes, tunnel lengths

Q (typical range) = $\left(\frac{80-100}{6-9}\right) \times \left(\frac{1-2}{1-2}\right) \times \left(\frac{.66-1}{1}\right)$ Q (mean) = $\left(\frac{82}{8.7}\right) \times \left(\frac{1.6}{1.7}\right) \times \left(\frac{.7}{1.3}\right)$ Q (most freq.) = $\left(\frac{82}{8.7}\right) \times \left(\frac{1.6}{1.7}\right) \times \left(\frac{.7}{1.3}\right)$

RQD %

Core pieces $\geq 10\text{ cm}$

J_n

Number of joint sets

J_r

Joint roughness - least favourable

J_a

Joint alteration - least favourable

J_w

Joint water pressure

SRF

Stress reduction factor

ACTIVE STRESS

Exc. Inflows High Press Wet Dry

Squeeze Swell Faults Stress/Strength

or Sketch

300-319 Rr.sh/Rr.st (310-312) Kst

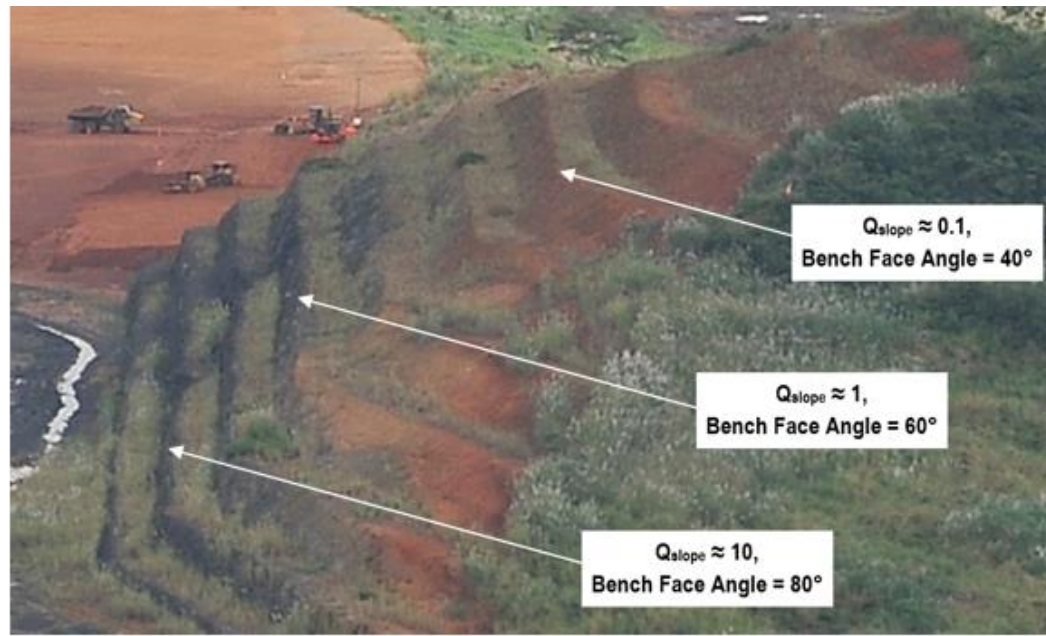
319-326 diabao

326-330 Rr.sh/Kst

330-352 knolle

352-360 diabao

Q-slope



Q-SLOPE METHOD

(Barton and Bar, 2015)

Q-slope = 0.01 : slope angle $\approx 25^\circ$

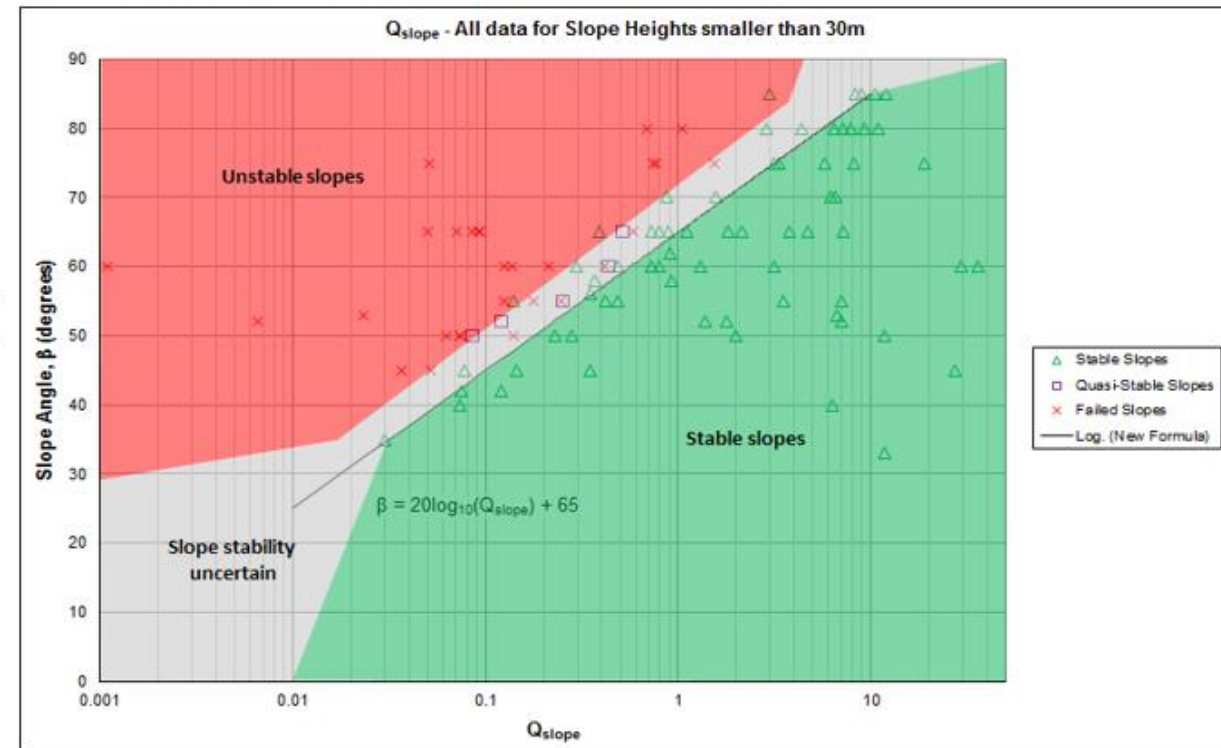
Q-slope = 0.1 : slope angle 45°

Q-slope = 1.0 : slope angle 65°

Q-slope = 10 : slope angle 85°

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

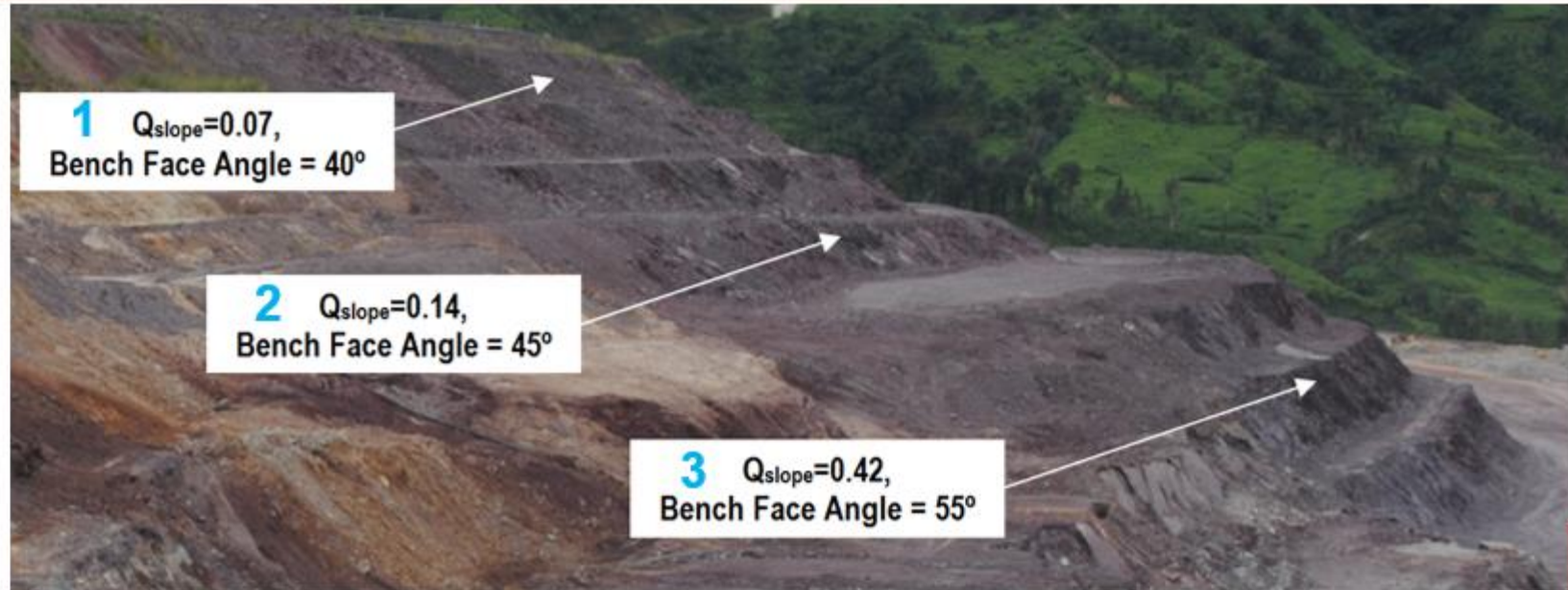
$$\beta = 20 \log_{10} Q_{slope} + 65^\circ$$



