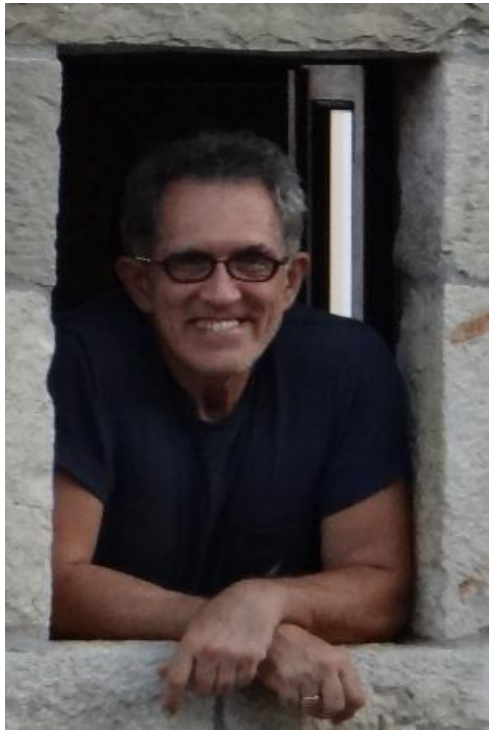
ROCK AS THE CONSTRUCTION MATERIAL FOR TUNNELS

Nick Barton, NB&A, Norway

COOPERATION WITH THREE SPECIAL COLLEAGUES



STAVROS BANDIS
(Greece)

EYSTEIN GRIMSTAD
(Norway)

BAOTANG SHEN
(Australia)

SHALLOW STATION CAVERN (TEMPORARY)

OLD WEST-COAST ROAD TUNNEL (PERMANENT)

THE ROCK IS CLEARLY THE ‘STABILIZING’ / LOAD-BEARING MEDIUM.

- TANGENTIAL STRESS IN THE ARCH

ROCK AS THE CONSTRUCTION MATERIAL:

INVESTIGATED UNDER FOUR HEADINGS

1. FRACTURING OF INTACT ROCK (usual challenge is high stress/ fracturing/rock bursting?)

2. JOINTED ROCK (2a. Arching and over-break, 2b. NMT and over-break 2c. Control of water in NMT and NATM, 2d. Lattice girders, steel sets, RRS

3. LESSONS FROM TWO DRAMATIC FAILURES

4. FAULTED ROCK (delays to TBM, deceleration ***-m***)

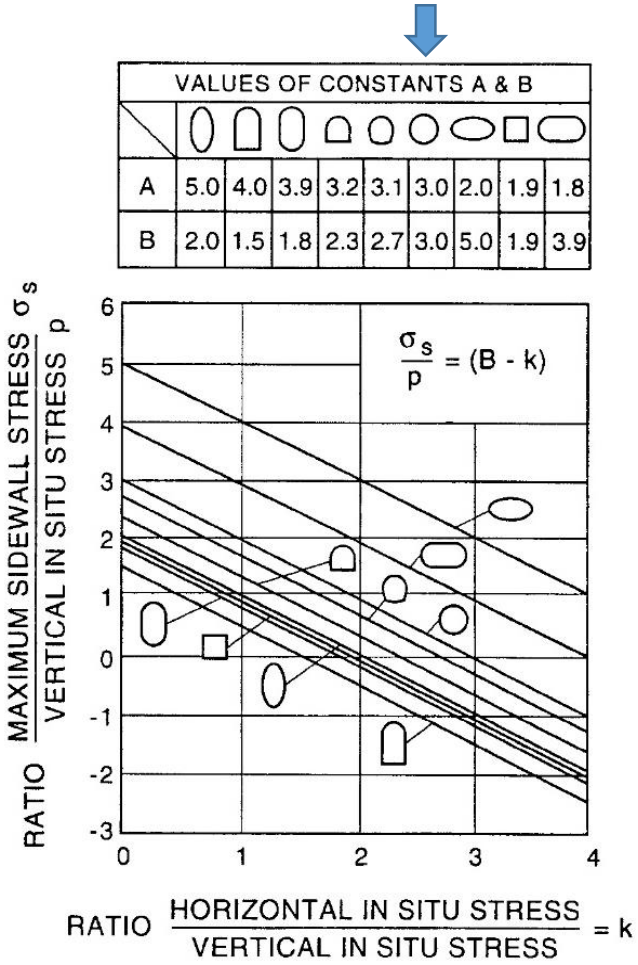
CONCLUSIONS

1. INTACT ROCK

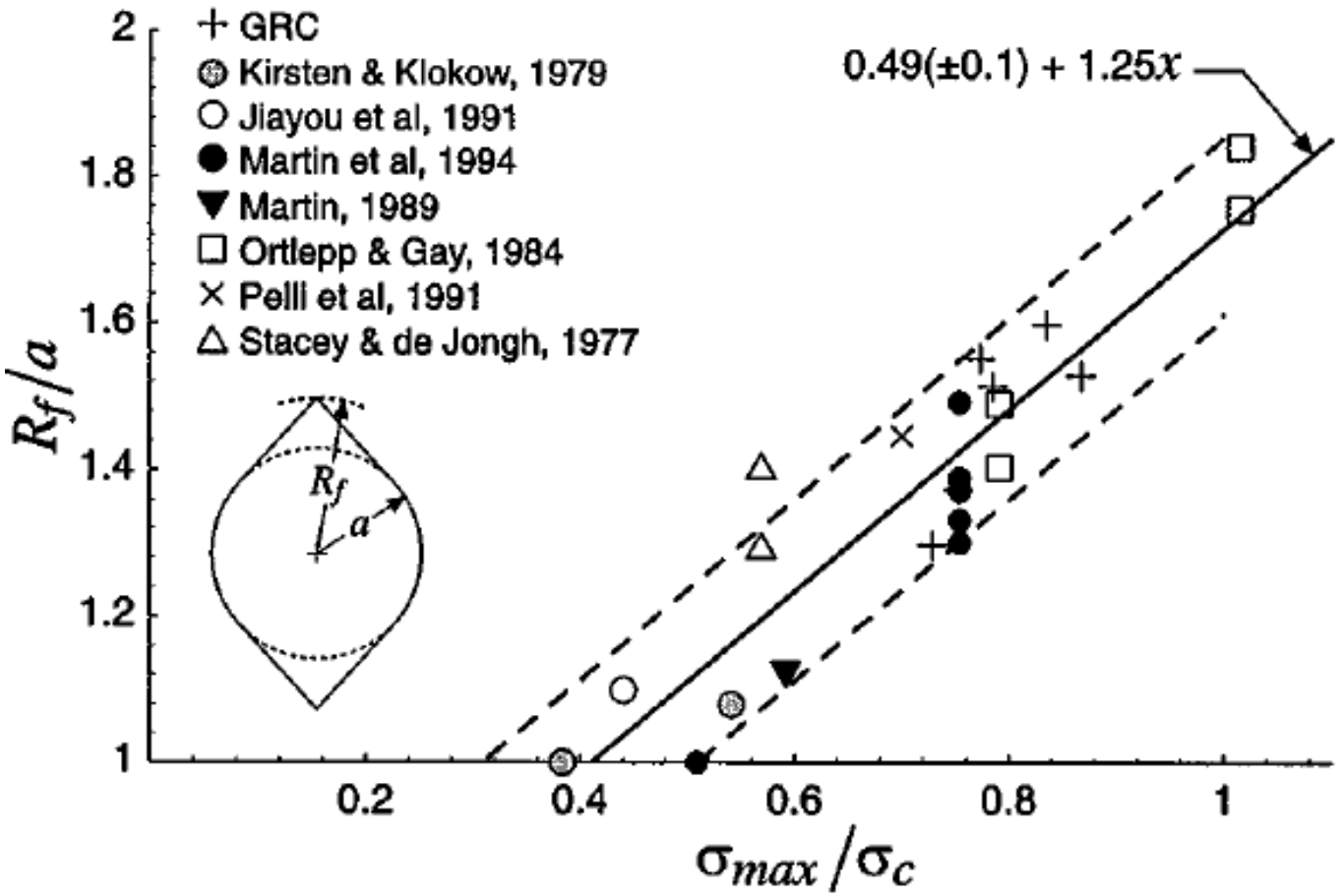
(i.e. massive rock)

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)

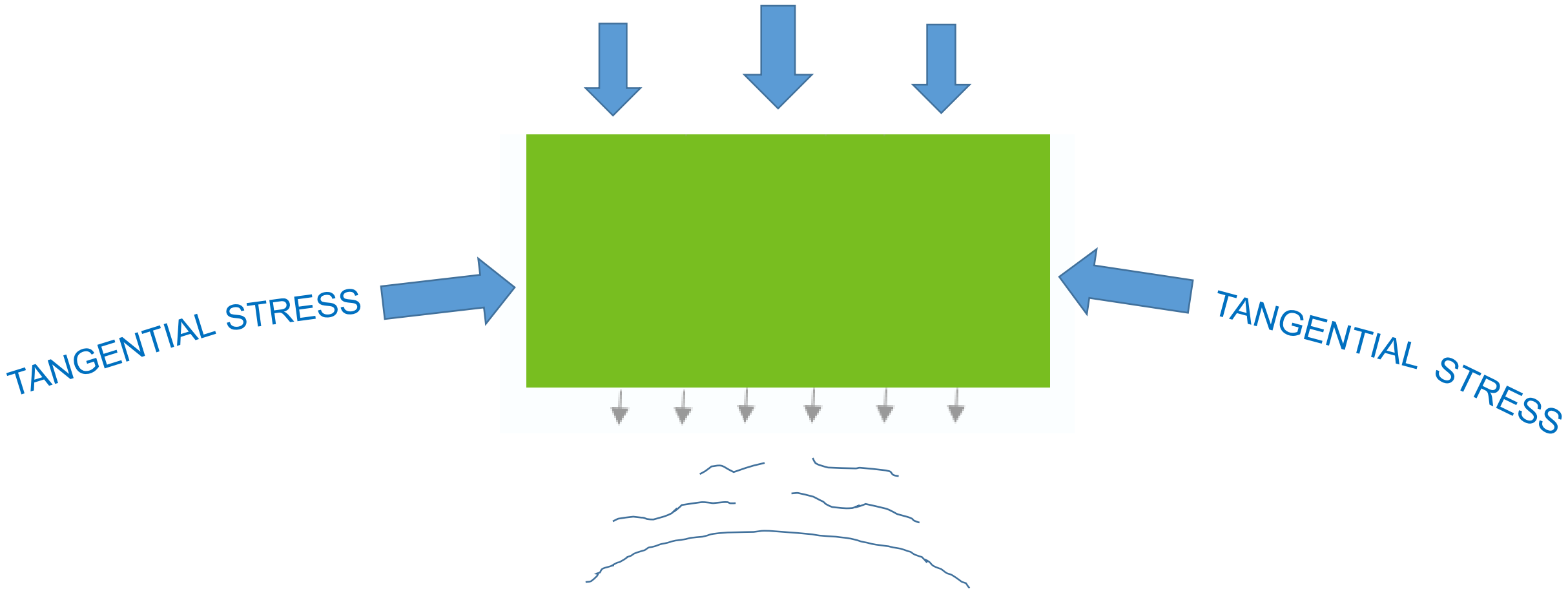
IN Q-SYSTEM, SAME EXPECTATION. If $\sigma_{\theta\,max}/\sigma_c > 0.4$, get: high SRF – and lower Q-value – more tunnel support.

(σ_c = UCS unconfined compression strength)

(Table 6b of Grimstad and Barton, 1993)

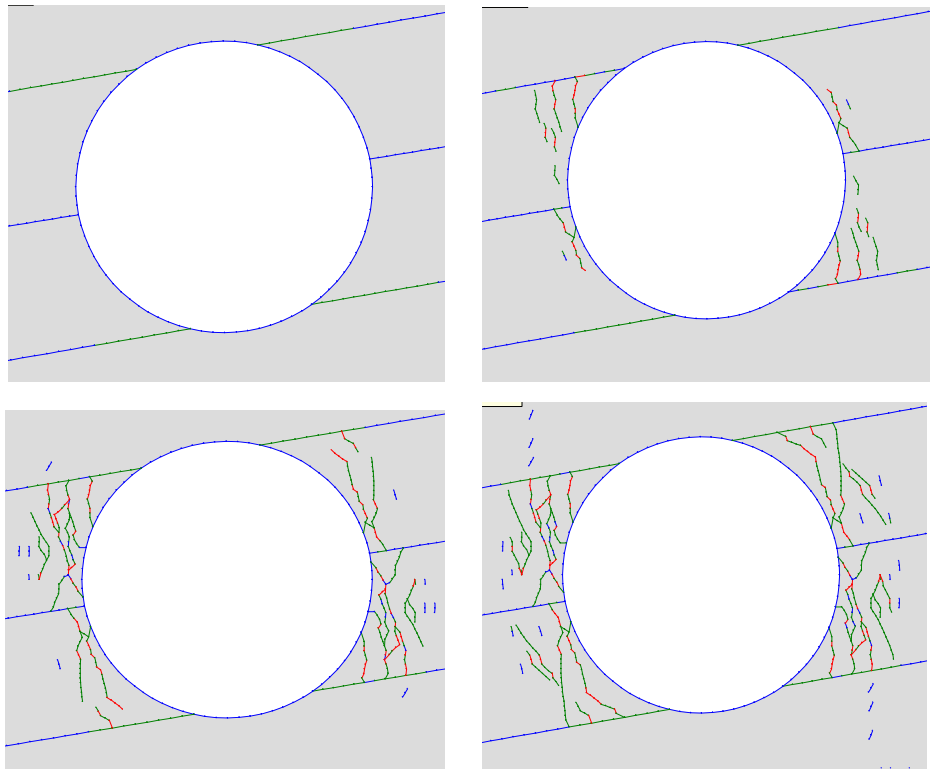
b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c	SRF
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	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

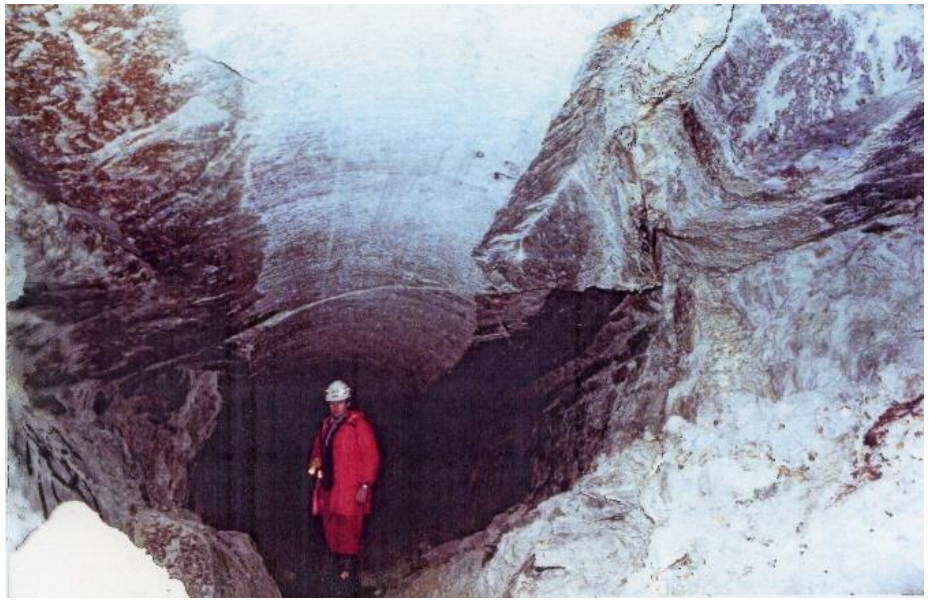
AROUND A TUNNEL: **Poisson's ratio** causes lateral strain



