Cavern and Tunnel Failures due to Adverse Structural Geology and Inadequate-in-the-Circumstances Support Designs

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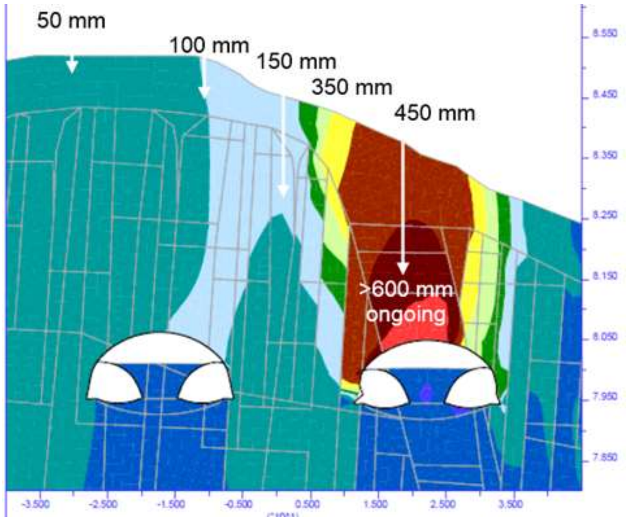


UNEXPECTED LOADINGS FROM ***UNEXPECTED STRUCTURAL GEOLOGIES***, AND THE USE OF 'DEFORMATION-INVITING' ***LATTICE GIRDERS*** (OR STEEL ARCHES), WERE THE ***COMBINED CULPRITS*** OF THESE FAILURES.

THE FAILURES OCCURED IN THE TEMPORARY SUPPORT PHASE OF THE NATM-TYPE PROJECTS.

CONTENT of LECTURE

1. UNEXPECTED IRRESISTABLE FORCES, CONVENTIONAL SUPPORT OVER-COME
2. #1 METRO CAVERN FAILED DUE TO A FREAK MORPHOLOGICAL FEATURE
3. OTHER MASSIVE FAILURES DUE TO INADEQUATE SUPPORT
4. CONTRASTING DOUBLE-SHELL NATM AND SINGLE-SHELL NMT SUPPORT
5. THE 'SOFTNESS' OF LATTICE GIRDERS AND STEEL SETS: RRS PREFERABLE
6. #2 STEEL SETS IN HEP-CAVERN ARCH, OVER-LOADED IN 'IGNORED' FAULT ZONE
7. #3 NATM MOTORWAY TUNNEL FAILURE: INADEQUATE LATTICE GIRDER DESIGN
8. ISOTROPIC CONTINUUM CONTRA DISCONTINUOUS ANISOTROPIC REALITY
9. PROGRESSIVE FAILURE AND STRAIN INDUCED FAILURE CONCEPTS
10. CONCLUSIONS

Acknowledgements

1. Dr. Stavros Bandis † (former professor at Univ. of Thessaloniki)

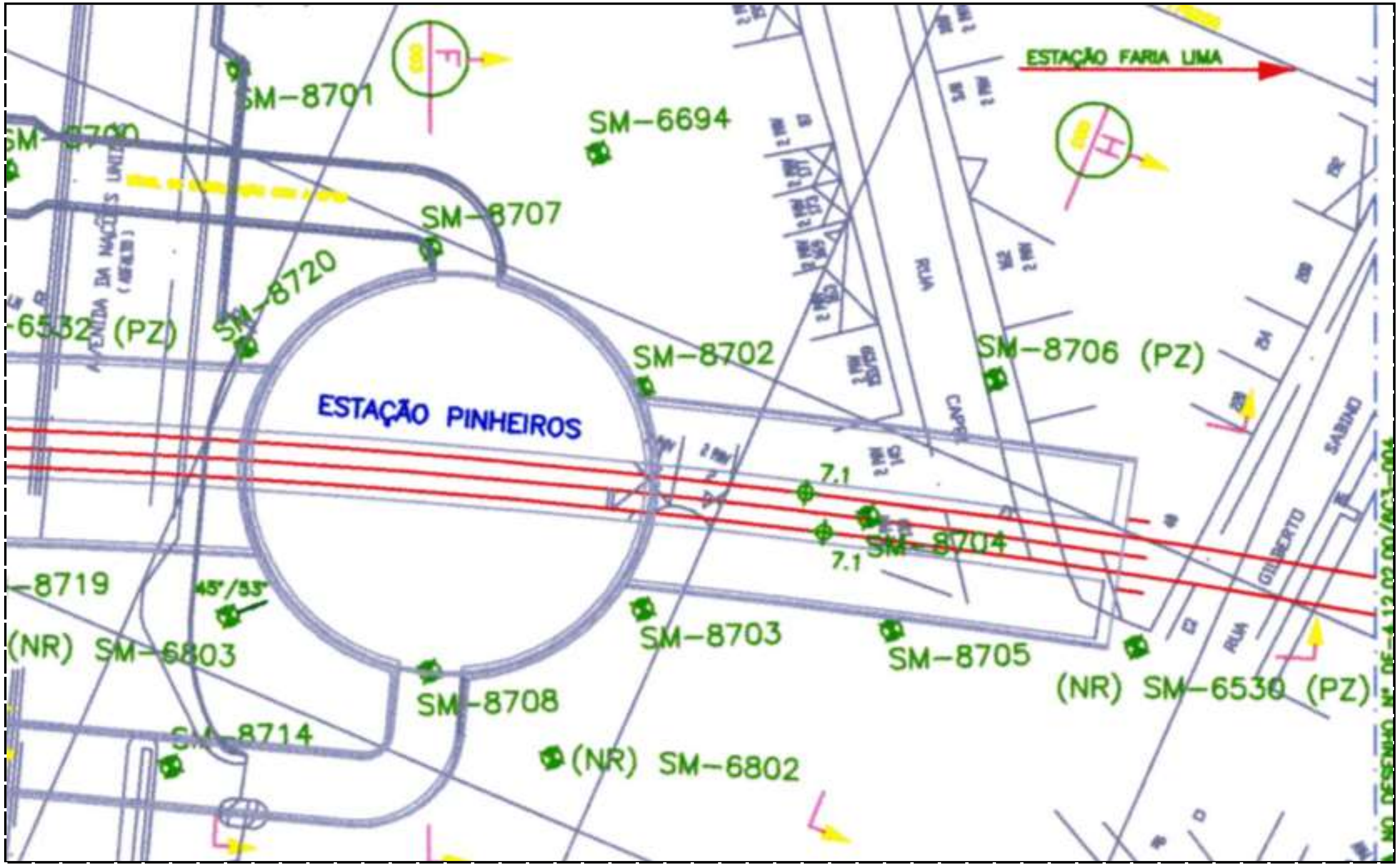
2. Dr. Baotang Shen (senior scientist, CSIRO, Brisbane, Australia)

(For respectively their UDEC/3DEC and FRACOD modelling expertise and friendship)

COLLAPSE # 1

A METRO STATION CAVERN

(with undiscovered 15,000 tons ridge-of-rock above cavern arch in soil)

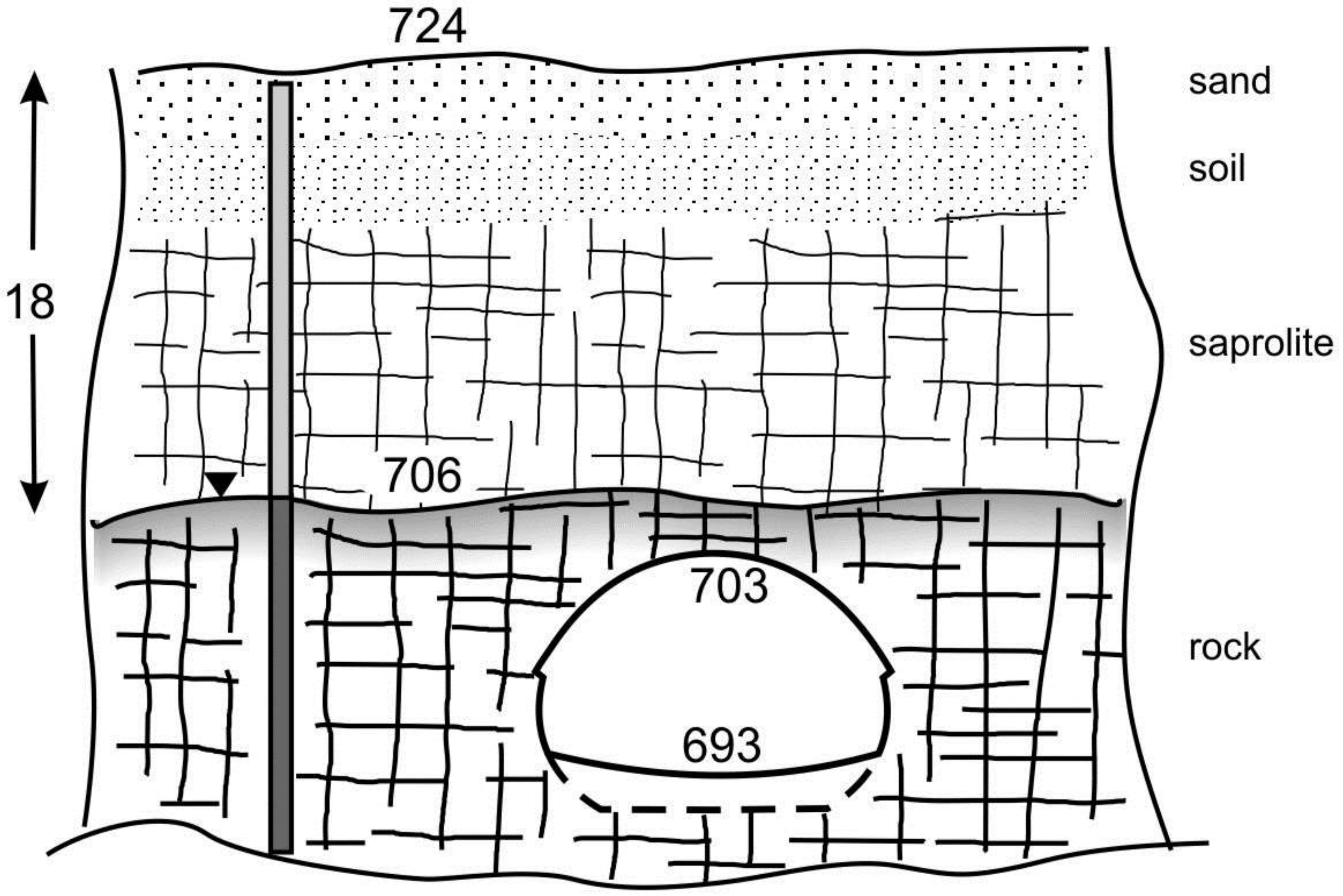


***Eleven* boreholes around shaft and eastern station cavern.**

L borehole / L tunnel ………international norm exceeded by a factor of ≈ 2 to 4

See core of SM-8704

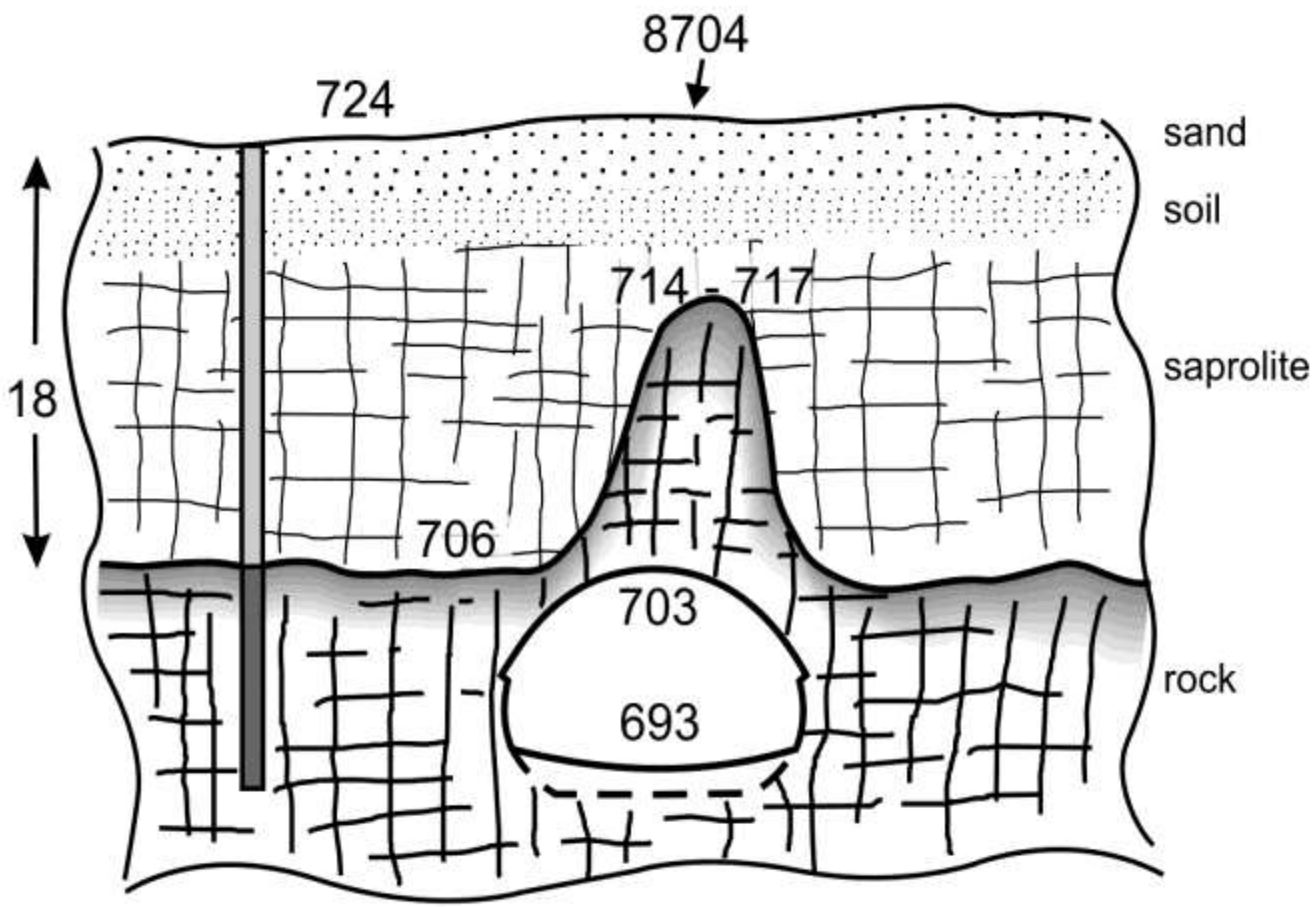
WHAT WAS EXPECTED – ON AVERAGE – CONCERNING ROCK COVER



Borehole SM-8704 drilled near centre of (future) station cavern.

Rock was encountered at 18 m depth, at elevation 706m. This is 3 m above the cavern roof.

