TBM in DIFFICULT ROCK CONDITIONS

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TBM-DIGs WUHAN Nov 2017

SUBJECTS TO BE COVERED:

1. Q USEFUL FOR *ROCKMASS* DESCRIPTIONS
2. TBM DELAYS IN *HARD-ROCK*: LOW PR, *MIXED-FACE*
3. *EXTREME DEPTH CONSIDERATIONS:* $0.4\sigma_c$ or σ_t/ν ?
3. TBM *CASE RECORD* PERFORMANCES (> 1,000 km)
4. TBM DELAYS IN *FAULT ZONES* – MANY COUNTRIES
5. DECELERATION *(-m)* QUANTIFIED IN *FAULT ZONES*
6. Q_{TBM} PROGNOSIS EXAMPLES: *MASSIVE* AND *WET-ZONES*
7. DO NOT FORGET TO USE *HYBRID D+B and TBM!*

FIRST SOME DEFINITIONS:

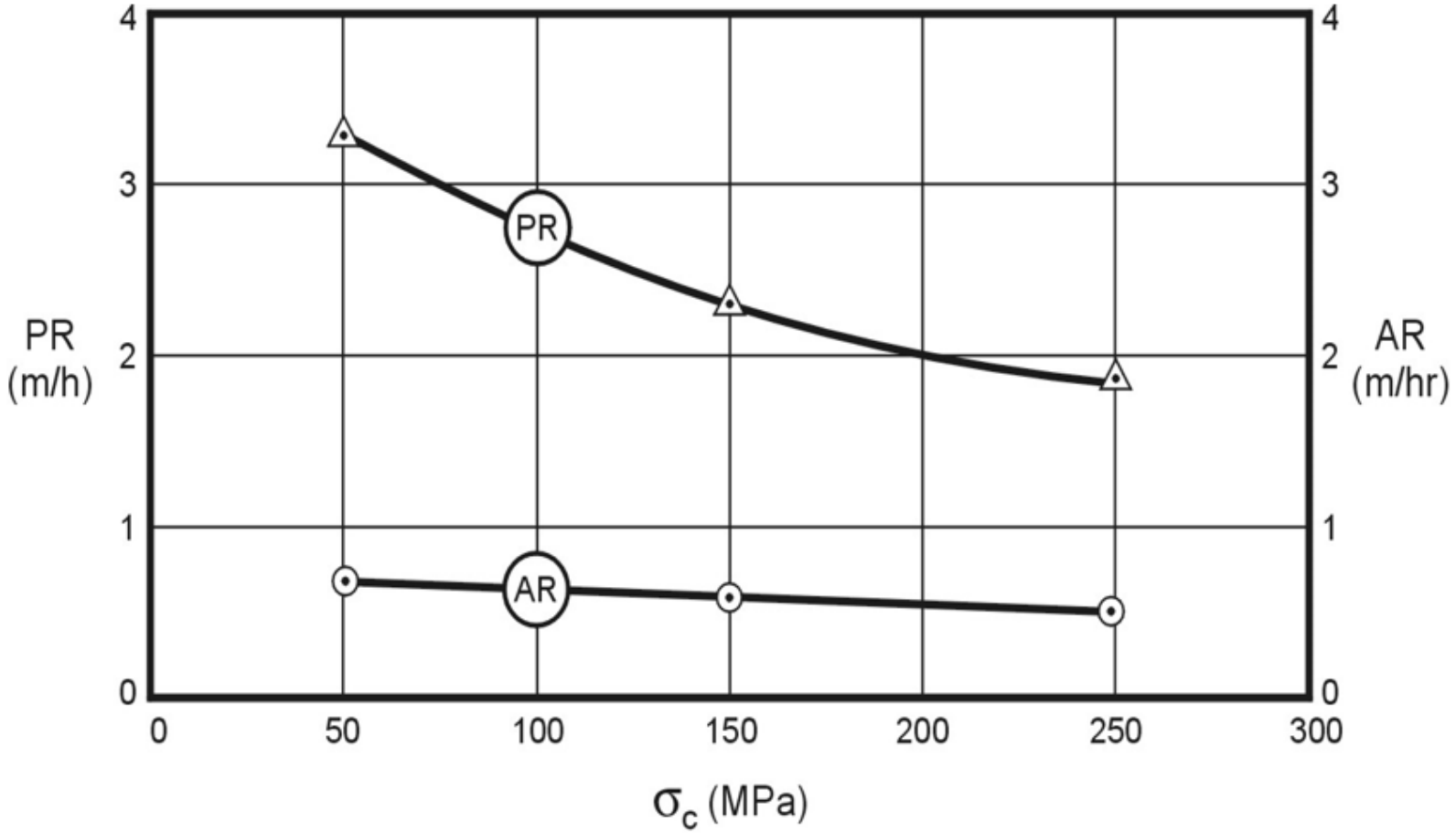
PR, AR, U

PENETRATION RATE (PR) **……CONTINUOUS (SHORT-TERM) RATE OF BORING**

ADVANCE RATE (AR) …..ACTUAL RATE OF TUNNEL ADVANCE: INCLUDE STOPS

EXAMPLES of PR and AR:

Shale, tillite, sandstone σ_c = 50, 125, 250 MPa. (Fawcett, 1993 data, plotted in Barton 2000).



AR = PR x U ???

- **U changes with rock conditions**
- ***U also changes as both time and tunnel length increase!***

1. Q-METHOD IS USEFUL – ALSO when PLANNING TBM!

Q ('rock mass quality') = RQD/Jn x Jr/Ja x Jw/SRF

RQD / Jn = relative block size

Jr / Ja = frictional strength

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

Q = 1000 (or better)

Q = 0.001 (or worse)

(Q = 100/0.5 x 4/0.75 x 1/1)

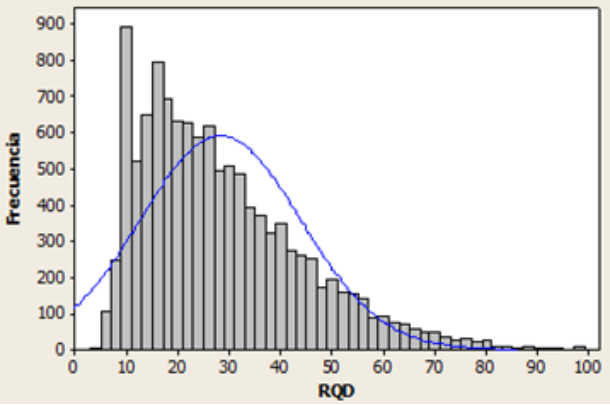
(Q = 10/20 x 1/8 x 0.5/20)

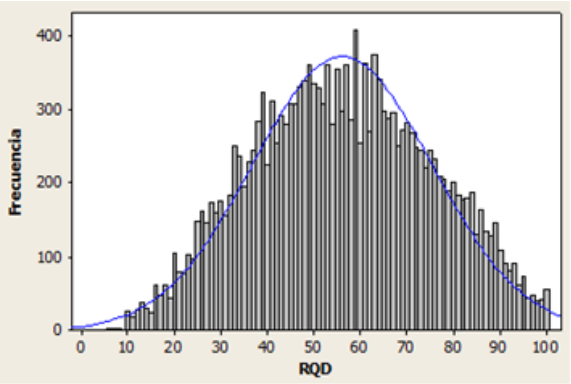
WITH TBM, BOTH OF THE ABOVE CONDITIONS ARE ADVERSE FOR PROGRESS, OBVIOUSLY FOR VERY DIFFERENT REASONS.

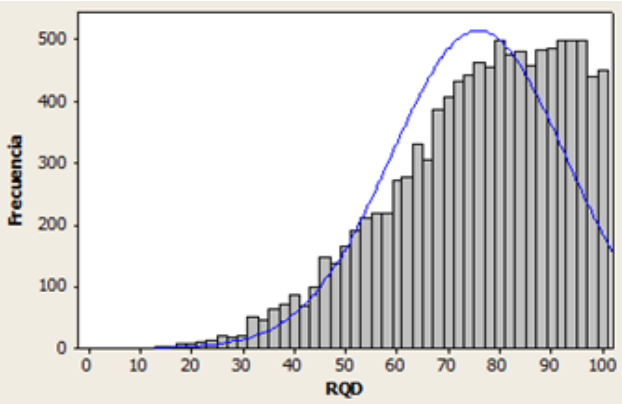
Q-CLASSES 2, 3, *4* AND 5, WITH RESPECTIVE Q-RANGES

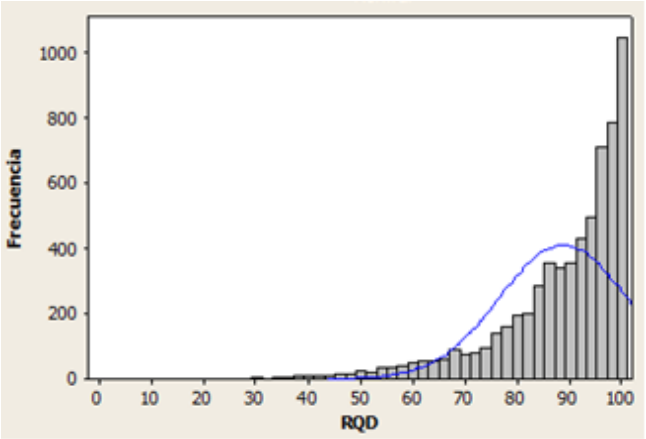
0.1-1, *1-4*, 4-10, 10-40 …….

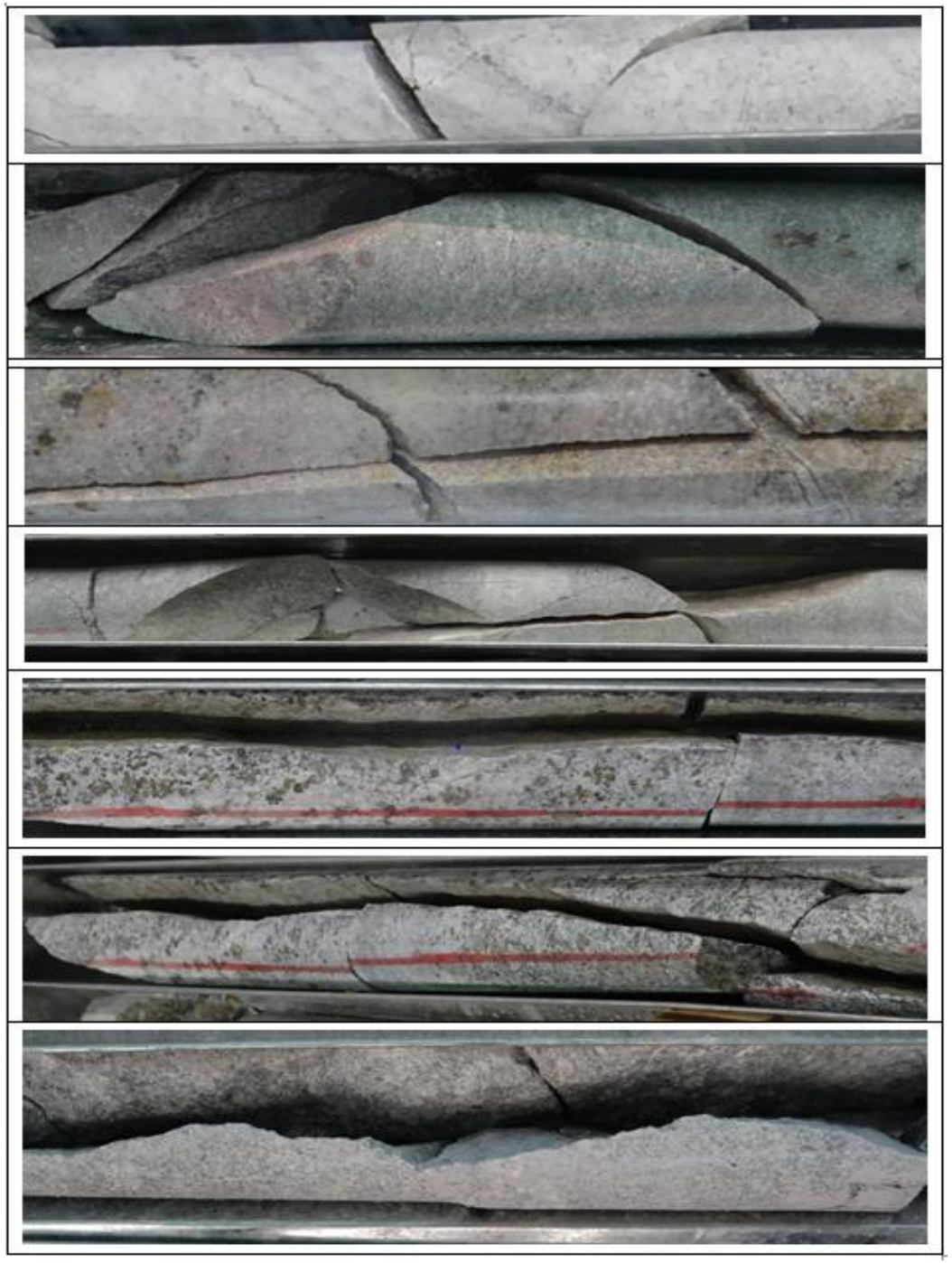
demonstrate central role played by RQD in commonly experienced rock mass conditions. (> 40 km of core)







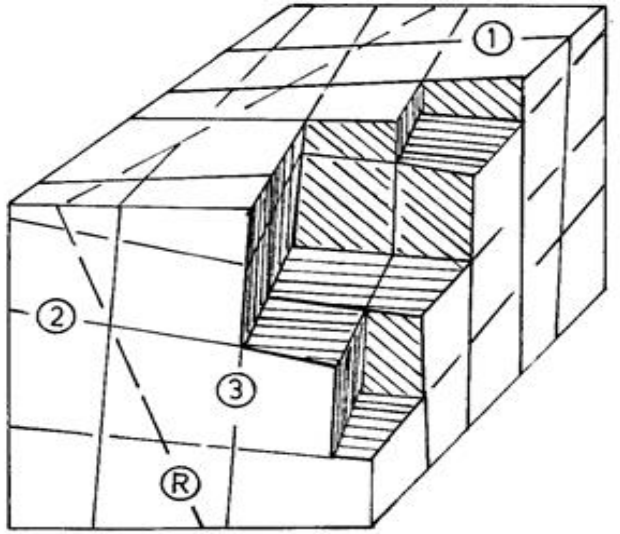


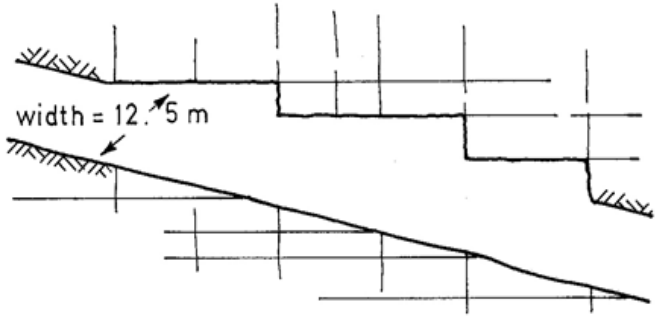


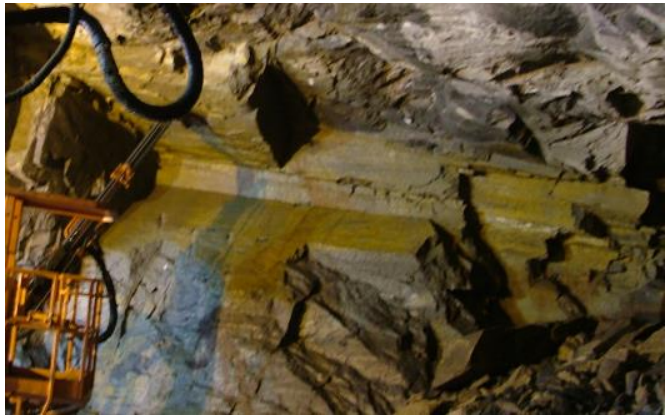
Photos of core with the following Jr values:

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

OVERBREAK WITH Jn/Jr ≥ 6







Jn = number of sets

Jr = roughness

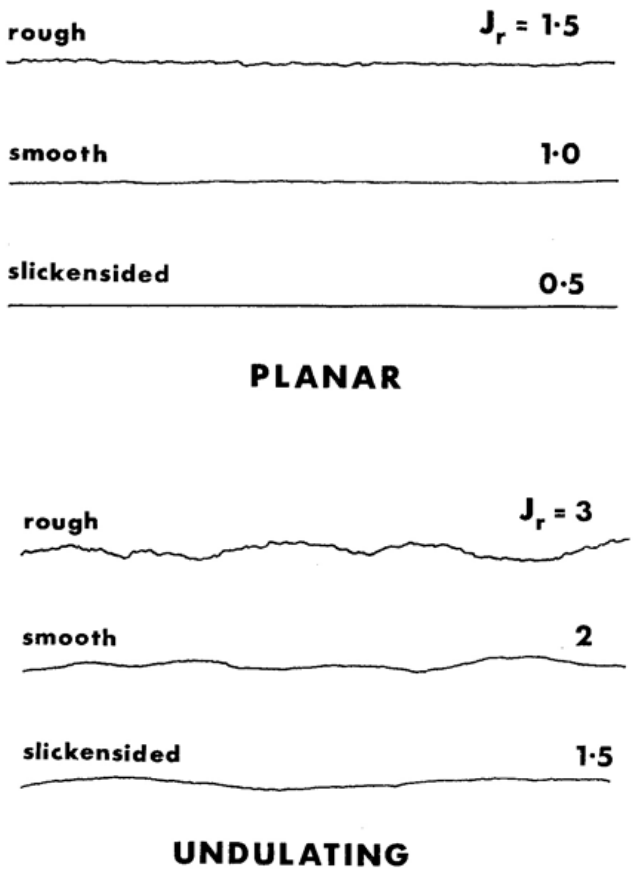
6/1.0 9/1.5

12/2 15/3

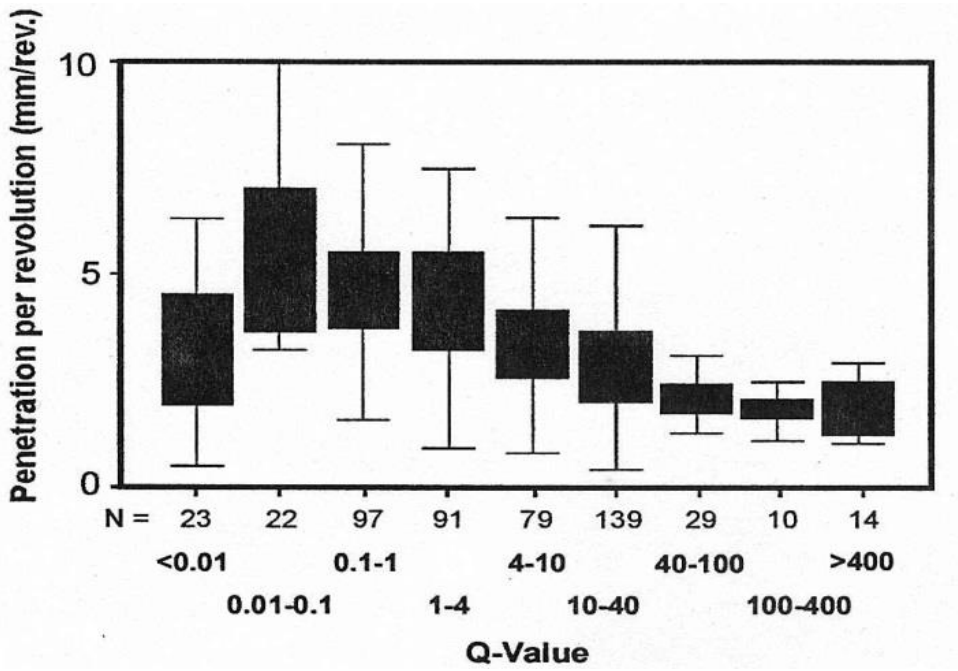
(DESPITE FOUR JOINT SETS, TOO MUCH ROUGHNESS AND DILATION)

In photos:

Jn/Jr = 9/(1-1.5)

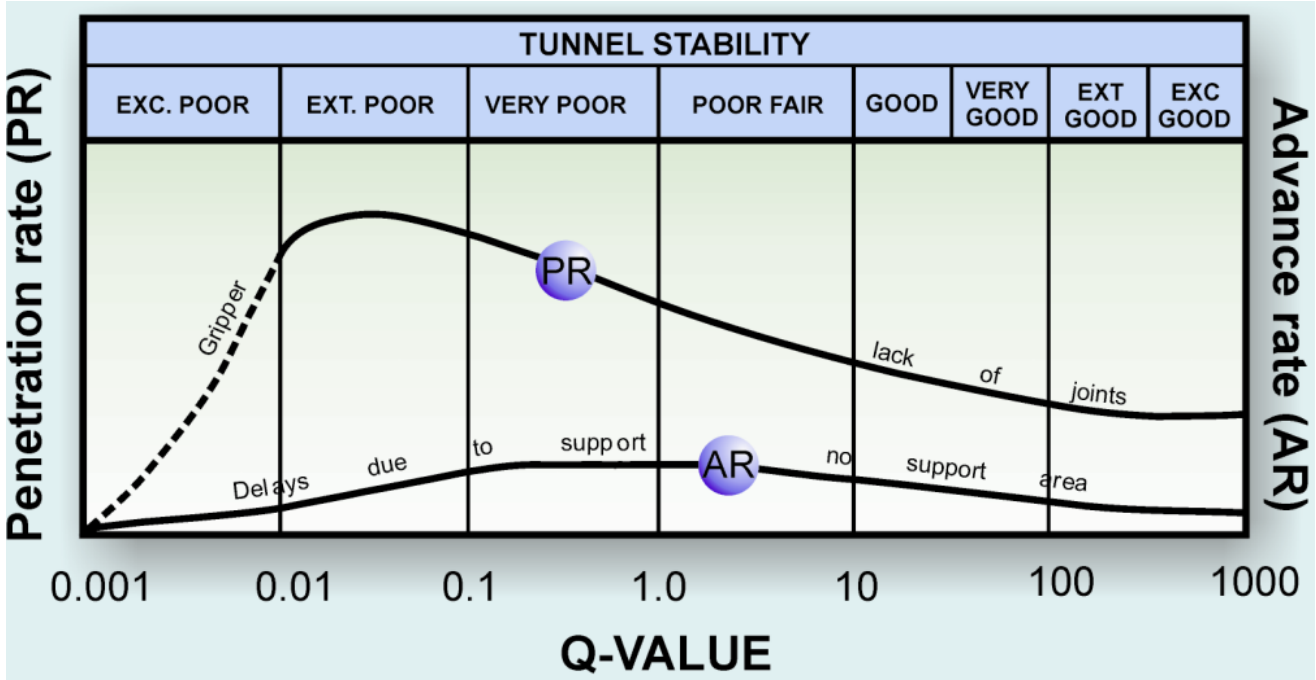


EVIDENCE LINKING Q-VALUES WITH TBM PERFORMANCE – but need new adjectives!



