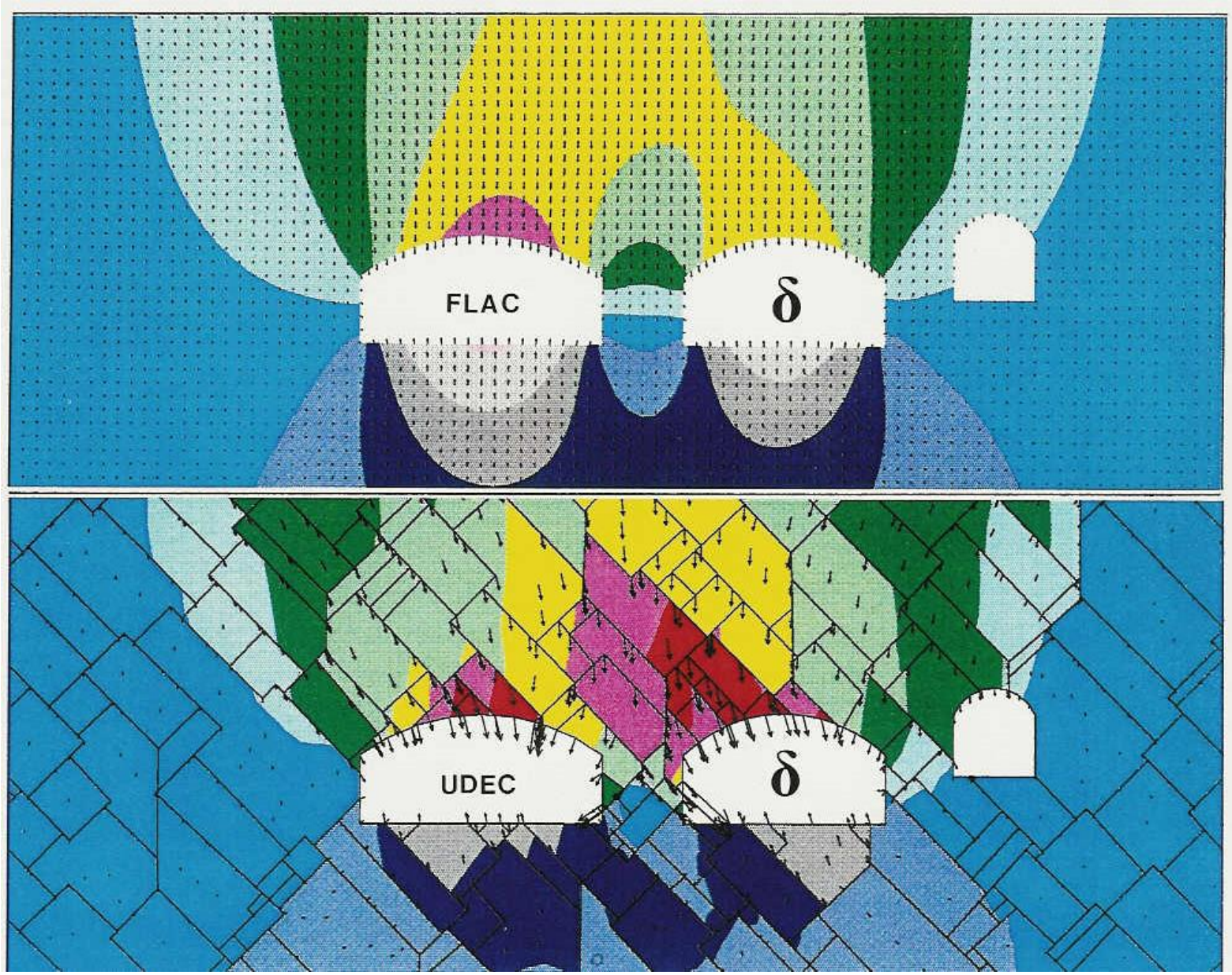
CONTINUUM OR DISCONTINUUM MODELLING – THAT IS THE QUESTION (also in mining)