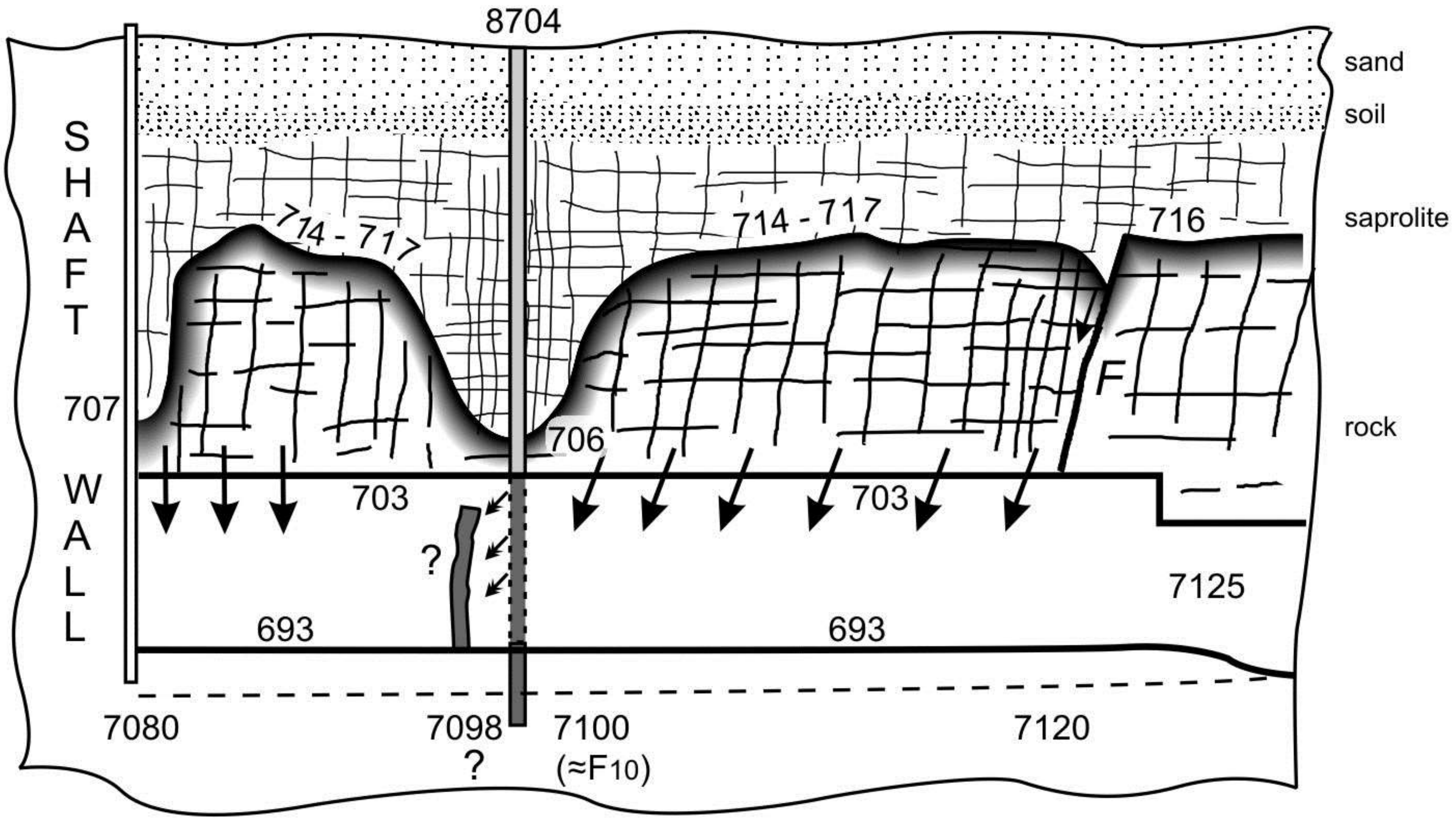
Low rock cover was 'confirmed' – almost the same as the mean of the five nearest holes.

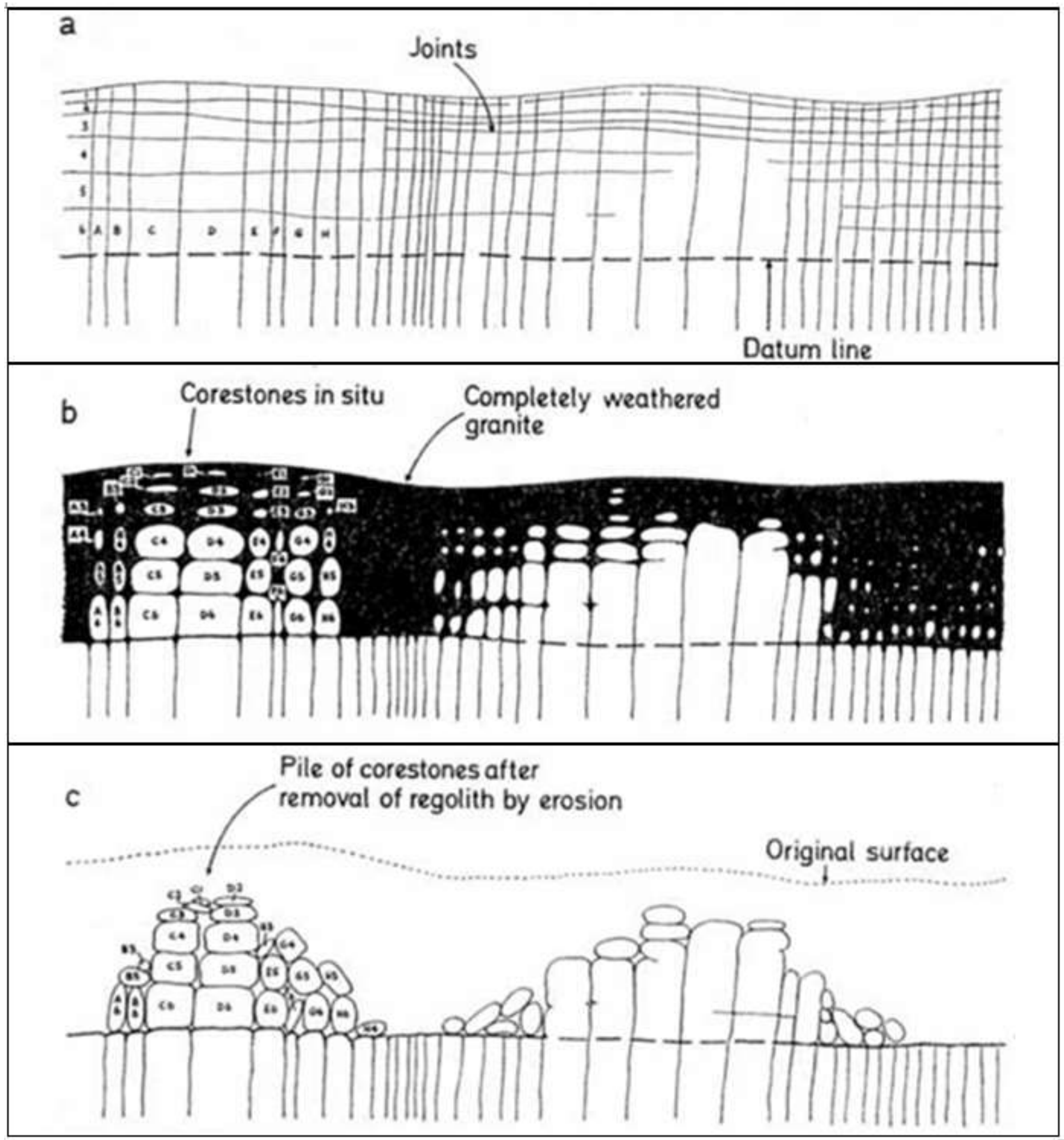


THE EXTRAORDINARY REALITY: **SUB-SURFACE RIDGE-OF-ROCK THAT WENT UNDETECTED**

MOST OF THE COLLAPSED ROCK IN THE CENTRE OF THE CAVERN FELL 10 M, REACHING ELEVATION 704-707 M, i.e. REMAINING 1 TO 4M ABOVE THE (ORIGINAL) CAVERN ARCH.

THIS SHOWS WHY THE RIDGE WAS MISSED WHEN DRILLING SM-8704



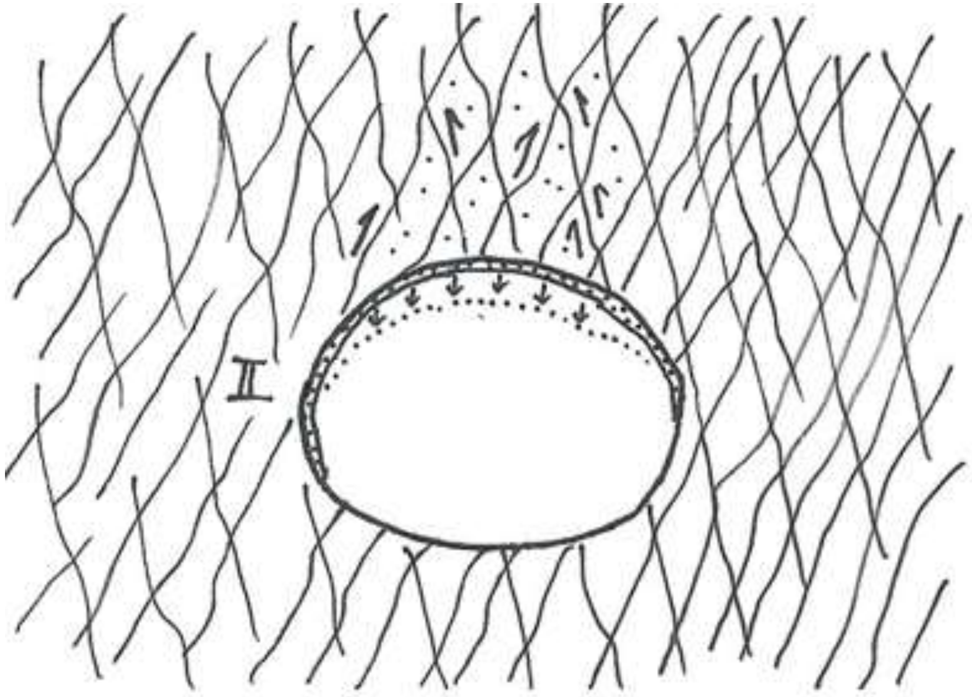


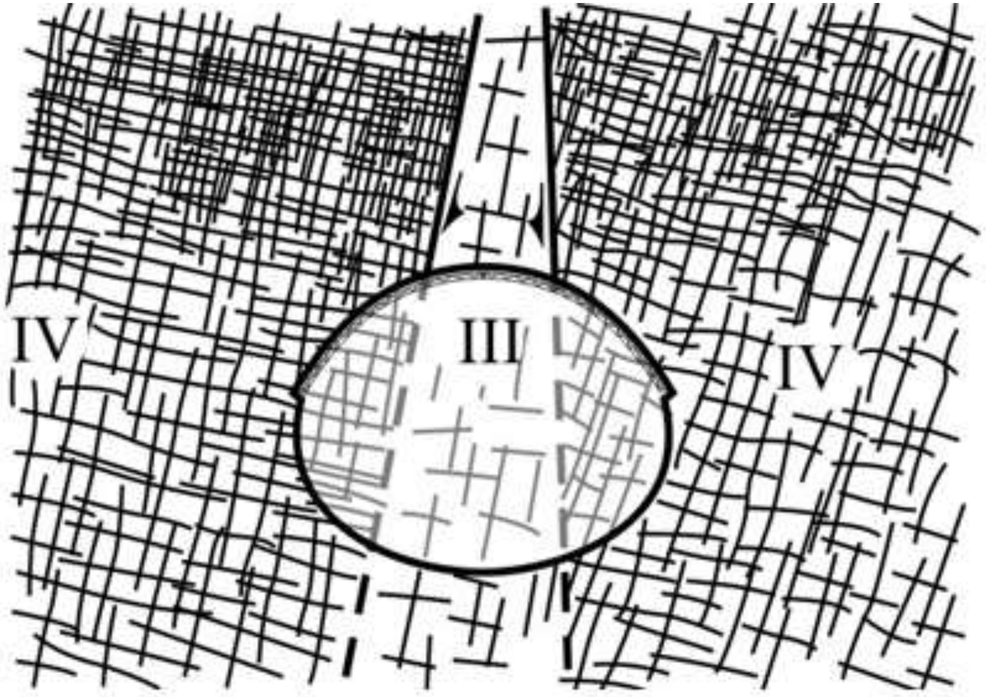
Linton, 1955. A classic model of differential weathering.

STAGE (b) is relevant to the origin of the cavern collapse

'Tors' from Dartmoor, S.W. England. Previously surrounded by saprolite and soil and sand

The sub-surface in areas of deeply-weathered granite, gneiss, limestone, etc. must be extremely 'rough' beneath the smooth soil cover.





(Left) Conventional wedge loading

(Right) Unconventional quality change

BEFORE AND AFTER

A first bench had been finished in relation to the top-heading seen in the left photograph.

LOOKS ROBUST – BUT WHAT IF POOR CONTACT WITH OVER-BREAK, AND NON-UNIFORM LOADING DUE TO A WEAK CONCEALED STRUCTURE?

NO BOLTS IN THIS CASE DUE TO ASSUMED LOW COVER, AND FRAGMENTED WEATHERED ROCK. BUT S(fr) ≈ 40 to 50 cm

January 2007 collapse. Collapse so sudden that pedestrians and minibus sucked into void. (Seven die)

