MINIMIZING THE USE OF CONCRETE IN TUNNELS AND CAVERNS – COMPARING NATM AND NMT

2017 GEOMEAST International Congress & Exhibition

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CONTENT OF LECTURE

1. ***NATM*** = ‘NEW’ AUSTRIAN TUNNELLING METHOD
   in preliminary graphic summary (*‘double-shell’ method)*

2. ***NMT*** = NORWEGIAN METHOD OF TUNNELLING
   in preliminary graphic summary *(‘single-shell’ method)*

3. ROCK MASS CLASSIFICATION to get APPROPRIATE SUPPORT

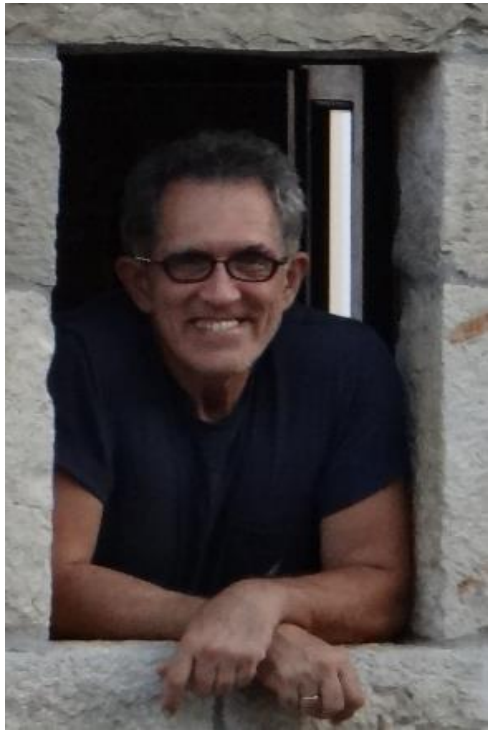
4. OVER-BREAK – and how it influences each method’s use of concrete

5. LATTICE-GIRDERS – or RIB-REINFORCED SHOTCRETE ARCHES

6. SUSCEPTIBILITY TO UNEVEN LOADING LEADING TO FAILURE

COOPERATION WITH THREE SPECIAL COLLEAGUES

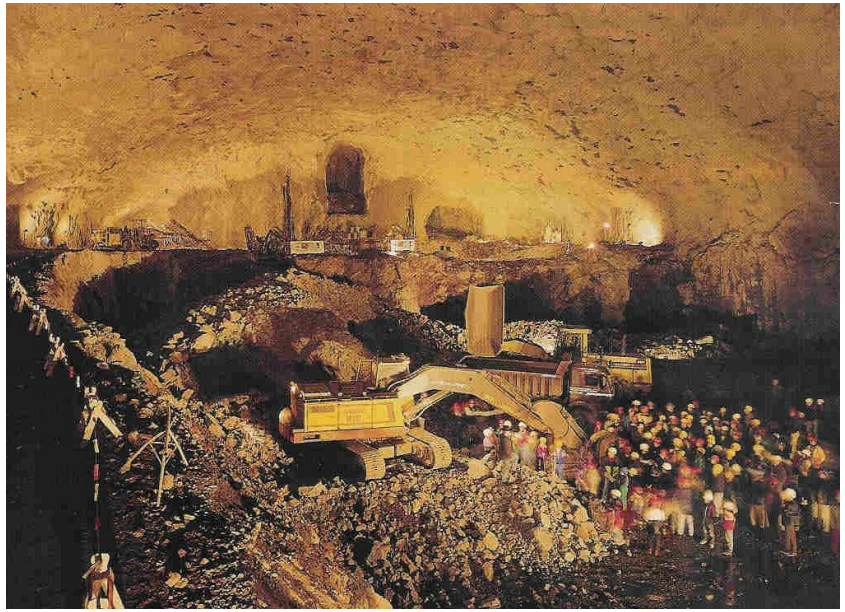
EYSTEIN GRIMSTAD
(Norway)



STAVROS BANDIS
(Greece)

BAOTANG SHEN
(Australia)

MANY EXTREMES (of size and method) ARE SEEN IN TUNNELLING



SHALLOW STATION CAVERN (TEMPORARY)

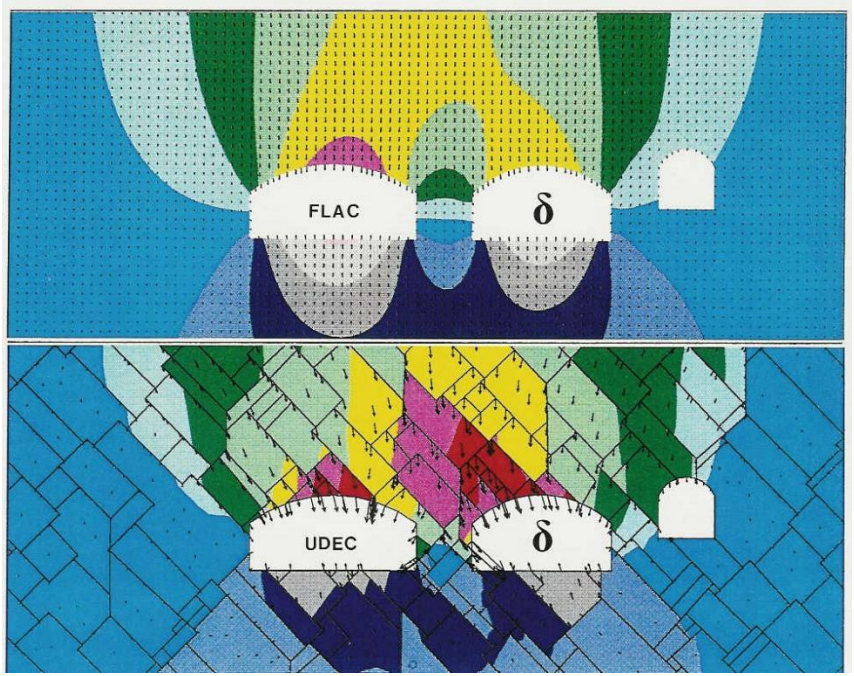
OLD WEST-COAST ROAD TUNNEL (PERMANENT)

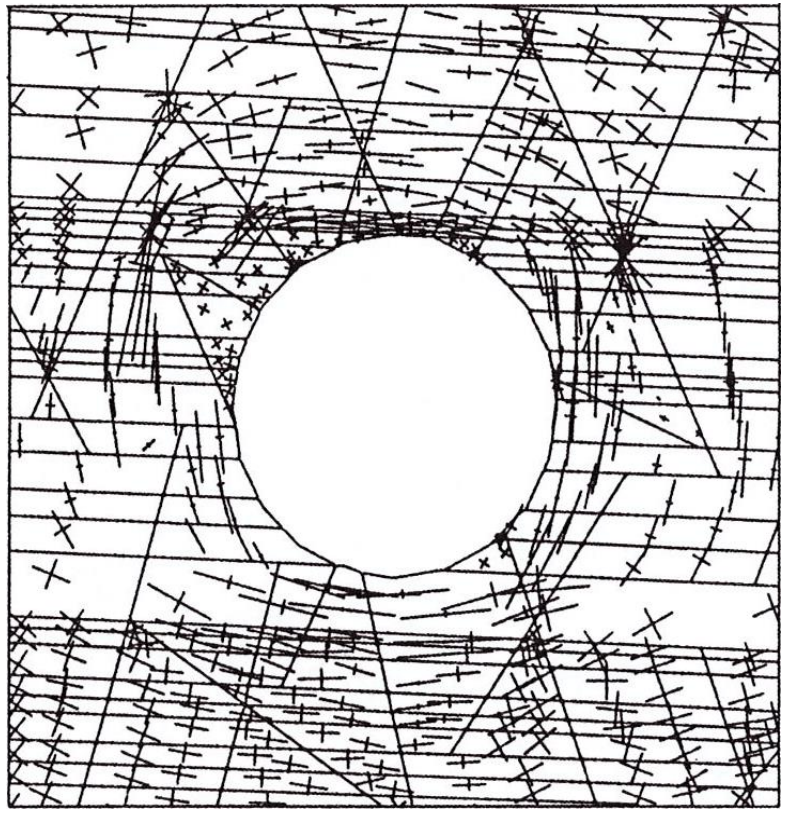
THE ROCK IS FREQUENTLY THE ‘STABILIZING’ LOAD-BEARING MEDIUM. SUPPORT IS A MINOR (BUT ***IMPORTANT***) ‘DETAIL’

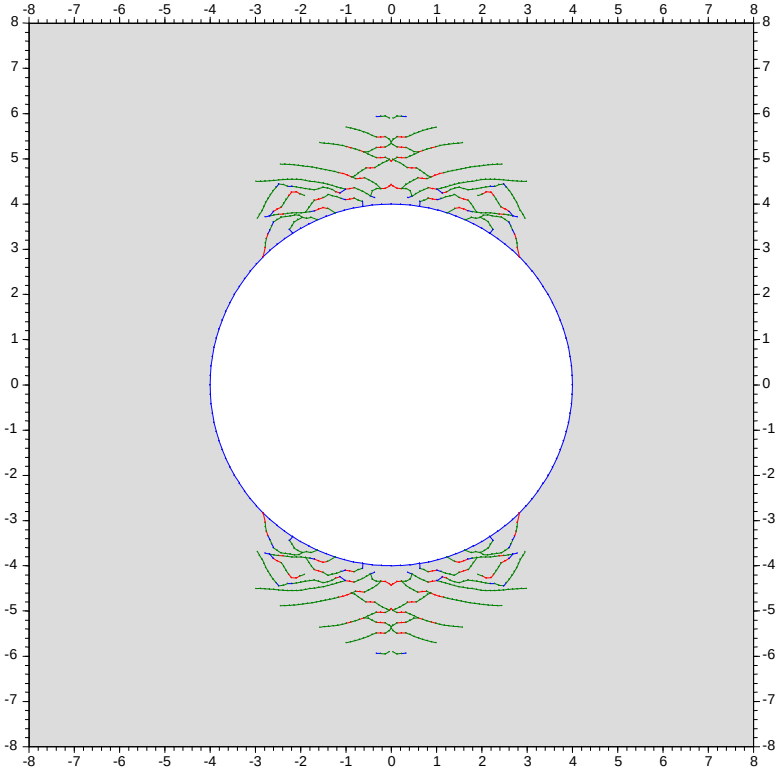
- TANGENTIAL STRESS IN THE ARCH IS FUNDAMENTAL
- *PRESERVE THIS BY KEEPING THE ‘PERIPHERY’ IN PLACE*

THREE EXAMPLES OF NUMERICAL MODELLING, PRIOR TO SHOWING THE EMPIRICISM OF NMT (FLAC, UDEC-BB, FRACOD).

CAN BE USED TO DOUBLE-CHECK EMPIRICAL SOLUTIONS when DESIRED.







NMT or NATM?

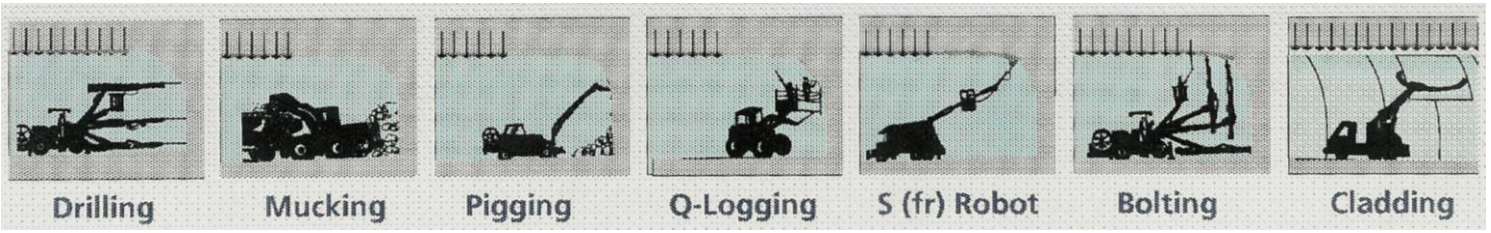
1. ***SINGLE-SHELL* METHODS OF *SUPPORT (Sfr) + BOLT REINFORCEMENT (B)* ARE USED IN 'ALL' THE WORLD'S HYDROPOWER GENERATION CAVERNS, OIL STORAGE CAVERNS, MINE ACCESS ETC.**

2. **BUT IN OTHER EXCAVATIONS (LIKE ROAD, RAIL, METRO TUNNELS) THERE IS A DECISION TO BE MADE: 'NATM' (expensive) or 'NMT' (cheap)?**

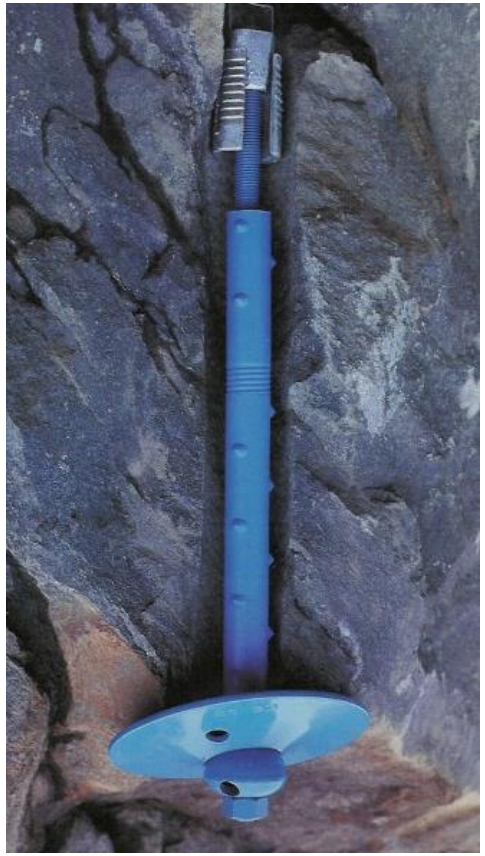
NMT OPERATIONS IN SUMMARY

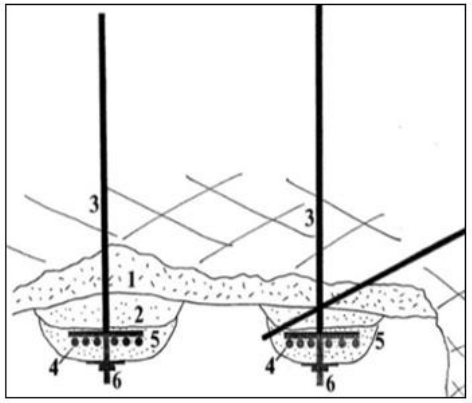
(how to apply S(fr) + B)

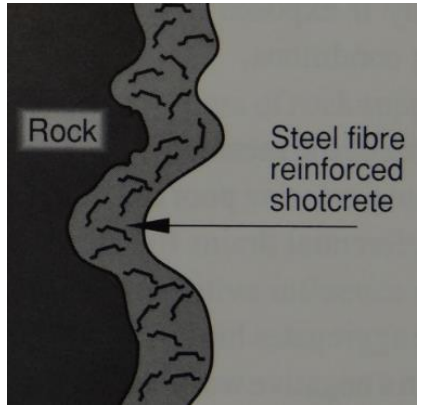
NMT OPERATIONS: in summary



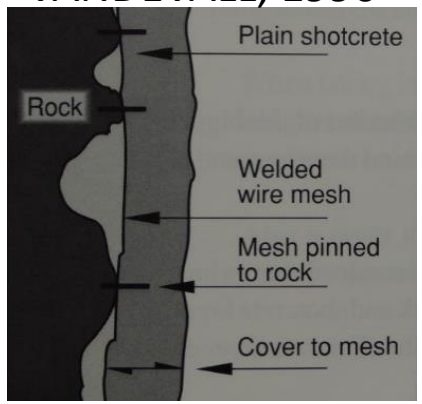
APPROPRIATE SUPPORT







VANDEVALL, 1990



S(fr) PREFERRED TO S(mr)….. IN THE LAST 35 YEARS of NMT

Design

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

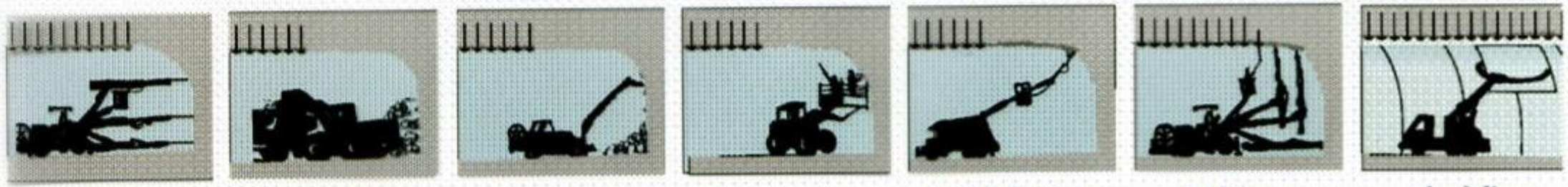
Final support is selected during tunnel construction based on tunnel logging and use of the Q-system support recommendations.

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

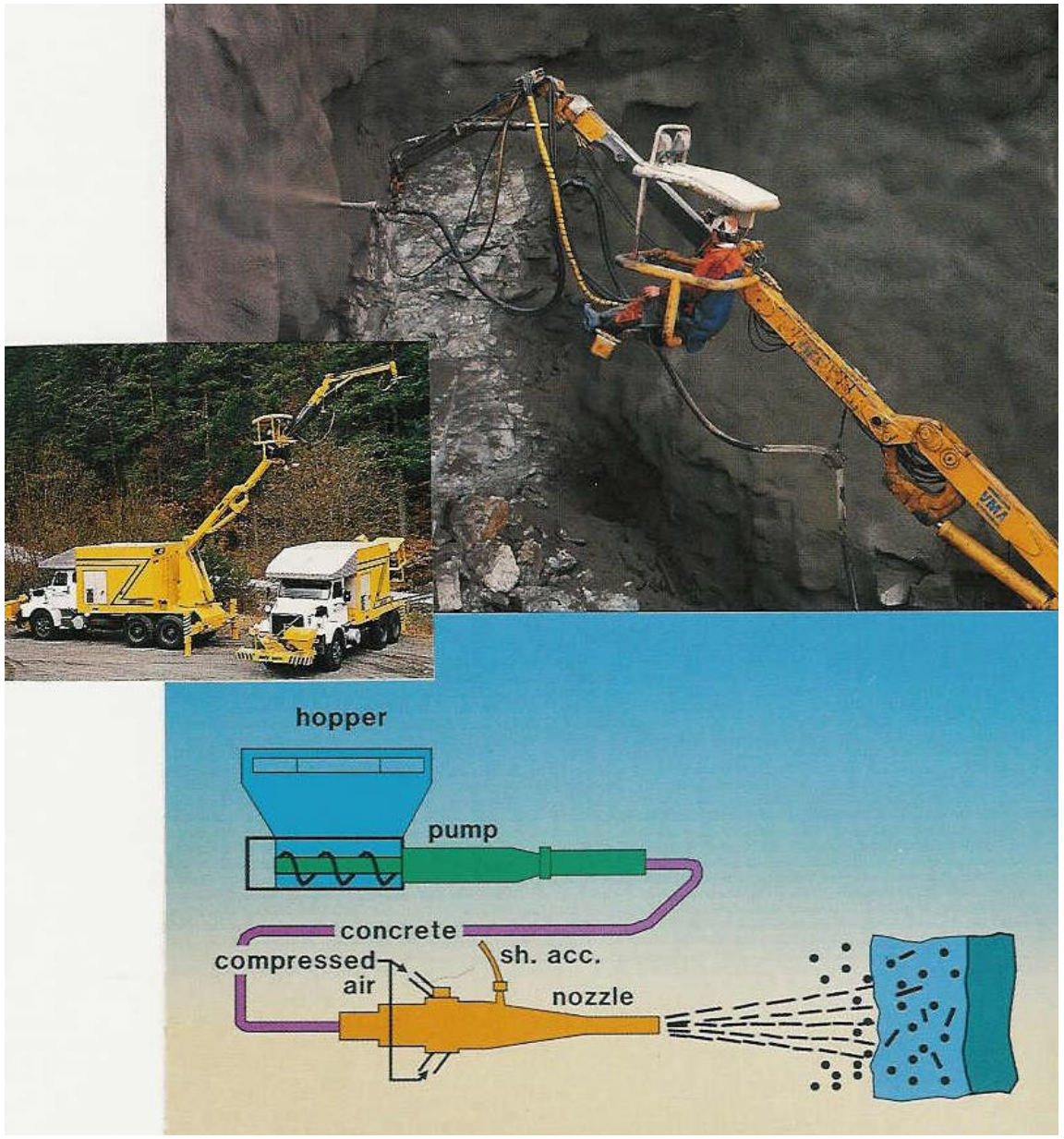
NMT MAY LOOK LIKE THIS.