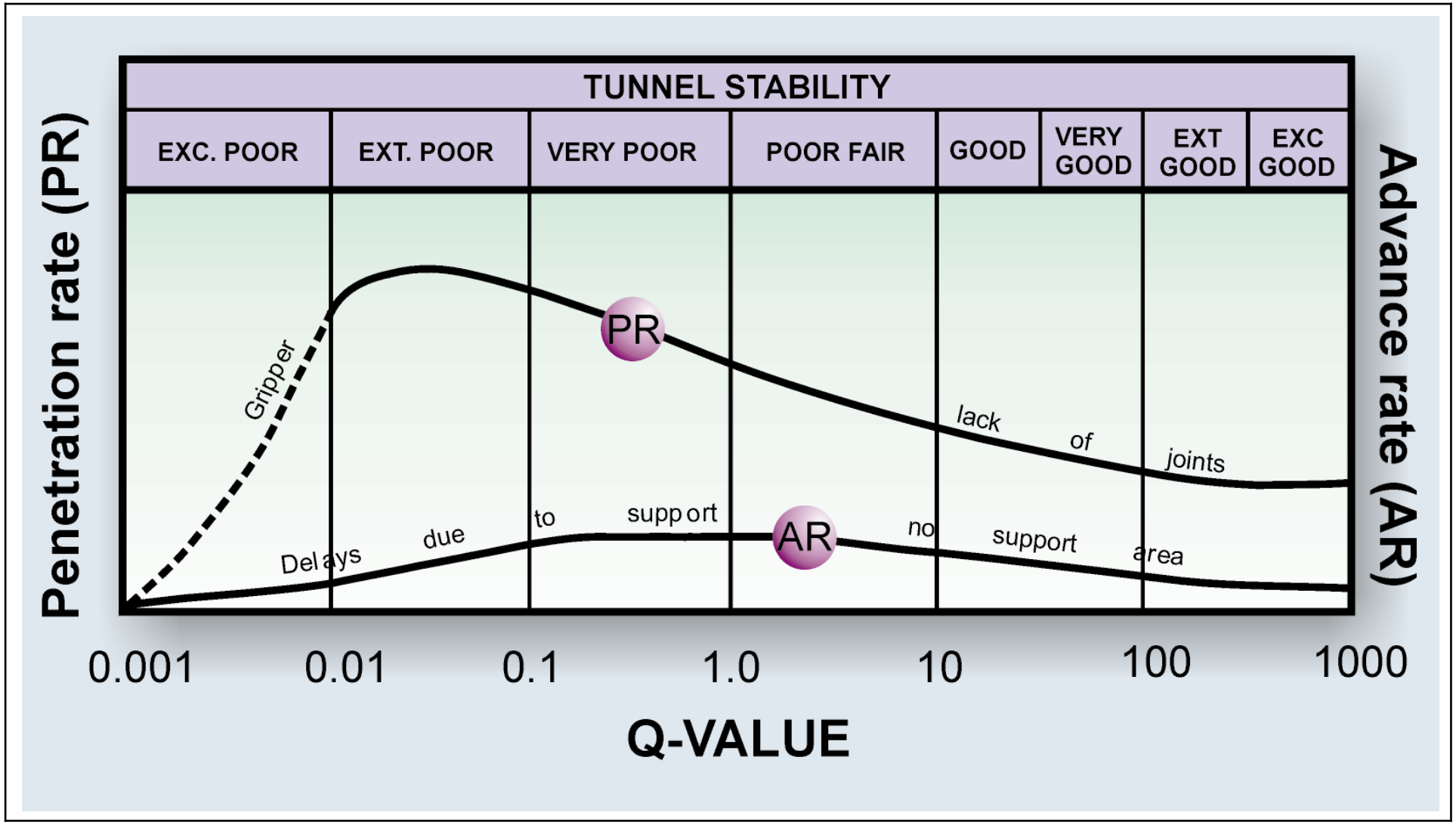
2.85 km in granites. Q-values with all joint sets included (not just least favourable Jr/Ja)

(Sundaram and Rafek, 1998)

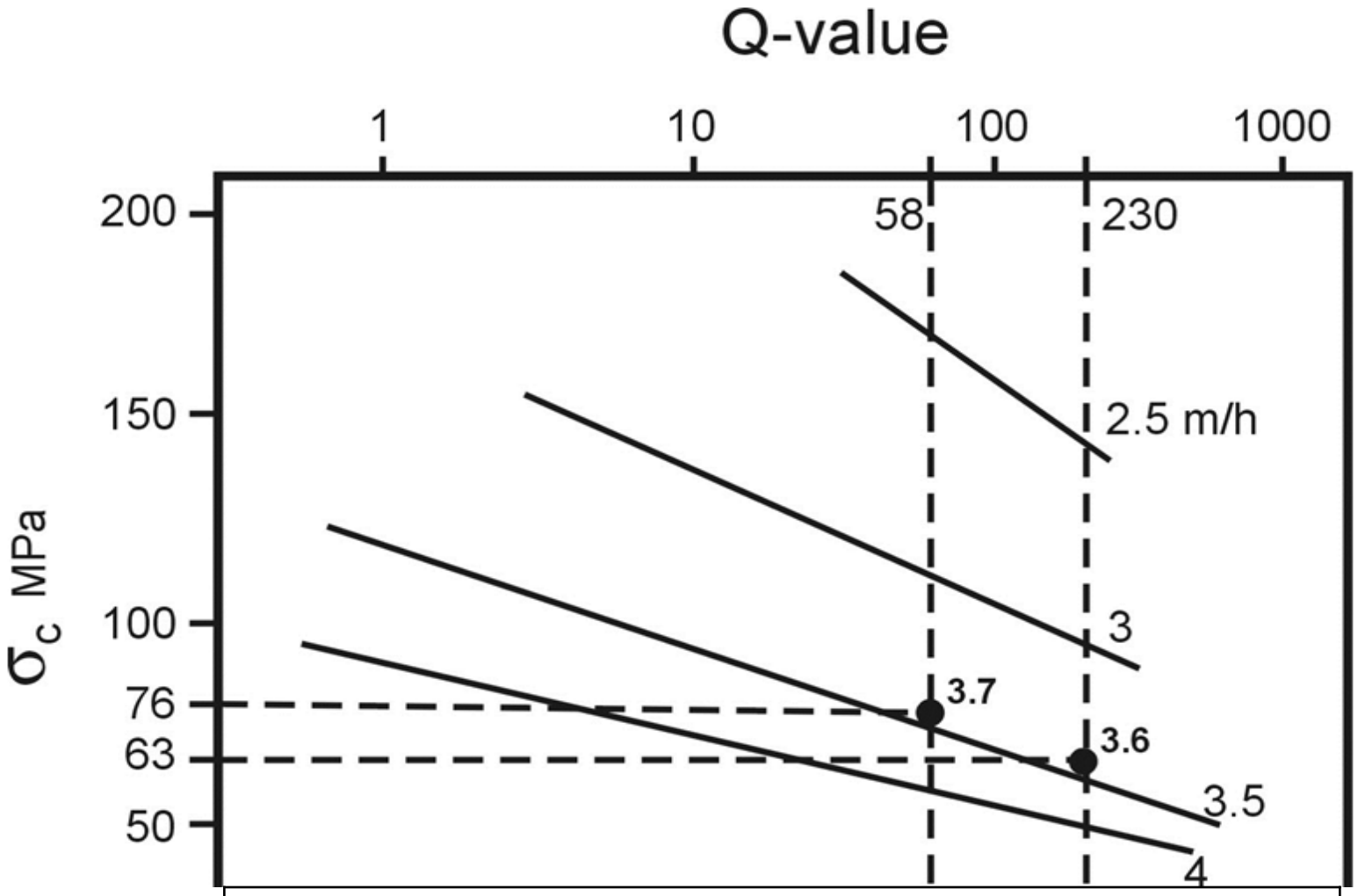


Q-SYSTEM *ADJECTIVES* ARE *MISLEADING* FOR TBM !!

(They are modified later, in *QTBM PROGNOSIS MODEL*)



LOGICAL TRENDS: high Q, high σ_c, low PR



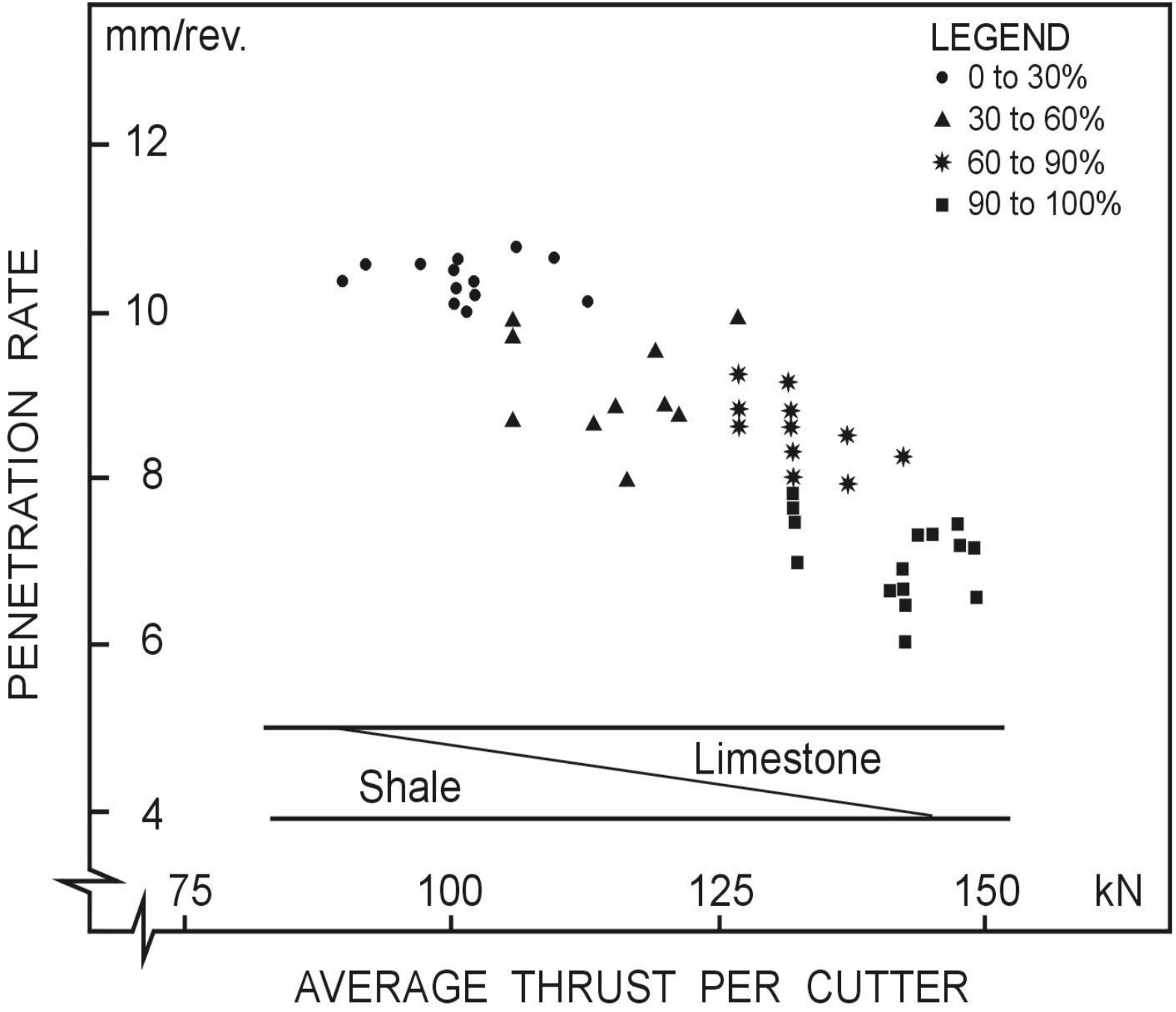
(After Innaurato et al. 1991)

2. HARD ROCK DELAYS

CUTTER FORCE
COMPARED TO AN ESTIMATE OF
ROCK MASS STRENGTH

MIXED-FACE / HARD ROCK

CLI



UNDER-POWERED TBM FROM 1980's.

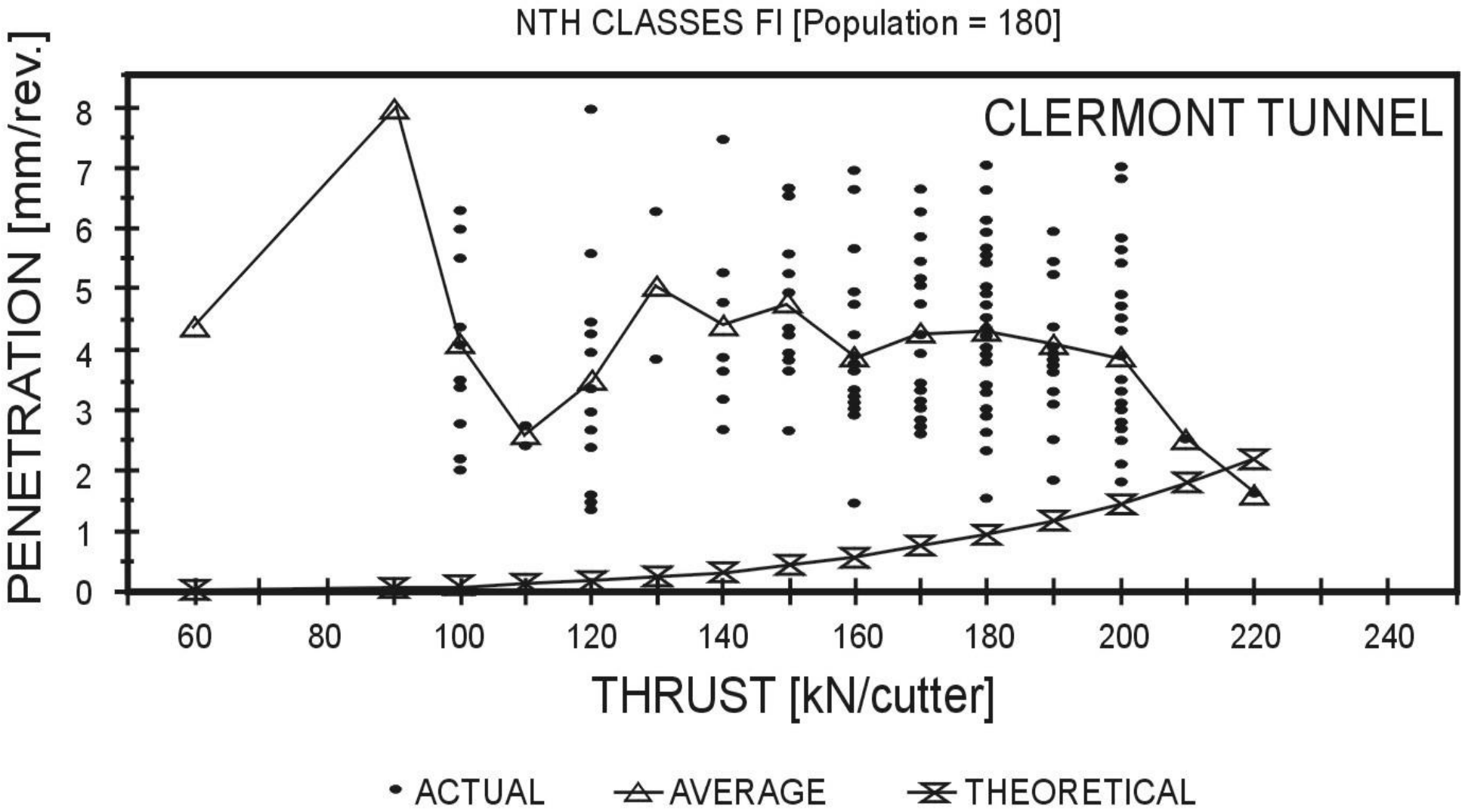
REDUCED *PR* DESPITE INCREASED THRUST/CUTTER.

% HARD LIMESTONE SHOWN. (NELSON ET AL. 1983).

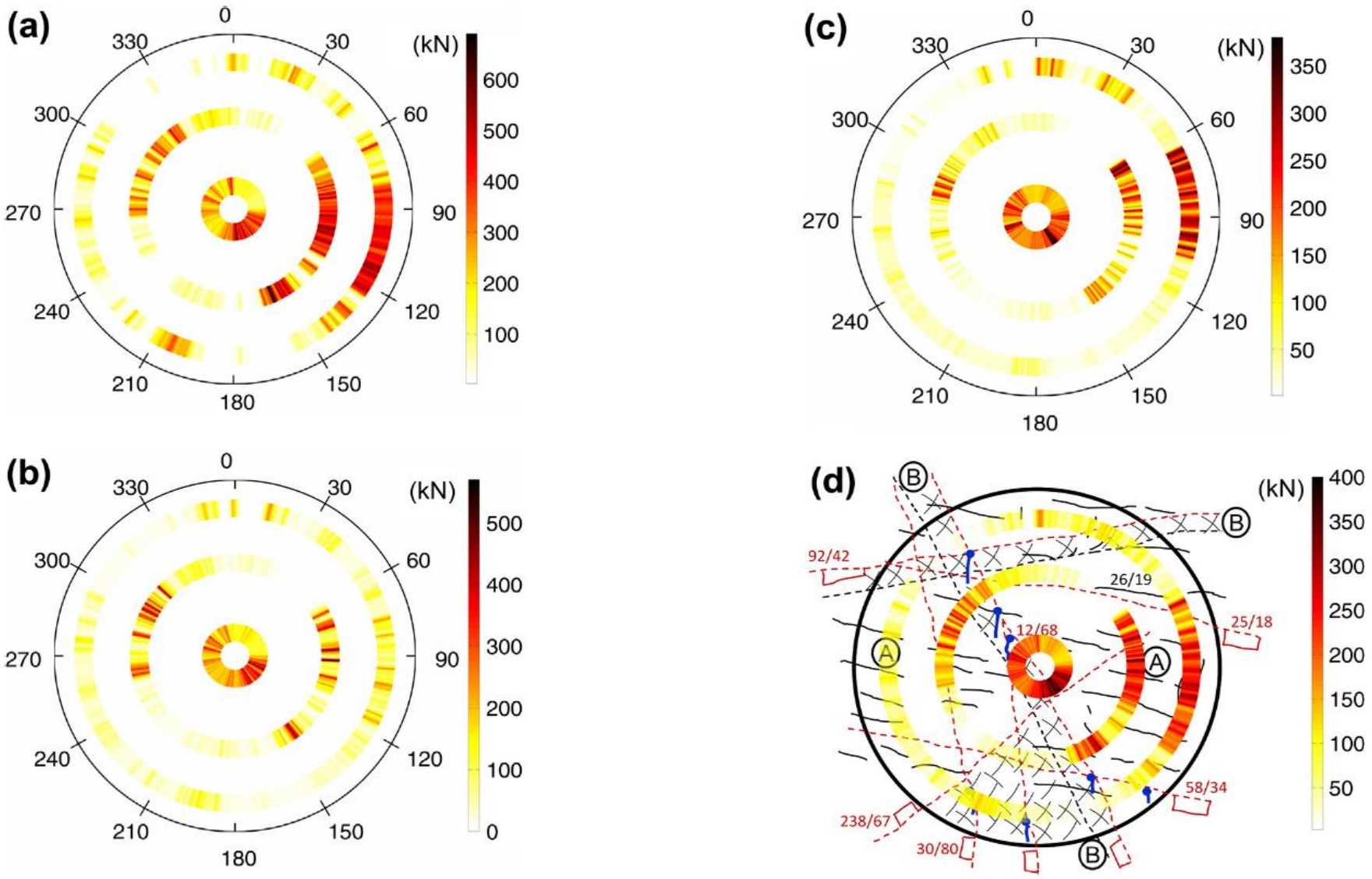
(40 MPa / 130 MPa)

(CAN OCCUR 'TODAY' WITH 150 ➡ 250 MPa)

TBM PROGNOSIS FAILS: …….REDUCED PROGRESS WITH INCREASED CUTTER THRUST, WHEN TBM UNDER-POWERED for VERY HARD META-SANDSTONES.
JOINTING / ROCK STRENGTH (?) INCORRECTLY MODELLED.
(McKelvey et al. 1996)



NORMAL FORCES MONITORED DURING THREE CONSECUTIVE CUTTERHEAD REVOLUTIONS (a–c). AVERAGED FORCES COMPARED WITH THE CORRESPONDING GEOLOGICAL MAPPING (d). (KORALM TUNNEL: Entacher et al., 2013)



OVERBREAK due to JOINTING

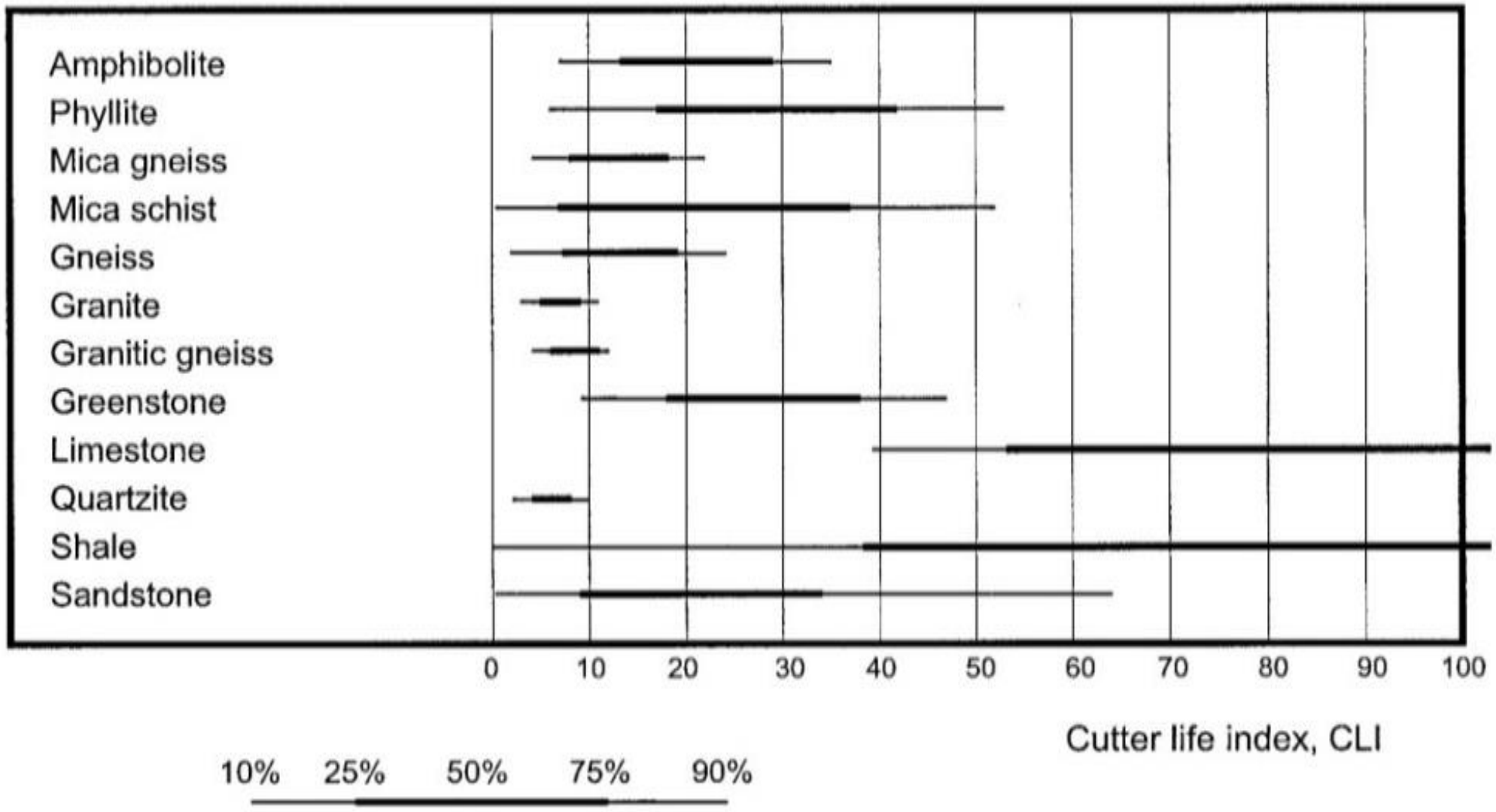
or due to

MIXED-FACE CONDITIONS

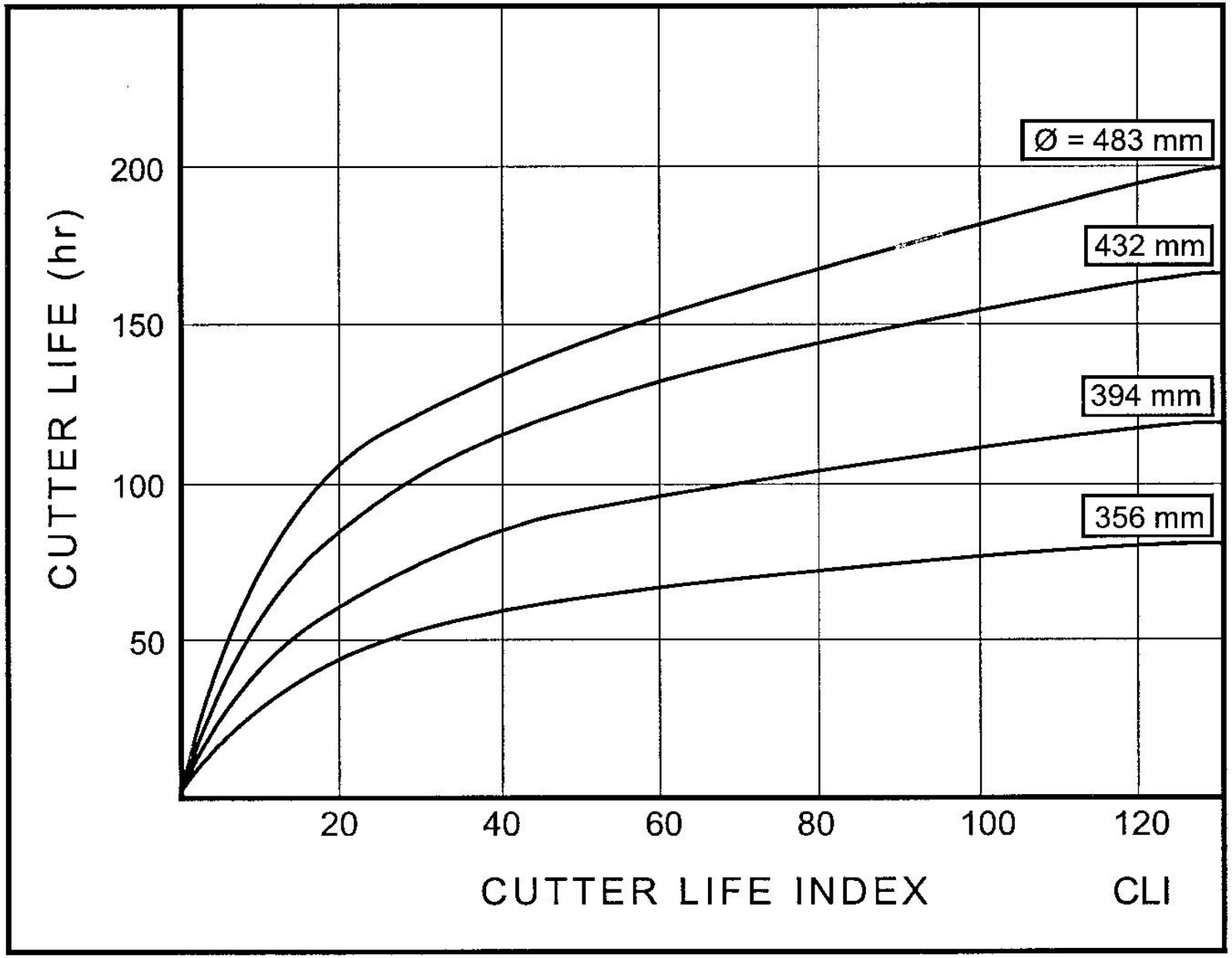
IN VERY HARD ROCK

……

MAY DELAY PROGRESS AND INCREASE CUTTER REFURBISHMENT COSTS DUE TO DAMAGE TO BEARINGS



CUTTER LIFE INDEX (CLI)……NTH/NTNU 1994



LARGEST CUTTERS (19”/483 mm, even 20”) BEST, BUT MORE DIFFICULT TO CHANGE DUE TO HEAVY WEIGHT.