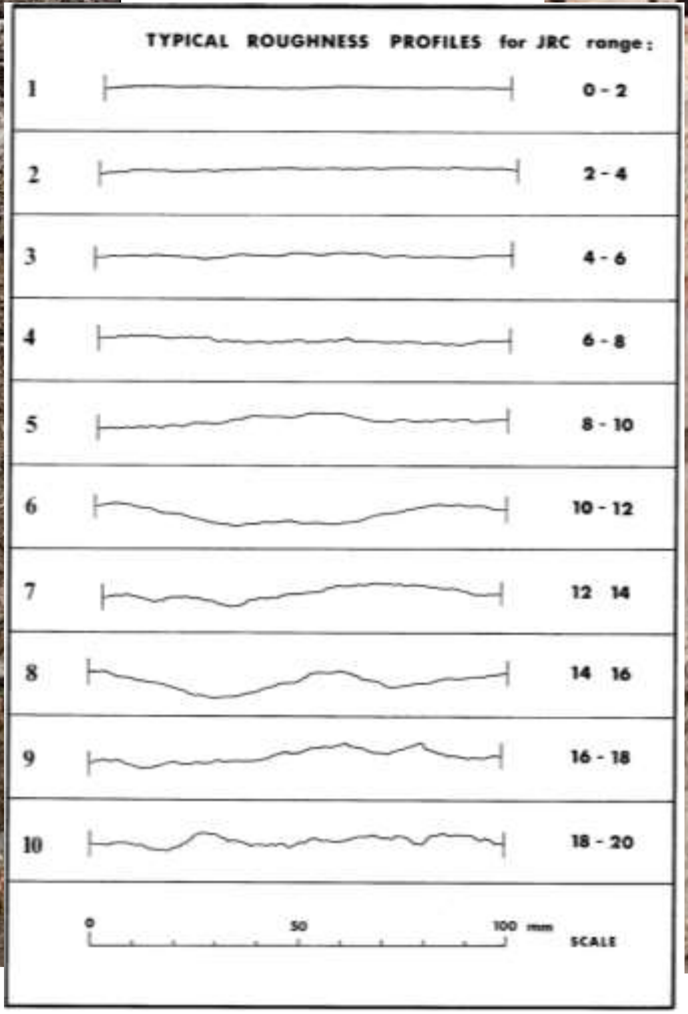
Thin arrows mark same truck

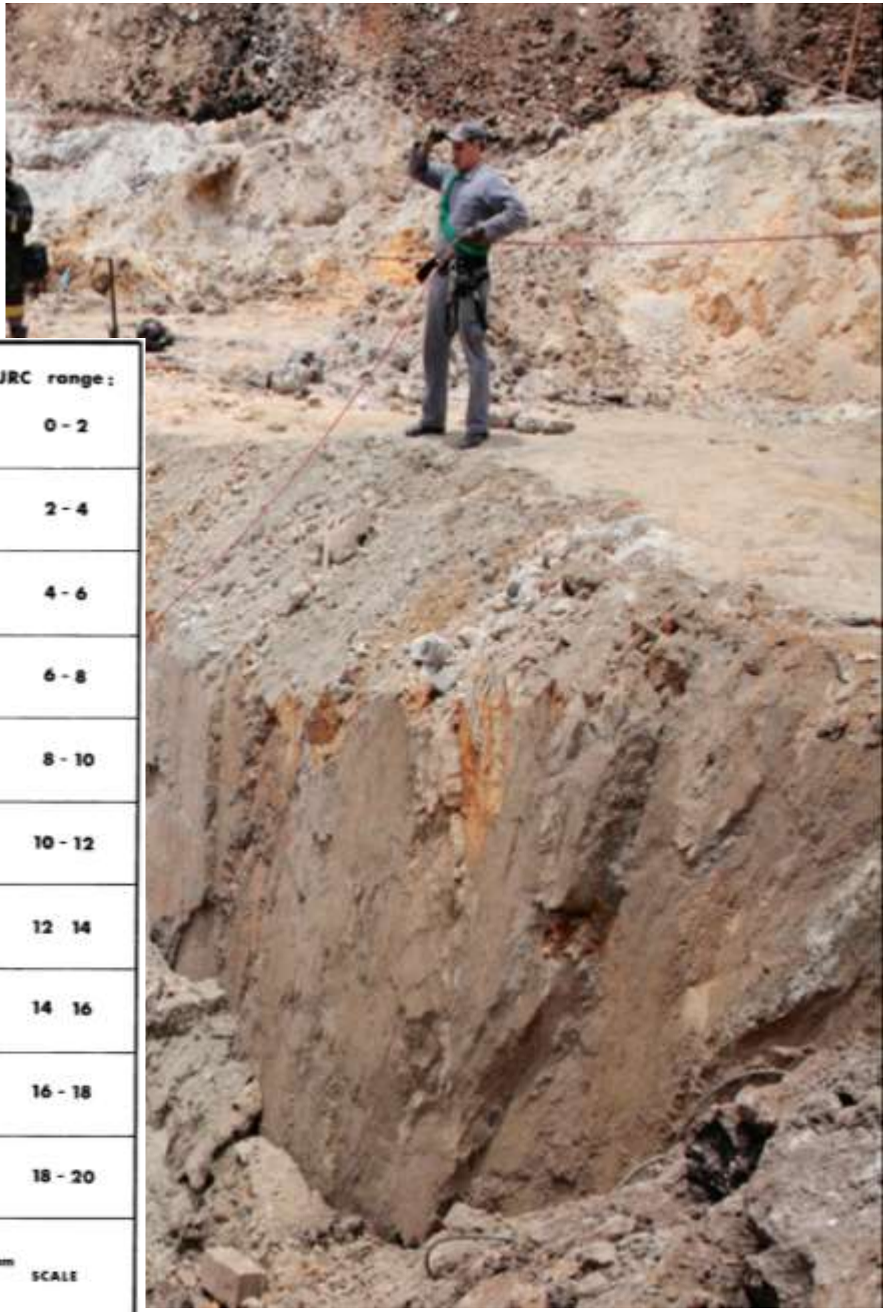
The smooth discontinuity marking the limit of the collapse

Discontinuity marking 'end' of collapse:

Very low JRC

(ALSO WATER)



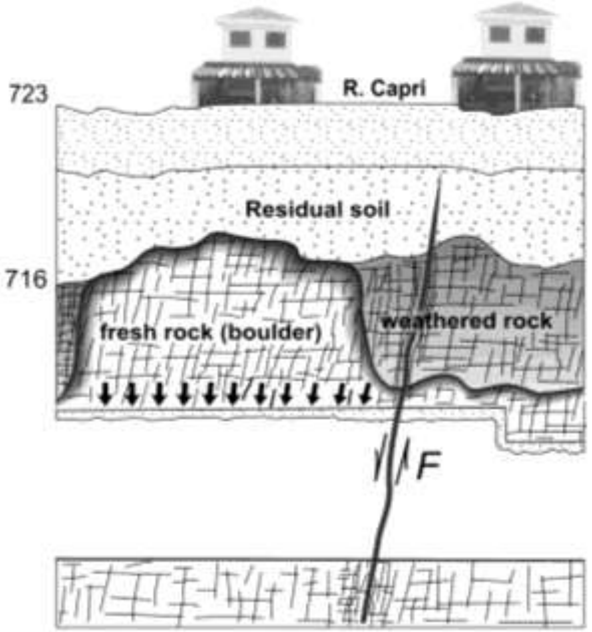


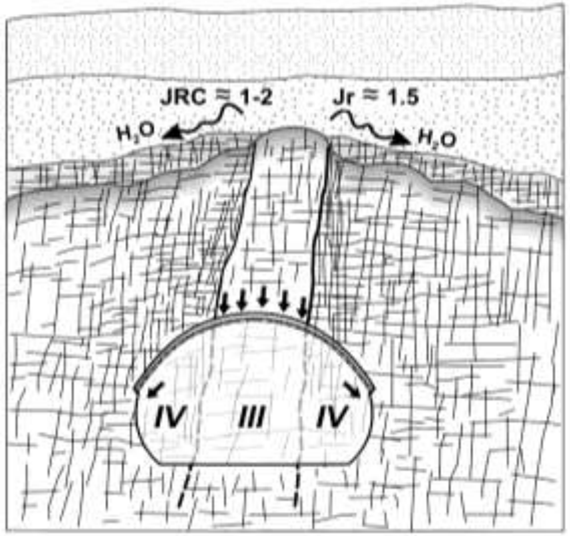
After many months of excavation – discover folded 25 x 25 x 32 mm lattice-girders (and grouting tubes). Note 40-50 cm of S(fr) lower-left.

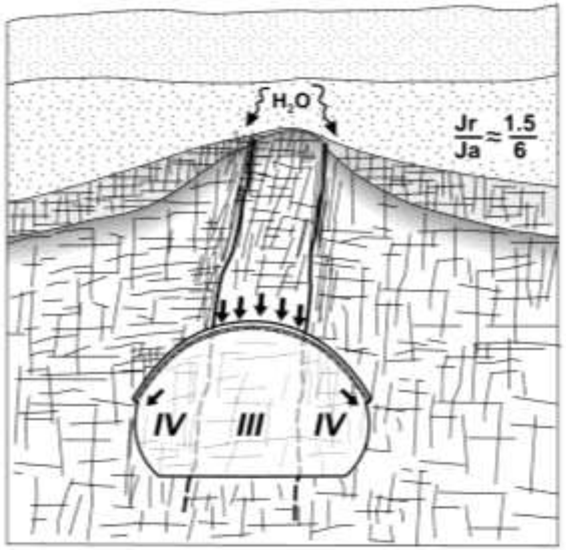
After many months of excavation

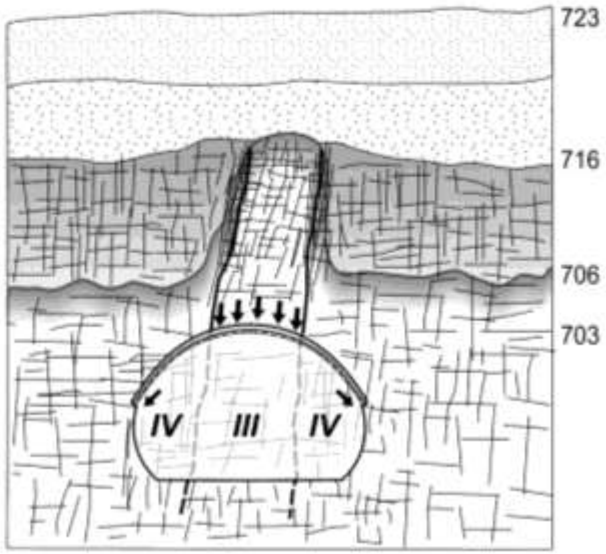
- **Smooth, weathered, curved, top-of-ridge-of-rock, L > 30 m.**
- **This jointed gneiss has fallen 8 to 10 m, but has remained like loosened 'pack-of-cards'.**

Imagined progressive formation of ridge

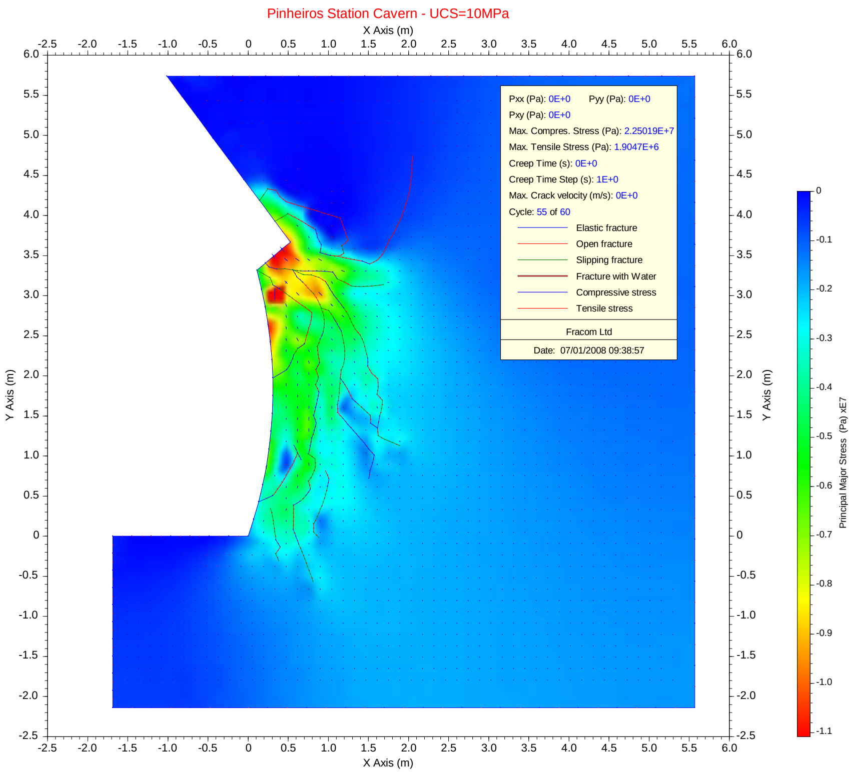








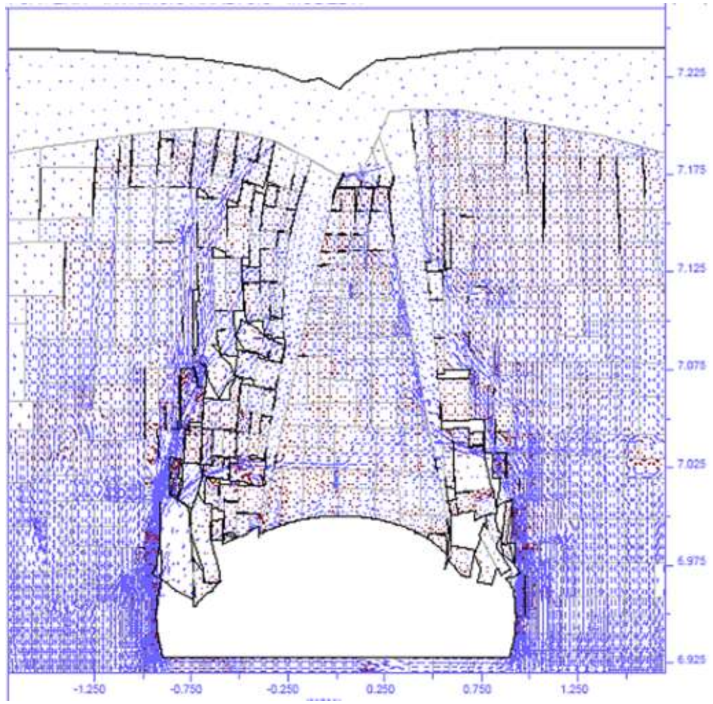
In effect the (RMR III) ridge is preserved and the more jointed (RMR IV) surroundings deteriorate, eventually providing low-friction boundaries.

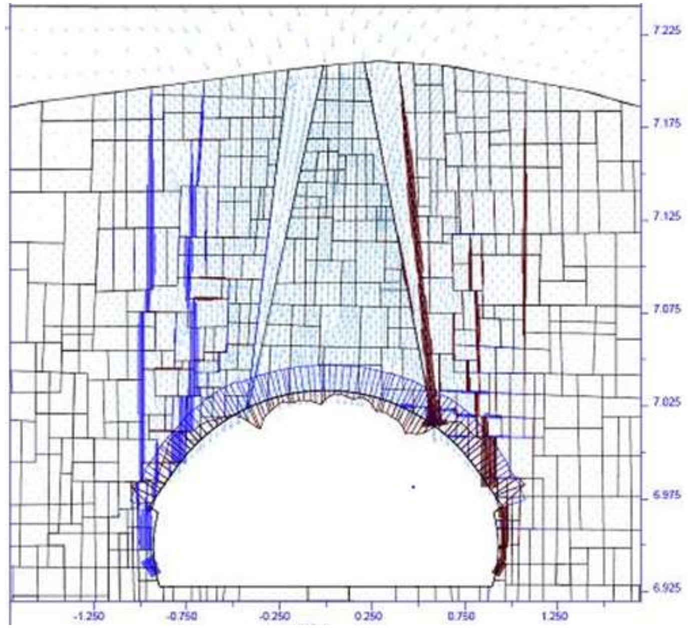


1. Possible early failure beneath 'elephant-feet' in 'left'wall. FRACOD model by Dr.Shen.

2. 'Intrinsic' (without support) failure with UDEC. (Dr. Bandis)

3. Loading on lattice girders and development of 'plastic hinges' prior to failure. (Dr. Bandis)





BEFORE DISCUSSING THE NEXT TWO FAILURES

I WILL ILLUSTRATE:

TYPICAL COMPONENTS OF NATM AND NMT

TUNNEL AND CAVERN SUPPORT

AND REINFORCEMENT

CONTRASTING THE TYPICAL COMPONENTS of NATM and NMT:

1. **‘DOUBLE-SHELL’ (‘NATM’)**
   (<u>Temporary</u>: Sfr/Smr, B, steel/lattice girders,
   <u>Permanent</u>: fleece, membrane, cast concrete, CCA