THIS SHALY LIMESTONE HAS BEEN ***PRE-INJECTED.***

BOLTING AND FIRST LAYER OF SHOTCRETE WAS APPLIED CLOSE TO THE FACE.

FOLLOWING Q-SYSTEM LOGGING, LATEST TUNNEL ADVANCE GETS SUPPORT.

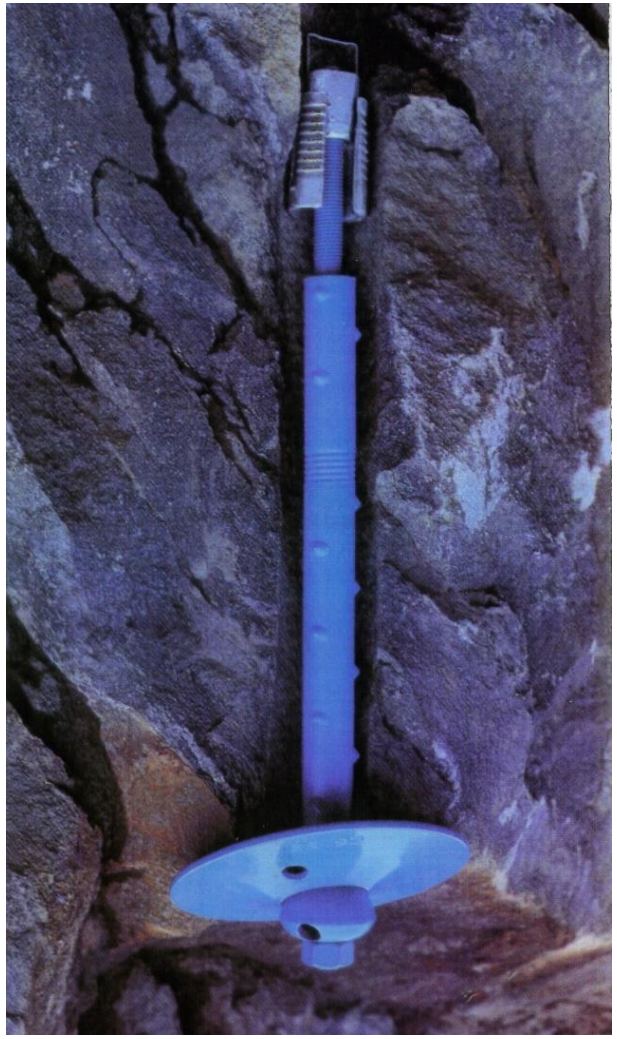
NMT IS BASICALLY SAFE, and AS ECONOMIC AS POSSIBLE



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

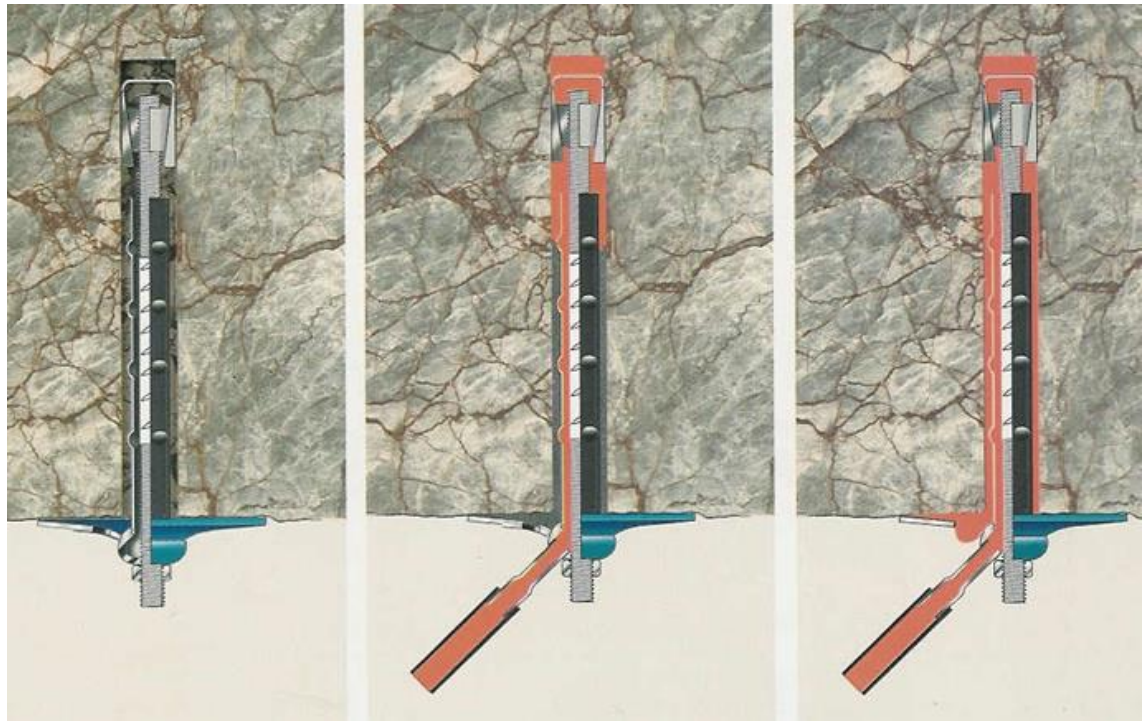
DETAILS of S(fr) from 1990's contractor brochure

Pre-grouting, shotcreting, charging holes with explosives.

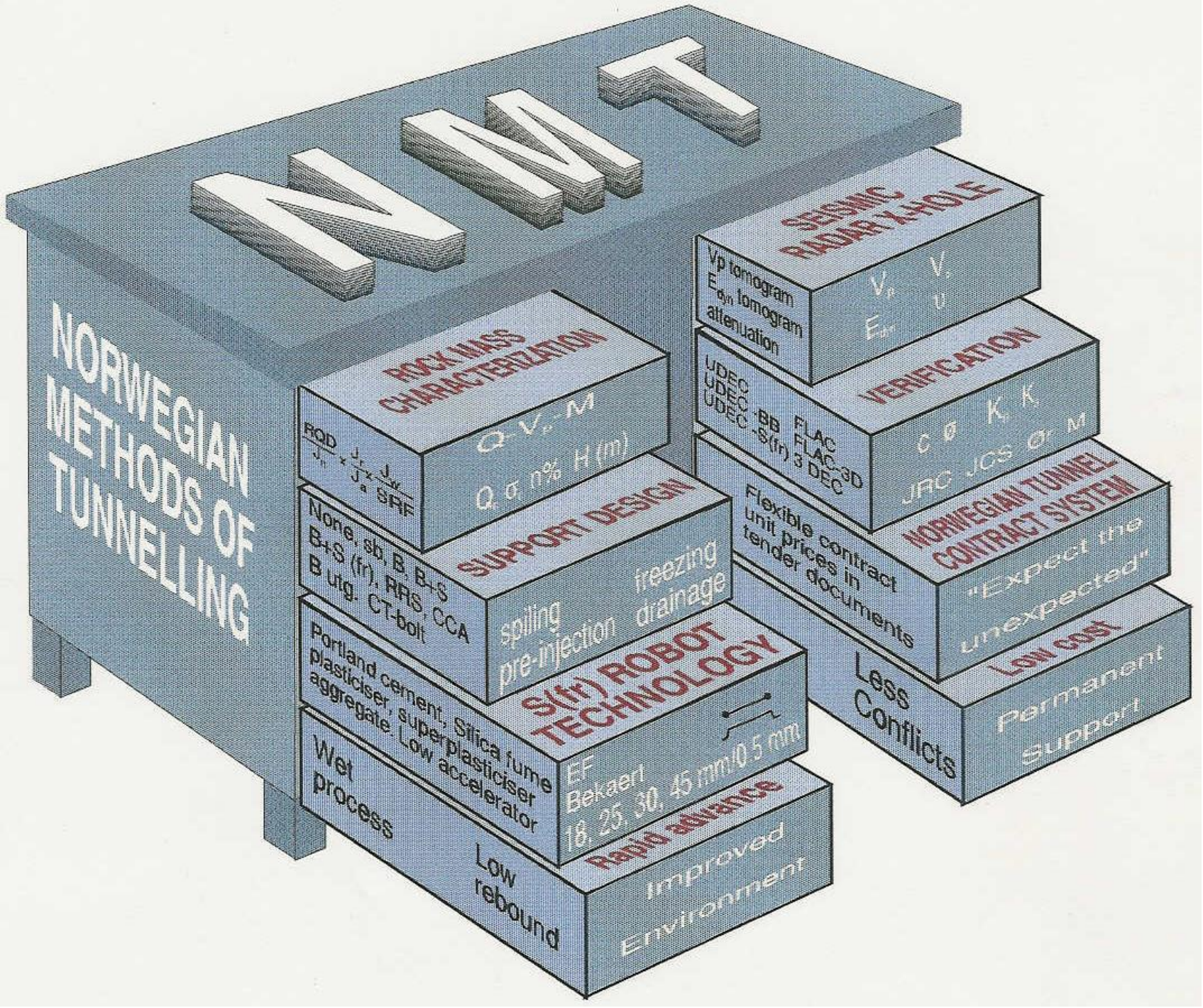


The principles of the CT-bolt, which has multiple layers of protection against corrosion.

Lengths could be 3, 4, 5 or 6 m.



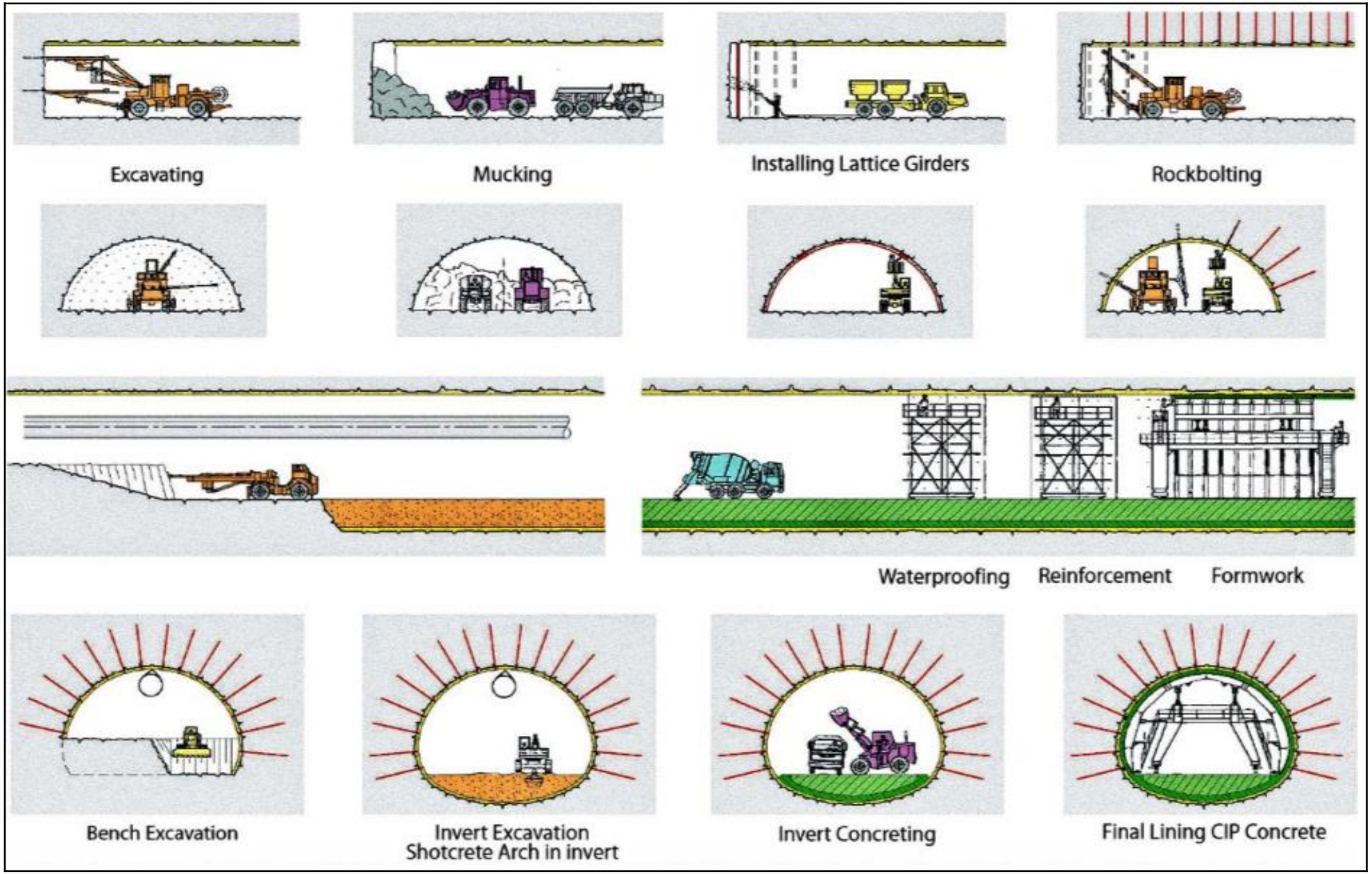
Note the cross-section with the outer (only) cracked grout annulus, the normal fate of conventional bolts.



NMT IN A 'NUT-SHELL' (or in an office desk)

Barton, 1996

NATM OPERATIONS IN SUMMARY

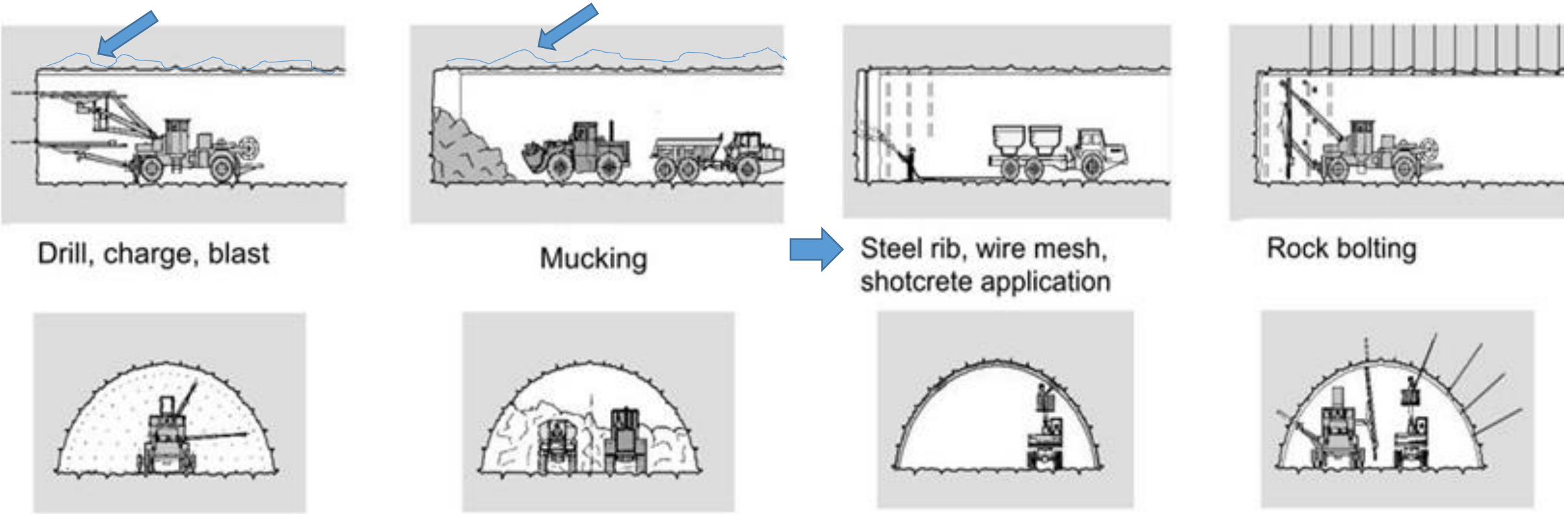


NATM OPERATIONS in summary

(ASG, 2010)

From ILF consultants

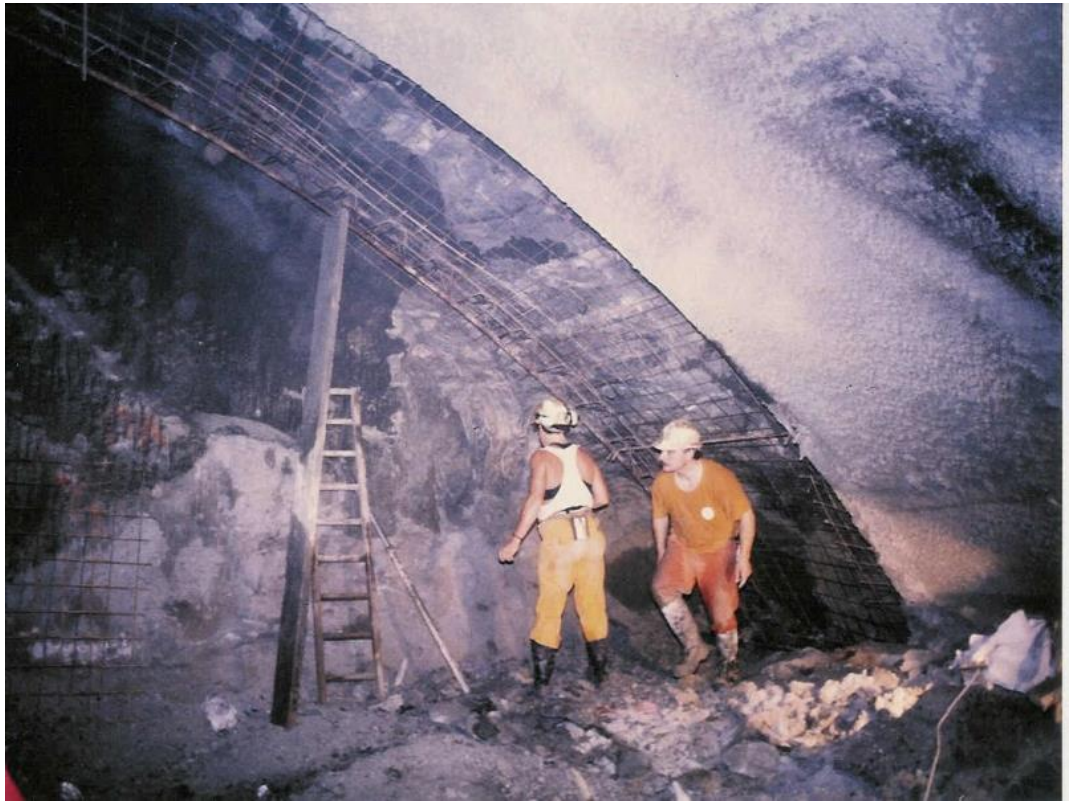
OVER-BREAK MAY EFFECT MANY OPERATIONS IN NATM



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

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

(THESE PROBLEMS HAVE MUCH LESS EFFECT ON NMT).