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:

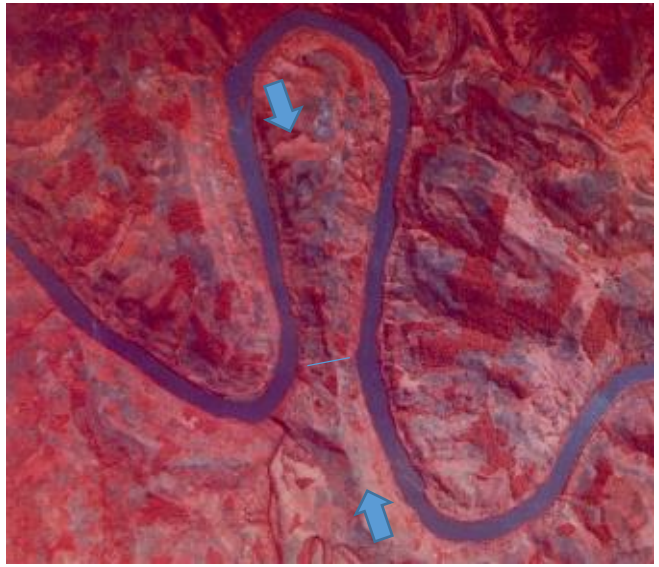
(Not 'compression' failure)

(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:)

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



HYDRO-ELECTRIC PROJECT:
ALL (10) TUNNELS (and spillway) SUFFERED ***EXTENSION CRACKING***.

$\sigma_{\theta\ max}$/UCS ≈ 0.65-0.7
(from 2.5-3m break-out)
($\sigma_{\theta\ max}$ ≈ *130-140MPa)*

UCS OF BASALT ≈ **200 MPa**)

(BUT CRITICAL $\boldsymbol{\sigma_t/\nu}$ ≈ 20/0.25 ≈ *80MPa*. THIS WOULD BE START OF ***ACOUSTIC EMISSION, (i.e. 'POPPING') AND EXTENSION CRACKING***)

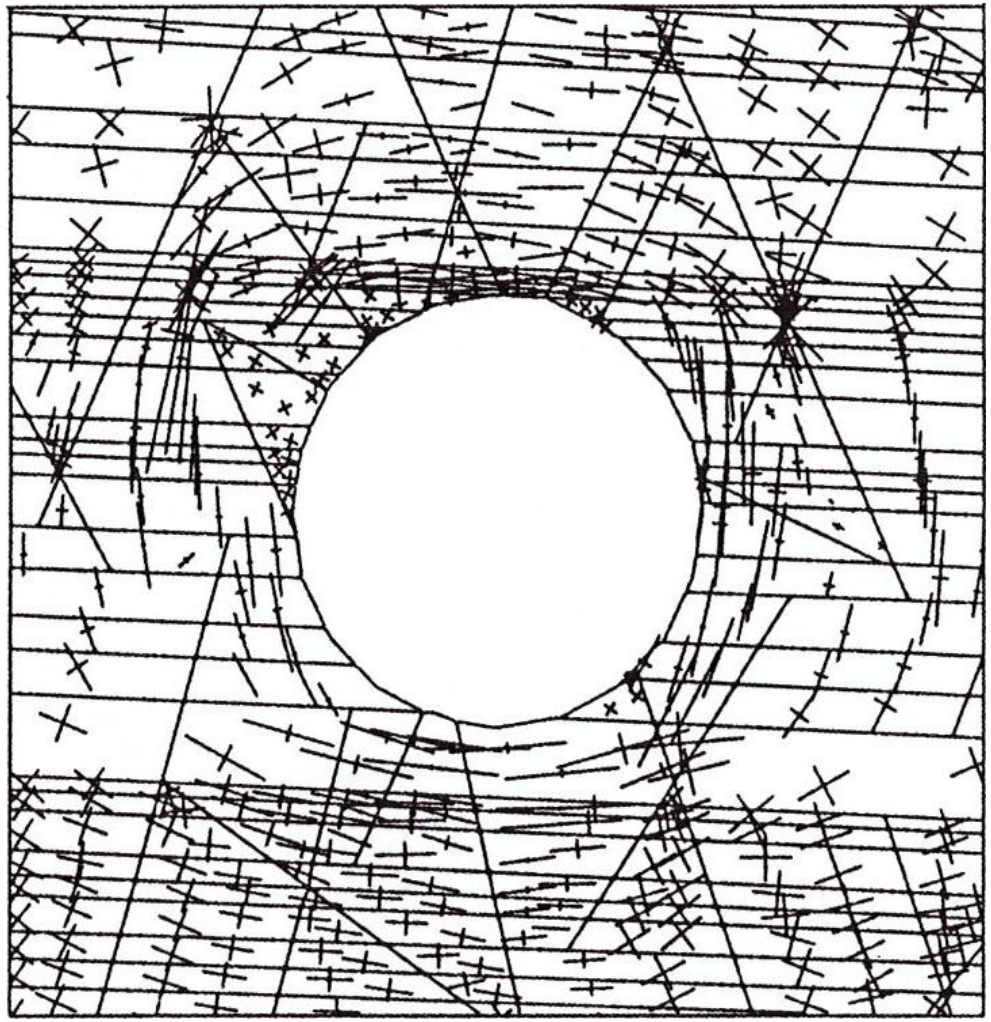
EXAMPLES OF STRAIN-INDUCED ***CRACKING AND BURSTING. JINPING I, CHINA***

INSUFFICIENT UCS IN RELATION TO DEPTH (Max. up to 2.5 km)

TANGENTIAL STRESS CAUSES ***TOO MUCH EXTENSION STRAIN: DYNAMIC SHEARING, BURSTING.***

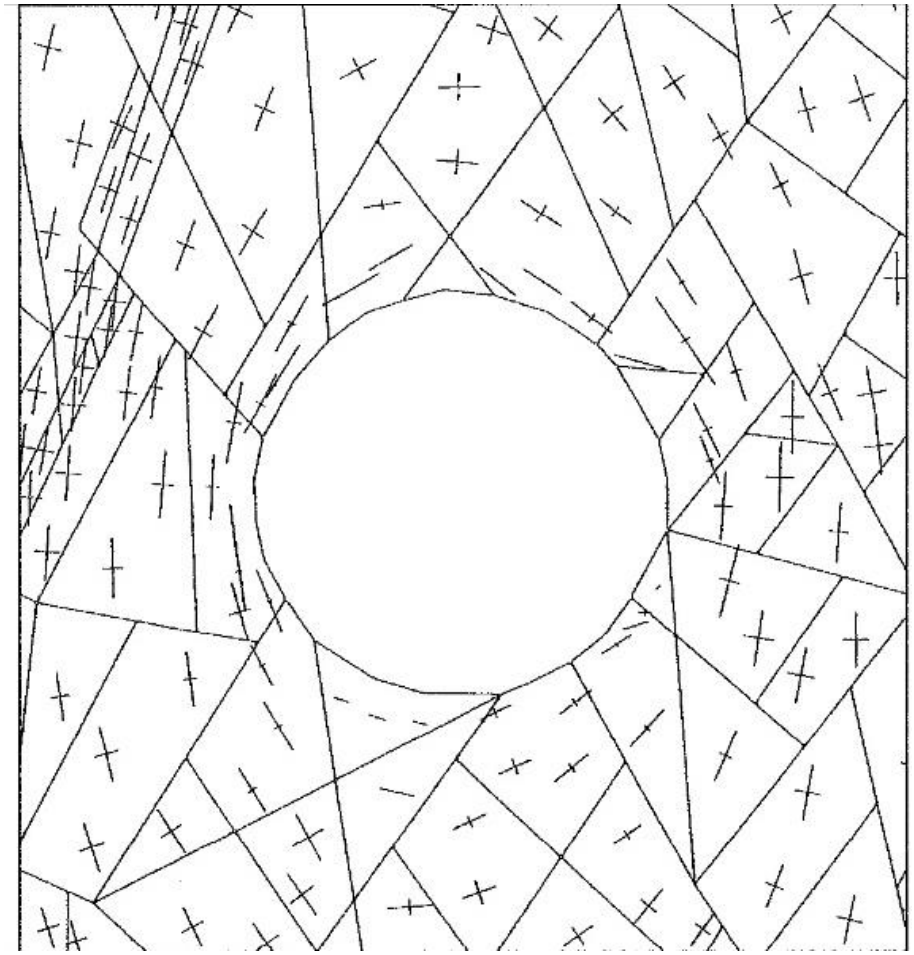
2a. JOINTING
(arching and over-break)

ILLUSTRATES ***'ARCHING' STRESSES*** AND THE EFFECT OF JOINTS



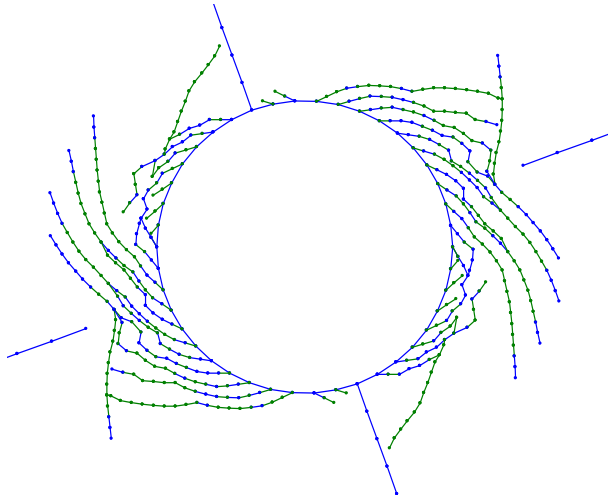
NGI STUDIES OF TBM ACCESS RAMP FOR UK NIREX

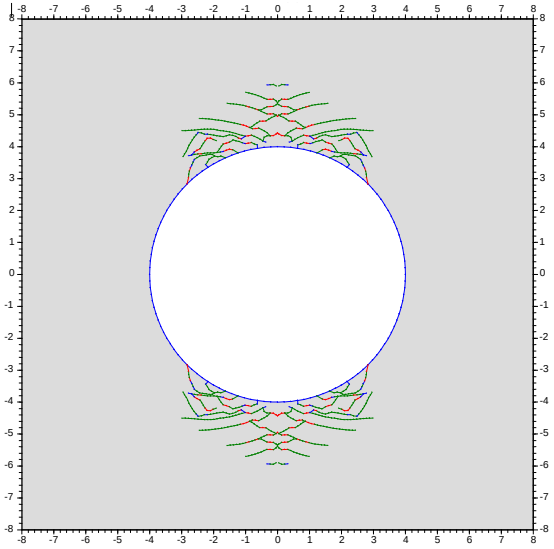
(Chryssanthakis 1991 and Hansteen 1991)