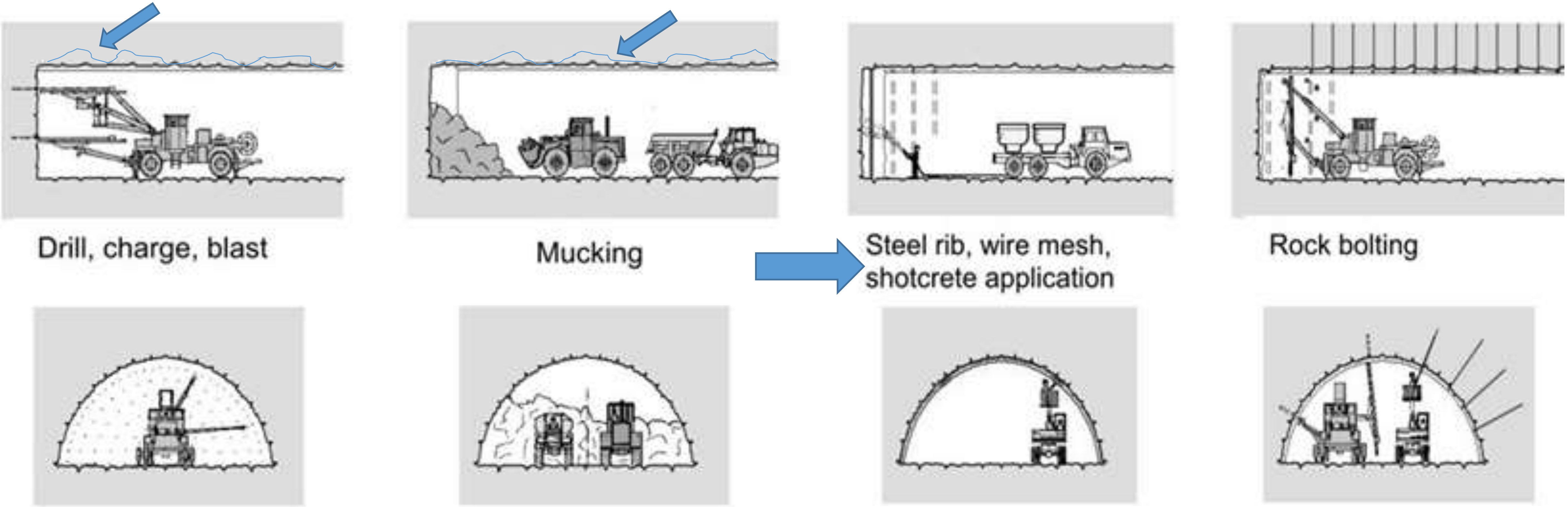
   ……….needs large work force

2. **‘SINGLE-SHELL’ (NMT)**

   (pre-grouting?) + <u>B + Sfr</u> + (RRS?)

   …………. *needs small work force (x 1/10?)*

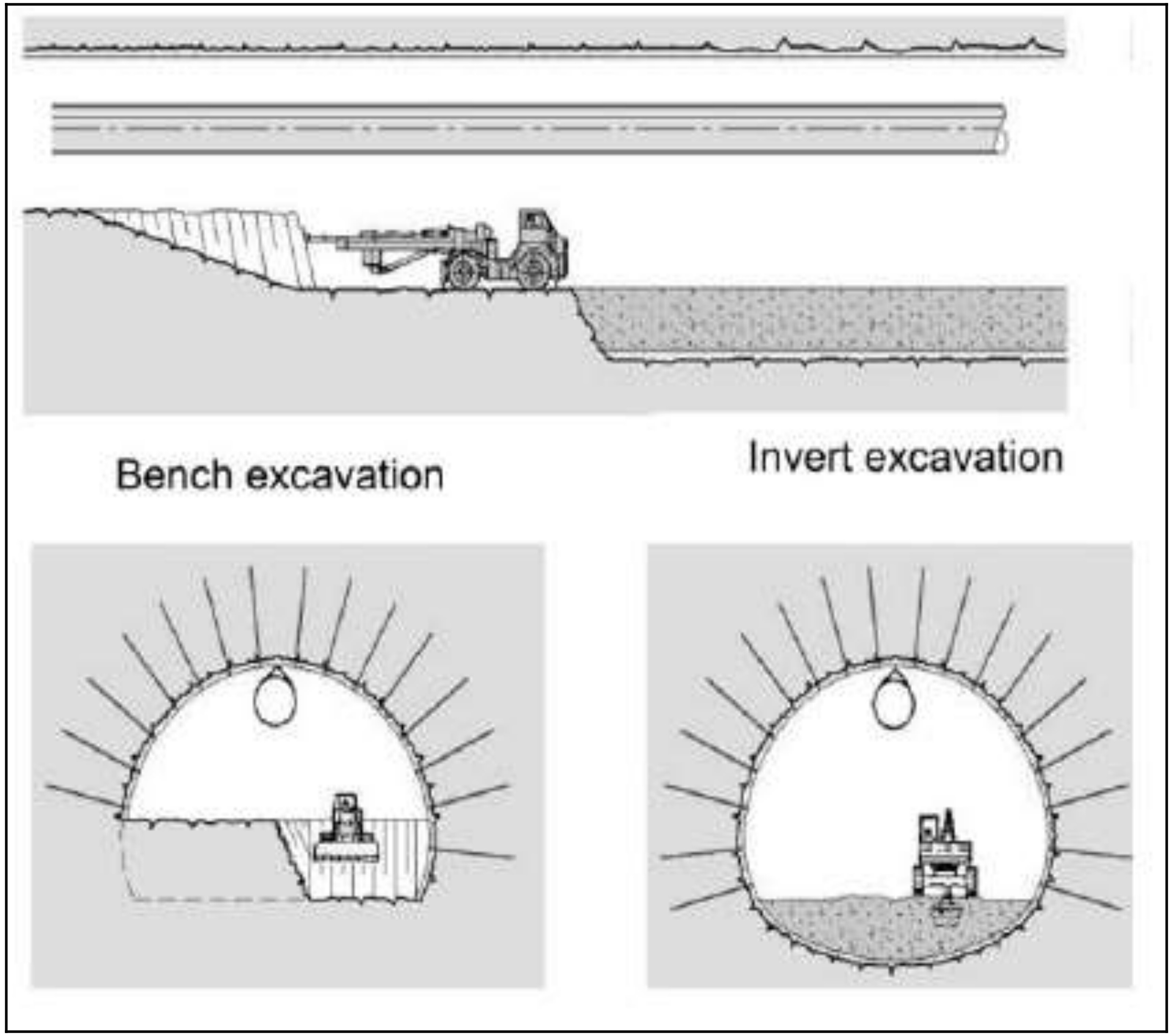
WHAT ARE THE PRINCIPAL OPERATIONS IN NATM?

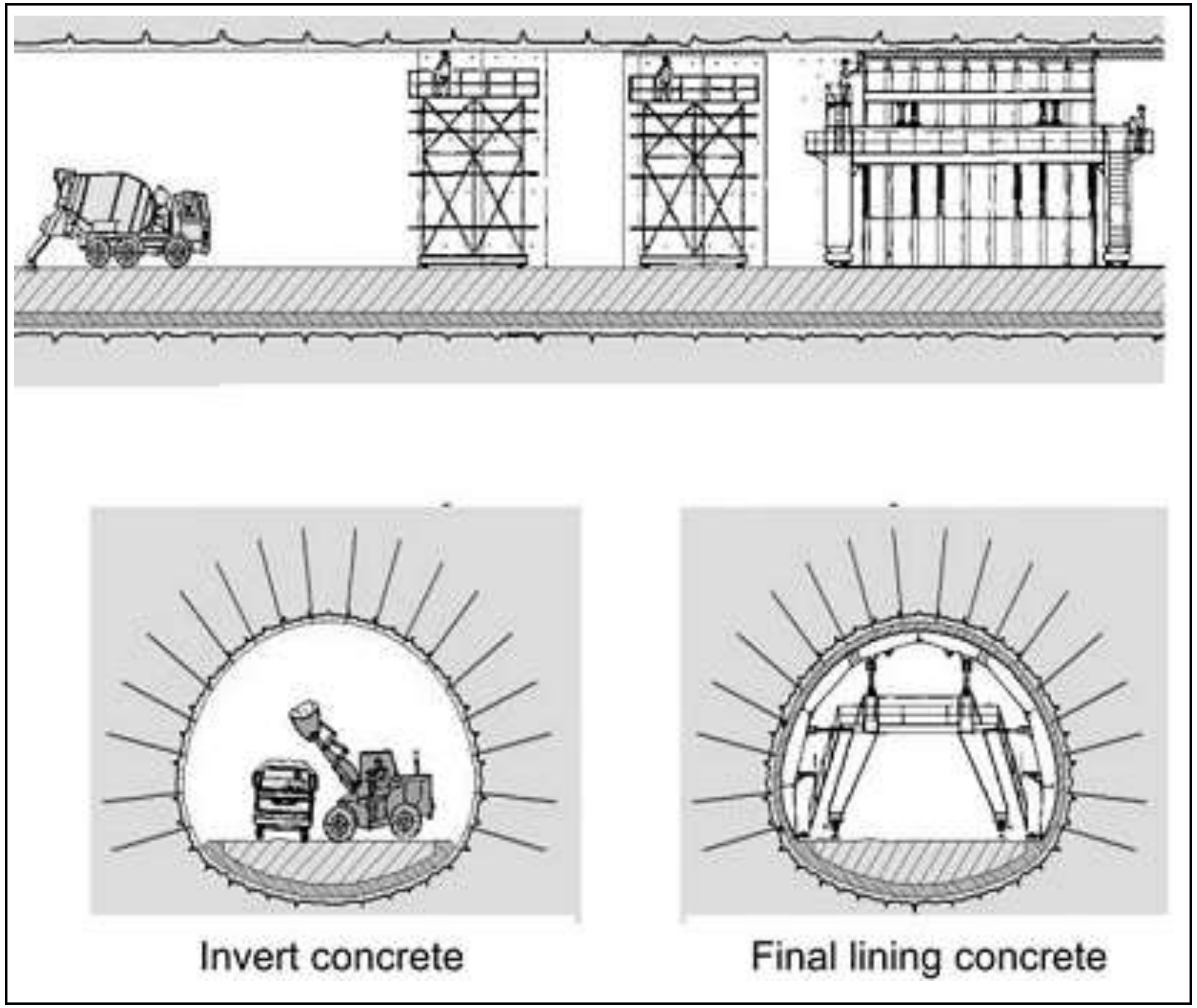


(ASG, 2010. NATM: THE AUSTRIAN PRACTICE OF CONVENTIONAL TUNNELLING)

OVER-BREAK? LATTICE-GIRDER FOOTINGS? BENCHING-DOWN – LATTICE GIRDER EXTENSION? SEVERAL STAGES WITH QUESTIONABLE QUALITY, WHEN WITH OVER-BREAK…….DUE TO PRESENCE OF ROCK AND NEED TO BLAST.

LONG CONSTRUCTION TIMES: LABOUR INTENSIVE

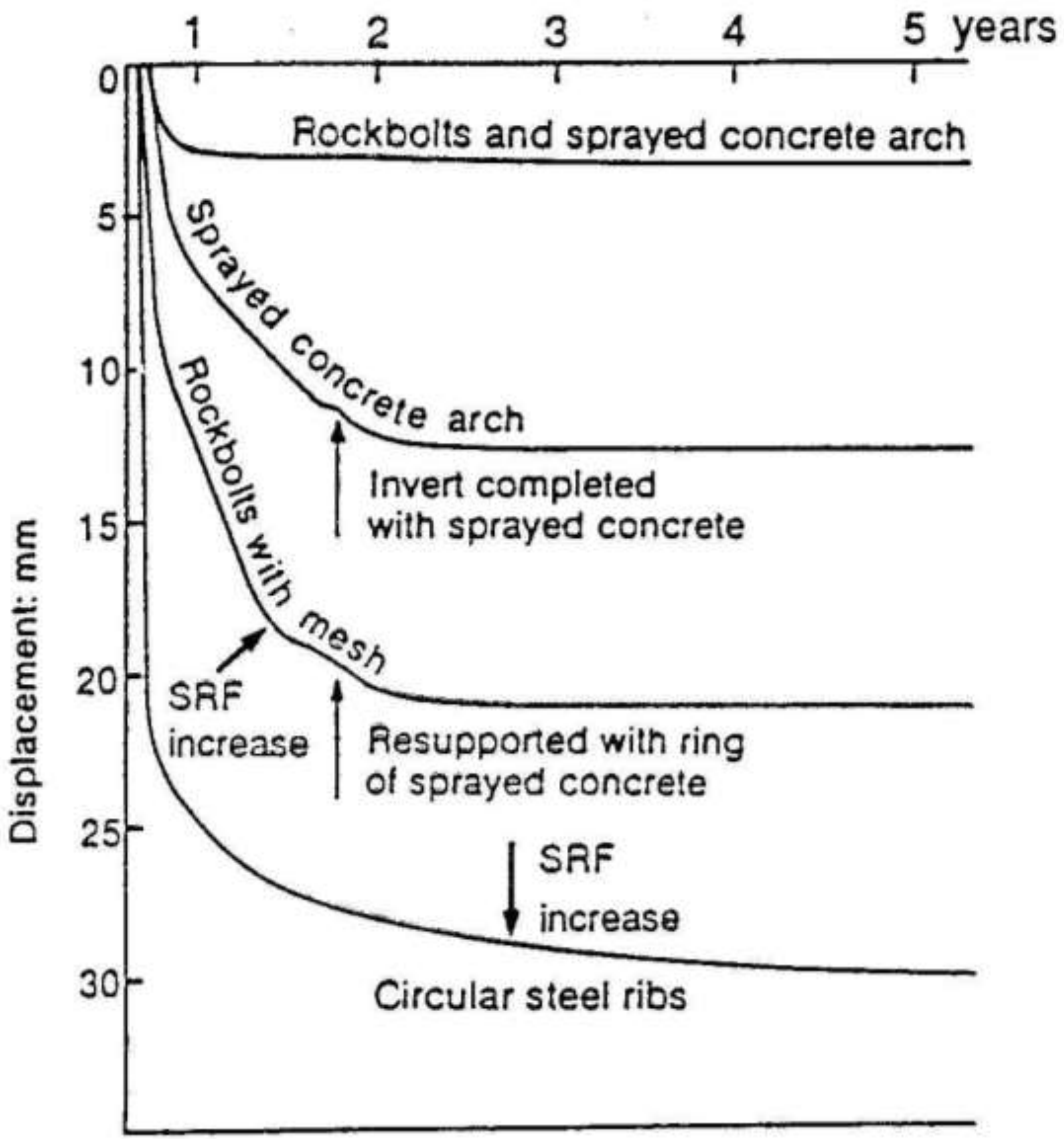


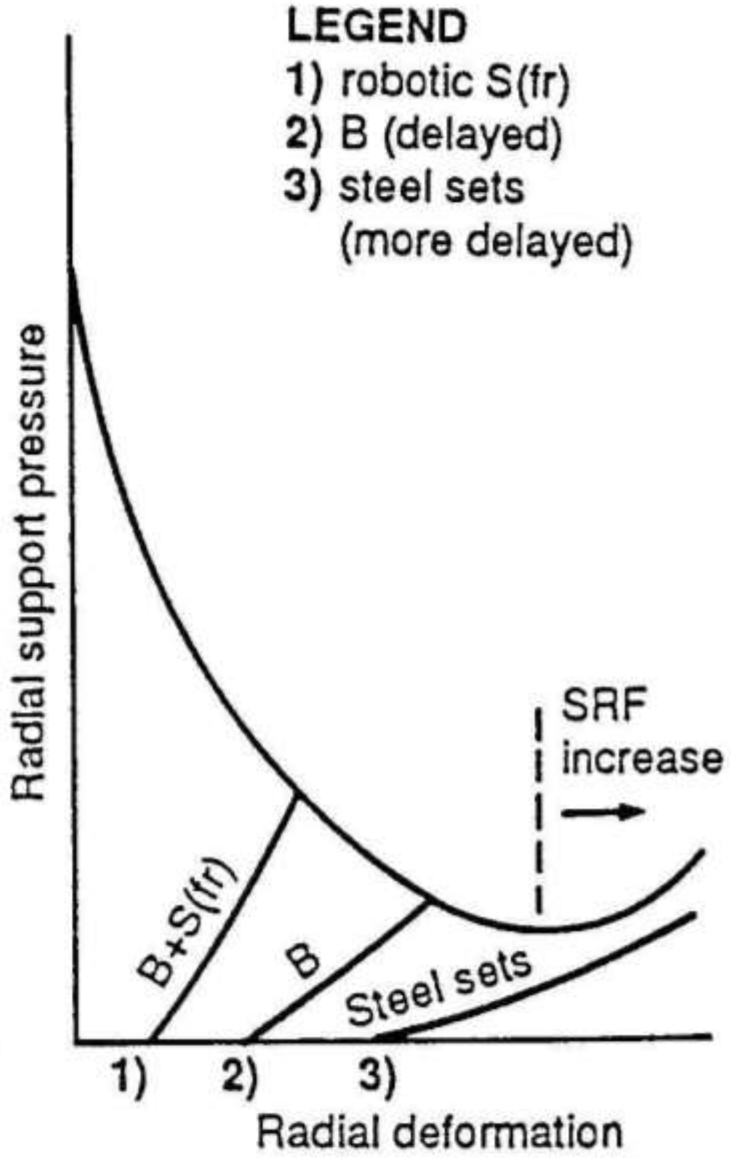


THE TEMPORARY SUPPORT PHASE IS CRITICAL – AND TOO LONG – BECAUSE OF THE DELAY INVOLVED IN PERFORMING ALL THESE FINAL-LINING OPERATIONS