TEMPORARY SUPPORT PHASE OF NATM: S(mr) + B? + LATTICE GIRDERS?

MAY NOT ALWAYS INSPIRE CONFIDENCE – CRITICAL PHASE (of potential instability) IS EVIDENT.

EUROTUNNEL SUB-SEA CROSS-OVER CAVERN, CHANNEL TUNNEL PROJECT.

FINAL CCA.

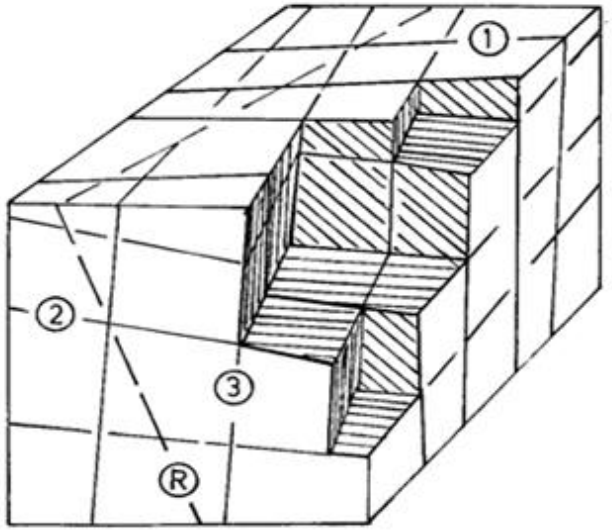
CONFIDENCE IS OBVIOUSLY RESTORED.

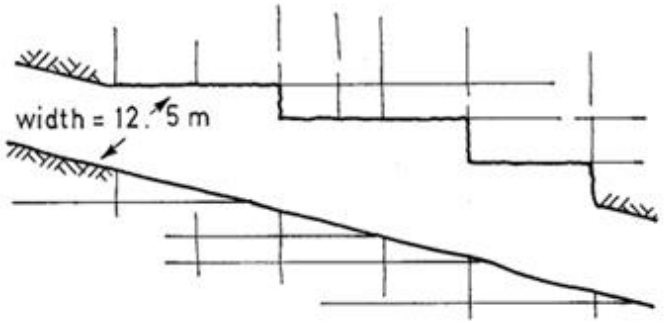
HIGH-SPEED RAIL TUNNEL THROUGH JOINTED CHALK IN SOUTHERN ENGLAND, HAD FINAL *(YEAR 2000)* COSTS OF US$ 128M /3.2 KM, OR $ 40,000 PER METRE.

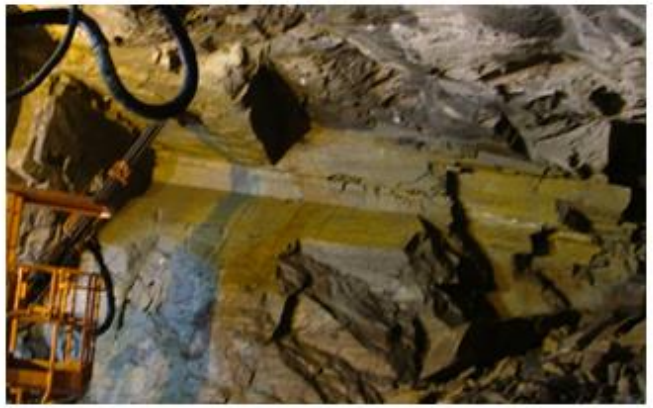
THIS *WAS* THREE TO FOUR TIMES HIGHER THAN A TYPICAL NMT TUNNEL, WITH SIMILAR Q-VALUE ROCK, USING B+S(fr) AS PERMANENT ROCK SUPPORT, AND A PC-ELEMENT + MEMBRANE LINER, FOR A DRAINED-BUT-DRY SOLUTION.

How does over-break influence NMT and NATM?

SOME EXTREME OVER-BREAK – CAUSED BY JOINTING







OVERBREAK IF Jn/Jr ≥ 6

Jn = number of sets

Jr = roughness

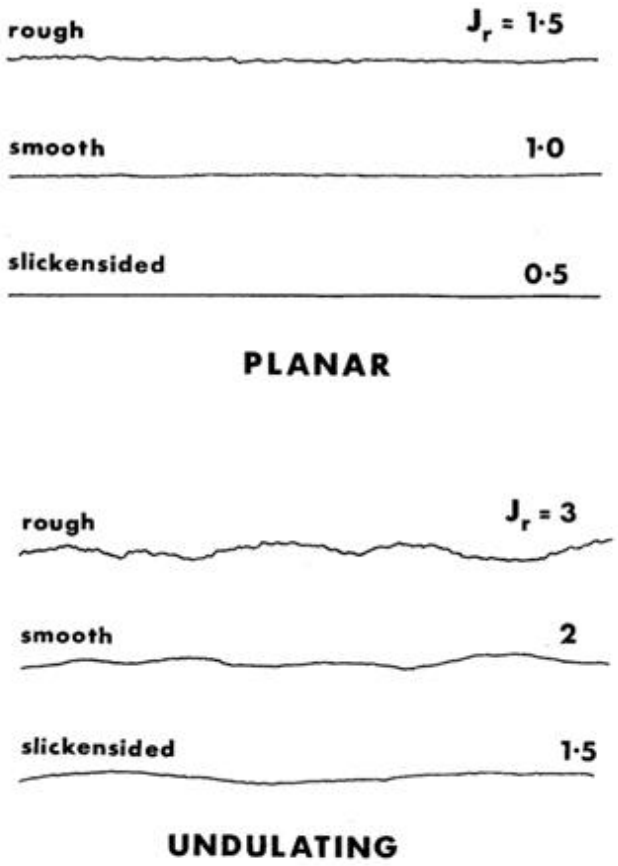
6/1.0 9/1.5

12/2 15/3

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

In photos:

Jn/Jr = 9/1.5



TWO OF THE Q-SYSTEM PARAMETERS CONTROL *OVER-BREAK*

(Ja helps too!)

NOTE TO CONTRACTORS:

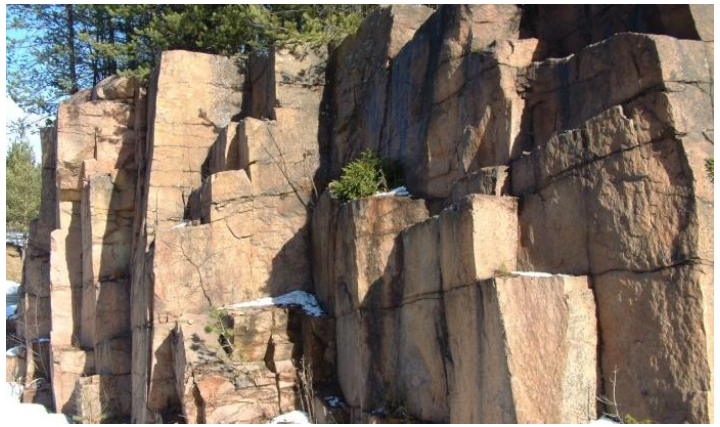
***Jn/Jr ≥ 6* HAS BEEN USED IN SEVERAL RECENT METRO CLAIMS!**

Barton, 2007.

TAMROCK

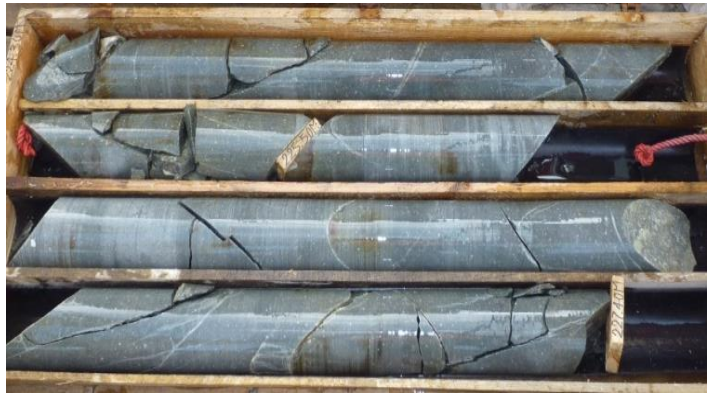
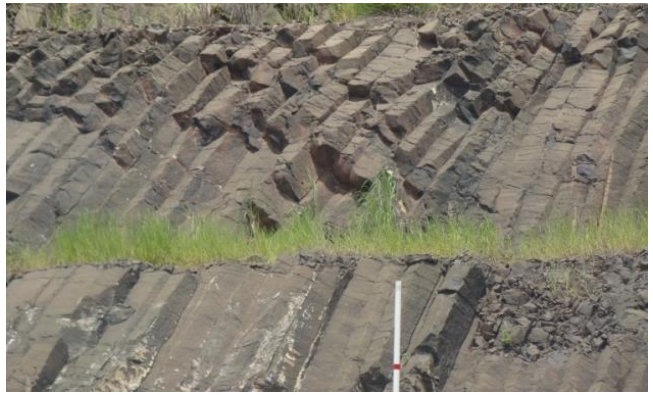
WHAT IS THE ‘Q-SYSTEM’ ?

(YOU ARE MOSTLY SOIL, FOUNDATION AND STRUCTURAL ENGINEERS?)



VARIABLE, ROCKY WORLD

NEEDS *BROAD-REACH CHARACT-ERIZATION* METHOD.

HOW TO GET ‘DESIGN’ PARAMETERS ?

THE ‘Q-system’ ?

Q means *rock mass quality*.

Q consists of *ratings for six parameters*.

= (Block size) x (friction) x (‘active stress’)

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

Q correlates with E_{mass}, V_p, deformation

Q used here!

SUGAR LOAF MOUNTAIN, RIO DE JANEIRO

TOP END OF ROCK MASS QUALITY SCALE.

Q ≈ 100/0.5 x 4/0.75 x 1/1

i.e. >1000

BRAZILIAN HYDROPOWER PROJECT COLLAPSE IN FAULT ZONE

LOWEST END OF THE ROCK MASS QUALITY SCALE.

Q ≈ 10/20 x 1/8 x 0.5/20

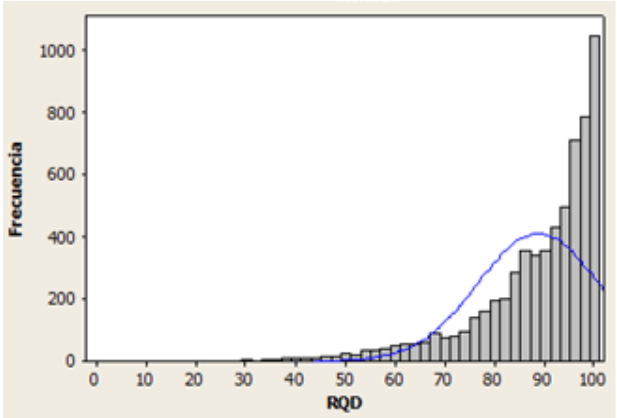
i.e. < 0.001

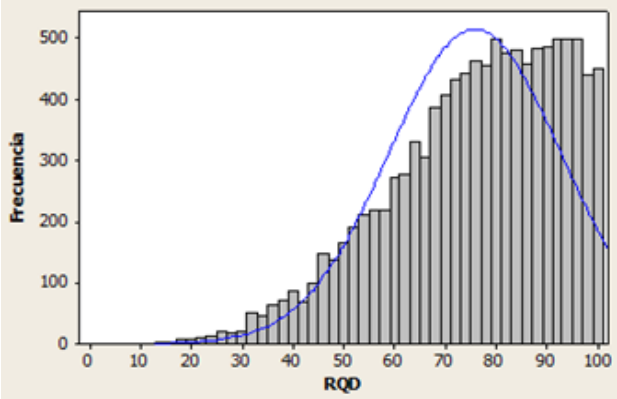
Strength contrast,
modulus contrast,
constructability contrast
(15 years /1 year)

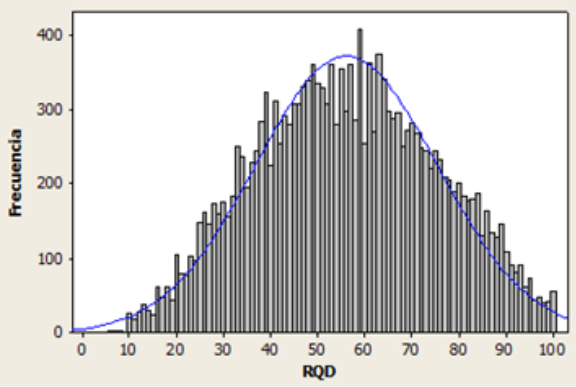
0.001→1000 ?
or 5→95 ?
or F7→F1 ?

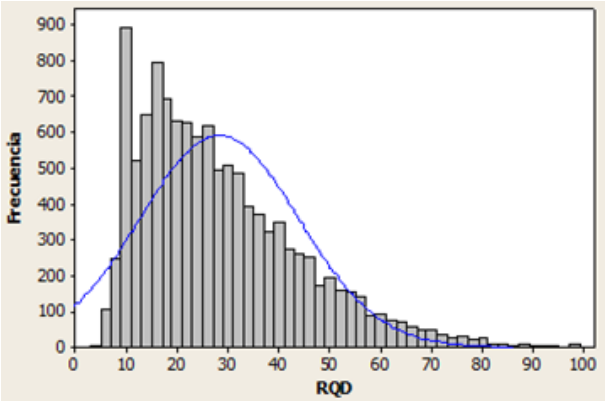
(Q-scale, RMR-scale, Austrian-scale)

RQD STATISTICS:
Q-classes 2, 3, *4* and 5, with Q-VALUES
0.1-1, *1-4*, 4-10, 10-40.



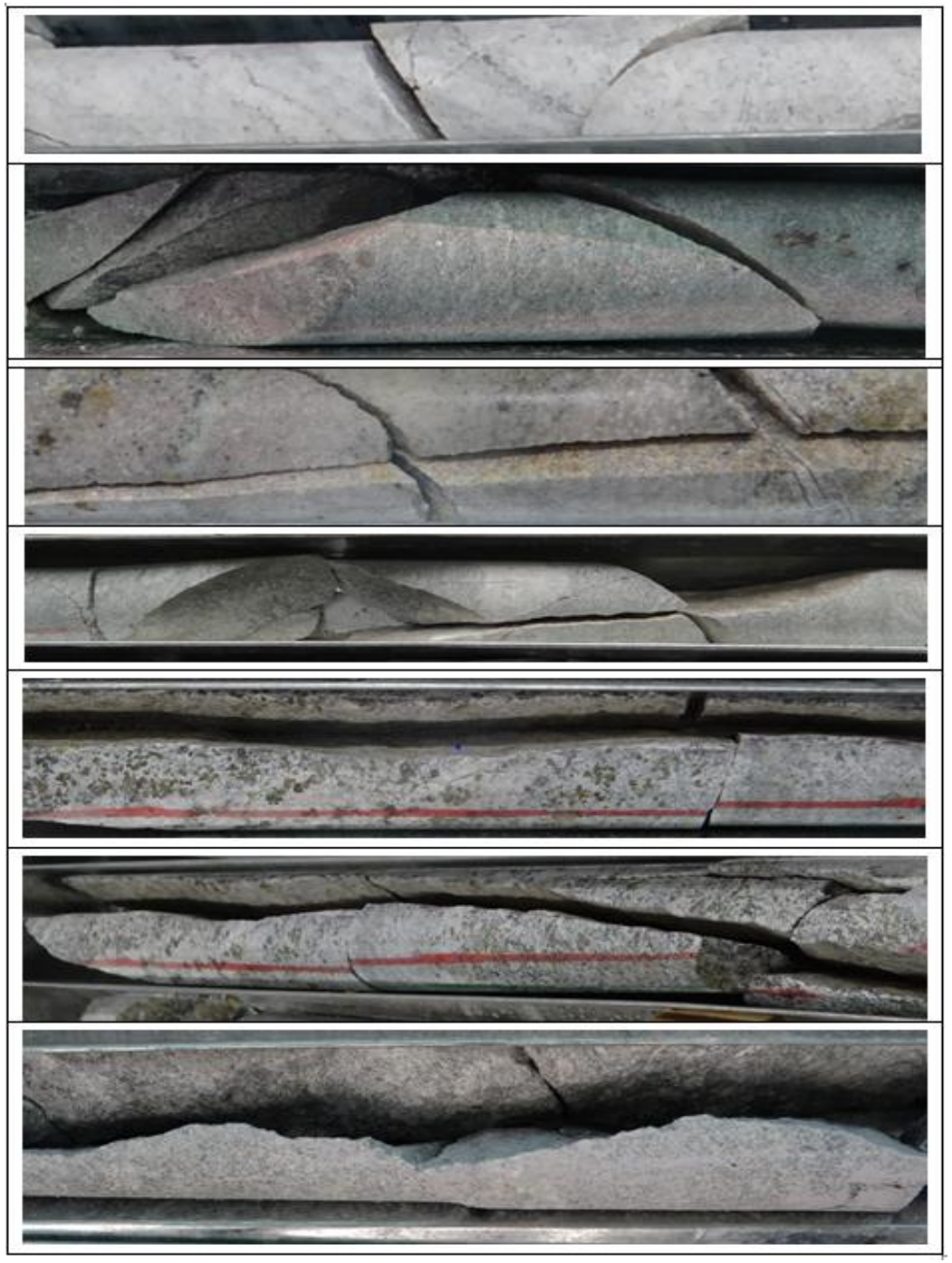






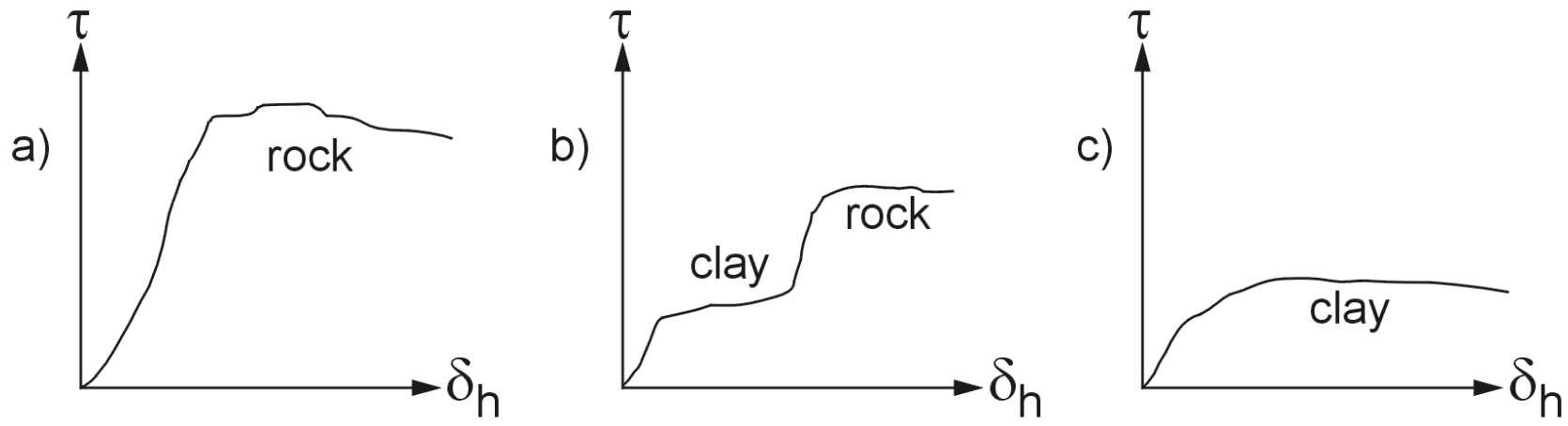
They demonstrate the central role played by RQD in commonly experienced rock mass conditions.