(NTH, 1994).

3. EXTREME DEPTH *CONSIDERATIONS:*

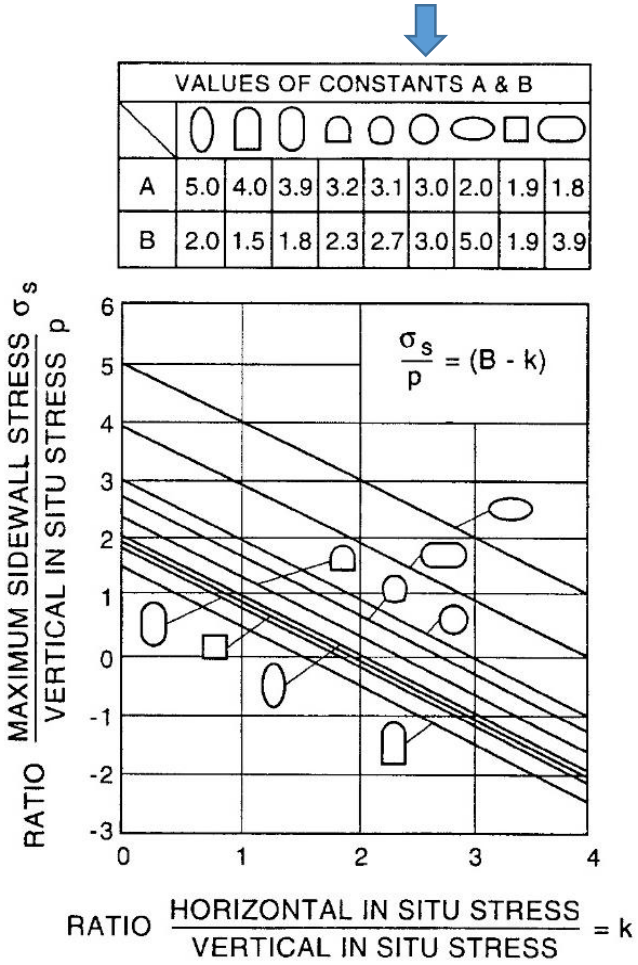
(Jinping II, 2.5km, new project 3.0km?!)

≈ 0.4 x σ_c, ***or σ_t /ν (newly discovered)***

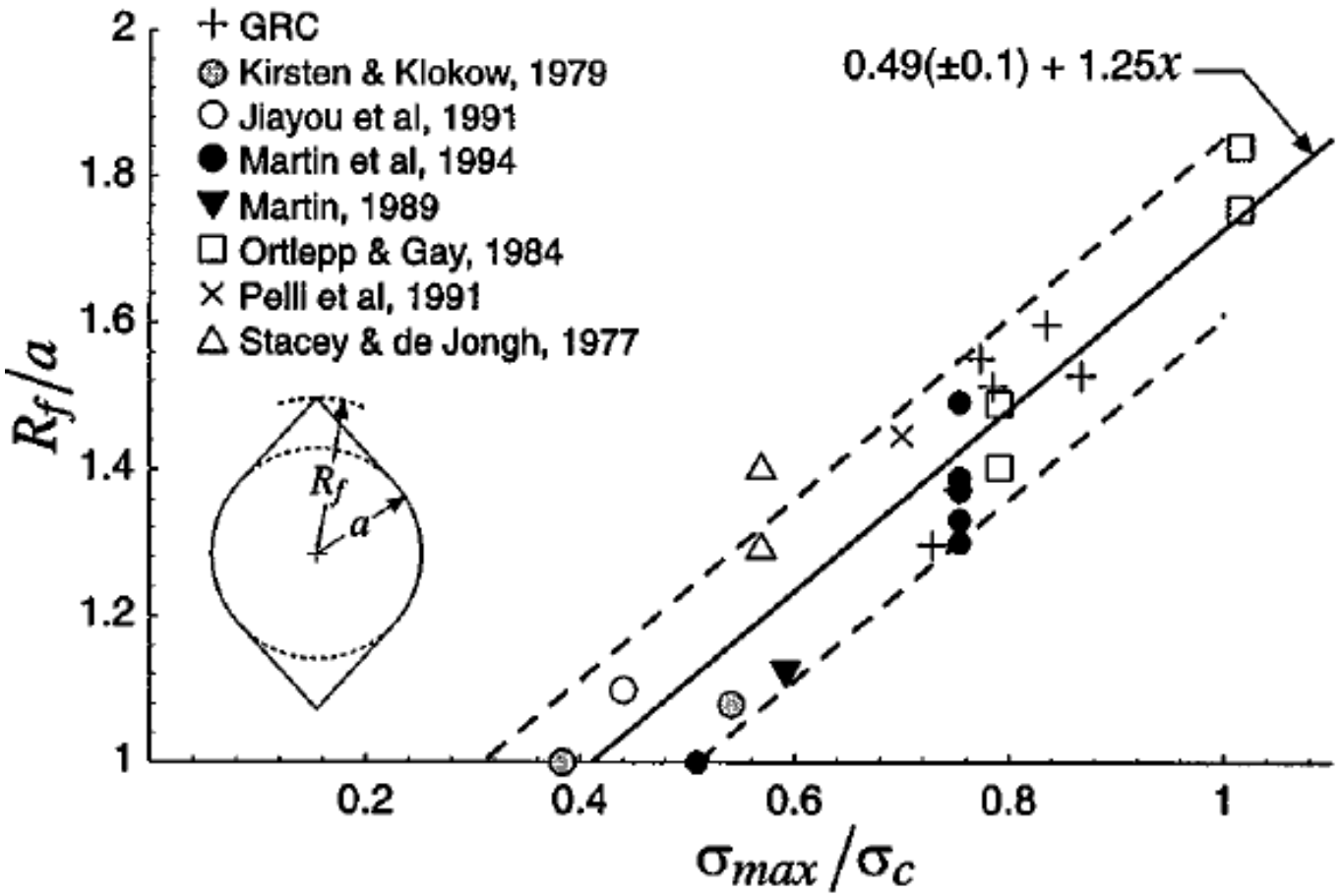
for fracture initiation stress?

TUNNELS IN MASSIVE ROCK: STRESS (or strain?) INDUCED FAILURE? We traditionally expect 'stress-induced' failure when:

$\sigma_{\theta\,max}/\sigma_c > 0.4 +/- 0.1$ …..Maximum tangential stress from: $\sigma_{\theta\,max} = 3\sigma_1 - \sigma_3$



(Hoek and Brown, 1980)



(Martin et al. 1997)

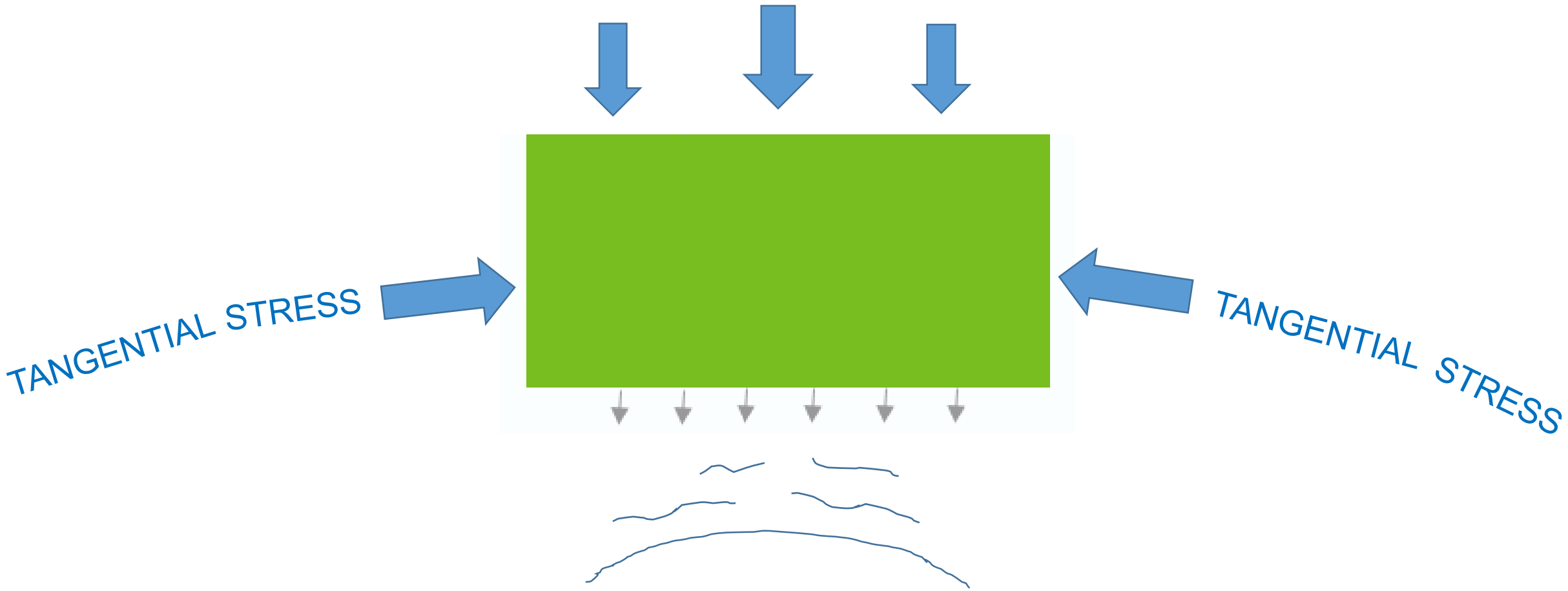
IN Q-SYSTEM, SAME EXPECTATION. If $\sigma_{\theta\,max}/\sigma_c > 0.4$, get: high SRF – and lower Q-value – more tunnel support.

(σ_c = UCS unconfined compression strength)

(Table 6b of Grimstad and Barton, 1993)

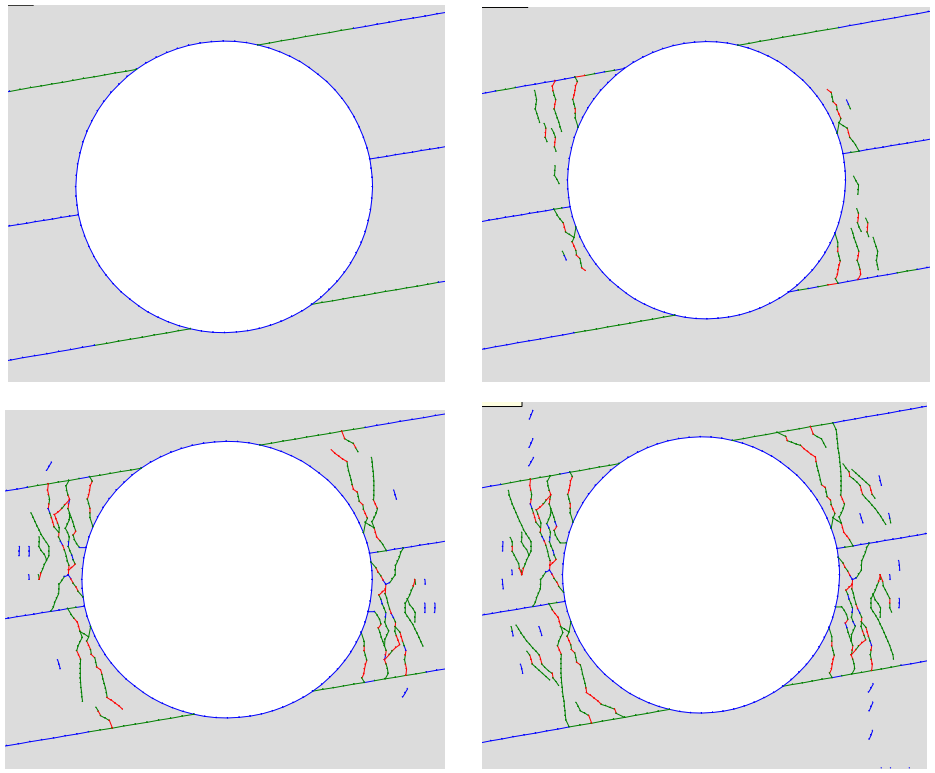
b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c	SRF
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4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

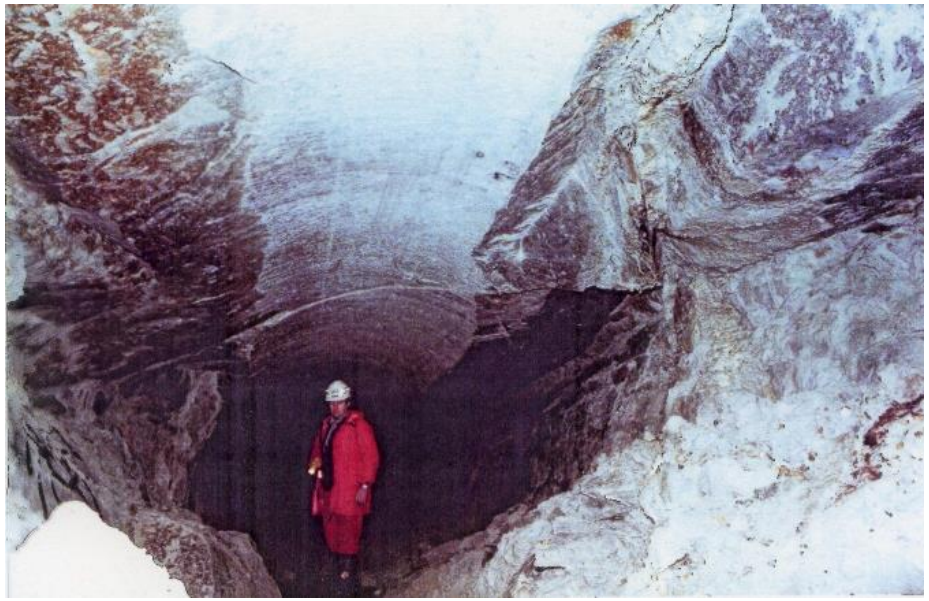
AROUND A TUNNEL: **Poisson's ratio** causes lateral strain



NEXT TO THE TUNNEL MAY GET TENSILE CRACKING

– EVEN WHEN ALL STRESSES ARE STILL COMPRESSIVE





CRACKING IS ACTUALLY CAUSED BY EXCEEDING THE ***CRITICAL EXTENSION STRAIN:***

Cracking in tension, then shear:

(Not 'compression' failure)

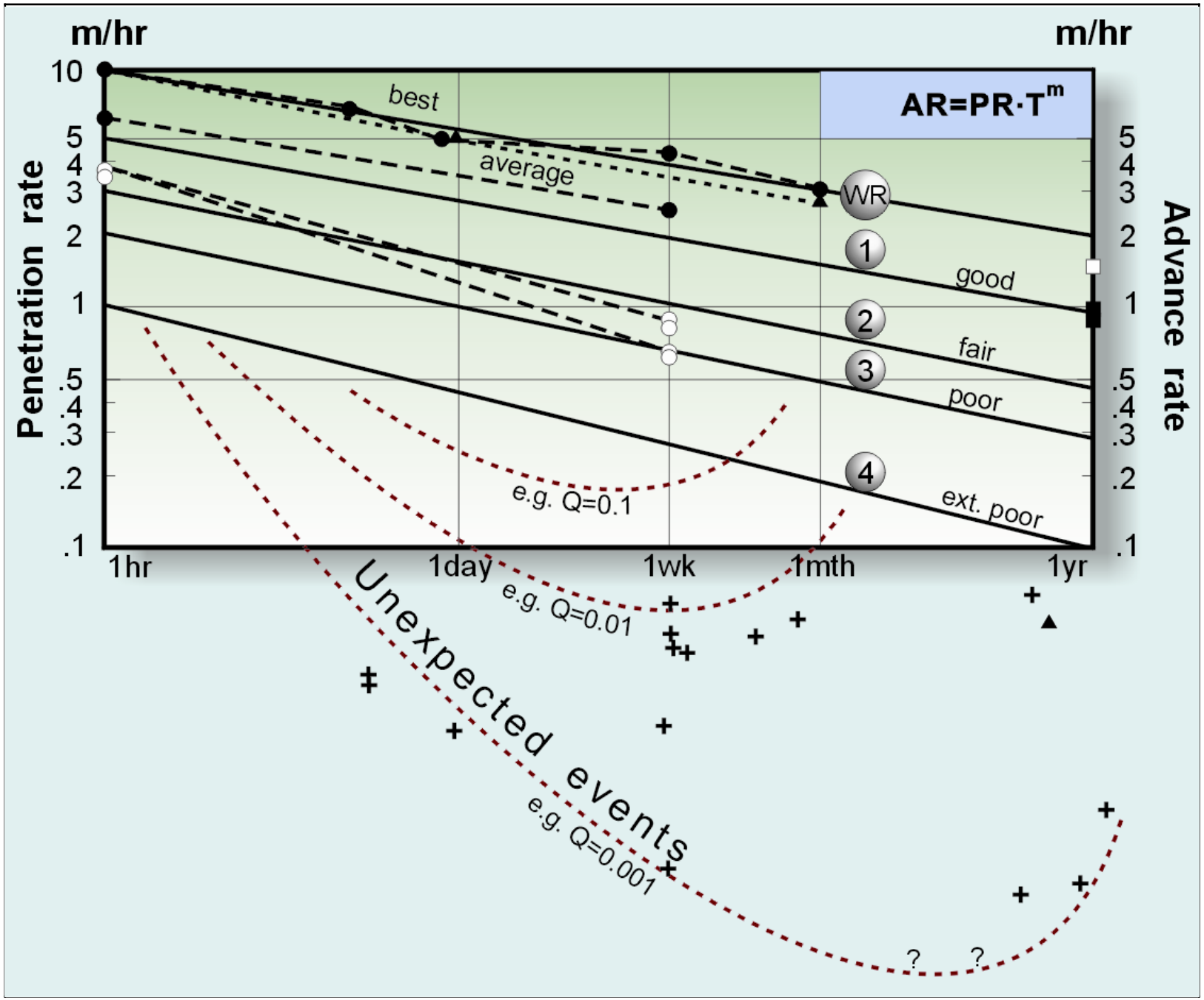
(Stacey, 1981 and Baotang Shen……Barton and Shen, 2017)

$$\sigma_{critical\ tangential\ stress} \approx (0.4 \times UCS) \approx \sigma_t / \nu$$

(derived from $\varepsilon_3 = [\ \sigma_3 - \nu.\sigma_1]\ /E$ and:)

$$\sigma_t / \nu \approx \boxed{\frac{UCS}{10\nu} = \frac{UCS}{10 \times 0.25} = 0.4 \times UCS}$$

4. CASE-RECORD SURVEY for MOSTLY OPEN-GRIPPER TBM (AND COMPARE TO WORLD-RECORD TBM PERFORMANCES



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

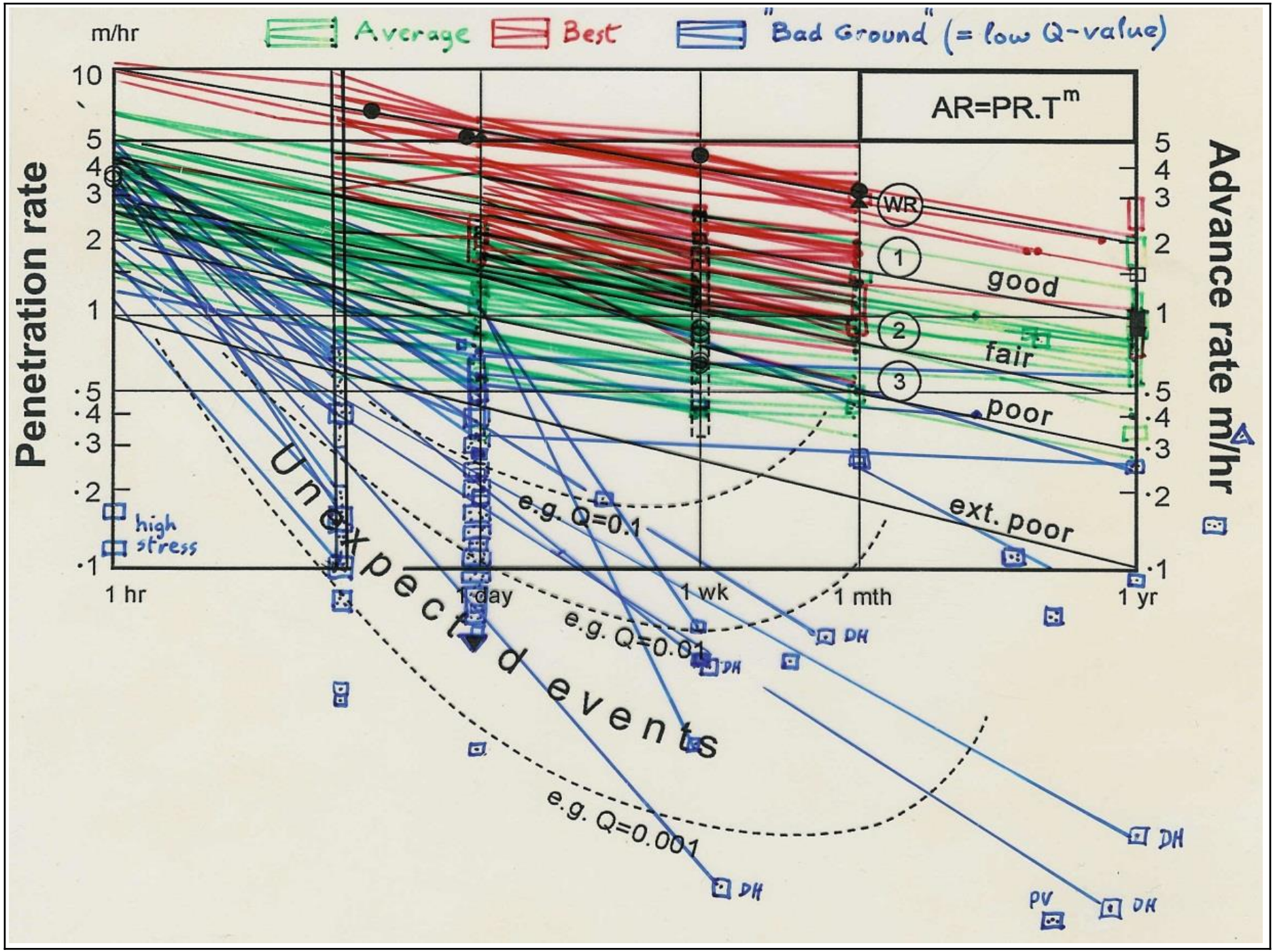
(Mostly open-gripper cases)

Conventional equation:

AR = PR x U

but reality is :

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



BEST

MEAN

WORST

Note: no horizontal lines!