ADEQUATE CONTACT WITH THE ROCK? (IT IS NOT EASY)

ADEQUATE FOOTING STIFFNESS? ADEQUATE RESISTANCE WHEN ’POINT’ LOADED? OWN DEFORMABILITY? ACTUALLY A VERY ’SOFT’ SYSTEM, THEREFORE CAN BE UNSAFE WHEN WAITING FOR THE LINING.





LEFT: Ward et al. 1983.

RIGHT: Barton and Grimstad, 1994.

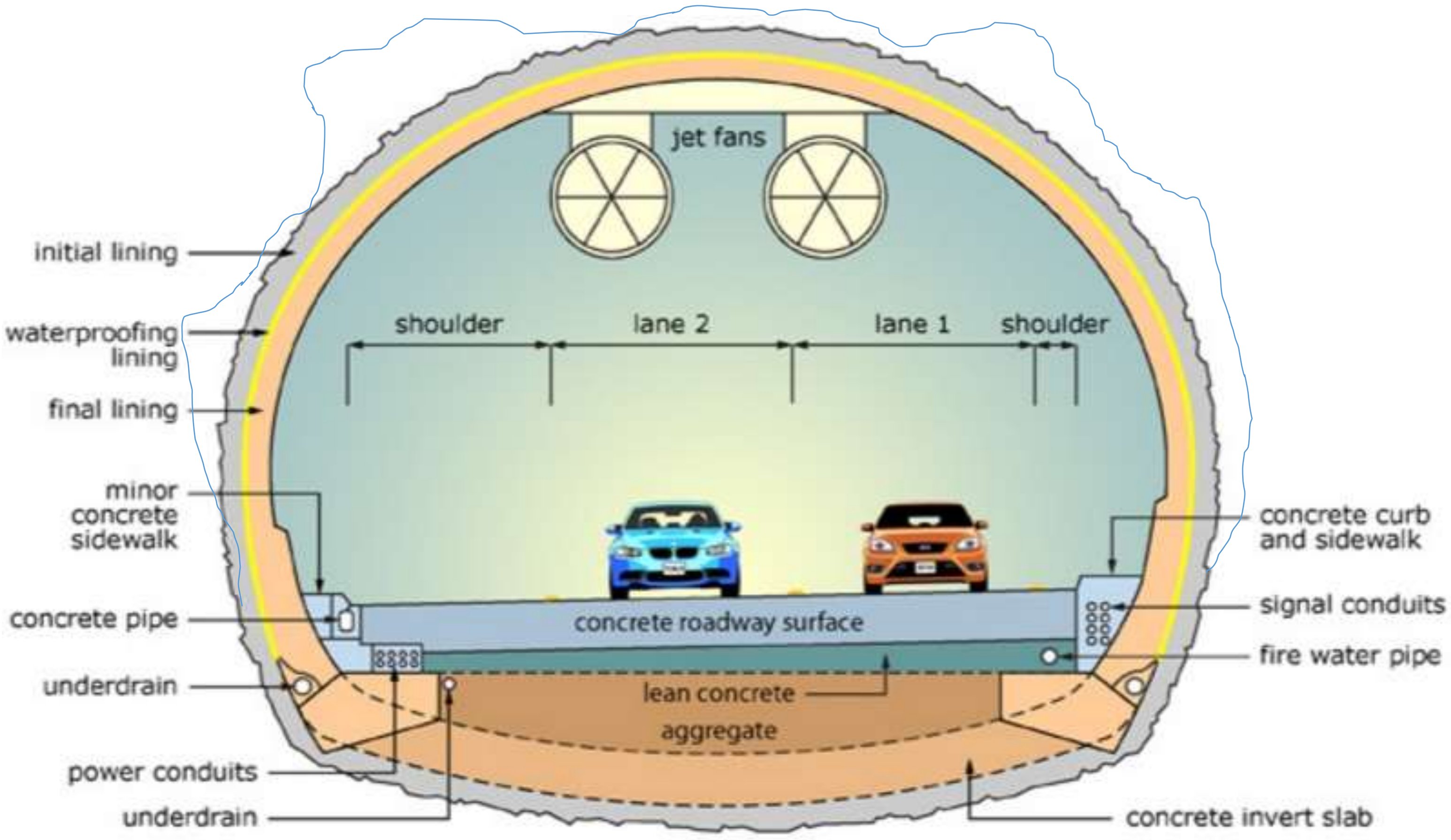
The water-proof membrane phase. Difficult if over-break.

Approximately 12 to 15 km of membrane welds per 1 km of tunnel.
(Like garden swimming pool REPAIR).

FINAL STAGE OF NATM – SHOWN BELOW – IS THE PERMANENT CONCRETE LINING.

An earlier (temporary support) phase of the same project.....not very convincing level of safety. Note mesh and lattice-girder.

What about the reality of over-break?

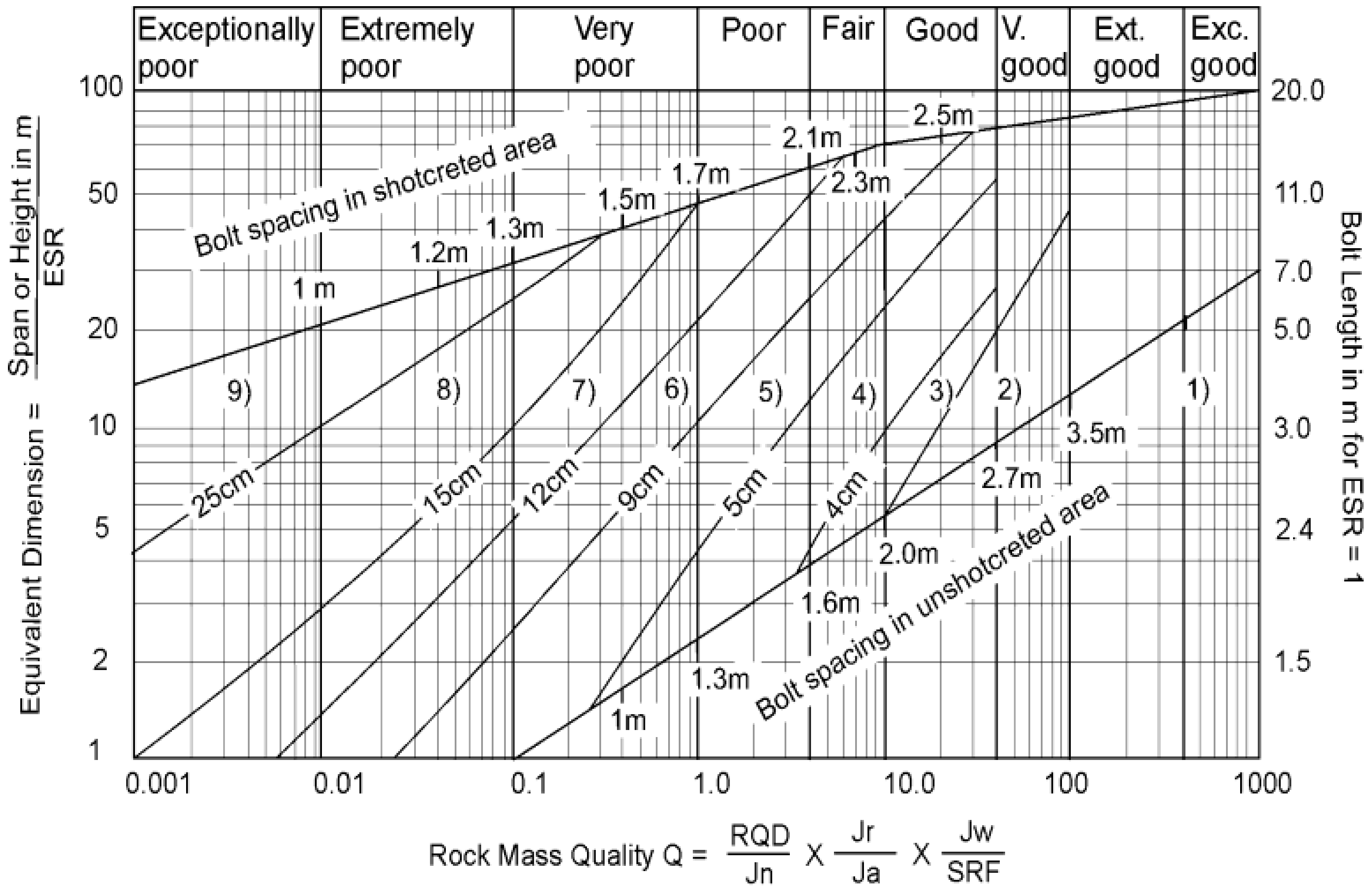


NMT - the Norwegian Method of Tunnelling

1. Q-system logging for selecting support class
2. S(fr)
3. B (utg) - CT-type
4. RRS (rib-reinforced shotcrete arches, bolted)
5. *PRE-GROUTING FOR DRY TUNNEL, DISPLACING WATER*
6. FREE-STANDING, BOLTED PC-ELEMENTS WITH OUTER MEMBRANE for DRY TUNNEL, *BUT ALLOWING DRAINAGE*

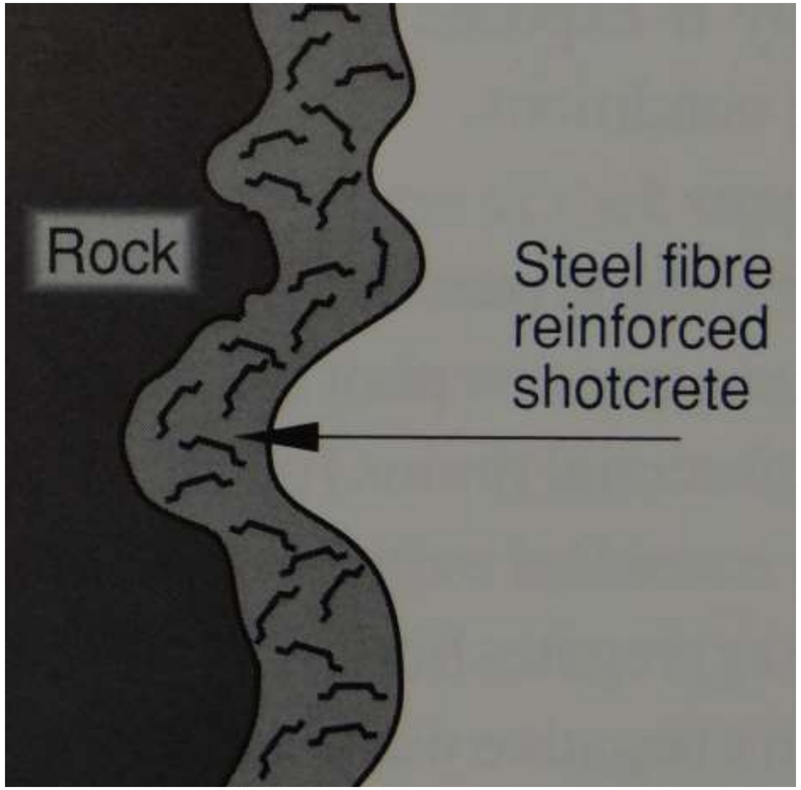
(NMT is 'single-shell'.......................NATM is 'double-shell')

Grimstad and Barton, 1993 Q-update: S(mr) changed to S(fr)

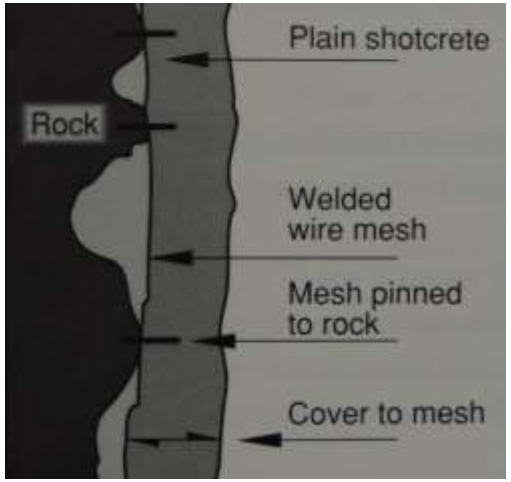


REINFORCEMENT CATEGORIES

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



S(fr) used in Norway and Sweden since 1979

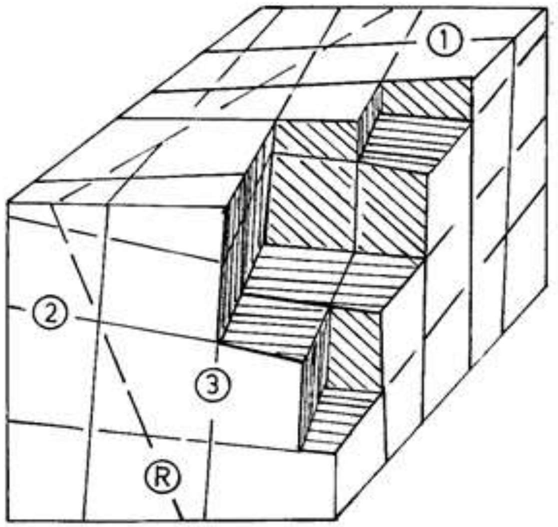
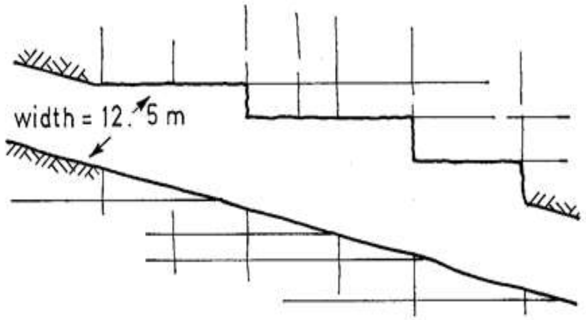


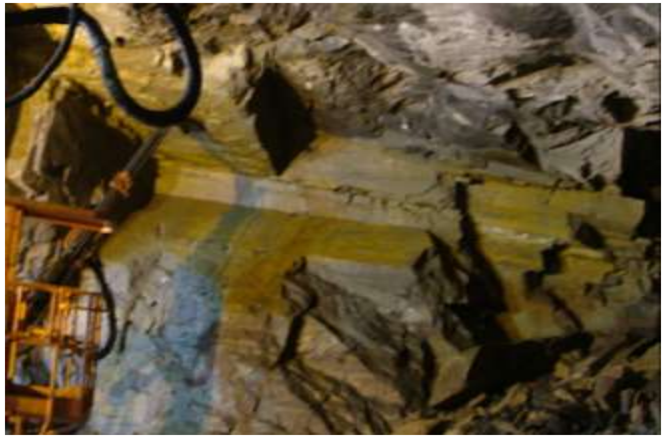
- **The old-fashioned method of temporary support S(mr) which is still recommended in NATM. (A deliberately chosen example showing 'shadow' problems)**

Do not use S(mr), especially not where there is over-break!