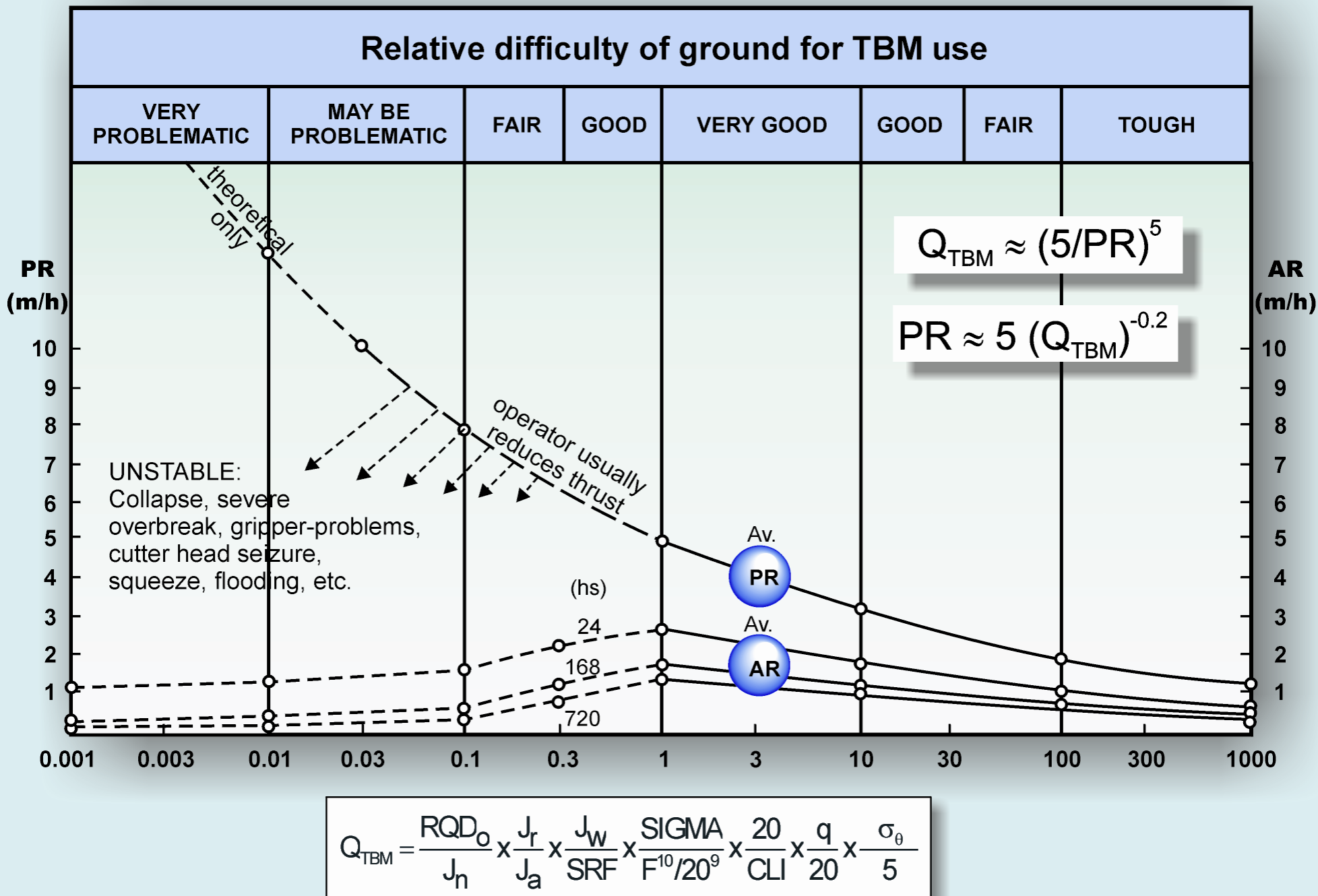
Case Study 3: Q-slope mining application

Local	RQD (%)	Jn	Jr	Ja	0-factor	Jwice	SRFa	SRFb	SRFc	Q-slope	β (slope angle °)
1	10-25	6	1	4	0.5	0.5	2.5	1	N/A	0.0729	42
2	10-25	6	1	3	0.75	0.5	2.5	2	N/A	0.1458	48
3	25-50	9	2	3	0.75	0.5	2.5	2	N/A	0.4166	57

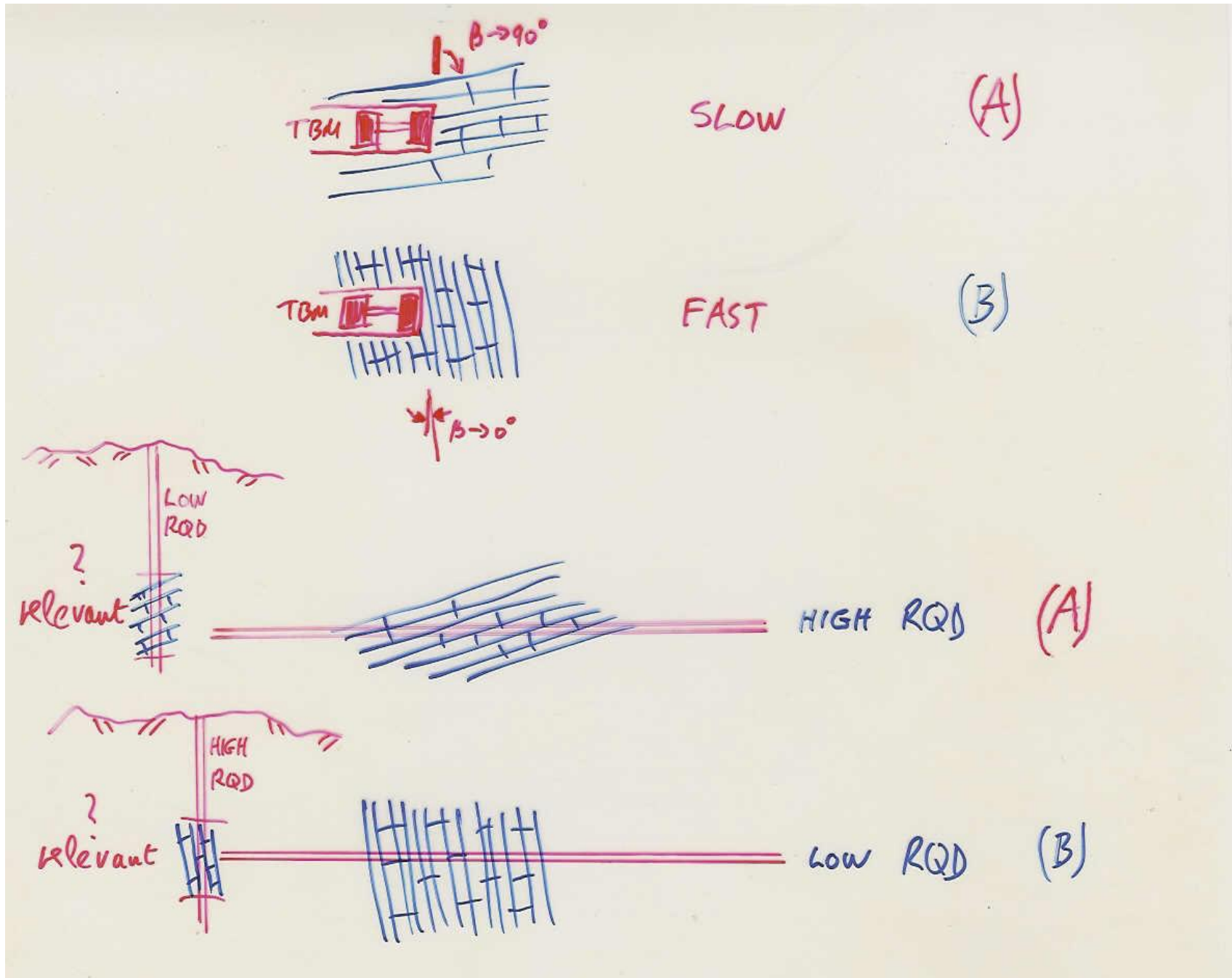
- RQD improves with depth
- Orientation factor improves with depth (bedding)