(> 40 km of core)



Photos of core with the following Jr values:

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



(a) Rock wall contact

		(thin coatings)				
	$Ja/Jr =$	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)°$				
A. Discontinuous joints	4	79°	76°	63°	53°	45°
B. Rough, undulating	3	76°	72°	56°	45°	37°
C. Smooth, undulating	2	69°	63°	45°	34°	27°
D. Slickensided, undulating	1.5	63°	56°	37°	27°	21°
E. Rough, planar	1.5	63°	56°	37°	27°	21°
F. Smooth, planar	1.0	53°	45°	27°	18°	14°
G. Slickensided, planar	0.5	34°	27°	14°	9.5°	7.1°

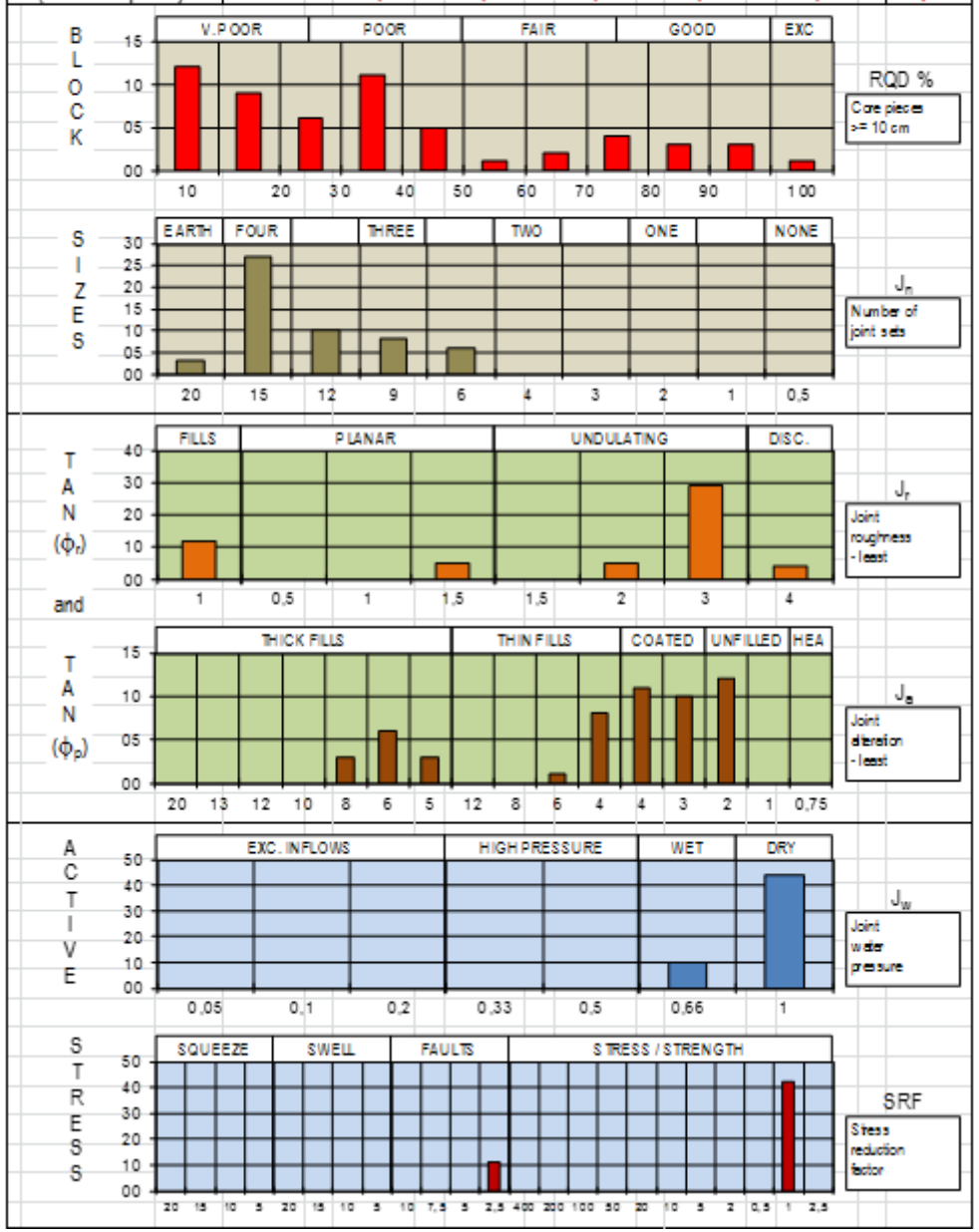
Jr/Ja is like a ‘friction coefficient’

FAULT ZONES ARE UNIQUE CHALLENGES FOR TUNNELLERS BECAUSE…….

RQD, Jn, Jr, Ja, Jw, SRF……..all Q-parameters may be adverse

also TIME + COST

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



I ROCK MASS STRUCTURE

1 RQD Deere et al., 1967)
2 J_n = joint set number
3 F = joint frequency (per metre)
4 J_v = volumetric joint count (Palmström, 1982)
5 S = joint spacing (in metres)
6 L = joint length (in metres)
7 w = weathering grade (ISRM, 1978)
8 α/ß = dip/dip direction of joints (Schmidt diagram)

block size { Q Q

II JOINT CHARACTER

9 J_r = joint roughness number
10 J_a = joint alteration number
11 JRC = joint roughness coefficient
12 a/L = roughness amplitude of asperities per unit length (mm/m)
13 JCS = joint wall compressive strength
14 ϕ_r = residual friction angle
15 r,R = Schmidt rebound values for joint and rock surfaces

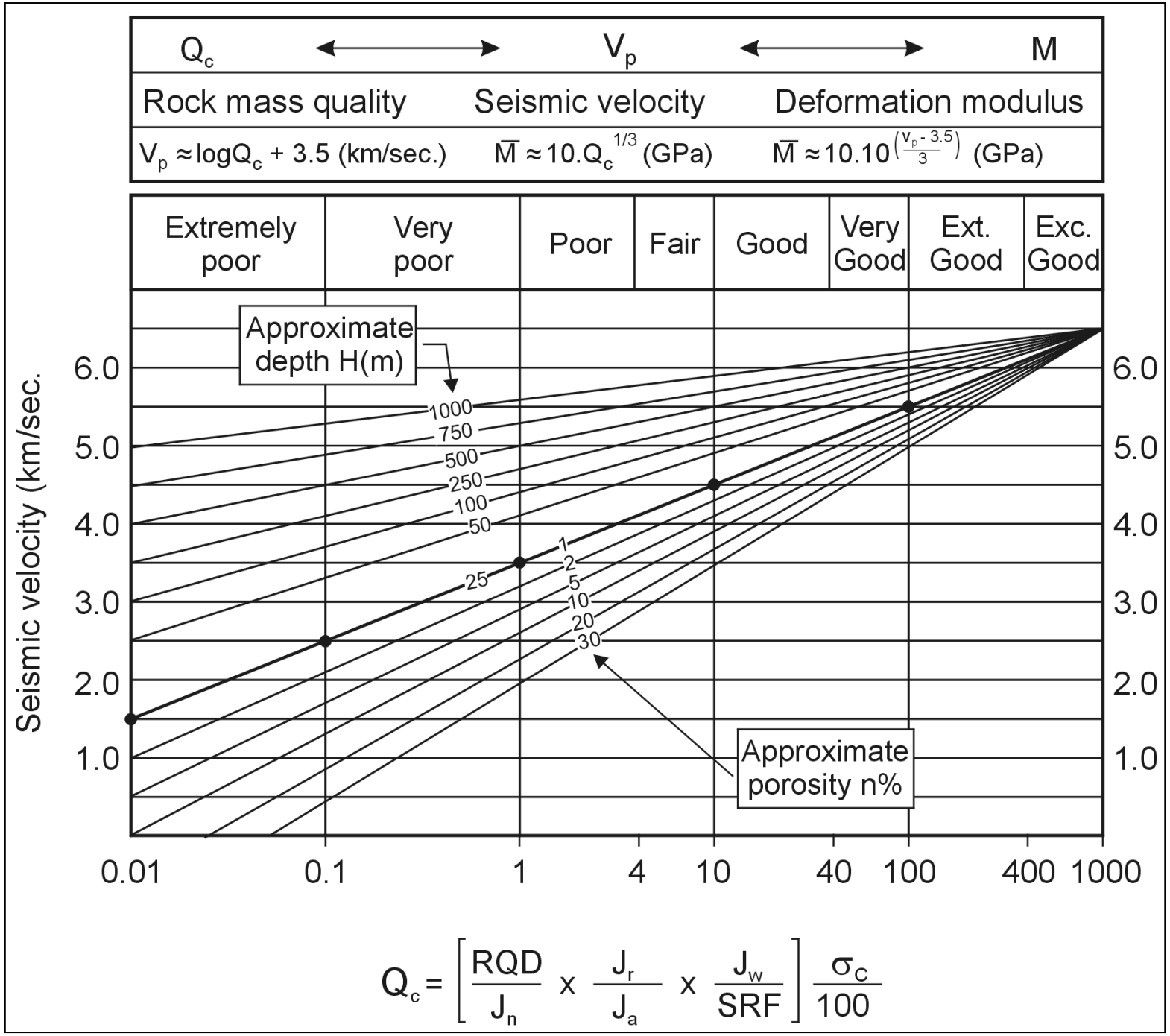
shear strength { Q Q

III WATER, STRESS, STRENGTH

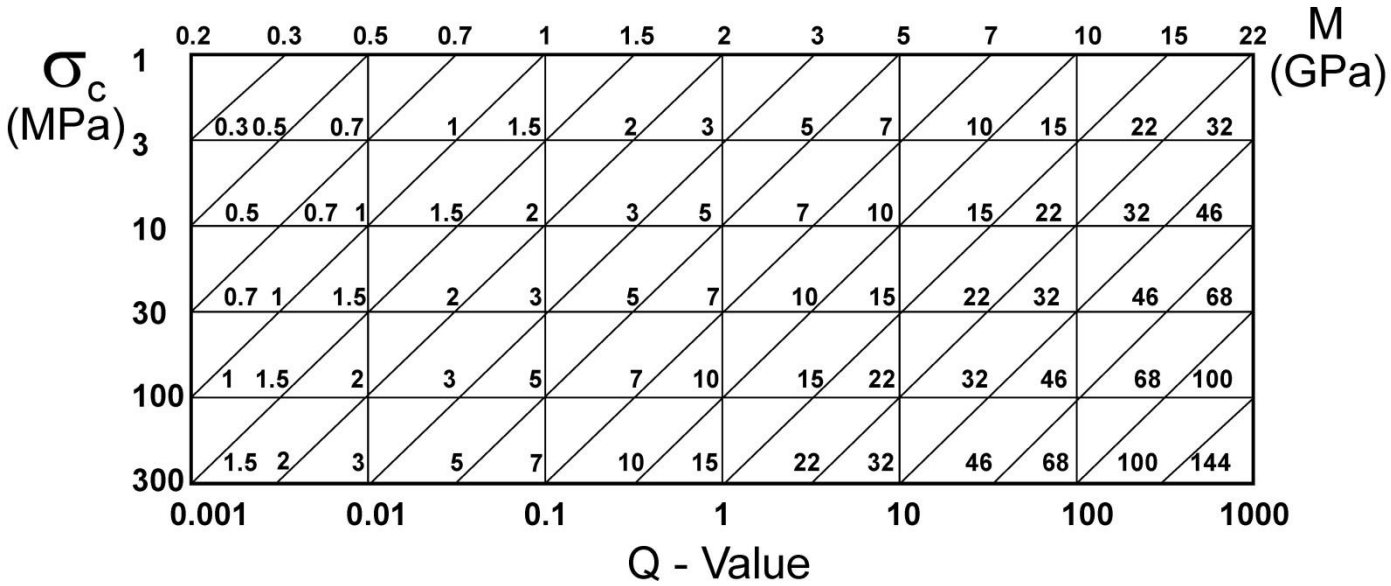
16 J_w = joint water reduction factor
17 SRF = stress reduction factor
18 K = rock mass permeability (m/s)
19 σ_c = compressive strength
20 σ_1 = major principal stress

active stress { Q Q

Q IS ONLY PART OF A ROCK MASS DESC-RIPTION EXERCISE

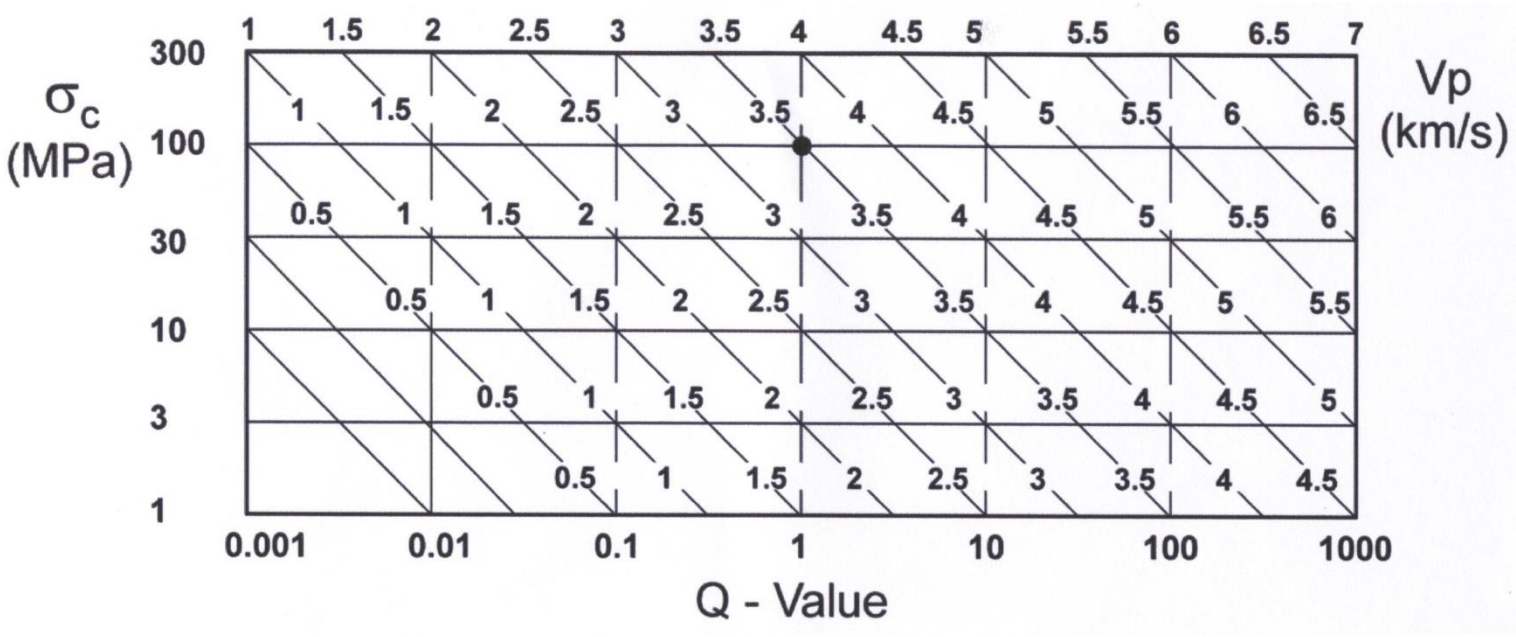


NOTE CORRECTION FOR DEPTH (OR STRESS) – from central diagonal nominal depth 25m



$$E_{mass} \approx 10^{(V_p - 2.5 + \log \sigma_c)/3}$$

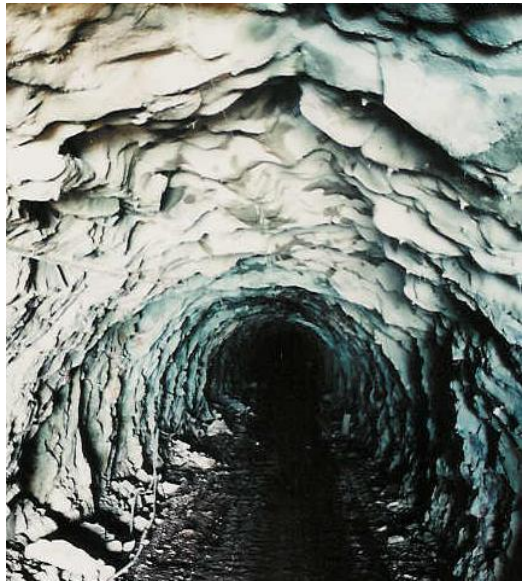
Depth-dependent solution. Barton, 2007



DEFORMATION MODULUS AND P-wave VELOCITY. NO CORRECTION FOR DEPTH (OR STRESS) IN THE DIAGRAMS. Derived from central diagonal in previous figure – nominal depth 25m

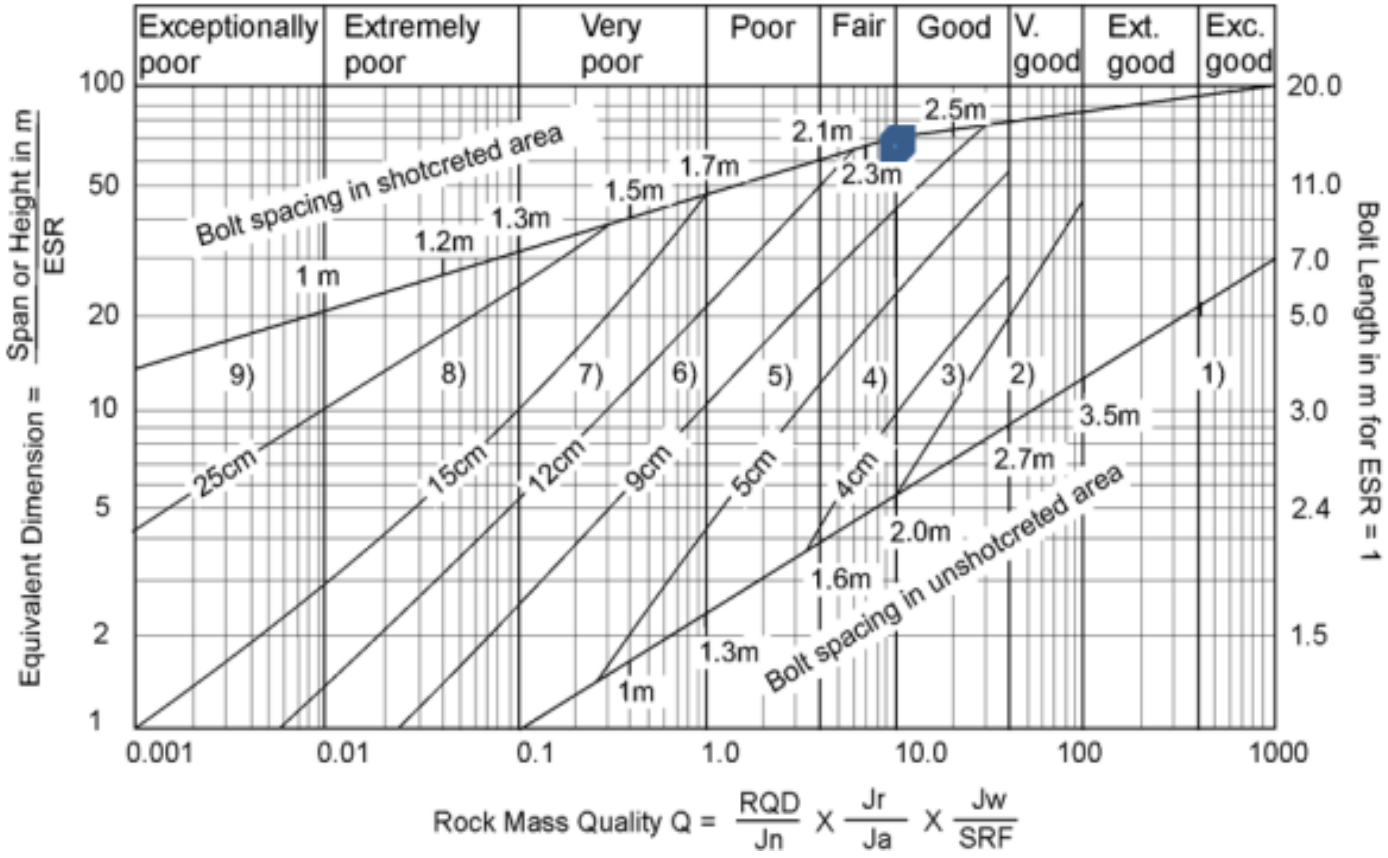
BACK TO OVER-BREAK

(AND IMPLICIT USE OF CONCRETE)