WORLD RECORDS FOR HIGH SPEED TUNNEL EXCAVATION

DIAMETER	3 - 4 m	4 - 5 m	5 - 6 m	6 - 7 m
BEST DAY	172 m Robbins Katoomba Australia ★	128 m Robbins SSC No. 4 USA	99 m Robbins Little Calumet USA	114 m Robbins Dallas Metro USA
BEST WEEK	703 m Robbins Katoomba Australia ★	477 m Robbins SSC No. 4 USA	562 m Robbins Little Calumet USA	500 m Robbins Dallas Metro USA
BEST MONTH	2066 m Robbins Oso USA	1822 m Robbins Yellow River China	2163 m Robbins Little Calumet USA ★	1690 m Robbins Dallas Metro USA
MONTHLY AVERAGE FOR PROJECT	1189 m Robbins Katoomba Australia	1352 m Robbins Yellow River China ★	1095 m Robbins Yindaruqin China	1187 m Robbins Dallas Metro USA

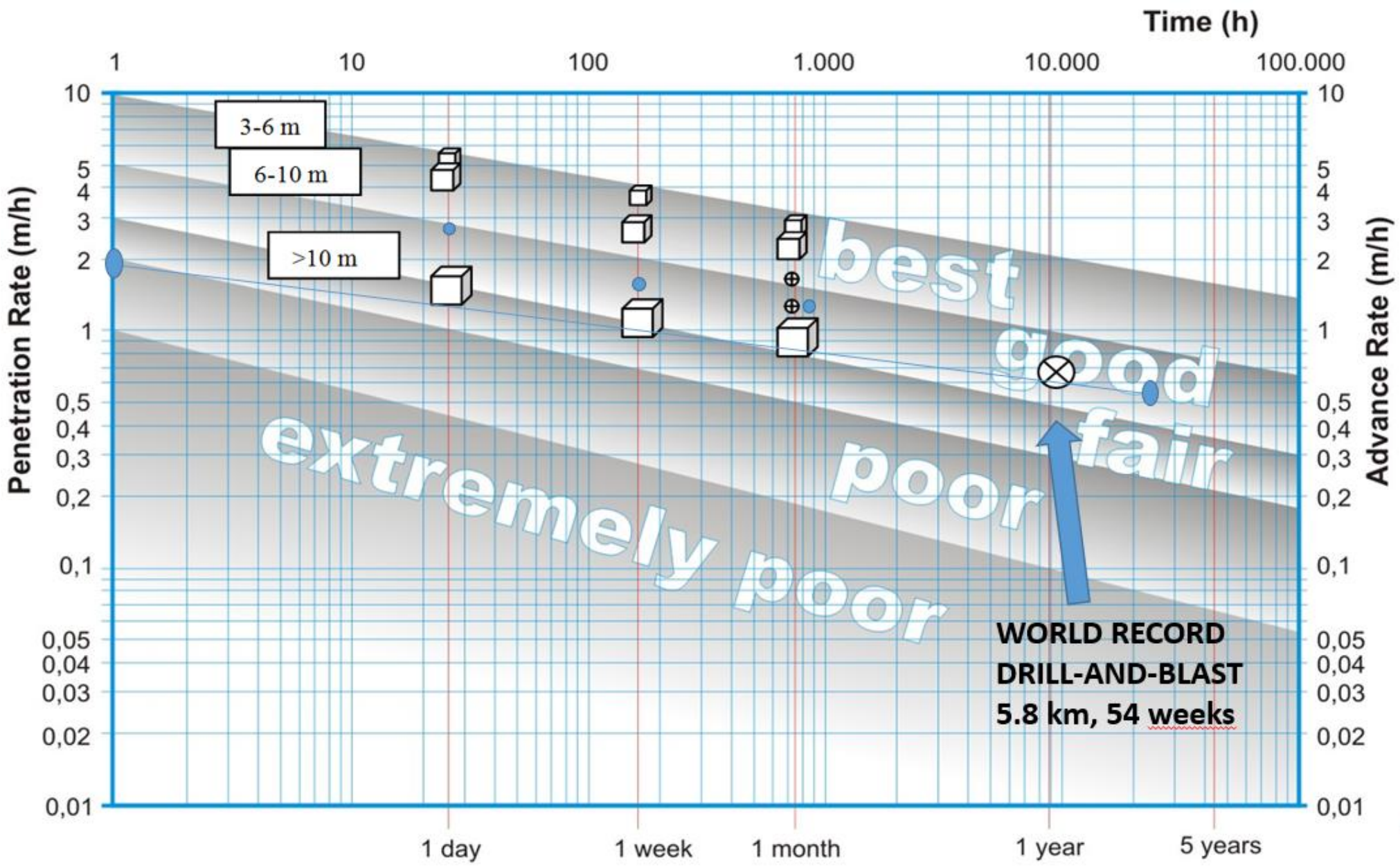
DIAMETER	7 - 8 m	8 - 9 m	9 - 10 m	10 - 11 m	11 - 12 m
BEST DAY	115 m Robbins Karahnjukar Iceland	75 m Robbins Channel Tunnel UK	74 m Robbins TARP Chicago USA	48 m Robbins TARP Chicago USA	30 m Herrenknecht Murgenthal Switzerland
BEST WEEK	428 m Robbins Karahnjukar Iceland	428 m Robbins Channel Tunnel UK	324 m Robbins TARP Chicago USA	185 m Robbins TARP Chicago USA	100 m Robbins Bozberg Switzerland
BEST MONTH	1482 m Robbins TARP Chicago USA	1719 m Robbins Channel Tunnel UK	982 m Wirth Guadarrama Spain	685 m Robbins TARP Chicago USA	385 m Robbins Bozberg Switzerland
MONTHLY AVERAGE FOR PROJECT	770 m Robbins TARP Chicago USA	873 m Robbins Channel Tunnel UK	715 m Robbins TARP Chicago USA	none reported	none reported

ROBBINS WEB SITE. TBM RECORDS

★ **172m one day !**
★ **703m one week !**
★ **2163 m one month !**
(16 km one year !)

BEST MONTH = 2163m, BUT BEST MONTHLY AVERAGE *'ONLY'* 1352m. ★

UK chalk marl: UCS 5-9 MPa



WORLD RECORDS COLLECTED IN SIZE BRACKETS:

(3-6m, 6-10m, > 10m).

MOSTLY ROBBINS WORLD RECORDS)

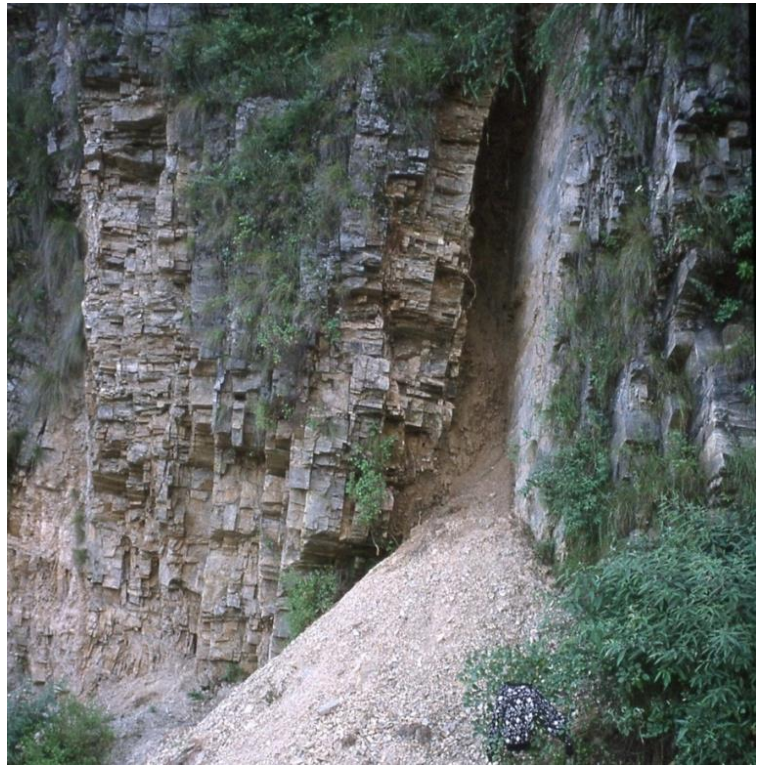
- 4x14km best
- mean 56km
- Guadarrama 9m

(Barton, 2013)

5. TBM DELAYS (mostly) IN FAULT ZONES:

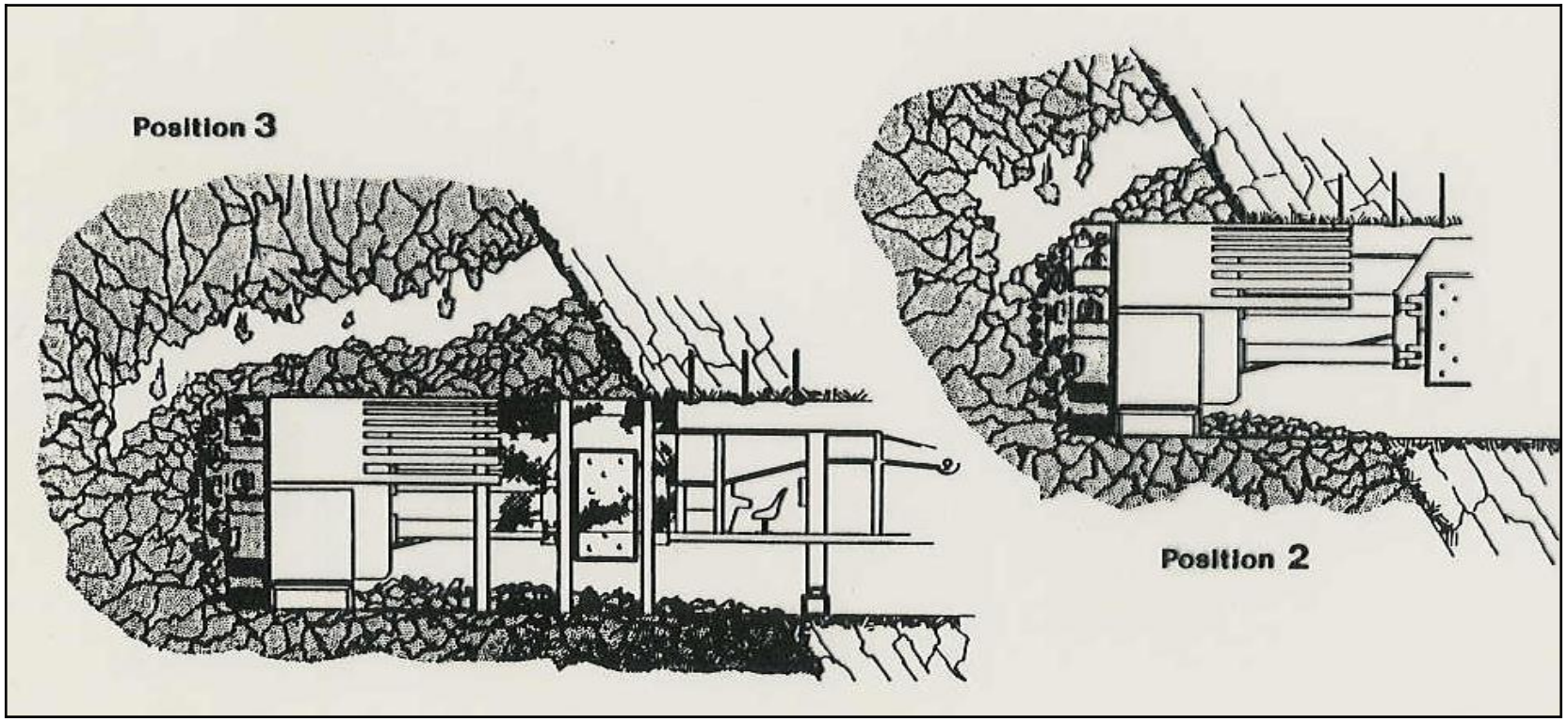
(USA, Greece, Chile, Taiwan, Italy, Kashmir, Iran etc.)

FAULT ZONES ARE UNIQUE CHALLENGES FOR *TUNNELLERS IN GENERAL* BECAUSE…….



RQD, Jn, Jr, Ja, Jw, SRF……..

all the Q-parameters *(and everybody else's parameters!)* may be adverse, also TIME + COST

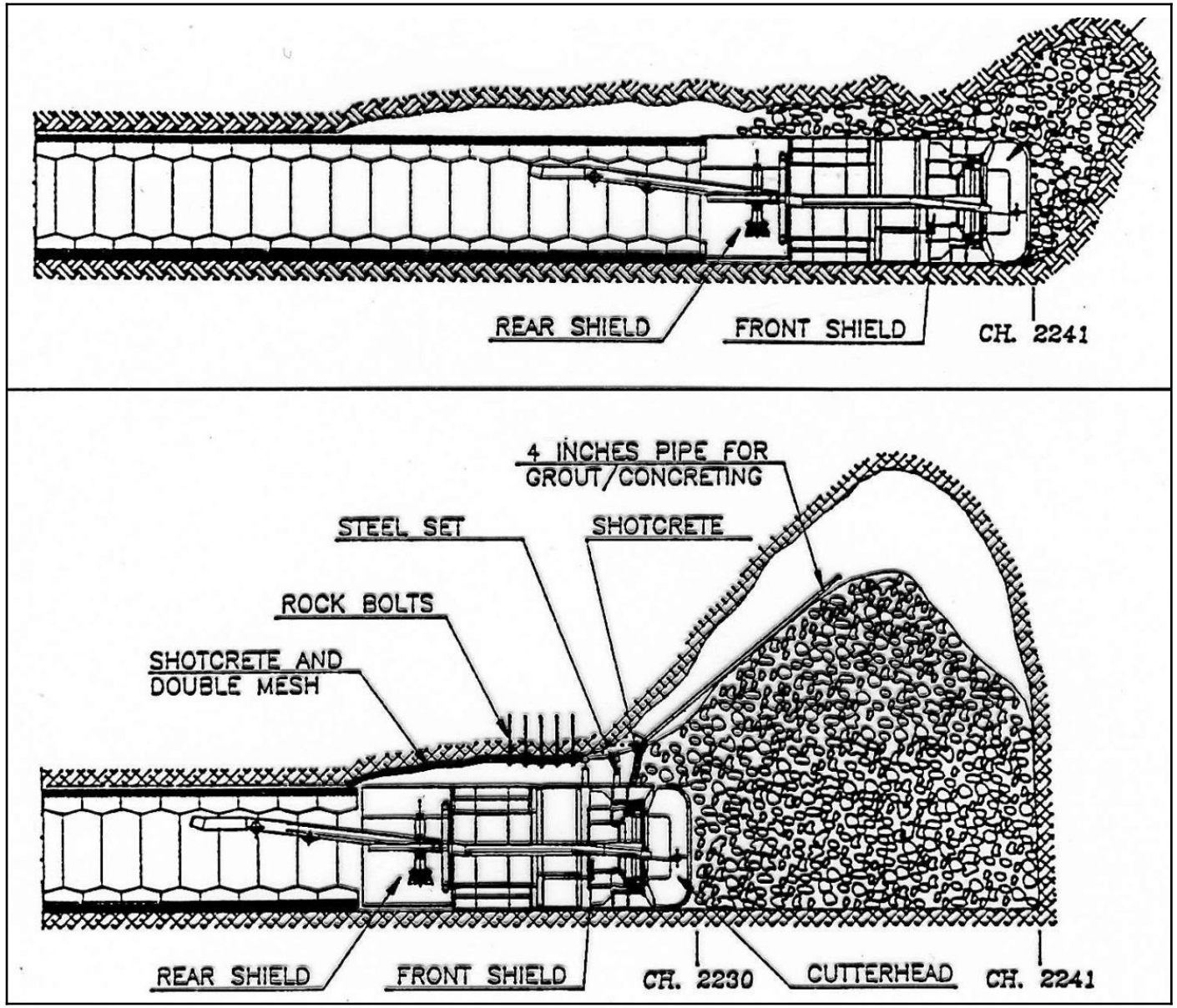


‘TYPICAL’ SCENARIO: FAST PROGRESS, PROBE DRILLING NOT BEING DONE. HIT PROBLEM. CUTTER-HEAD BLOCKED.

SEVERAL MONTHS LOST

SAME PROJECT: WORLD RECORD BREAKING 2.1 km IN BEST MONTH.

(ROBBINS, 1982)



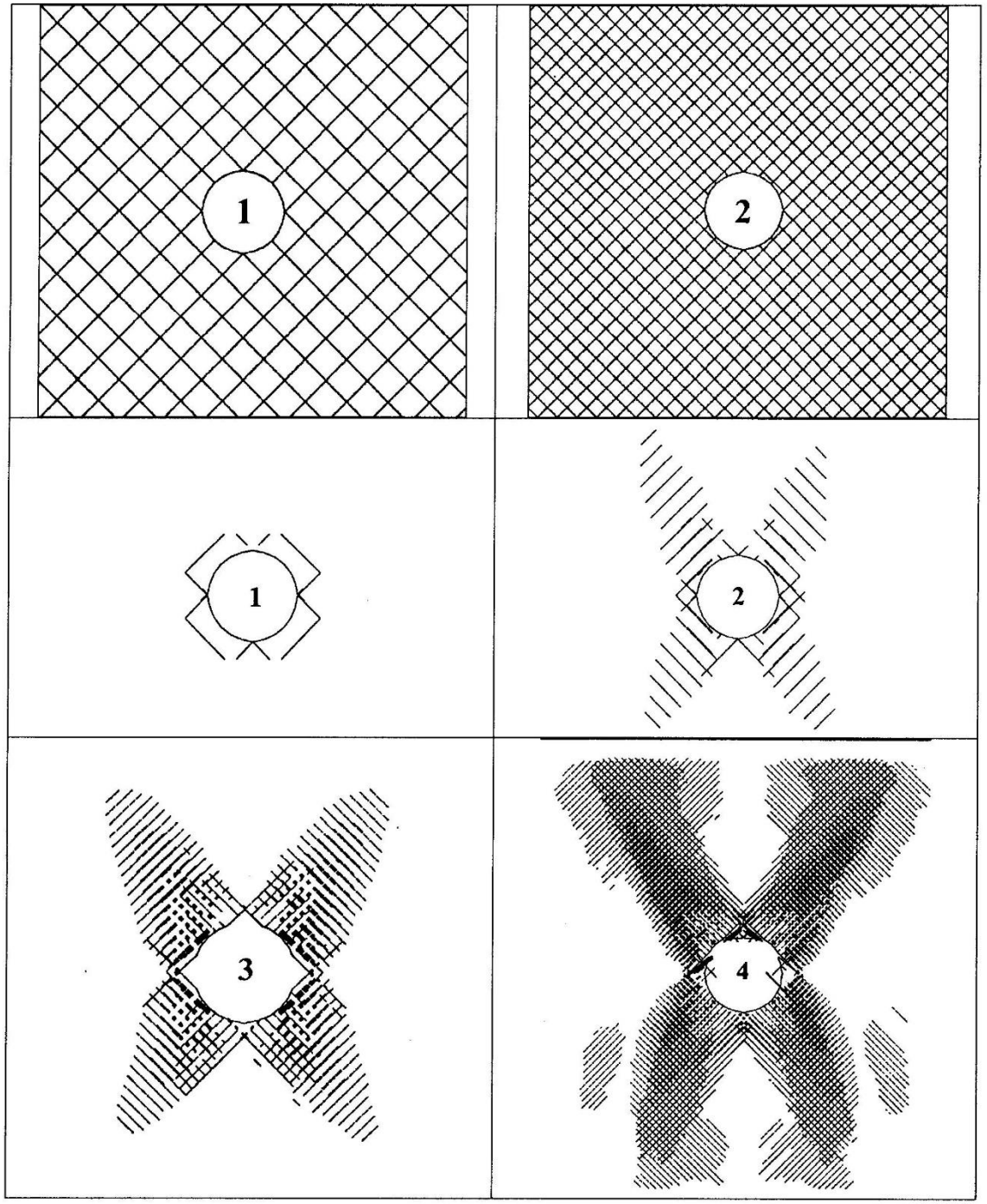
EVINOS-MORNOS WATER TUNNEL, *GREECE*

FAULT ZONES ALSO CREATE *PROBLEMS FOR DOUBLE-SHIELD* TBM –

IF ZONE IS NOT PRE-TREATED (FOLLOWING PROBE-DRILLING DISCOVERY ??)

(Grandori et al., 1995).

LESSON: AVOID TBM WITHDRAWL

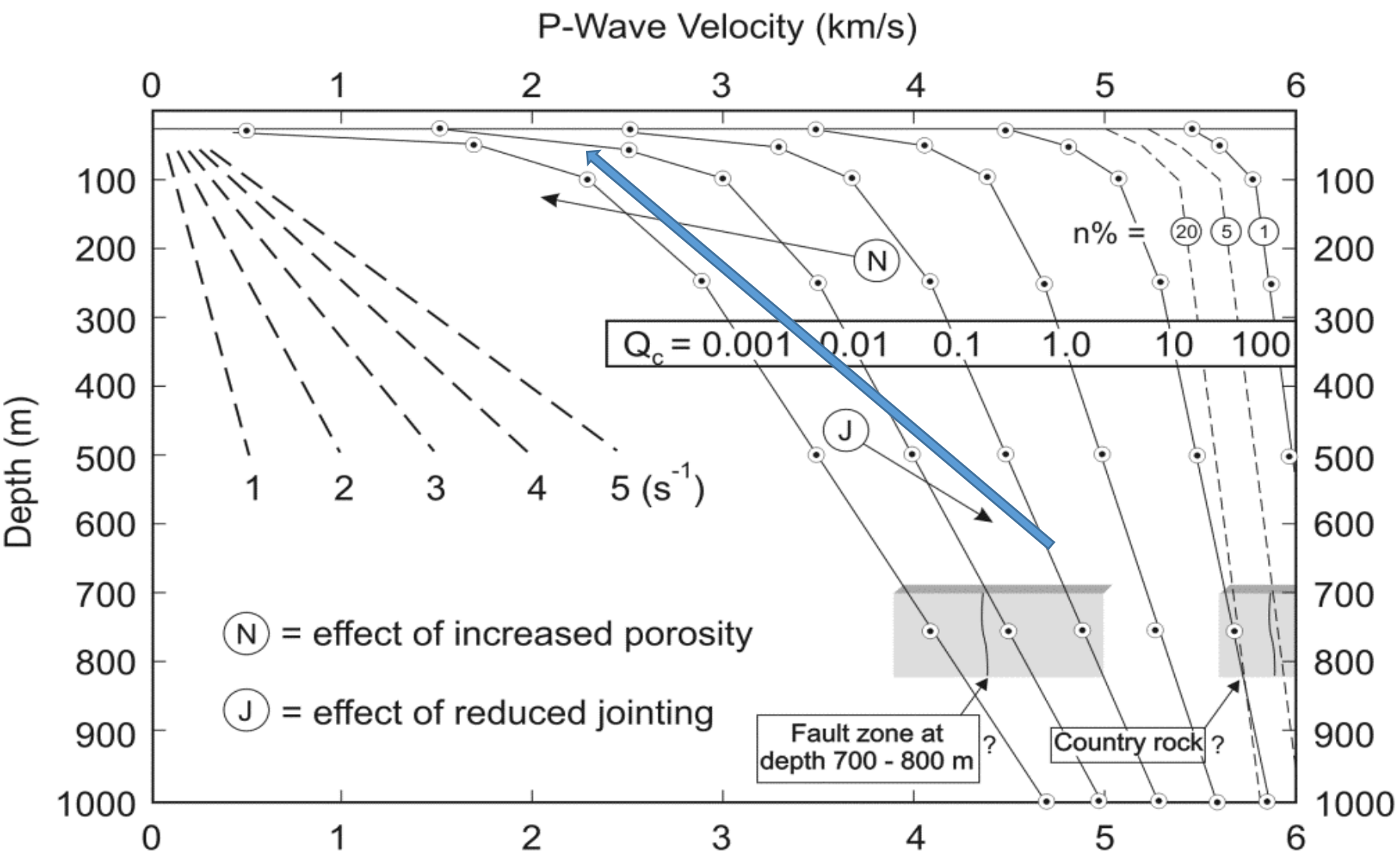


DISTINCT ELEMENT UDEC MODELS

SUGGEST POTENTIAL ‘TRAUMA’ IN (heavily fractured) FAULT ZONES

i.e. VERY DEEP EDZ

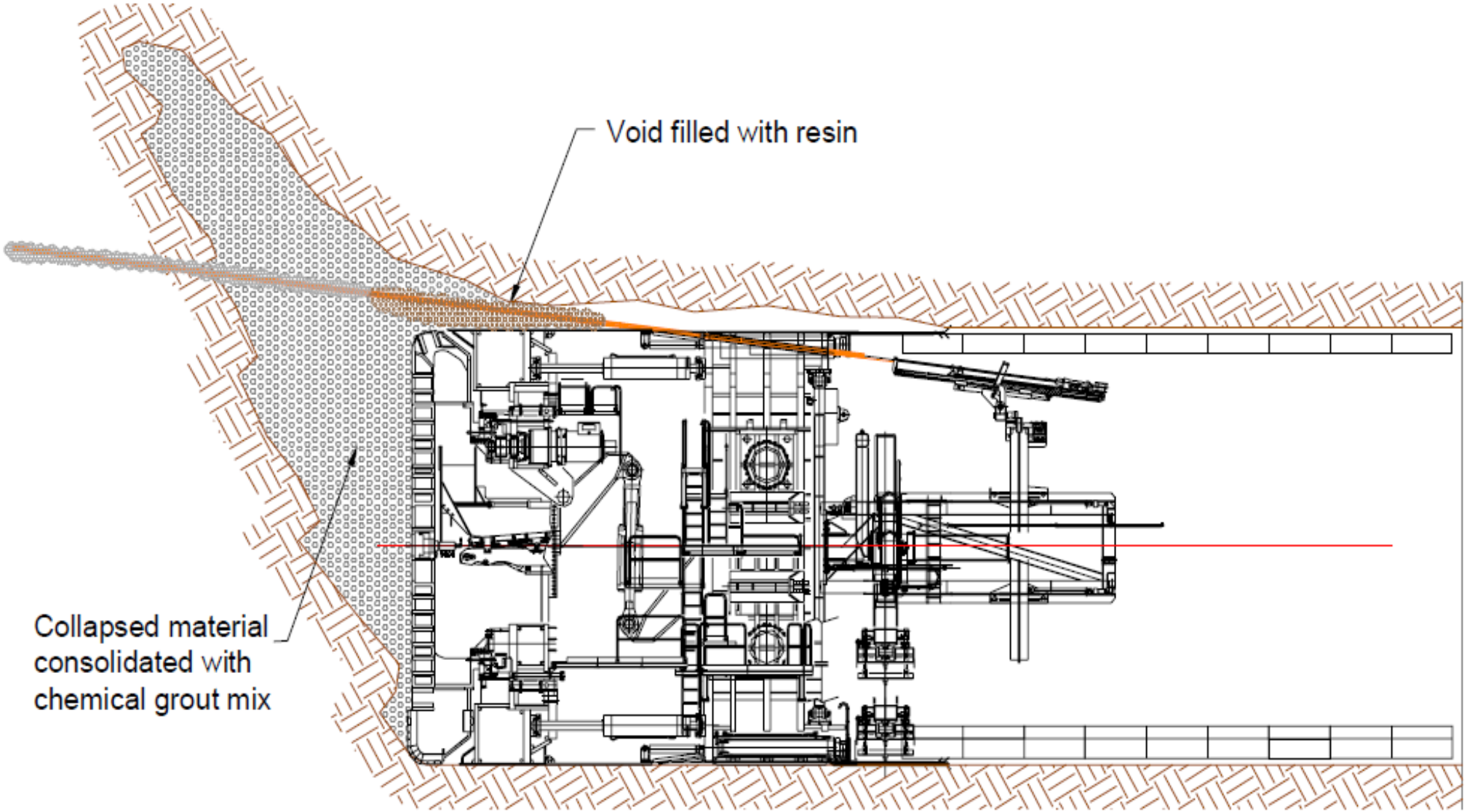
(Shen and Barton, 1997)