QTBM



Note AR estimation
for 24 hrs, 1 week,
1 month



Important to use RQD as a directional parameter (when needed)

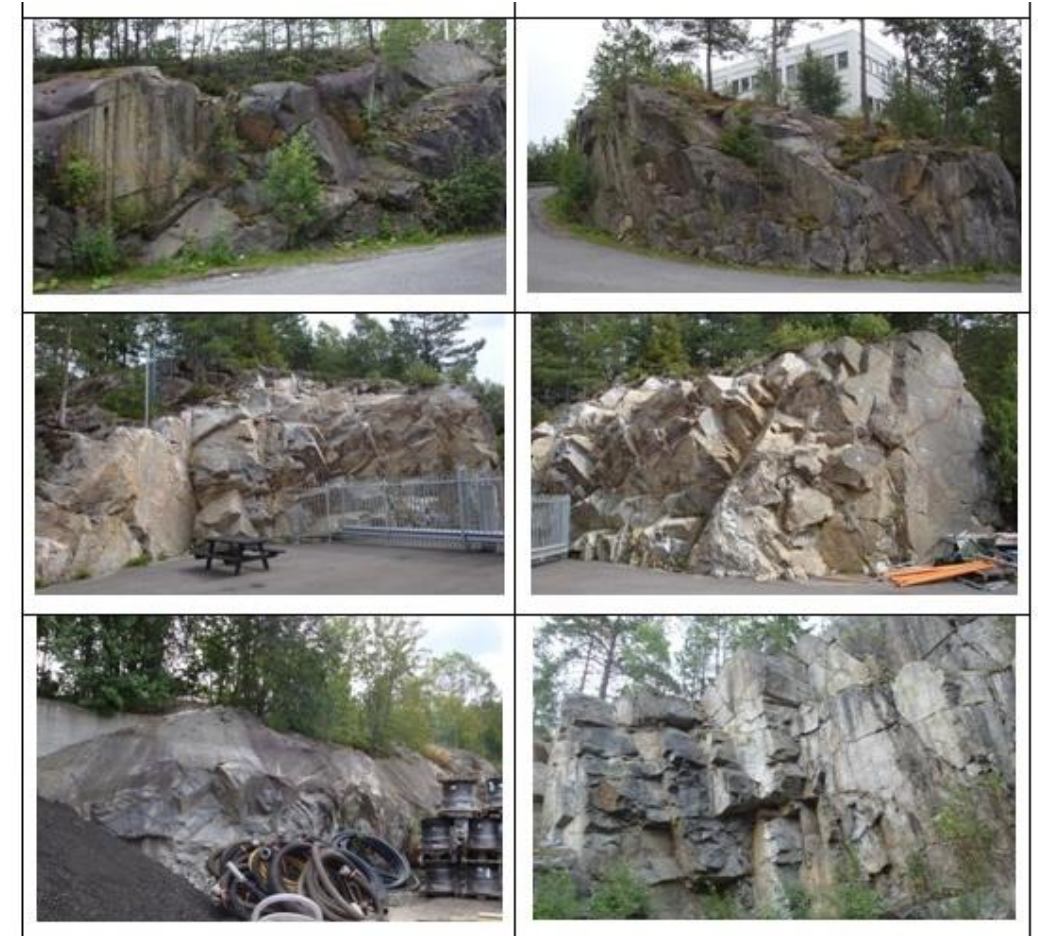
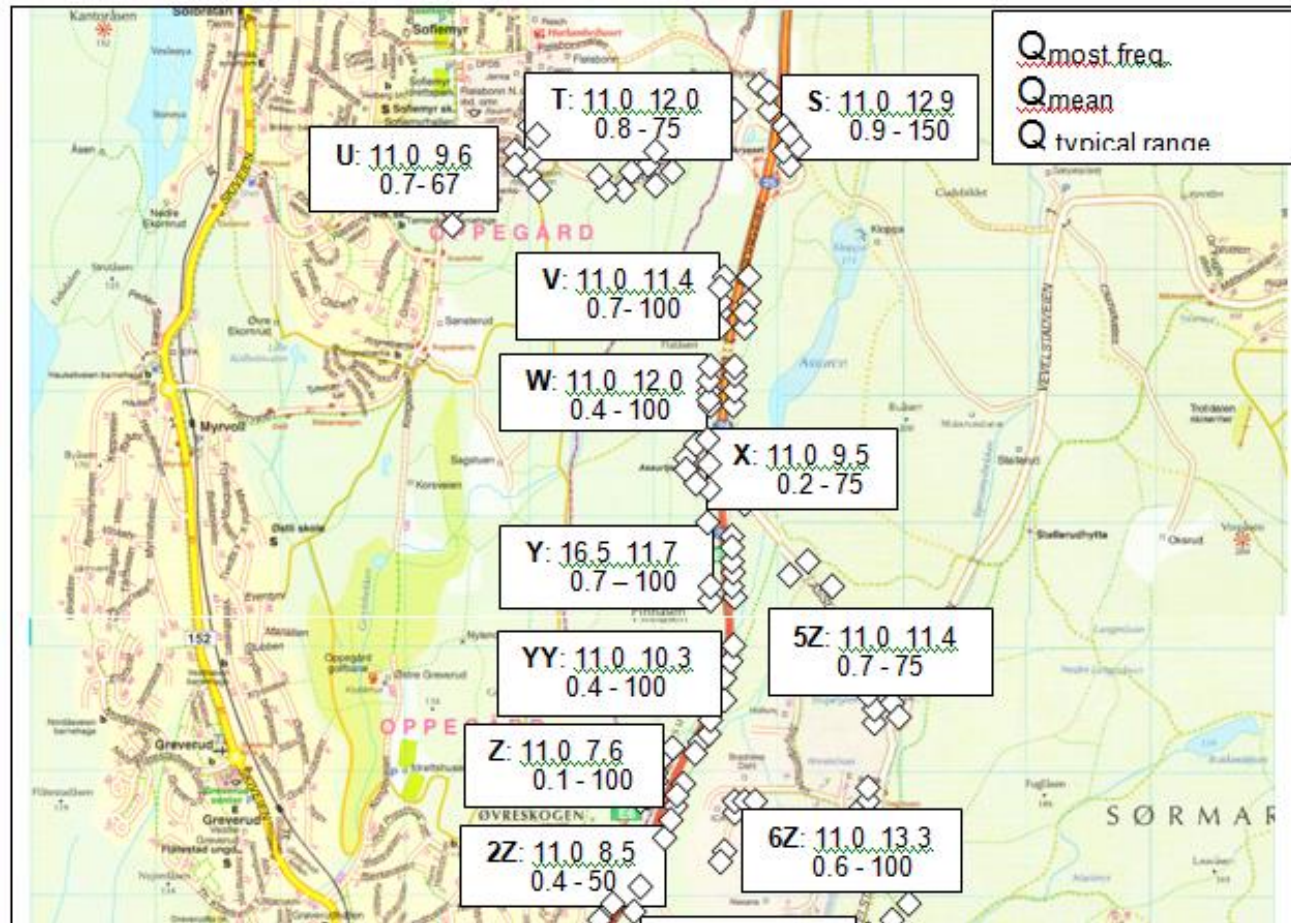