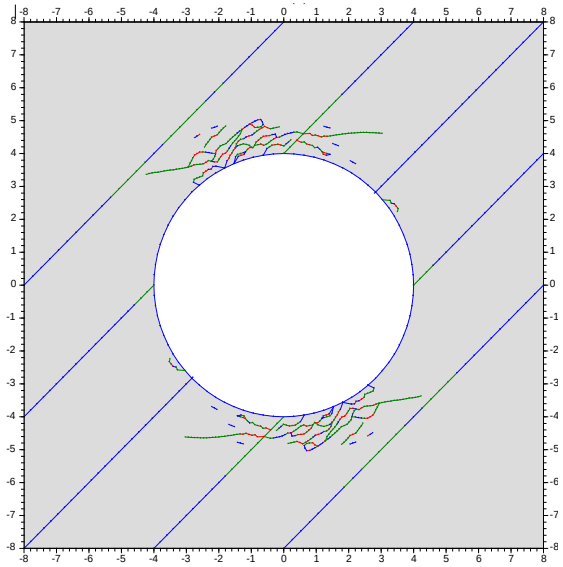


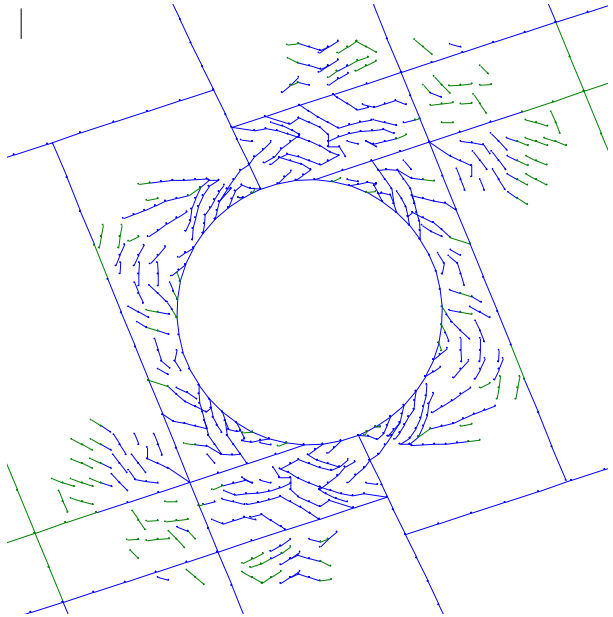
THE DESIRABLE PRESENCE OF JOINTING IF ‘TOO’ MASSIVE ROCK

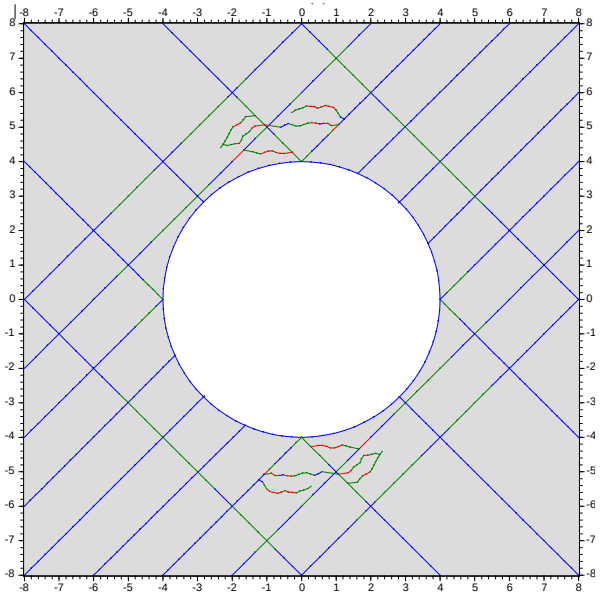
(HELPS TO DISSIPATE FRACTURING THAT STARTS WITH EXTENSION *STRAIN*





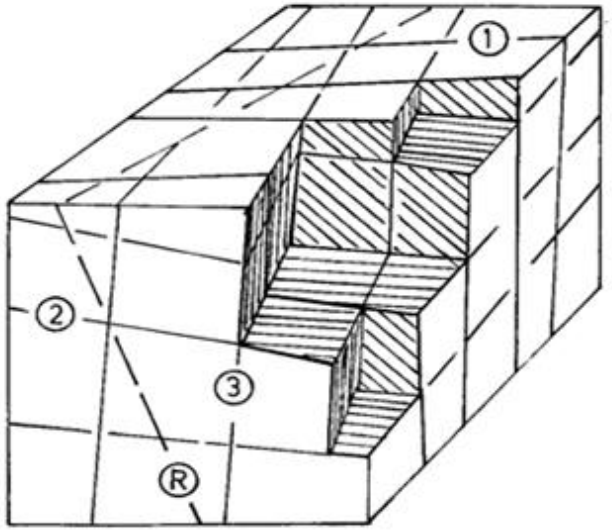


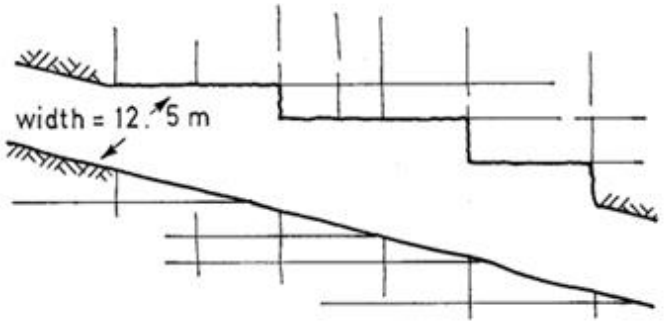


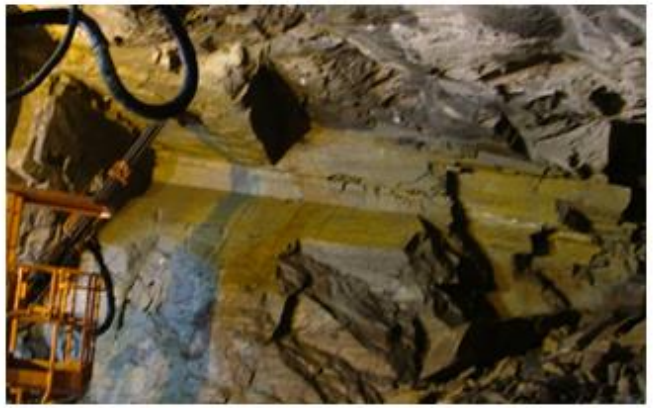


(FRACOD modelling by Shen, 2007, see Barton and Shen, 2017)

INTRODUCTION TO ***OVER-BREAK*** – CAUSED BY JOINTING







OVERBREAK IF Jn/Jr ≥ 6

Jn = number of sets

Jr = roughness

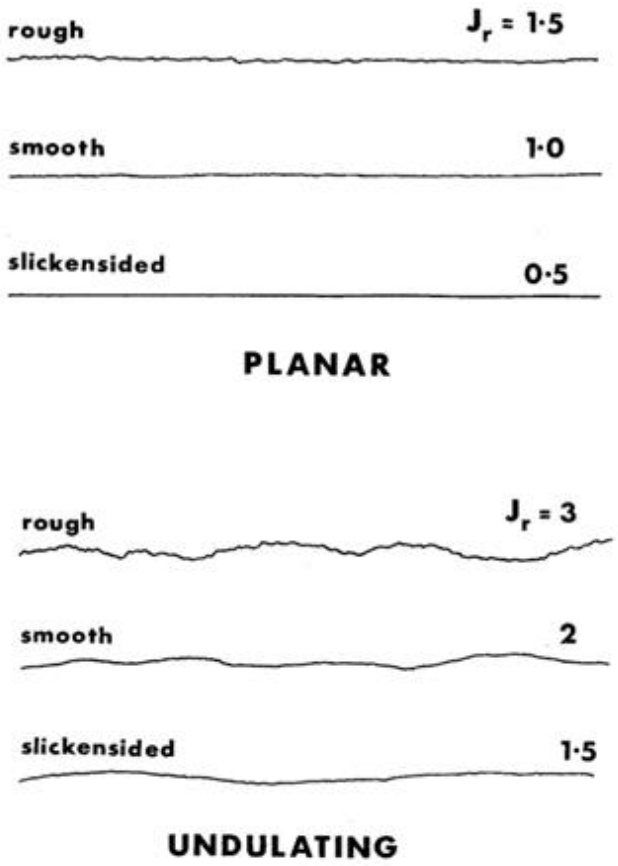
6/1.0 9/1.5

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:

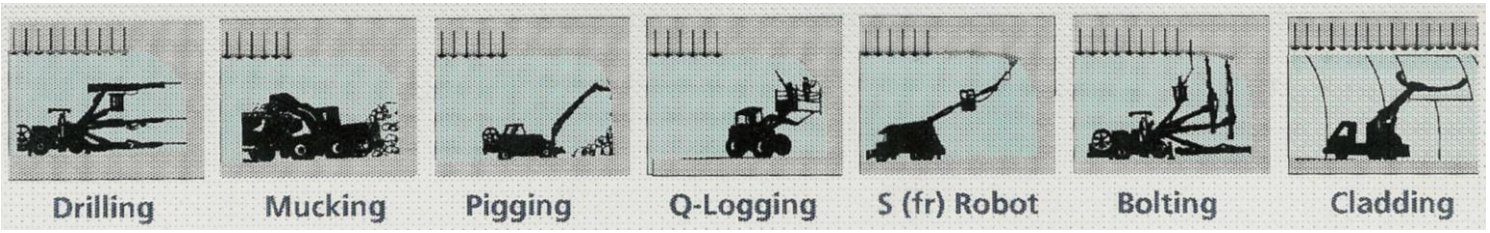
***Jn/Jr* ≥ *6* HAS BEEN USED IN SEVERAL RECENT METRO CLAIMS!**

Barton, 2007.

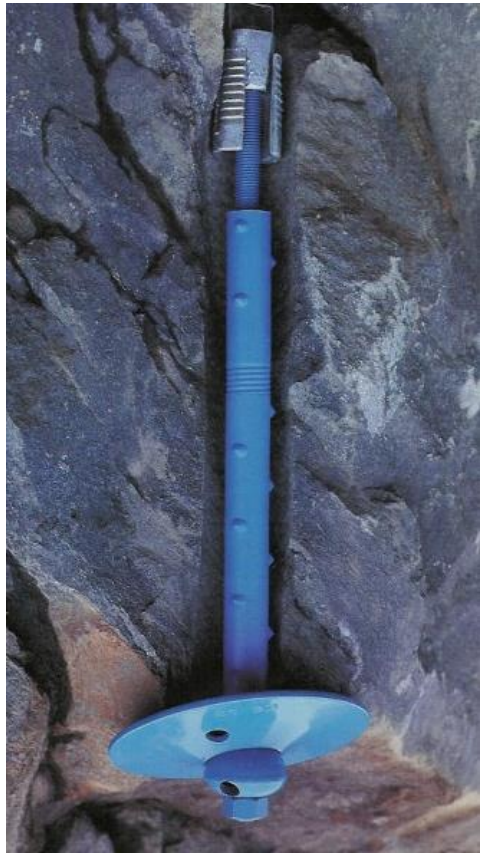
2b.

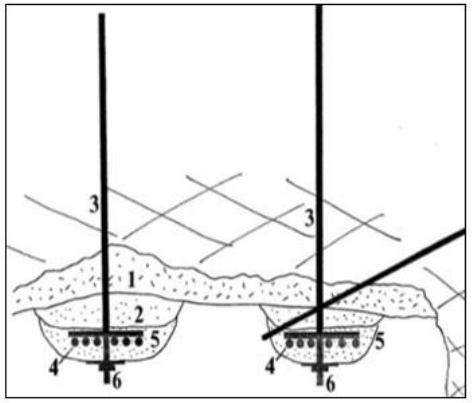
NMT and over-break

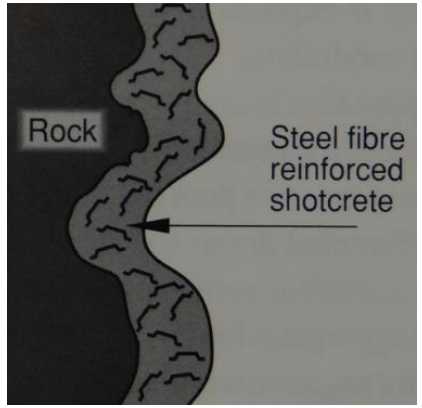
NMT OPERATIONS: in summary



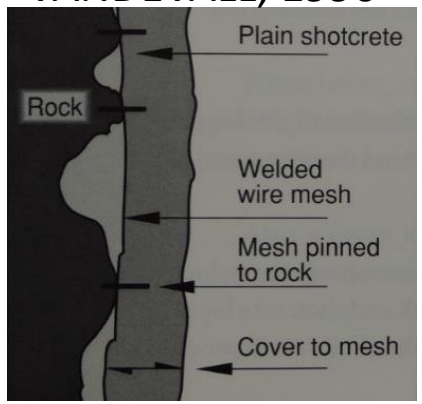
APPROPRIATE SUPPORT



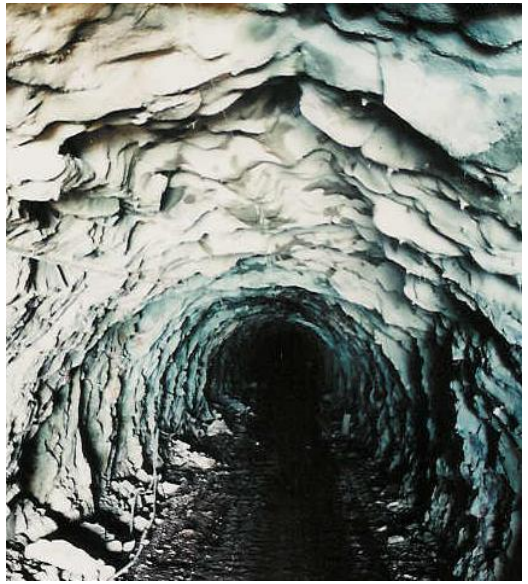




VANDEVALL, 1990

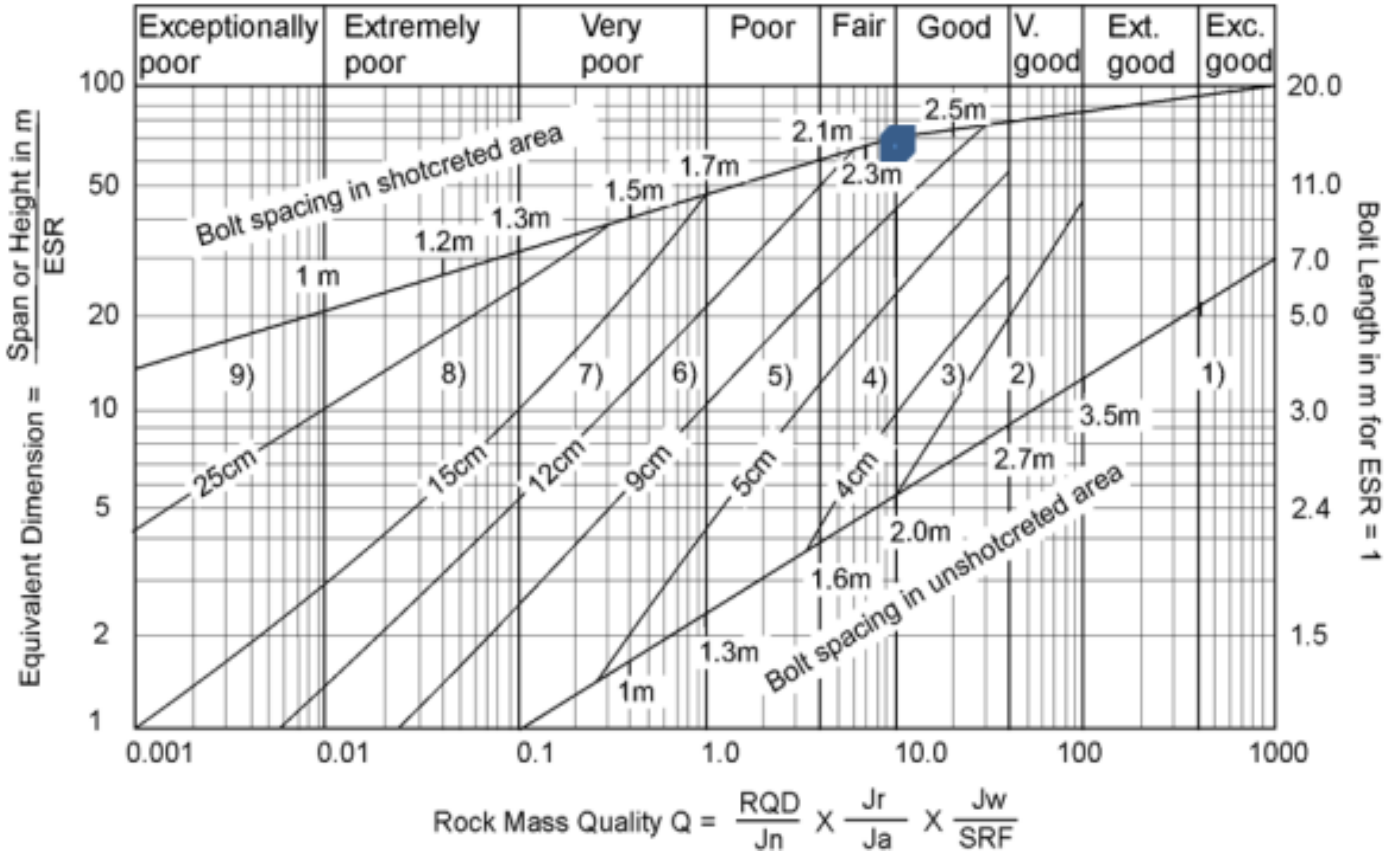


S(fr) PREFERRED TO S(mr)….. IN THE LAST 35 YEARS of NORWEGIAN TUNNELLING



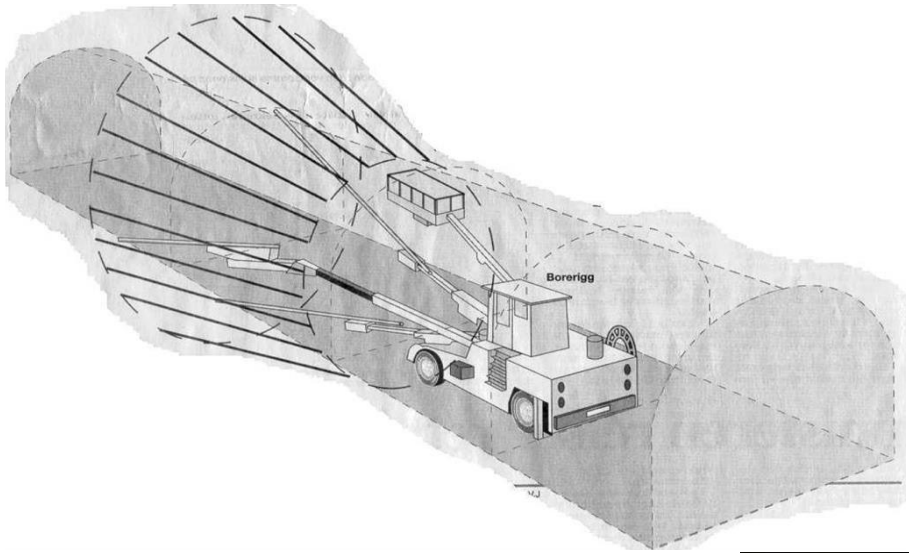
GJØVIK CAVERN ARCH WITH 10cm S(fr) AND ≤ 1m OF OVER-BREAK