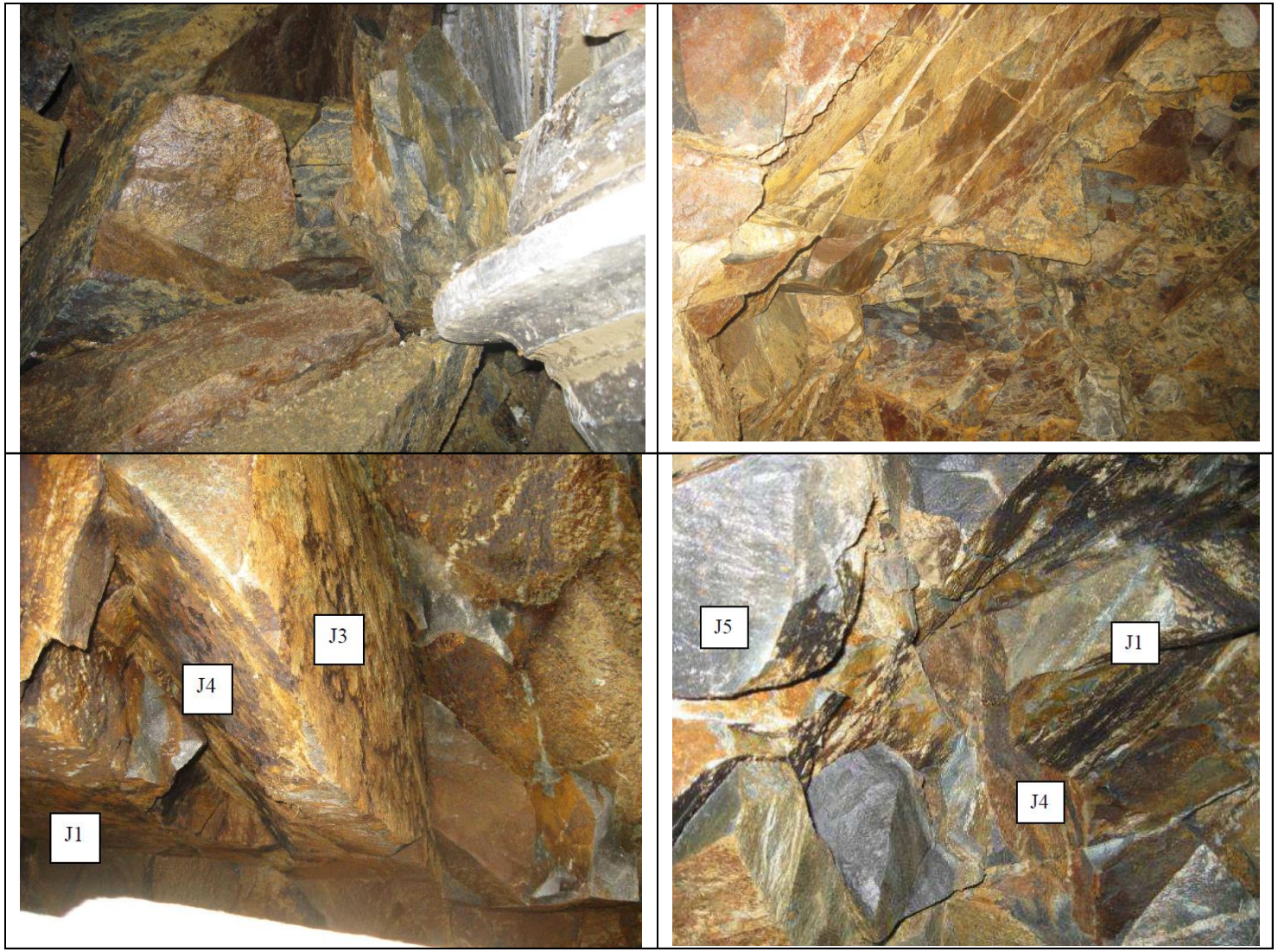


BECAUSE VELOCITY Vp IS STRESS-DEPENDENT, STRESS RELEASE (BY WITH-DRAWING A TBM) HAS AN ADVERSE EFFECT ON PROPERTIES AND STAND-UP TIME

(Barton, 2006)

OVER-BORING IN *FAULTED ROCK*: CARE WITH VOID-FILLING MATERIAL! 15-25 m/day reduction to 2.5-5 m/day, FOR ≈ 1 MONTH





MINE ACCESS TUNNEL

DOUBLE-SHIELD MACHINE 'OVER-EXCAVATED' IN THIS FAULTED ZONE.

WHEN Jn/Jr ≥ 6, OVER-BREAK OR OVER-BORING IS LIKELY

Q ≈ 40/*15* x *1.5*/4 x 1.0/2.5 = 0.4 'very poor'

.....(i.e. Jn/Jr ≥ 6)

DUL HASTI HEP, INDIAN KASHMIR

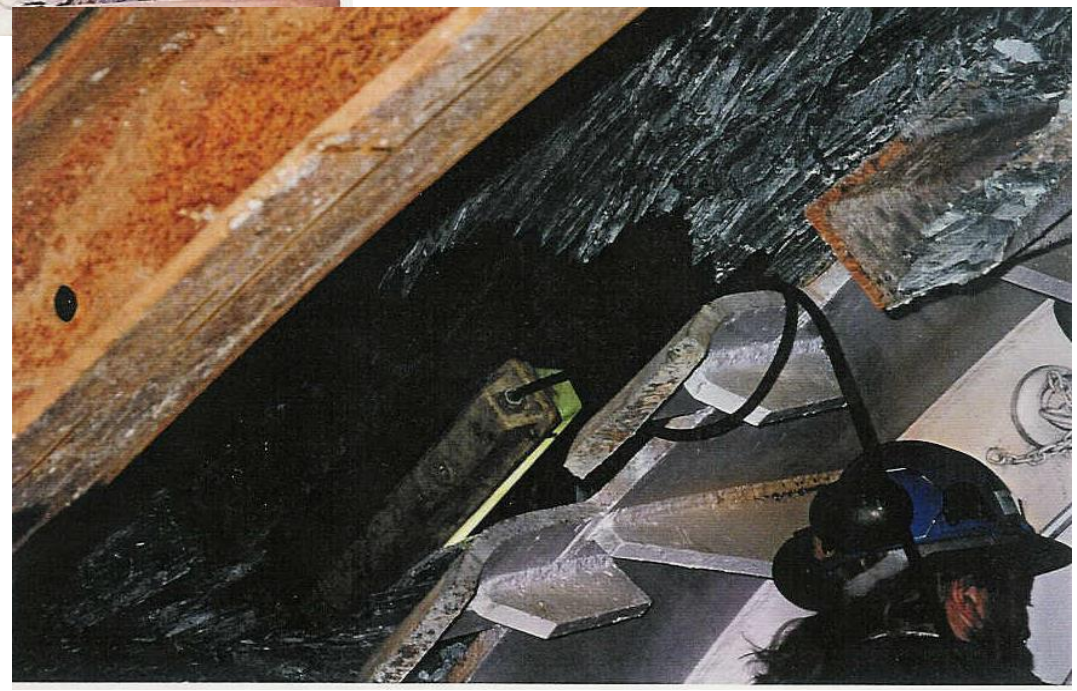
OVER-BORING PROBLEMS IN SHEARED, TALCY- PHYLLITE

(New contractor, using inherited TBM)

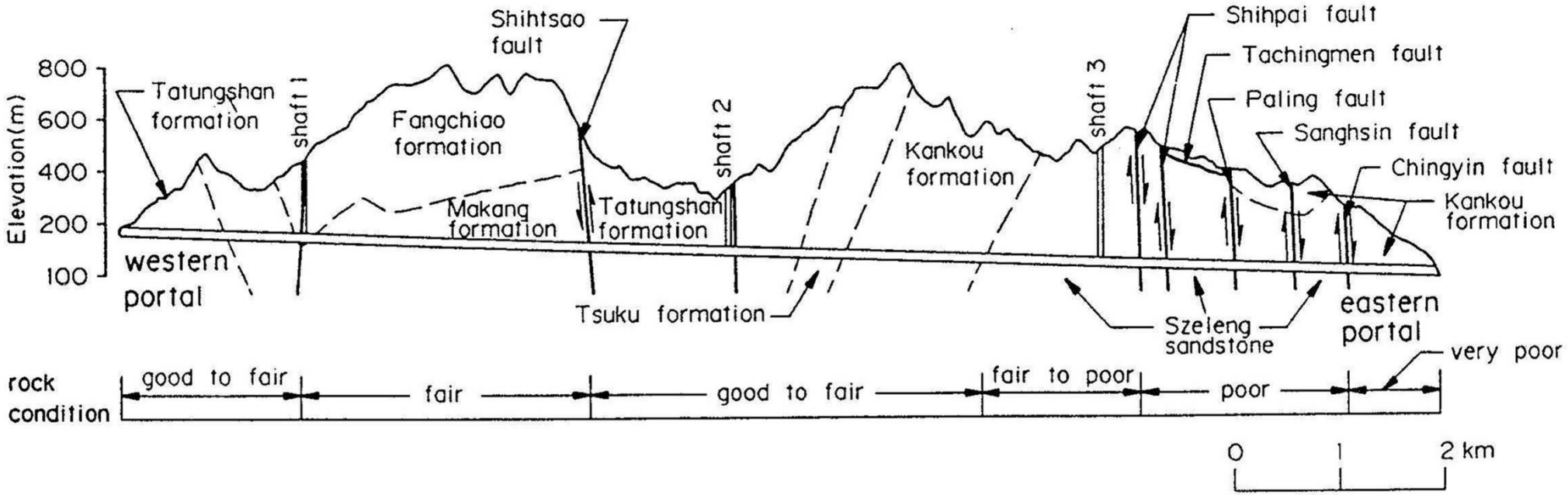
'OVER-EXCAVATED' VOID OF 3-4m IN THE LEFT WALL: 'SPAN' increase to 11-12m

TALCY PHYLLITES. DEBRIS PROPERTIES:

'WALKING ON BARS OF DRY SOAP'



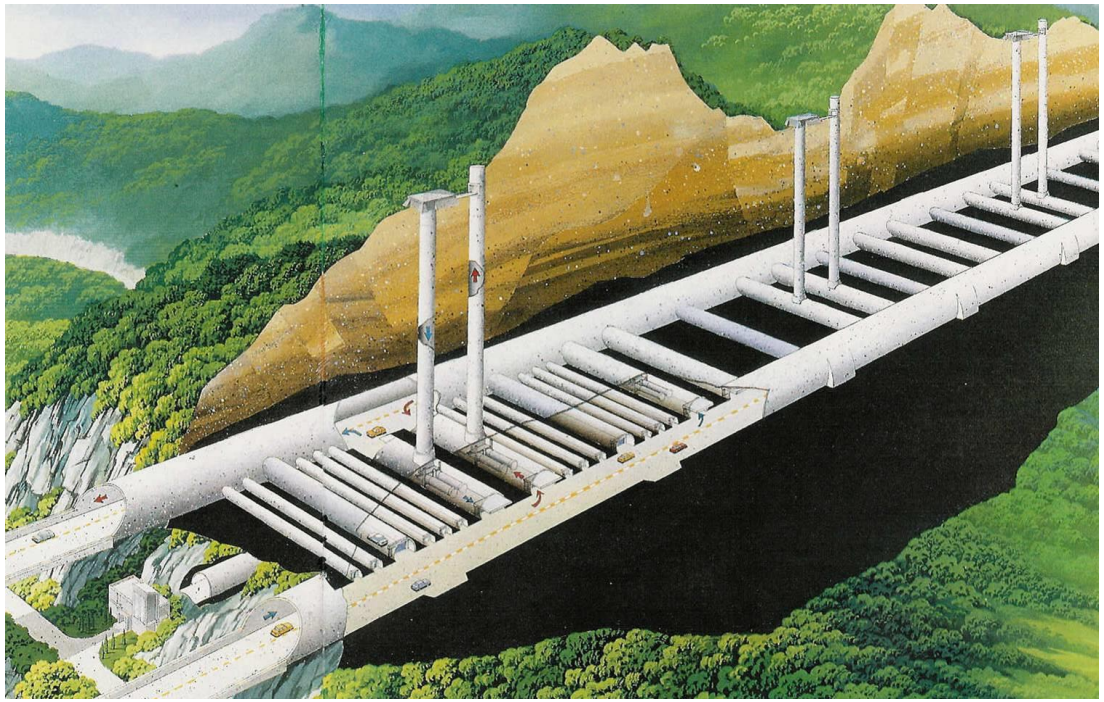
SHEARED ZONE WITH *ZERO* STAND-UP TIME



PINGLIN,TAIWAN

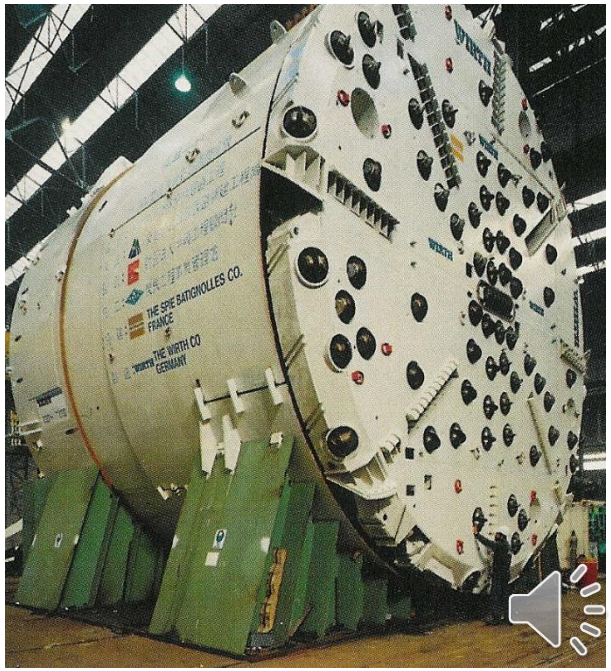
FAULT ZONE CHALLENGES.

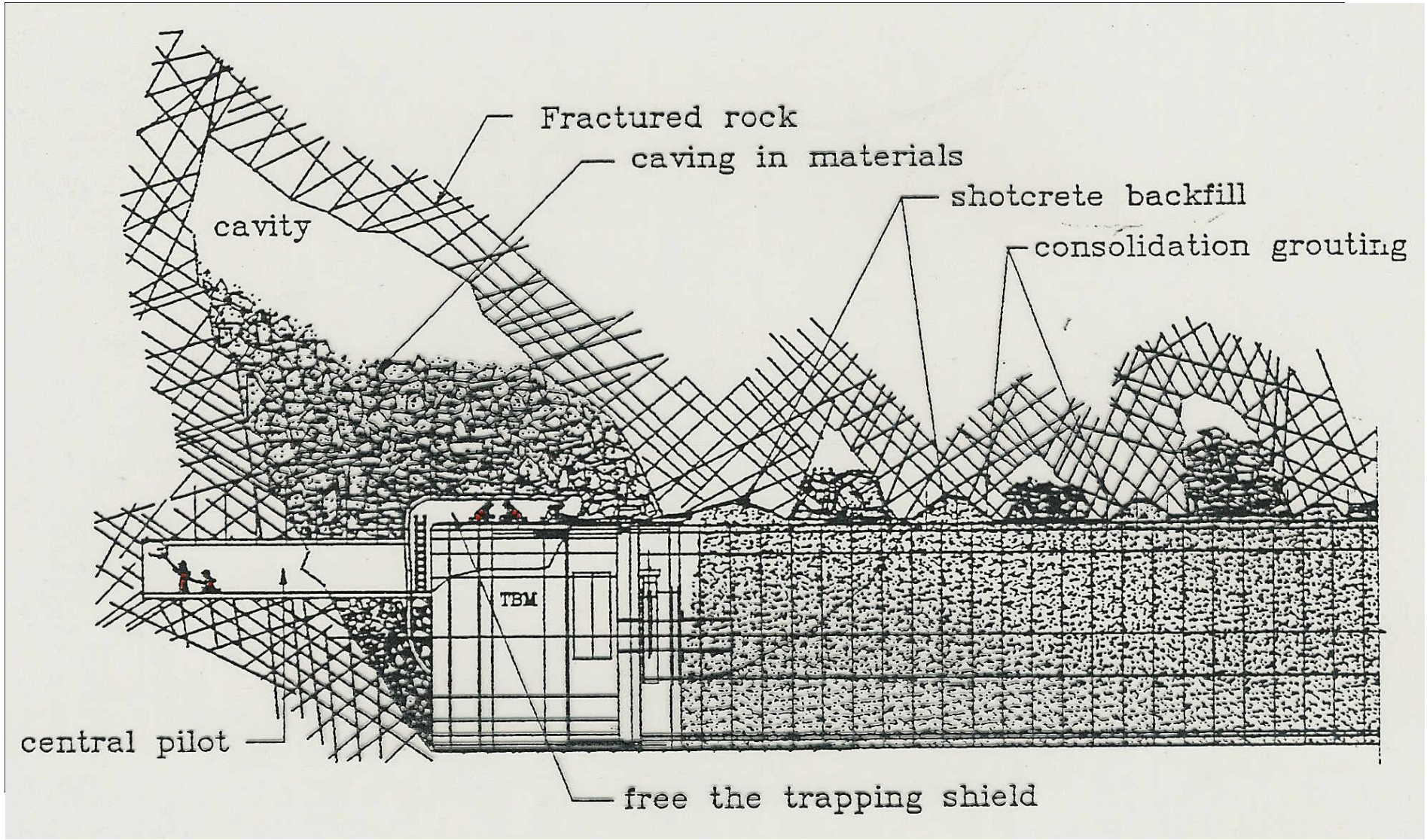
INITIALLY THREE TBM FROM EASTERN PORTAL.



Progressive start-up with pilot TBM ≈ 2km advanced in relation to left (southern) main tunnel. Pilot TBM cutter-head jammed frequently (> 13 times)

Two 11.7 m diameter 'giants' from Wirth.





BY-PASS FOR 11.7 m DIA. TBM AT PINGLIN.

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

(SHEN ET AL. 1999)

FINALLY, ALL TUNNELS COMPLETED BY DRILL-AND-BLAST.

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

(Top photo: Chris Fong, Taiwan)

THE META-SANDSTONES WORE OUT THE 11.7m

FACE ARMOUR (just now replaced) IN 4 TO 5 km

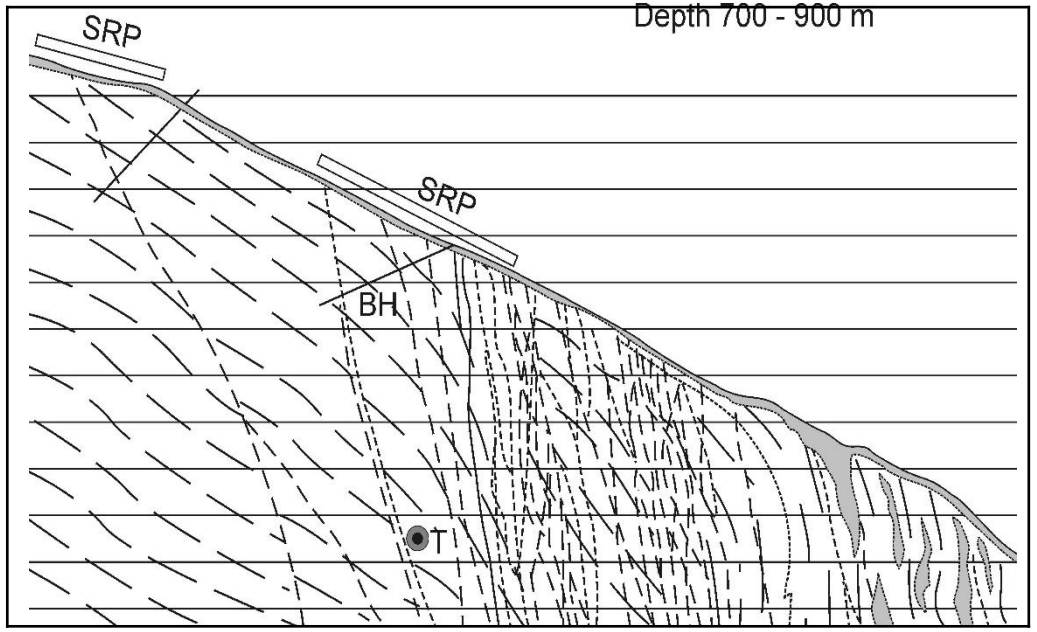
(Pinglin, Taiwan. Photo NB)