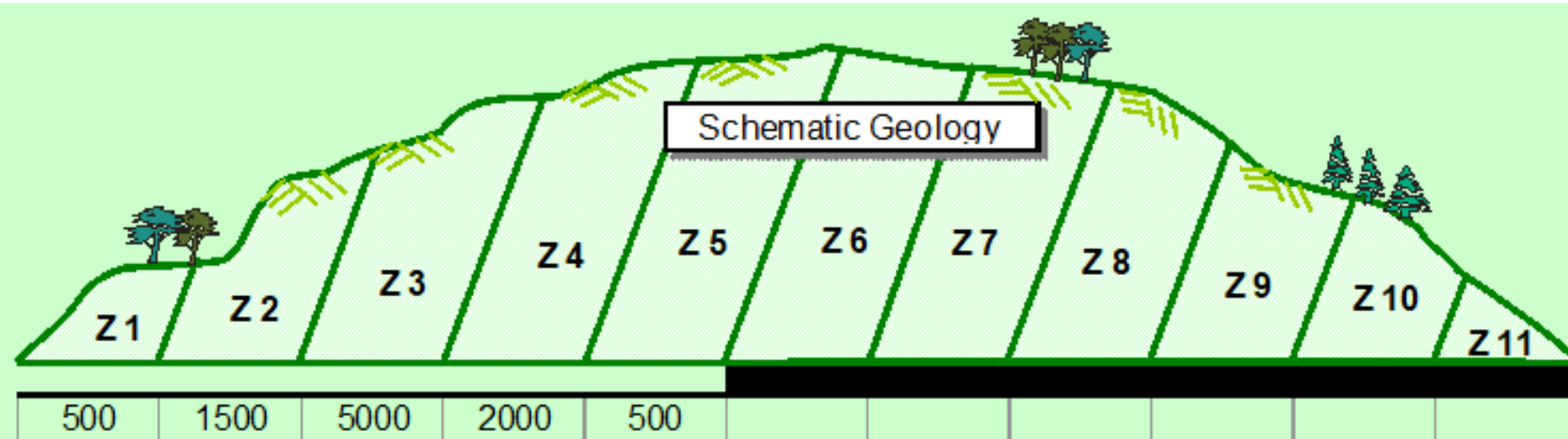
Figure A20. Locations U1 to U8, Sofiemyr, mostly near Brannstasjon.

A selection of the 300+ locations which were Q-logged

	Location: TUNNEL-SOUTH JBV ÅSLAND-LANGHUS		Depth / chainage: ROCK EXPOSURES LOGGED		Date: 30.8.09																																																																																																																								
					Page: 40																																																																																																																								
Numbers for domains, core boxes, tunnel lengths (under-line, or specify)	Q (typical range) = 0.1-100 $(\frac{75-100}{4-15}) \times (\frac{1-4}{1-5}) \times (\frac{0.5-1.0}{1.0})$		Q (mean) = 11.1 $(\frac{98}{8.4}) \times (\frac{1.7}{1.3}) \times (\frac{0.75}{1.0})$		Q (most freq.) = 11.0 $(\frac{100}{9}) \times (\frac{1.5}{1.0}) \times (\frac{0.66}{1.0})$																																																																																																																								
	<table border="1"> <thead> <tr> <th></th> <th colspan="2">Very Poor</th> <th colspan="2">Poor</th> <th colspan="2">Fair</th> <th colspan="2">Good</th> <th colspan="2">Exc.</th> </tr> </thead> <tbody> <tr> <td>Σ</td> <td></td><td></td><td>2</td><td>6</td><td>18</td><td>46</td><td>123</td><td>297</td><td>650</td><td>4807</td> </tr> <tr> <td>HQR</td> <td></td><td></td><td>1</td><td>1</td><td></td><td>1 2</td><td>6 2 2</td><td>15 6 6</td><td>27 23 5</td><td>176 190 137</td> </tr> <tr> <td>TSU</td> <td></td><td></td><td></td><td></td><td>1</td><td>1</td><td>6 3 1</td><td>12 14 9</td><td>29 40 20</td><td>221 213 240</td> </tr> <tr> <td>VWX</td> <td></td><td></td><td></td><td></td><td></td><td>2 2</td><td>3 6 6</td><td>14 13 13</td><td>28 27 31</td><td>225 222 218</td> </tr> <tr> <td>Y 52 77</td> <td></td><td></td><td></td><td></td><td>2</td><td>1 1 4</td><td>4 4 7</td><td>13 10 18</td><td>30 34 32</td><td>192 221 207</td> </tr> <tr> <td>Z 67 22</td> <td></td><td></td><td>2</td><td>1</td><td>5</td><td>1 2 8</td><td>3 3</td><td>11 5 7</td><td>17 13 14</td><td>27 31 36</td> </tr> <tr> <td>72 82 32</td> <td></td><td></td><td>1</td><td>1</td><td>3</td><td>4 3</td><td>1 9 7</td><td>11 14 12</td><td>23 27 29</td><td>235 181 219</td> </tr> <tr> <td>112 102 42</td> <td></td><td></td><td></td><td></td><td>3</td><td>1 2 4</td><td>3 7</td><td>10 6</td><td>12 15 14</td><td>24 34 32</td> </tr> <tr> <td>127 92</td> <td></td><td></td><td></td><td></td><td></td><td>1</td><td>2 4</td><td>8 11</td><td>23 34</td><td>147 220</td> </tr> <tr> <td>132</td> <td></td><td></td><td></td><td></td><td>1</td><td>1</td><td>4</td><td>13</td><td>34</td><td>187</td> </tr> </tbody> </table>						Very Poor		Poor		Fair		Good		Exc.		Σ			2	6	18	46	123	297	650	4807	HQR			1	1		1 2	6 2 2	15 6 6	27 23 5	176 190 137	TSU					1	1	6 3 1	12 14 9	29 40 20	221 213 240	VWX						2 2	3 6 6	14 13 13	28 27 31	225 222 218	Y 52 77					2	1 1 4	4 4 7	13 10 18	30 34 32	192 221 207	Z 67 22			2	1	5	1 2 8	3 3	11 5 7	17 13 14	27 31 36	72 82 32			1	1	3	4 3	1 9 7	11 14 12	23 27 29	235 181 219	112 102 42					3	1 2 4	3 7	10 6	12 15 14	24 34 32	127 92						1	2 4	8 11	23 34	147 220	132					1	1	4	13	34
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Summing
the raw
data