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



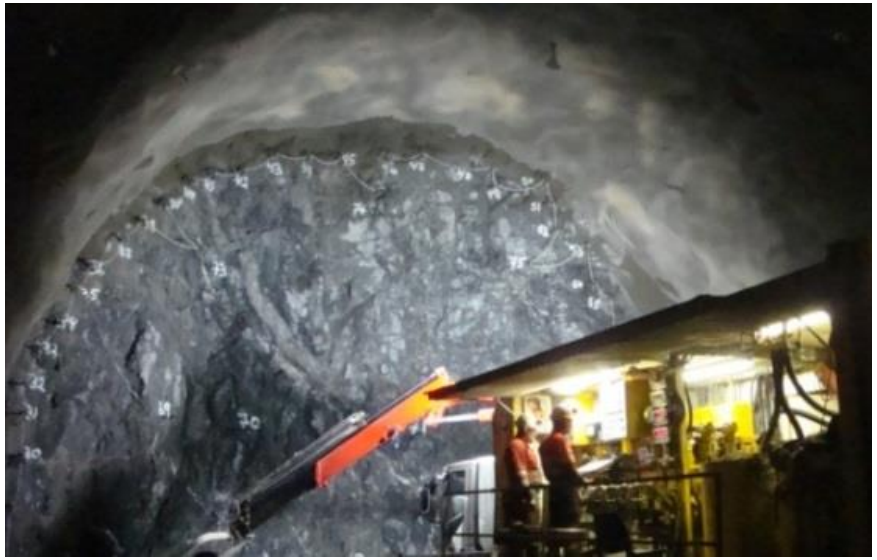
2c. CONTROL OF WATER

(IN NMT and NATM)



PRE-INJECTION:

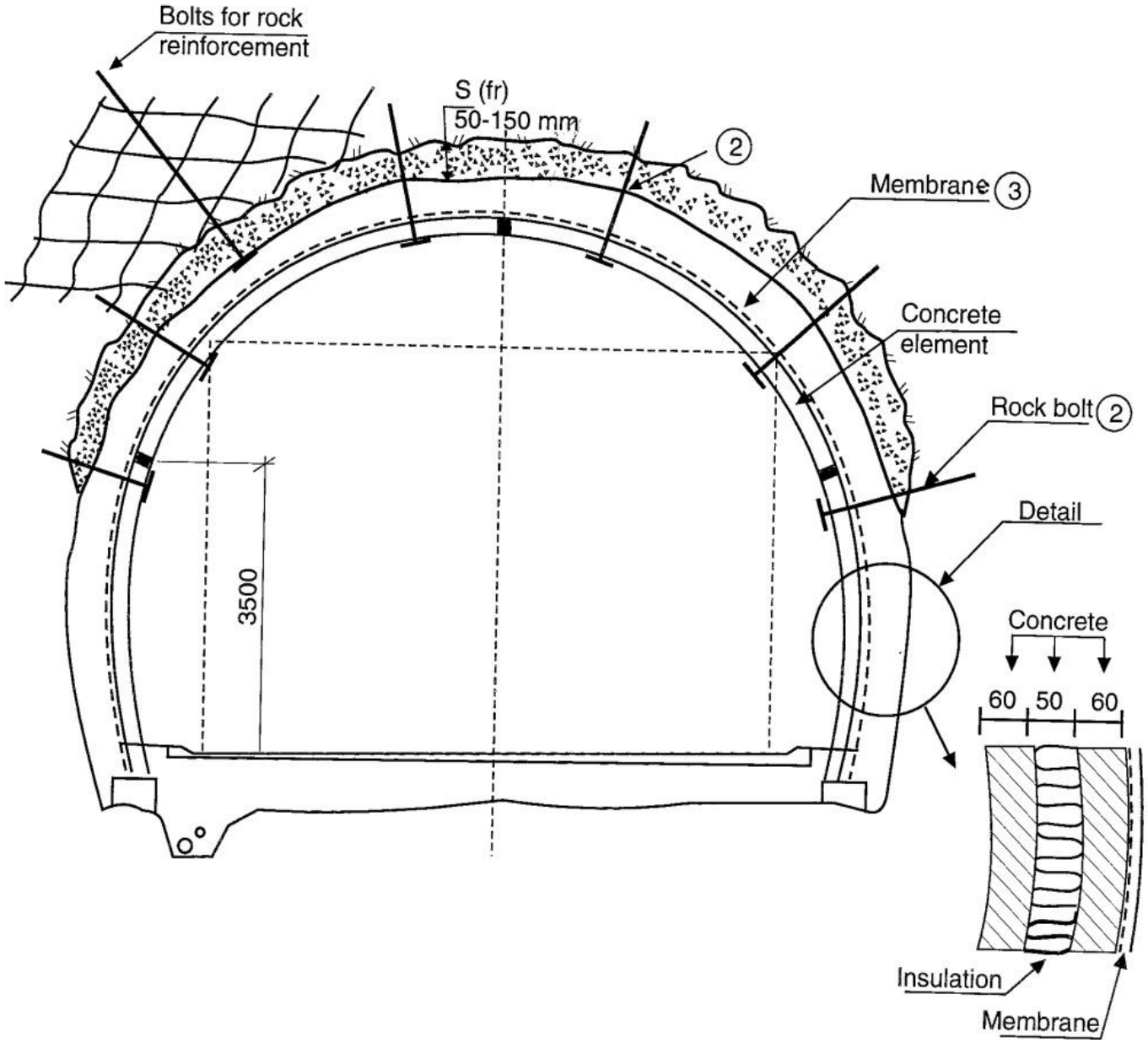
AN IMPORTANT COMPONENT OF NMT, WHICH INCREASES THE (LOW) COST BY ABOUT 20% (IF CHOSEN).

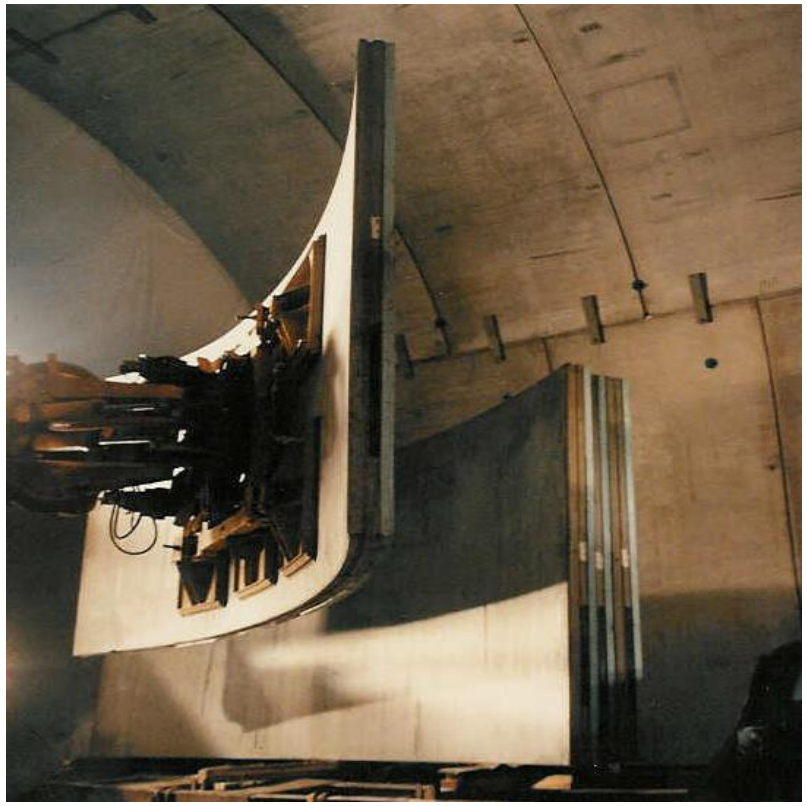


24-30 hours for all hole-drilling and injection per ‘umbrella’ screen.

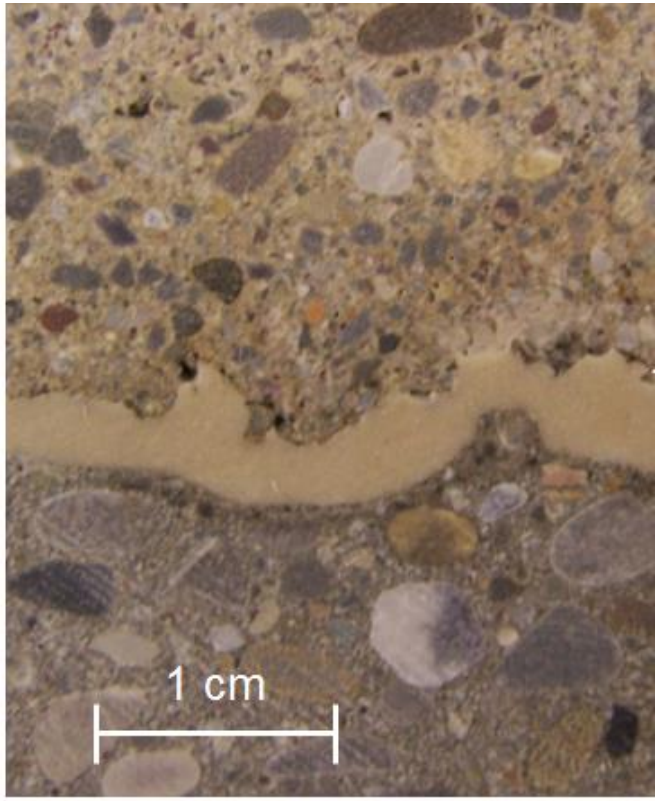
AN ALTERNATIVE TO PRE-INJECTION:

PC-ELEMENTS WITH OUTER MEMBRANE

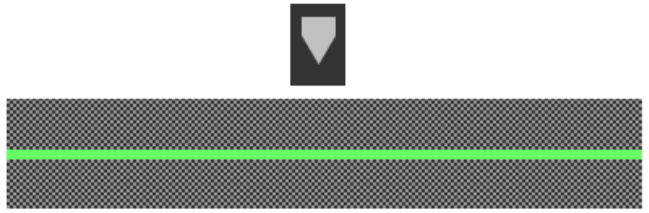




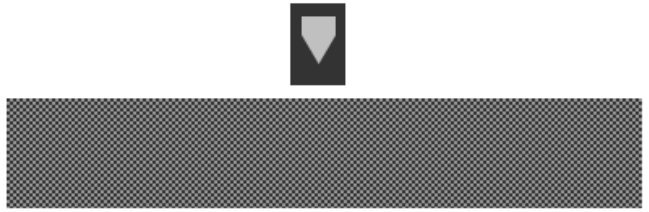
Kveldsvik and Karlsrud, 1996

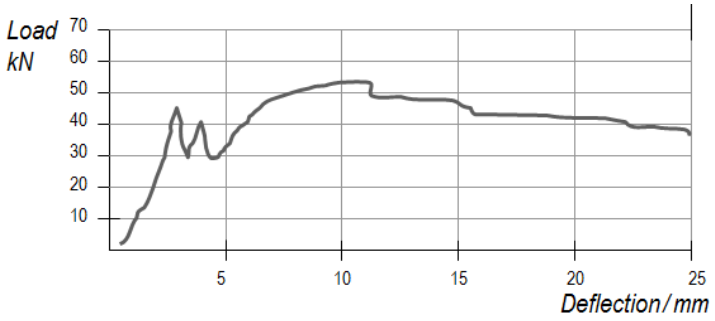


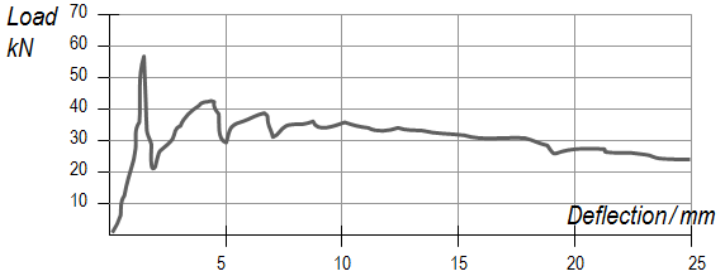
1. Sprayed concrete with 3mm membrane, reinforcement: structural pp-fibres



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)

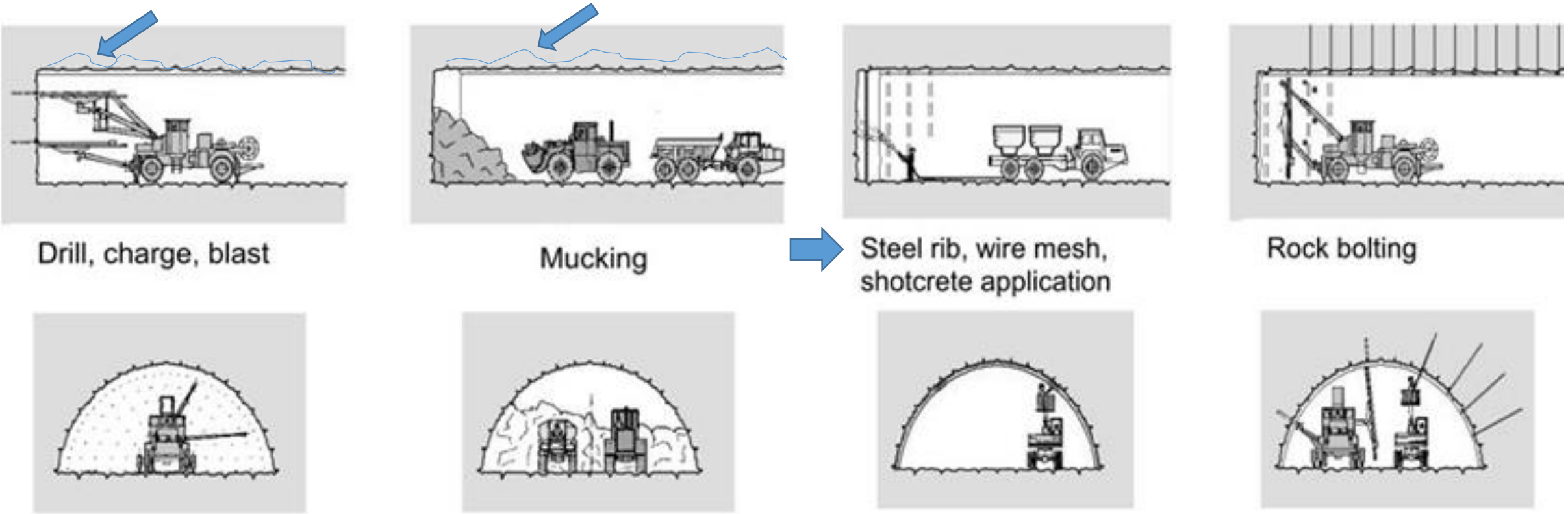
Holter and Nymoen, 2009.