PONT VENTOUX, N.W. ITALY

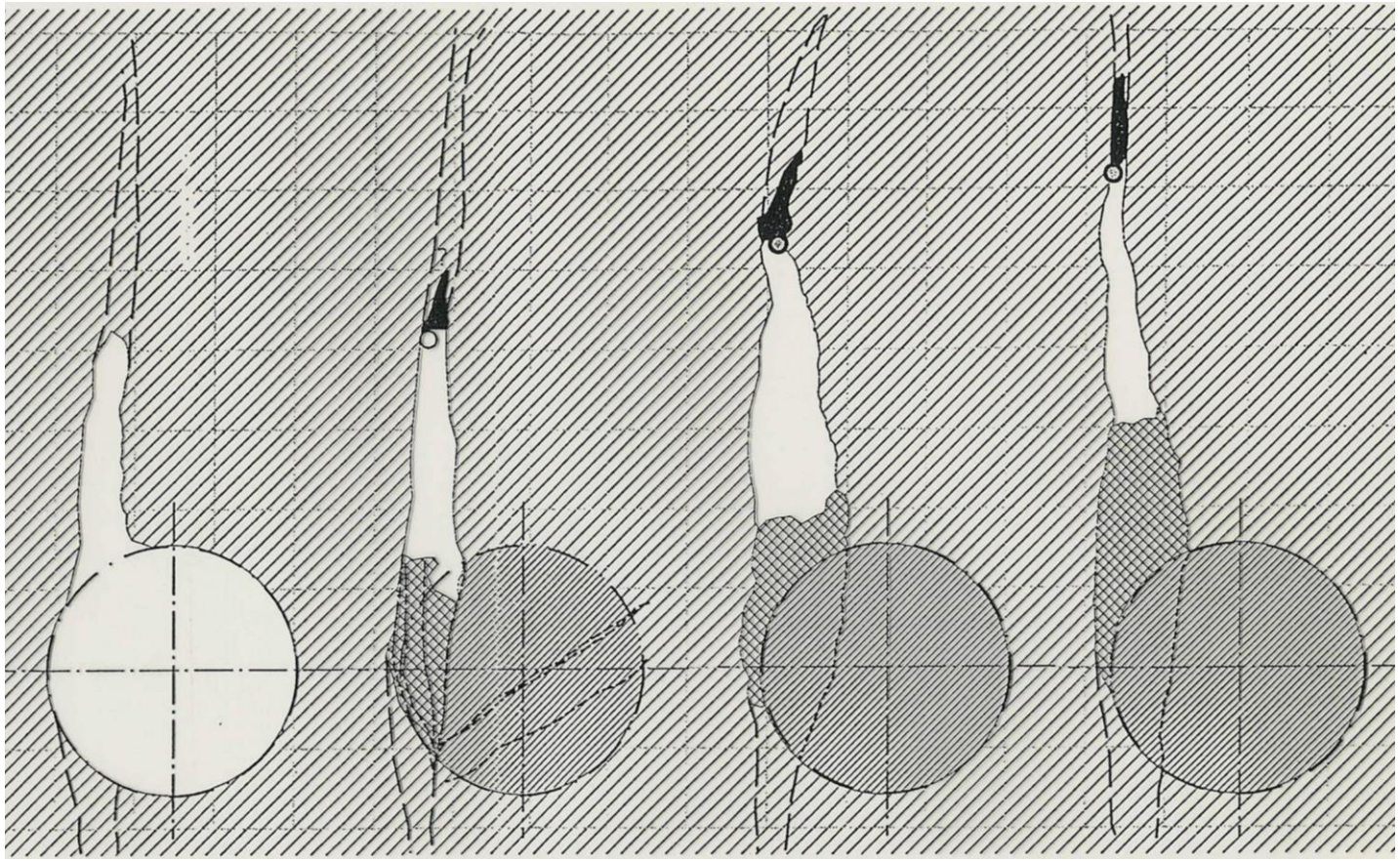
TBM STOPPED BY

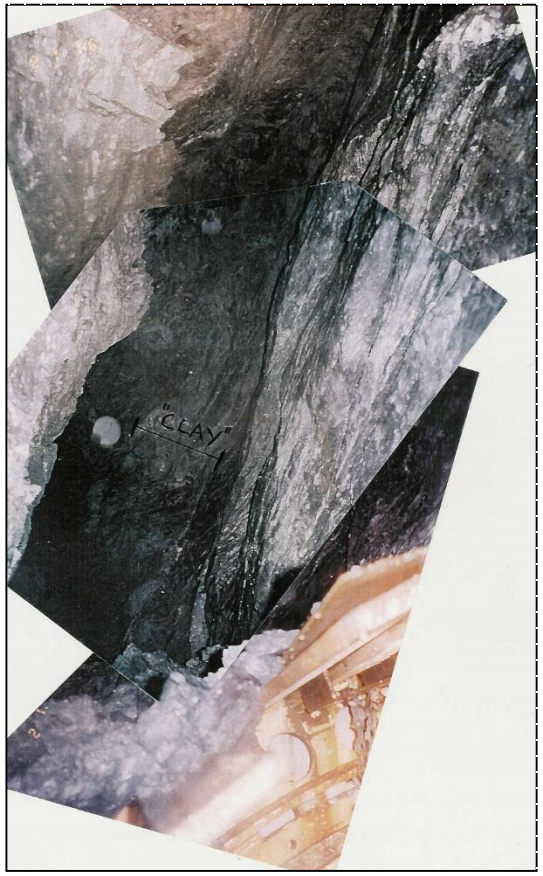
MULTIPLE-FAULTS IN WATER-BEARING SCHISTS.

GEOLOGIC SECTION DRAWN AFTER TBM STUCK!

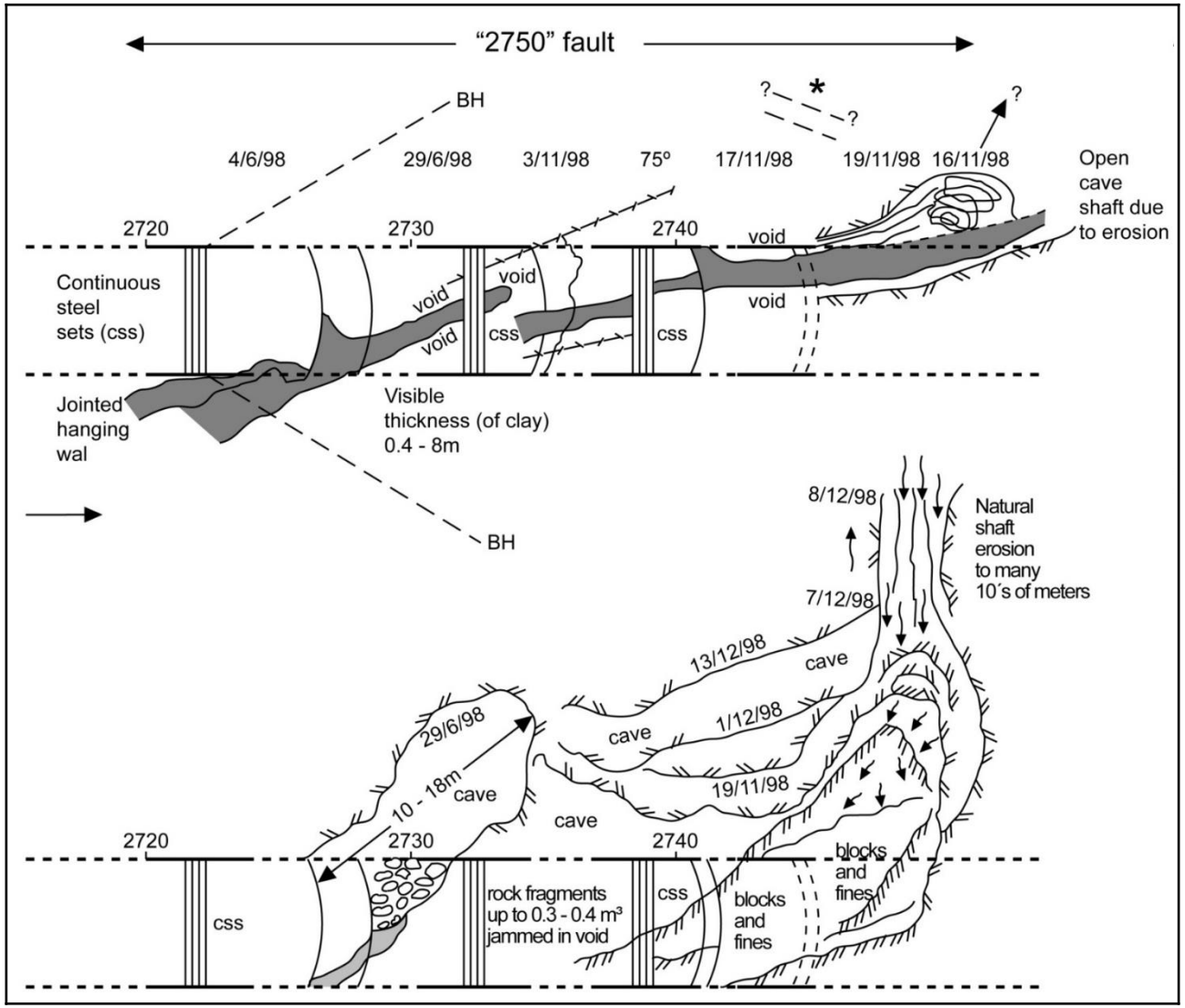


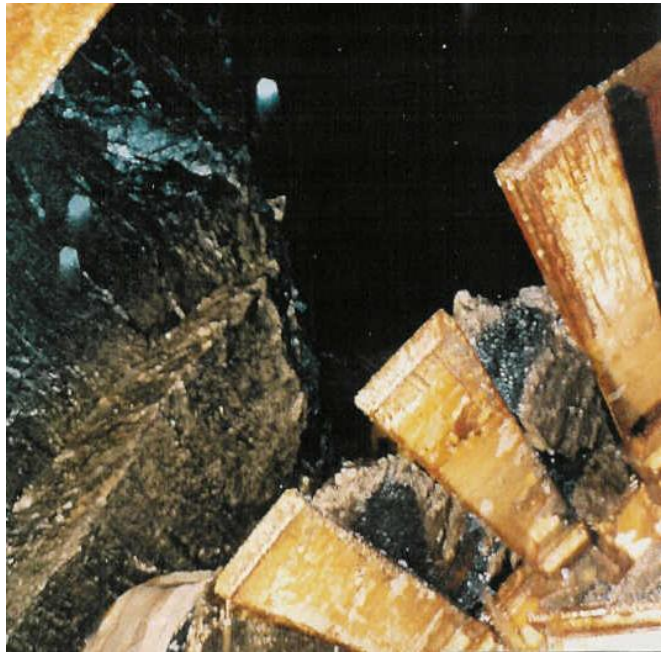
AN EXAMPLE of PROBLEMS : Fault at 2498-2517m

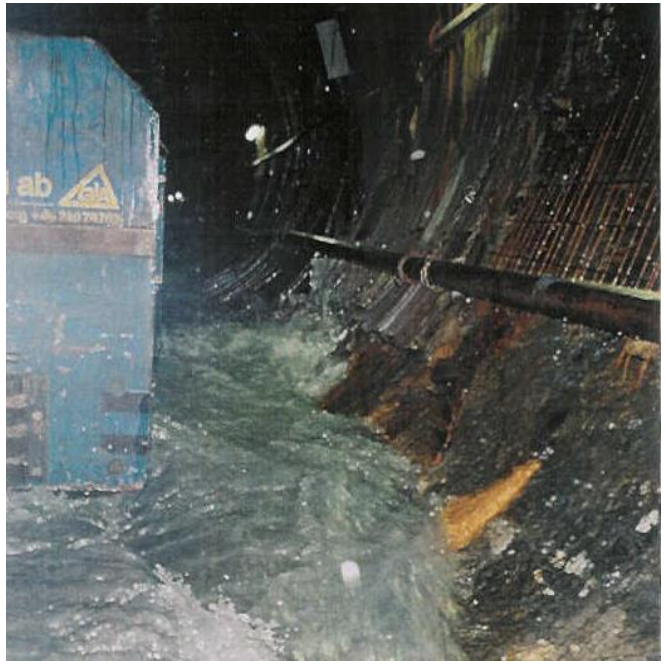




1. CLAY COMPROMISES GRIPPERS
2. WATER ERODES SHAFT AND LOOSENS BLOCKS
3.TUNNEL STABILITY REDUCES
4. CUTTER-HEAD REPEATEDLY BLOCKED



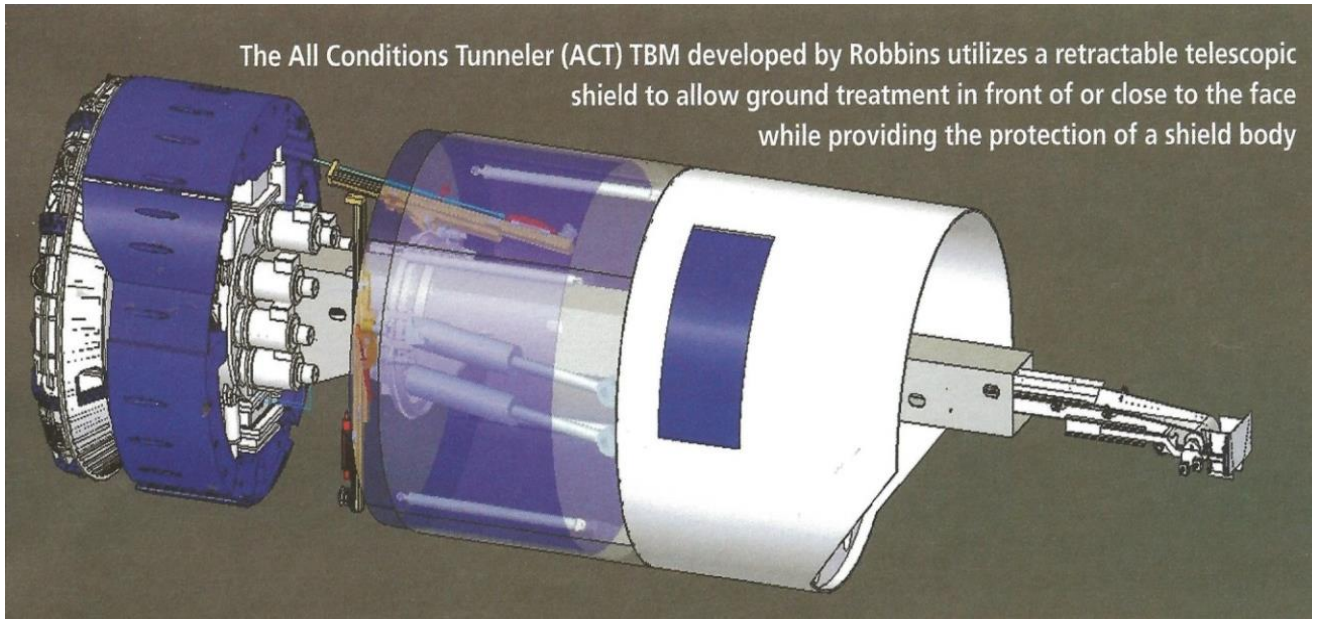




THIS SUB-PARALLEL FAULT DELAYED THE PROJECT 30m/5 months. SHAFT ERODED BY WATER AND FALLING BLOCKS. FINALLY D+B TO COMPLETE.

(Figures, photos, Karl G.Holter and NB)

IRAN: WET TBM TUNNEL IN KARSTIC LIMESTONES (ONE OF TWO). EQUIVALENT Q-VALUE VERY LOW DUE *TO EXTREMELY LOW Jw-FACTOR. (INITIALLY 1 AND 4 m3/SEC INRUSHES, THE BIGGEST WITH DEBRIS).* DECELERATION *(-m GRADIENT*) IS LARGE, TIME T > 10,000 HOURS DELAY).

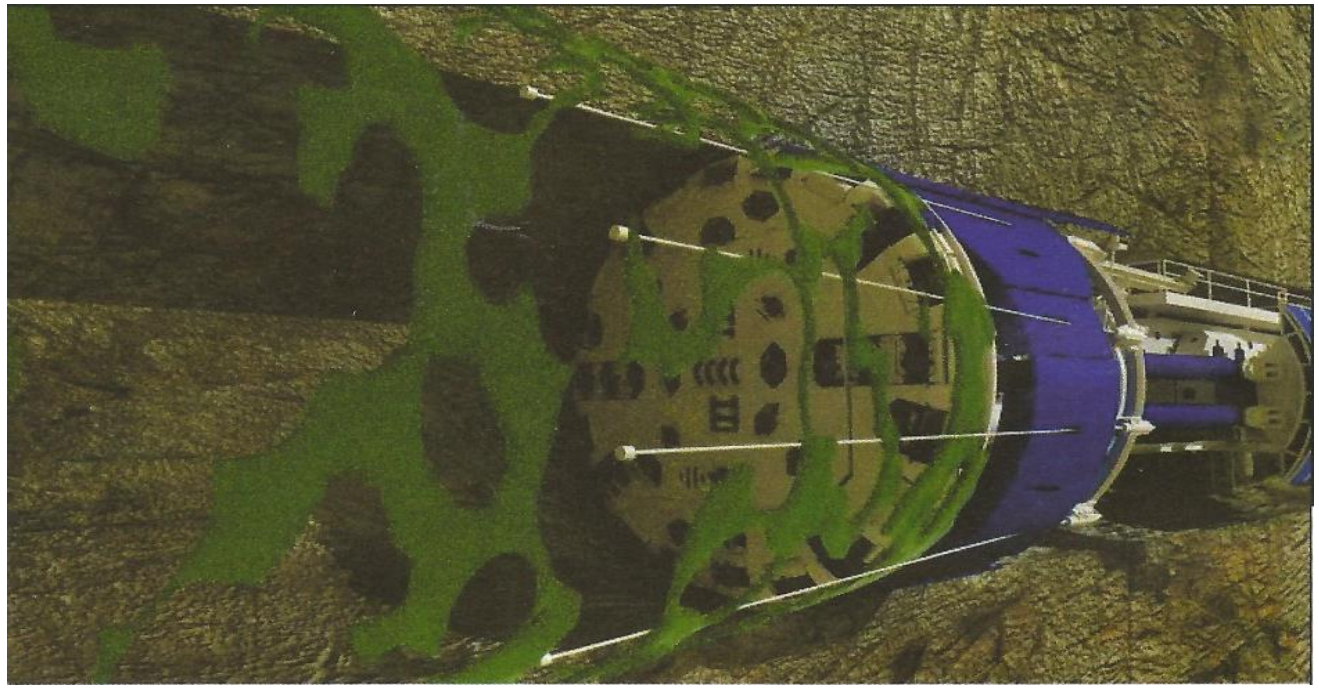


Robbins ALL CONDITIONS TUNNELLER (ACT)

LOOKS VERY PROMISING for PRE-TREATING FAULT ZONES ***(Willis, 2012)***

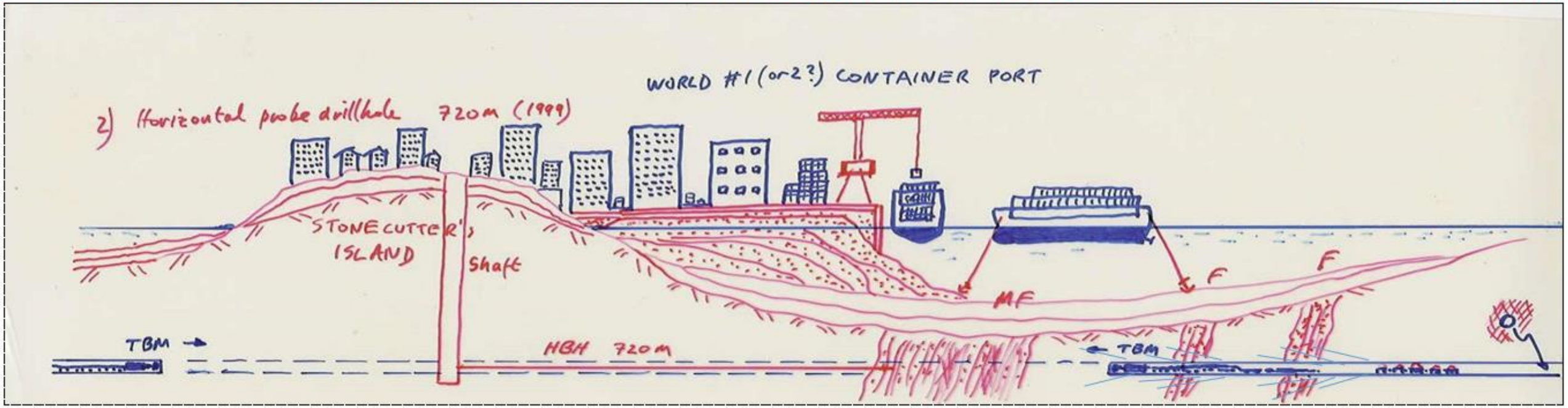
HERRENKNECHT TBM also allow significant pre-injection efforts!

IT MAY BE ESSENTIAL: ? 1km to 3km? subsidence zone is possible.



FAULTED SUB-SEA ROCK MASS: HONG KONG (SSDS, TUNNEL 'F' BY Skanska)

- MAJOR REGIONAL (TOLO CHANNEL) FAULT ZONE AHEAD – BUT UNKNOWN!
- NOT DRILLED: SUB-SEA SEISMIC INVESTIGATION STOPPED BY CONTAINER-PORT TRAFFIC.
- 'PILOT' HOLE: (DRILLED BACKWARDS FROM SHAFT). HOLE ONLY 731m….. *STOPPED* BY THE TOLO CHANNEL FAULT ZONE.
- BUT..! PRE-INJECTION ALLOWED THE 3.3m TBM TO GET THROUGH THE ZONE



Q-PARAMETER STATISTICS FOR THE (FAULT ZONE) *AT THE END OF* THE 720m LONG BOREHOLE

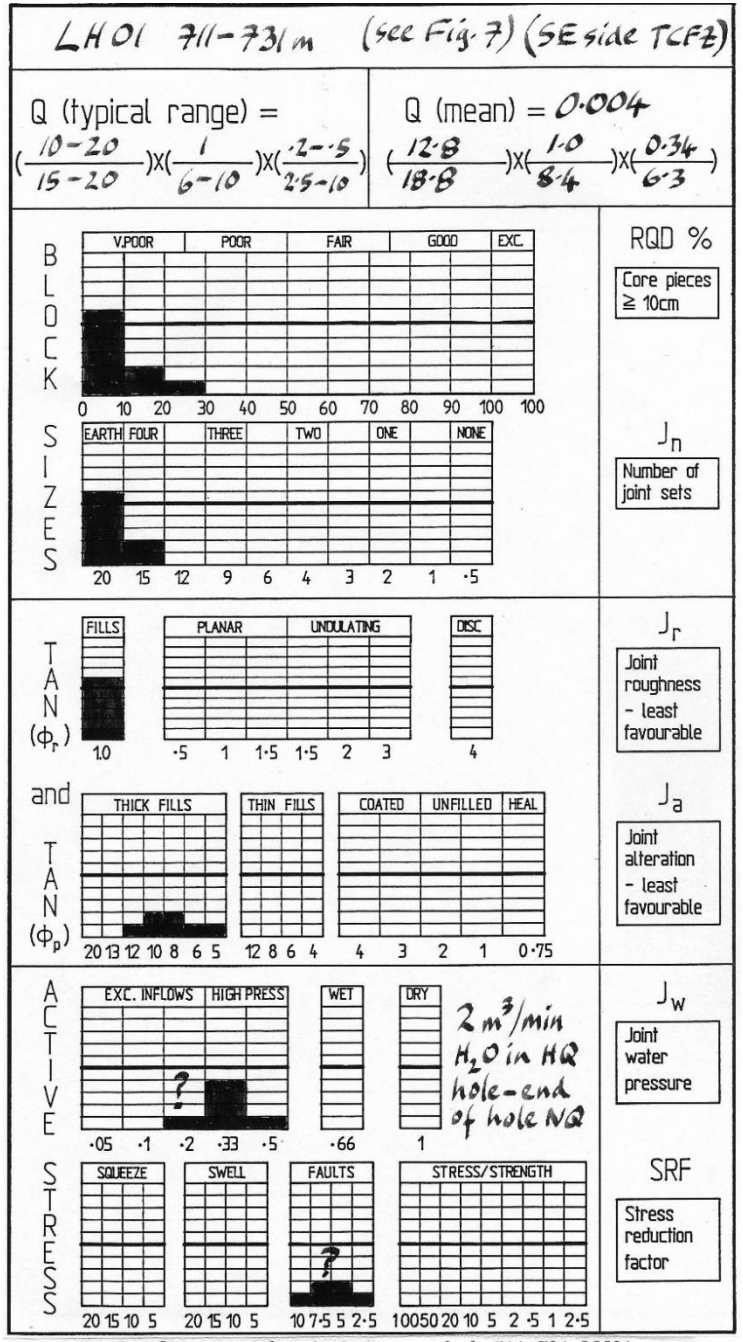


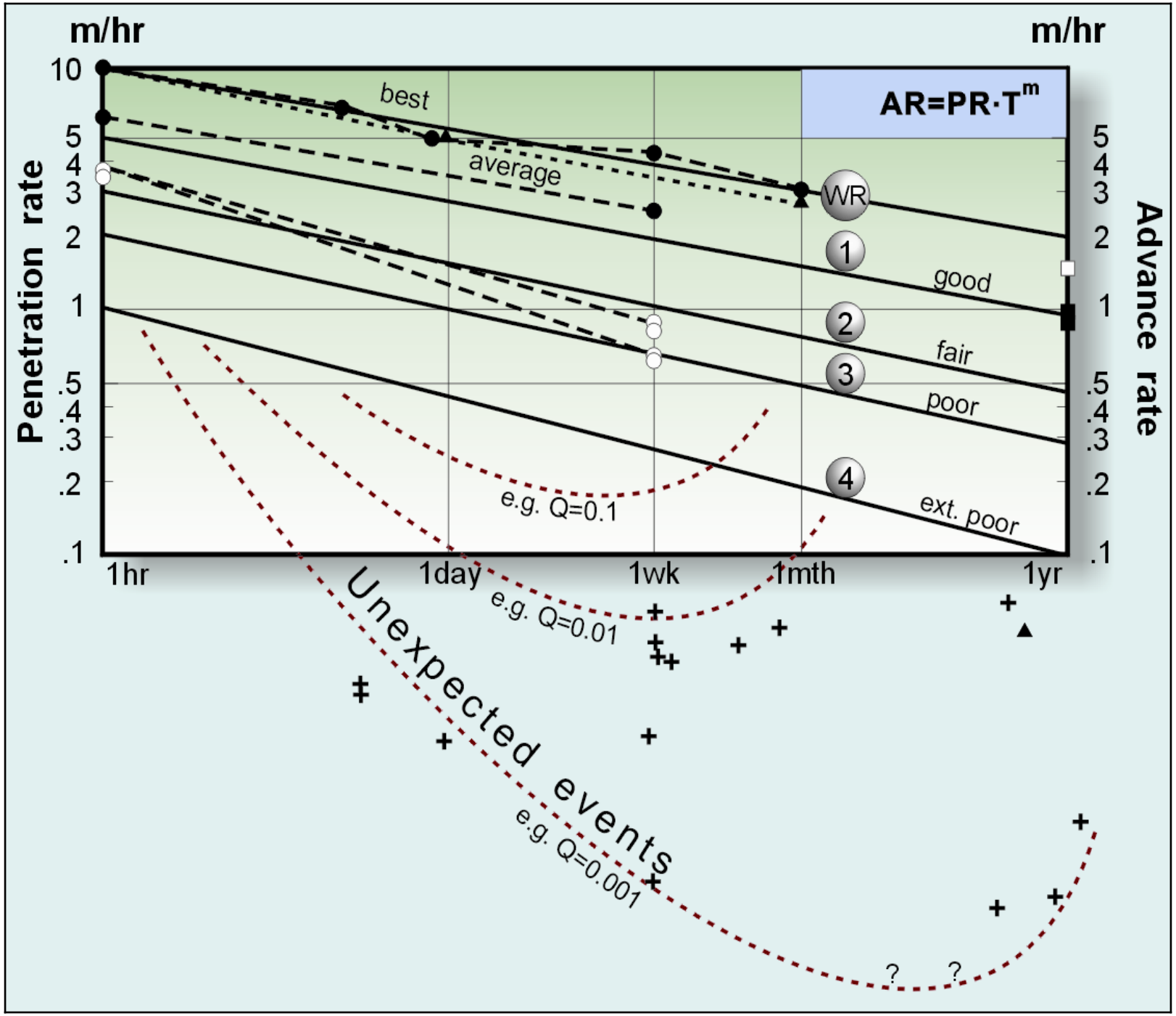
Fig. 8. Q-parameter log of TCFZ material, ch. 711–731, LH01.