Input-data screen for assumed Class 1 rock mass



ZONE 5

LITHOLOGY Class 1 granitic gneiss

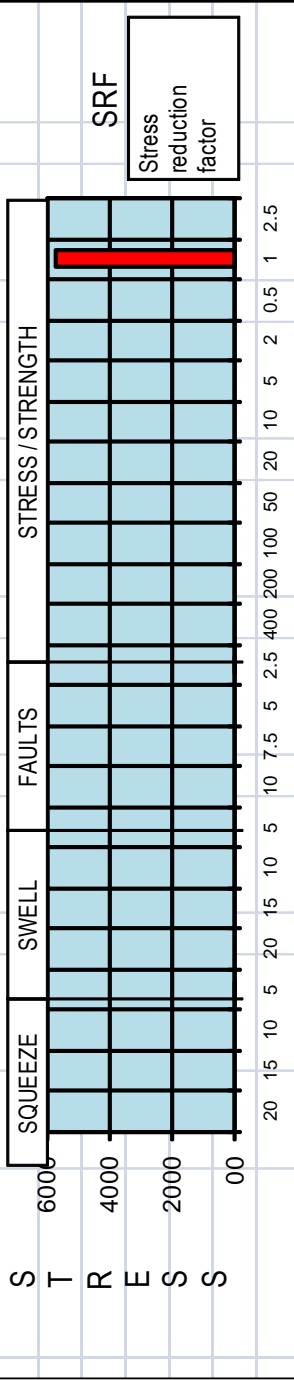
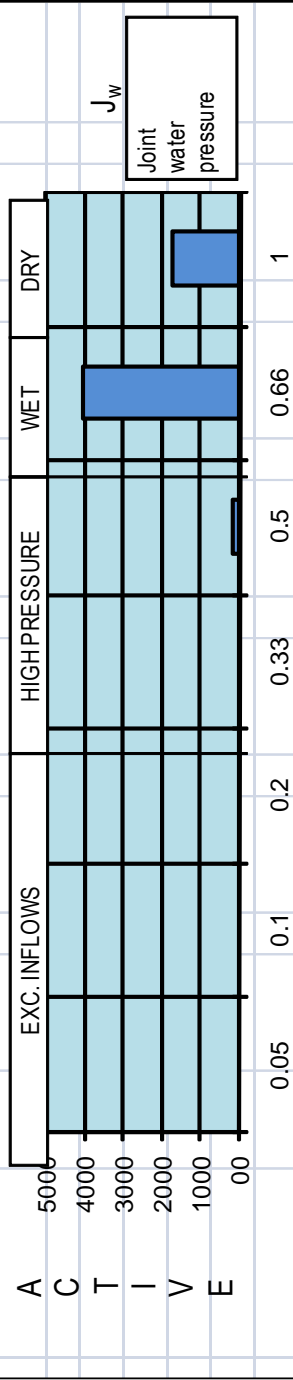
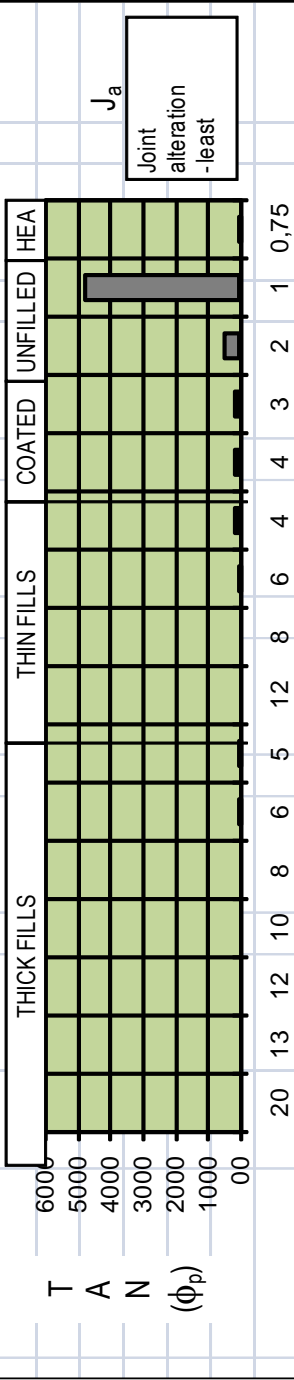
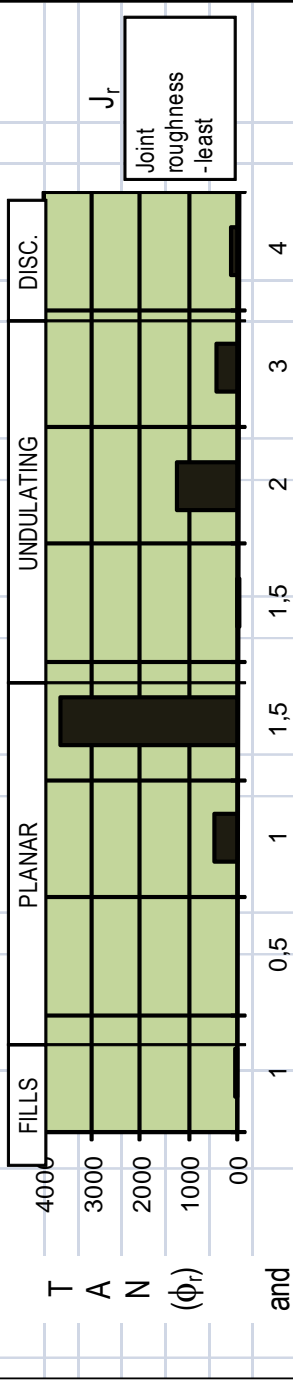
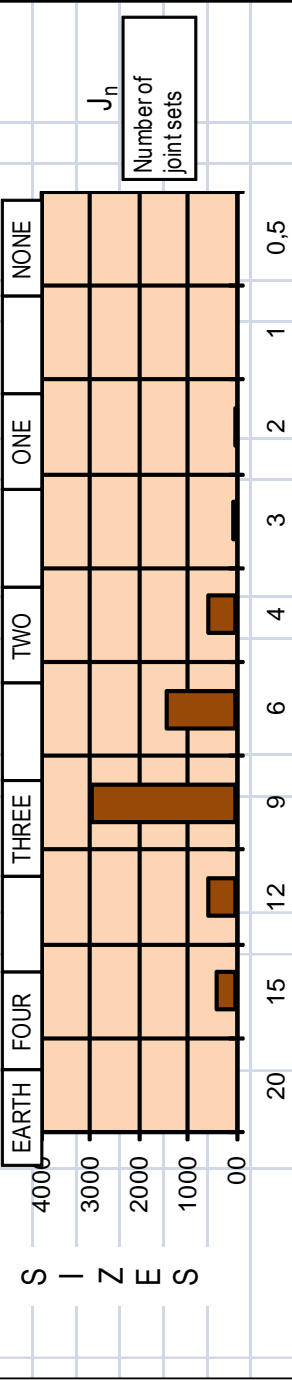
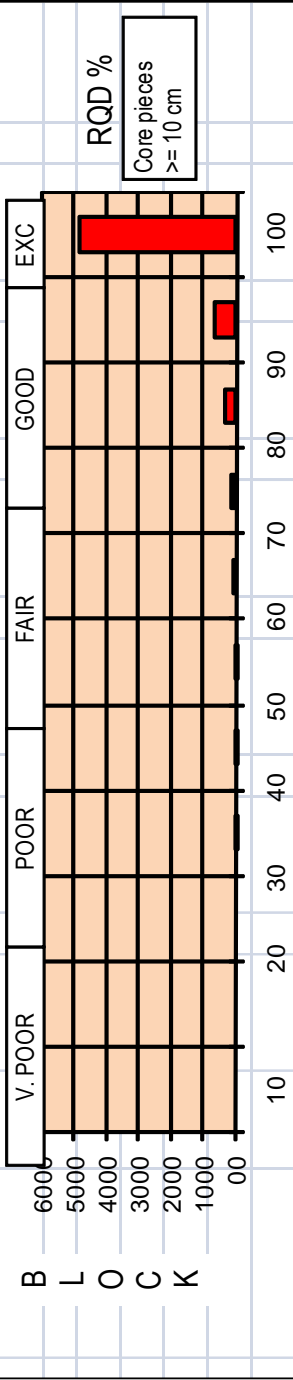
ZONE LENGTH 500

INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD ₀	γ (g/cm ³)	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

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	5.0	*	0.50	/	1.0	=	0.500
Q (typical max)=	100	/	4.0	*	4.0	/	1.0	*	1.00	/	1.0	=	100.0
Q (mean value)=	98	/	8.4	*	1.7	/	1.3	*	0.75	/	1.0	=	11.07
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	0.66	/	1.0	=	11.00



JBV OSLO-SKI										Rev.	Report No.	Figure No.
											NB&A #1	10
Q-histogram based on compilation of all rock-exposure										Borehole No. :	Drawn by	Date
logging for TUNNEL-SOUTH, therefore excluding core										Rock slopes	NB&A	31.8.09
and weakness zones.										Depth zone (m)	Checked	
										near-surface	nrb	
											Approved	



Q_{H_2O}

Q_c	0.1	1	10	100
Lugeon	10	1	0.1	0.01
$K(\text{m/s}) \approx$	10^{-6}	10^{-7}	10^{-8}	10^{-9}
V_p (km/s)	2.5	3.5	4.5	5.5

**Typical trends
(of permeability)
if no clay.**

No clay present:

$$L \approx 1/Q_c$$

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

(1 Lugeon $\approx 10^{-7}$ m/s $\approx 10^{-14}$ m² for water at 20°C)

$$Q_c = \text{RQD}/J_n \times J_r/J_a \times J_w/\text{SRF} \times \sigma_c/100$$