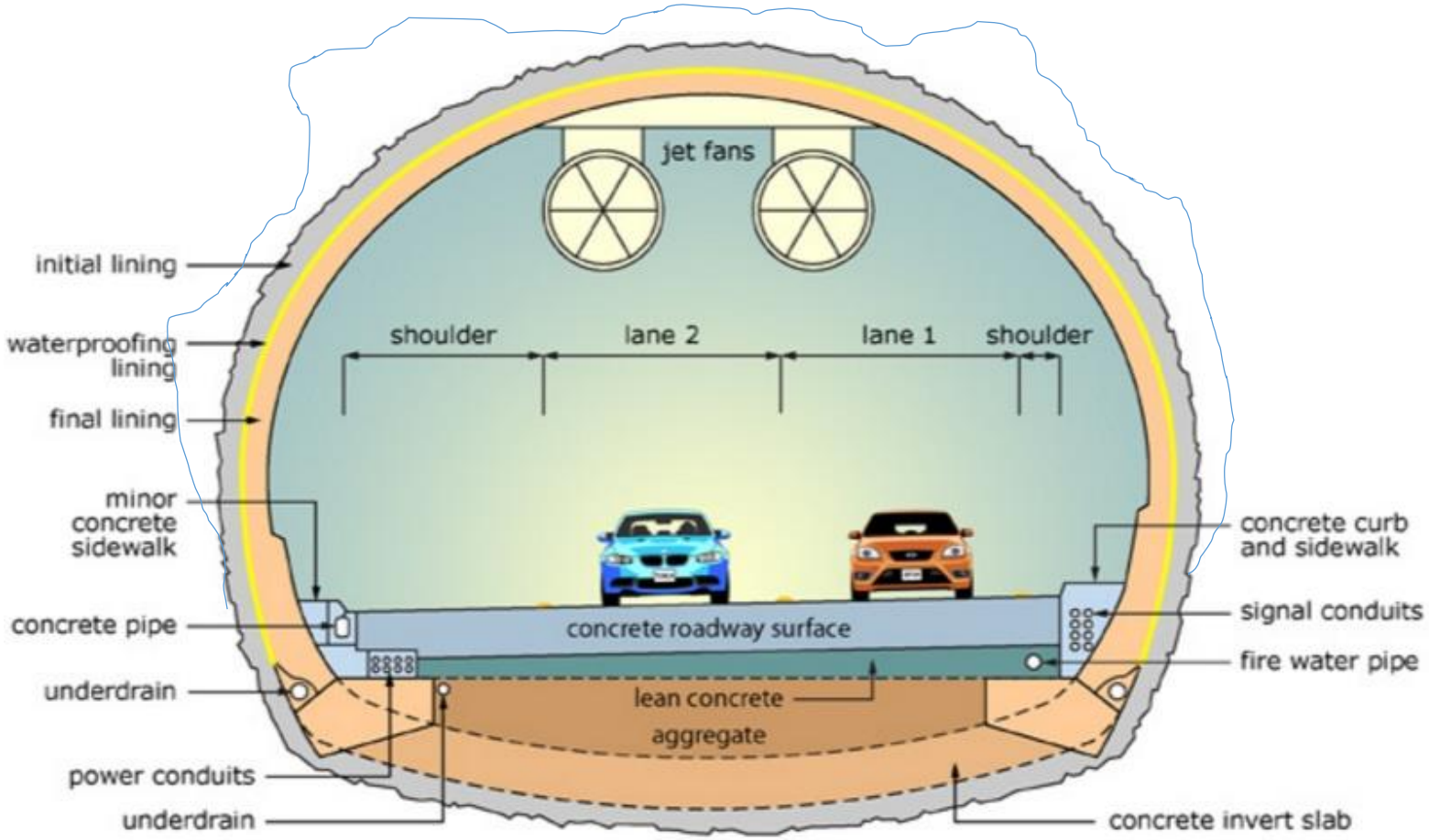


GJØVIK CAVERN ARCH WITH 10cm S(fr) AND ≤ 1m OF OVER-BREAK

IN NMT OVER-BREAK HAS LIMITED IMPACT. DO NOT HAVE TO FILL WITH SHOTCRETE or CONCRETE!



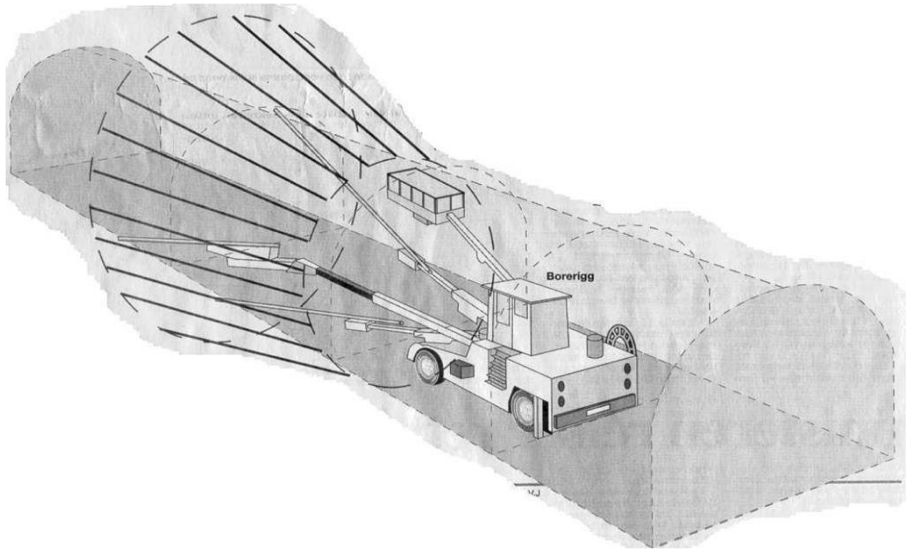
Over-break ignored in drawings, stability, volumes?



A Botnia rail tunnel, Sweden

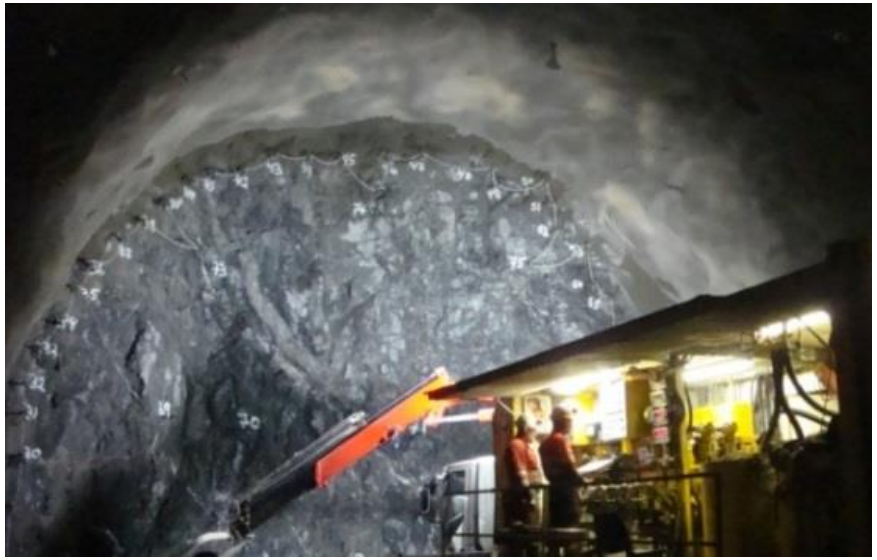
CONTROL OF WATER

(IN NMT and NATM)

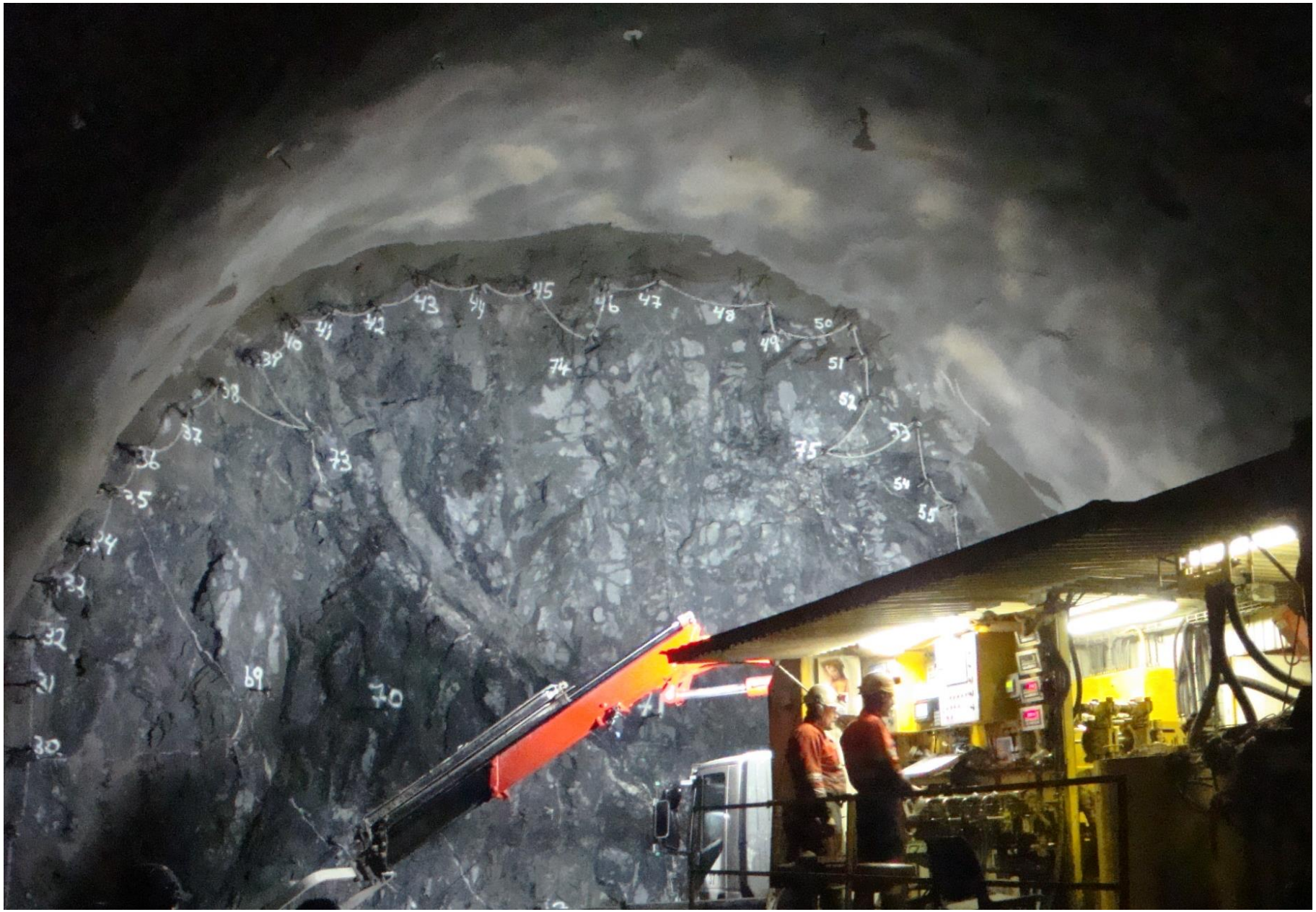


PRE-INJECTION:

AN IMPORTANT COMPONENT OF NMT, WHICH INCREASES THE (LOW) COST BY ABOUT 20% (IF CHOSEN).



24-30 hours for all hole-drilling and injection per ‘umbrella’ screen.

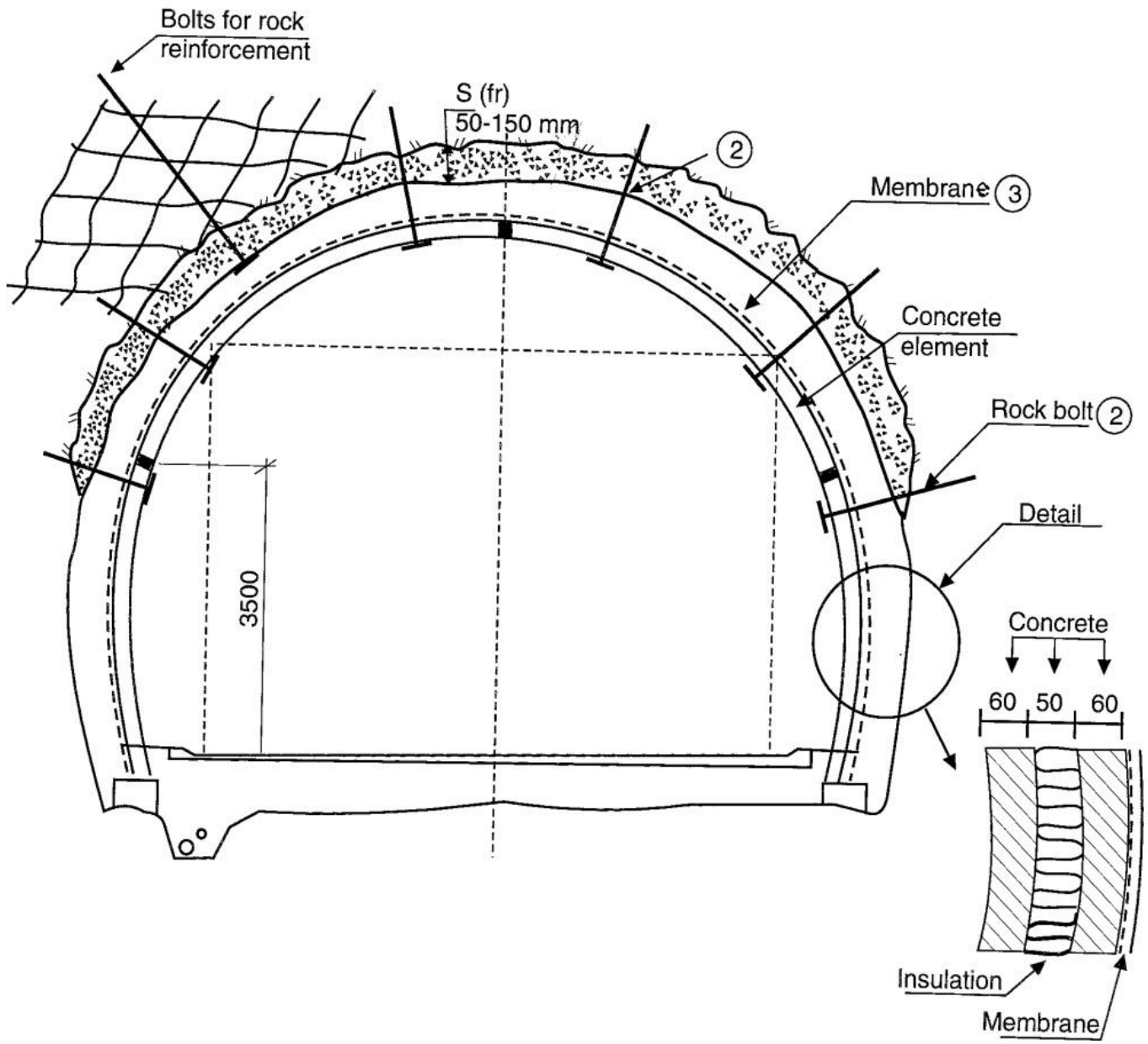


PRE-INJECTION FOR HIGH-SPEED DOUBLE-TRACK RAIL TUNNEL

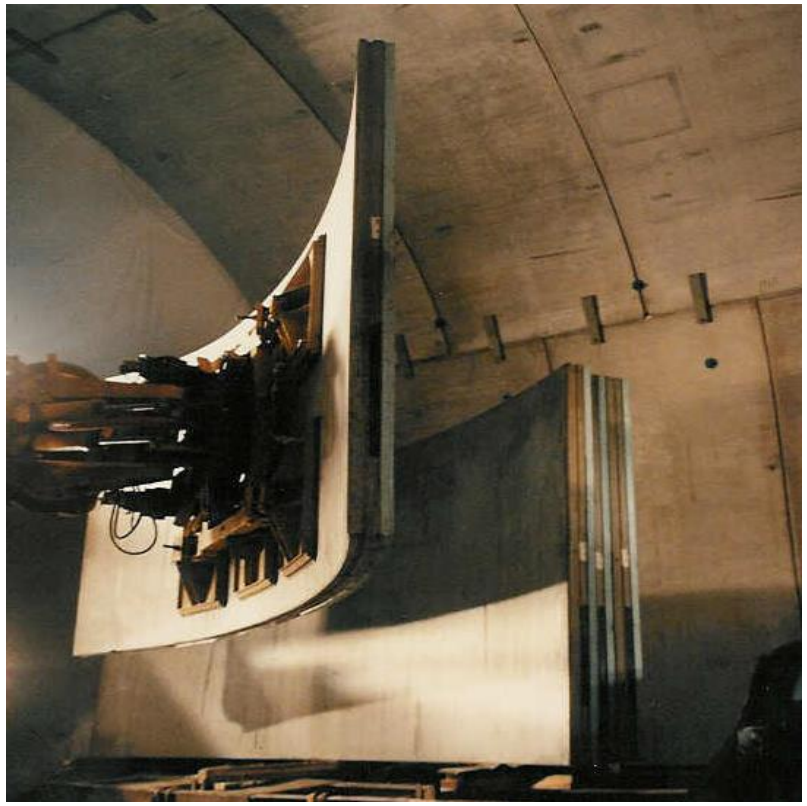
Q-BASED PERMANENT SUPPORT IS B + S(fr)

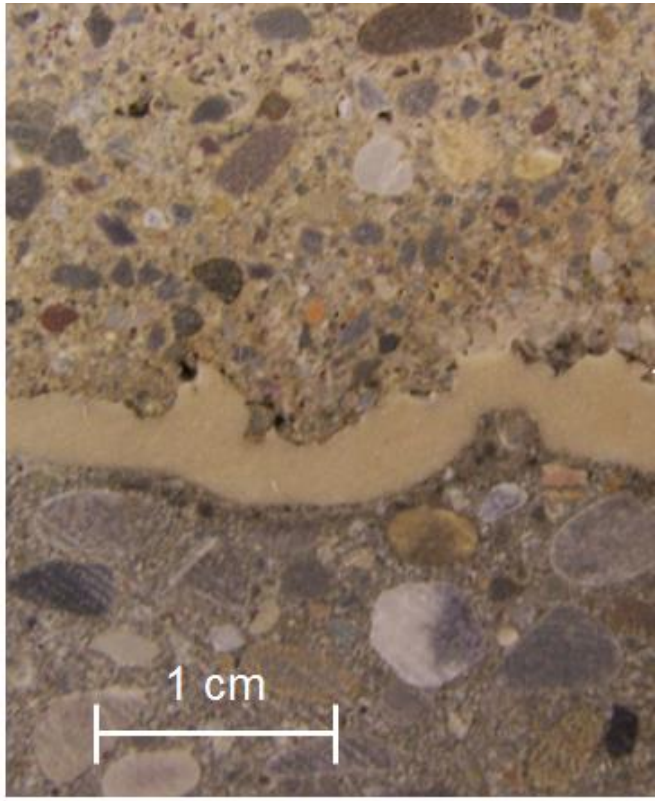
AN ALTERNATIVE TO PRE-INJECTION:

PC-ELEMENTS WITH OUTER MEMBRANE

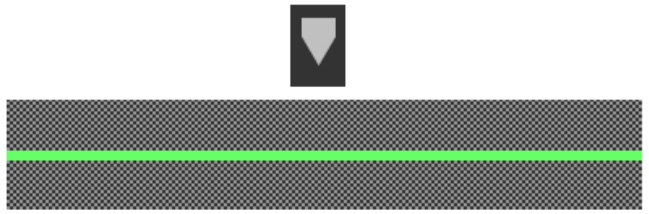


Kveldsvik and Karlsrud, 1996

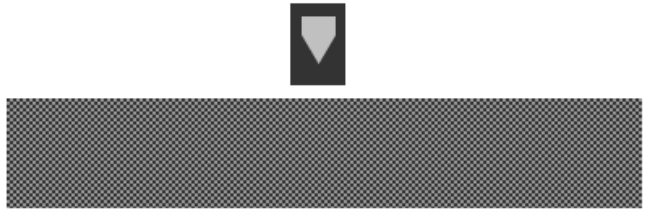


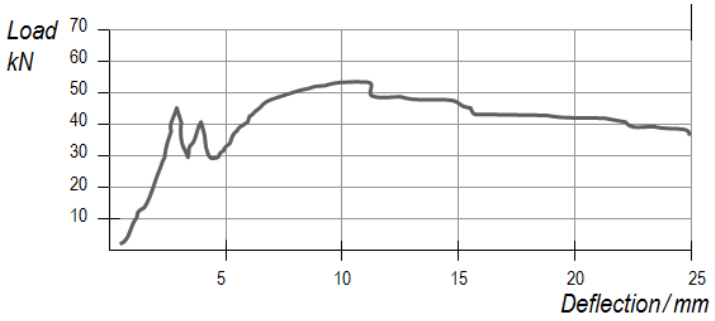


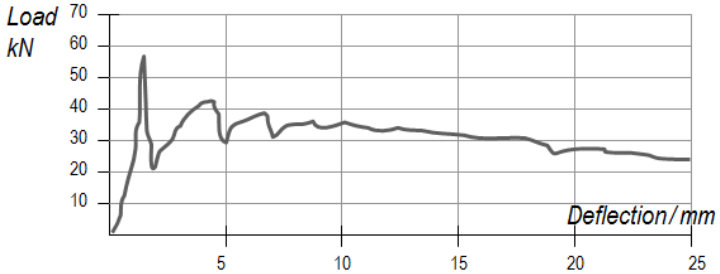
1. Sprayed concrete with 3mm membrane, reinforcement: structural pp-fibres



2. Pure sprayed concrete, reinforcement: structural pp-fibres







THE LAST STAGE OF WATER-PROOFING (if needed)

SPRAYED MEMBRANE IN S(fr) SANDWICH (BASF 345): IMPROVED S(fr) TOUGHNESS (GREATER FRACTURE ENERGY)

Holter and Nymoen, 2009.

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

APPROX. 12-15km OF MEMBRANE WELDS PER 1km OF (DOUBLE-TRACK) RAIL TUNNEL

…IF LEAKAGE (through unreinforced concrete?):
WHERE DOES THE LEAK COME FROM?

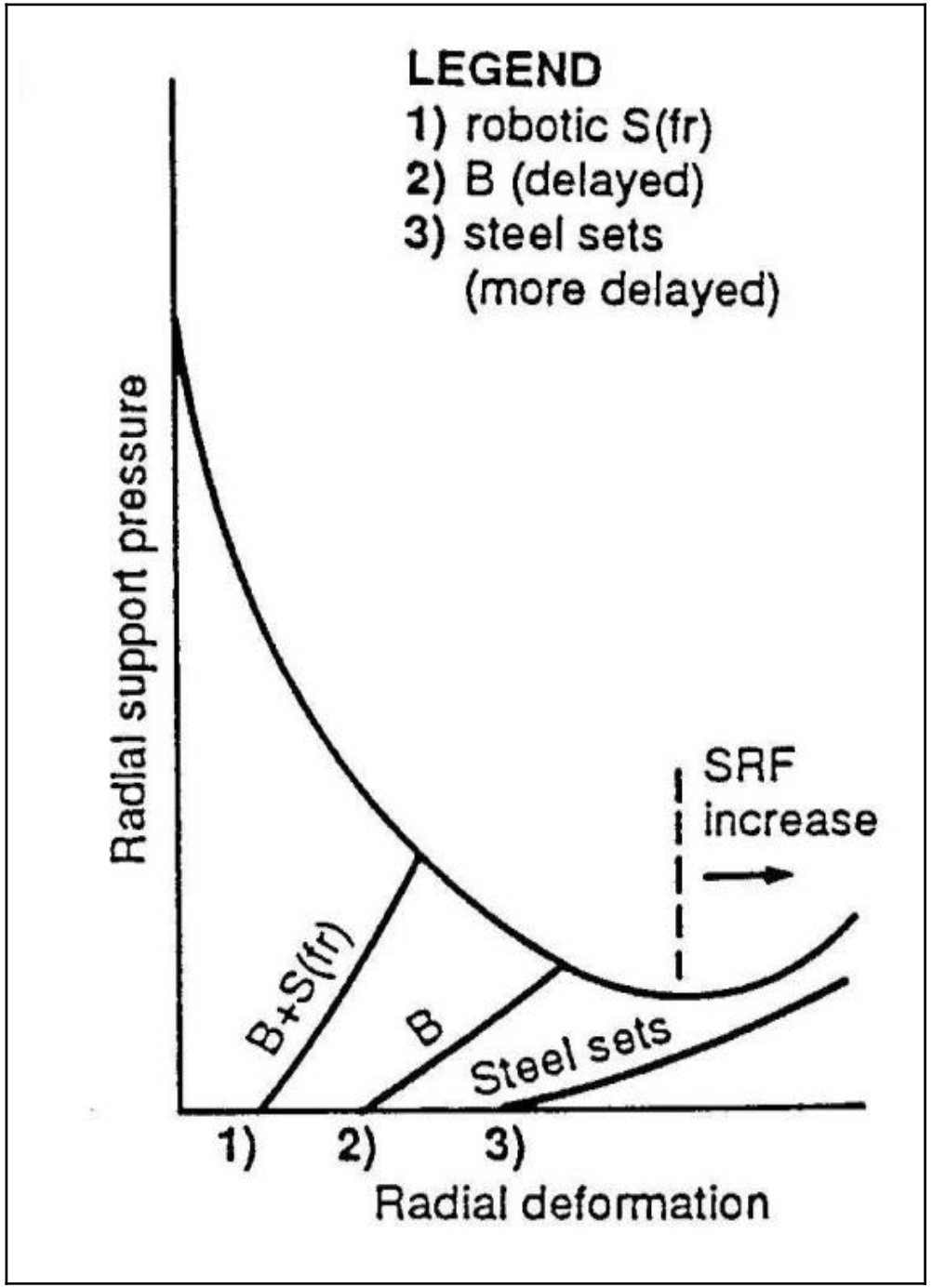
FOR THOSE WHO HAVE **ADOPTED** NMT, SUCH **(CAVERN or TUNNEL) COMPLEXITY** IS **NEVER SEEN**

(CLEARLY A MUCH MORE LABOUR INTENSIVE METHOD THAN NMT)

LATTICE GIRDERS, STEEL SETS, or RRS ?

ADEQUATE CONTACT WITH THE ROCK IS NOT EASY!

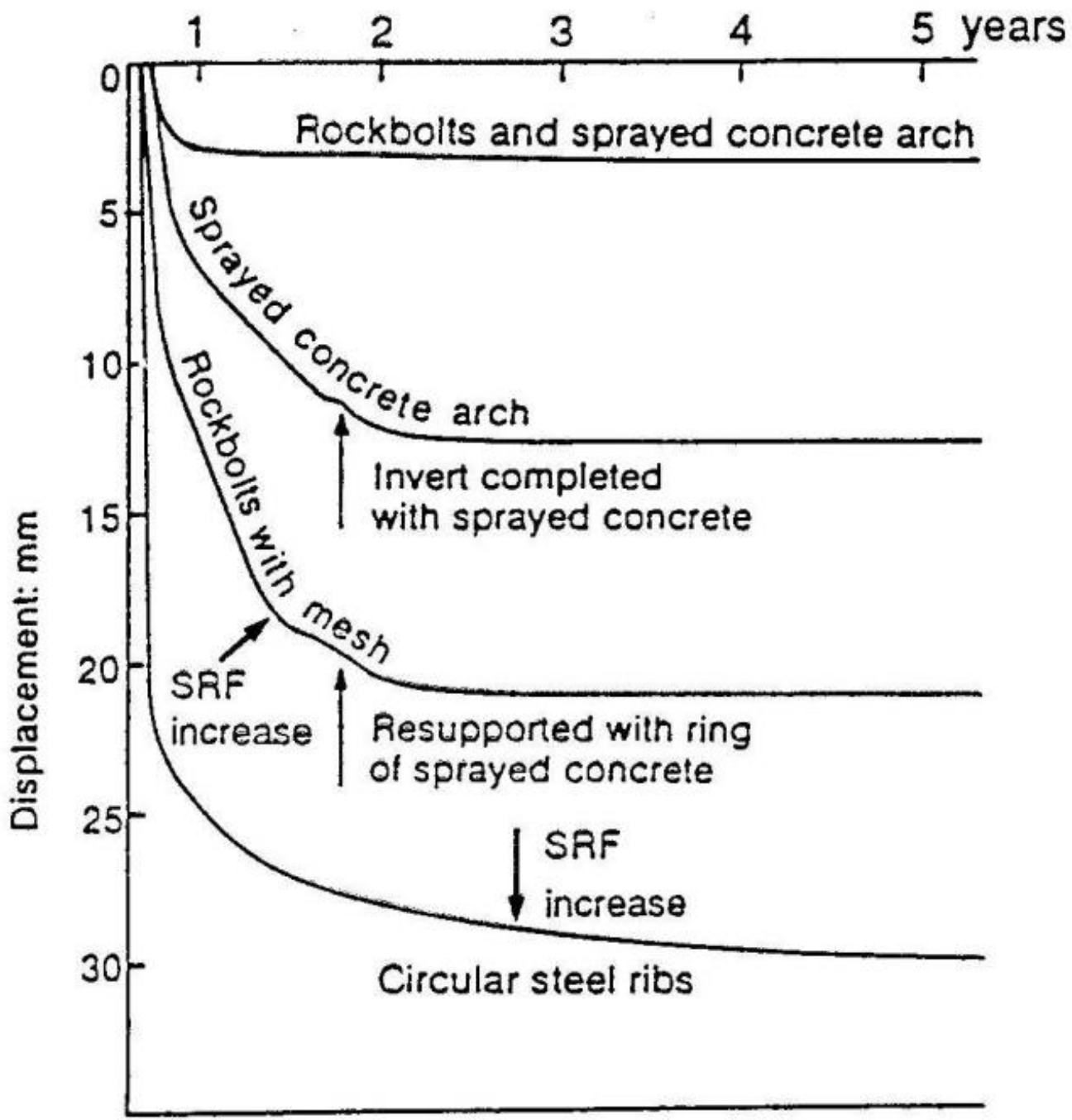
VERY 'SOFT' SYSTEM :
CAN BE UNSAFE WHEN WAITING FOR THE CONCRETE LINING.



STEEL SETS AND LATTICE GIRDERS ALLOW (INVITE?) LOOSENING (i.e. SRF increase)

1. ADEQUATE FOOTING STIFFNESS ?
2. RESISTANCE WHEN 'POINT-LOADED' ?
3. CONTACT WITH TUNNEL SURFACE ?
4. OWN DEFORMABILITY ?

Barton and Grimstad, 1994



Avoidance of steel sets (or lattice girders) remains an important advisory for NMT Q-system users.

Experimental tunnel in mudstones.

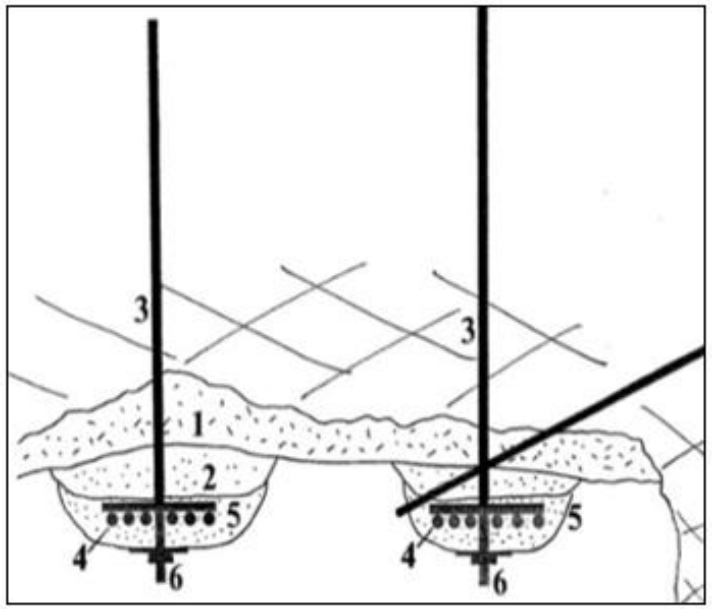
Ward et al. 1983

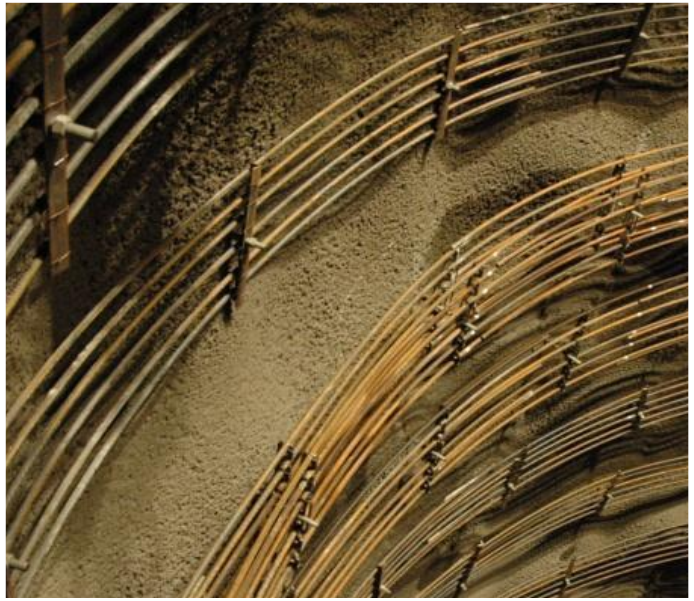
WHAT HAPPENS TO LATTICE GIRDERS or STEEL-SETS) WHEN A TUNNEL CROSSES A MAJOR JOINT OR FAULT?

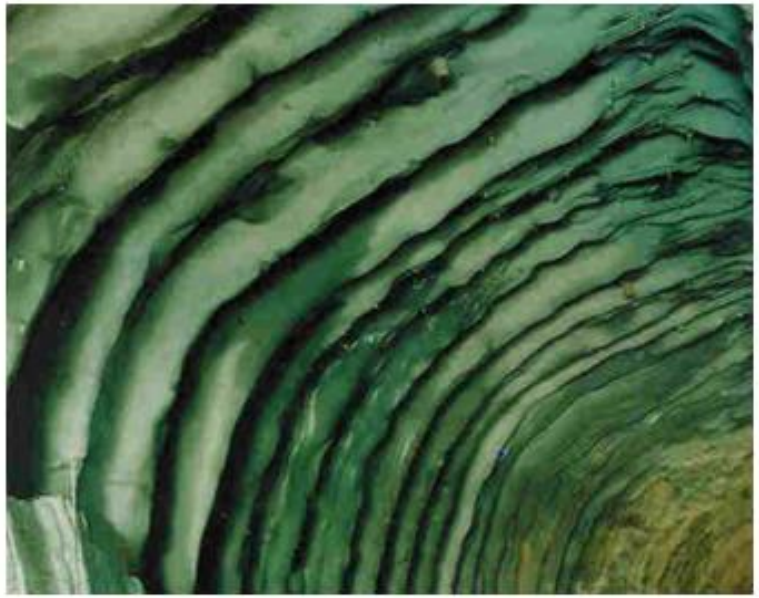
A MAJOR RAILWAY STATION CAVERN

Reportedly without bolting of the lattice girders. (Relies on prior bolting of the rock. Why not combine as in RRS?)

If over-loaded, lattice girders demonstrate minimal strength.