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).

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

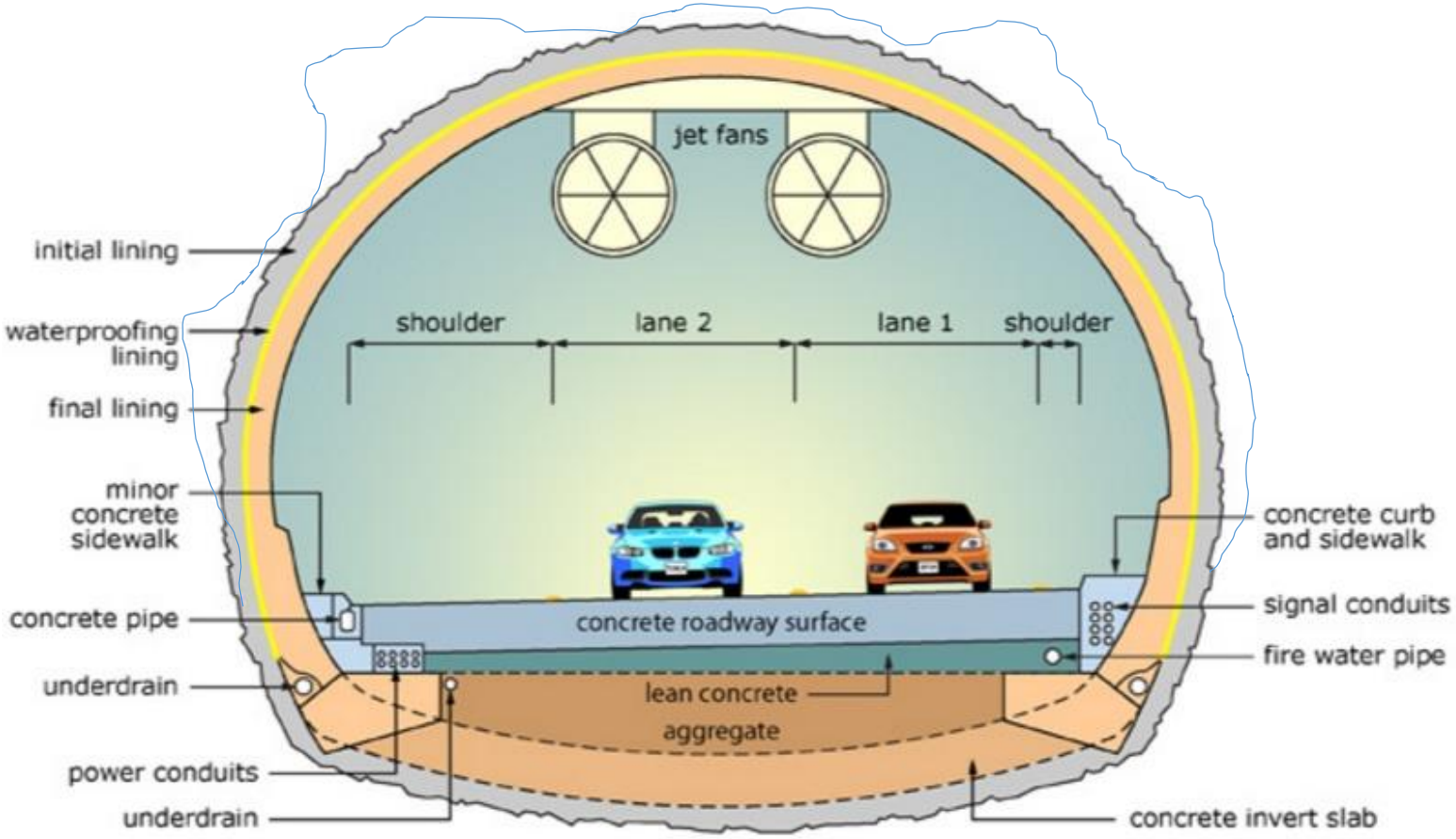
APPROX. 12-15km OF MEMBRANE WELDS PER 1km OF (DOUBLE-TRACK) RAIL TUNNEL

…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)

Over-break ignored in drawings, stability, volumes?



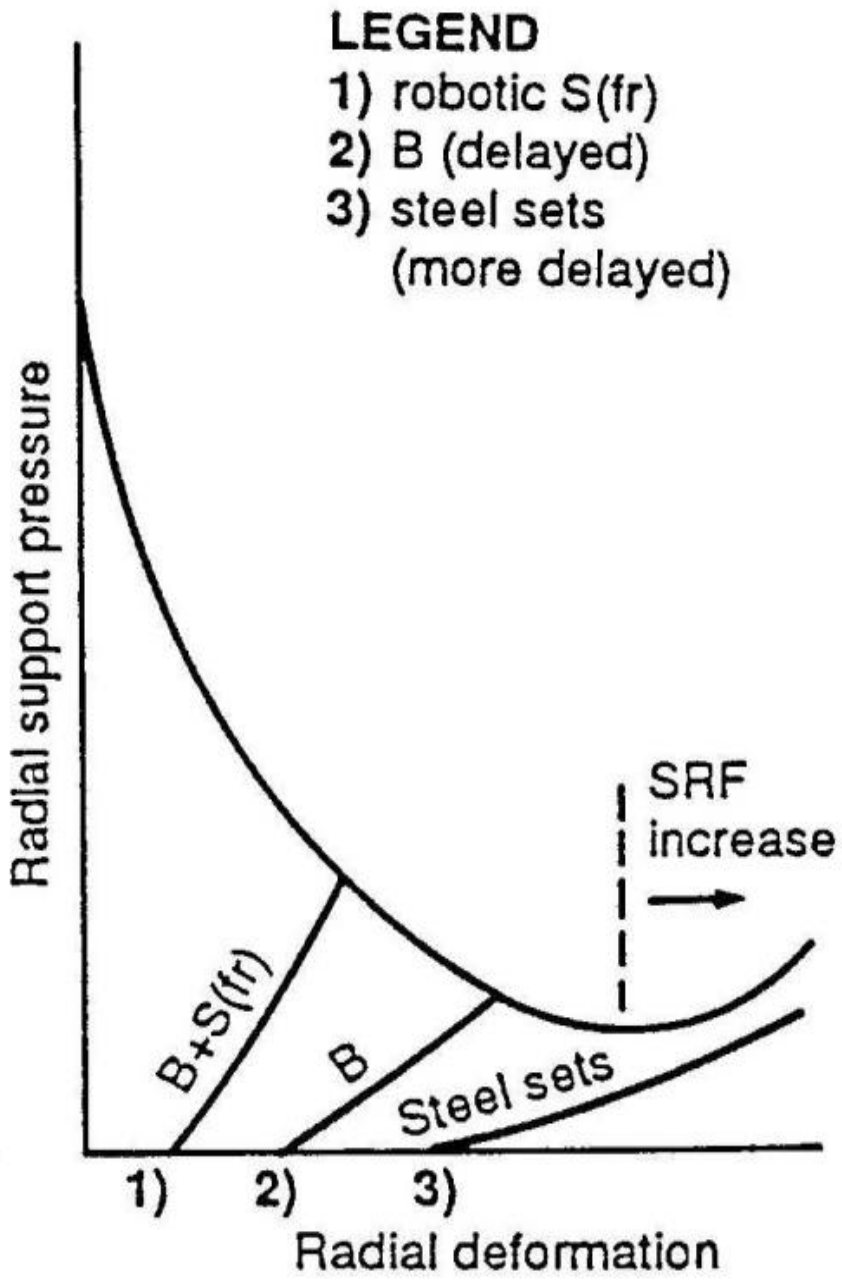
A Botnia rail tunnel, Sweden

2d.

LATTICE GIRDERS, STEEL SETS, 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)

ADEQUATE FOOTING STIFFNESS?

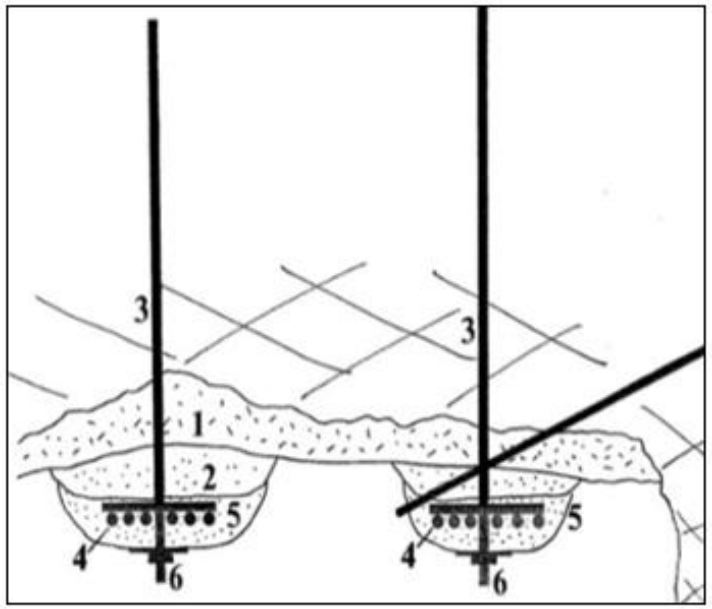
RESISTANCE WHEN 'POINT-LOADED'?

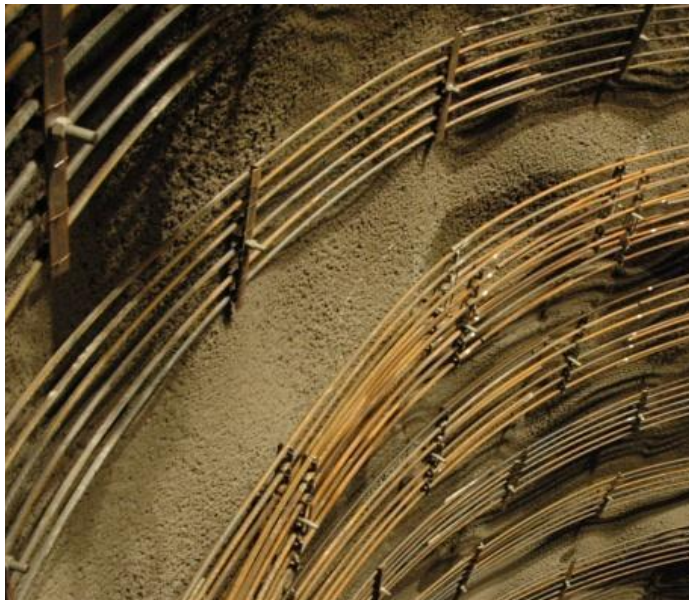
CONTACT WITH TUNNEL SURFACE?

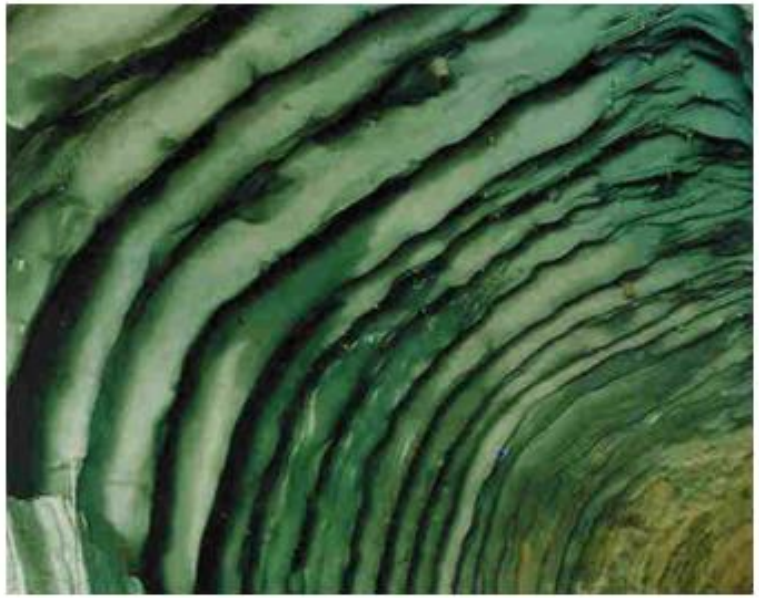
OWN DEFORMABILITY?

