4th Indian Rock Conference

Waknaghat

Rock Engineering Challenges and some Solutions for Hydropower Projects

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The Challenges

Hydropower projects in many mountainous regions, but especially in India and Kashmir, present geological, geo-hydraulic and construction challenges perhaps second to none.

The tectonic influences, the intense jointing and continued deformation, the contrasting rock types, the high-pressure water, the barriers to flow, the clay-filled fault zones, the wide thrust belts and landslides:

All combine to test the ingenuity of the Designer, test the patience of the Owner, and especially to test *the skill and endurance of the Contractor.*

Can we minimise the chance of long delays in fault zones (D+B or TBM) ?

Are long (deep headrace) tunnels faster by TBM, as often assumed?

Lecture Content

This lecture describes some of the practical lessons learned by the writer during a forty-years professional career, spanning thirty five countries and hundreds of projects.

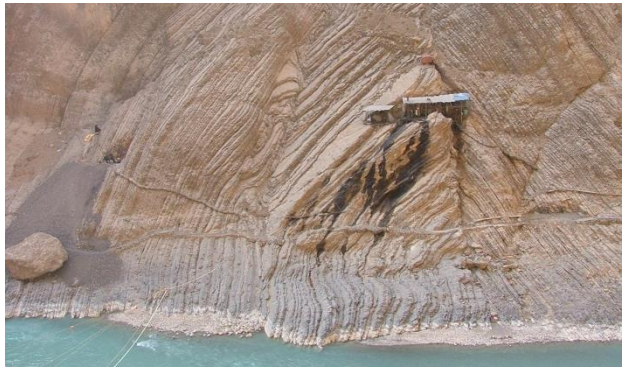
The main topics will be headrace and pressure tunnels, both by drill-and-blast and by TBM, and how to make these more economic, and perhaps avoid big delays.

There will be description and liberal use of the Q-system, also for its use in TBM prognosis through the Q_{TBM} method.

TBM delays can be explained (using Q) and may be mitigated.

Modified single-shell NMT tunneling is preferred to double-shell NATM due to speed and cost ?

Some standard numerical modelling is questioned for its relevance to *rock masses* and to rock *engineering*.



VARIABLE HYDROPOWER GEOLOGY **CANNOT ALWAYS BE COMPUTER MODELLED – BUT IT CAN BE CHARACTERIZED / QUANTIFIED.**

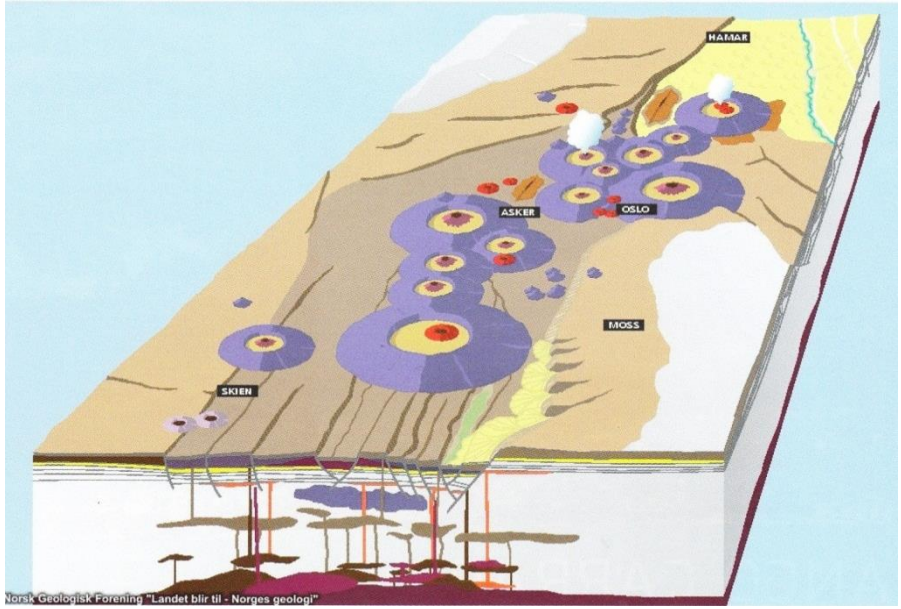
NORWEGIAN BACK-GROUND

With 3,500 km of hydro-power related tunneling, and about 180 underground power houses, it was necessary to construct economic tunnels (and power-house caverns) from the start.

The Q-system development from 1974 always reflected this, and 50% of initial case records were from Norwegian and Swedish hydro power projects, with *fifty different rock types* in the first two hundred case records.

There are those who doubt the applicability of the Q-system 'in their country'

('We do not have pre-Cambrian granitic gneiss here'……Sir!)



THE REALITY: Some rock exposures close to Oslo – 'home of Q',

and (top-left) at least 10 named collapsed caldera/super volcanoes in the (former) 'Oslo region'

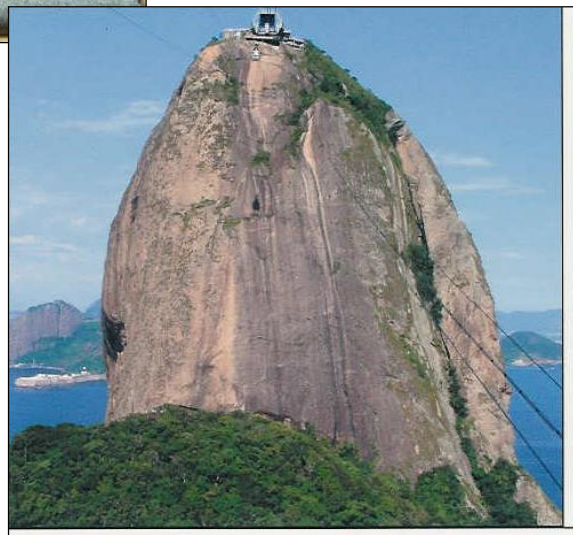
TERZAGHI, NATM, RSR, RMR, Q, RMi, GSI, NMT…….

What methods shall we choose?

(To be addressed – with persuasive arguments!)

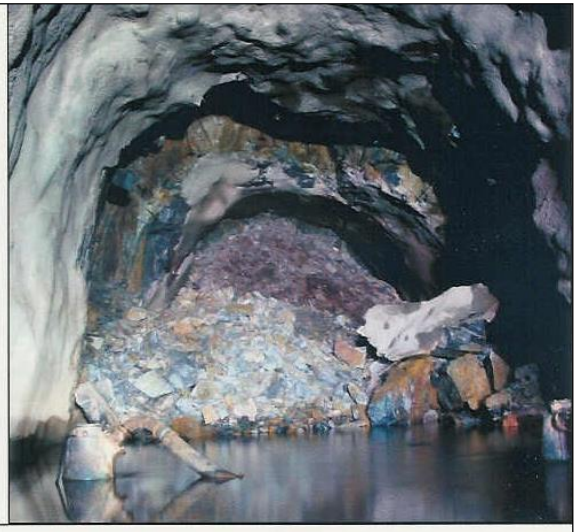
Familiar rock engineering parameters vary by orders of magnitude (modulus, strength, permeability, construction time).

It helps if descriptive methods do also. Equations will then be simpler.



Massive rock at the Sugar Loaf, Rio de Janeiro

Q = 1000 (or better)

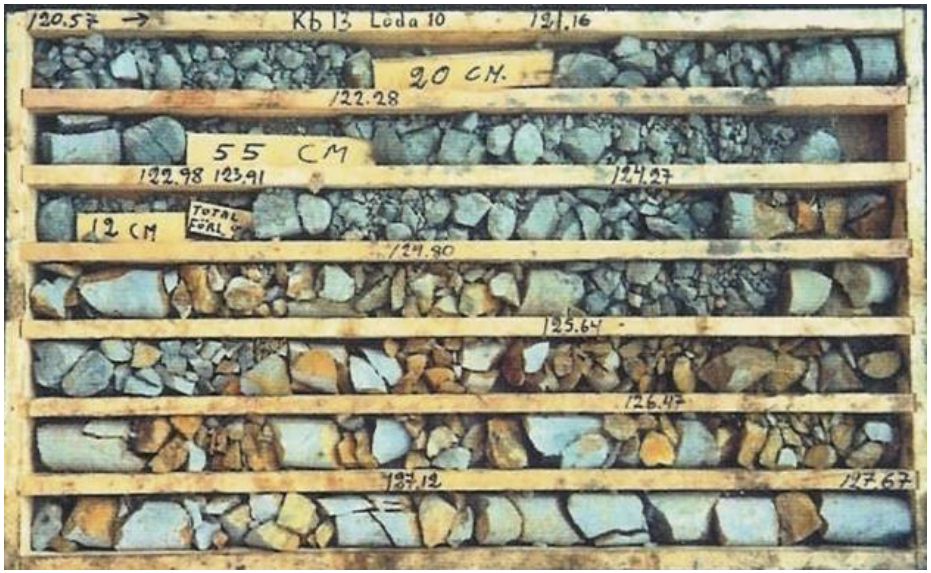


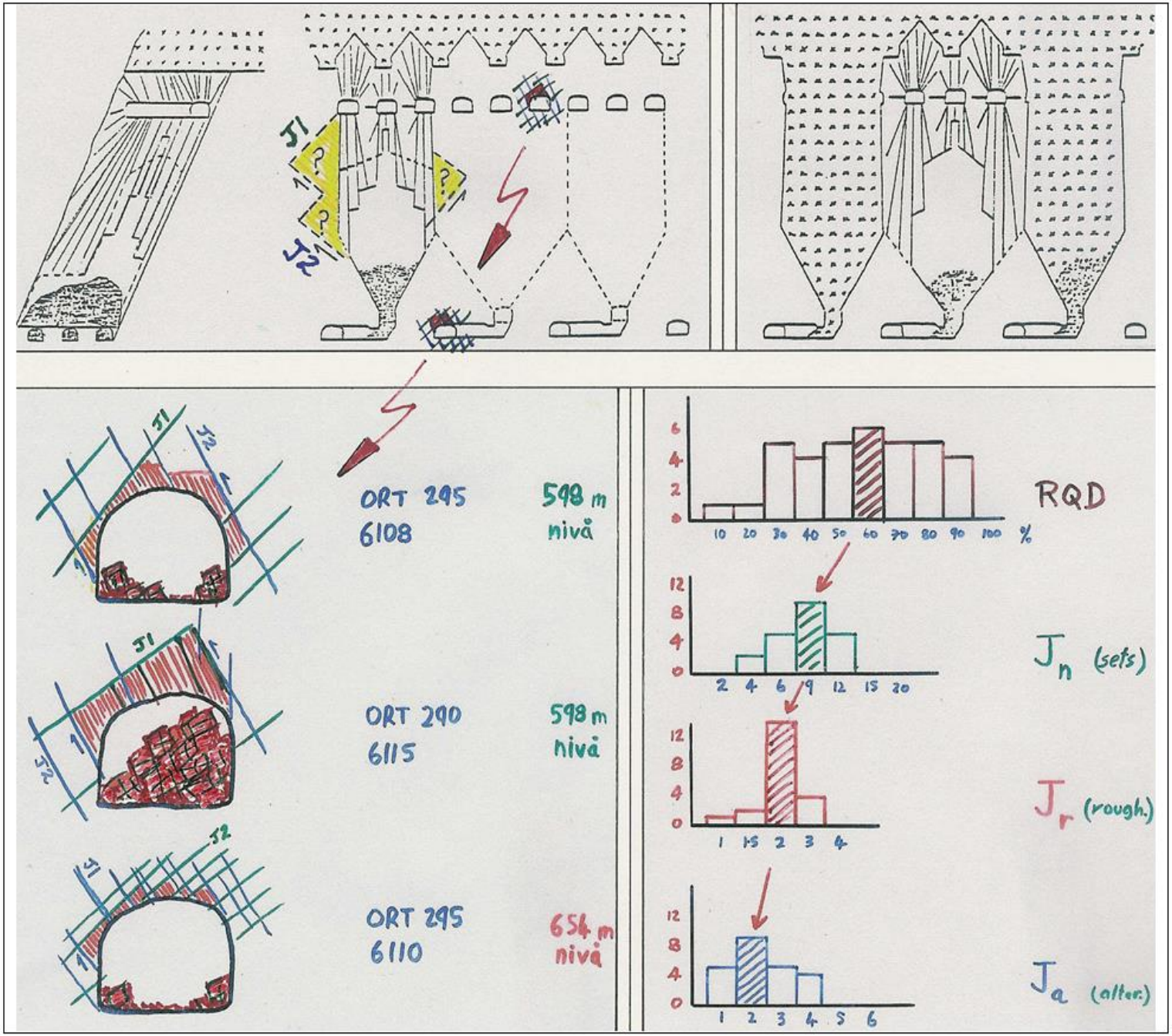
Faulted rock causing tunnel collapse, Brazil

Q = 0.001 (or worse)

LET US CONTINUE WITH Q FOR A WHILE

Many, many different conditions have to be quantified by 'Q' – and it is best to use all six parameters. SRF and Jw may be very important!





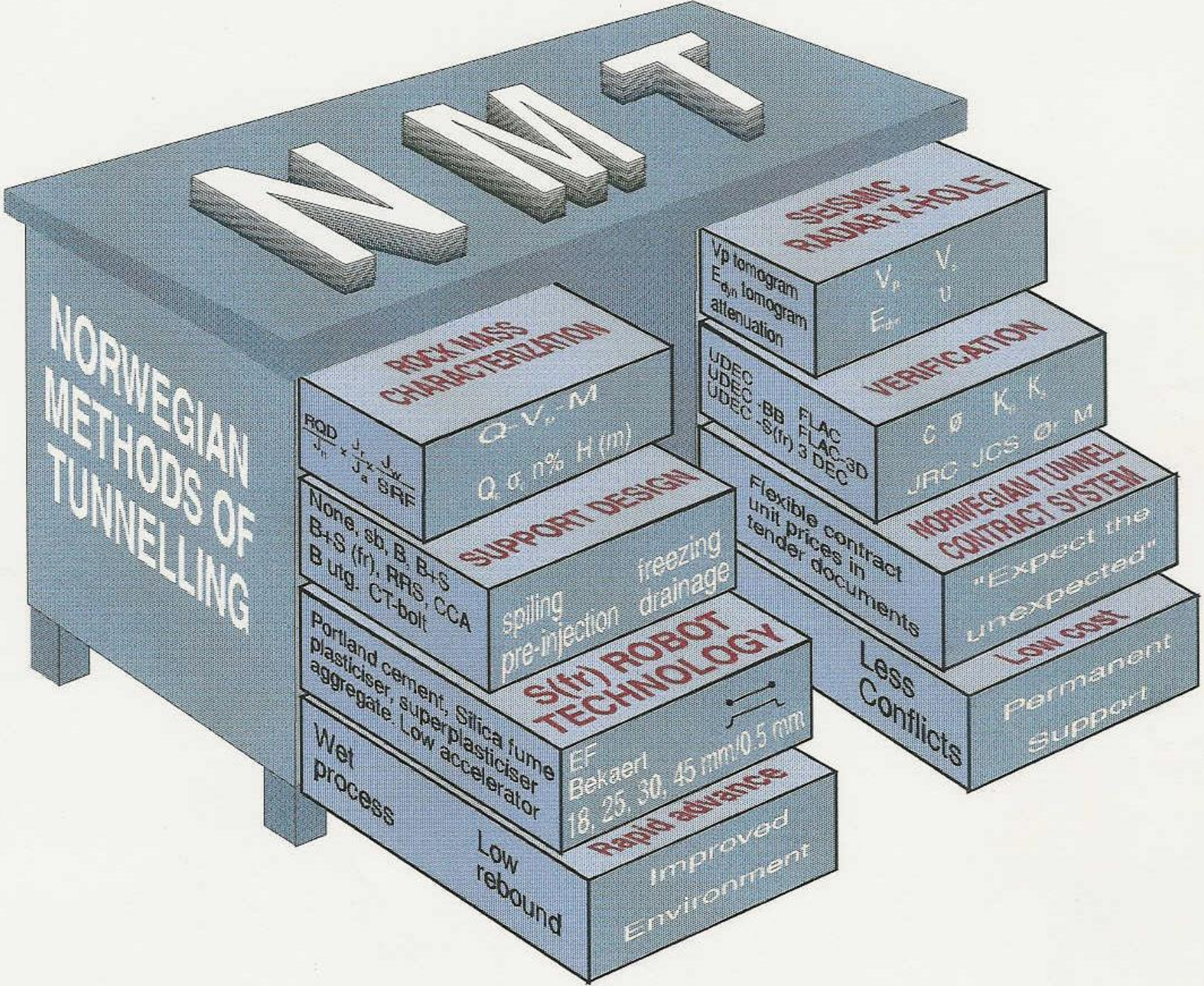
But in mining, the Stability Graph method uses only Q'

…….

the first four parameters

Plenty of **Jr/Ja** to worry about, sometimes **SRF** too.

Jn /Jr ≥ 6 for over-break (and natural block caving)


NMT
NORWEGIAN METHODS OF TUNNELLING
SEISMIC RADAR X-HOLE
Vp tomogram
Edyn tomogram
attenuation
Vp Vs
Edyn U
ROCK MASS CHARACTERIZATION
RQD/Jn x Jr/Ja x Jw/SRF
Q-Vp-M
Q, σ, n% H (m)
VERIFICATION
UDEC
UDEC-BB
UDEC-S(fr)
FLAC
FLAC-3D
3 DEC
c ø K, K,
JRC JCS Ø M
SUPPORT DESIGN
None, sb, B, B+S
B+S (fr), RRS, CCA
B utg. CT-bolt
spiling
pre-injection
freezing
drainage
NORWEGIAN TUNNEL CONTRACT SYSTEM
Flexible contract
unit prices in
tender documents
"Expect the unexpected"
Less Conflicts
LOW COST
Permanent support
S(fr) ROBOT TECHNOLOGY
Portland cement, Silica fume
plasticiser, superplasticiser
aggregate. Low accelerator
EF
Bekaert
16, 25, 30, 45 mm/0.5 mm
Wet process
Low rebound
Rapid advance
Improved Environment

Design

Preliminary design is based on field mapping, drill core logging and seismic interpretation.

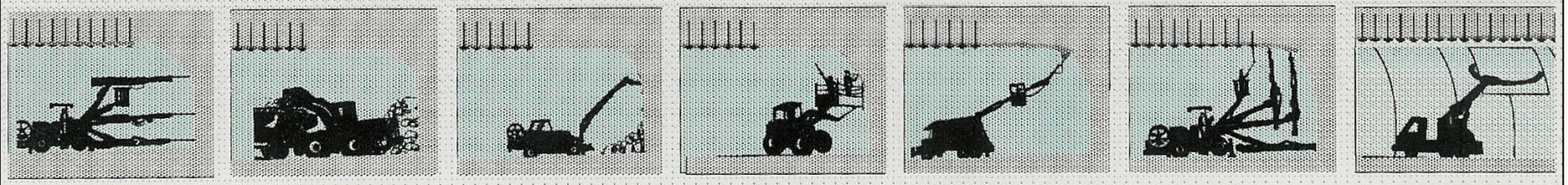
Final support is selected during tunnel construction based on tunnel logging and use of the Q-system support recommendations.

Support

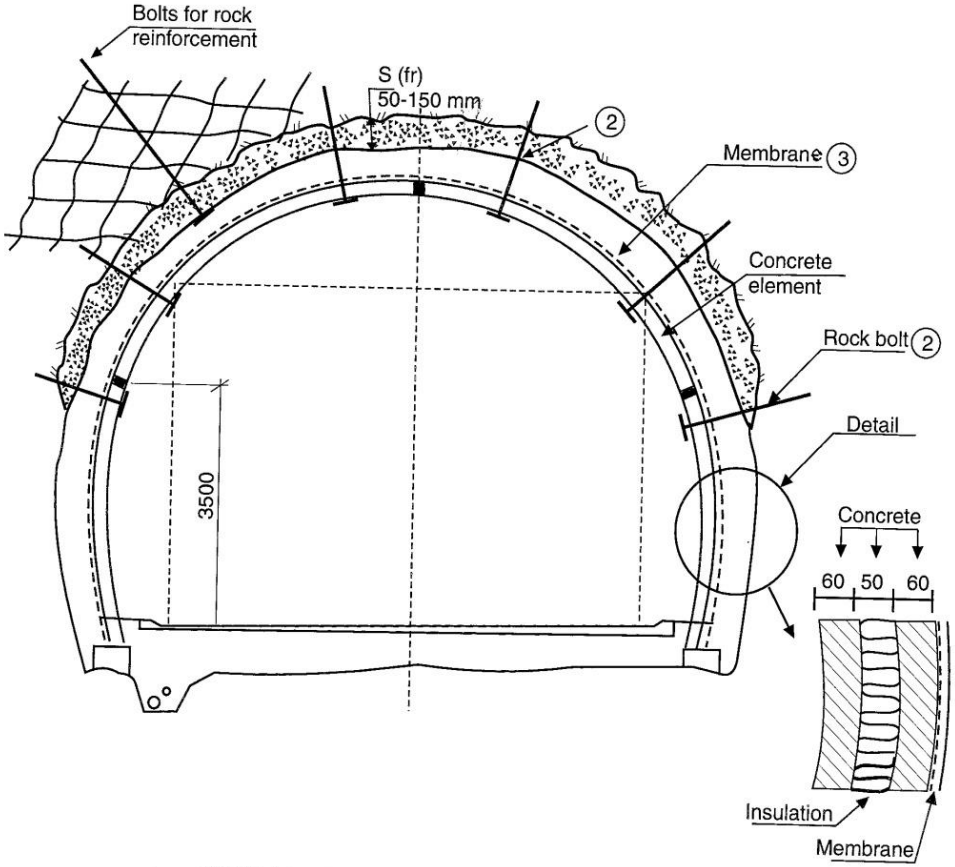
The permanent support usually consists of high quality wet process, fibre reinforced shotcrete and fully grouted, corrosion protected rock bolts.

Contract

The owner pays for technically correct support. Needed support is based on the agreed Q-value, and may vary frequently.

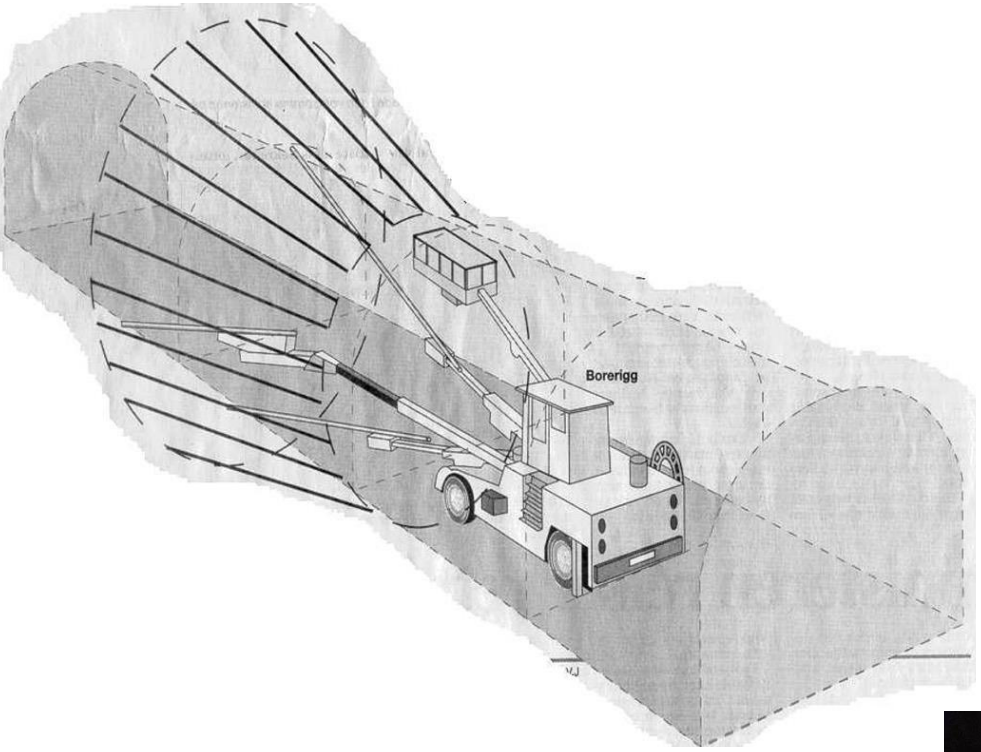


Drilling | Mucking | Pigging | Q-Logging | S (fr) Robot | Bolting | Cladding



If water has not been sufficiently controlled, due to inadequate pre-injection……

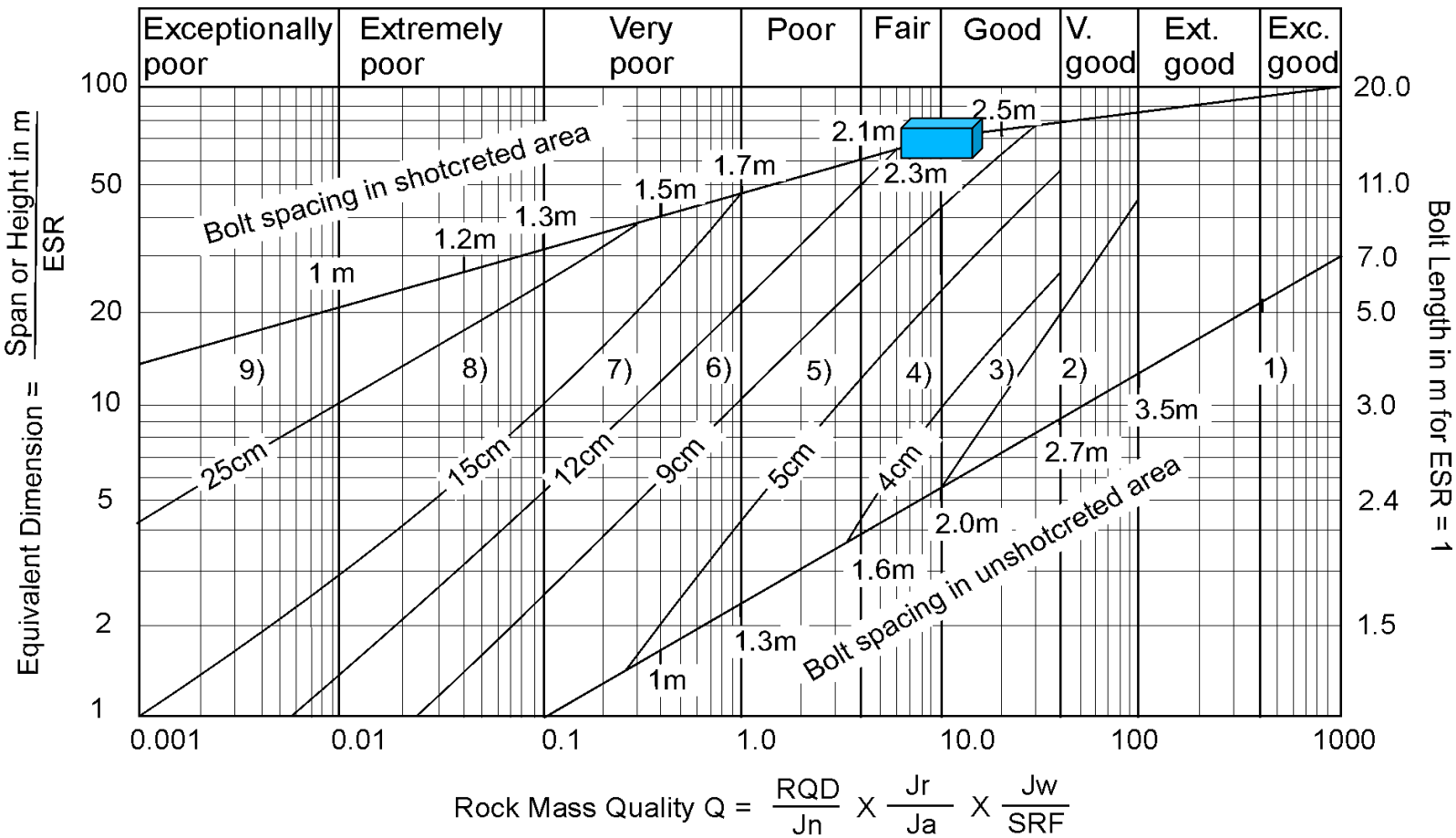
….then PC-elements with outer membrane sheet can be used.