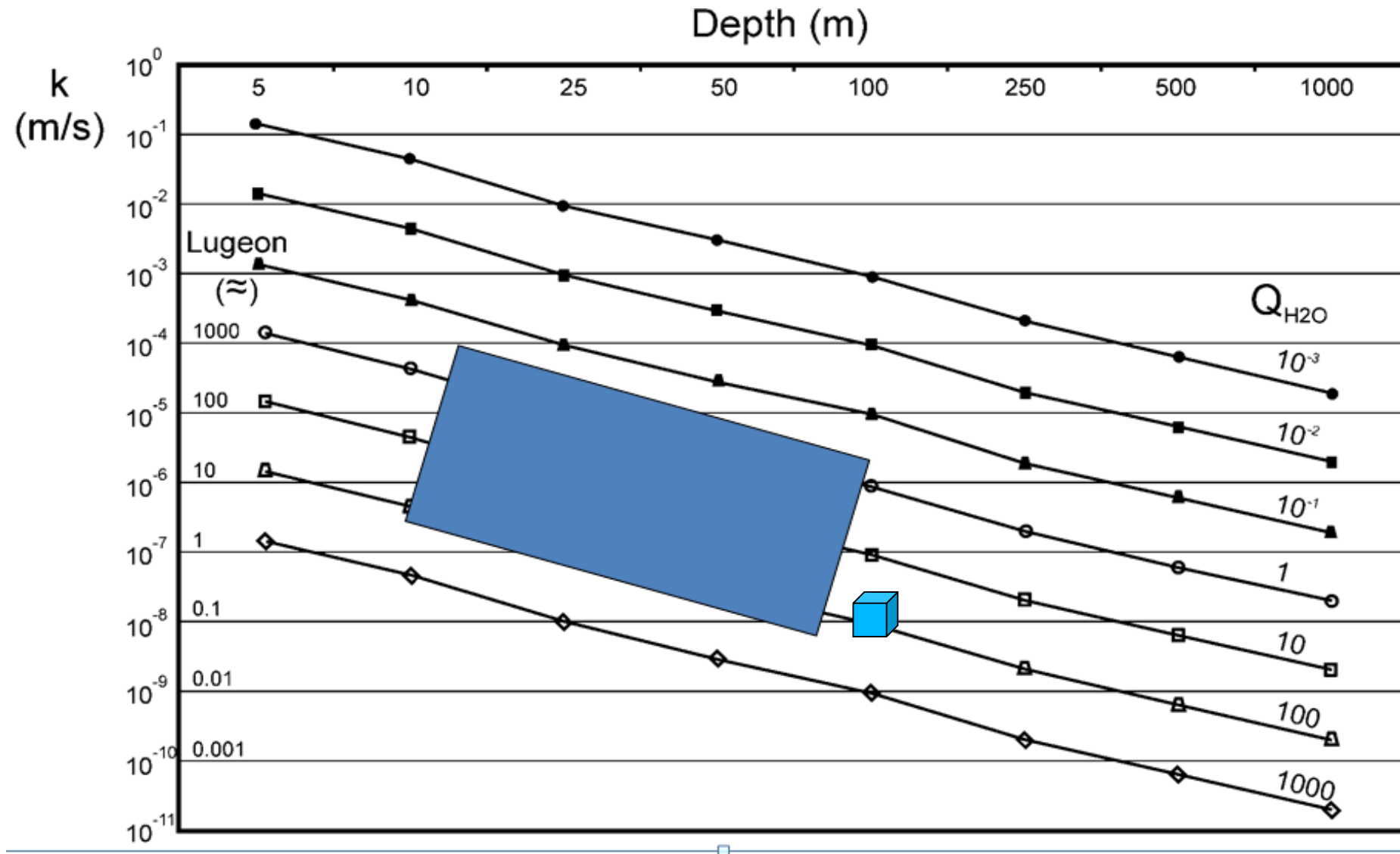
(standard equation, normalized by $\sigma_c/100$)

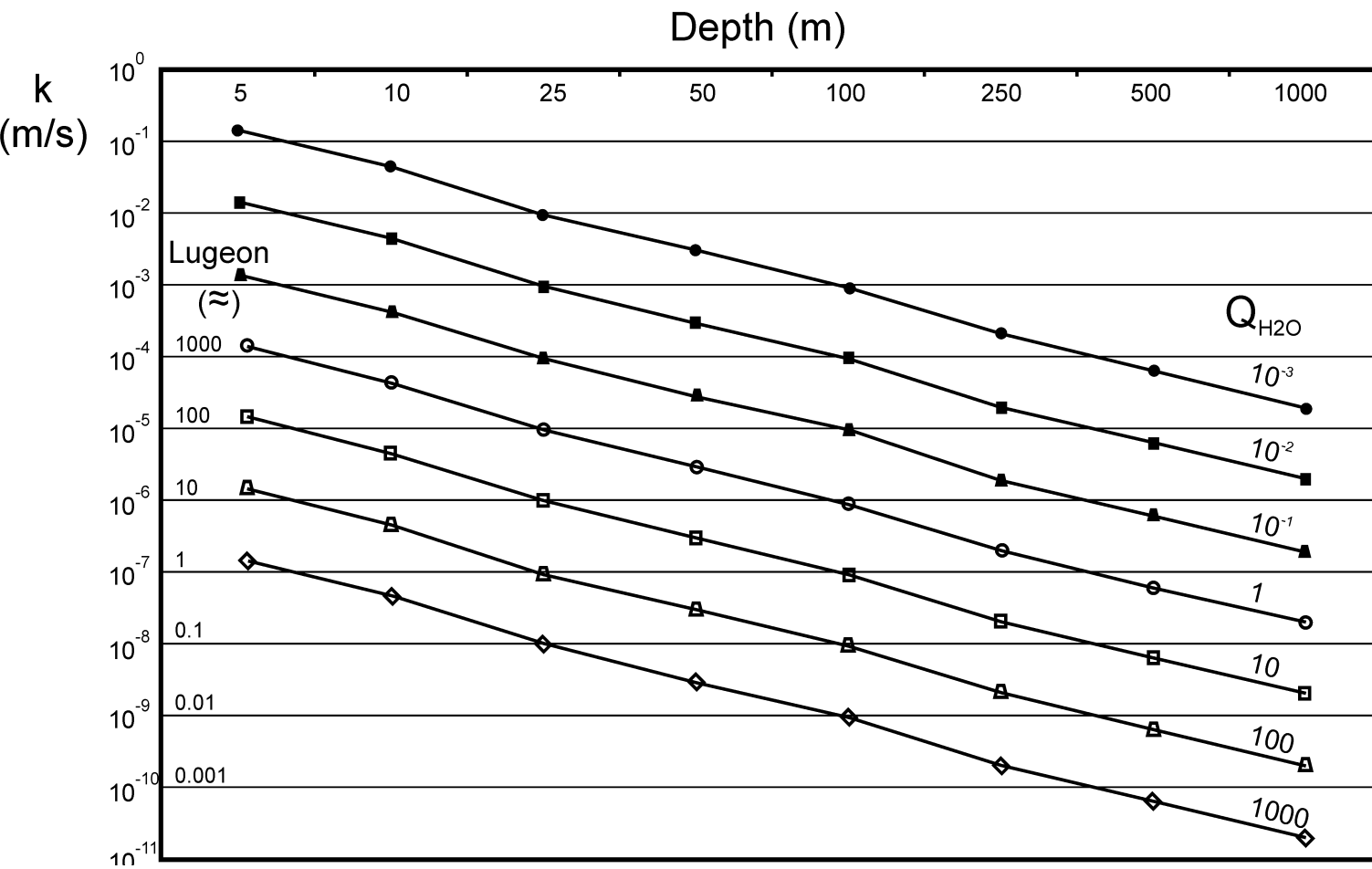
*General case, with or without clay, with depth
or stress allowance, and consideration of
joint wall strength JCS*

$$Q_{\text{H}_2\text{O}} = \text{RQD}/J_n \times J_a/J_r \times J_w/\text{SRF} \times 100/\text{JCS}$$

$$K \approx 0.002 / (Q_{\text{H}_2\text{O}} D^{5/3}) \text{ m/s}$$

USUAL RANGE OF K at DAM SITES





Example of Q_{H_2O} estimation: Weak, well-jointed rock at 100 m depth with a low assumed joint-wall-compression-strength JCS of 10 MPa:

Regular Q-value =

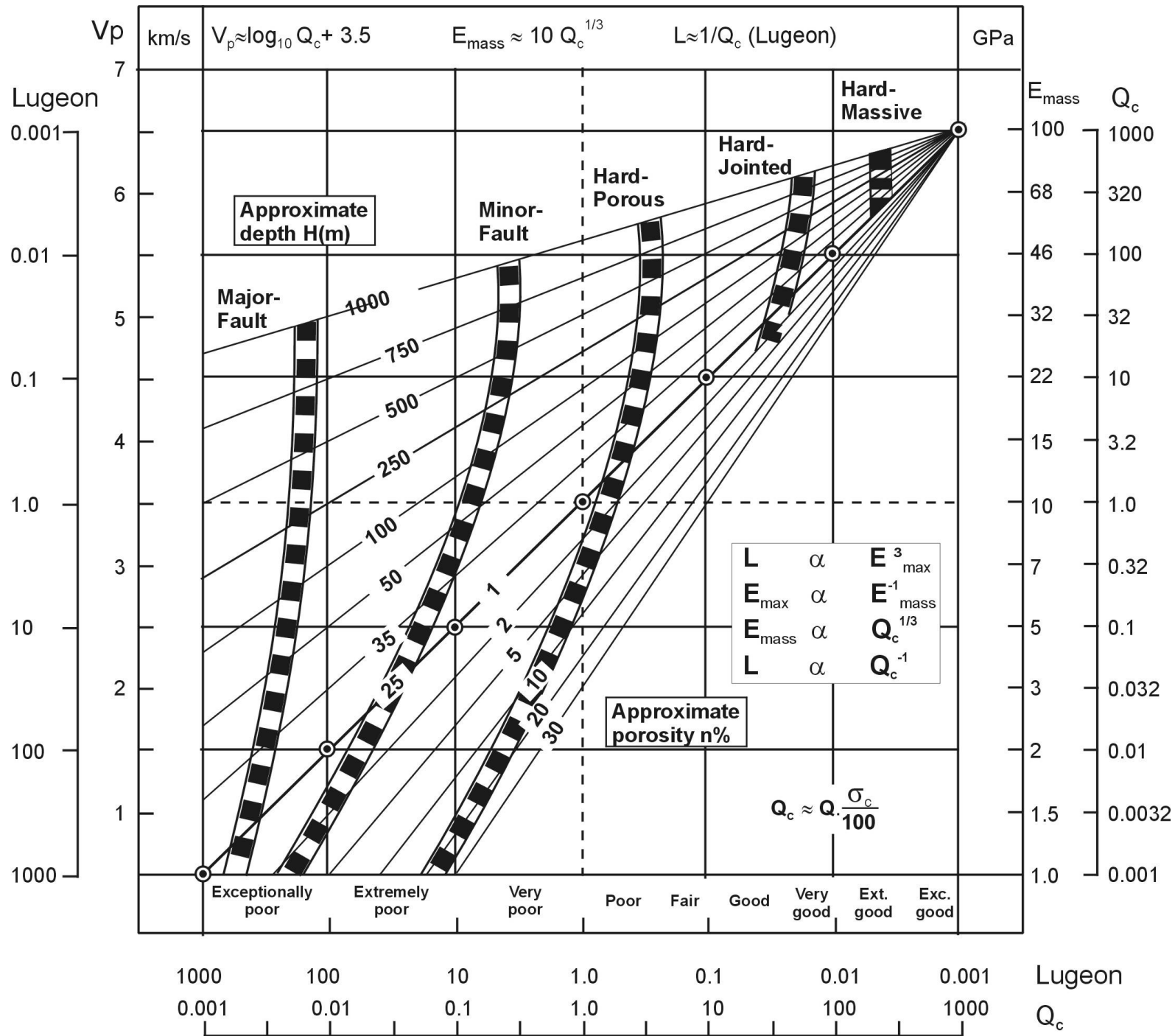
$$\frac{50}{9} \times \frac{1.5}{4} \times \frac{0.66}{1}$$

= 1.4, i.e. 'poor quality'

$$Q_{H_2O} = \frac{50}{9} \times \frac{4}{1.5} \times \frac{0.66}{1} \times \frac{100}{10} = 98$$

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

(Quite low permeability despite the extensively jointed nature of this rock mass, due to nearly closed, compressible, clay-coated joint walls).

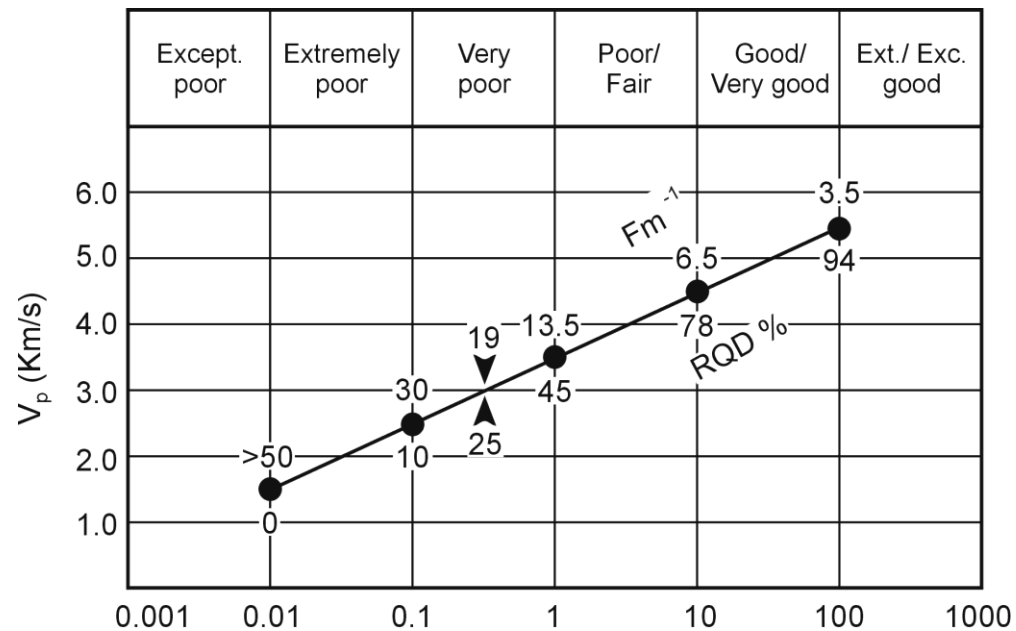
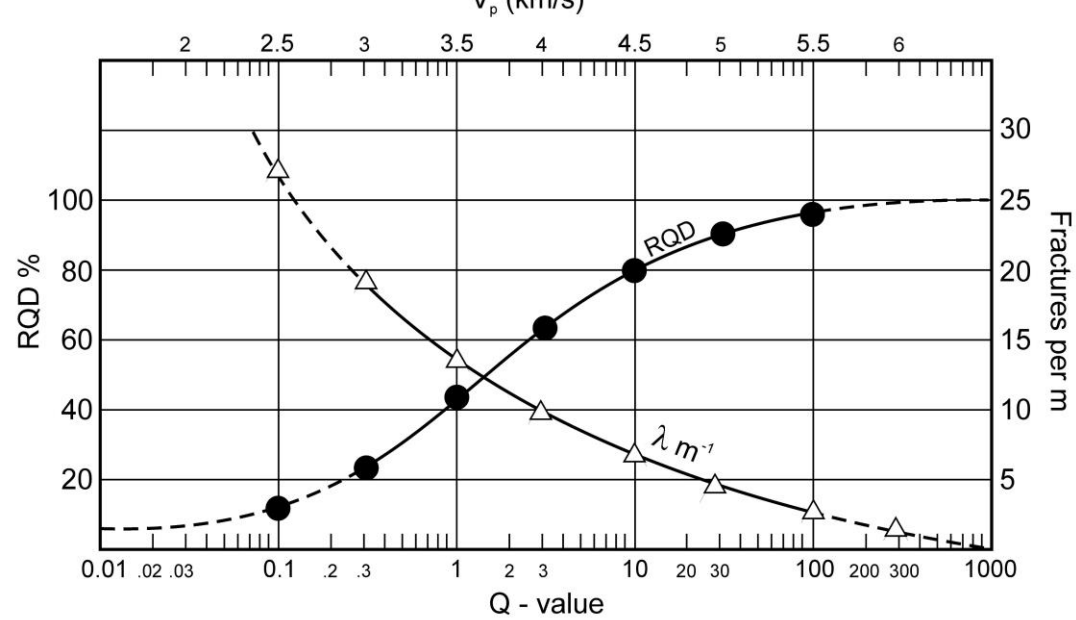