Barton and Grimstad, 1994

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

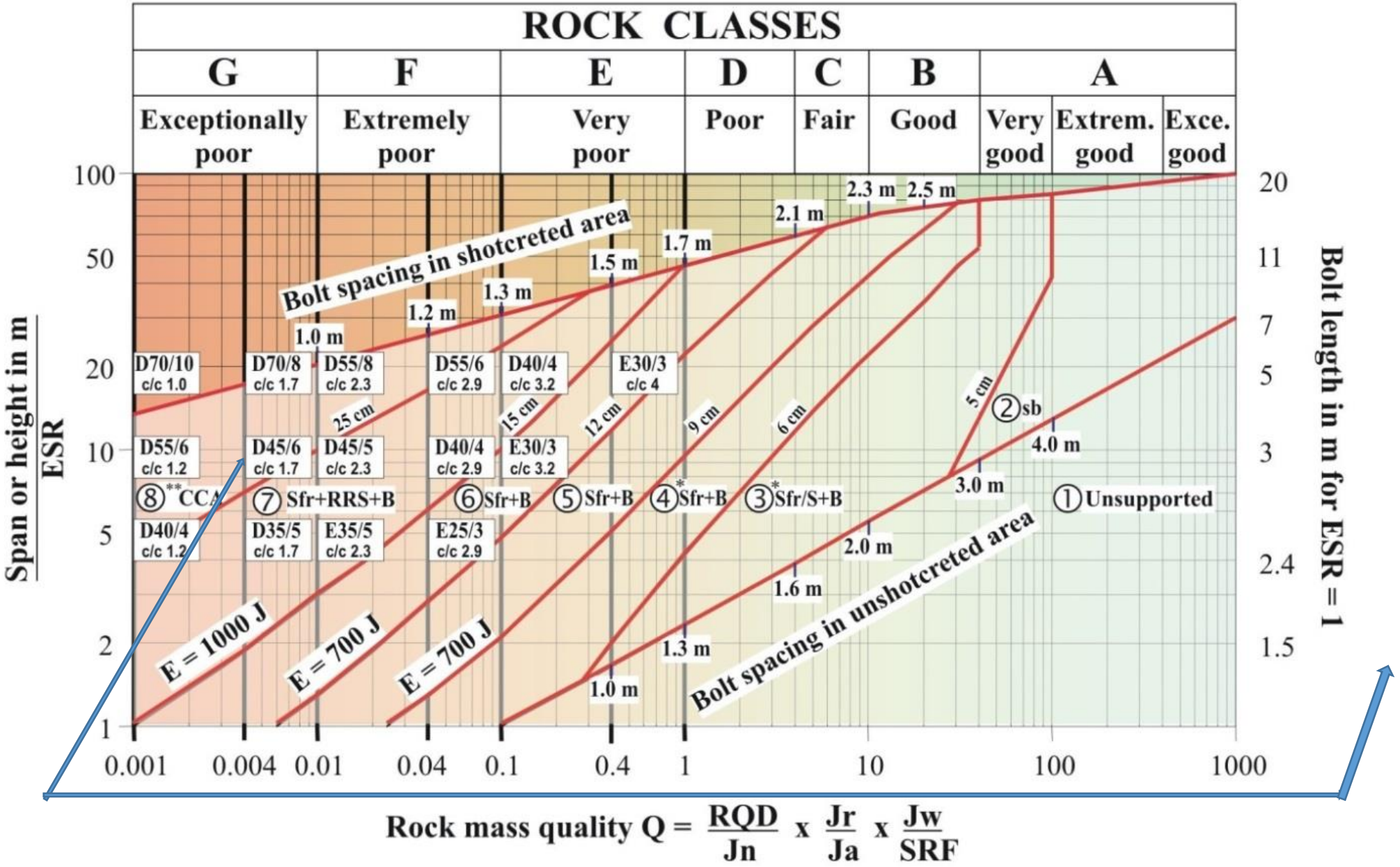






RRS IN NMT: MORE ROBUST

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



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

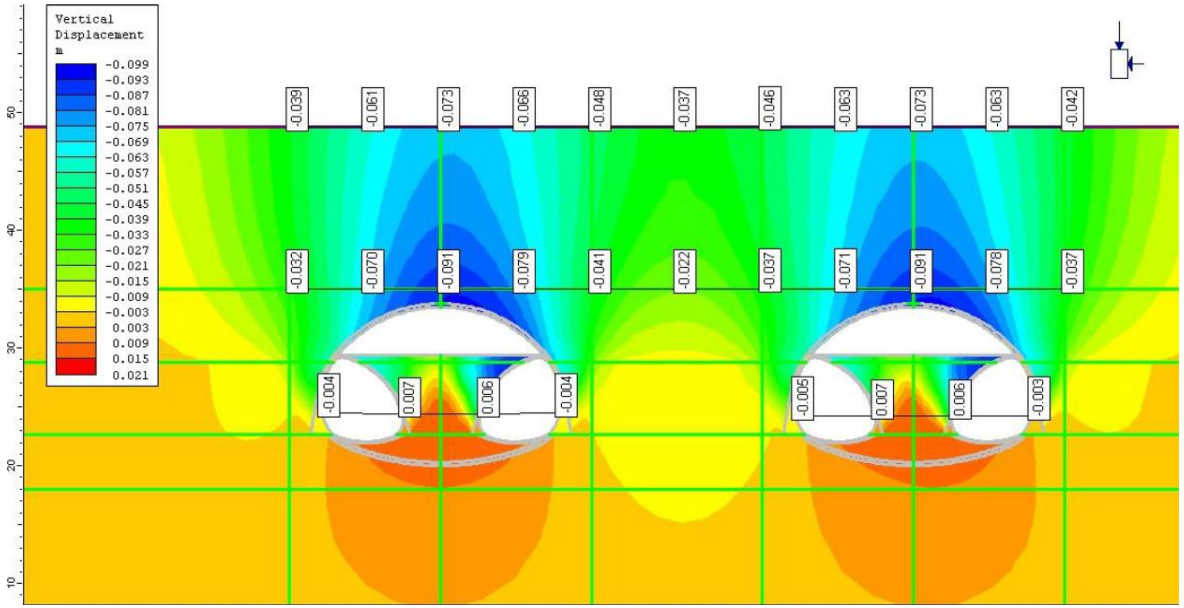
(AVOID COSTLY COLLAPSE as in next screens)

Grimstad in Barton and Grimstad, 2014

3.1 COLLAPSE # 1

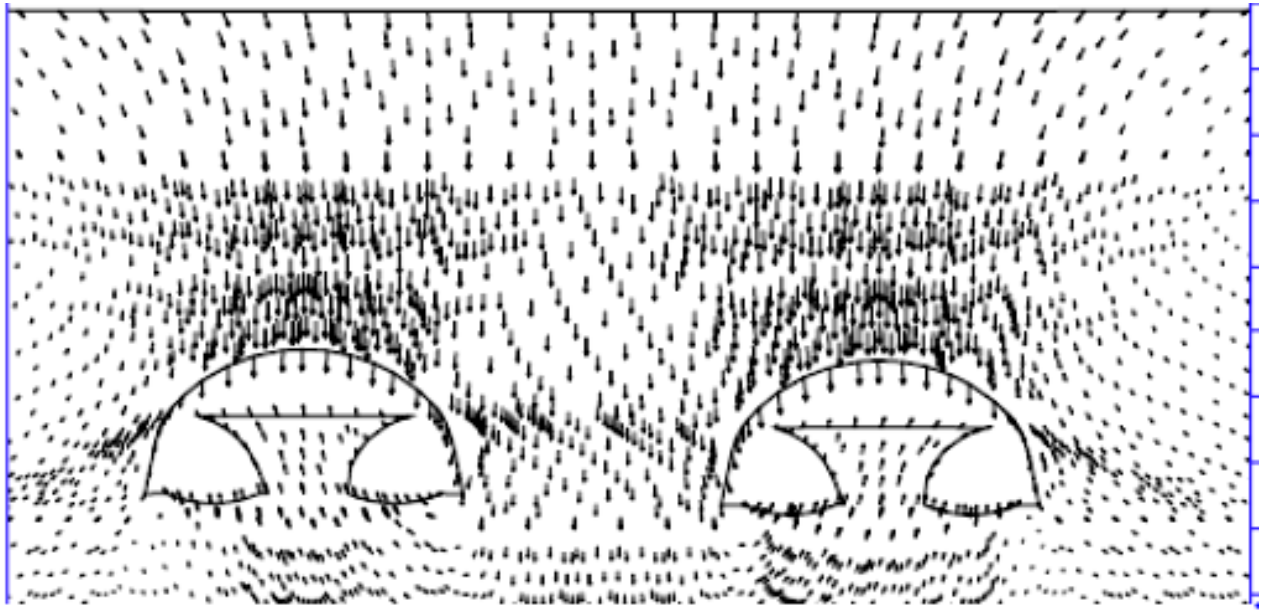
A TWIN-MOTORWAY TUNNEL

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



OPTIMISTIC SYMMETRIC DESIGN, WHEN ACTUALLY SLOPING GROUND.

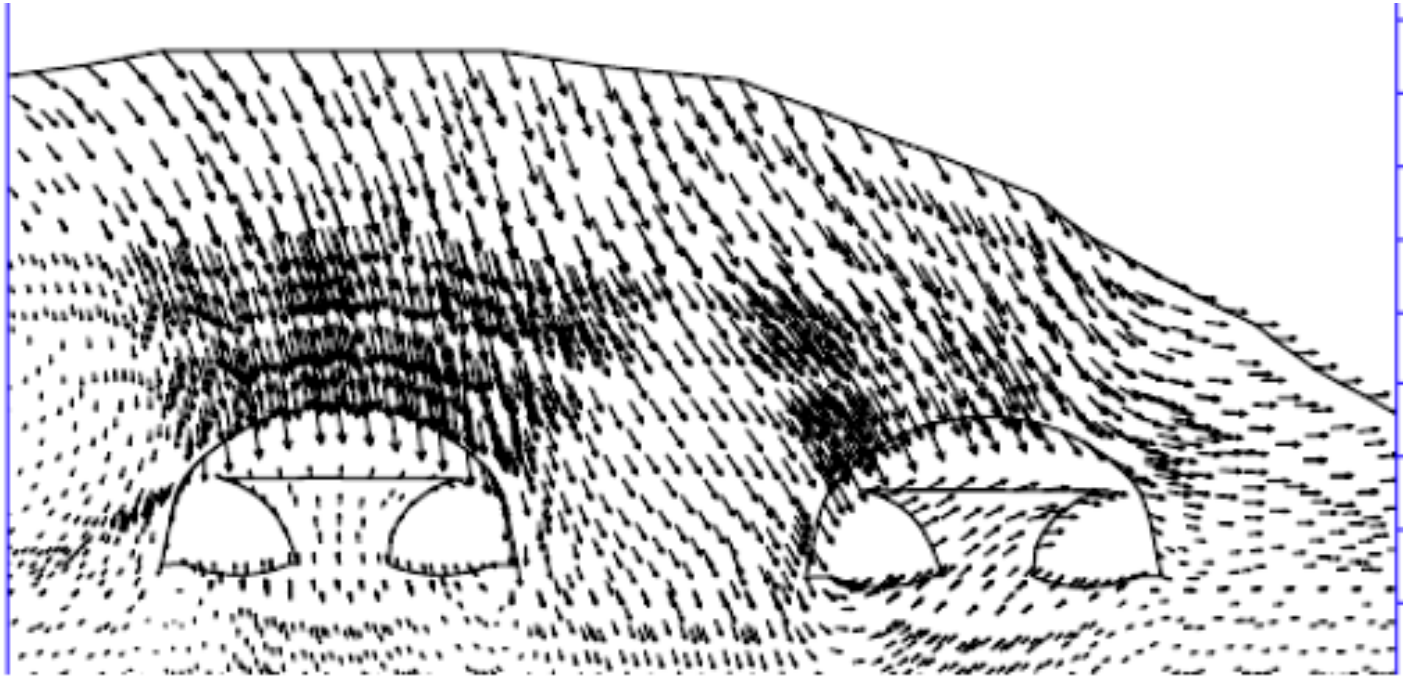
LIGHT LATTICE GIRDERS. NO BOLTS DUE TO SAPROLITE. MUCH MORE THAN SPECIFIED SHOTCRETE DUE TO OVER-BREAK.



EFFECT OF SLOPING HILLSIDE ON EQUILIBRIUM

NOT SO SIMPLE 2D 'REALITY'

(Bandis, 2015)



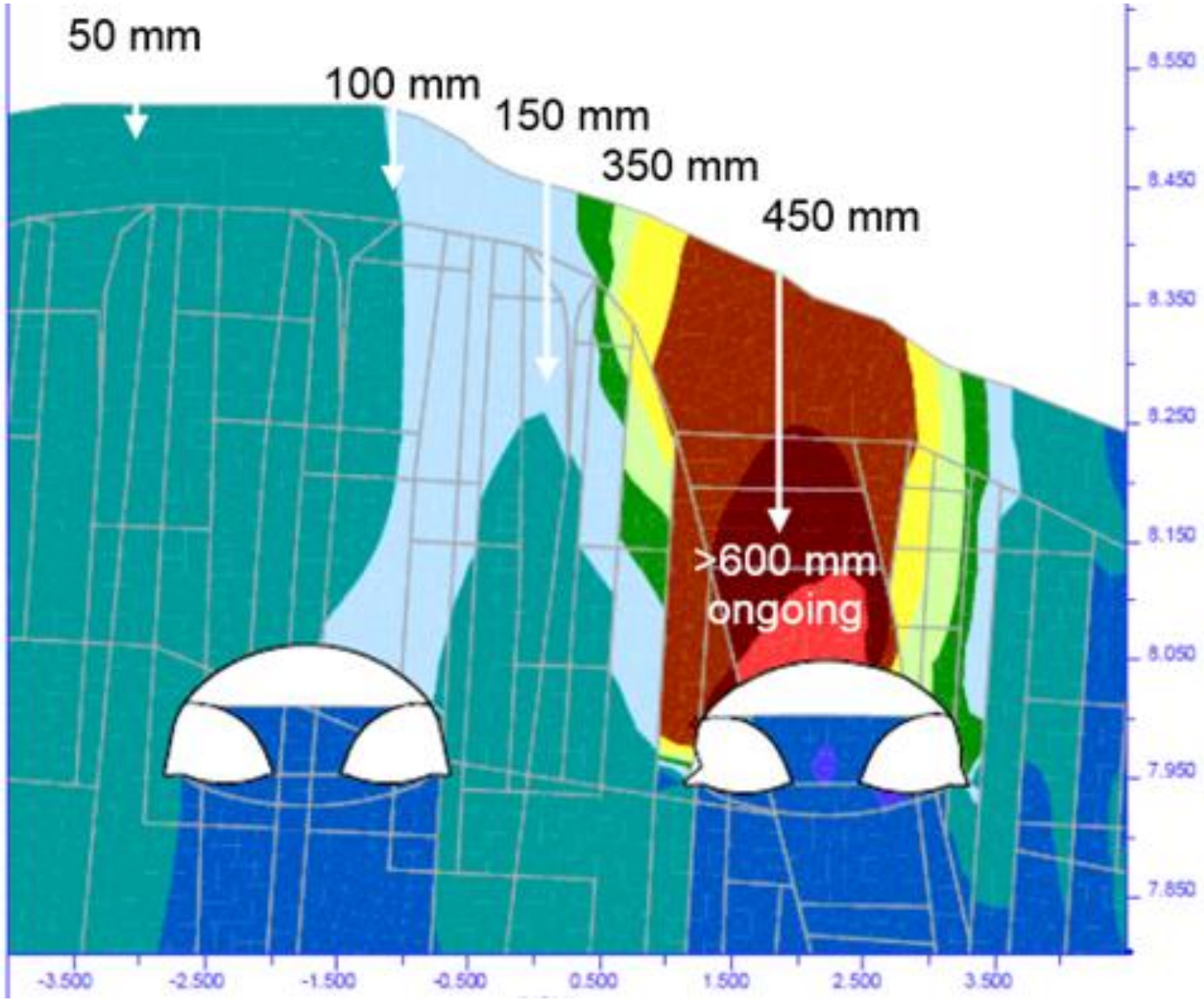
SOME OF THE TOUGH 2D ’REALITY’:

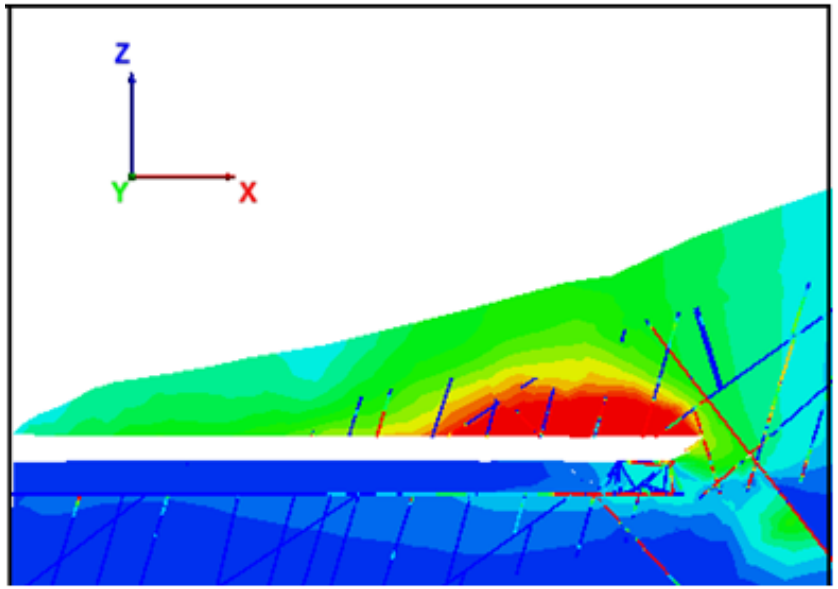
(VERTICAL STRUCTURE AND WEATHERED DIKE)

NOW INCLUDED, IN A UDEC MODEL.