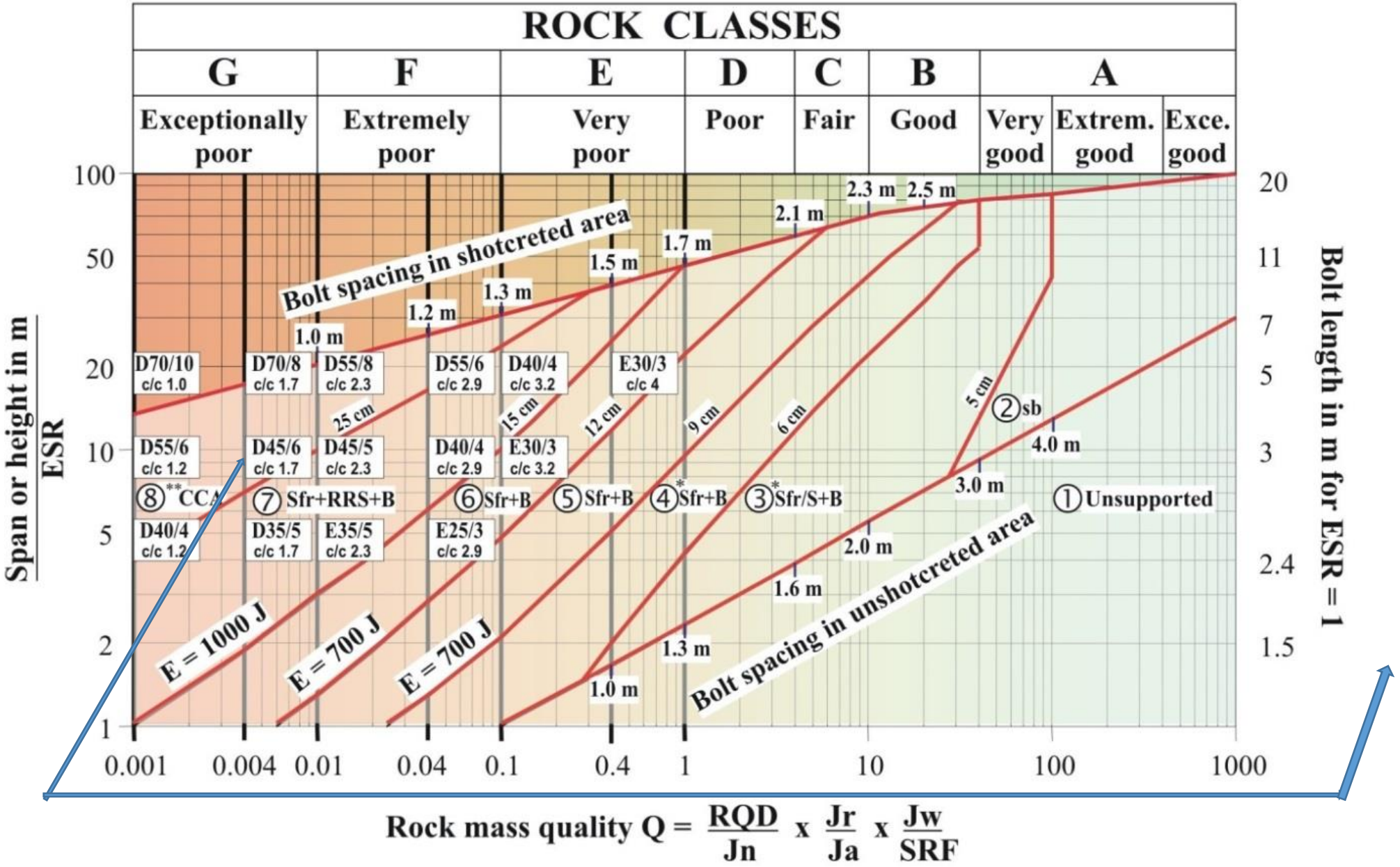






RRS IN NMT: MUCH MORE ROBUST

(TAKES MORE TIME, BUT ALL STAGES MORE SUPPORTIVE ***of 'rock as the construction material'***



D45/6 c/c 1.7

(for Q ≈ 0.004)

(double layer, 6 bars, 45cm thick arch, 1.7m c/c)

TAKE TIME TO GET THE **LOCAL HEAVY SUPPORT** APPROPRIATE TO THE JOB IN HAND

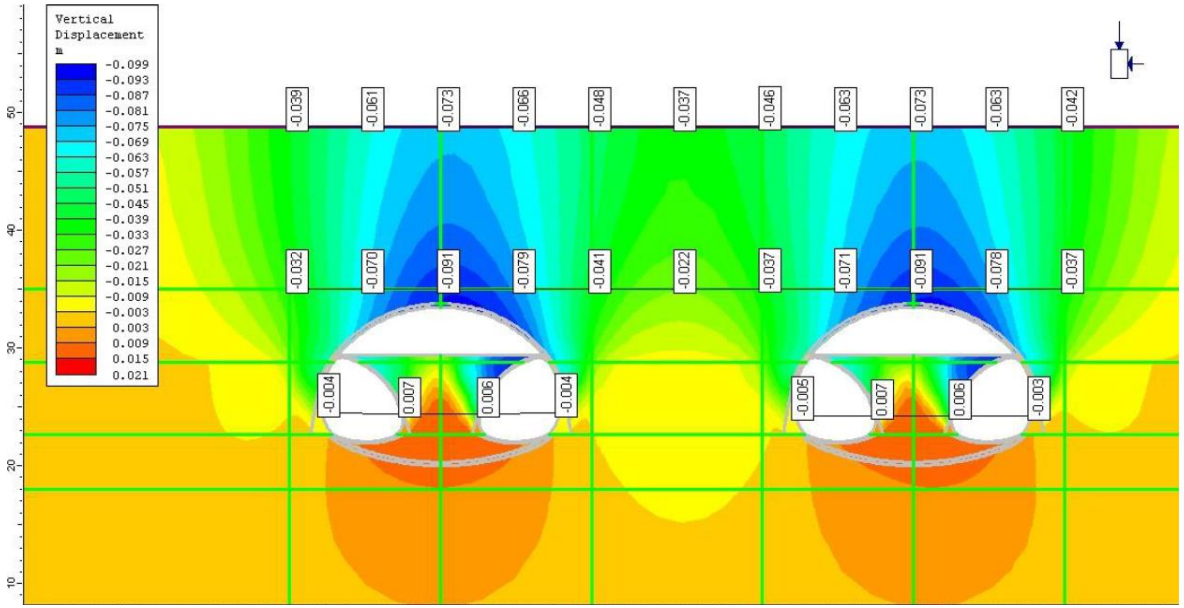
(AVOID COSTLY COLLAPSE as in next screens)

Grimstad in Barton and Grimstad, 2014

COLLAPSE # 1

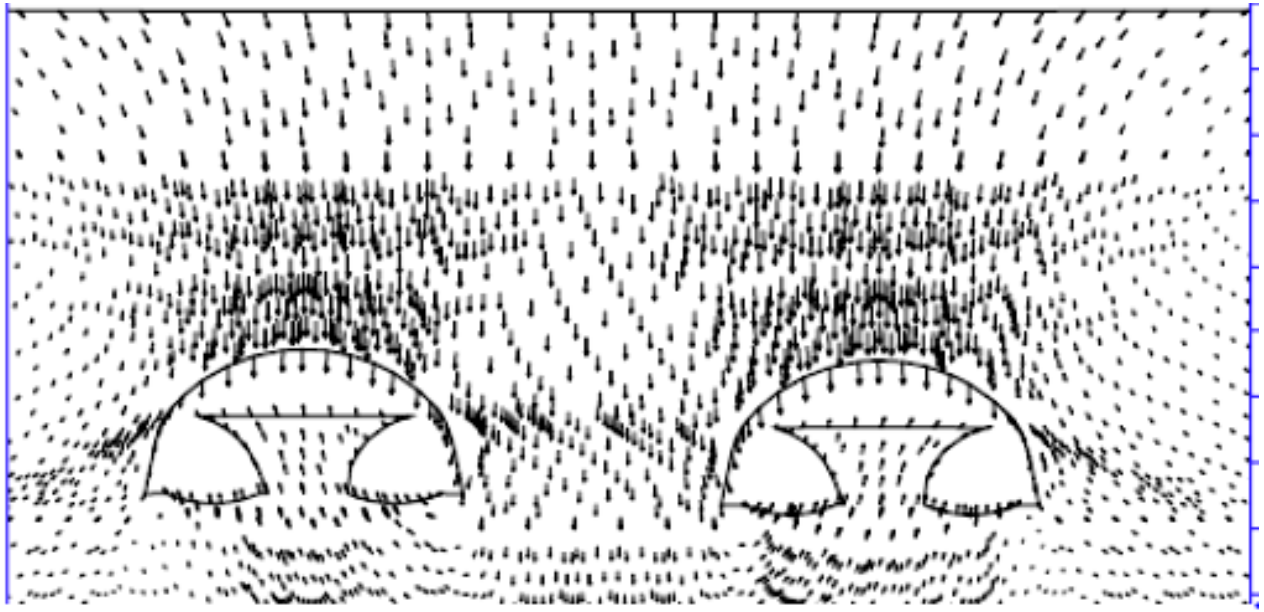
A TWIN-MOTORWAY TUNNEL

(with light, inadequate, temporary support, and *anisotropic challenges <u>from an actual rock mass</u>*)



OPTIMISTIC SYMMETRIC DESIGN, WHEN ACTUALLY SLOPING GROUND.

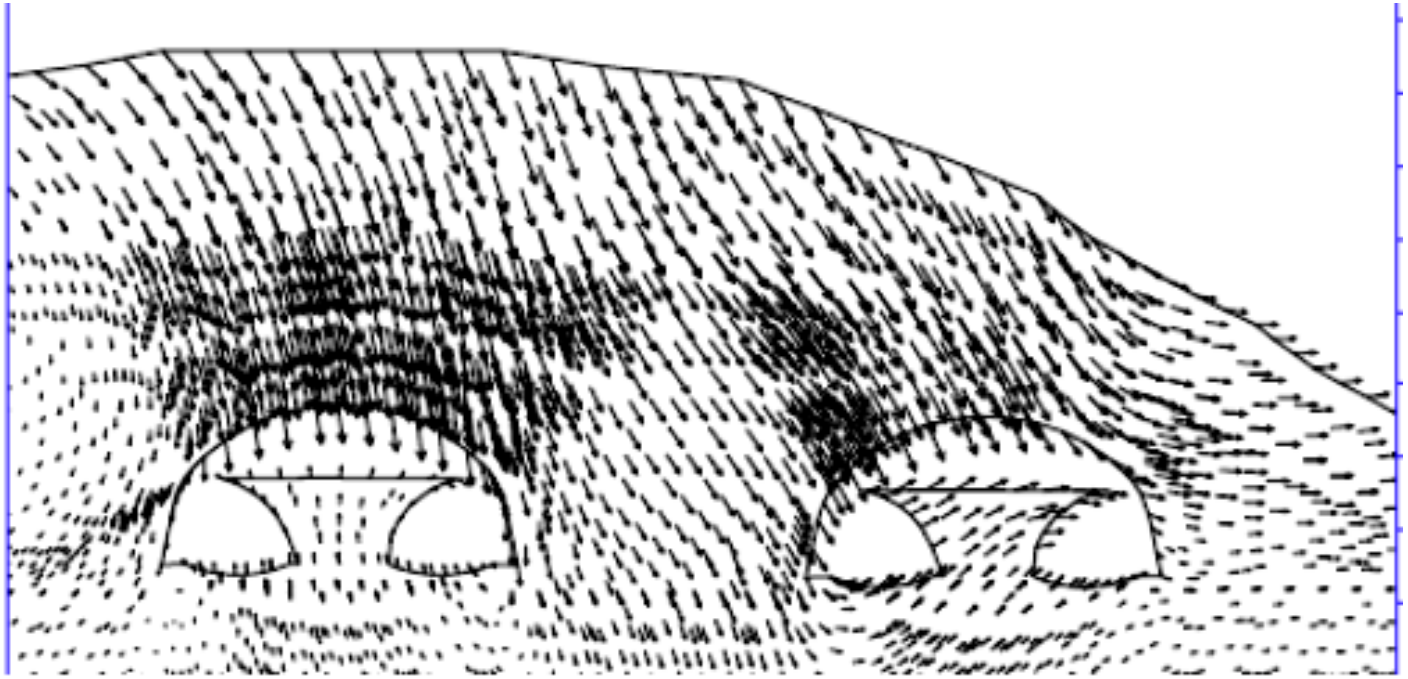
LIGHT LATTICE GIRDERS. NO BOLTS DUE TO SAPROLITE. MUCH MORE THAN SPECIFIED SHOTCRETE DUE TO OVER-BREAK.



EFFECT OF SLOPING HILLSIDE ON EQUILIBRIUM

NOT SO SIMPLE 2D 'REALITY'

(Bandis, 2015)



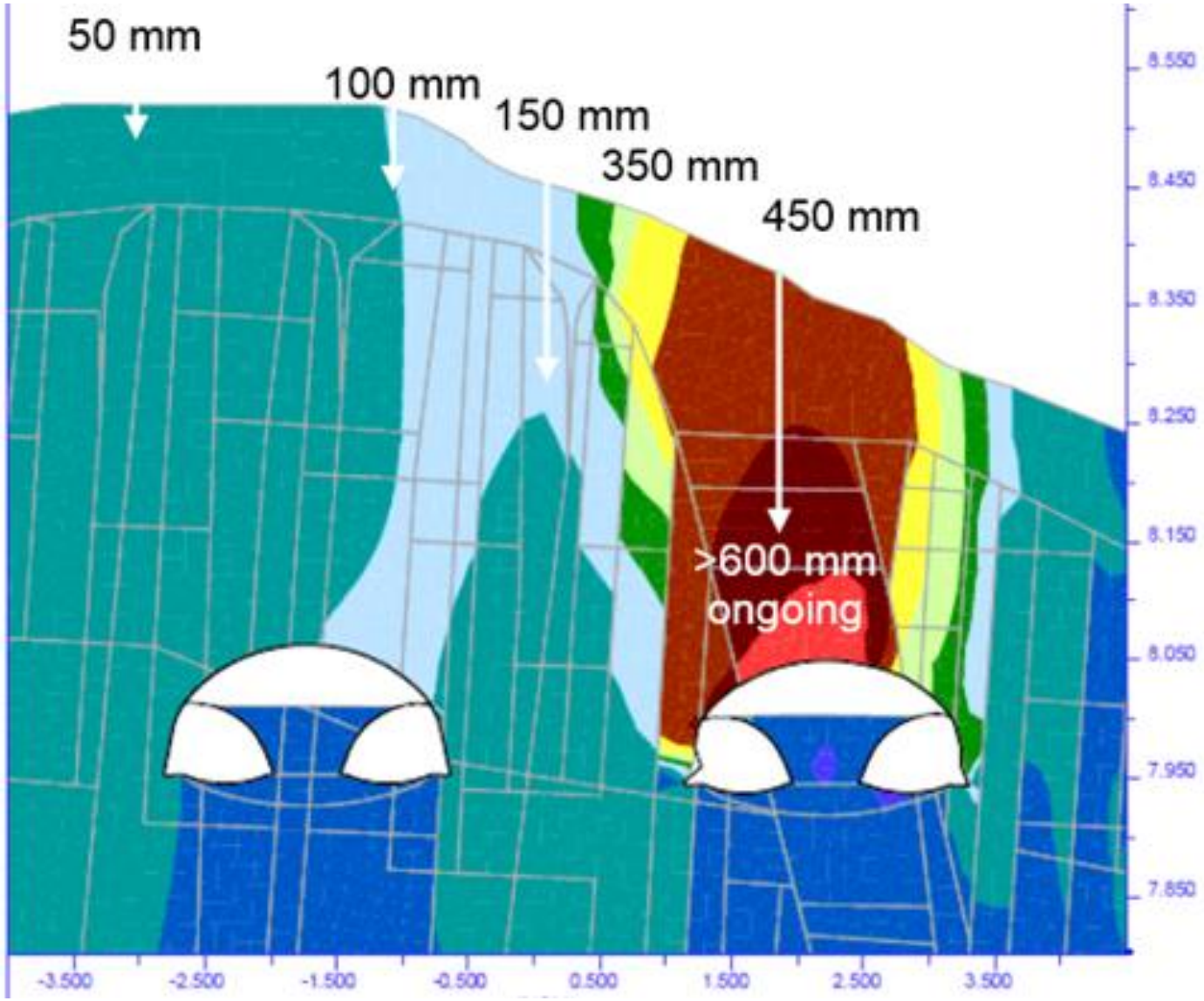
SOME OF THE TOUGH 2D ’REALITY’:

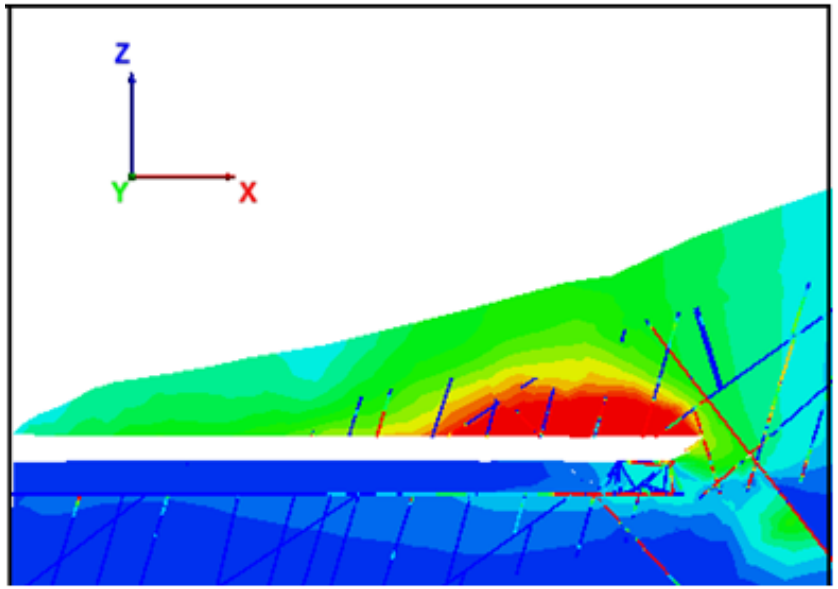
(VERTICAL STRUCTURE AND WEATHERED DIKE)

NOW INCLUDED, IN A UDEC MODEL.

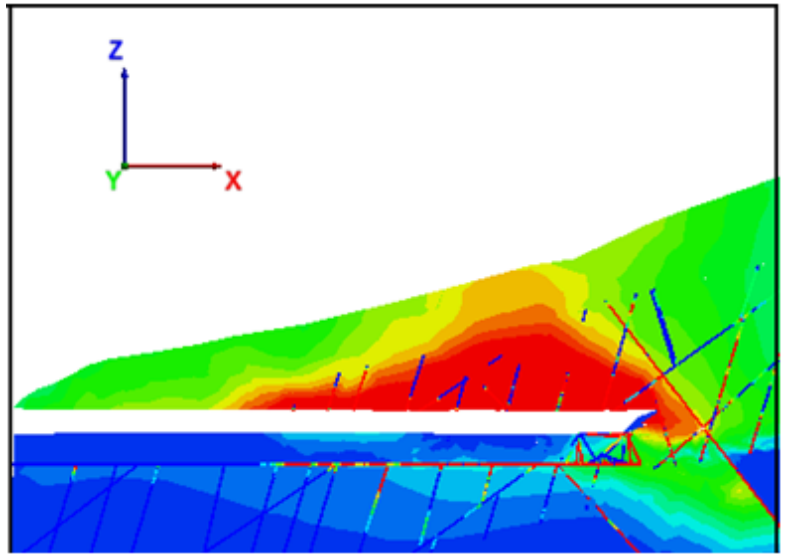
RAPID PROGRESSION TOWARDS MASSIVE FAILURE

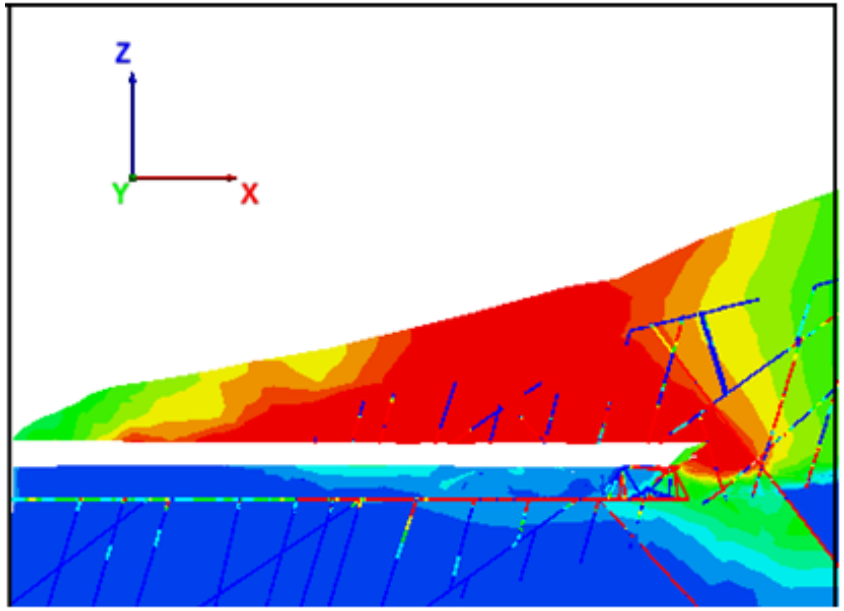
(Stavros Bandis, UDEC)





Due to limitations of the design, retrogressive failure back to the portal. 140 m of tunnel lost.