But we prefer
5 to 10 MPa
pre-injection
with microcement
and micro-silica…..

….and in the future
probably sprayed
membrane in a
sandwich for any
remaining damp
spots.

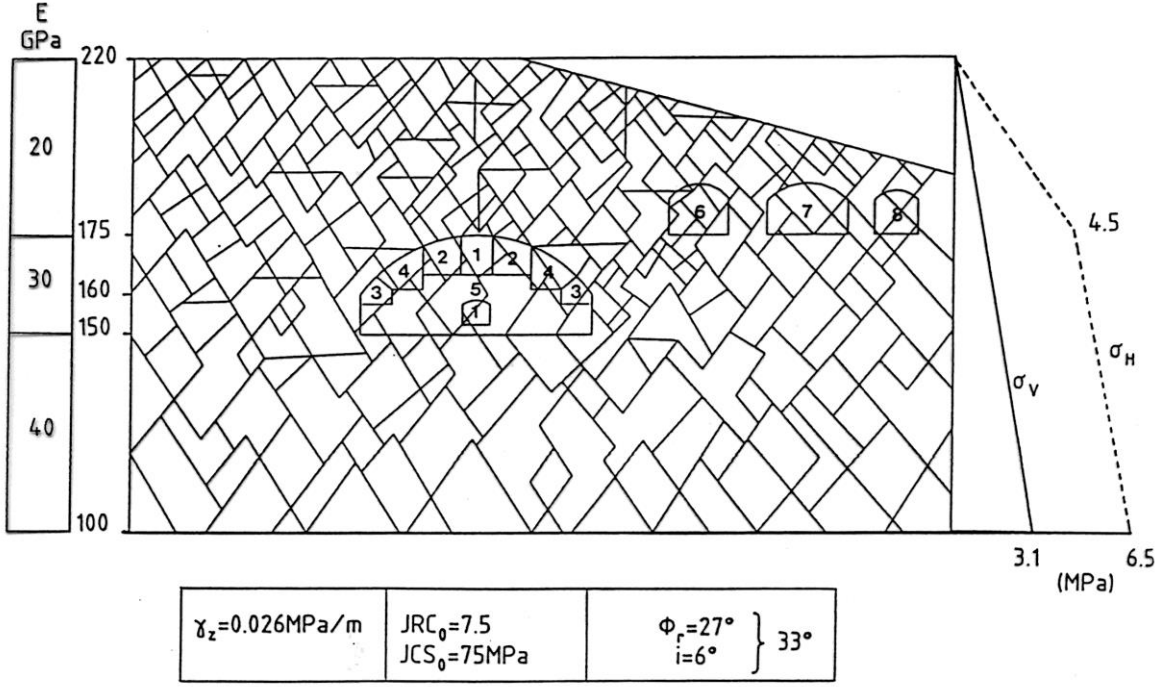
NMT ('single-shell') for tunnels and caverns!



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

(Grimstad and Barton, 1993, Barton and Grimstad, 1994)



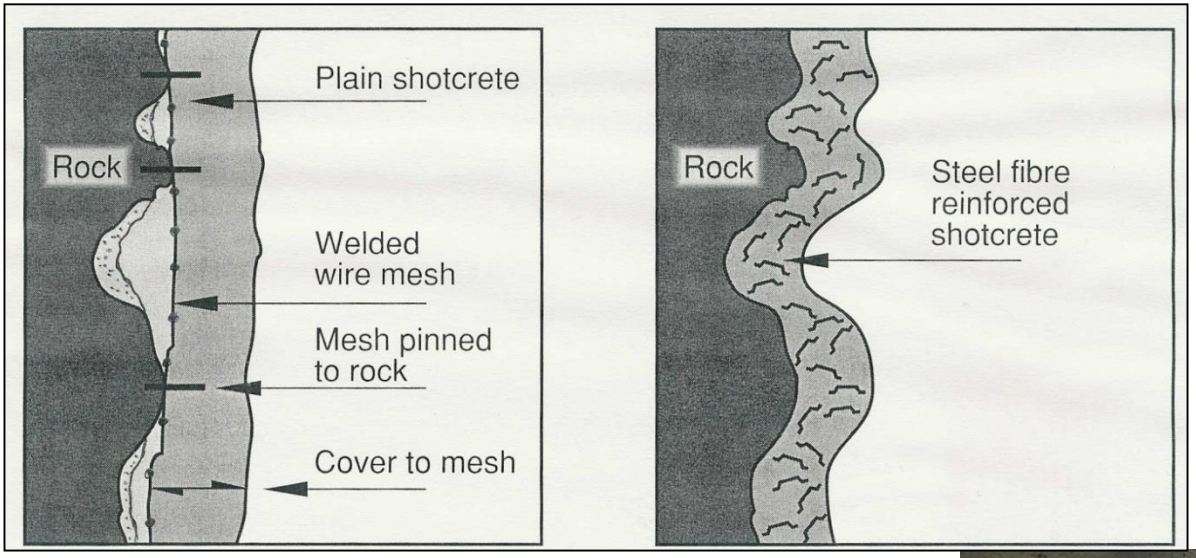
GJØVIK CAVERN JOINT GEOMETRY ASSUMPTIONS

(Boundary stresses, excavation stages, moduli variation with depth/stress, BB-joint input regarding JRC, JCS, ϕ_r and ..... Patton 'i' (Barton et al. 1994).

Permanent rock mass support from Q-system: 'single-shell' B+S(fr) 2.5 m c/c and 10 cm S(fr)

NMT ('single-shell') in shales….110 m2 high-speed rail tunnel – double track. Dry tunnel behind the pre-injection.

Note closeness of last blast to B+S(fr)



A universal move to S(fr).....after 35 years availability should be obvious!

One process, not three,

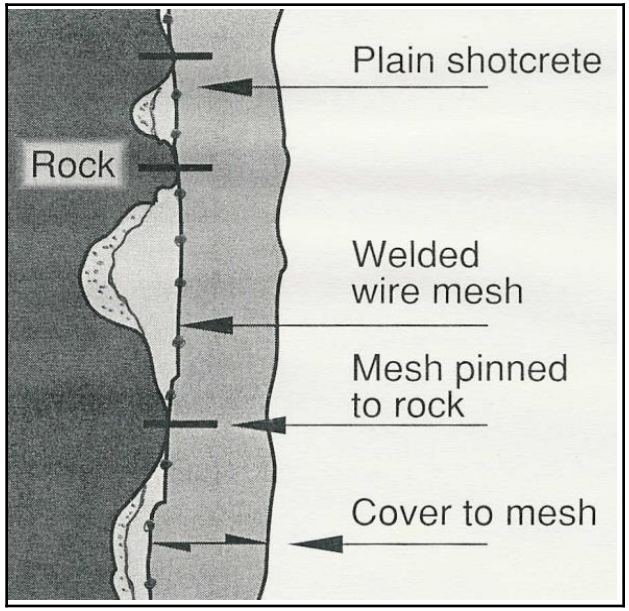
Worker safety guaranteed, gives 20 to 25 m3/hour reinforced concrete.

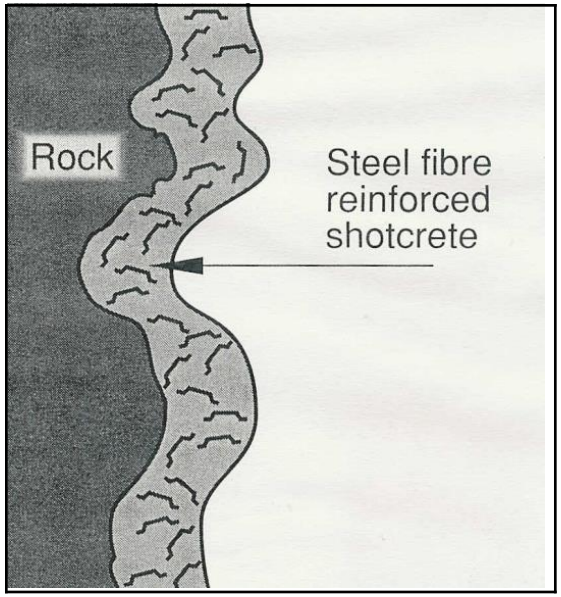
(Spray first in arches when water, instability).

‘NATM’ or ‘NMT’ ?

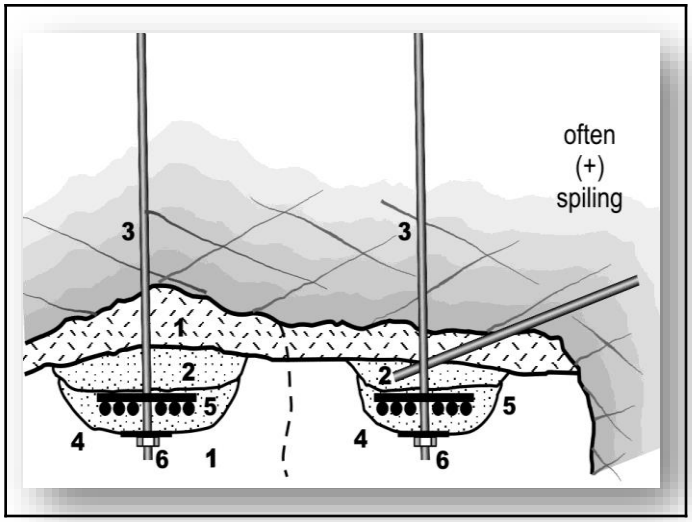
Use of thicker S(fr) in ‘one’ process, and no cast-concrete liner, therefore quicker project completion, needs careful economic assessment.

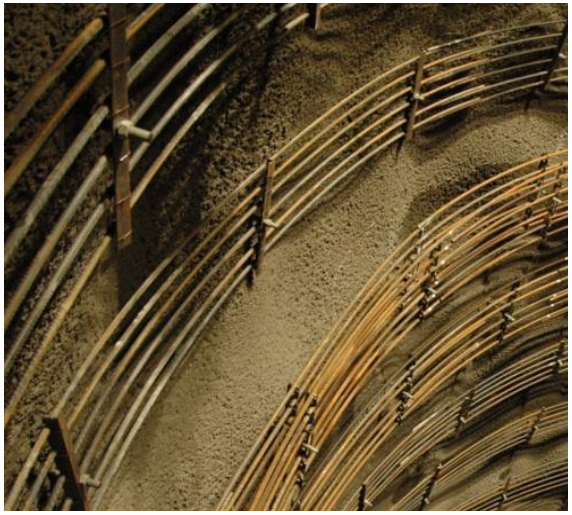
It may pay off handsomely. Higher unit prices can also give cheaper tunnels!

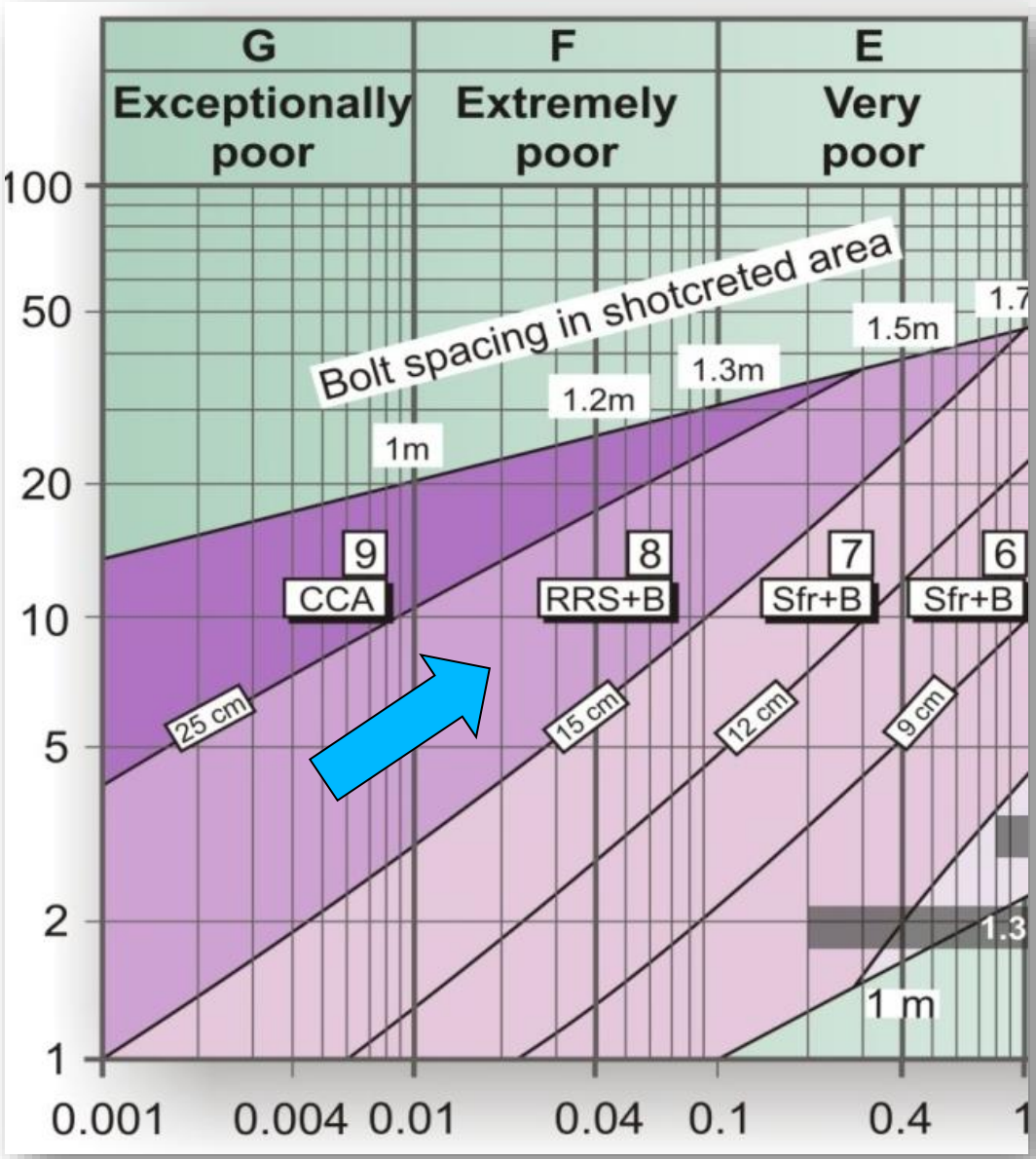




Wet process robotic S(fr) – since 1978 – **is better than S(mr). RRS: not steel sets, not lattice girders.**



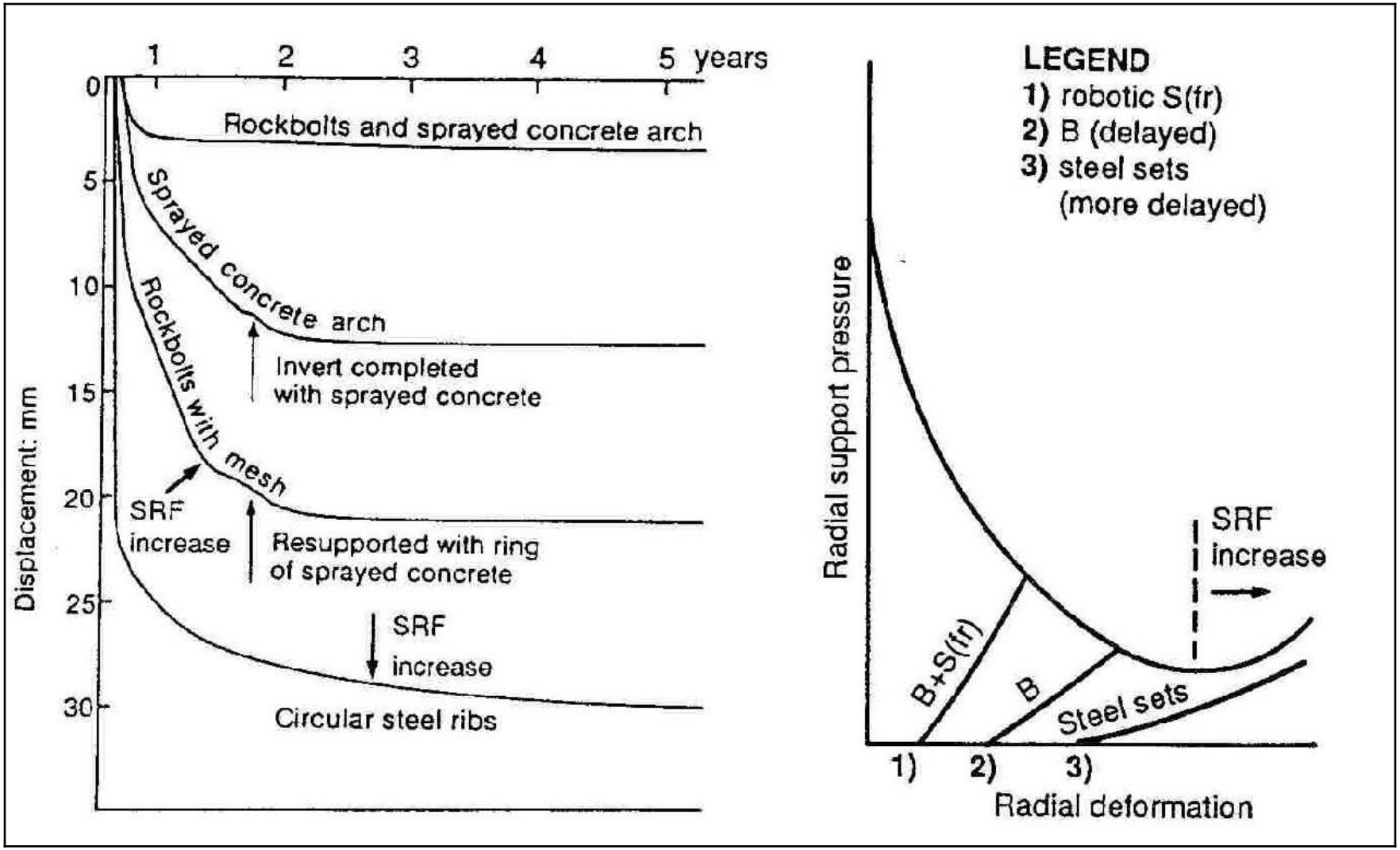




RRS is a flexible but bolted-to-be-stiff 'lattice' girder.

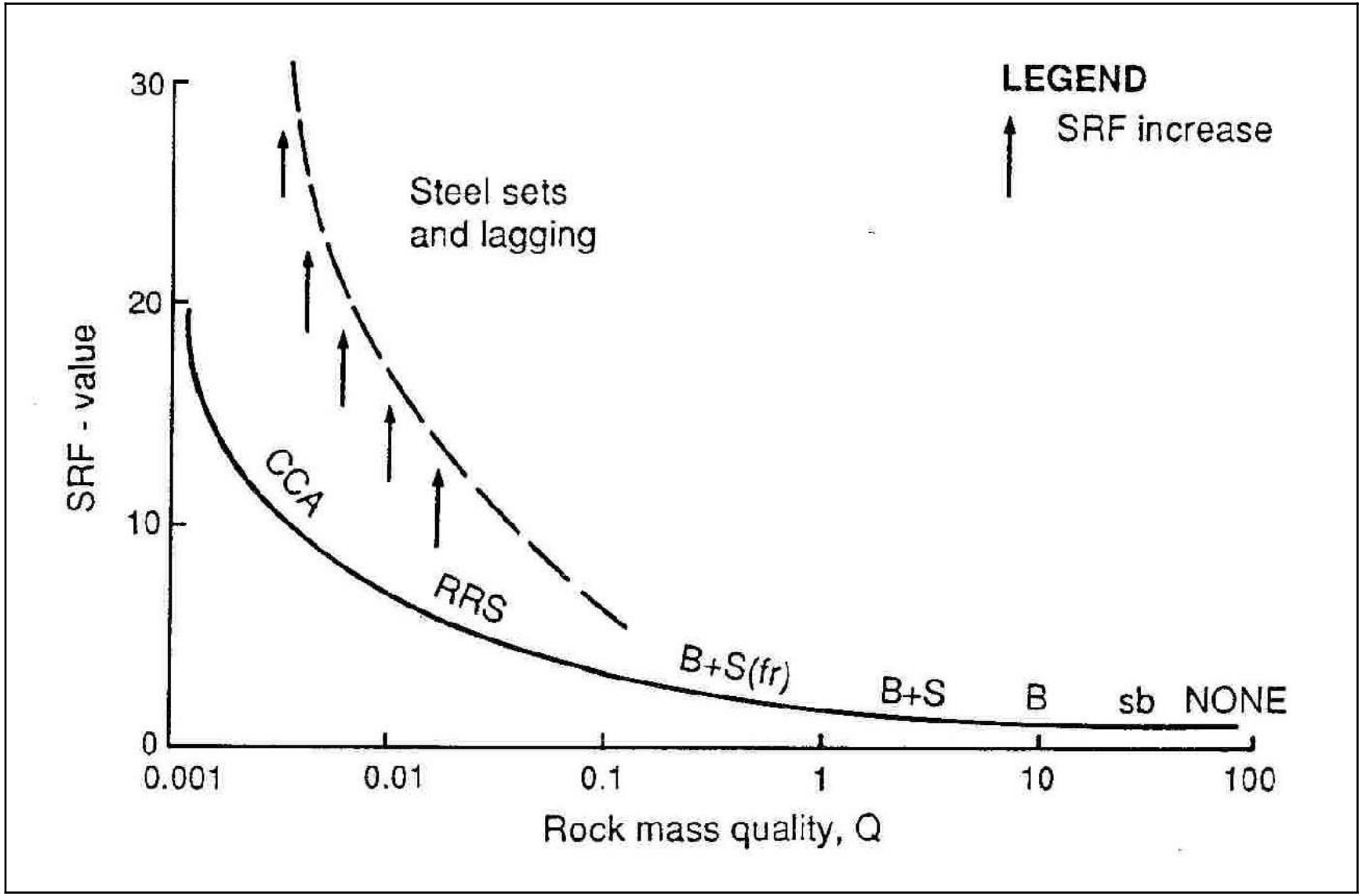
3D effect because of S(fr) arches.

Add smoothing shotcrete / concrete afterward



If the objective is to minimise loosening: avoid steel sets, and also avoid 'initially standing in the air' lattice girders.