S(mr) was dis-continued in early 1980 when using single-shell Q-based NMT.

OVERBREAK
IF
Jn/Jr ≥ 6



Jn = number of sets

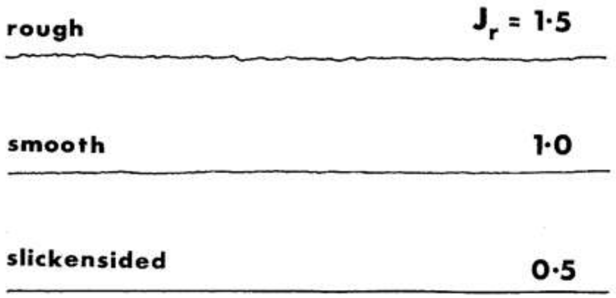
Jr = roughness

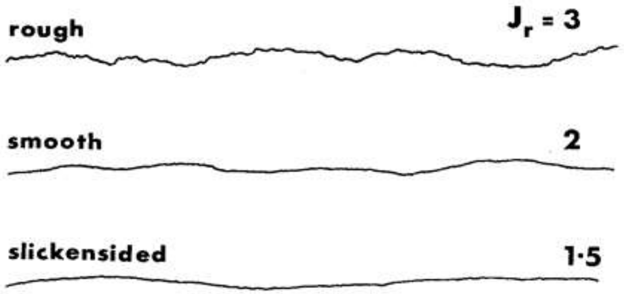
6/1.0	9/1.5
12/2	15/3

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

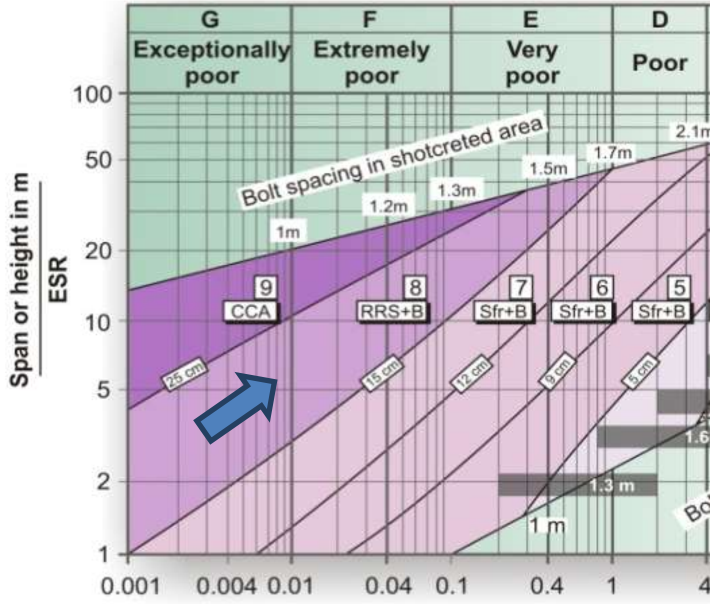
In photos:

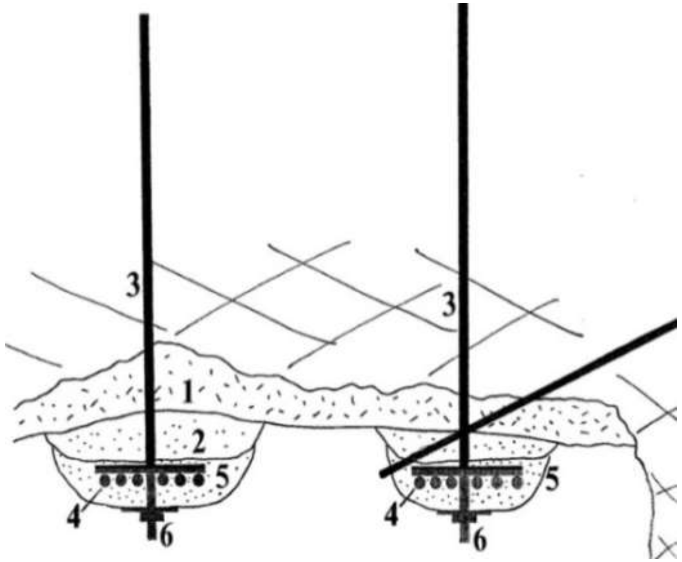
Jn/Jr = 9/1.5





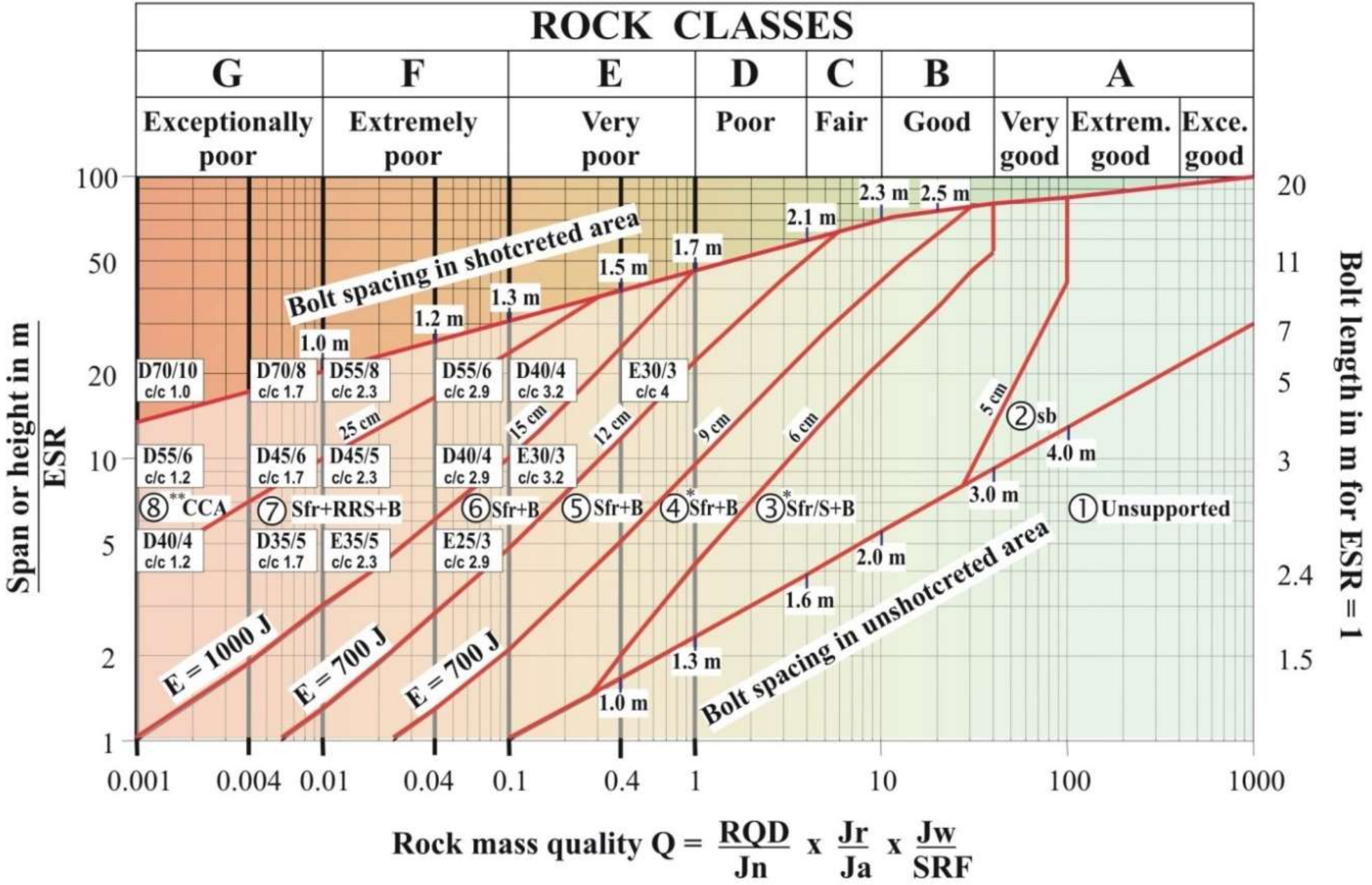
Principles of CT bolt: Right: Joint/crack deformation next to the bolt *does not initiate* a potential process of corrosion, which it might in the case of a conventional bolt without the PVC sleeve. **4-layers of protection remain.**



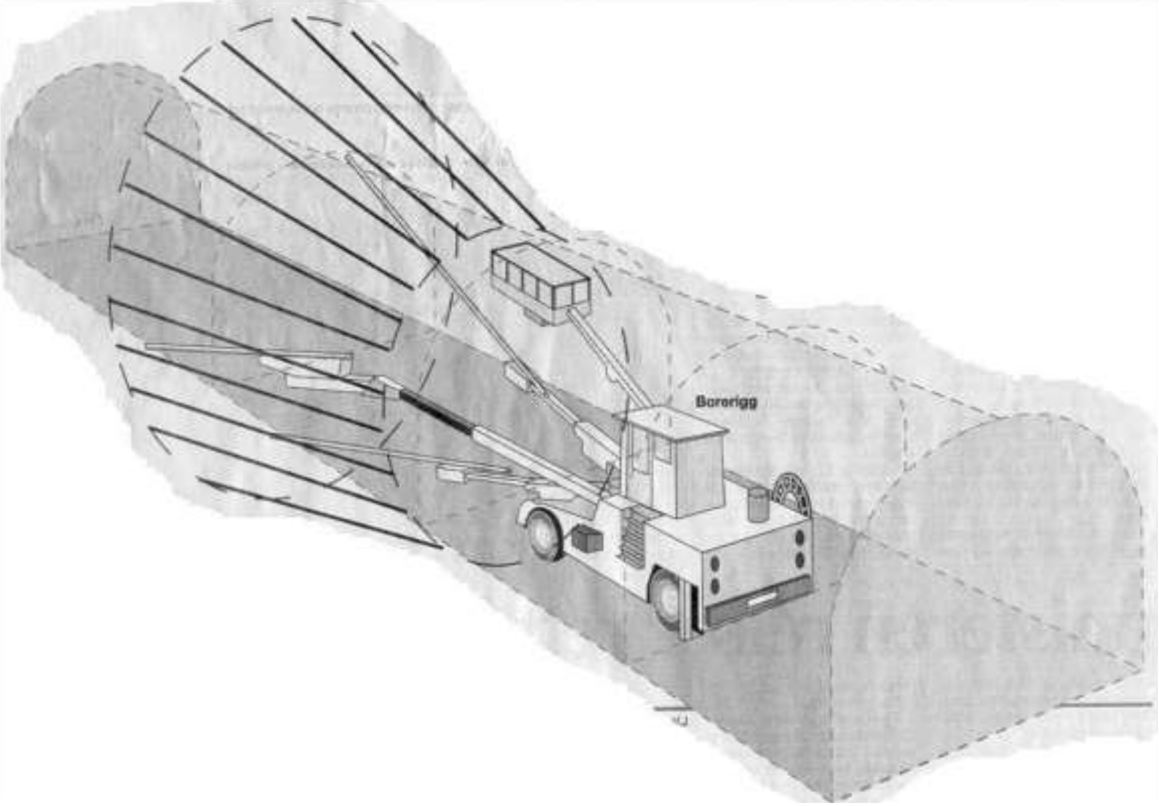


When compared to lattic-girders which are unbolted, RRS (rib-reinforced shotcrete arches) with their systematic bolting, *are far more reliable for faulted rock masses.*

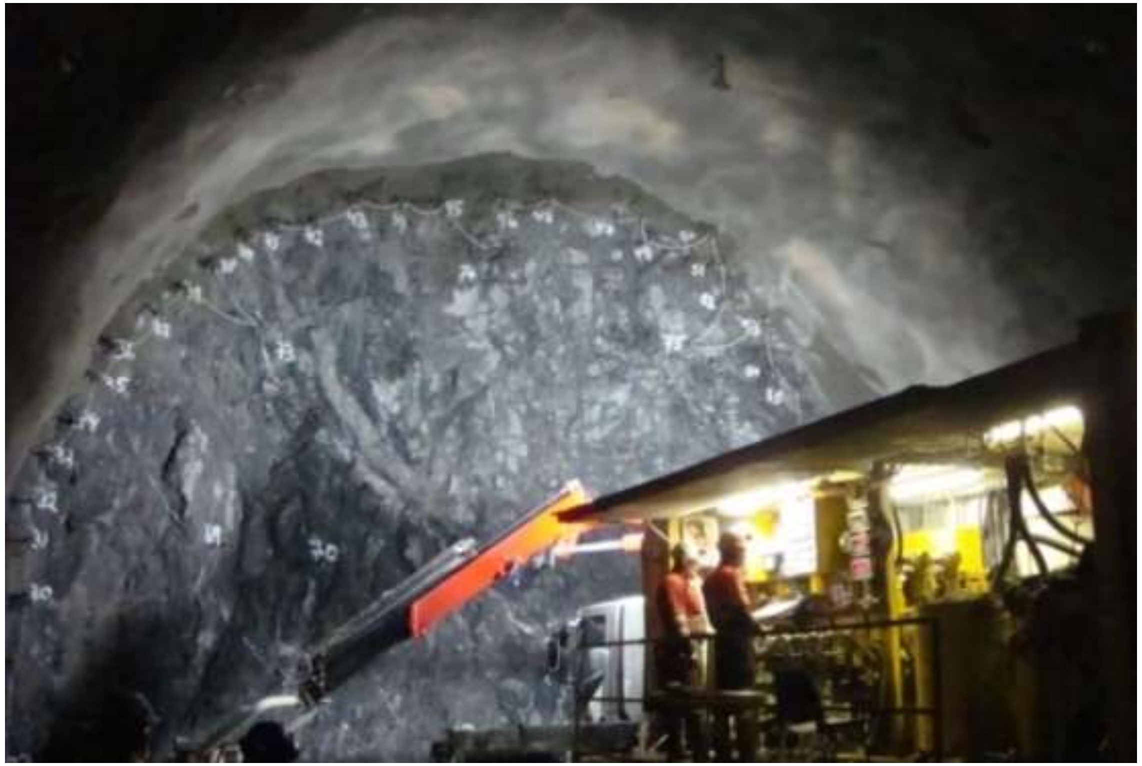
S(fr) arches take care of the over-break.