CHARACTERISTICS OF THE ZONE ALL PLOT 'TO THE LEFT

Q_{MEAN} = 0.004…..NEEDS PRE-GROUTING IMPROVEMENT

6. DECELERATION (-*m*)

ACCENTUATED IN FAULT ZONES – ONE EQUATION NEEDED



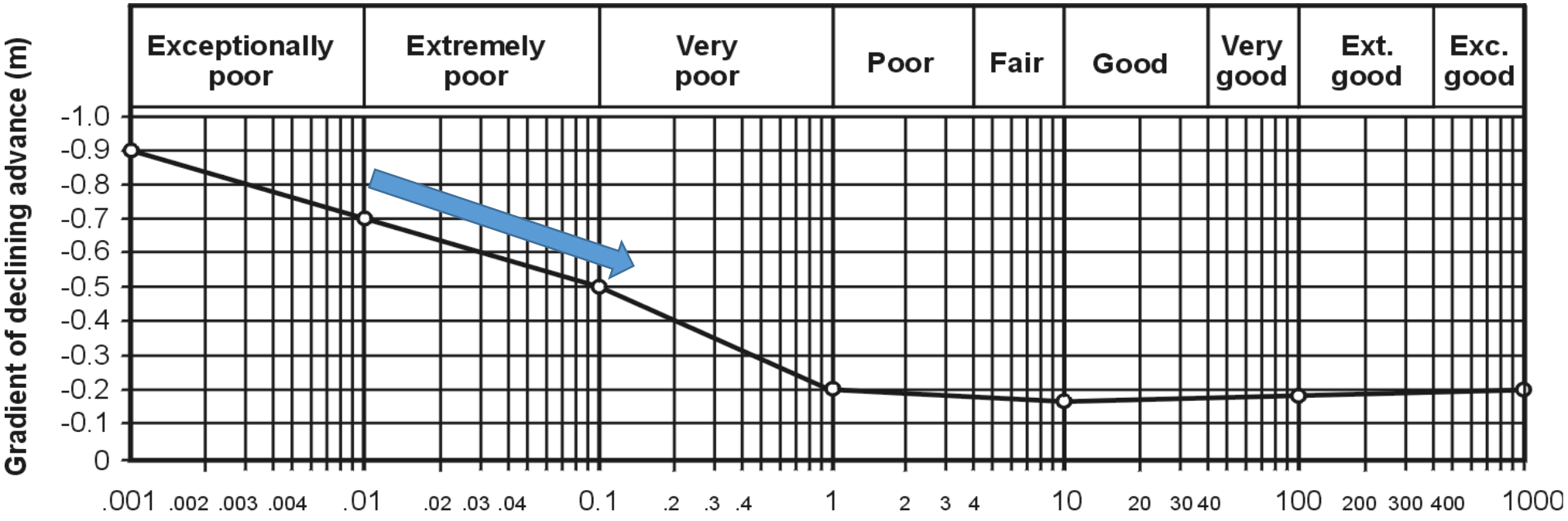
Remember:

consequences of too low Q !!

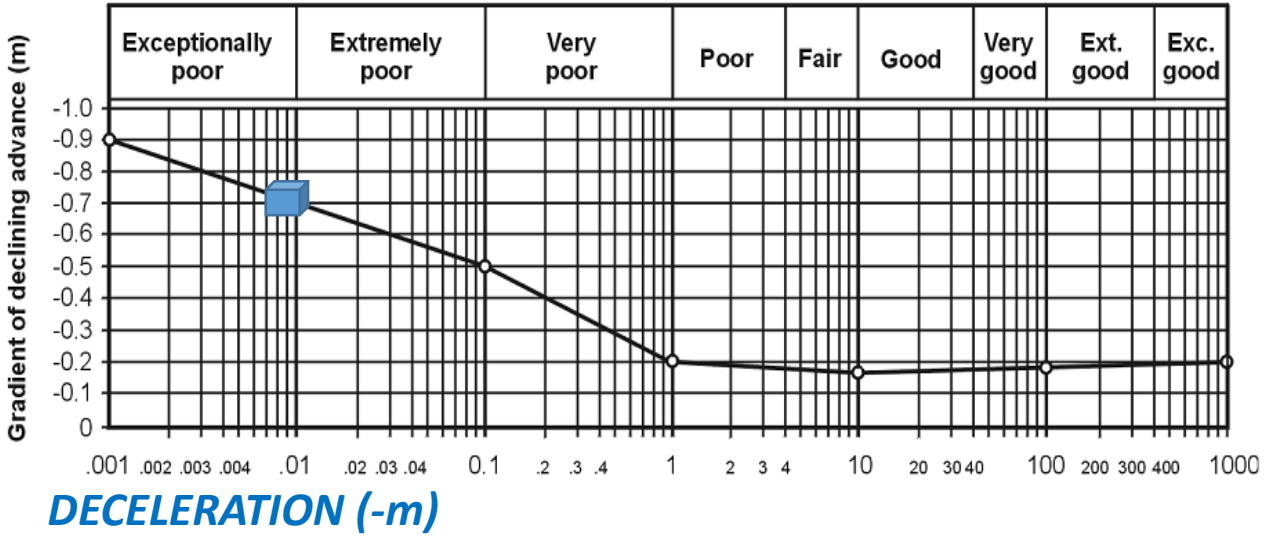
DECELERATION GRADIENTS (-m) ARE *Q-VALUE RELATED: WHEN* Q < 1.

(BUT Q COULD BE IMPROVED BY PRE-GROUTING !)

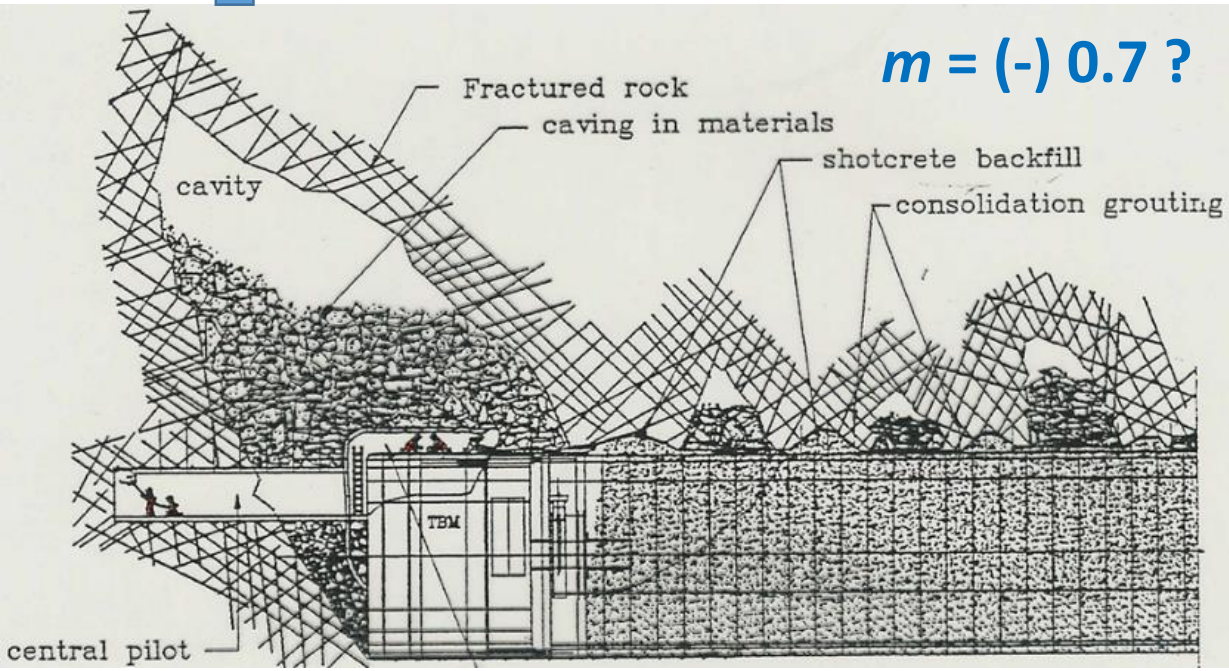
(improves many Q-parameters, reduces negative –m)



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



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



Shen et al. 1999

1. AR = PR x U
(All TBM must follow this).

2. U = T^m
(***Reducing utilization with time,***
<u>time T must always be quoted</u>!

3. T = L / AR
Time T for advancing length L.
(**Also applies to walking!)**

4. T = $(L/PR)^{1/(1+m)}$
THIS IS (-ve) !!

➢ ***1/(1+m)*** **= 1/(1-0.7) = 1 / 0.3 = 3.3!**

7. PROGNOSIS METHOD: Q_{TBM}

IMPORTANT MACHINE / ROCK INTERACTION PARAMETERS are comined with Q:

Q-VALUES……CUTTER FORCES……. UCS….ROCK MASS STRENGTH (ESTIMATE)…… STRESS-ON-TUNNEL FACE…… *CLI*……QUARTZ CONTENT……POROSITY…..TBM DIAMETER…..

ALL ARE INCORPORATED IN THE Q_{TBM} PROGNOSIS MODEL

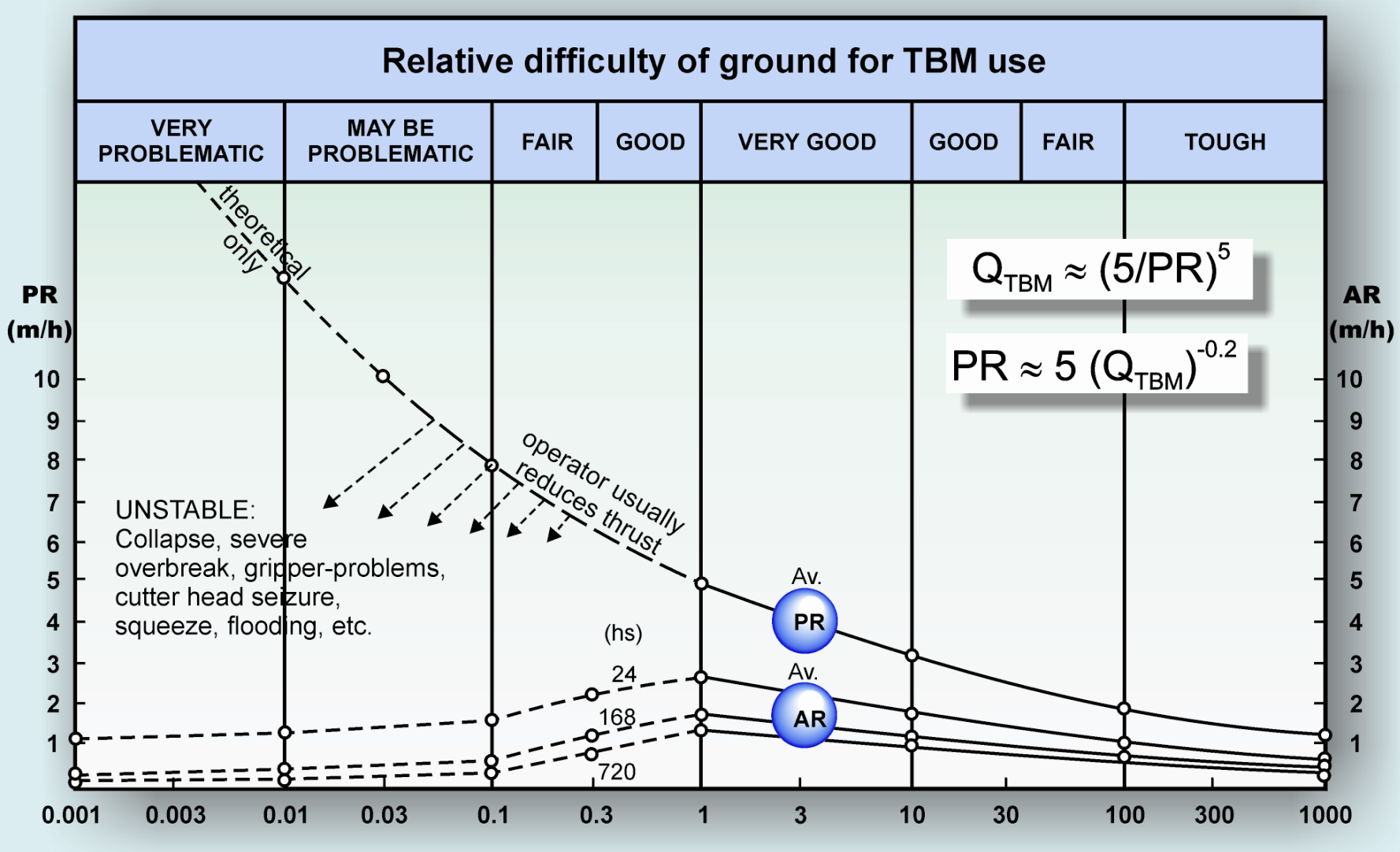
THE Q_{TBM} MODEL FOR TBM PROGNOSIS

involves Q , and machine/rock interaction 'normalizations'

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

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

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



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

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

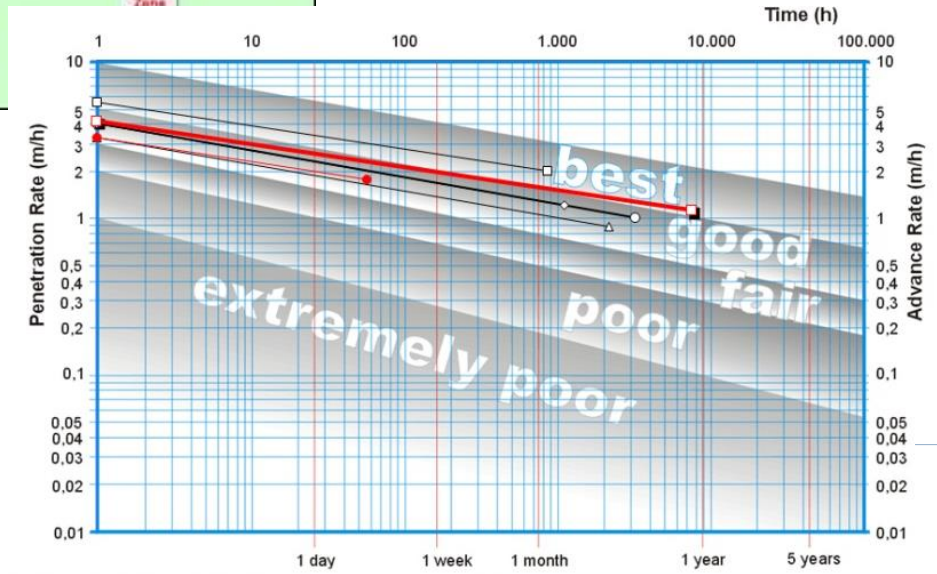
$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

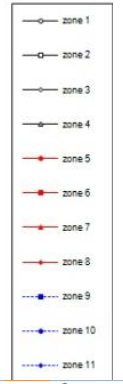
THE Q_{TBM} EQUATION WAS DEVELOPED BY TRIAL AND ERROR.

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

THE THREE QTBM SCREENS

DEVELOPED FROM NB EQUATIONS
BY Ricardo Abrahão, RAGeociencias





Nick Barton & Associates

Q TBM

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

INPUT DATA

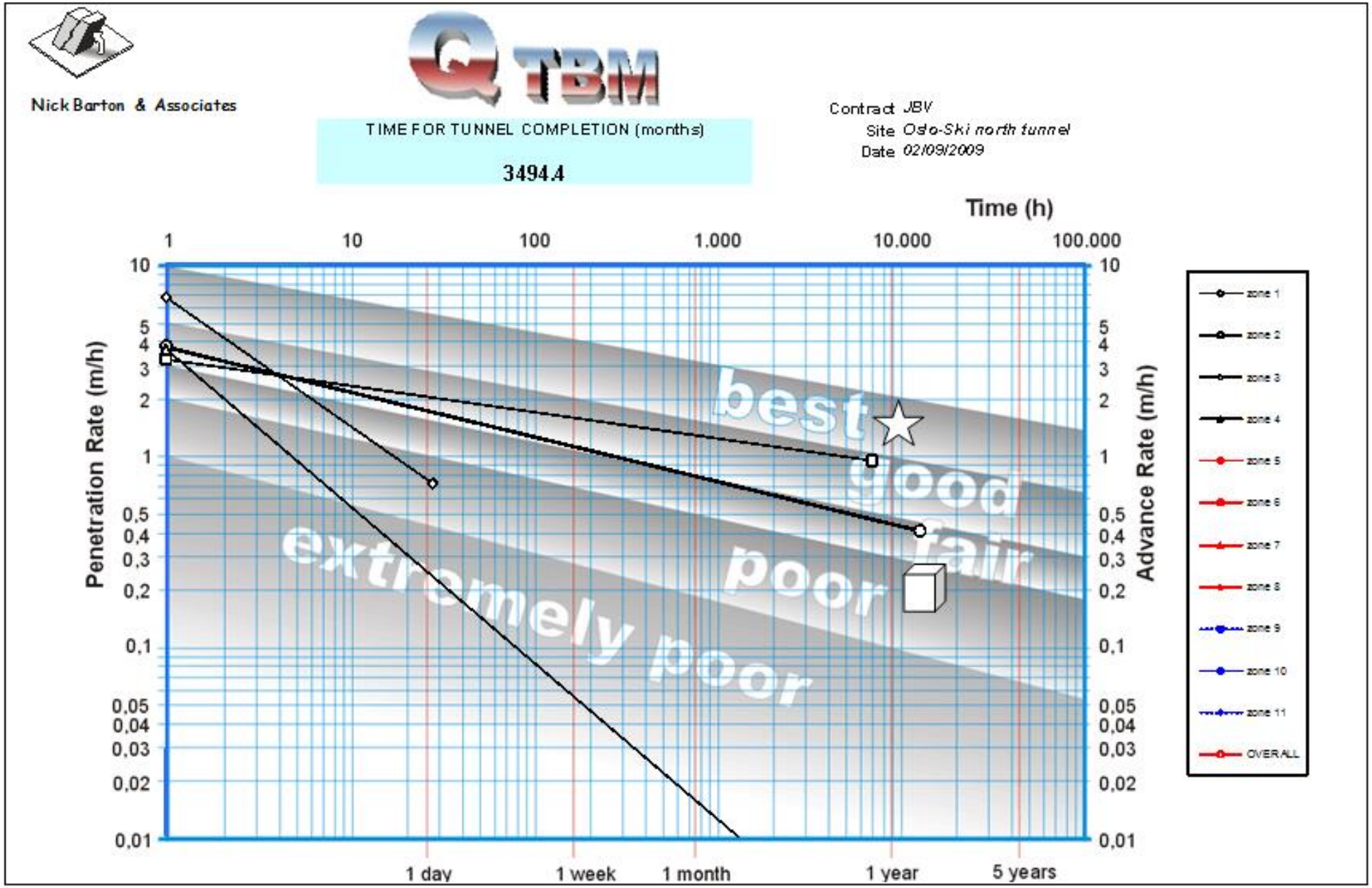
ZONE	LITHOLOGY	RQD	J_n	J_r	J_a	J_w	SRF	m_s	RQD_0	γ	β*	σ_c	I_{50}	F	CLI	q	σ_θ	D	n	L	Vp
1	CUARZOMONZONITA	92.00	6.10	1.70	2.10	0.92	0.90	-0.17	92.00	2.80	60.00	200.00	10.00	27.50	10.00	10.00	15.00	4.50	2.00	3,150.00	0.00
2	ANDESITA	71.00	11.60	1.60	2.60	0.78	1.30	-0.19	71.00	2.80	60.00	150.00	7.70	22.50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

BASIC CALCULATION

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

PERFORMANCE

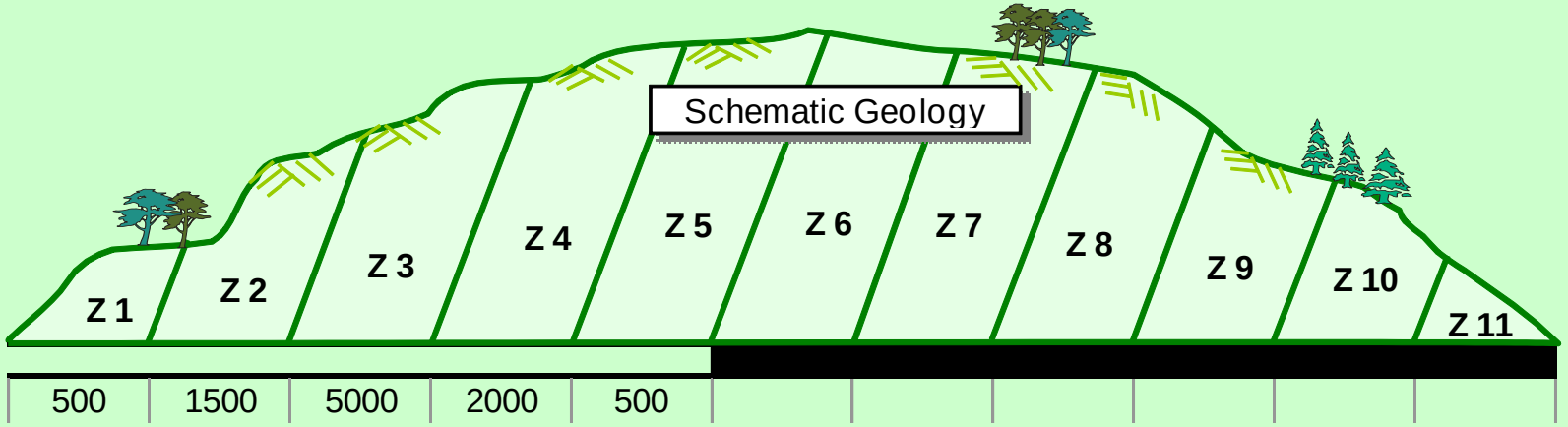
ZONE	LITHOLOGY	PENETRATION		TIME TO ADVANCE		OVERALL PERFORMANCE		
		PR	AR	T	check	ΣL	ΣT	
1	CUARZOMONZONITA	3.37	0.93	3,186.25	3,150.00			PRL(av)
2	ANDESITA	5.42	1.98	858.23	1,700.00			
3	PORFIDO RIODACITIC	3.36	1.19	1,095.75	1,300.00	8,100.00	7,336.26	4.10
4	BRECHA TURMALINA	3.24	0.87	2,138.68	1,850.00	m	h	
5	BRECHA-CLORITA/-BI	3.20	1.74	57.35	100.00			
6		0.00	0.00	0.00	0.00			ART(av)
7		0.00	0.00	0.00	0.00			
8		0.00	0.00	0.00	0.00	8.10	10.19	
3		0.00	0.00	0.00	0.00	km	month	1.10
10		0.00	0.00	0.00	0.00			
11		0.00	0.00	0.00	0.00			



DEMO OF **SINGLE-SHIELD** *(CUBE)* AND **DOUBLE-SHIELD** (STAR) *(F = 28 OR 26 tnf).*

DIFFERENT GRADIENTS (-m) GIVE THE MAJOR DIFFERENCES.