(Ward et al., 1983 and Barton and Grimstad, 1994)



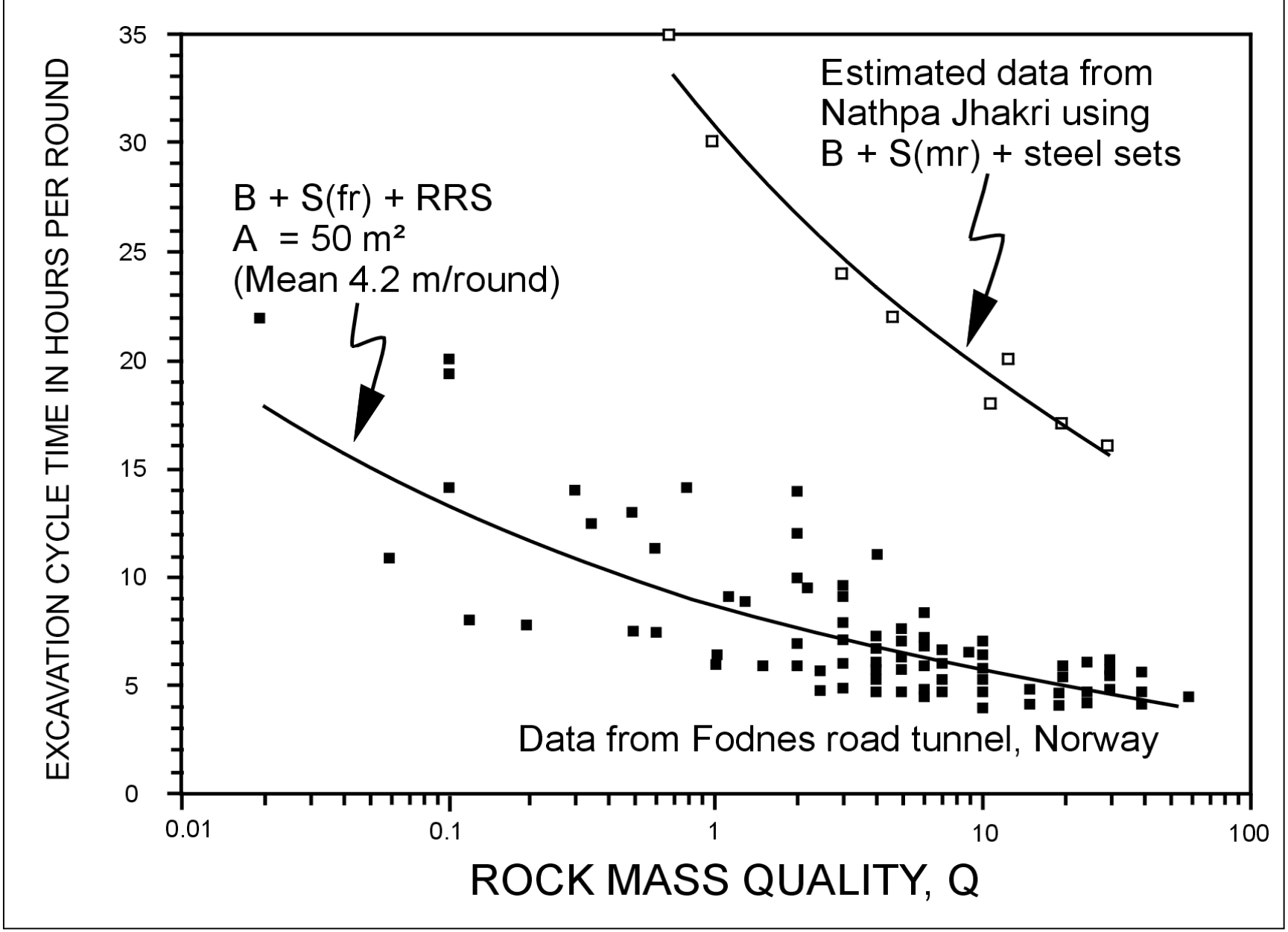
A guaranteed way to worsen the effective rock quality and increase deformation – hence the 'need' for NATM.

THE POTENTIAL (ACTUAL) INEFFECTIVENESS OF STEEL SETS and LATTICE GIRDERS, UNTIL (IF?) THEY ARE SPRAYED IN CONTACT WITH THE TUNNEL ARCH.

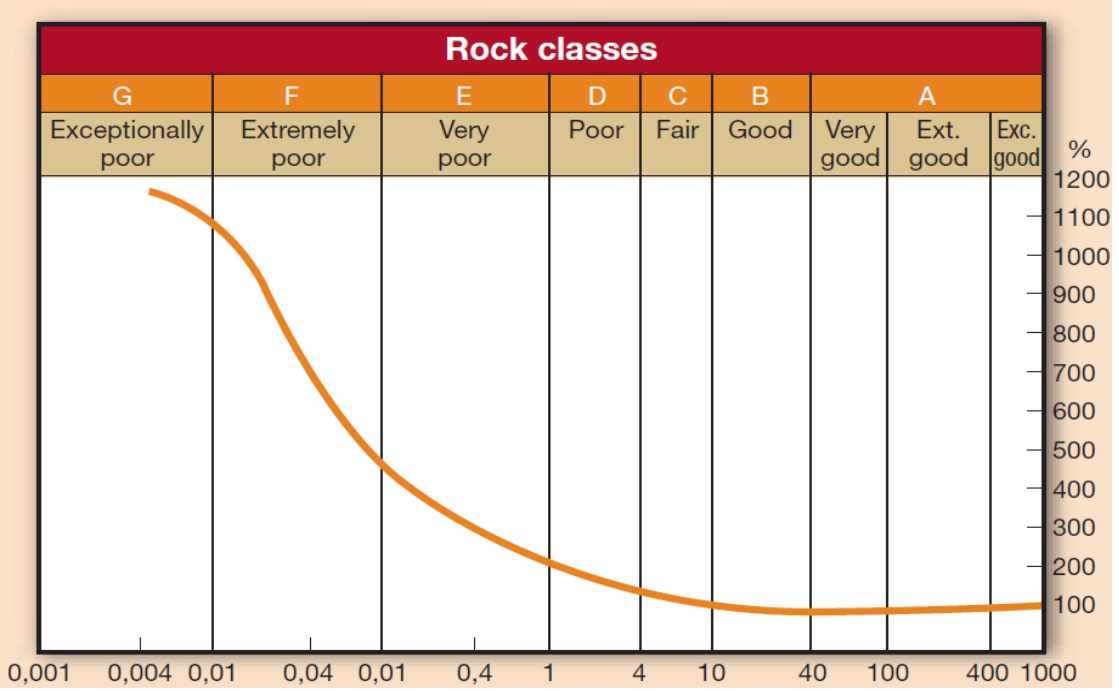
THEN THEY DEFORM, AND FOOTINGS DISPLACE.

ONLY THE SPILING BOLTS DRILLED INTO THE FACE ARE GOING TO BE FULLY EFFECTIVE, WHEN THE NEXT ADVANCE IS MADE.

Scandinavian contractors may *travel* with lattice girders and concrete-lining slip-forms, as part of their 'international baggage', but will use them as little as possible, preferably never.

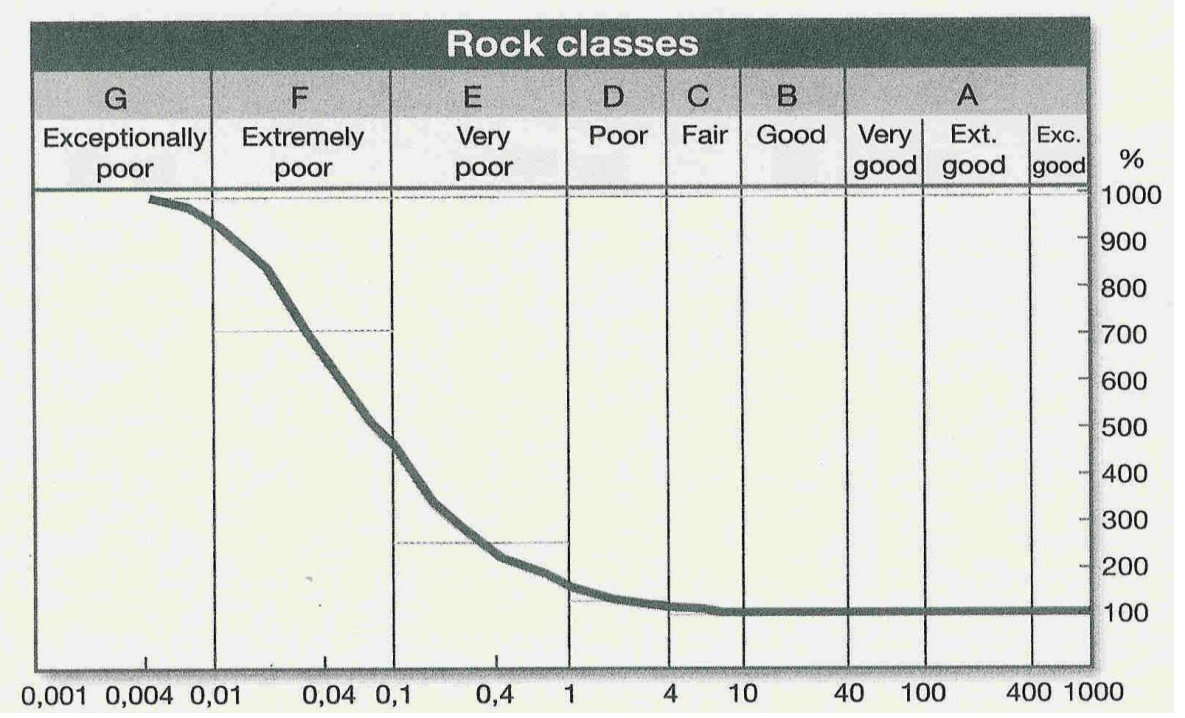


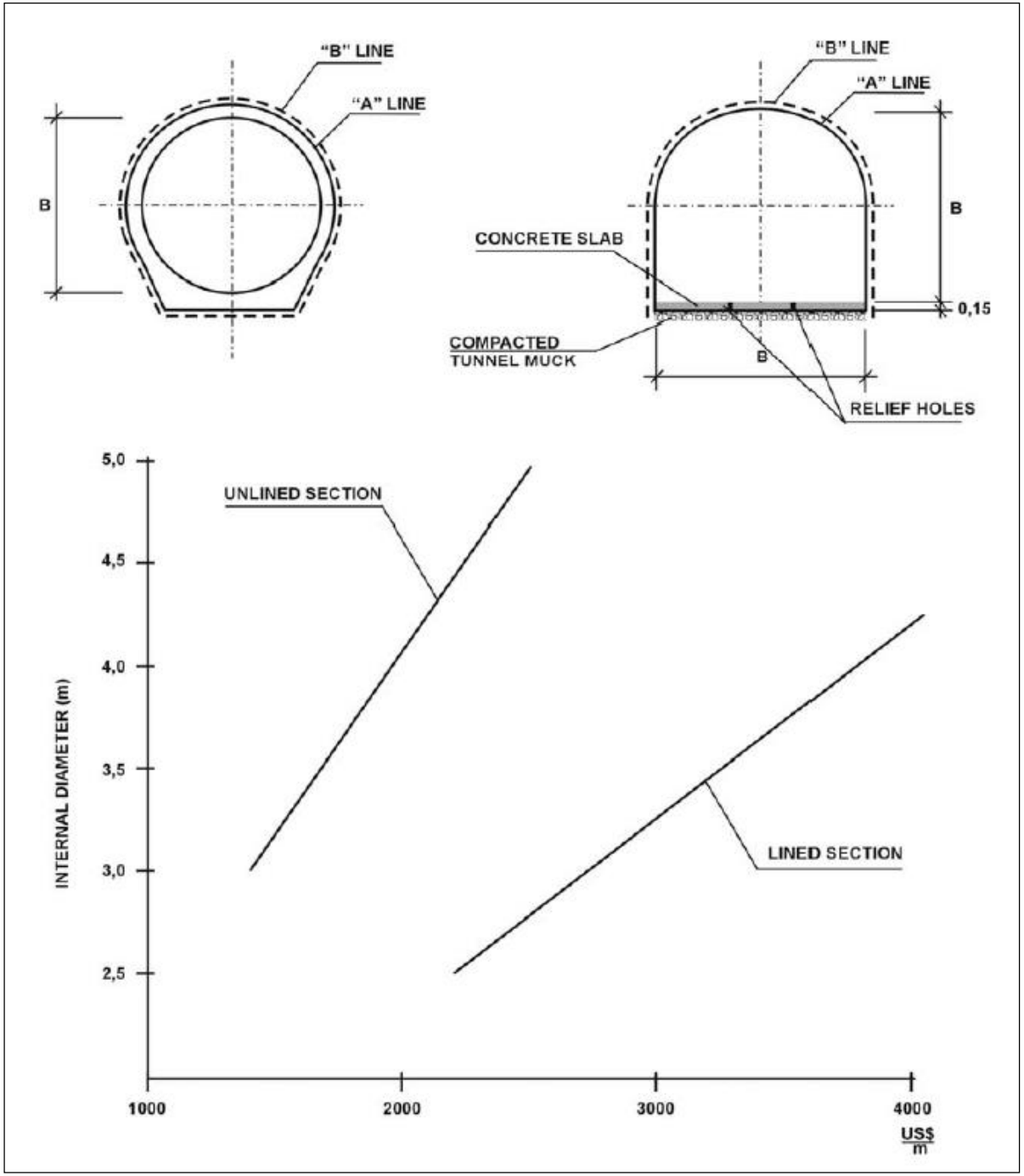
Observations made by Grimstad, 1996.



Relative **cost** versus Q

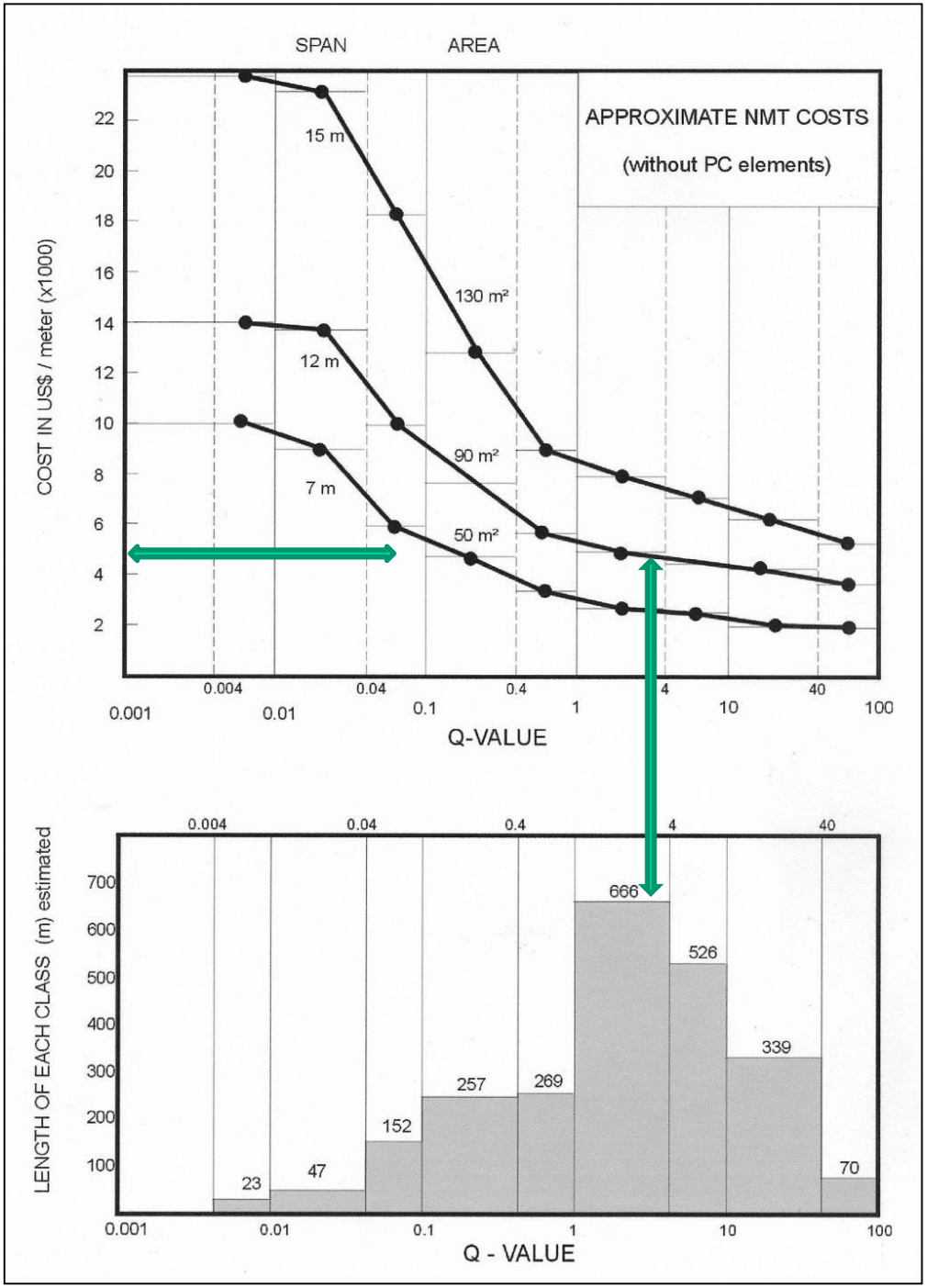
Relative **time** versus Q





Larger cross-section with NMT principles of permanent support, compared with a concrete-lined (horse-shoe, 'D' or circular tunnel)

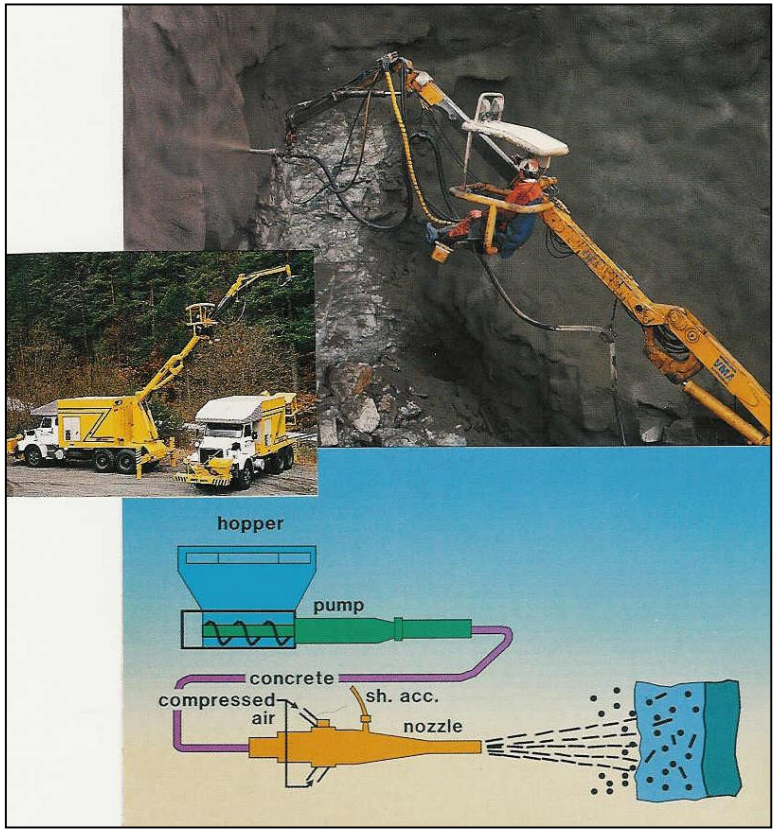
(Relative costs from early 1990's)



Multiplication of *frequency* by *cost/meter* for given rock classes.

Note that pre-injection could potentially 'transfer' much of the low-Q-high-cost area towards the right.

(Costs from early 2000's)

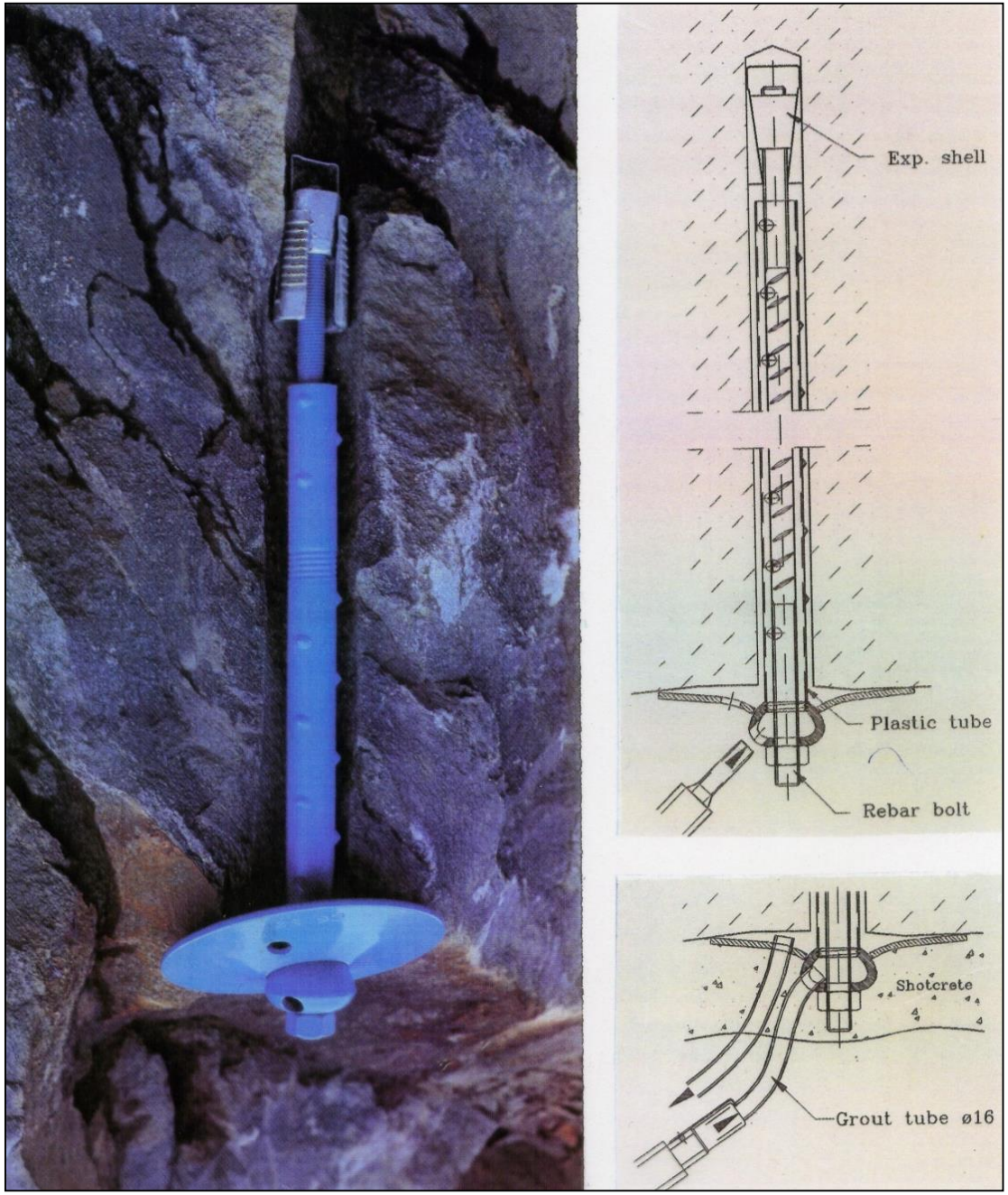


A typical mix design for shotcrete used in Norway:

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

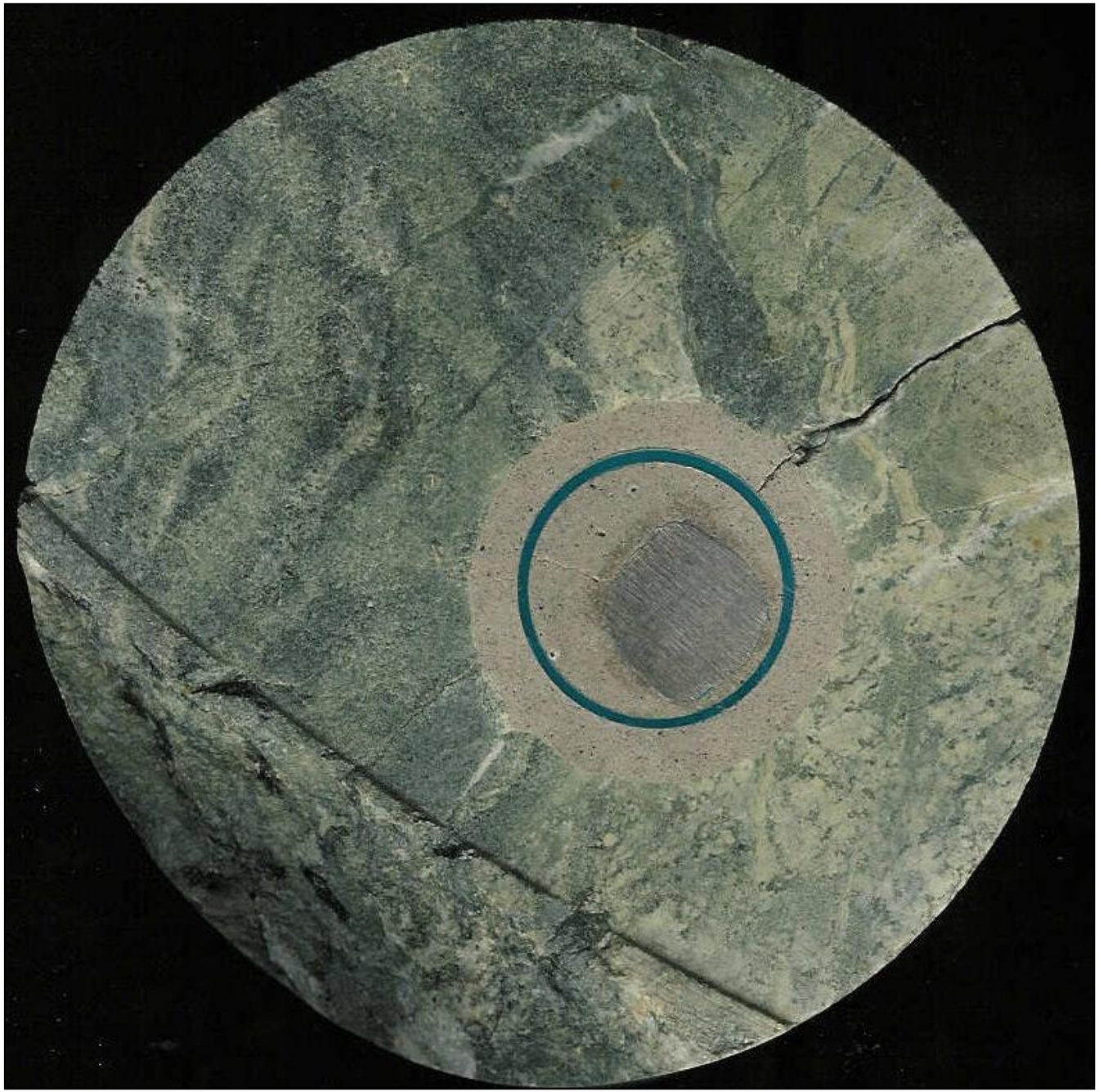
Typical S(fr) mix design for C45 to C55 (MPa) shotcrete.