(Barton, 2006)

Attempts at an
integrated
rock-mass
model

(RQD is of course
embedded in Q_c)

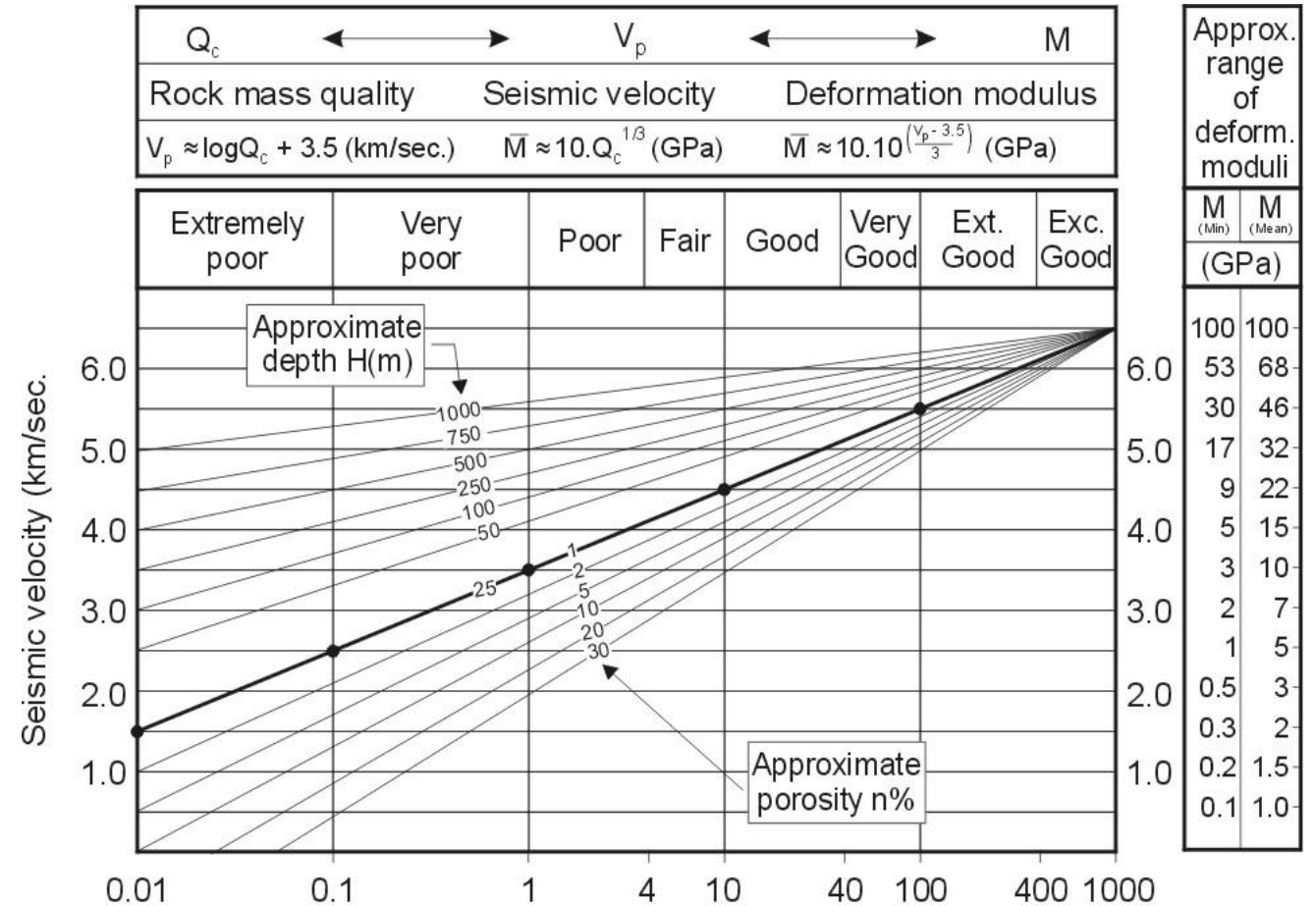
**RQD and
seismic velocity V_p**



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

Sjögren et al. 1979: RQD/Fm-1/Vp
 NB added Q-value scale, 1995: hard rocks.
 (120 km ref. seis., 2.2km core)

Below: NB, 1995: general case



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

HOEK-BROWN

GSI-BASED ESTIMATION

(AN ALTERNATIVE, WITH ***RQD*** INCLUDED)

$$E_m (GPa) = \left(1 - \frac{D}{2}\right) \sqrt{\frac{\sigma_{ci}}{100}} \times 10^{(GSI-10)/40}$$

$$\sigma'_{cm} = \sigma_{ci} \times \frac{(m_b + 4s - a(m_b - 8s)) (m_b/4 + s)^{a-1}}{2(1+a)(2+a)}$$

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

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

where

$$\sigma_{3n} = \sigma'_{3 \max} / \sigma_{ci} \quad (+GSI + a + s + m_b \text{ relations})$$

$$E_m \approx 10 \times Q_c^{1/3}$$

$$\sigma_{cm} \approx 5\gamma Q_c^{1/3}$$

$$\varphi \approx \tan^{-1} \left(\frac{I_r}{J_a} \times \frac{I_w}{1} \right)$$

$$c \approx \left(\frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100} \right)$$

FOR THOSE WHO ARE
SUSPICIOUS OF BLACK-BOX
EQUATIONS –

THERE ARE TRANSPARENT
ALTERNATIVES.....*also with RQD!*

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

Cut Q_c into two halves \rightarrow 'c' and 'φ'

$$Q_c = RQD/J_n \times J_r/J_a \times J_w/SRF \times \sigma_c / 100$$



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

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

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

$$FC = \tan^{-1} \left(\frac{J_r}{J_a} \times J_w \right)$$

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

$$CC \quad "c" \approx \left(\frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100} \right)$$

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

$$FC \quad " \phi " \approx \tan^{-1} \left(\frac{J_r}{J_a} \times \frac{J_w}{1} \right)$$

GSI-based
algebra for
'c' and 'φ'

contrasted
with

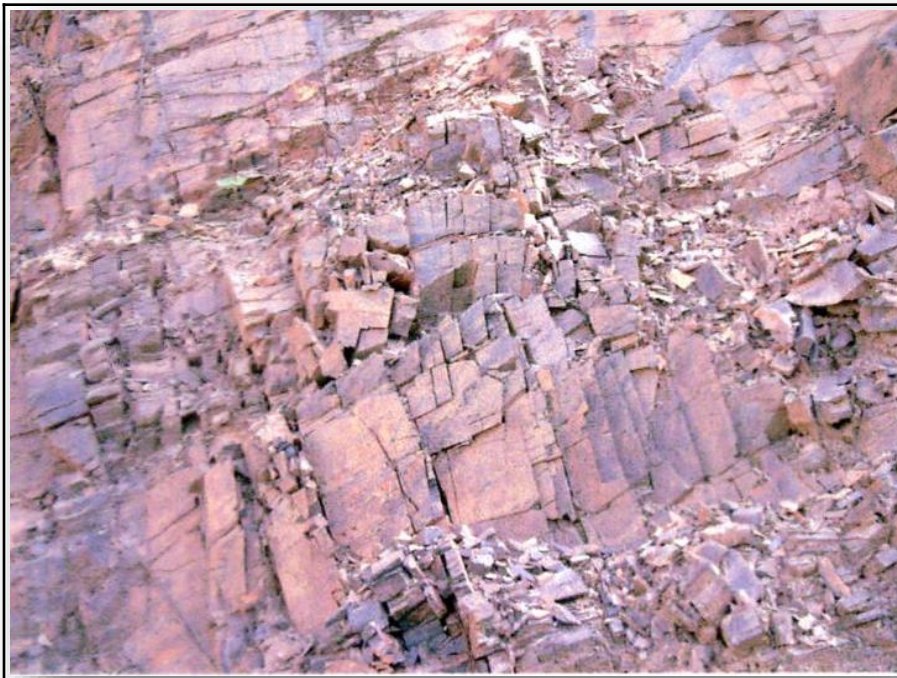
Q-based
'empiricism'

*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: *lower RQD*, more joint sets, more weathering, lower UCS, more clay.

Low CC –shotcrete preferred



Low FC – bolting preferred