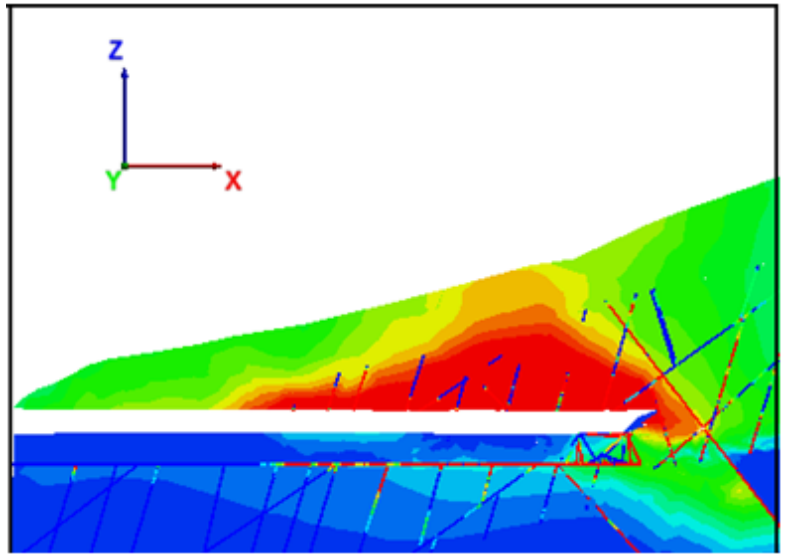
RAPID PROGRESSION TOWARDS MASSIVE FAILURE

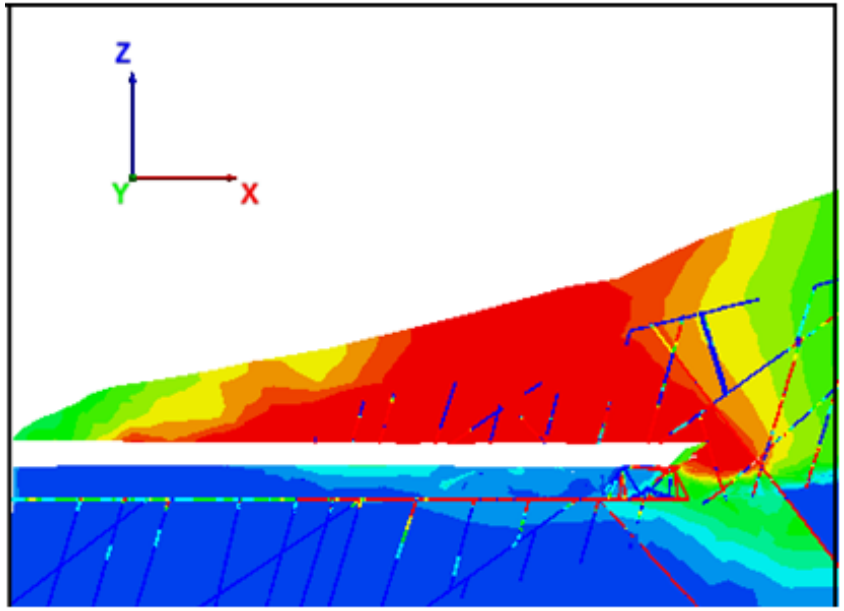
(Stavros Bandis, UDEC)





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)*

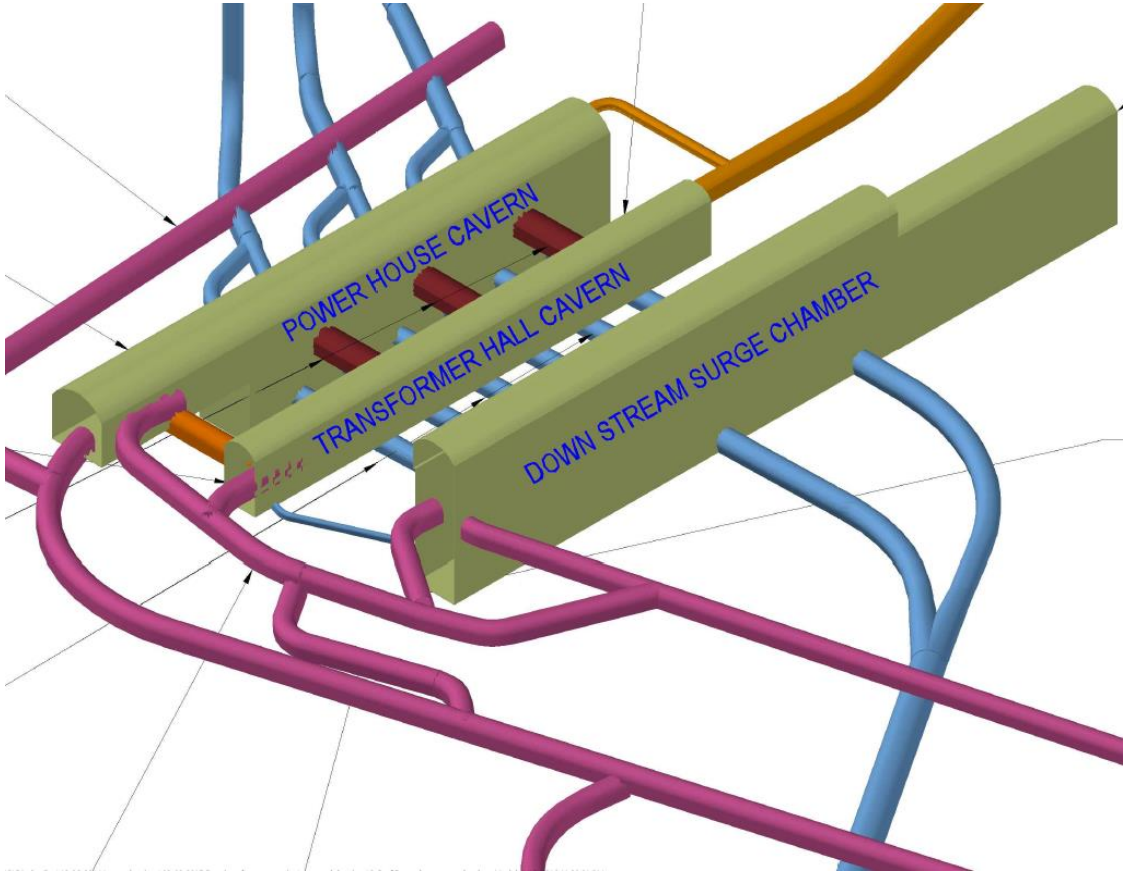
$\sum$ *FAILURE = 280m*

3.2 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.

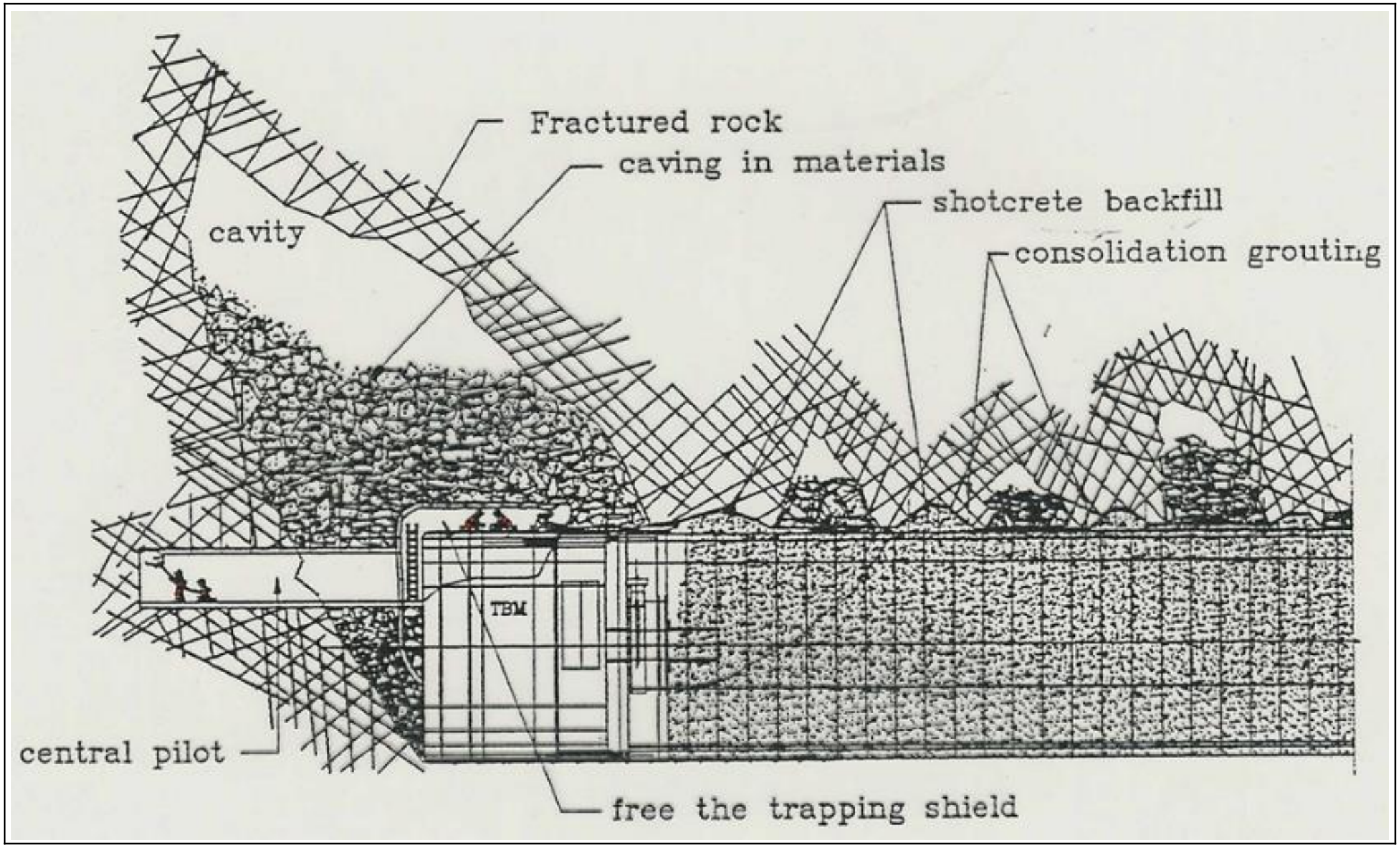
THEN VICTIMS CAN BE RECOVERED.

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

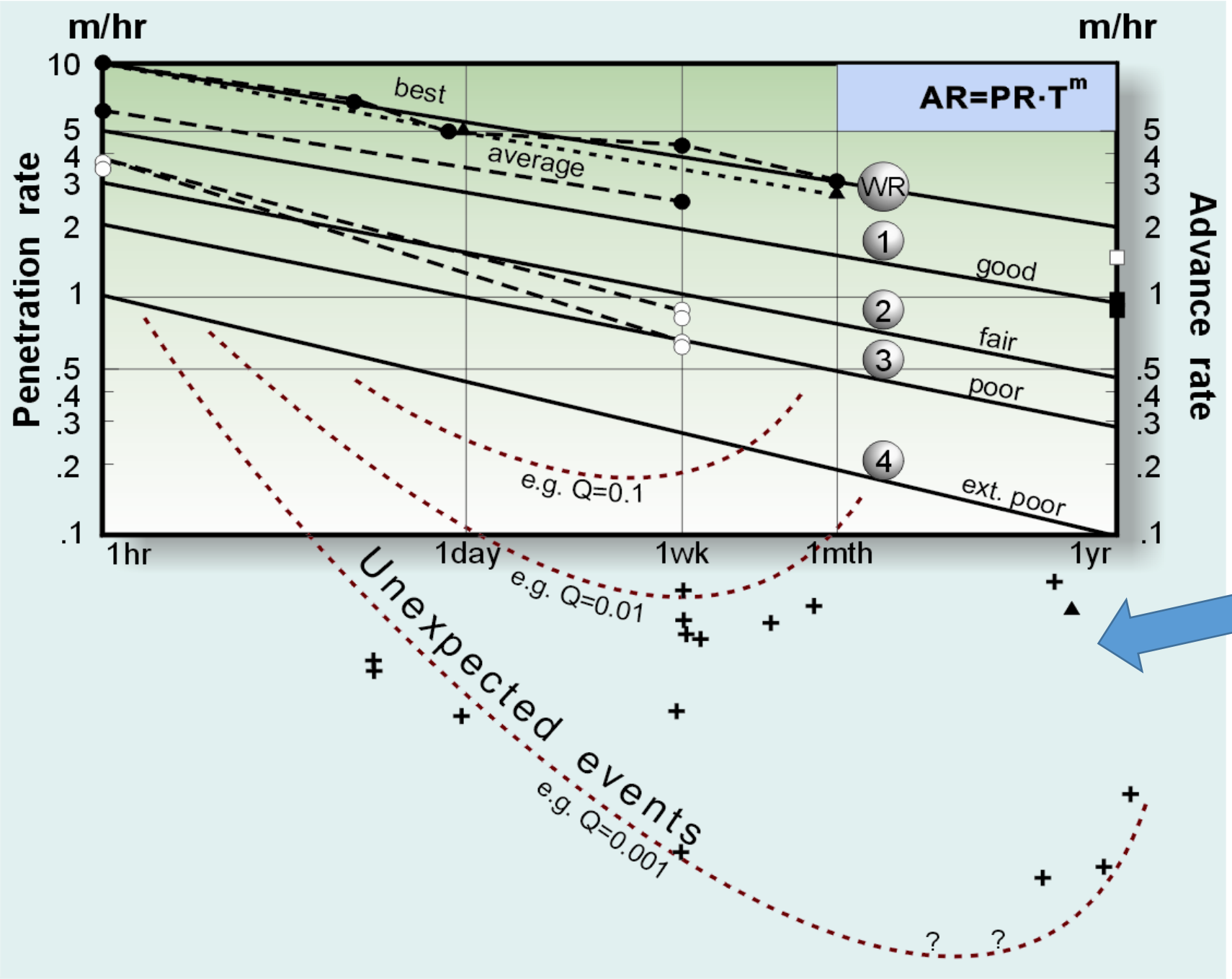
NOTE *(EXTRA)* DESTRUCTION OF STEEL SETS IN THE 'LEFT' ARCH.