Note operator location close to nozzle, where rebounds of 4 to 6% (and almost dust-free air) make quality control very easy.



Permanent bolts – *truely permanent bolts*, remove some of the need for concrete liners.

Grouting of the CT bolt can be performed after shotcreting, if desired.



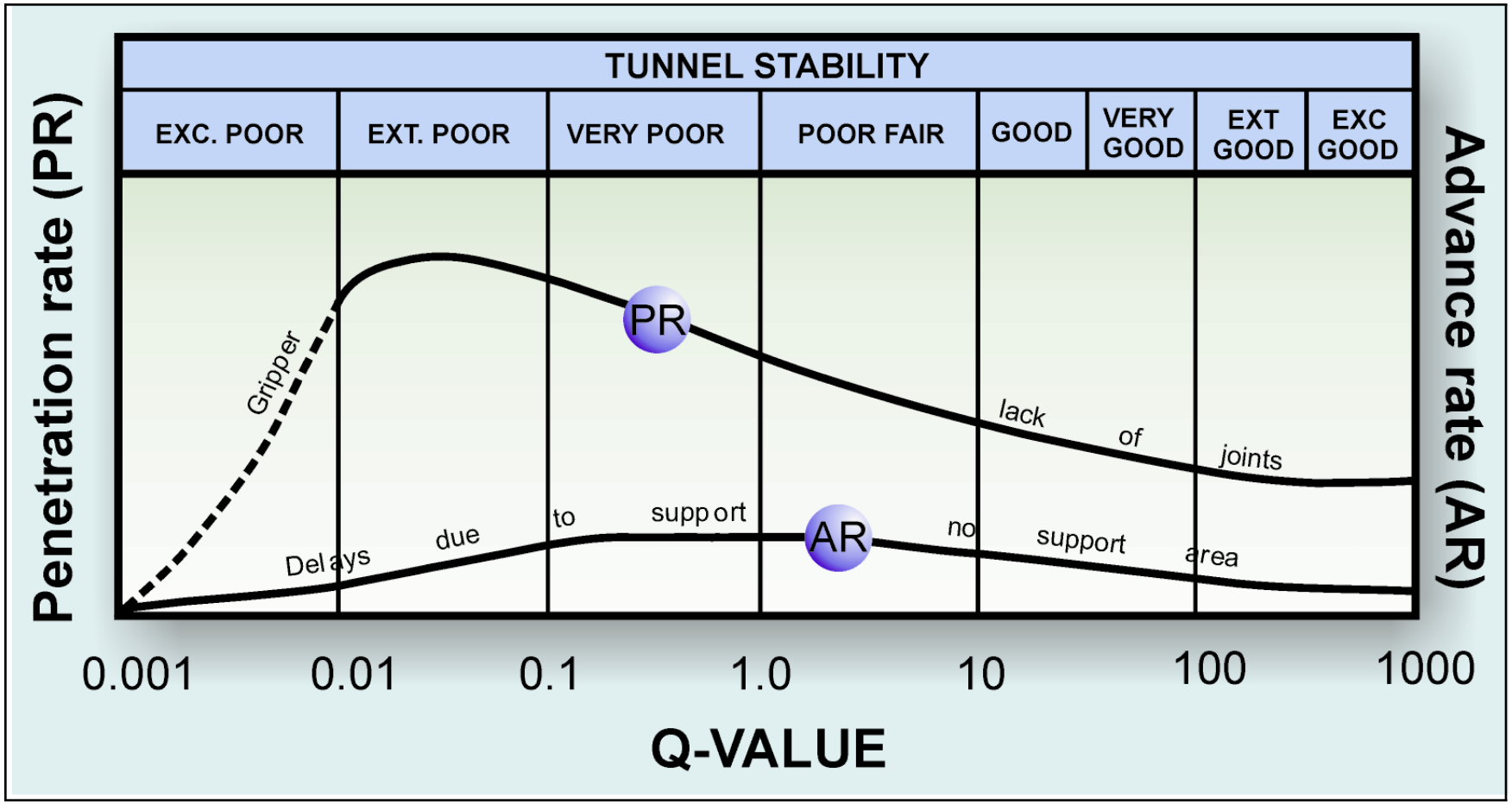
Four layers of corrosion protection remain after cracking of the outer layer of grout.

The cost and time involved in final concrete lining, compared to smoothing with thicker S(fr), needs careful comparison, weighing up the *higher unit cost, but maybe not total cost*, due to the potential saving of time. (But old shotcrete robots will prevent this advantage from being realized: need 20-25 m3/hour Sfr).

TBM TUNNELLING WHEN HEADRACE TUNNELS ARE LONG AND DEEP?

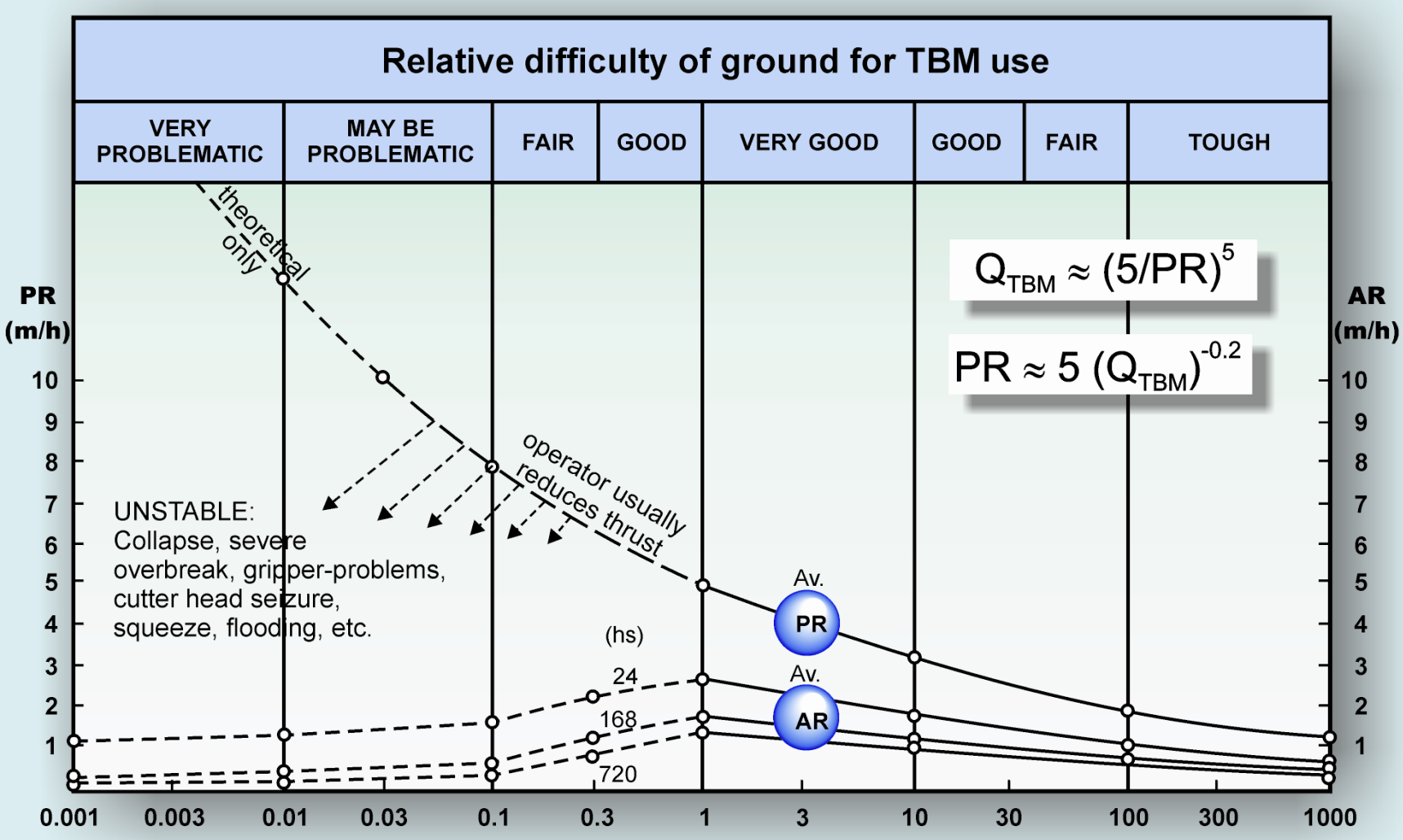
('The project was delayed 99 months')

A reminder that the standard 'Q-system' adjectives about "good" quality (for D+B) need to be modified....even for double-shield TBM.



Note change of adjectives. Massive hard rock is bad news.

Also faults are bad news.

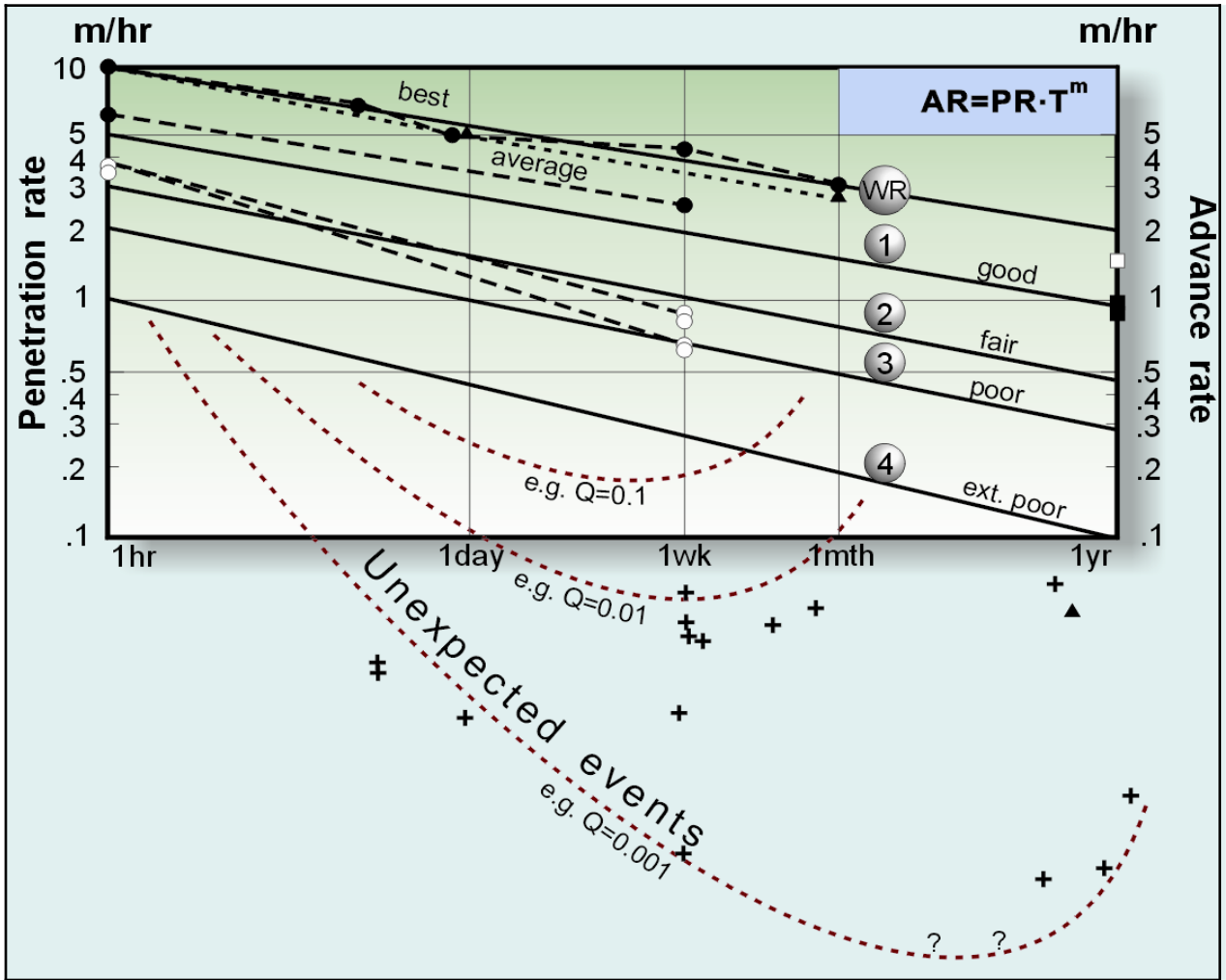


$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

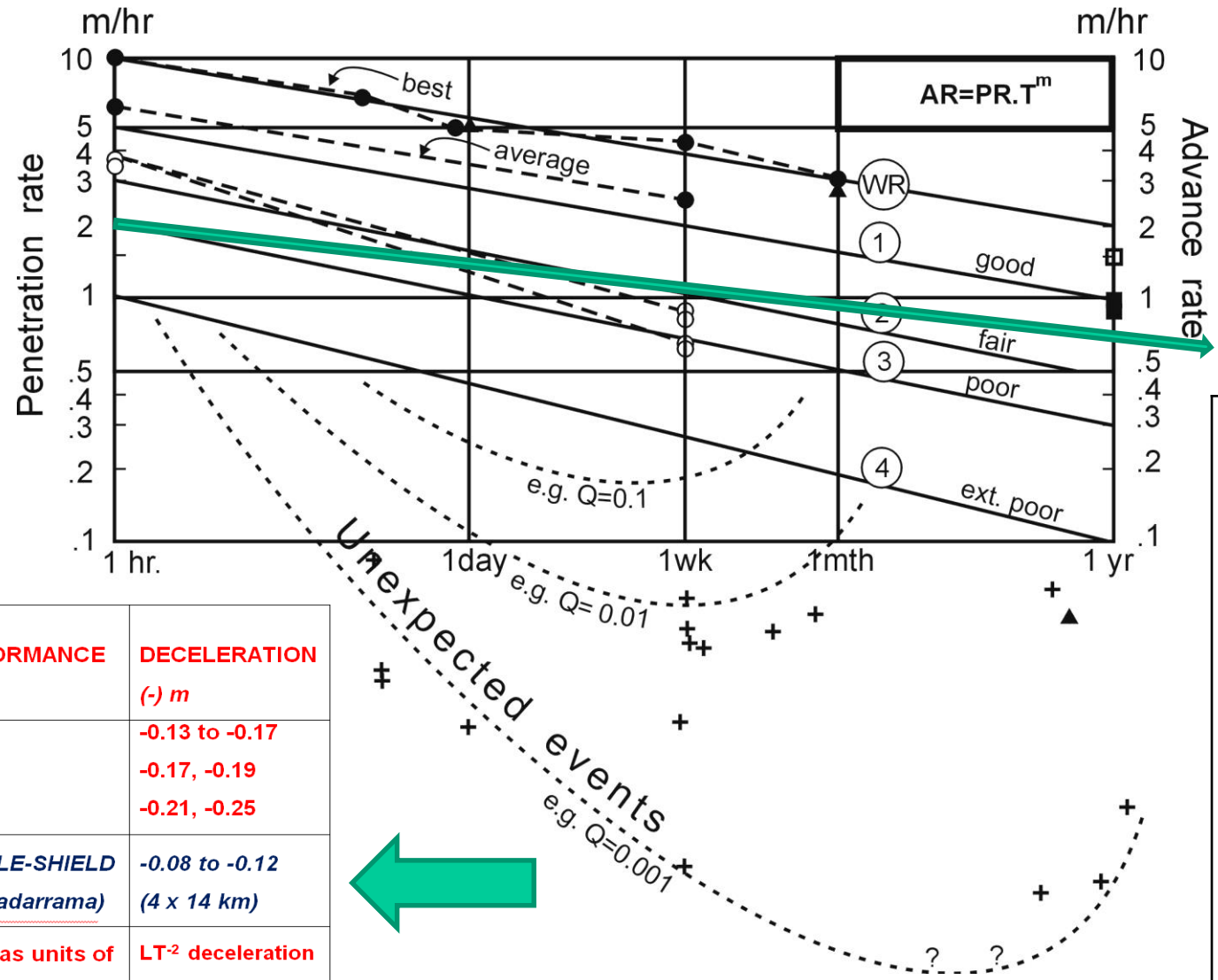
SYNTHESIS OF THE 145 CASE RECORDS (mostly OPEN-GRIPPER TBM) TOTALLING ABOUT 1000 KM OF TBM TUNNELLING. SEE lines *#1, 2 , 3.*

CONVENTIONAL TBM EQUATION: **AR = PR x *U*** → ***AR = PR x T^m***

U = UTILIZATION gradually declines with increased tunnel length.....*if all time, even down-time*, is included. ***Gradient (-)m is deceleration.***



Double-shield machines **with simultaneous liner assembly, and push-off liner capabilities** ***formed very few of these case records***. Rock quality can be described only approximately when *seen* ***with difficulty*** during e.g. cutter change.



PERFORMANCE LINE #	DECELERATION (-) m
WR	-0.13 to -0.17
1, 2,	-0.17, -0.19
3, 4	-0.21, -0.25
DOUBLE-SHIELD (at Guadarrama)	*-0.08 to -0.12 (4 x 14 km)*
(-) m has units of	LT^{-2} deceleration

The blue line

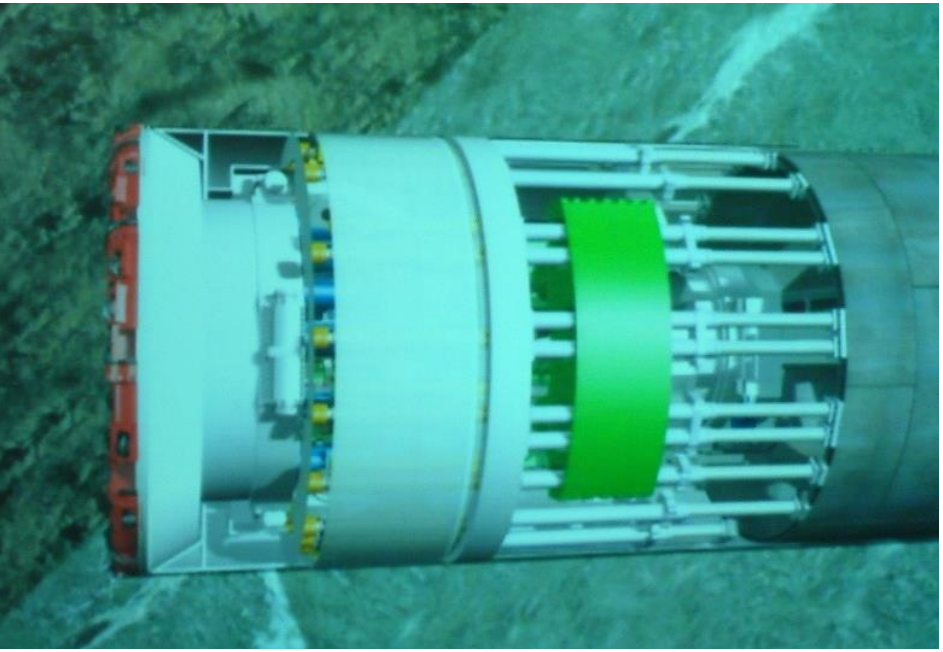
is the mean performance

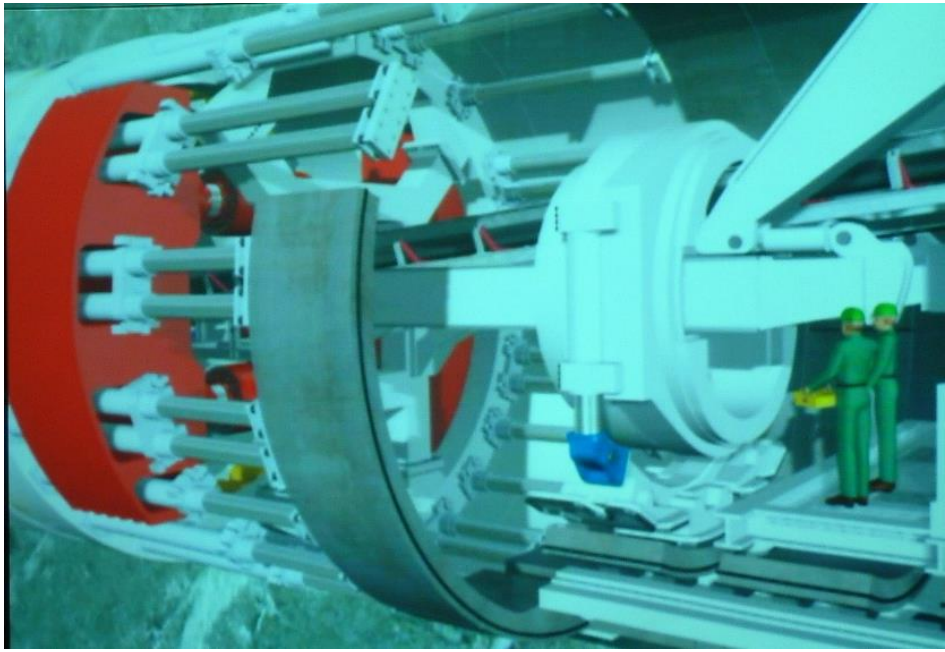
of four TBM

(2 x Wirth)

(2 x HKnecht) tunnelling 56km

(14km each) in mostly granites, two mountains.