(3DEC modelling by Dr. Stavros Bandis)

ROTATED ROAD, TREES AND TELEGRAPH POLE *(after 140m failure of second tube, some months later)*

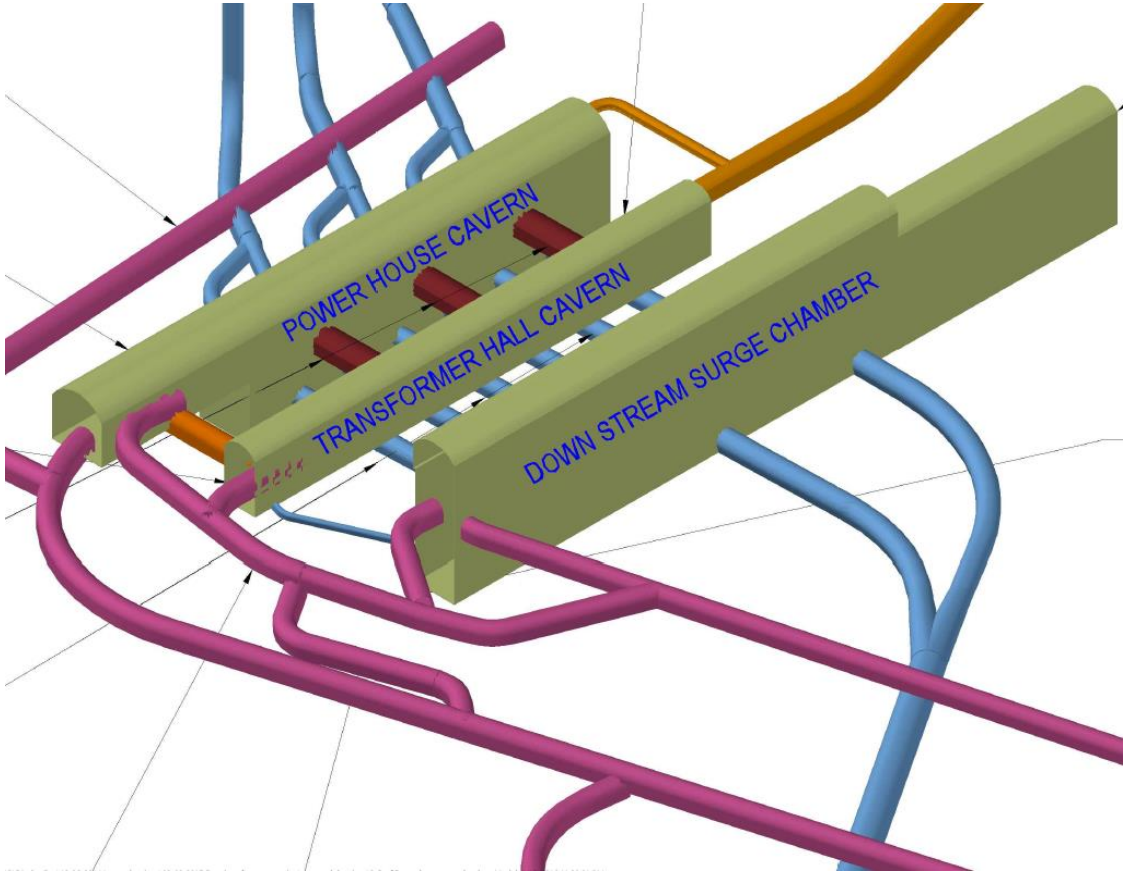
$\sum$ *FAILURE = 280m*

COLLAPSE # 2

CAVERN ARCH WITH STEEL SETS

(no change of design when encountering *fault zone on 'left' side of the arch*)

COLLAPSE IN PARTLY COMPLETED D/S SURGE CHAMBER ARCH.



- Tragically, six workers caught in the sudden collapse.
- First collapse ≈ 35,000 m3

NEW COLLAPSE. TOTAL OF 70,000 m³.

CAVITY L x H x W:
(50-60)m x (40-50)m x (30-35)m
HAS TO BE STABILIZED.

THEN VICTIMS CAN BE RECOVERED.

ATTEMPT TO REMOVE FALLEN ROCK (approx. 15,000 m³)

NOTE *(EXTRA)* DESTRUCTION OF STEEL SETS IN THE 'LEFT' ARCH.

CONCLUDING REMARKS IN THE FORM OF FIGURES / PHOTOS

(appropos reducing concrete use!)

‘Even in Austria’:

SOMEONE DECIDED TO USE ‘SINGLE-SHELL’

S(mr) + B

…..in this large machine-hall.

REISSECK II PUMPED STORAGE, AUSTRIA

(Similar decisions could/should be made about smaller tunnels?)

‘Even in England’:

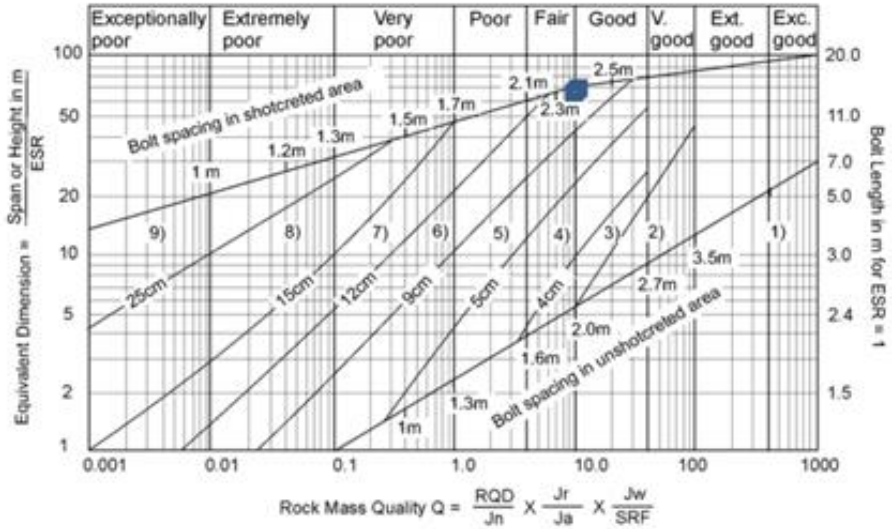
CROSSRAIL, LONDON. Stepney Green Station

40m depth, London Clay.

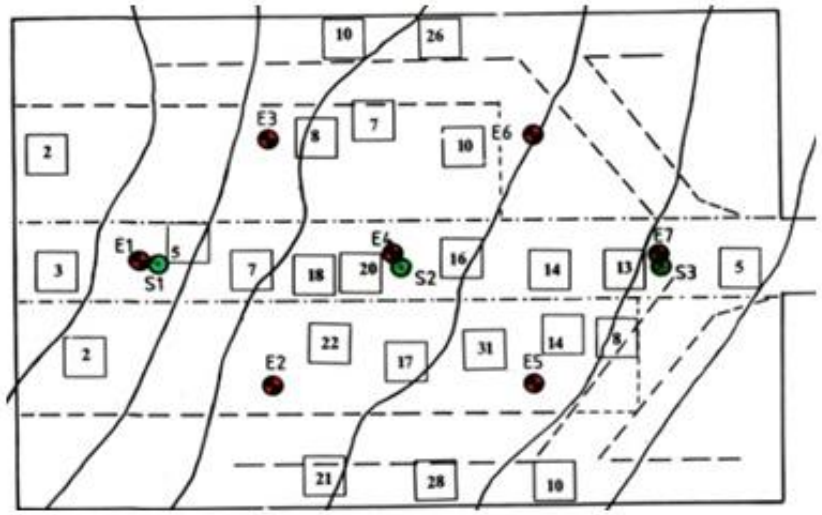
Final lining (2013) = multi-layer S(fr) (i.e.‘SCL’)

World's largest top-heading waiting for benching-down.

Mean 10 cm of S(fr). Note some over-break > 1 m.

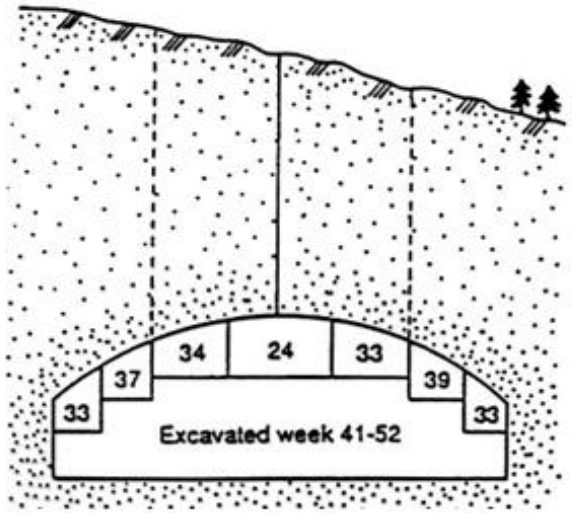


$Q_{mean} \approx 10$, span 62m. B 2.5m c/c + S(fr)10cm + cables.

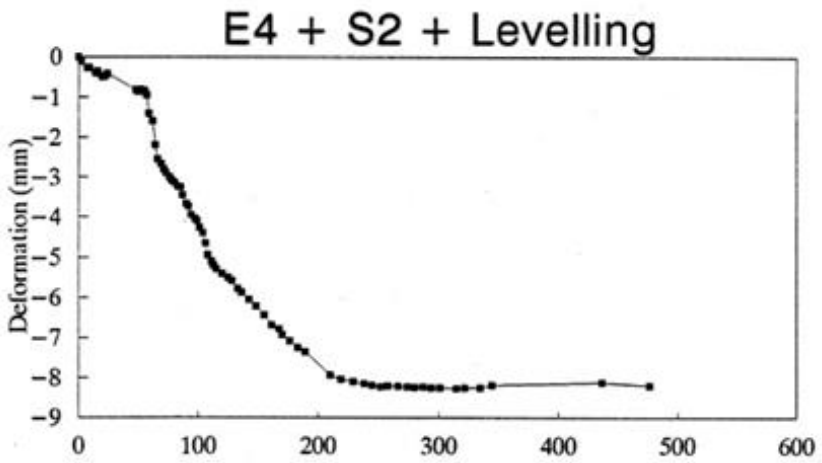


Q-values of arch (boxes): long external MPBX: in red

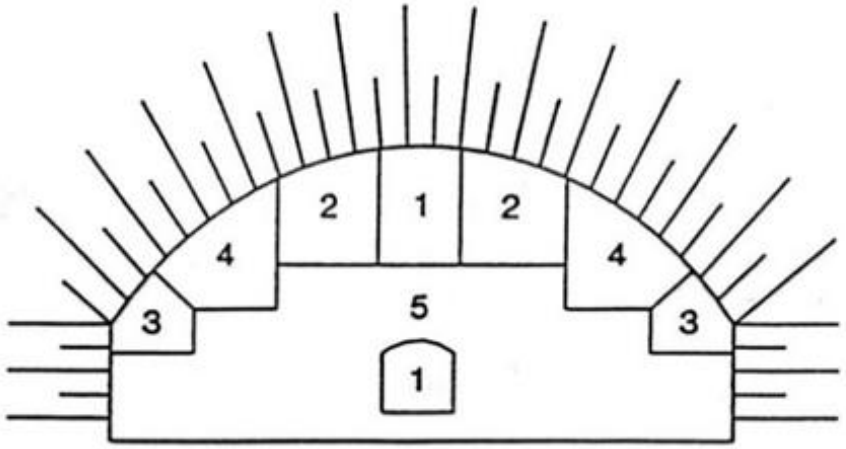
GJØVIK CAVERN
(1990-1992)



MPBX locations (three rows), excavation week in 1991.



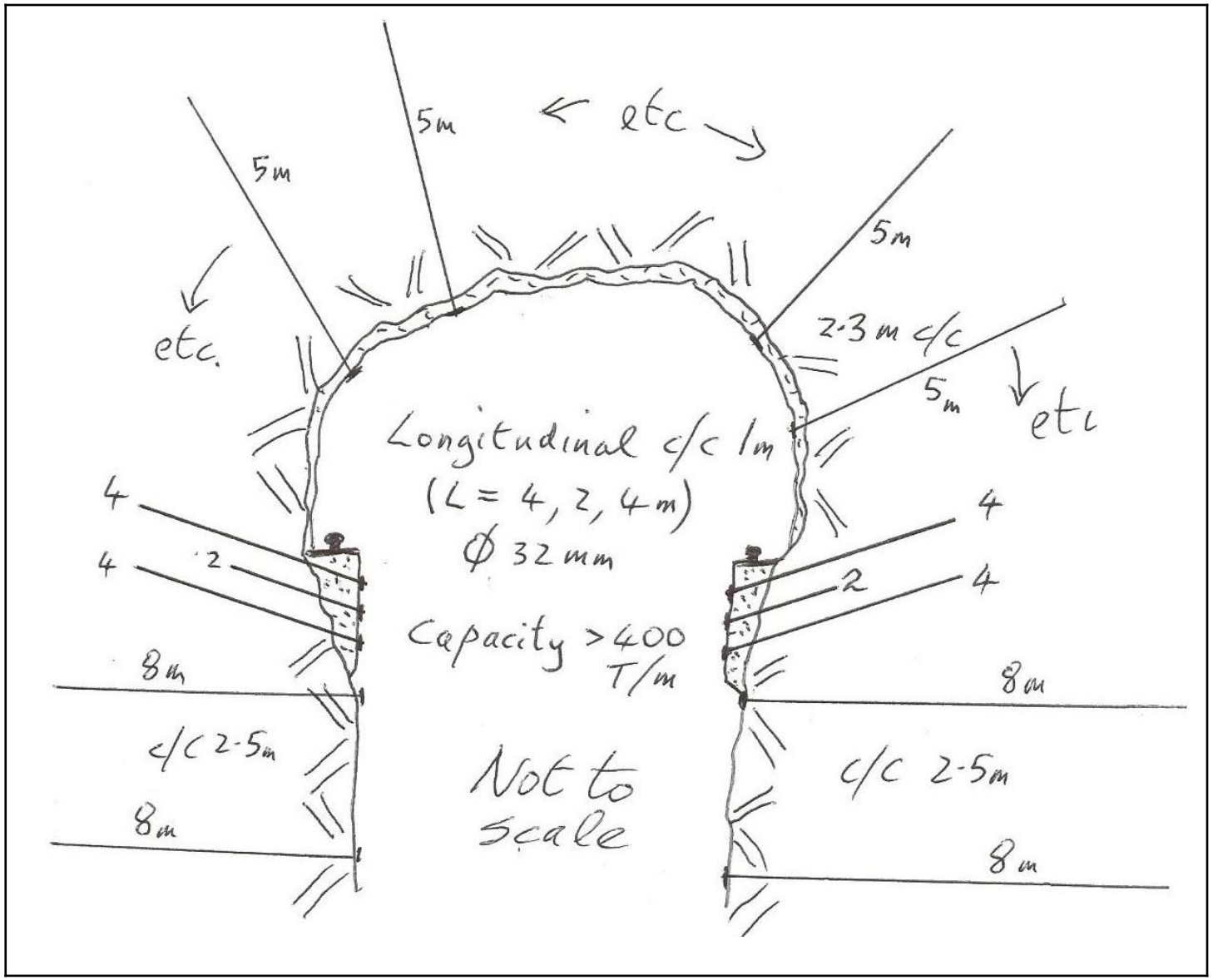
Central deformation 8 mm, ends: 7.0 mm and 7.5 mm



B 2.5m c/c L= 6m, + twin-strand anchors L=12m, c/c 5m

Early games: ice hockey in Winter Olympics of 1994.

The cavern houses 5500 spectators/ listeners/ for concerts.



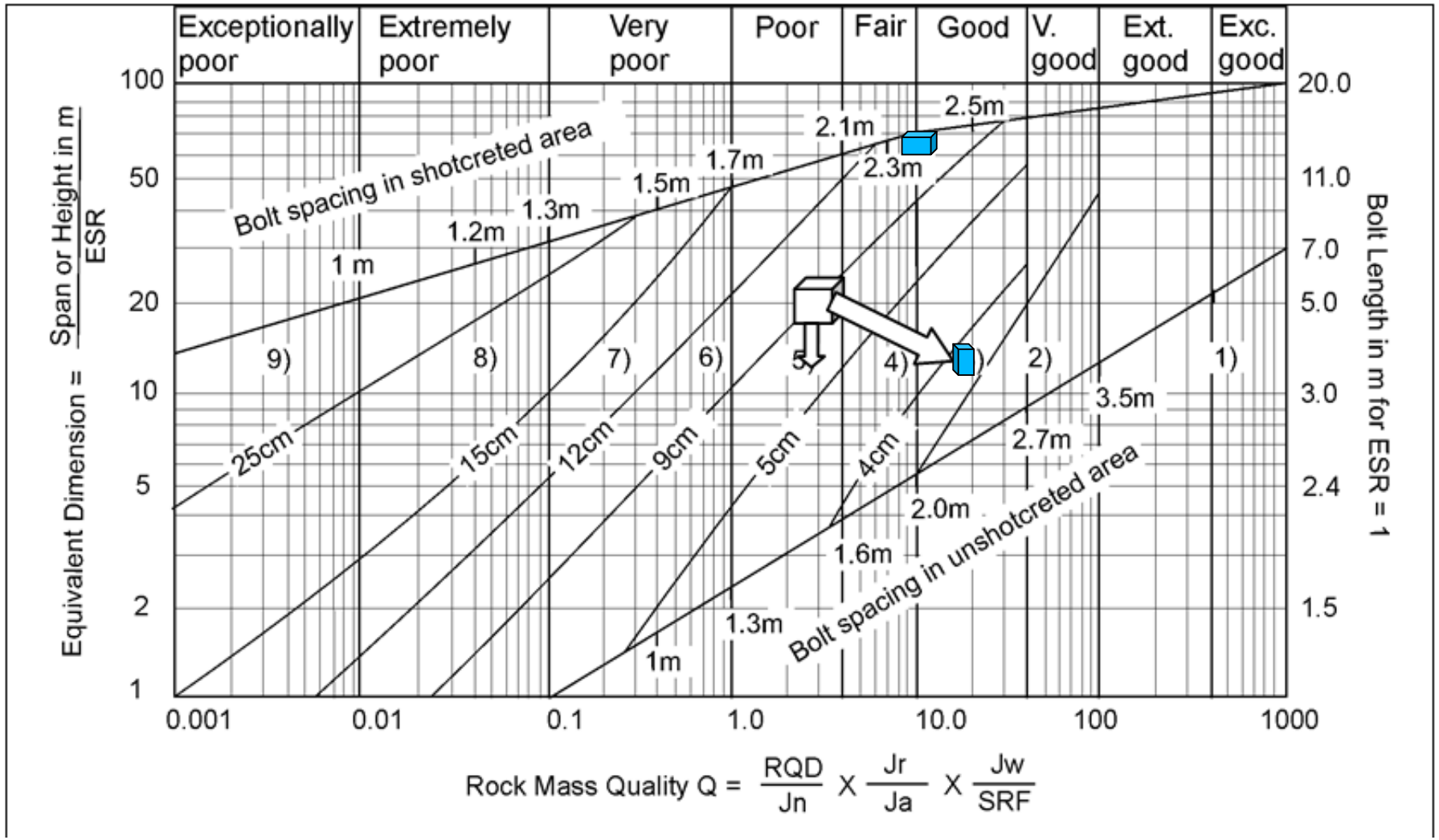
In the case of hydropower machine halls: besides use of B+S(fr), save concrete by *anchoring* crane-beams.

Avoid building ‘bridge columns’ from floor of cavern!

THOSE WHO INSIST ON NATM :
CAN USE Q FOR TEMPORARY SUPPORT SELECTION

5Q + 1.5 x ESR (Barton et al 1974)

(25 years use in HK road tunnels and metro tunnels)



CONCLUSIONS

1. NATM AND NMT TUNNELS ARE BASED ON RADICALLY DIFFERENT USE OF RESOURCES, WITH 3 x to 5 x DIFFERENCES IN CONCRETE VOLUMES.

2. NEED NOT FEAR OVER-BREAK WITH NMT. A BIGGER PROBLEM FOR NATM.

3. WELL-EXECUTED PRE-INJECTION IS MORE RELIABLE THAN 'MEMBRANES'.

4. BEWARE OF RISKS IN THE 'LATTICE-GIRDER' STAGE OF NATM.

5. IN NMT (AND NATM) PRELIMINARY SUPPORT SHOULD BE APPROPRIATE TO THE ROCK CONDITIONS *AS LOGGED ON SITE (not pre-conceived and uniform).*

6. WITH NMT AND Q-SYSTEM, FINAL SUPPORT ALSO MATCHES THE ROCK.