Barton and Grimstad, 2014 – with details of RRS in boxes



IF THE CHOICE IS *SINGLE-SHELL NMT*: ECONOMY AND PERFORMANCE ARE ENHANCED WITH PRE-INJECTION



EXAMPLE OF PRE-INJECTED SHALES: 110 m2 TWIN-TRACK HIGH SPEED RAIL TUNNEL

NMT high-speed rail tunnel 110m2

1. Pre-injection (of shales, limestones, igneous dykes)
2. S(fr)
3. B (CT-type)
4. (RRS not needed due to pre-injection)

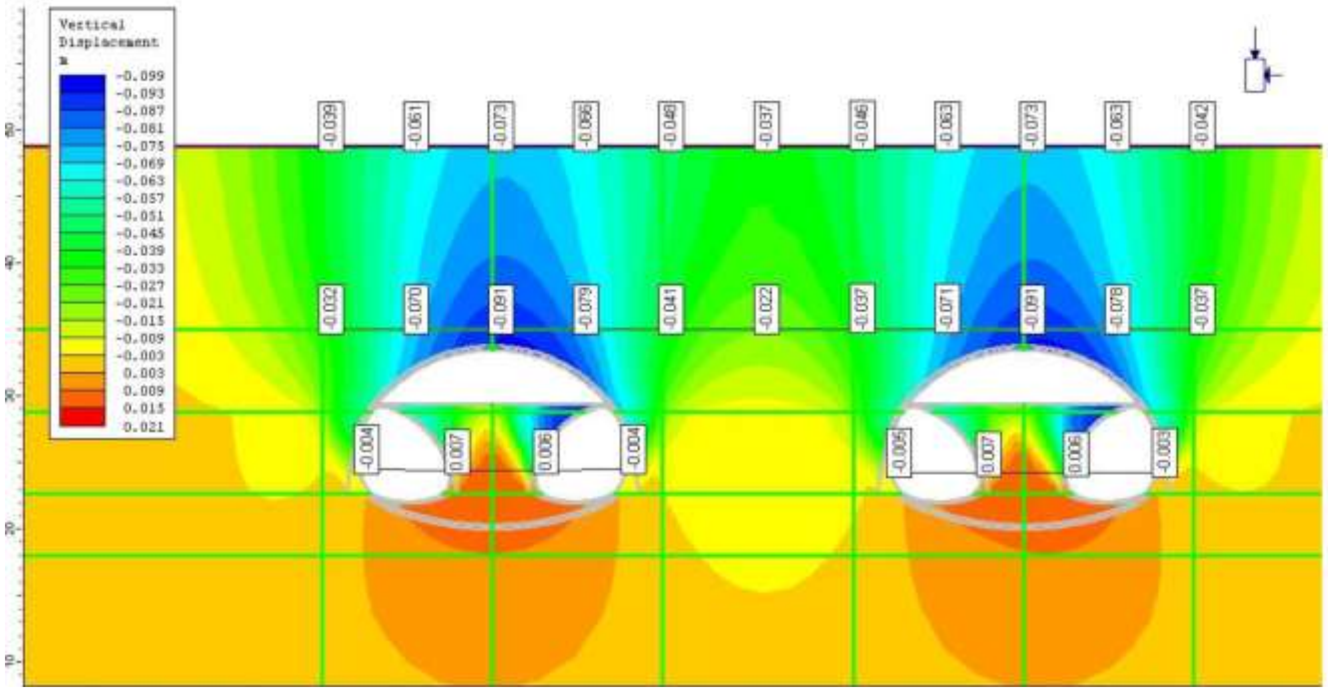
COLLAPSE # 2

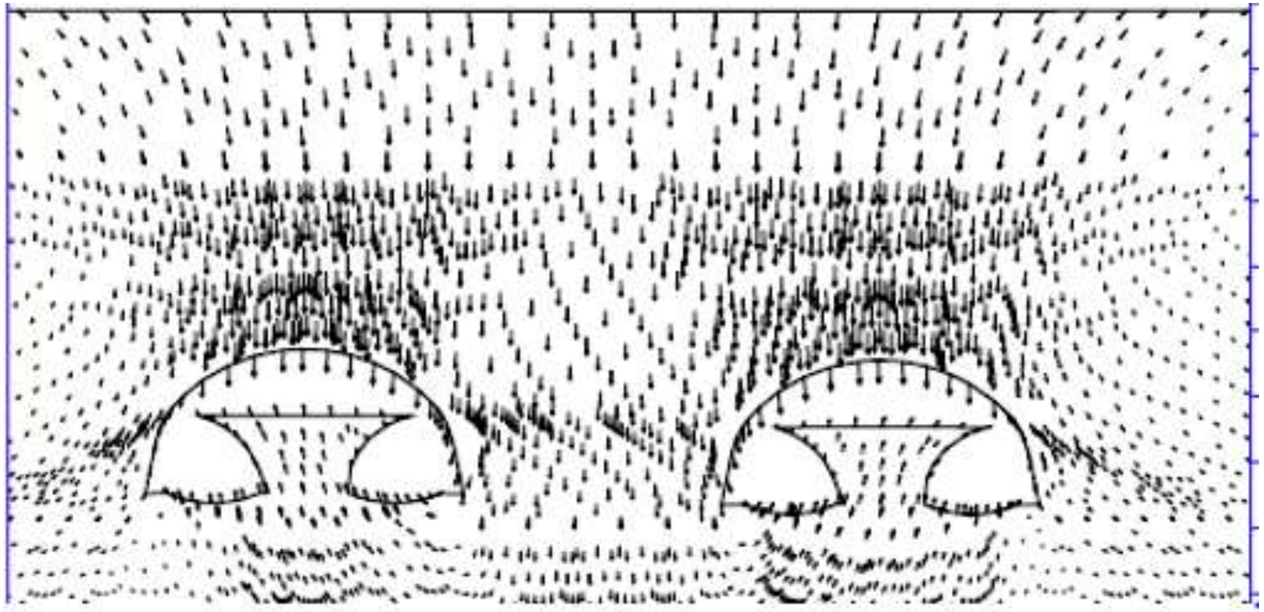
AN NATM TWIN-MOTORWAY TUNNEL

(with light, inadequate, temporary support, and anisotropic challenges from an actual rock mass)

OPTIMISTIC 'LIGHT' LATTICE-GIRDERS and UNREINFORCED SHOTCRETE. NO ROCK BOLTS.

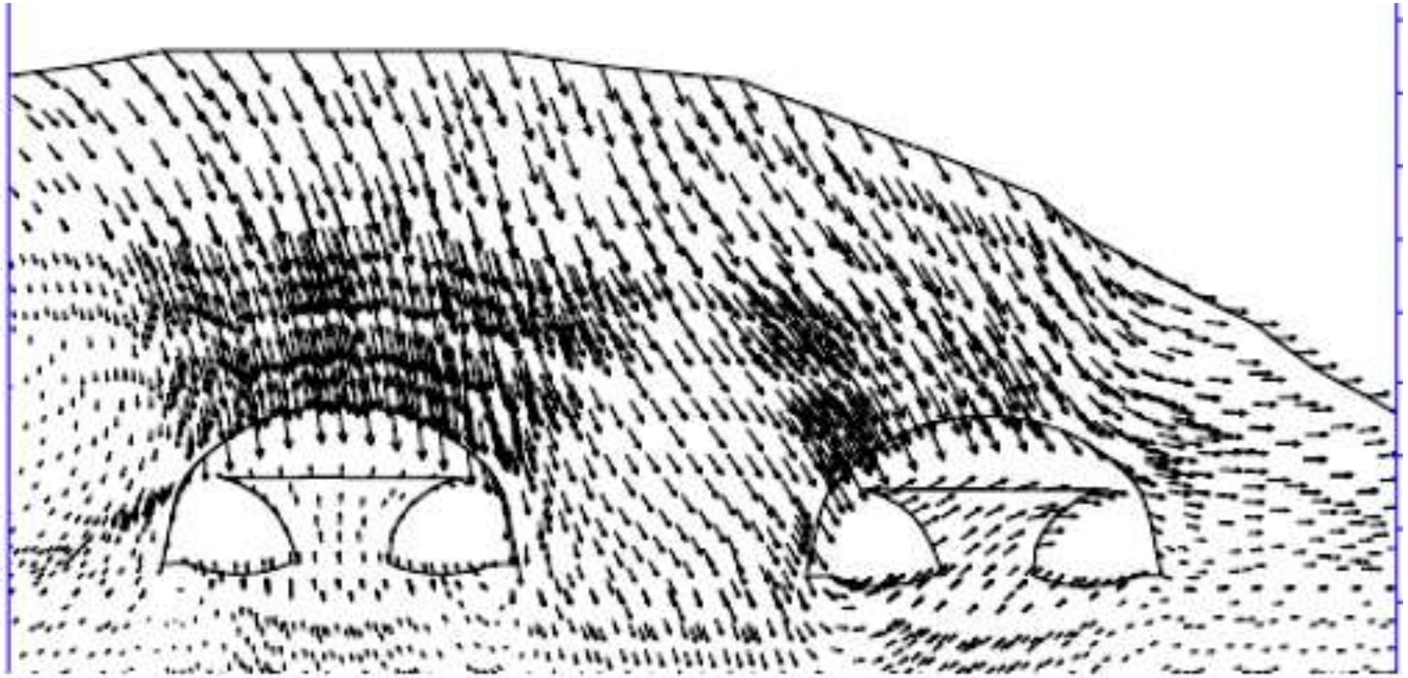
- **OPTIMISTIC AXISYMMETRIC UNIFORM LOADING ASSUMED.**
- **WHAT HAPPENS WITH VERTICALLY JOINTED PHYLLITE?**
- **WHAT HAPPENS WITH OVER-BREAK AND A WEATHERED DIKE?**



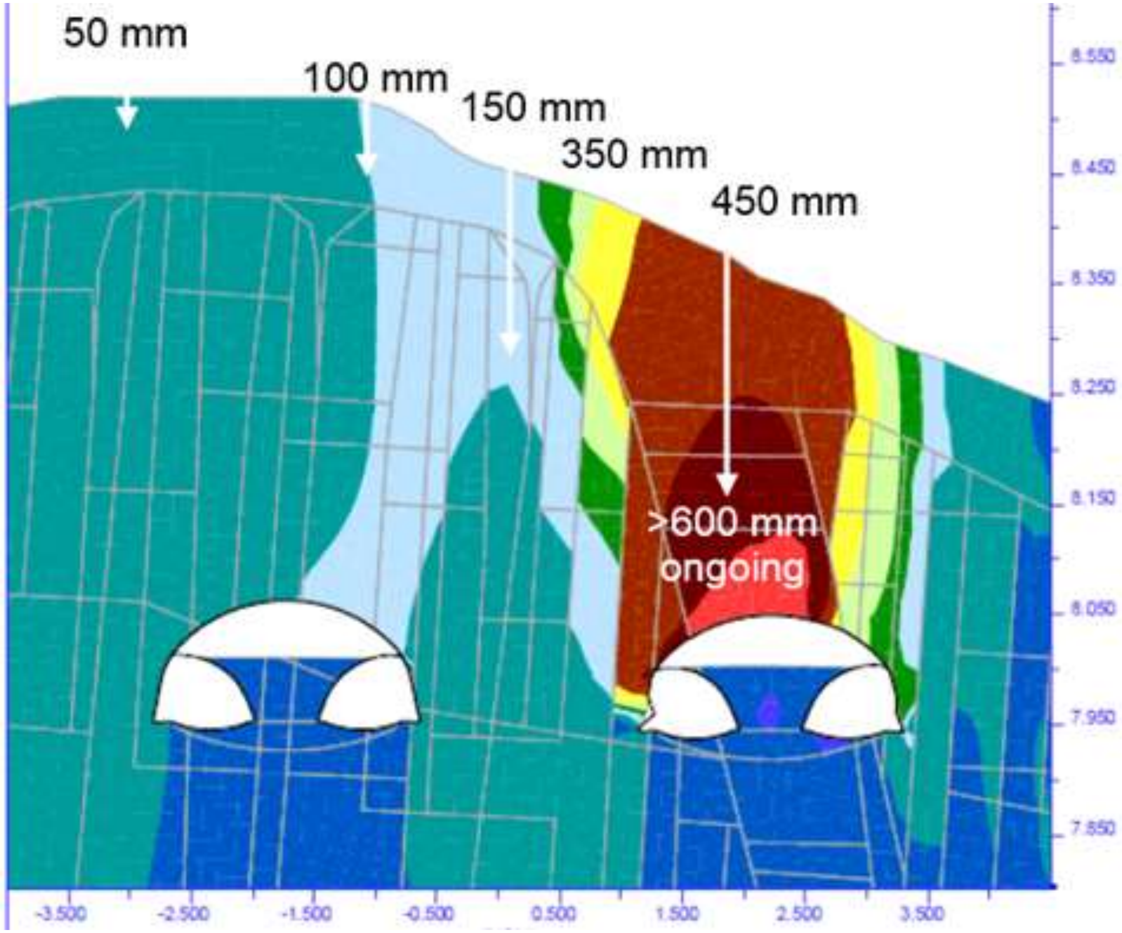


THE OPTIMISTS

A NOT QUITE SO SIMPLE 2D 'REALITY' – WITH THE STRONG EFFECT OF A SLOPING HILLSIDE NOW INCLUDED



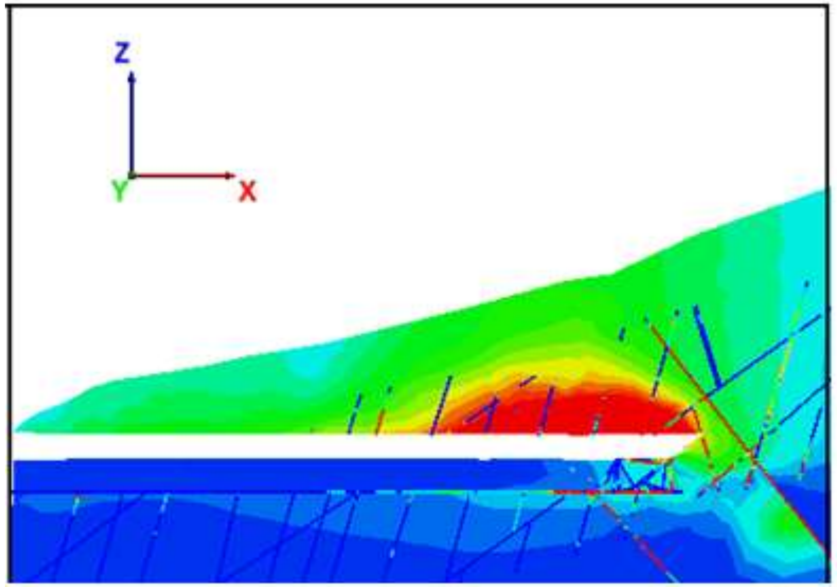
WEATHERED PHYLLITE (WITH STEEP DIP) AS SEEN IN THE NEIGHBOURHOOD OF THE TWIN TUNNELS