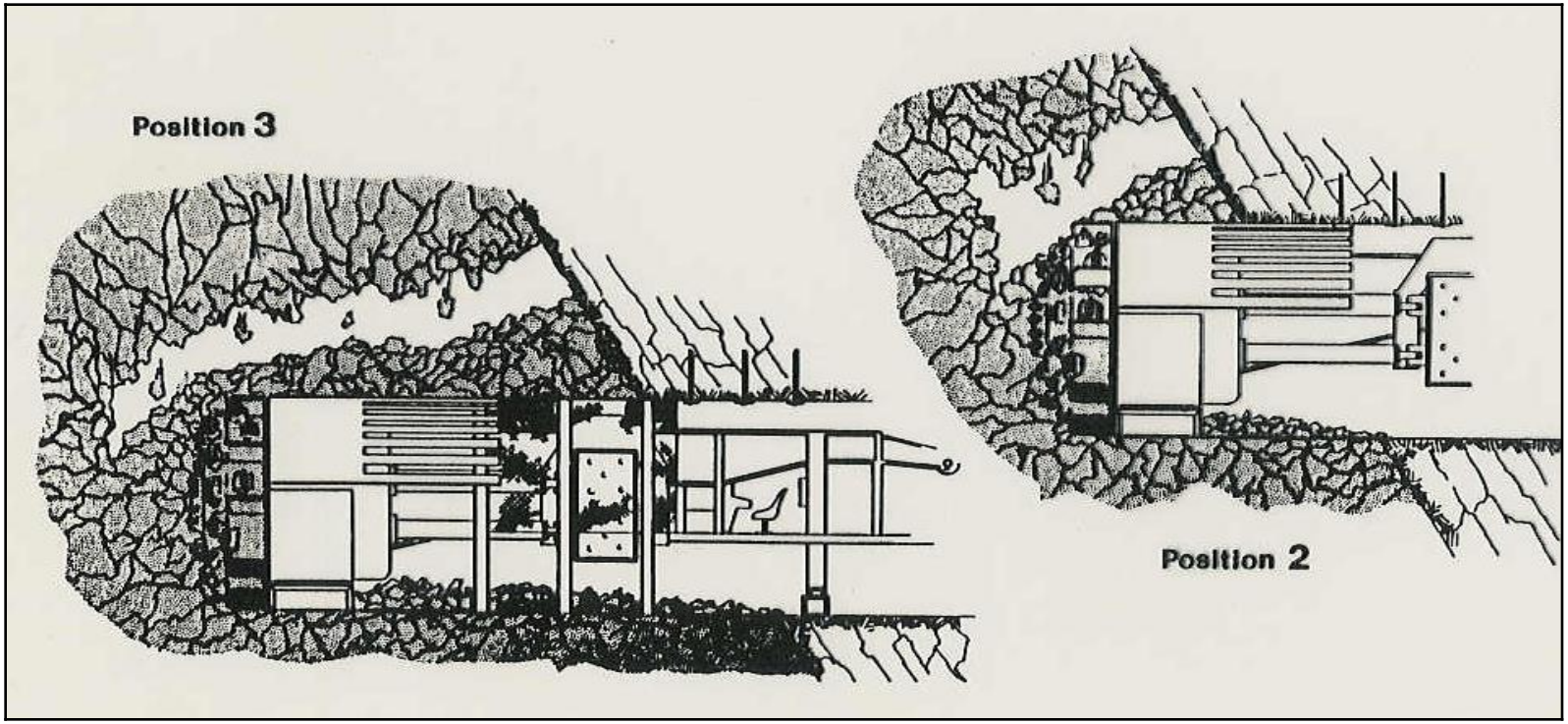
3065 VM

FAULT ZONES AND TBM

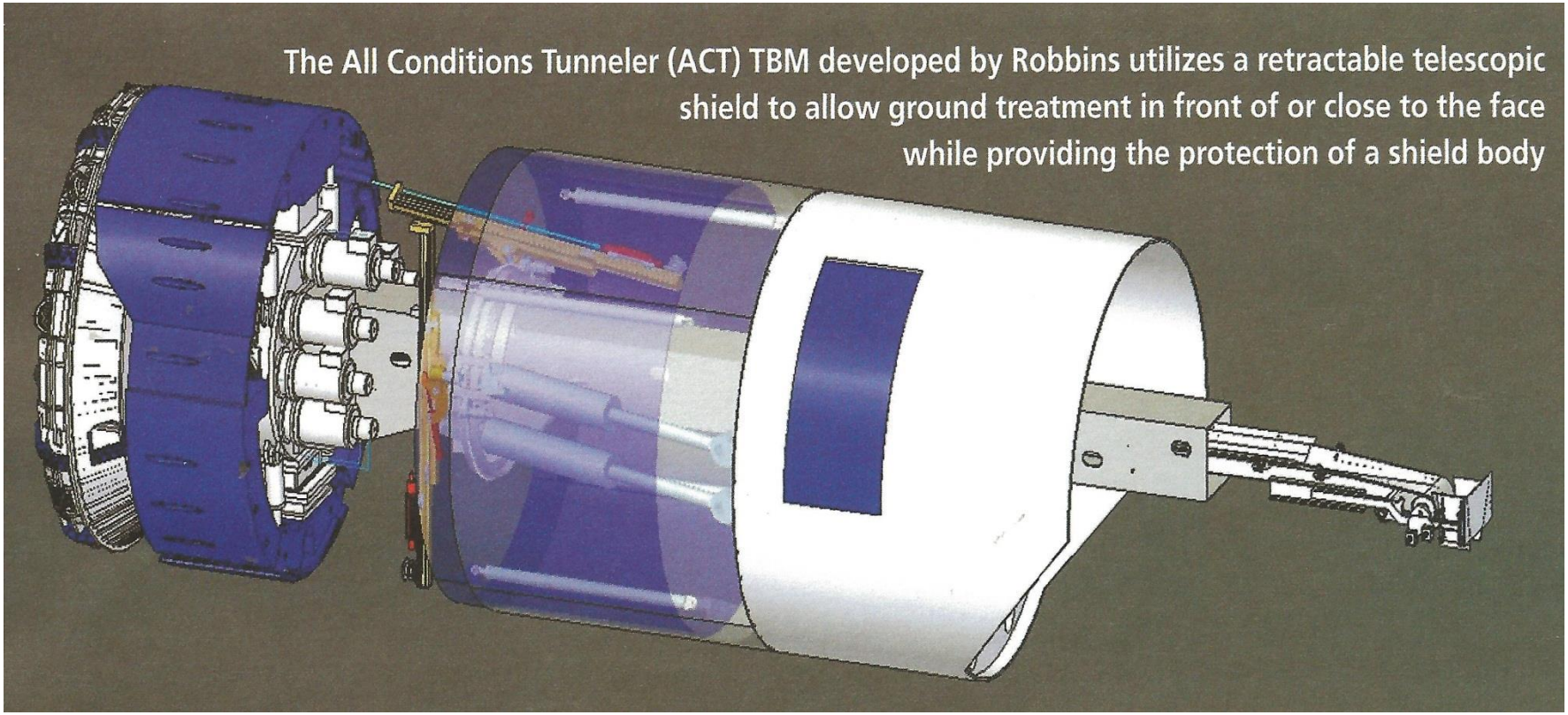
First some theo-empirical reasons for the possible delays

(TBM can occasionally go 2.0 km/month but more 'often' 0.0 km/month, and occasionally can go a record 16 km in one year, but more 'often' 0.0 km in one ultra-bad year, if stuck in a major fault).

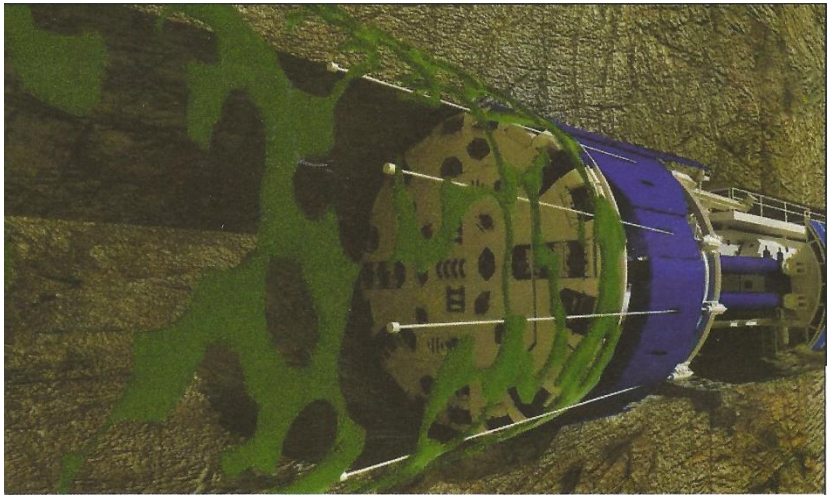
WHY DO FAULT ZONES TAKE SO LONG WITH TBM?

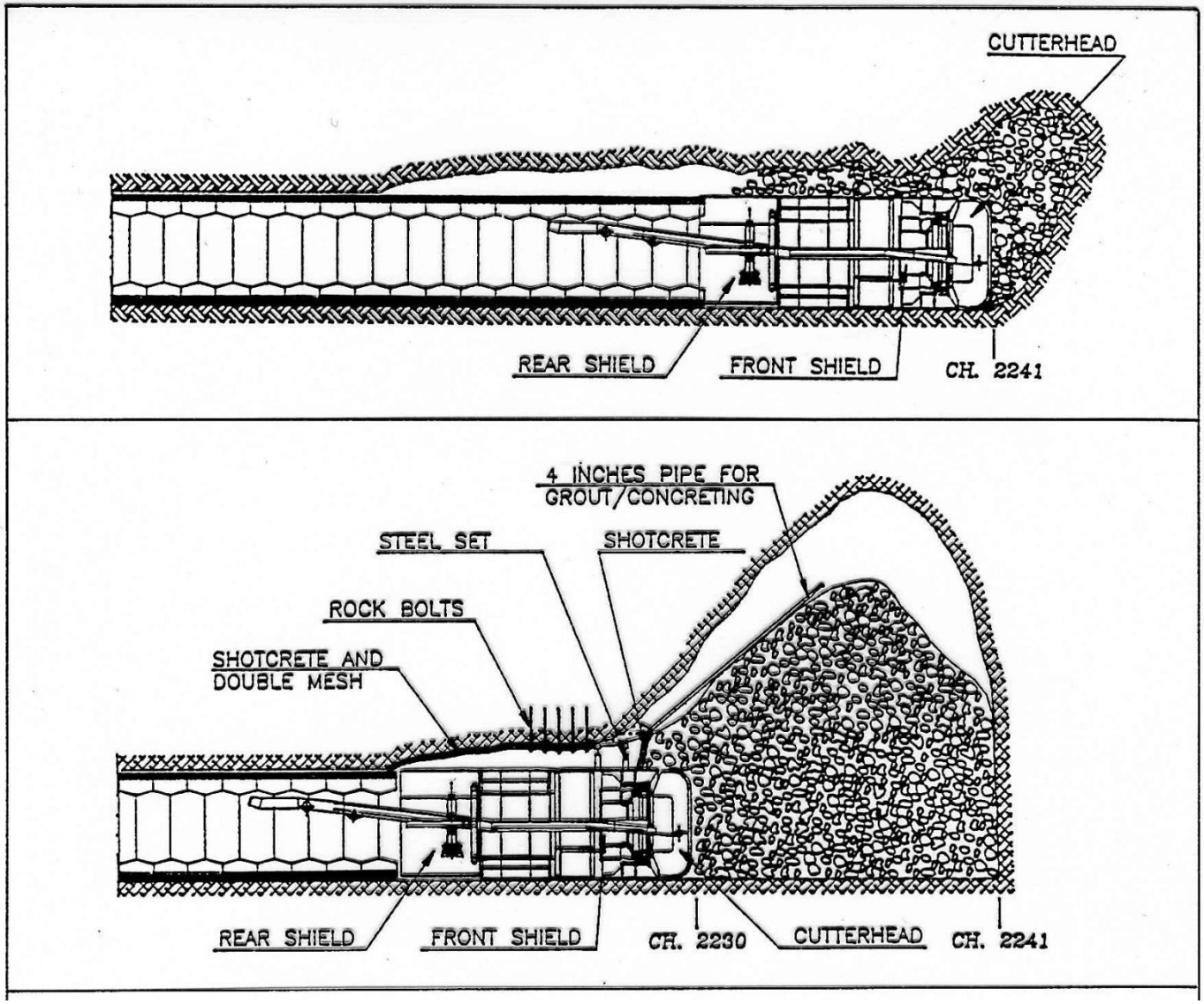


WITHOUT PROBE DRILLING…..ONE IS OFTEN TOO OPTIMISTIC (and the probe drilling is not usually done under the invert where first warnings would be detected……in this and many other cases)



TBM probe drilling and pre-grouting D.Willis, Robbins. Tunnelling Journal, 2012.



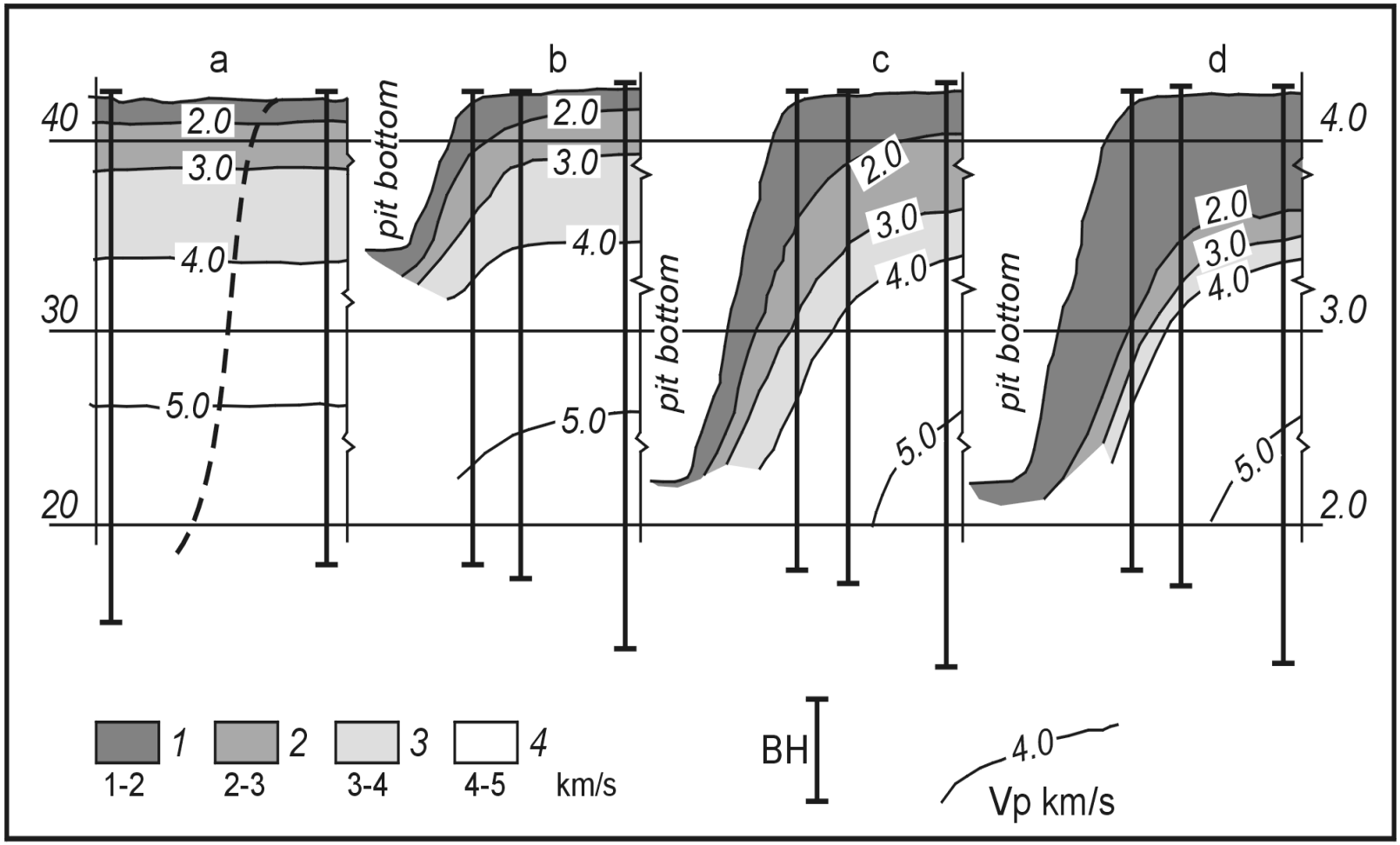


Fault zones also create *great problems for double-shield* TBM – if zone is not pre-treated following probe-drilling discovery!

(Grandori et al., 1995).

Also avoid too much TBM withdrawl.

ANALOGY OF TBM TUNNEL FACE WITH TBM WITHDRAWN



There is 1 year between 'c' and 'd' – presumably with insufficient support

THERE ARE VERY GOOD 'THEO – EMPIRICAL' REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM. (Barton, 2000.)

We need three basic equations to start with

1. ***AR = PR x 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)**

Therefore we have the following:

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

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

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

7. **It is important because very *negative* (-)m values make 1/(1+m) TOO BIG**

8. If the fault zone is wide (large L) and PR is low (due to collapses etc.) then L/PR gets too big to tolerate a TOO BIG component 1/(1+m).

9. ***It is easy (too easy) to calculate an almost 'infinite' time for a fault zone*** using this 'theo-empirical' equation. (Three permanently buried, or fault-destroyed TBM: Pont Ventoux, Dul Hasti, Pinglin…there are many more!)

BUT…Q CAN BE IMPROVED BY PRE-GROUTING !

(improve Q, reduce negative –m)

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

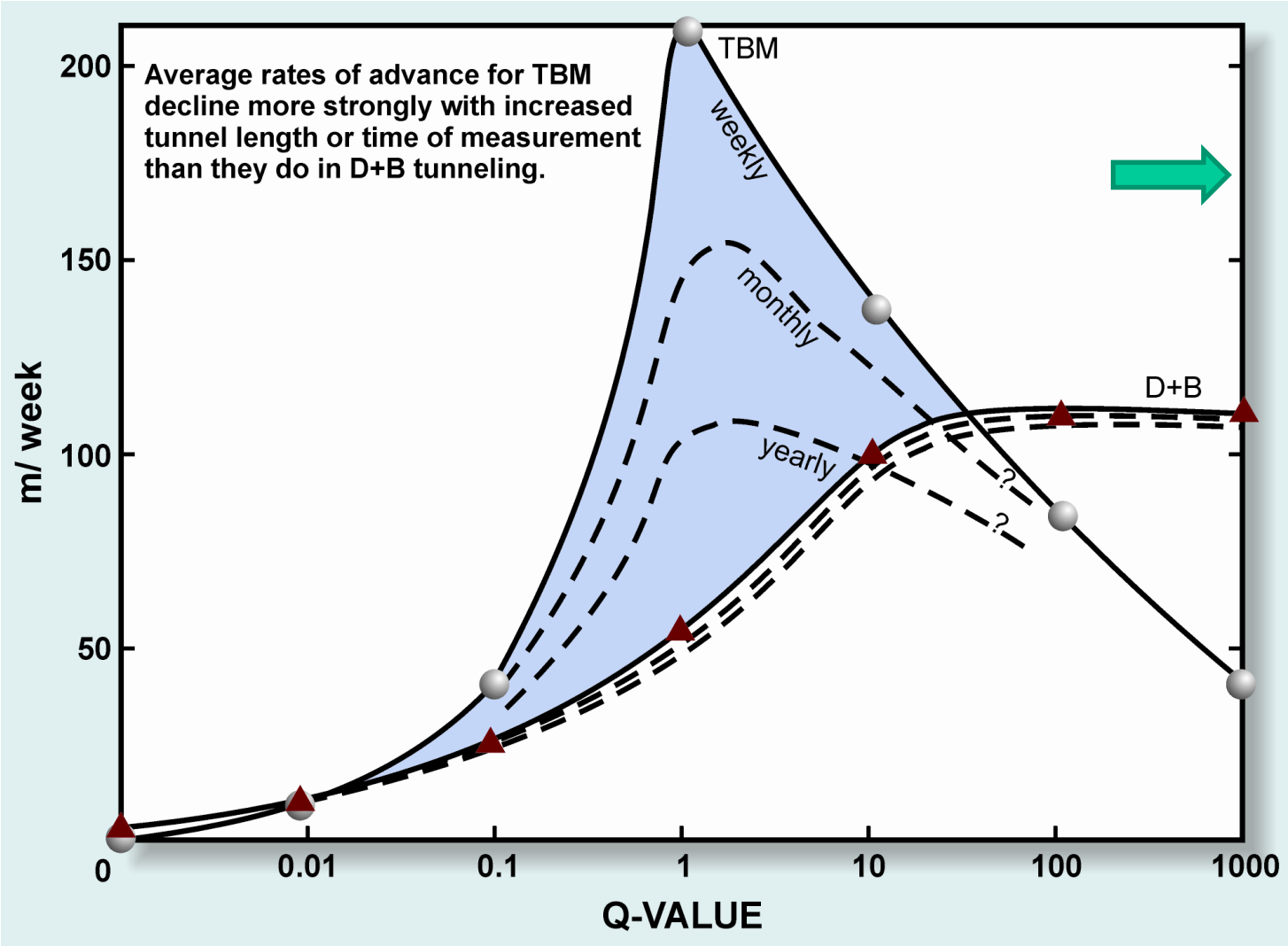
Comparing TBM with drill-and-blast

Central qualities are required – if the TBM is to be much faster than D+B

Are long tunnels faster with TBM?

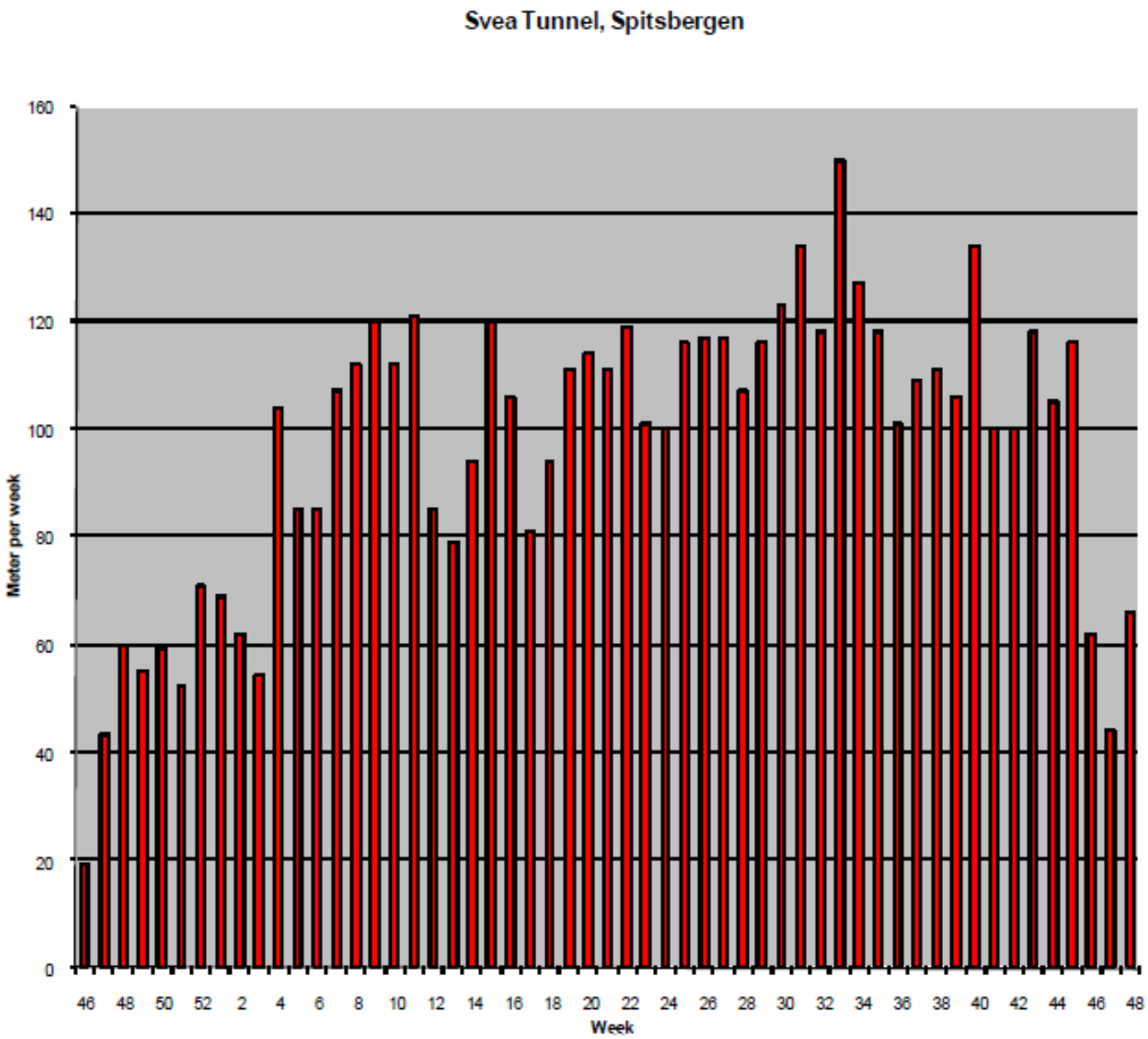
CENTRAL Q-VALUES AND Q_{TBM} VALUES ARE BEST FOR GOOD TBM PROGRESS. *TAIL-DISTRIBUTIONS 'BETTER' WITH D+B !*

(Note that this comparison is for an open-gripper machine *without* push-off liner capabilities in bad rock).



Note records for drill-and-blast:
173m/one face in 168 hours (7x24) week.

Whole project 108 m/week average (next screen).



LNS (Northern Norway contractor)

Leonhard Nilsen & Sonner A/S

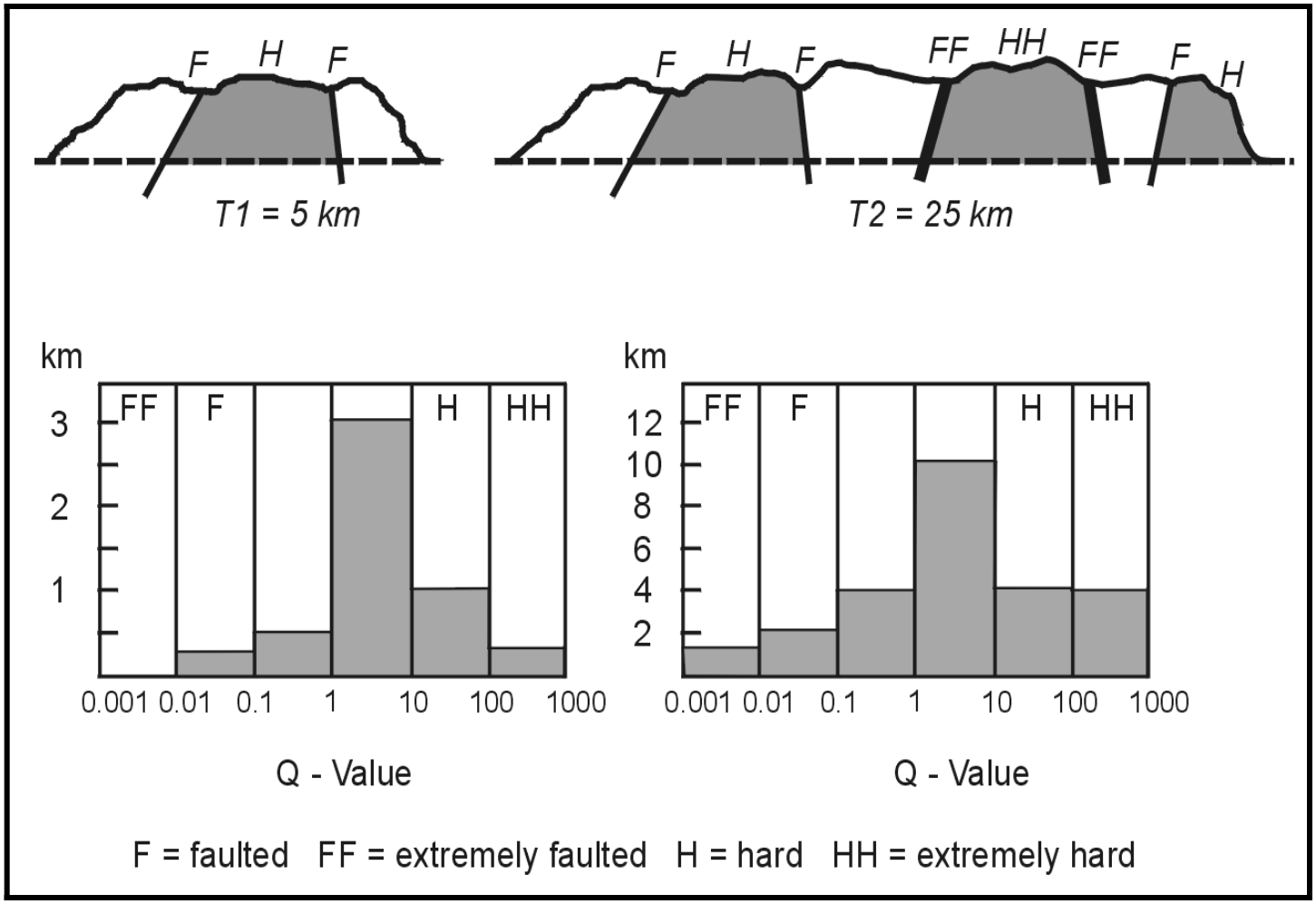
32 weeks >100m/week

(Drill-and-blast mine access tunnel, one face progress IN COAL MEASURE ROCKS.)