(NOTE: UNTREATED MAJOR FAULT (LOWEST LINE) 'STOPS TBM' IN SIMULATION)



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/cm³)	V_P (km/s)
100.0	2.0	3.0	1.0	1.00	1.0	-0.19	100.0	2.8	

β º	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

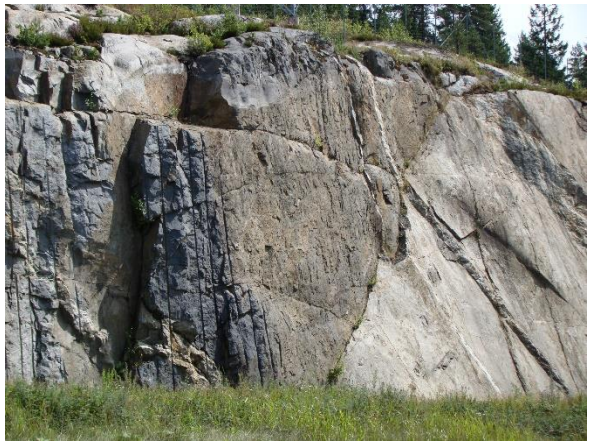
INPUT-DATA SCREEN FOR AN ASSUMED CLASS 1 (massive) ROCK MASS.

MANY ADVERSE CHARACTERISTICS FOR TBM: hard rock, too few joints, LOW PR).

IF MIXED FACE – EVEN MORE SLOW-DOWN

EXAMPLE OF CLASS 1 ROCK MASS:

MAY GIVE SLOW PR WITH TBM (BUT *PERFECT FOR DRILL-AND-BLAST*)



ADDING THE OBSERVATIONS: example of frequency of RQD, Jn and Jr Tunnel South.

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 ($\frac{75-100}{4-15}$)x($\frac{1-4}{1-5}$)x($\frac{0.5-1.0}{1.0}$)

Q (mean) = 11.1 ($\frac{98}{8.4}$)x($\frac{1.7}{1.3}$)x($\frac{0.75}{1.0}$)

Q (most freq.) = 11.0 ($\frac{100}{9}$)x($\frac{1.5}{1.0}$)x($\frac{0.66}{1.0}$)

RQD % — Core pieces ≧ 10 cm

	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 15	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
Y5ZYY						2	1 1 4	4 4 7	13 10 18	30 34 32	192 221 207
Z6Z2Z					2 1	5 1 2	8 3 3	11 5 7	17 13 14	27 31 36	199 216 208
7Z8Z3Z				1	1	3	4 3	1 9 7	11 14 12	23 27 29	235 181 219
11Z10Z4Z						3 1	2 4 3	7 10 6	12 15 14	24 34 32	115 204 214
12Z9Z							1	2 4	8 11	23 34	147 220
13Z						1	1	4	13	34	187
	0	10	20	30	40	50	60	70	80	90	100 100

All areas logged for T-S.

J_n — Number of joint sets

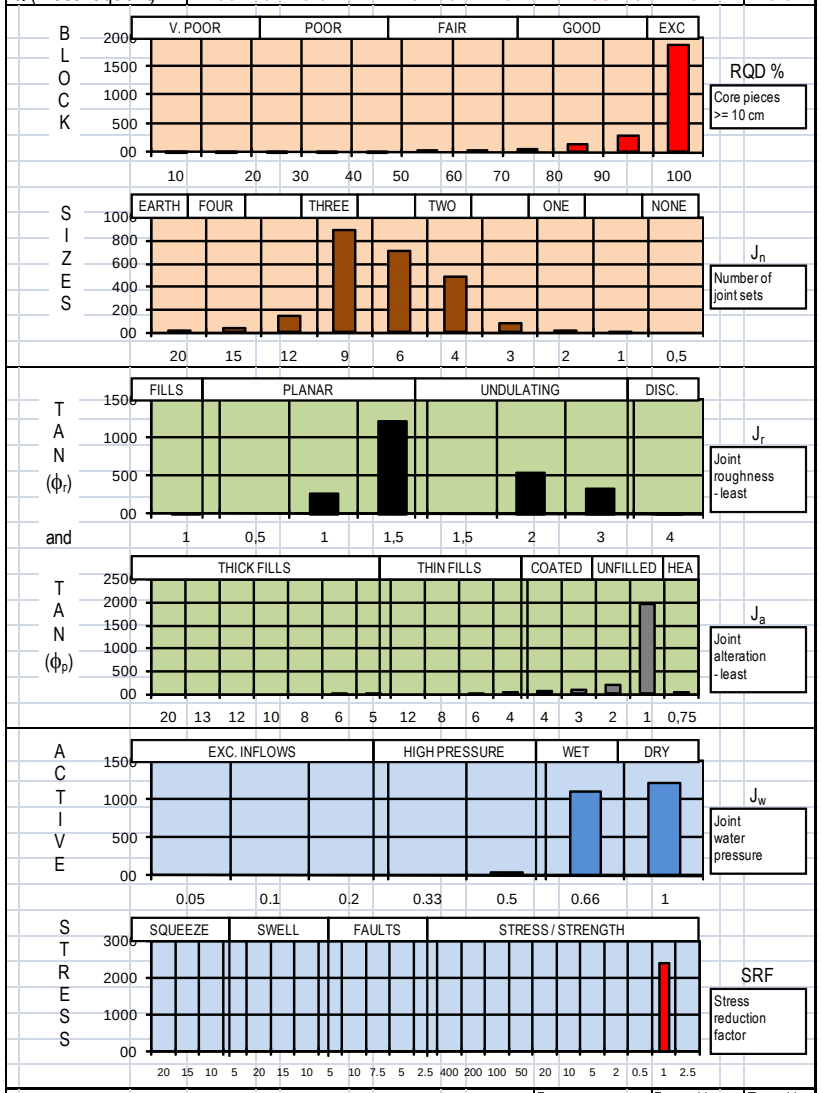
	Earth	Four		Three		Two		One		None
Σ		378	576	2966	1426	587	47	10		
HQR		5 2	11 5 8	152 45 48	51 61 70	6 93 34	19			
TSU		8 56	14 14 35	170 116 165	61 83 12	17 32 2	15	10		
VWX		16 9 8	32 18 24	121 109 165	89 85 58	12 49 15				
Y5ZYY		8 11 7	21 26 27	87 154 119	91 60 92	33 16 25	3			
Z6Z2Z		19 11 15	42 35 27	122 99 196	68 73 32	19 50 2	2			
7Z8Z3Z		11 91 13	31 19 28	126 78 111	47 48 61	52 4 57	3			
11Z10Z4Z		16 15 25	17 32 42	71 191 148	43 30 48	13 2 7				
12Z9Z		32	11 35	91 153	59 46	16 4	3			
13Z			22	131	58	27	2			
	20	15	12	9	6	4	3	2	1	0.5

J_r — Joint roughness - least favourable

	Fills	Planar		Undulating			Disc.
Σ	46	496	3675	2	1240	430	119
HQR	2	24 7 13	136 171 79		35 32 60	17 5 12	11 10
TSU		26 17 14	184 159 166		41 61 65	16 33 13	3 11
VWX	4 5	15 18 14	123 146 157	2	92 62 69	36 44 23	2
Y5ZYY	5	24 20 22	167 153 178		30 70 47	8 27 19	11 3 4
Z6Z2Z	10 4	16 28 27	166 133 197		63 56 31	10 29 14	5 20
7Z8Z3Z	6	28 26 32	178 174 172		54 30 50	10 4 8	10 6 8
11Z10Z4Z	2 2 6	13 44 27	88 189 135		32 30 80	17 5 22	8
12Z9Z		5 22	79 184		70 41	21 23	5
13Z		14	170		39	14	2
	1.0	0.5 1	1.5	1.5	2	3	4

1= 2= 3= 4= 5= 6=

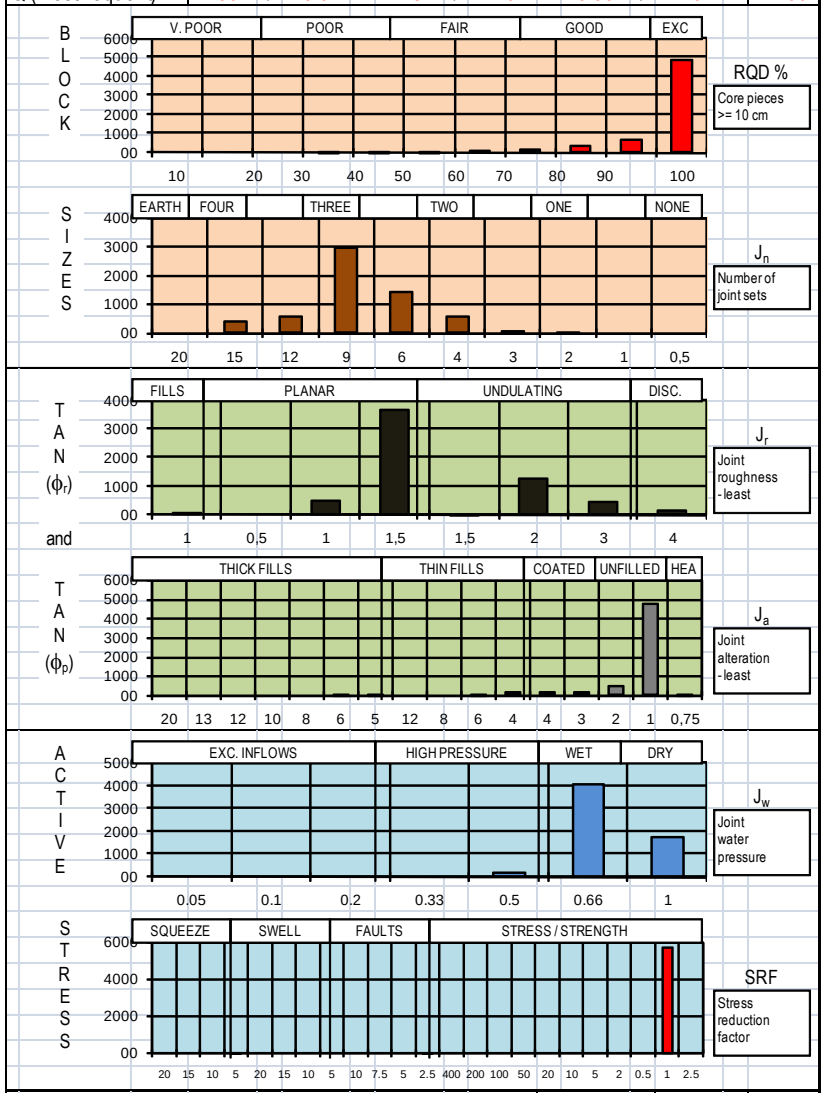
Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	4.0	*	0.50	/	1.0	=	0.625
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	1.0	=	100.0
Q (mean value)=	96	/	7.1	*	1.8	/	1.3	*	0.83	/	1.0	=	15.36
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	1.00	/	1.0	=	16.67



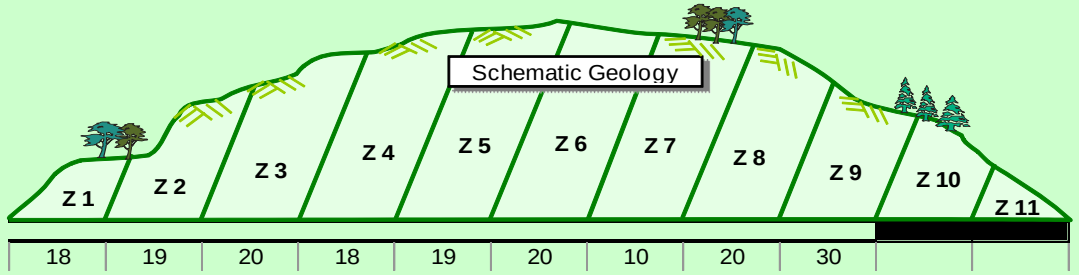
JBV OSLO-SKI	Rev.	Report No.	Figure No.
		NB&A #1	9
Q-histogram based on compilation of all rock-exposure	Borehole No. : rock exposures	Drawn by NB&A	Date 30.8.09
logging for TUNNEL-NORTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	

NORTH + SOUTH TUNNELS

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. : Rock slopes	Drawn by NB&A	Date 31.8.09
logging for TUNNEL-SOUTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	



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

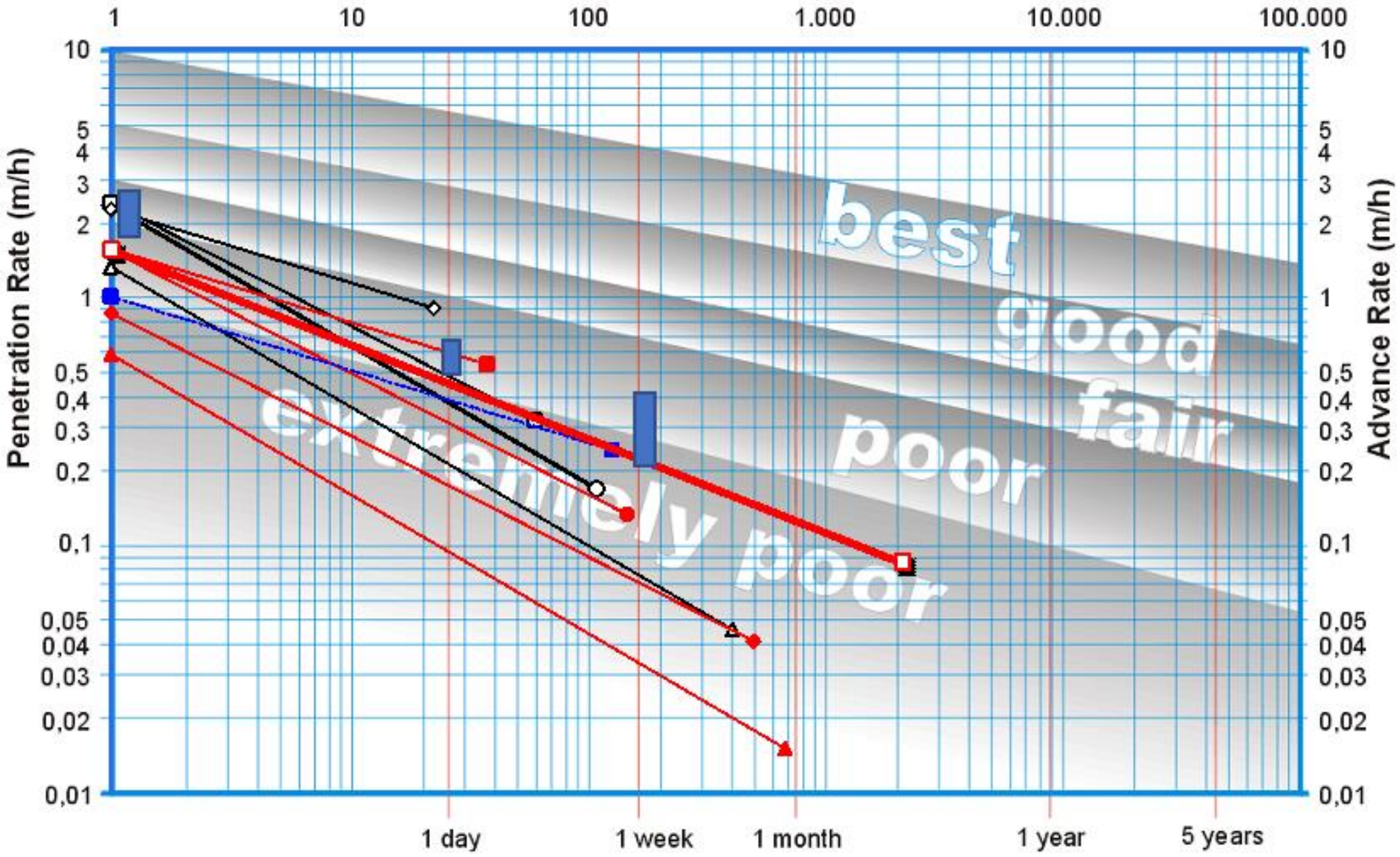
INPUT DATA

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

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

ACCUMULATED TIME FOR *NINE PERMEABLE* WEAKNESS ZONES = 2.9 MONTHS

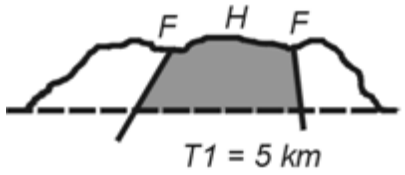
NOTE USE OF Vp
(For eventual shallow parts of tunnel, can use refraction seismic)

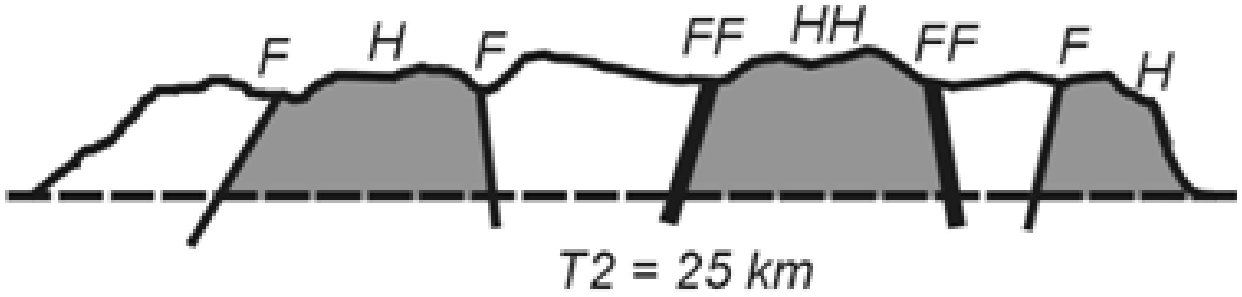

1
10
100
1.000
10.000
100.000
Penetration Rate (m/h)
Advance Rate (m/h)
10
5
4
3
2
1
0,5
0,4
0,3
0,2
0,1
0,05
0,04
0,03
0,02
0,01
best
good
fair
poor
extremely poor
1 day
1 week
1 month
1 year
5 years

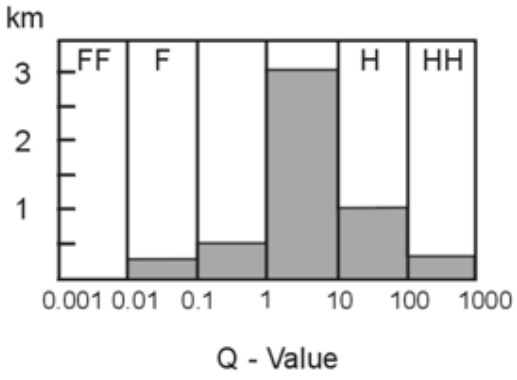
7. FINALLY: BECAUSE OF DIFFICULT CONDITIONS:

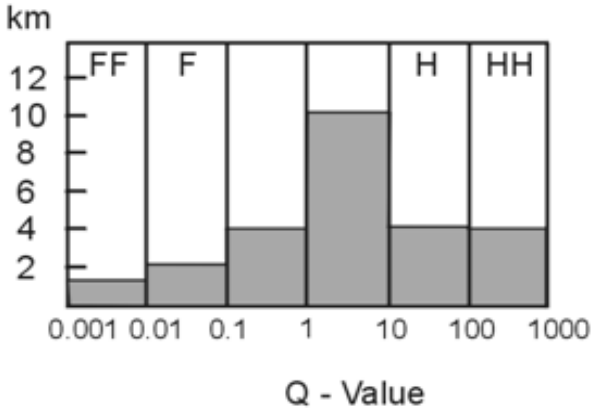
? HYBRID METHOD ?

D+B *and* TBM







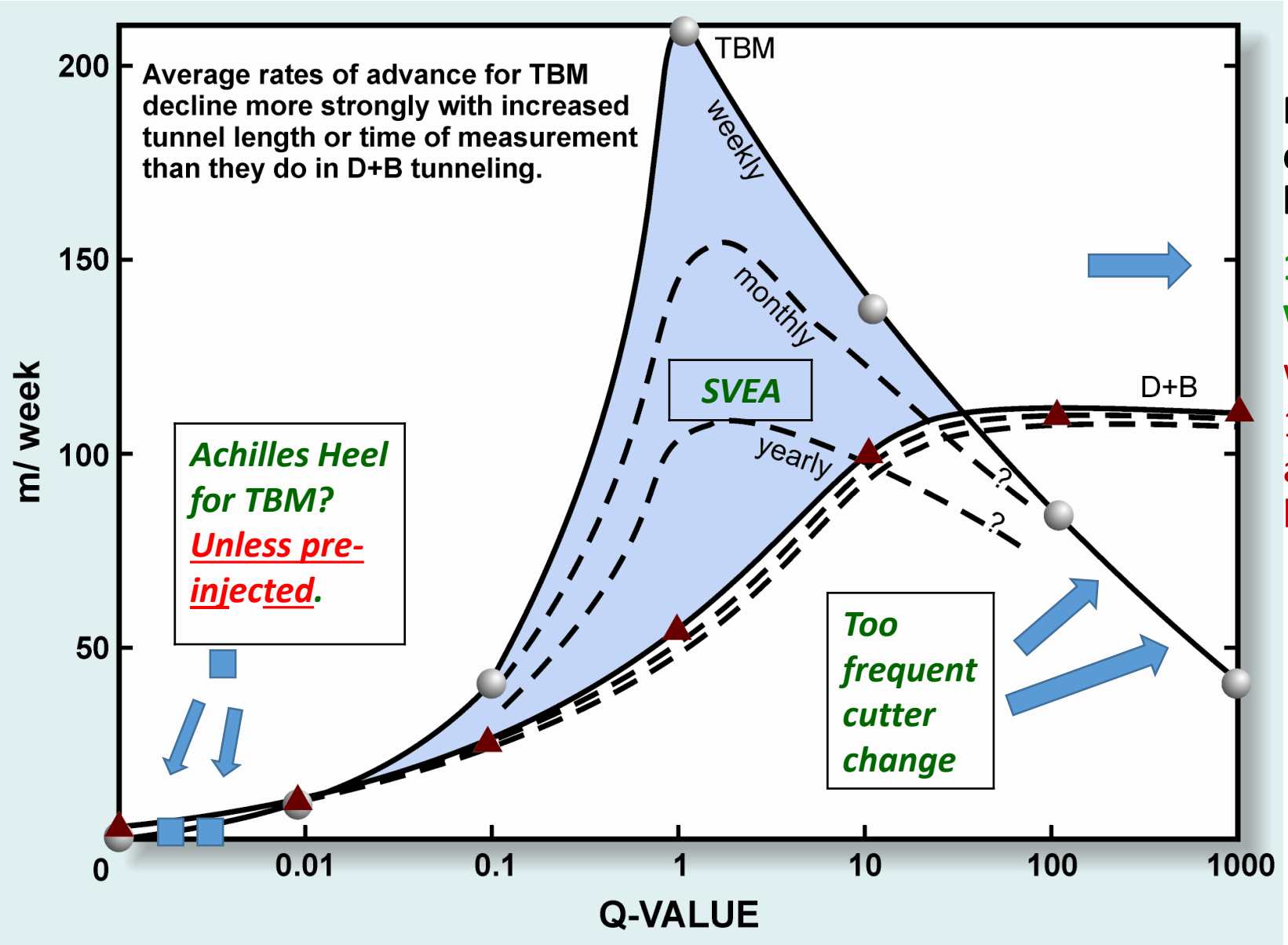


5 km, better investigated, fewer ‘extremes’, lower cover – probably.

25 km, much less investigated, maybe many ‘extremes’

CENTRAL Q-VALUES *AND* Q_{TBM} VALUES BEST FOR TBM.

TAIL-DISTRIBUTIONS (of Q) ARE 'faster' WITH D+B !



Record for drill-and-blast:

150m/BEST week (SVEA)

Whole project 104 m/week average, 5.8 km

LIST OF DIFFICULT CONDITIONS:
(with hard-brittle-rock bias)

1. Fault zones (low Q) – over-break, vibration, stuck TBM
2. Combination of water, erosion of fines, when low Q
3. Karstic water-filled / debris-filled void-phenomena
4. Mixed-face even/especially in hard rock formations
5. Massive, hard and abrasive rock – ultra-low PR
6. Massive, hard, highly-stressed, stress/strain fracturing
7. Rock-burst accidents

(RED CASES – CAN MEAN STOPPED/DAMAGED TBM)

All the above can *completely alter* the expected:

PR of 3 to 5m/hr, AR of 20-30m/day, 100-150m/week, 400-600m/month