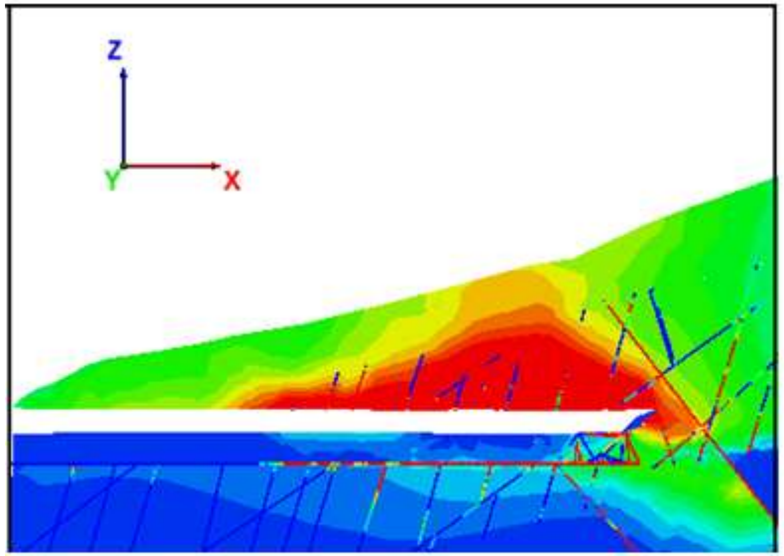


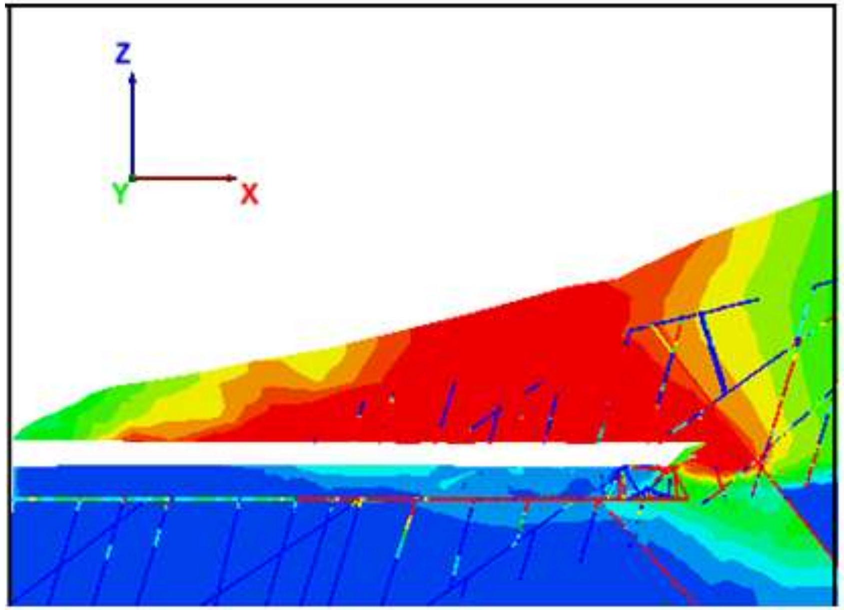
SOME OF THE HARSH 2D 'REALITY', AND RAPID PROGRESSION TOWARDS MASSIVE FAILURE

(Dr. Stavros Bandis, UDEC)

Due to limitations of the design, retrogressive failure back to the portal. All 140 m lost (LATER X 2!)







3DEC modelling by

Dr. Stavros Bandis

THEN THE LEFT-SIDE....................FIRST THE RIGHT-SIDE
(≈ 140 m COLLAPSE) ....(≈ 140 m COLLAPSE)

SOIL, THEN SAPROLITE, THEN WEATHERED PHILLITE, DIKE

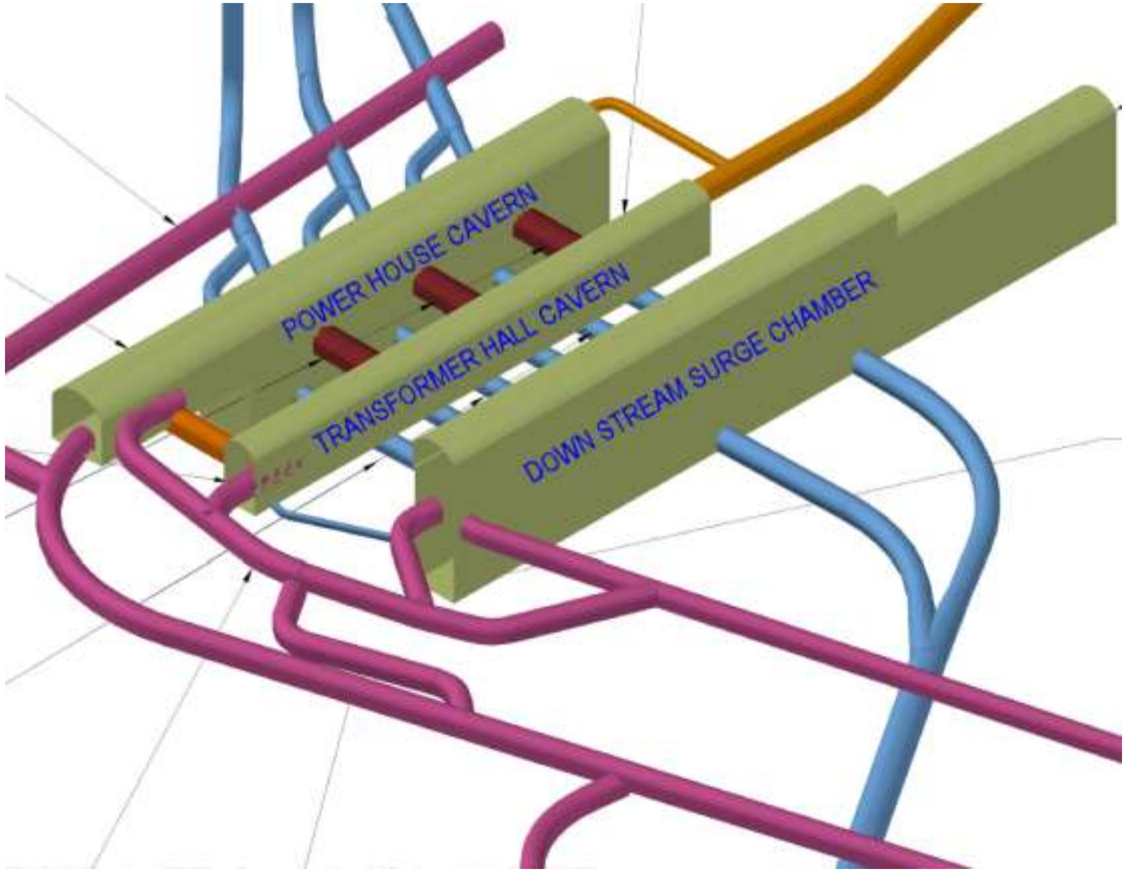
ROTATED ROAD, TREES AND TELEGRAPH POLE (after failure of second tube)

COLLAPSE # 3

CAVERN ARCH WITH STEEL SETS

(with no change of design when encountering fault zone on one 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

The attempt to remove some 15,000 m^3 of the fallen rock, revealed the destruction of the 'heavy' steel sets in the arch.

(It was too dangerous to continue)

A total of 70,000 m^3 may now have fallen. A cavity with approximate dimensions L x H x W of (50-60) m x (40-50) m x (30-35) m has to be stabilized, then victims recovered.

(FURTHER) LIMITATIONS OF LATTICE-GIRDERS

(OK for soil, saprolite, but when blasting begins in rock tunnel: over-break. The lattice-girder may then behave in a very deformable way.)

WHAT HAPPENS TO LATTICE GIRDERS WHEN A TUNNEL (OR CAVERN) CROSSES A MAJOR JOINT OR FAULT?

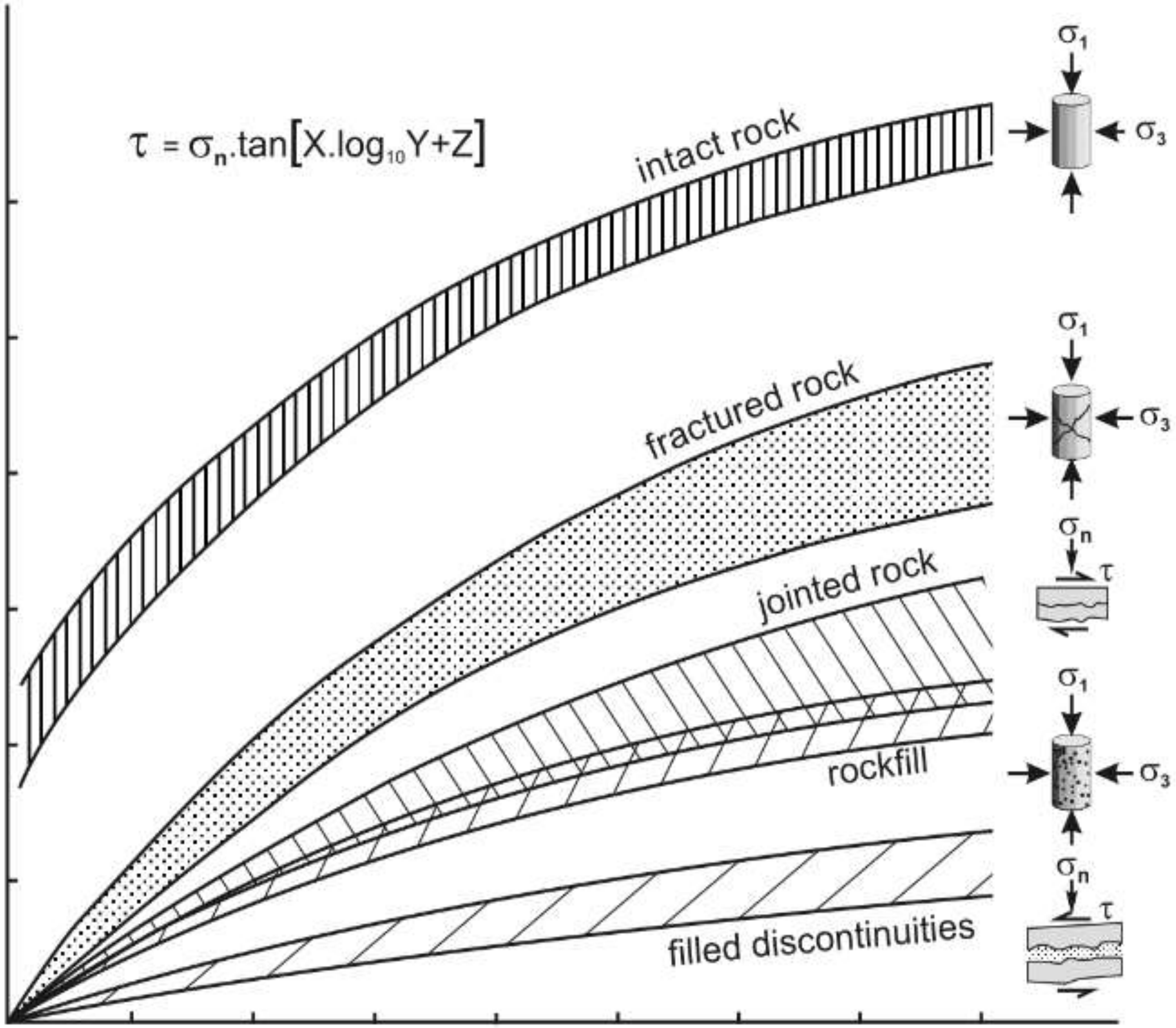
HIGHLY NON-UNIFORM LOADING IS INEVITABLE.

BESIDES THE POTENTIAL FOR NON-UNIFORM LOADING OF INADEQUATE SUPPORT (LATTICE GIRDERS) THE OTHER 'VIOLATION' OF CONVENTIONAL ASSUMPTIONS IS THAT THE ROCK MASS RESISTANCE ***MAY NOT*** CONSISTS OF
'$c + \sigma_n \tan \phi$' (LINEAR M-C or NON-LINEAR H-B)

PROGRESSIVE FAILURE: APPLYING TO LARGE TUNNELS, CAVERNS, AND MAJOR SLOPES WILL OFTEN COMPROMISE THE ***'c plus φ'*** ASSUMPTIONS.

BIGGEST OPEN-PIT MINE FAILURE EVER: KENNEKOTT COPPER BINGHAM MINE IN UTAH – MAYBE 70,000,000 m^3 OF WASTE ROCK AND ORE. CAUSED 5.1 Mag. AND 4.1 Mag. SEISMIC EVENTS, WITH 1½ HOURS SEPARATION.

NO *LOSS OF LIFE – DUE TO MONITORED PROGRESSIVE FAILURE. SO FAILURE WAS PRESUMABLY STEP-BY-STEP OVER-COMING OF THE VARIOUS AVAILABLE STRENGTH (OR WEAKNESS) COMPONENTS.*



LARGE-SCALE LOADING / OR UN-LOADING OF ROCK MASSES (i.e. big slopes, big dams, big underground excavations) IS NOT DESCRIBED BY CONVENTIONAL '$c + \sigma_n \tan \varphi$' (i.e. Mohr-C, Hoek-B)

THERE MAY BE FOUR (non-linear) COMPONENTS, EACH *MOBILIZED AT DIFFERENT STRAINS*.

THE MOST IMPORTANT COMPONENT IS THE JOINT SETS, (not an algebraically modified intact rock 'H-B strength' as optimistically used in continuum modelling).

SO WE CANNOT/SHOULD NOT ADD THE COHESIVE AND FRICTIONAL STRENGTH COMPONENTS, AS IF ALL RESISTED TOGETHER AT THE SAME SHEAR STRAIN/DISPLACEMENT.

CONCLUSIONS

1. Massive unexpected failures of tunnels and caverns may be a ‘logical’ combination of unexpected non-uniform loading, non-uniform strength, and ‘unexpected’ poor performance of some conventional tunnel/cavern support methods.

2. If isotropic continuum modelling is performed to ‘design’ tunnel / cavern support, one must expect surprises when the anisotropic and non-uniform reality engages with the support. A big part of the problem arises due to over-break and non-uniform structural geology.

3. Lattice girders (and steel sets) are fabricated from the hardest of materials typically used in civil engineering: steel. Suprisingly, they nevertheless represent one of the *most deformable components* of tunnel /cavern support (due to over-break, non-uniform loads, bending, deforming footings).

4. Bolted (where possible) steel-fiber-and-steel-bar reinforced arches of S(fr) called RRS (‘rib-reinforced shotcrete’ in NMT single-shell, Q-system) are in intimate contact with the rock, even when there is over-break, and they do not require (deformable) footings since they are 1m c/c bolted.