What happens (statistically-speaking) when a *long tunnel* is planned compared to a *short tunnel*?

LONG TUNNELS WITH FAULTS and HARD ROCK…….BEWARE !

(Assuming long tunnels are faster by TBM, is guaranteed to increase risk!)



(due to a ‘large scale’ Weibull theory…..more ‘flaws’ the larger the ‘sample’)

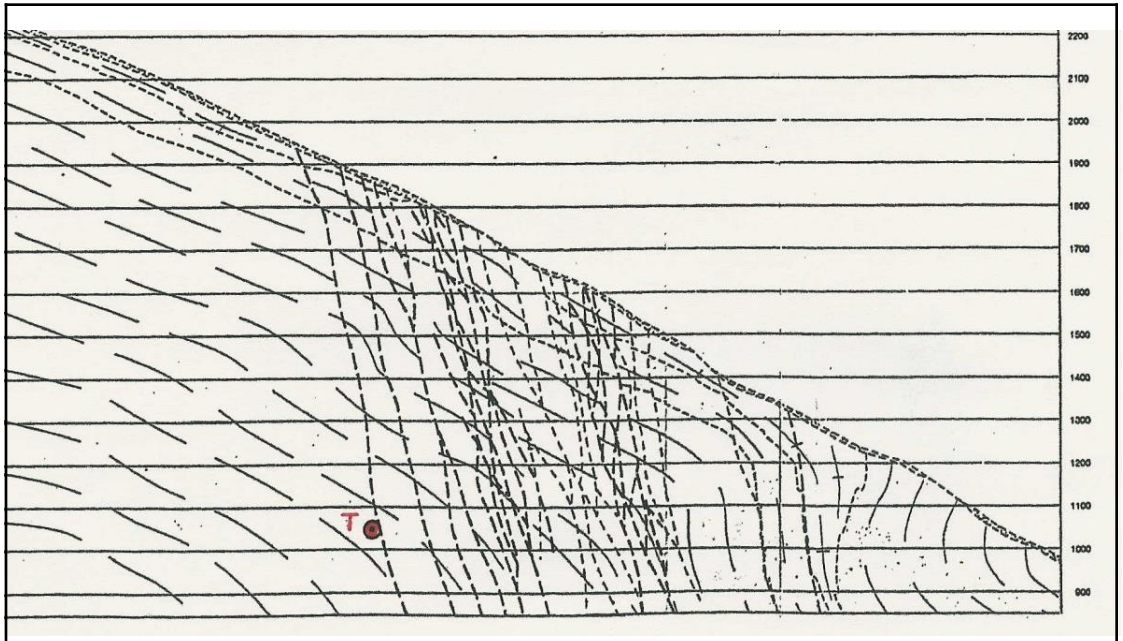
The inescapable dilemma is that as the TBM tunnel gets longer, a more-and-more 'central' rock mass quality distribution is needed, yet the *probable* reality, is that *the adverse extremes may themselves increase* as the tunnel gets longer.

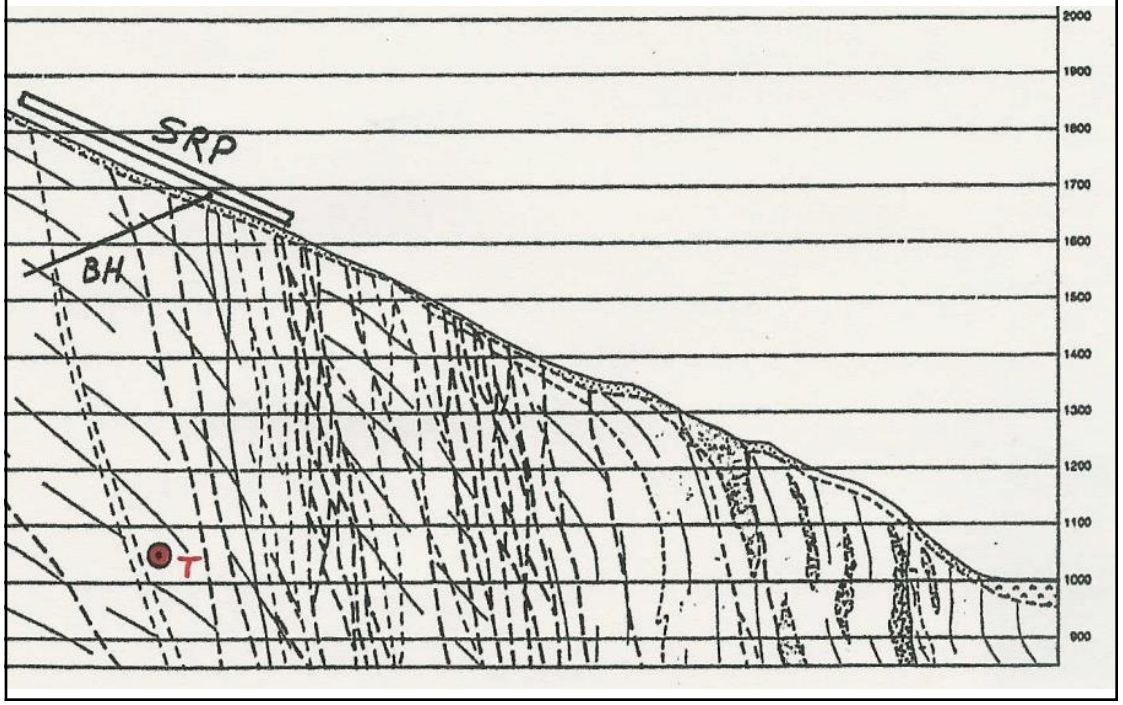
SOME EXAMPLES OF FAULT-ZONE PROBLEMS FOR TBM

Pont Ventoux, Italy:

Note schist roof tiles in local villages. The planned 7km tunnel was parallel to this valley……

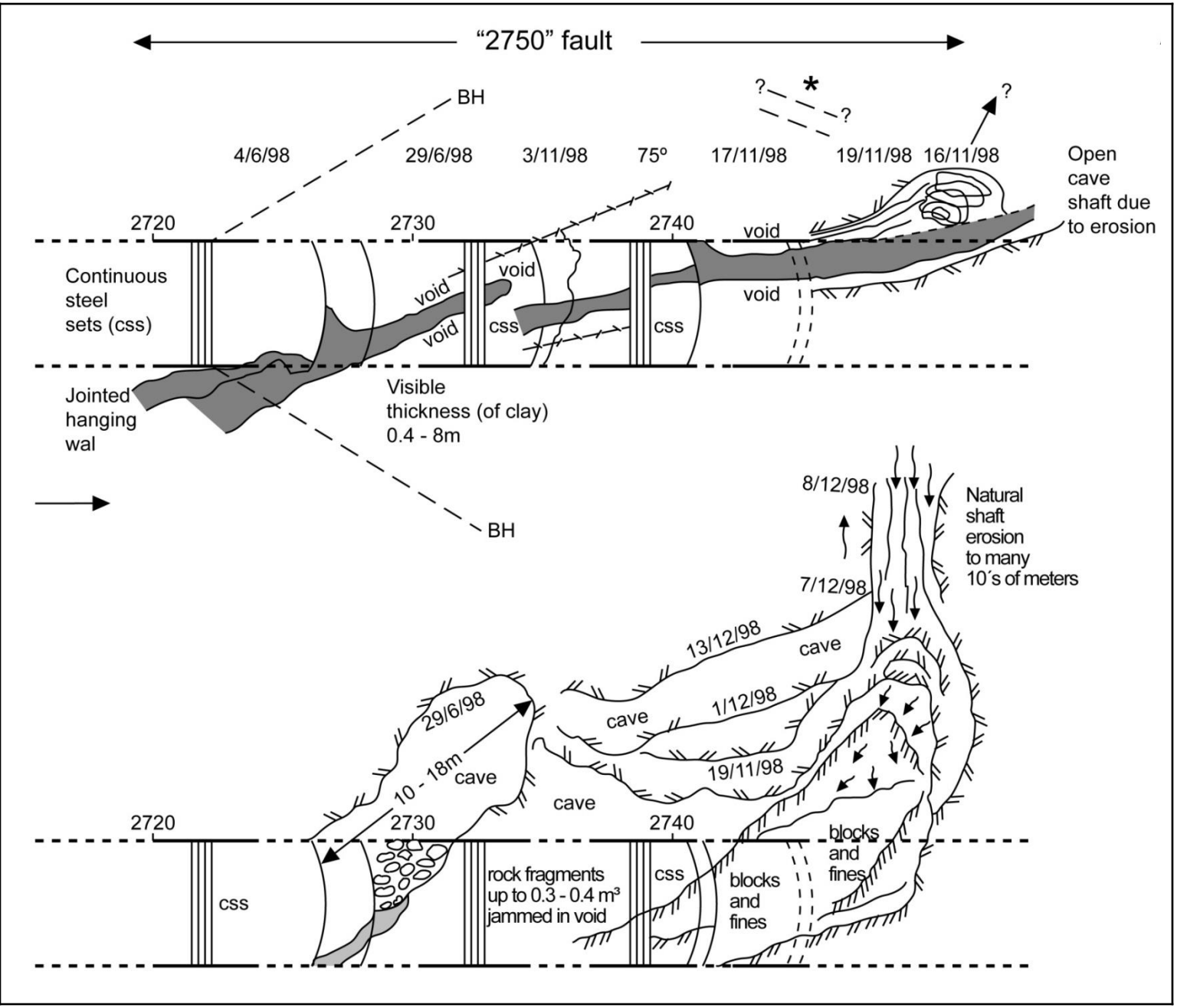
and parallel to the foliation…… and to the (later discovered) fault zones





The structural geology of the chosen tunnel route proved to be a guarantee for TBM disaster – BECAUSE *sub-parallel to a previously UNKNOWN 'fault swarm'.*

The tunnel was apparently 'too deep' for satisfactory geological investigations.



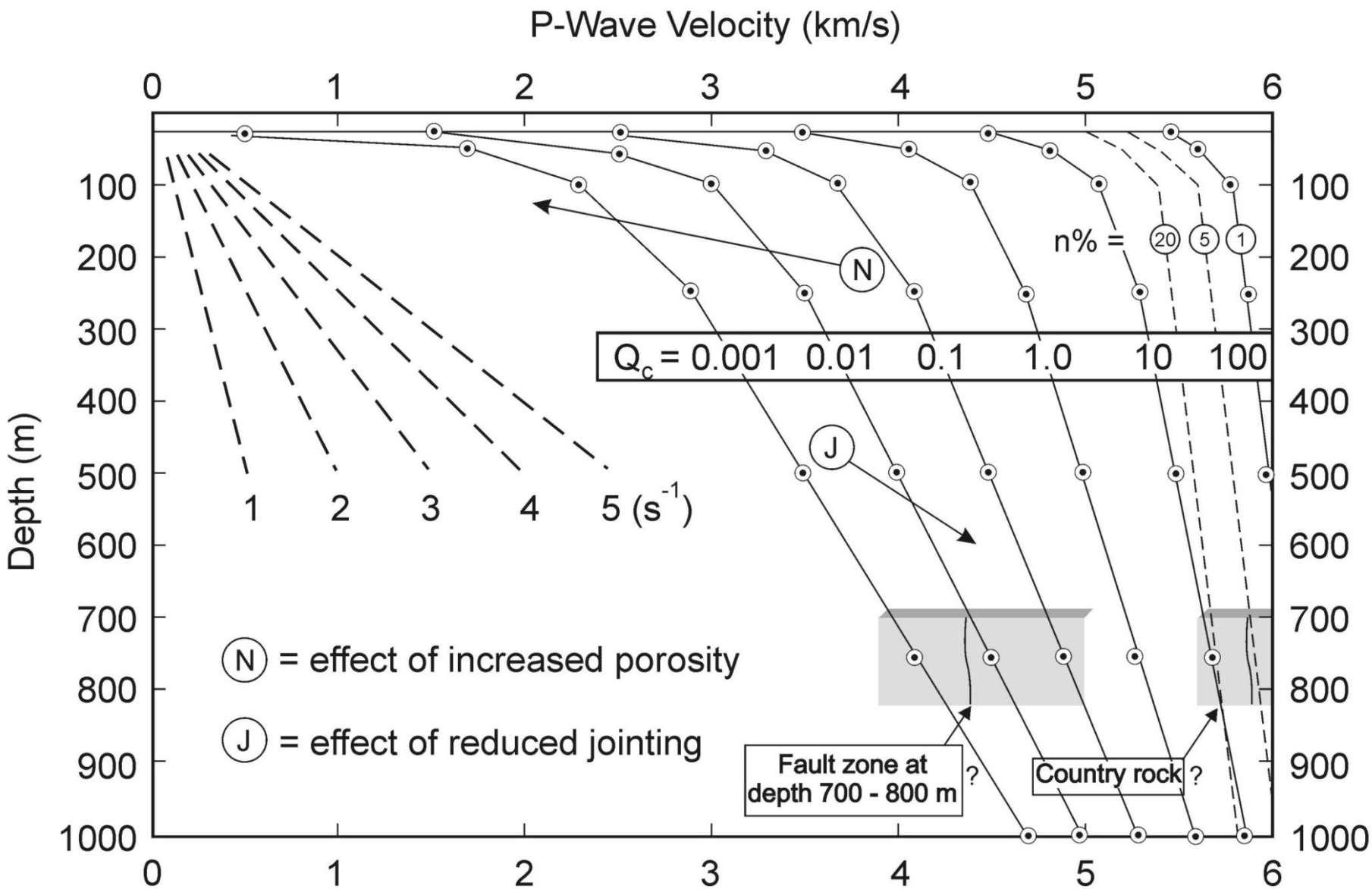
WHEN THE TBM STARTED RUNNING SUB-PARALLEL TO THE FAULTS, HUGE DELAYS OCCURRED.

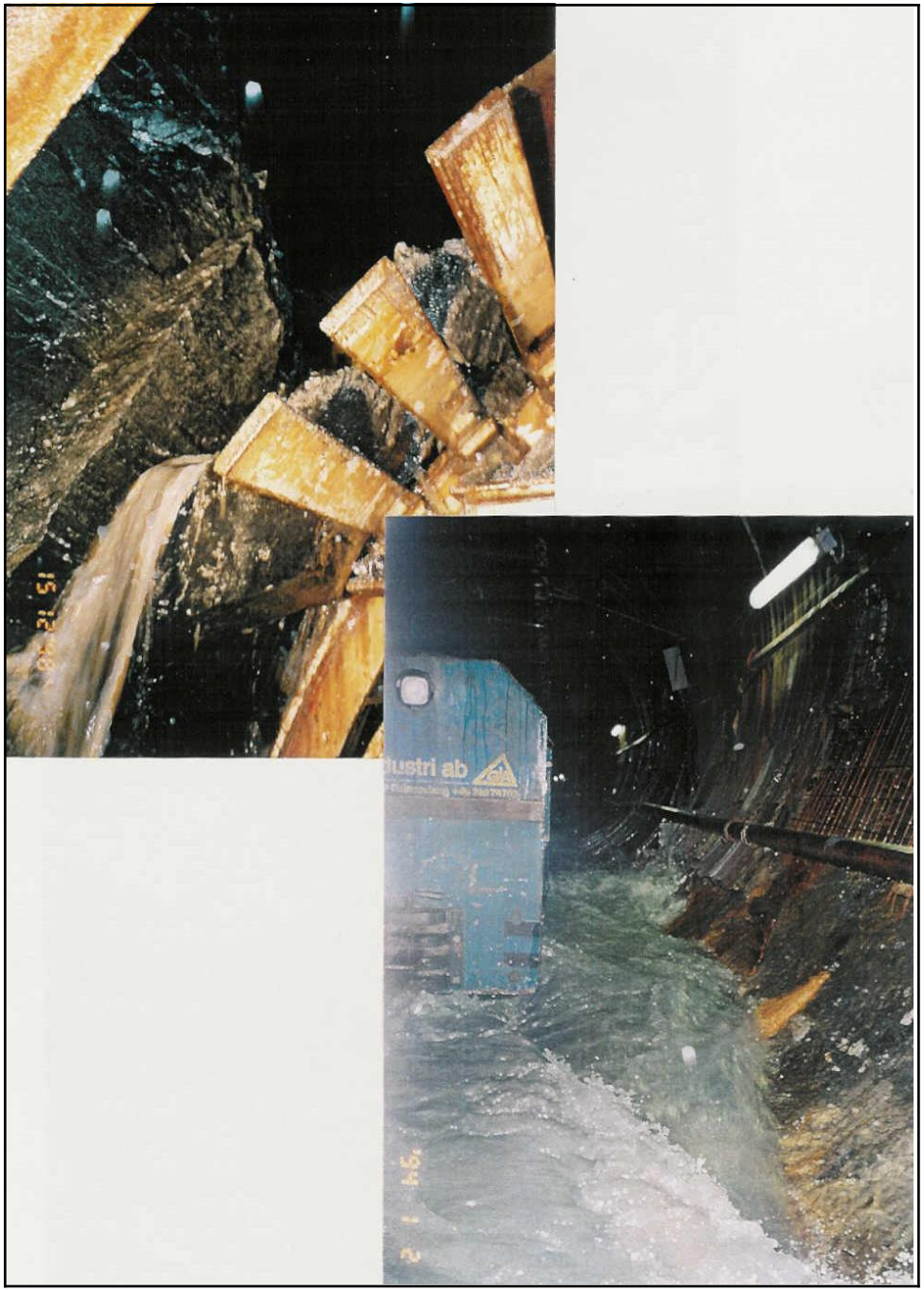
(6 months in this case alone).

Water-plus faulting problem.

FAULTED ROCK MAY BE ‘INVISIBLE’ AT MANY HUNDREDS OF METERS DEPTH – DUE TO COMPACTION

MEASURED V_P (at depth) MAY NEED *'DEPTH-CORRECTION'*



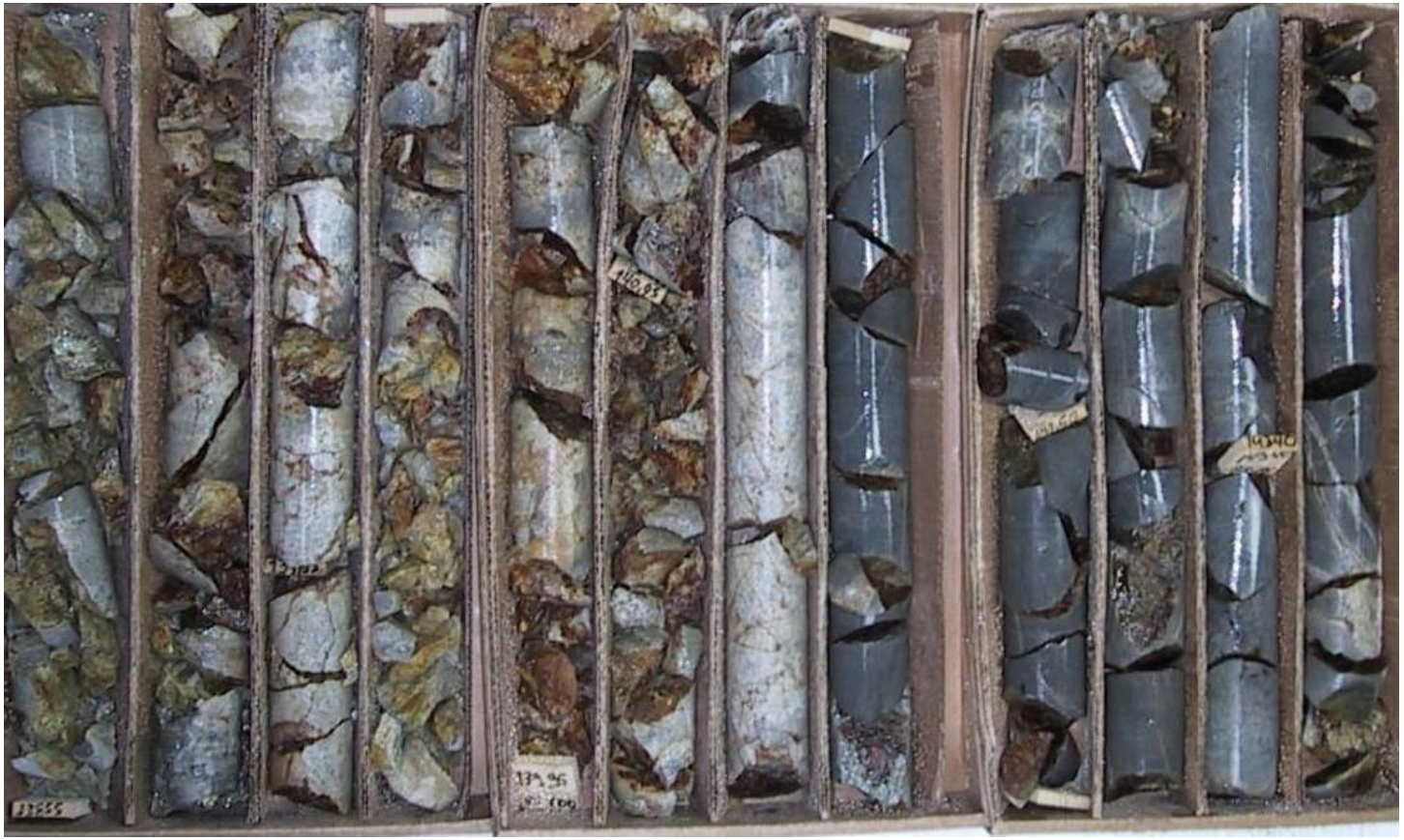


Too much water for stability in the fault zone. Blocks kept on falling, blocking the cutter-head. Sand/gravel ‘delta’ built up (in ‘still’ water) behind back-up.

Derailment of the train was therefore frequent behind the back-up.