4. TBM and FAULT ZONES

(very brief, if time)



EXTREME CHALLENGES IN *FAULTED ROCK* (PINGLIN TUNNELS, TAIWAN). Shen et al. 1999



SYNTHESIS of 1,000km OF TBM TUNNELS. (MOSTLY OPEN-GRIPPER).

(NO HORIZONTAL LINES! DECELERATION) GRADIENT = *(-m).*

***LOW Q-VALUES* HELP TO EXPLAIN LONG DELAYS)**

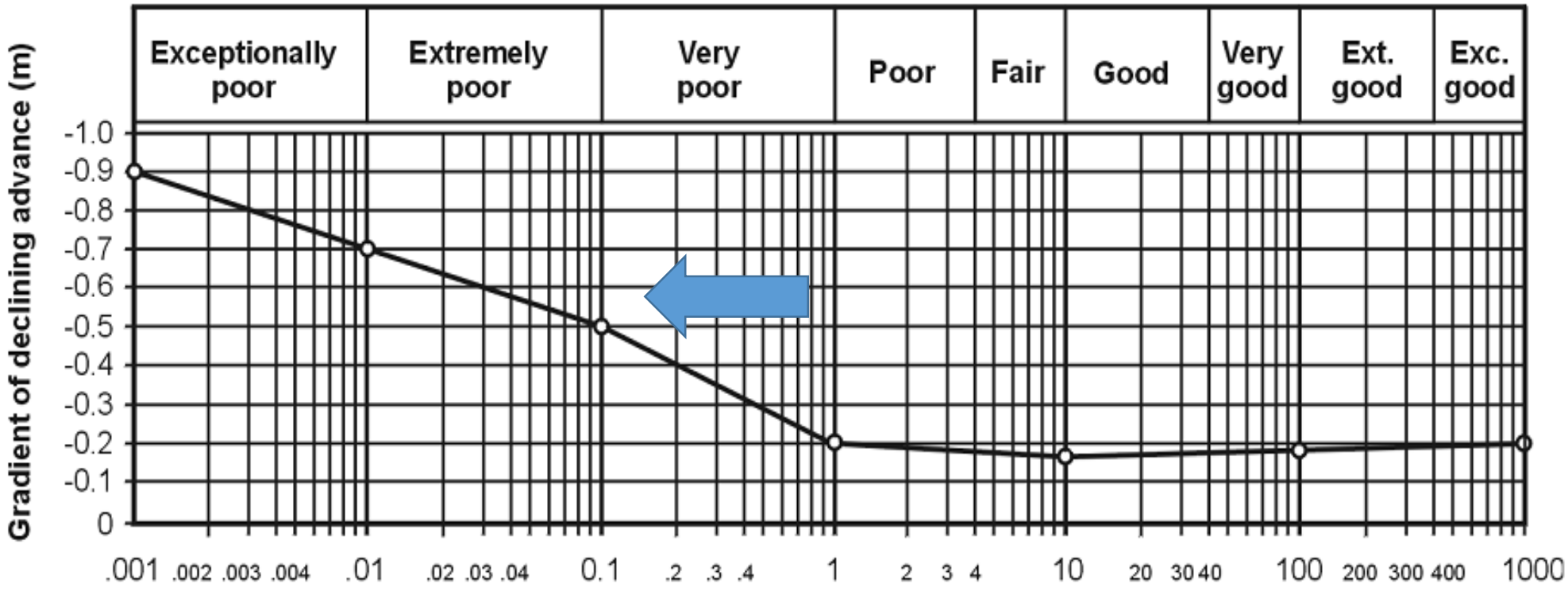
NOTE: AR = PR.U written as:

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

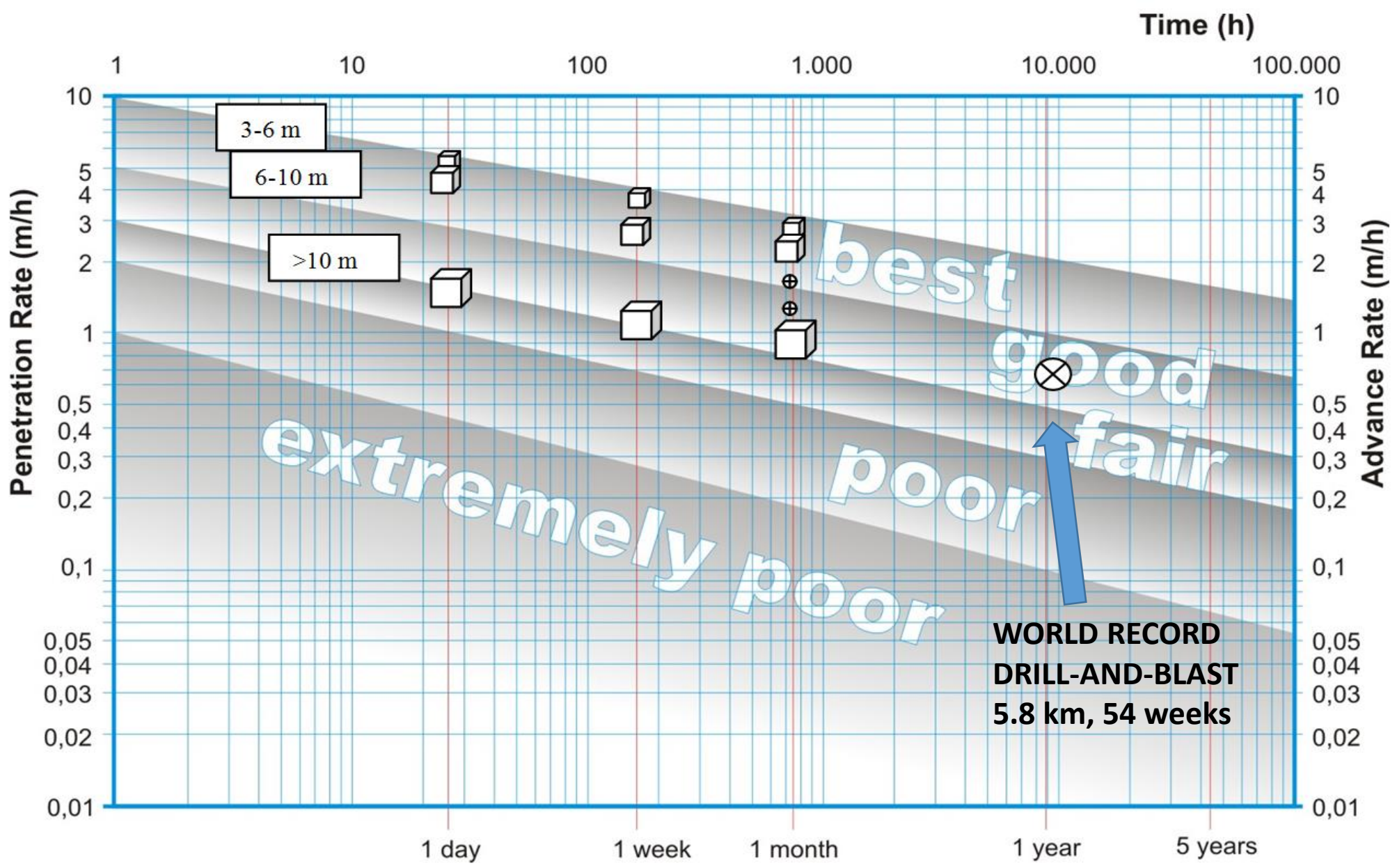
(Barton, 2000)

Q-VALUE CORRELATES WITH *(-) m* WHEN Q IS LOWER THAN 1.0.

DOUBLE-SHIELD, PRE-GROUTING, HELP 'push the hill' to the left.



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

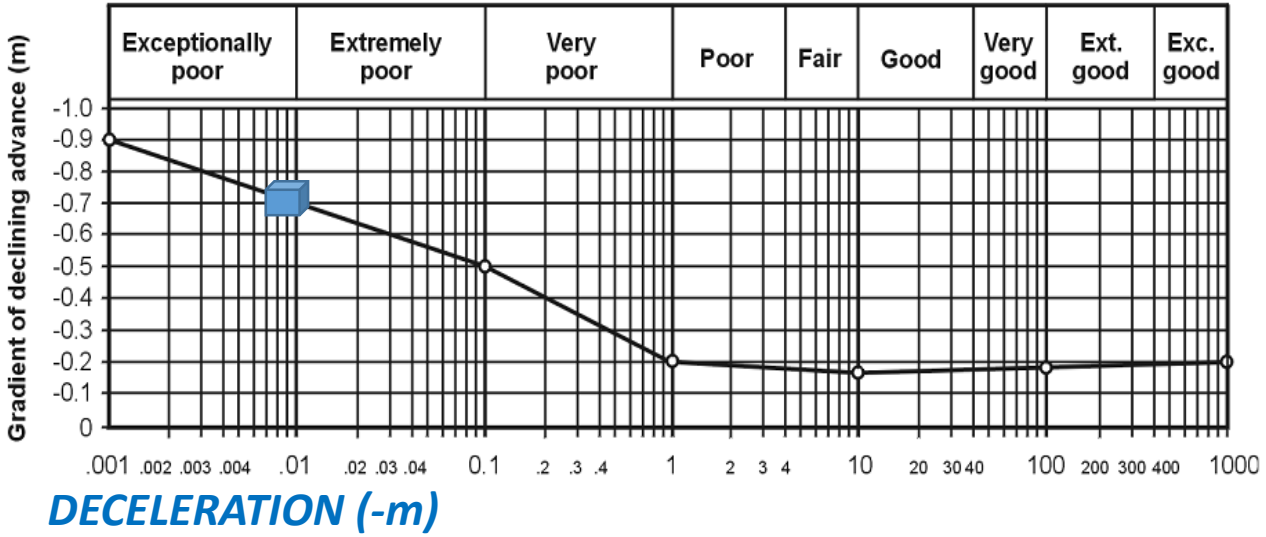


WORLD RECORDS COLLECTED IN SIZE BRACKETS:

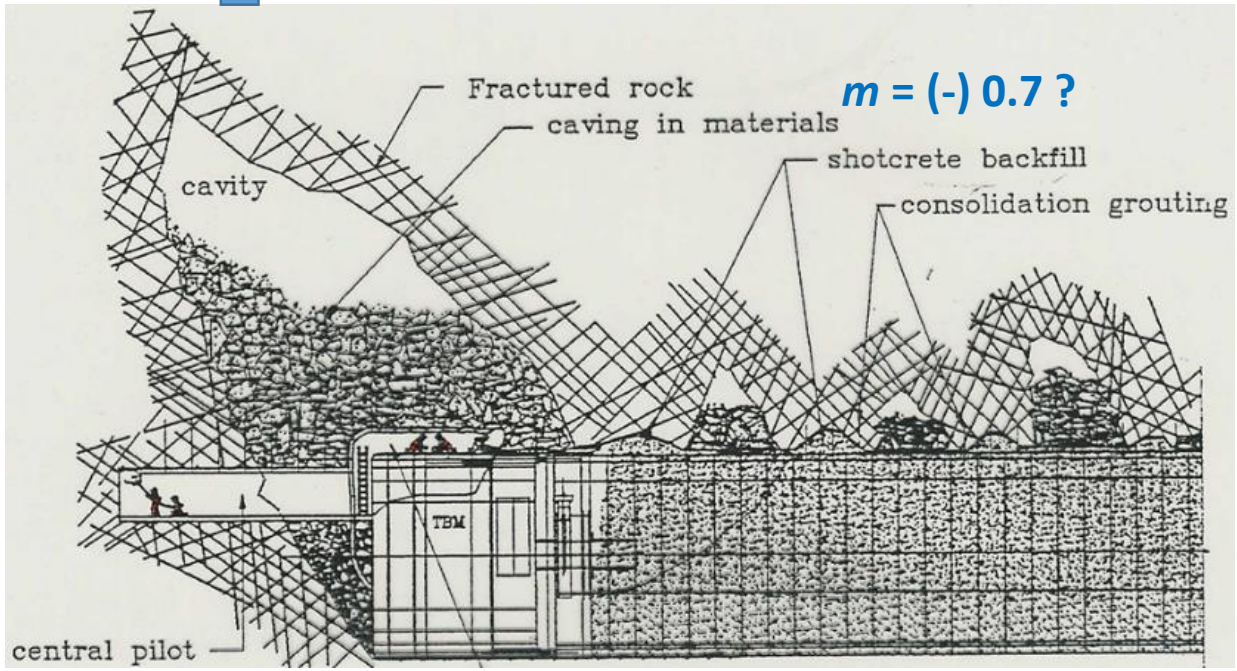
(3-6m, 6-10m, > 10m).

MOSTLY ROBBINS WORLD RECORDS)

Barton, 2013



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!**

CONCLUSIONS

1. FRACTURING IN DEEP TUNNELS – STARTS DUE TO EXTENSION STRAIN.

2. THE ASSUMED '0.4 X UCS' IS DUE TO σ_t (tensile strength) / ν (Poisson ratio).

3. JOINTING HELPS TO DISSIPATE TENDENCY FOR 'STRESS' FRACTURING.

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

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

6. IN NMT (AND NATM) SUPPORT SHOULD BE APPROPRIATE TO THE ROCK

7. DETECT, AND IMPROVE THE QUALITY OF FAULT ZONES AHEAD OF TBM!