DEEP TBM TUNNEL FOR MINERAL SAMPLING AND FUTURE MINE ACCESS

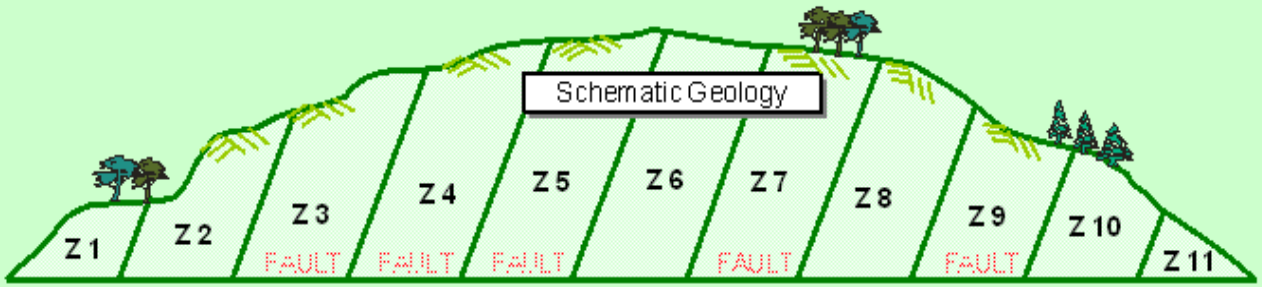
Application of QTBM where faulted zones are expected to interrupt fast progress



Note five fault zones modelled

Nick Barton & Associates

Q TBM



3150	2.5	5	5	7.5	1700	2.5	1300	2.5	1850	100

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

INPUT DATA

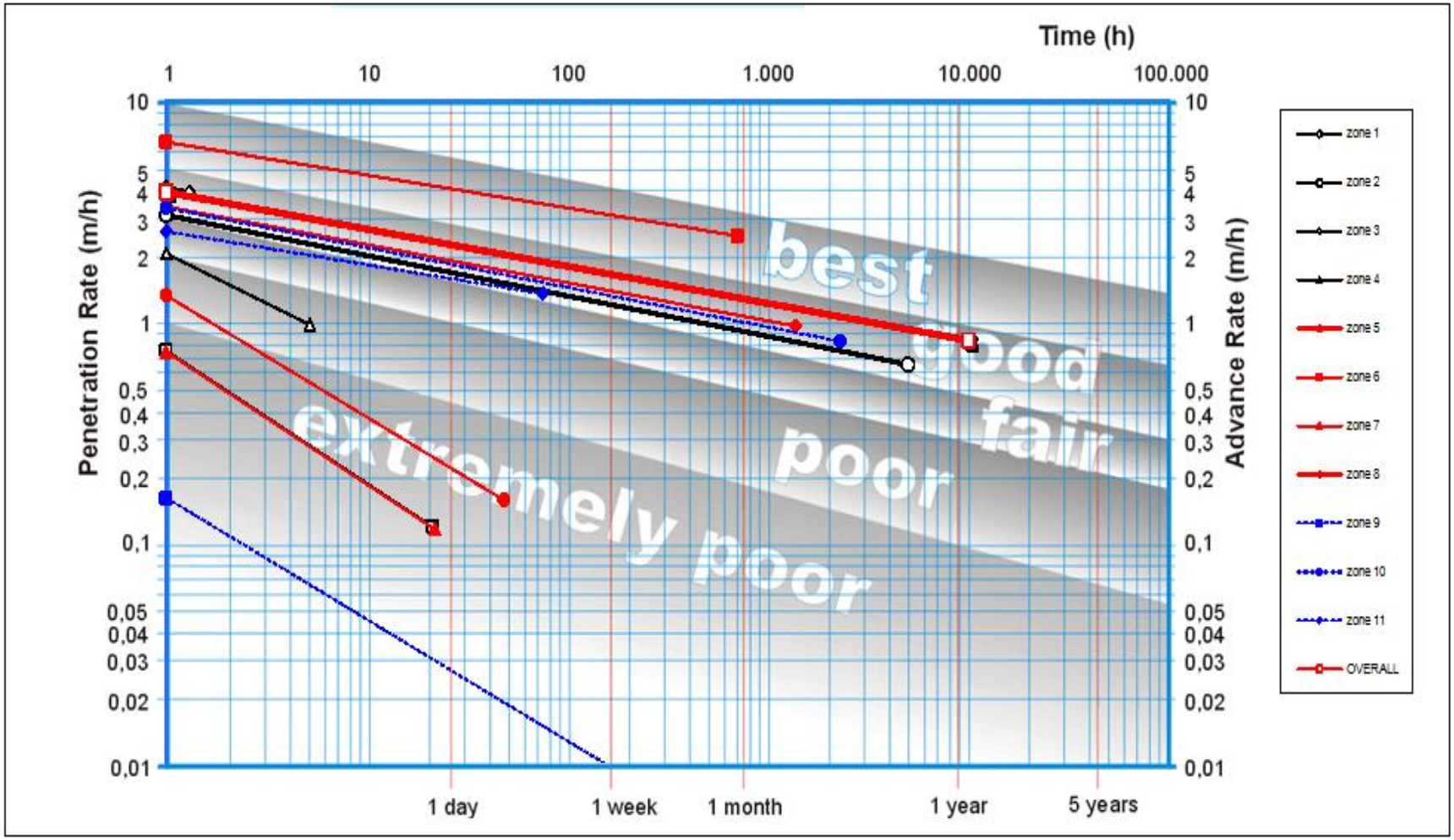
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)
100.0	4.0	1.5	3.0	1.00	1.0	-0.17	100.0	2.8

V_P (km/s)

β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
60.0	100.0	3.0	20.0	25.0	10.0	20.0	4.5	2.0

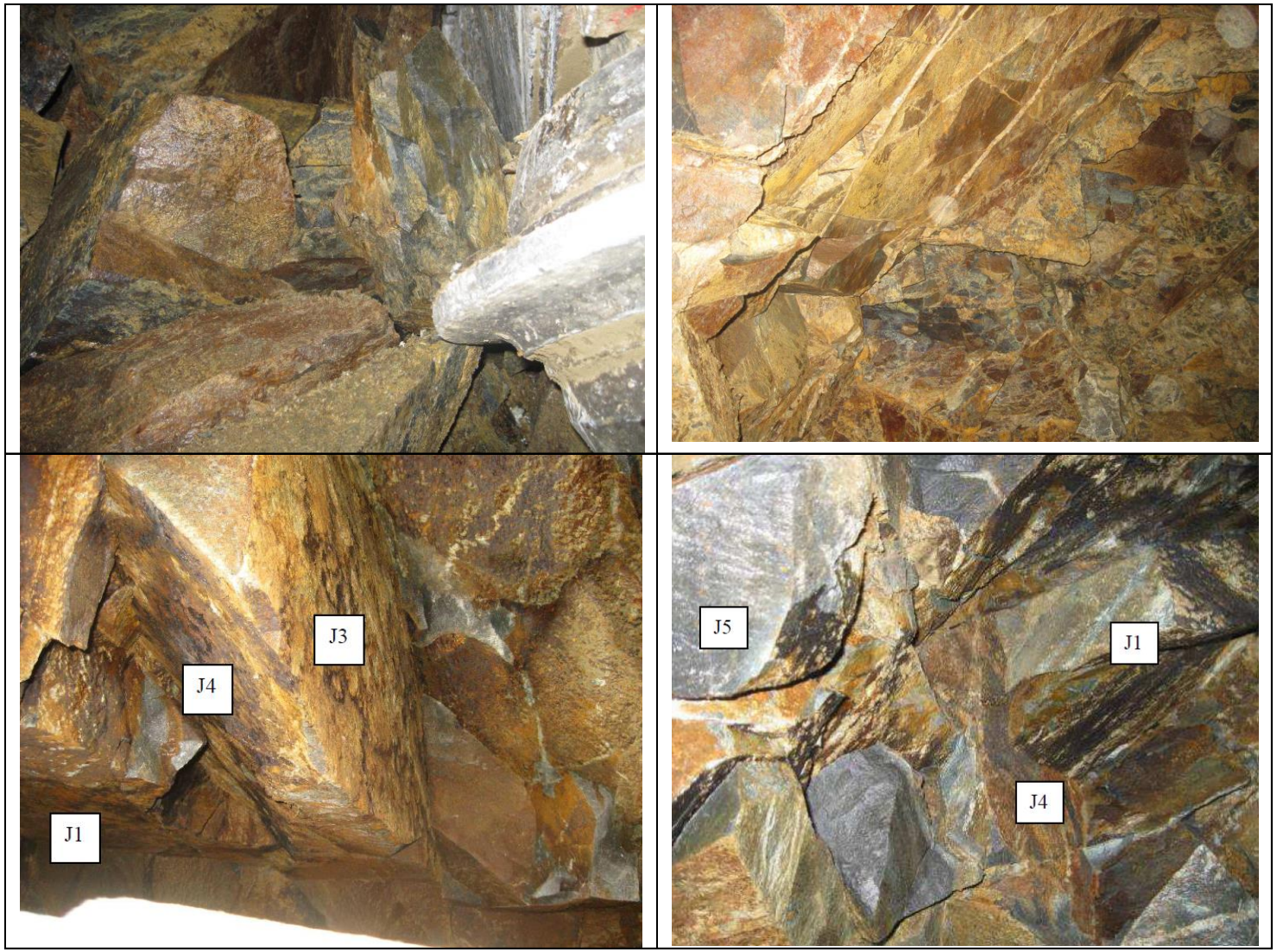
Date	20/Oct/2007

Part of the prognosis of the TBM mine-access tunnel, where a lot of deep coring was available from earlier mineral exploration holes.



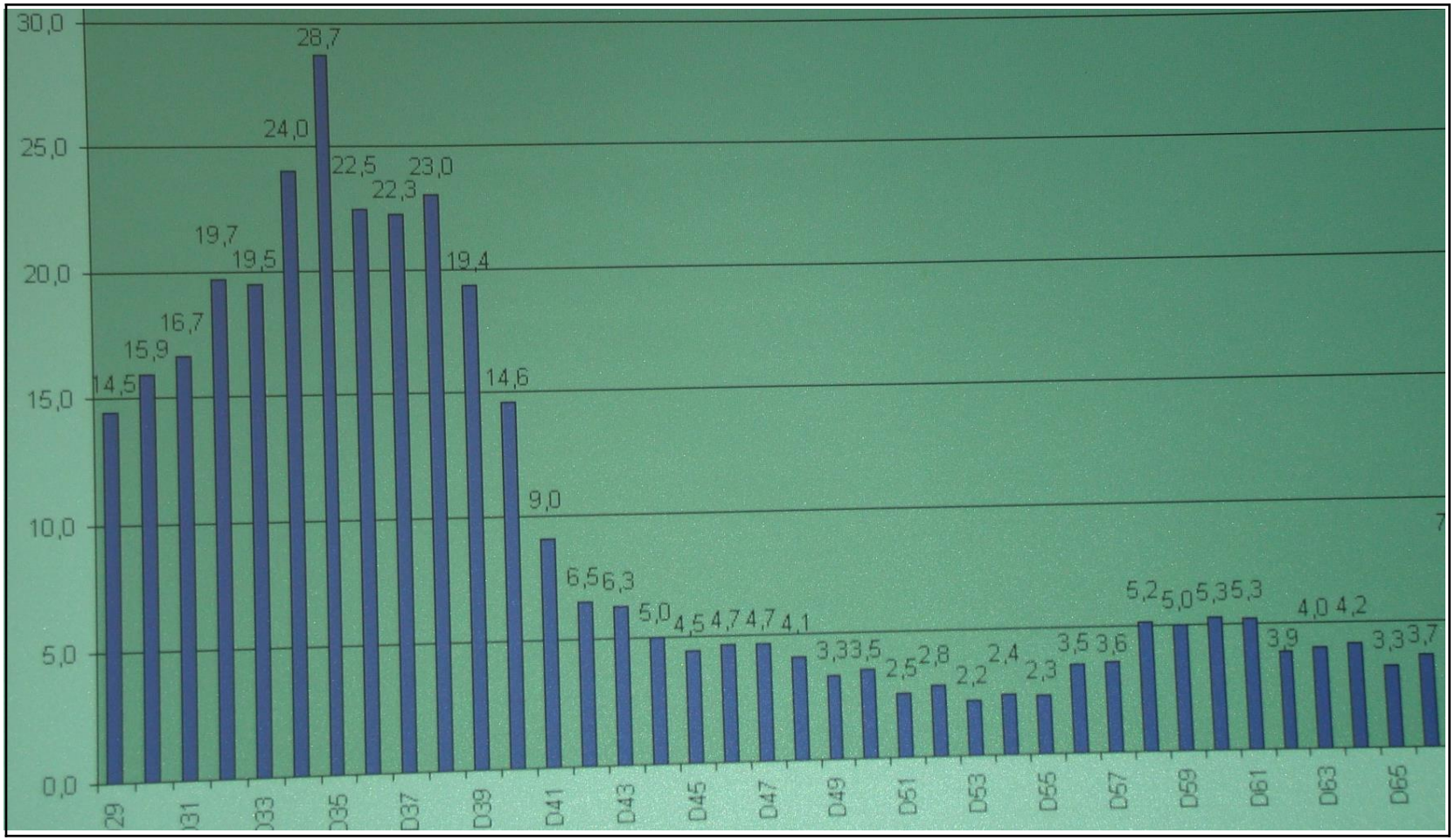
An example of some of the conditions met. The double-shield machine 'over-excavated' in this zone, due to 'too many' joint/fracture directions.

Insufficient shear strength (low Jr/Ja). Q ≈ *40/15 x 0.5/4 x 1.0/2.5 or worse.*



THE FAULTED ROCK THAT WAS *NOT ANTICIPATED, NOT PROBE-DRILLED, NOR PRE-TREATED*, CAUSED 'OVER-EXCAVATION' – VOID FORMATION

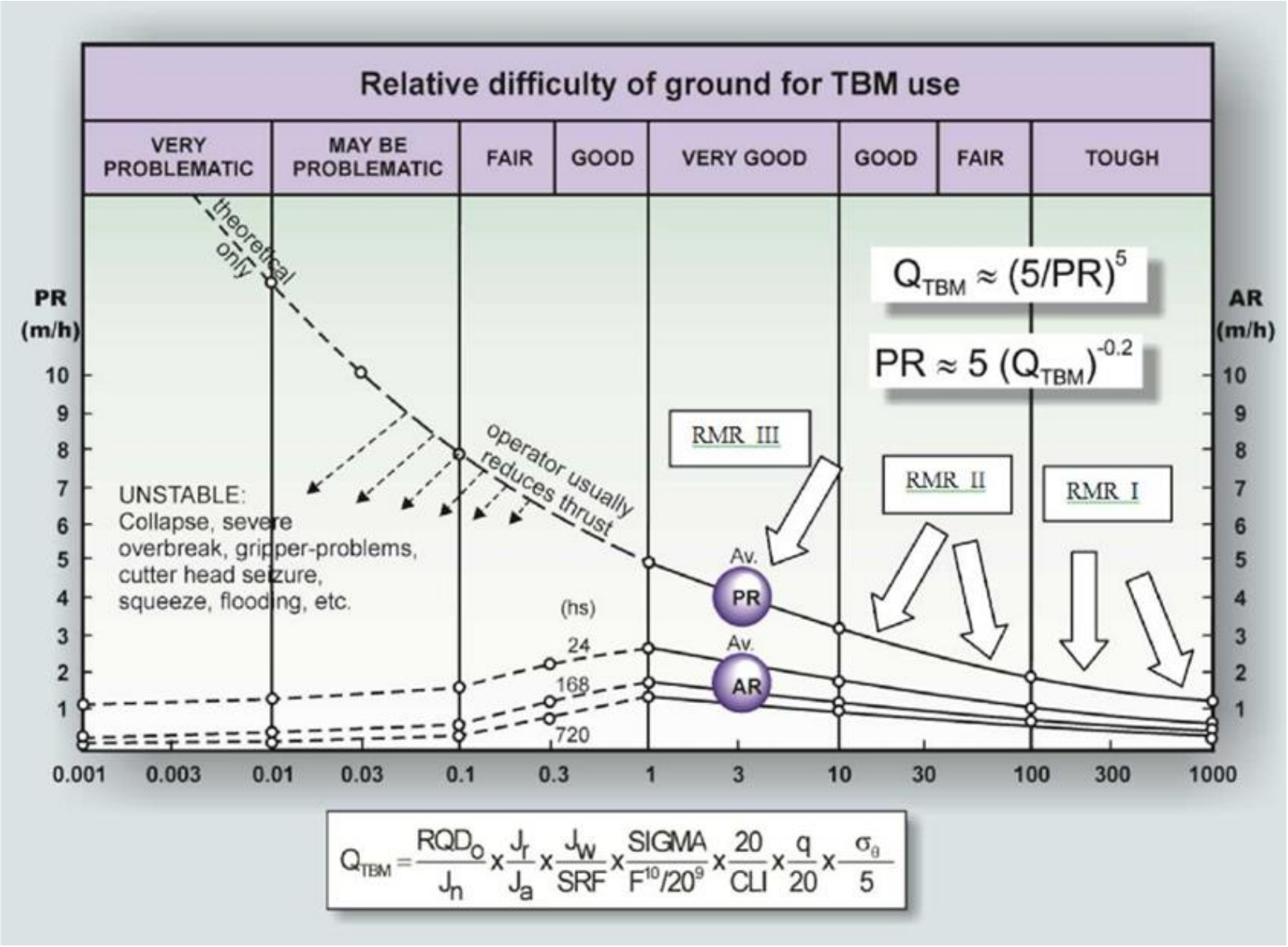
(See m/day reduction)



Additional Challenges

HARD MASSIVE ROCK *(HIGH Q, HIGH RMR)* ALSO A PROBLEM FOR TBM.

ULTRA-HIGH STRESS LEVELS ALSO A PROBLEM



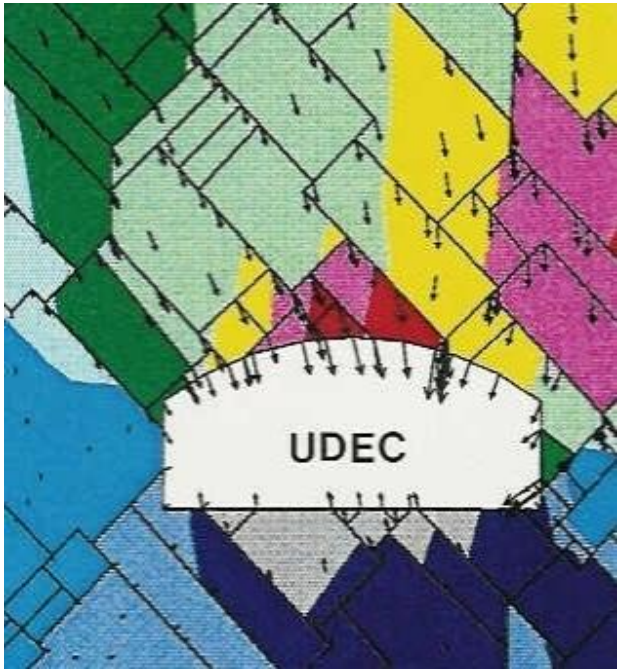
Exceptionally massive rock, with Q consistently more than 100, and frequently 600 or more, creates great problems for TBM contractors.

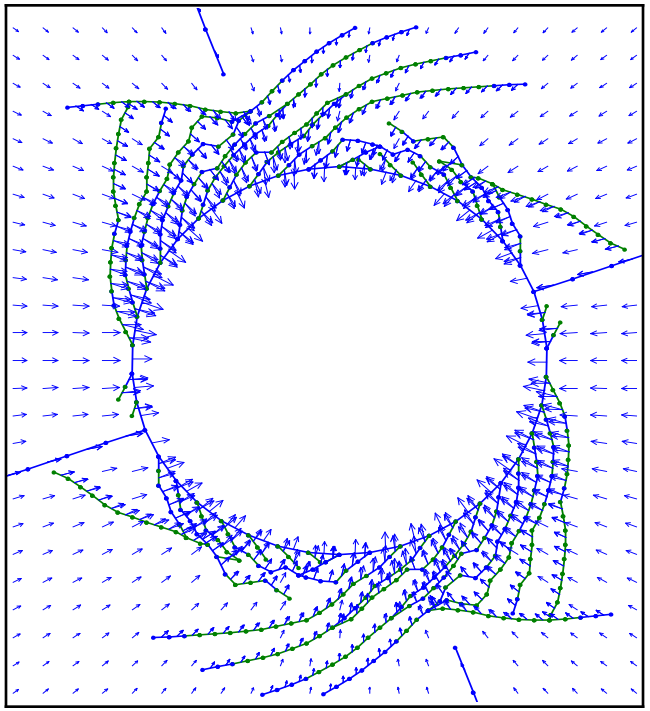
CONTINUUM (??)

or

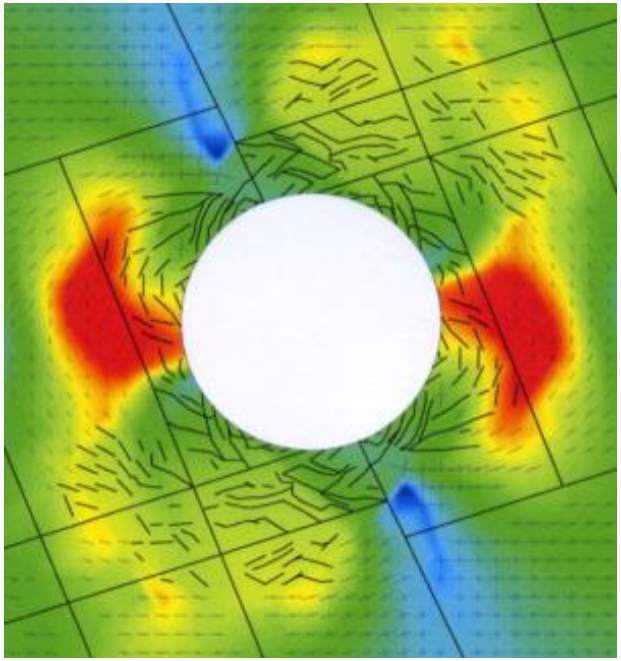
DISCONTINUUM MODELLING

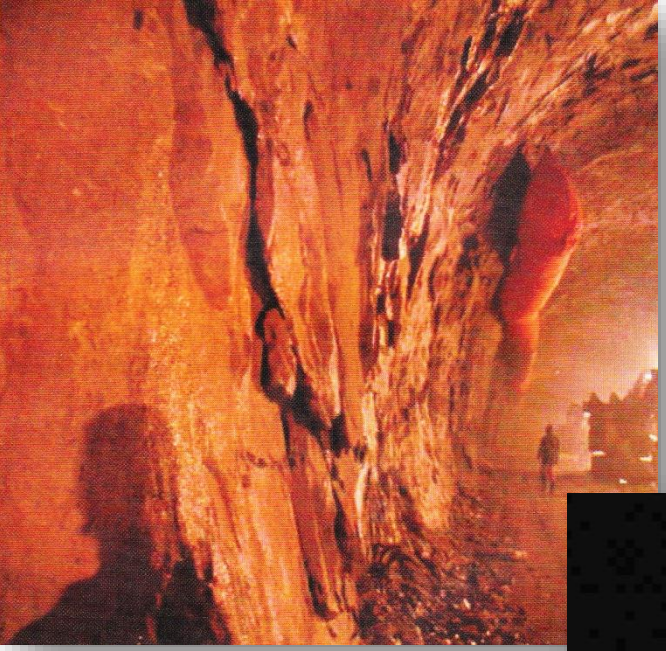
There are many options for numerical modelling.



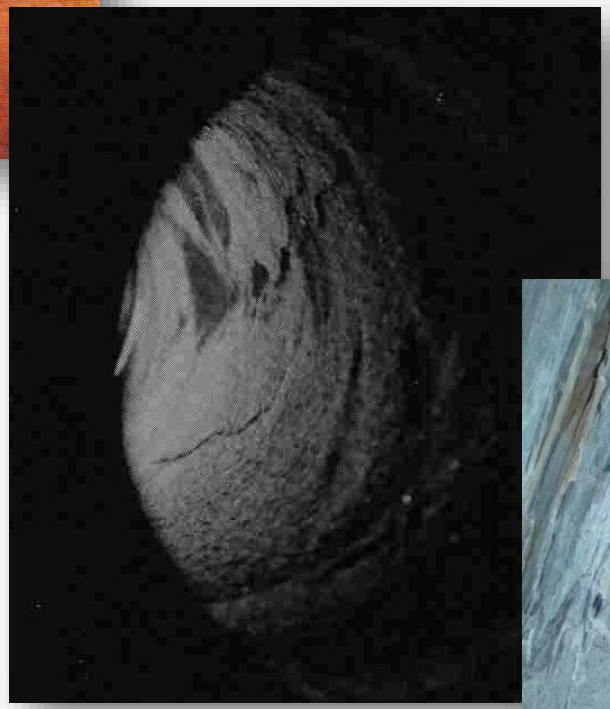


Continuum modelling may be easiest but does it mean anything?

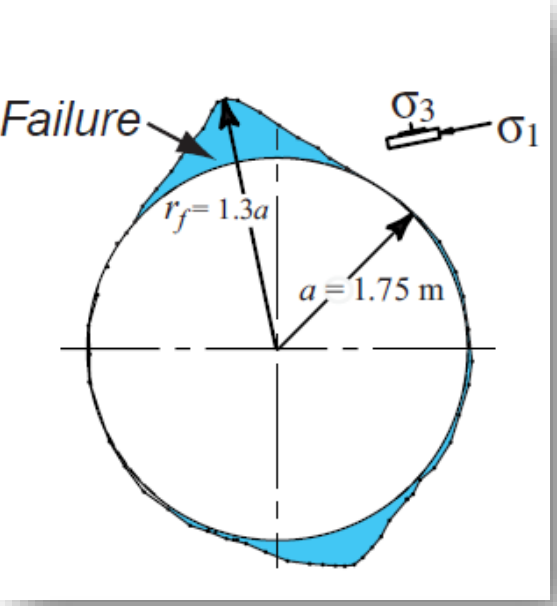




Jinping II (D+B) – ISRM News Journal
Physical model – bored under stress (NGI)
Jinping II (TBM) – ISRM workshop (NB)



Log-spiral shear modes in weaker rock types



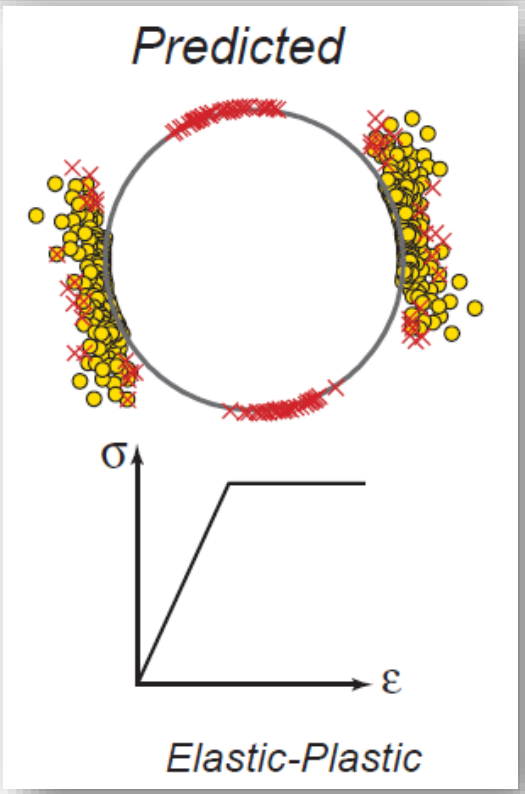
TIME for CHANGE?

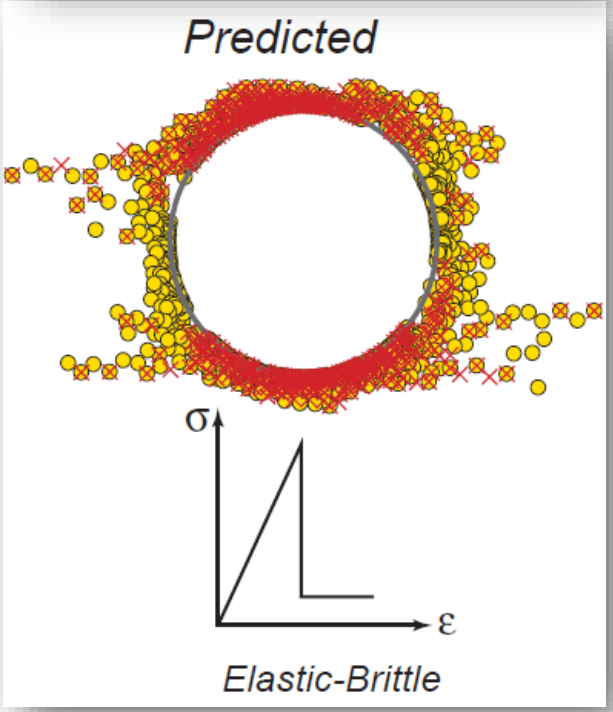
CONVENTIONAL continuum modelling misses the reality.

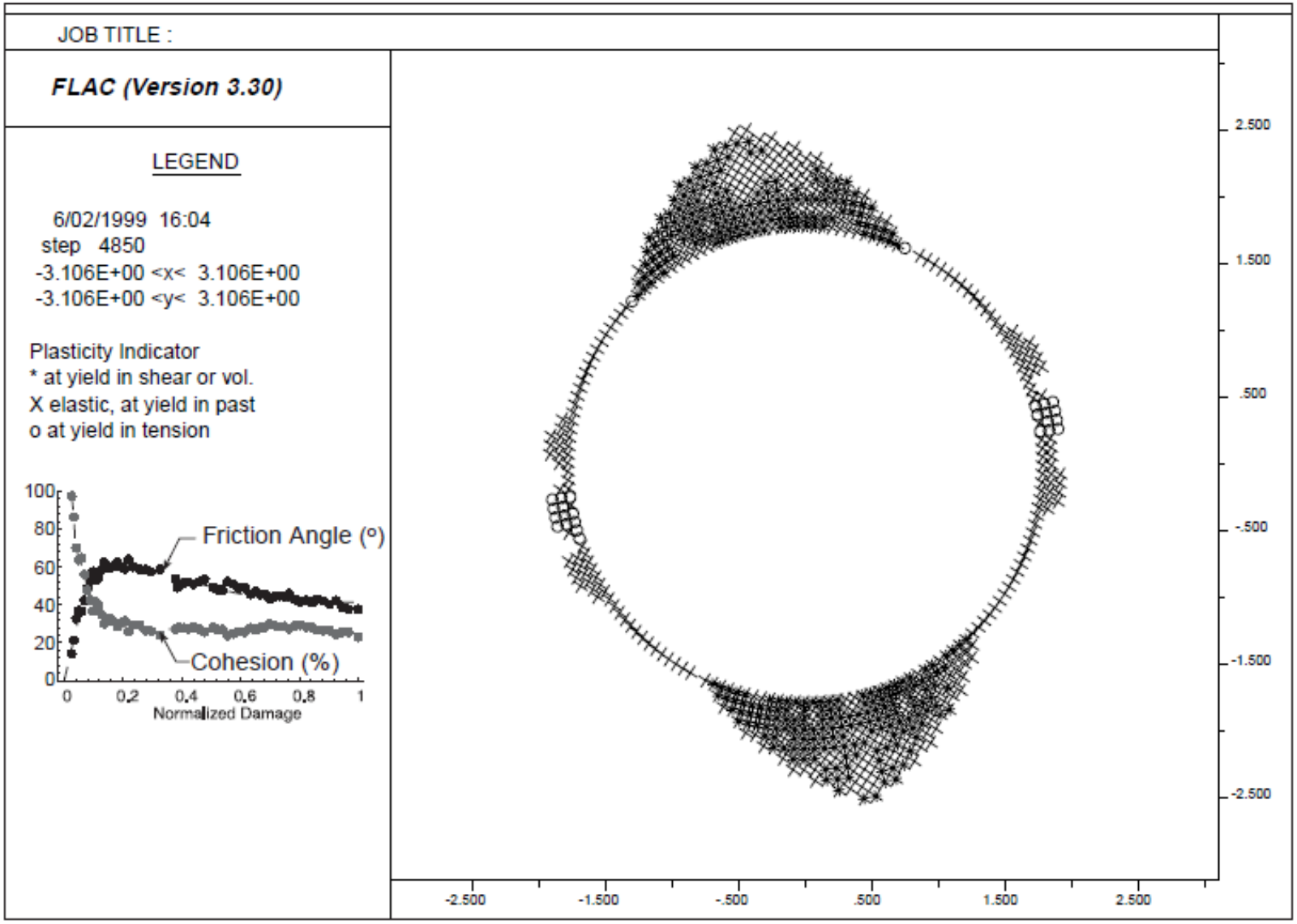
Poor simulation with Mohr Coulomb or Hoek and Brown strength criteria.

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

So why performed by so many consultants?







Degrade cohesion, mobilize friction: excellent match.

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

CC and FC from Qc = Q x *σc /100* :

Cut Qc into two halves → 'c' and 'φ'

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

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

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

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

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

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

GSI-based algebra for 'c' and 'ϕ'

contrasted with

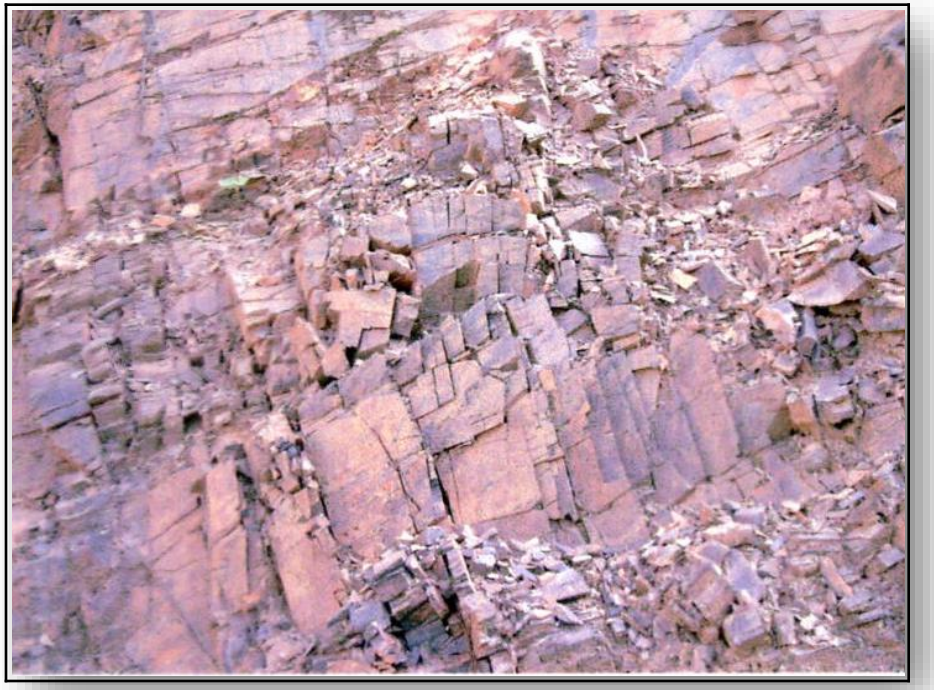
Q-based 'empiricism'

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

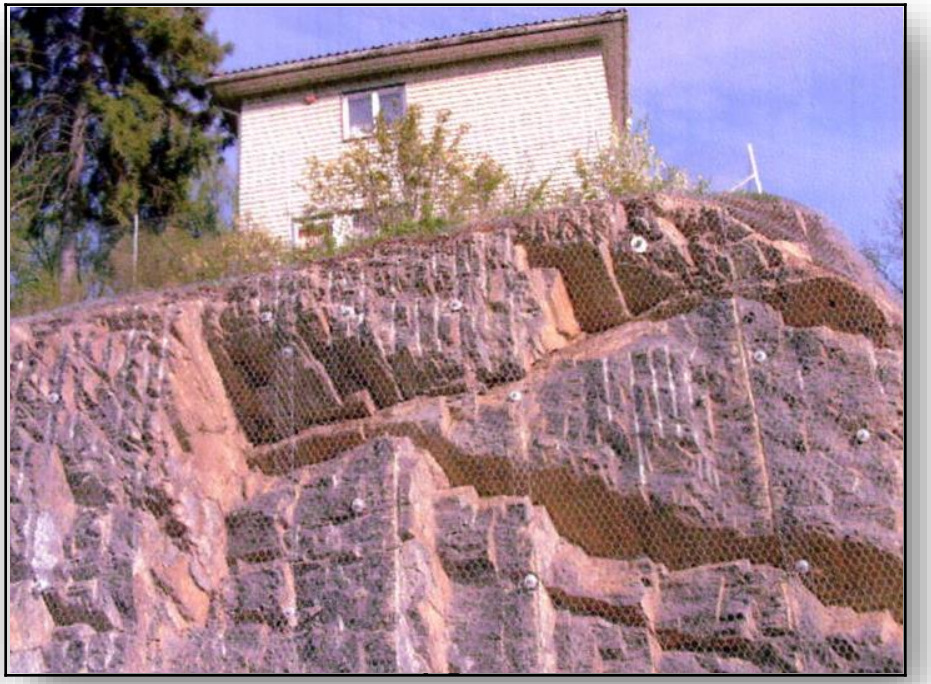
RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	*FC°*	*CC* MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5

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

Low CC –shotcrete preferred



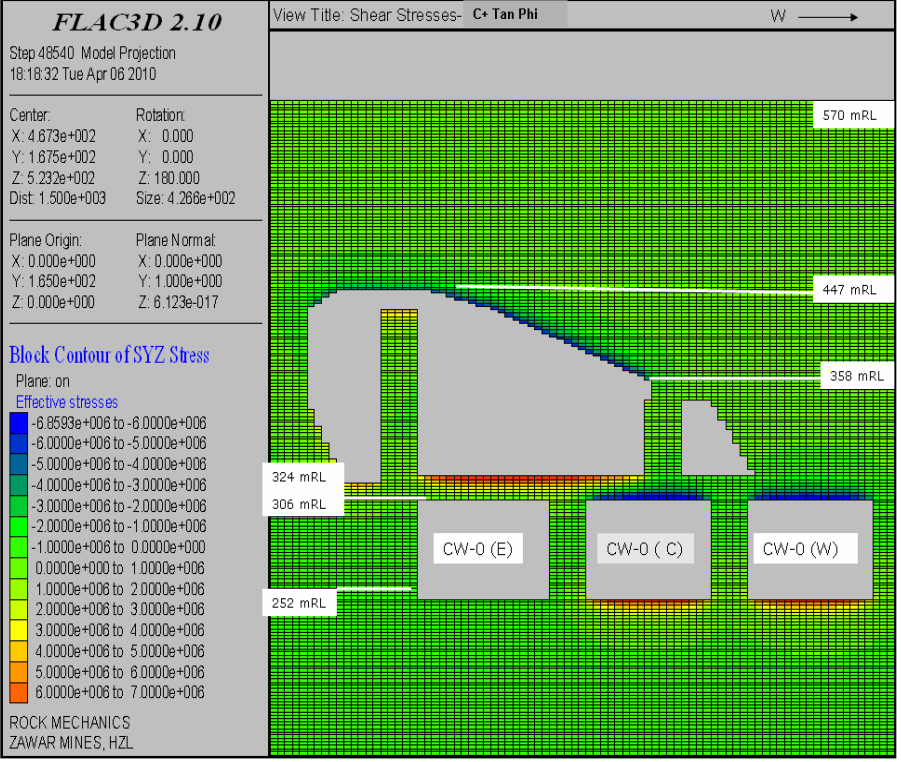
Low FC – bolting preferred

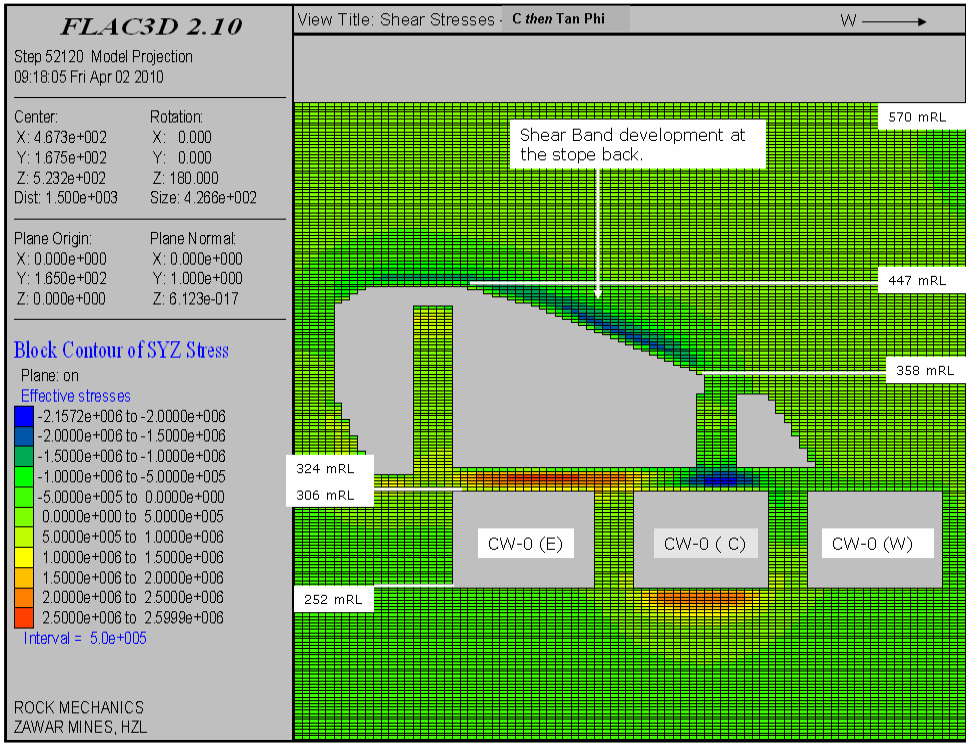


FLAC 3D

‘c+ tan ϕ’ (left)
‘c *then* tan ϕ’ (below)

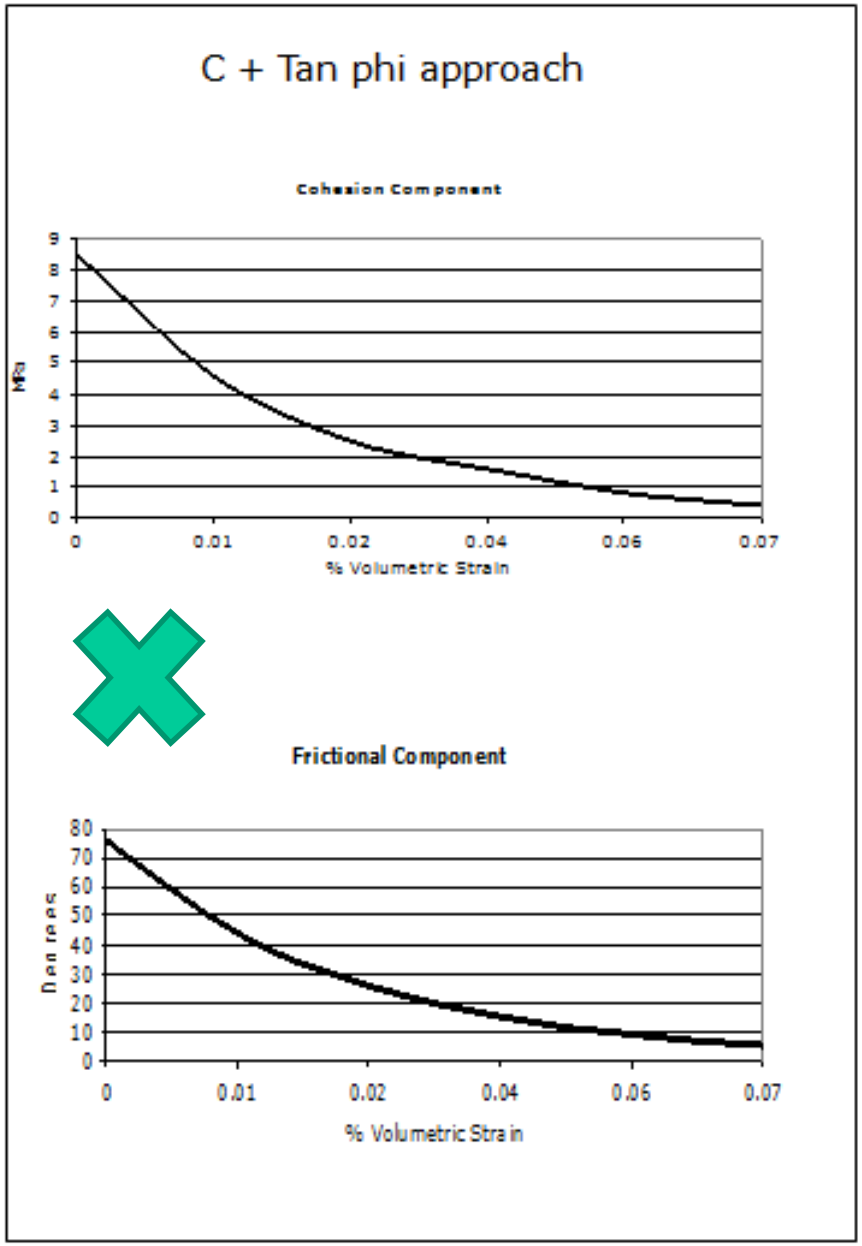
(Barton and Suneet Pandey, 2011)

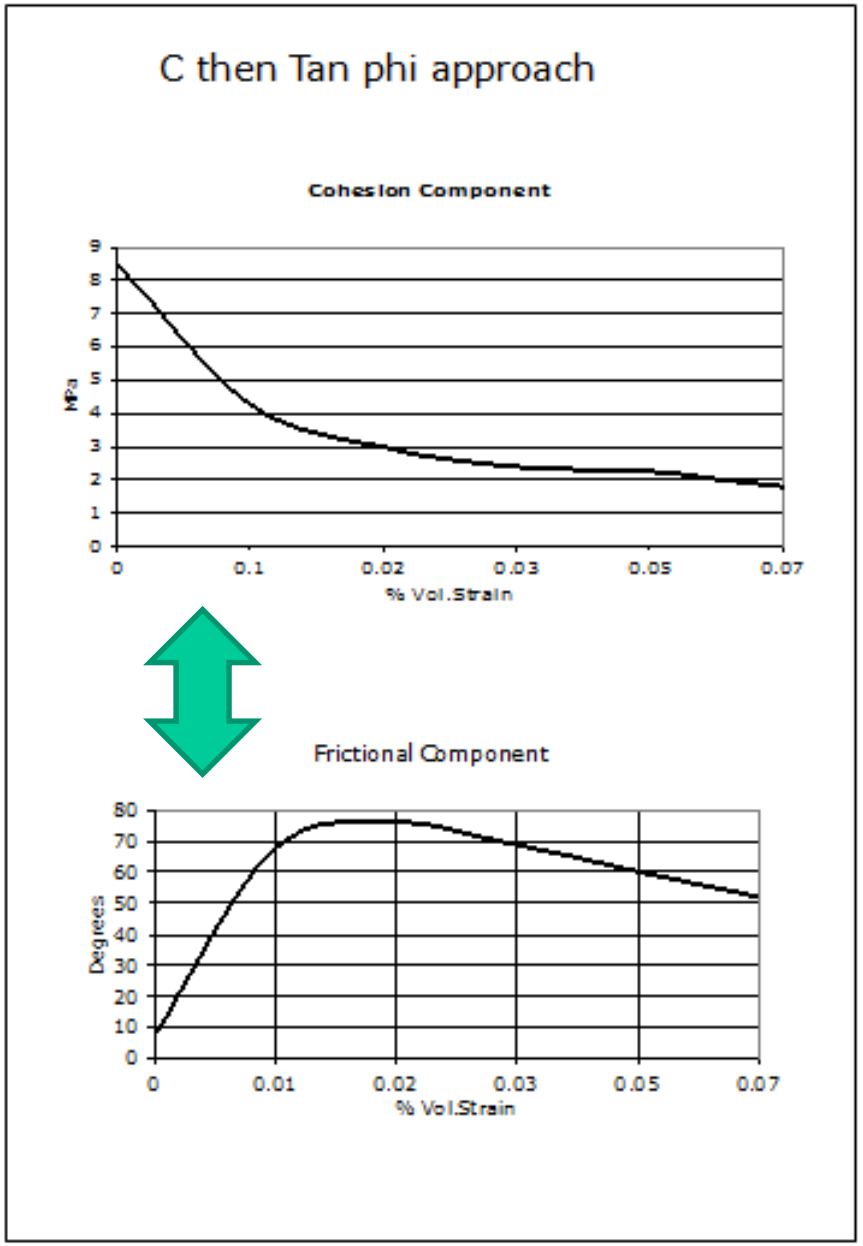


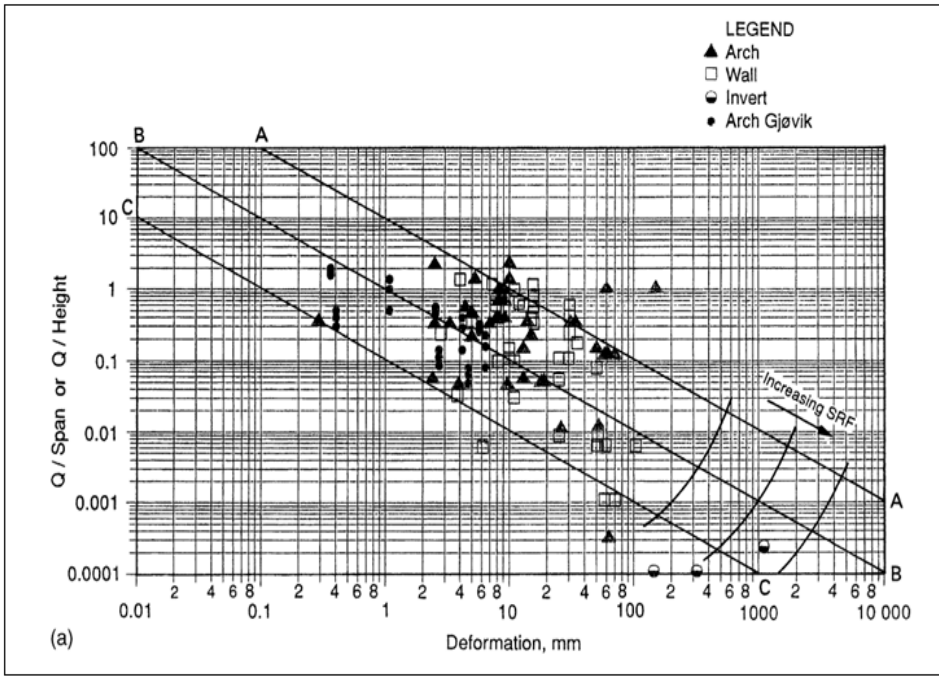


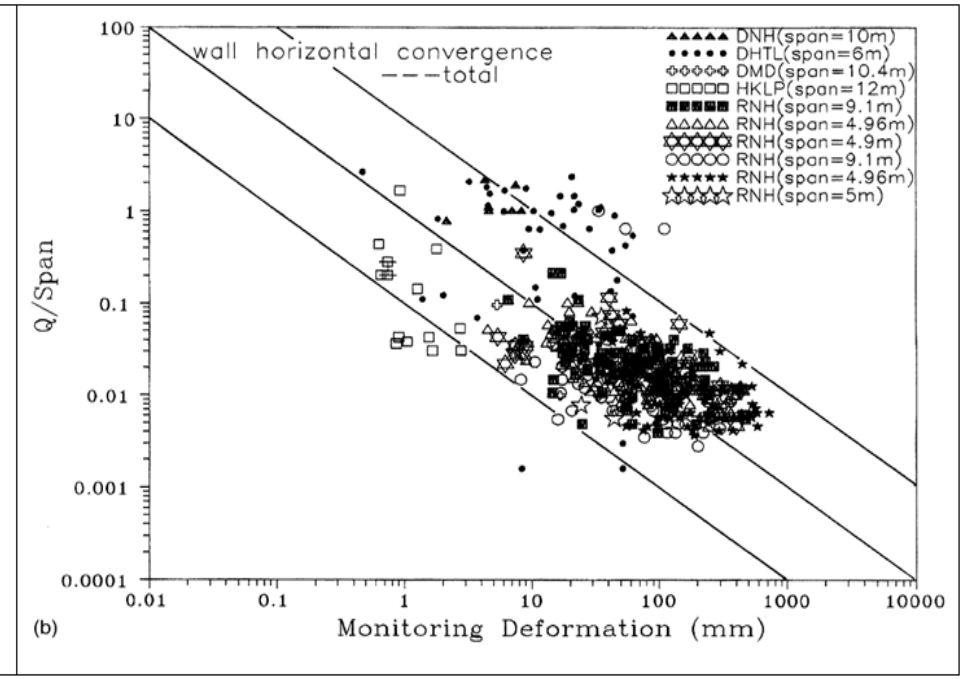
- ❑ **c *then* tan ϕ (not new, but rare!)**
- ❑ **Comparing modelled and measured displacements with pre-installed *MPBX*.**
- ❑ **Back-calculating Q from empirical Δ equations, as well as logged Q.**

‘C *then* tan phi’ (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)

CONCLUSIONS

1. NMT (meaning 'single-shell') saves a lot of money and many years in construction time – if carried out well with *high unit price S(fr)* additives, and *high unit price* rock bolts (e.g. CT) and *costly* modern S(fr) robots/drill-jumbos. Don't let the details (unit-price costs) kill the huge potential savings in money and time.

2. Long deep tunnels may not be faster by TBM, but a hybrid solution (D+B *and* TBM from the start) may be a very attractive possibility. TBM decelerate with time. Utilization reduces with tunnel length.

3. The shear strength of rock masses is not given by Mohr-Coulomb or Hoek-Brown or GSI. You cannot add 'c' and $\sigma_n \tan \varphi$. Cohesion (rock bridges) is broken at small strain, and the strength of the fracturing and rock joints is mobilized at larger strain – and is not described by MC, HB, GSI.