Nick Barton, NB&A, Oslo, Norway

SOME THOUGHTS AT THE BEGINNING

- Rock masses are by definition assemblies of rock blocks separated by joint sets and less frequent faults.
- They are not continua. Yet so often they are modelled as if they were without joints, without anisotropy.
- Of course this is easier. But is it of value?
- Perhaps it can even mislead us **– *and you the mine owners.***

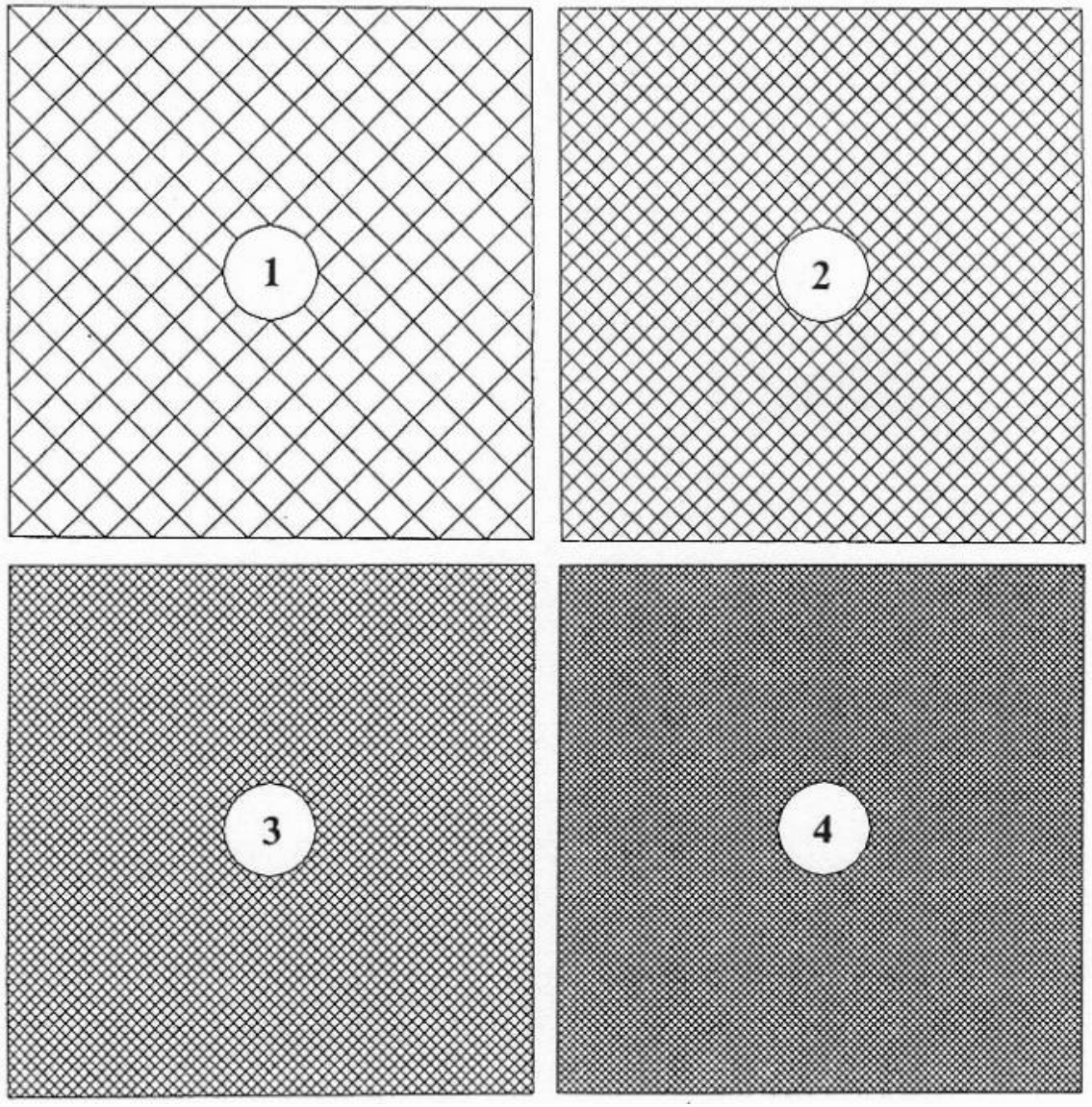


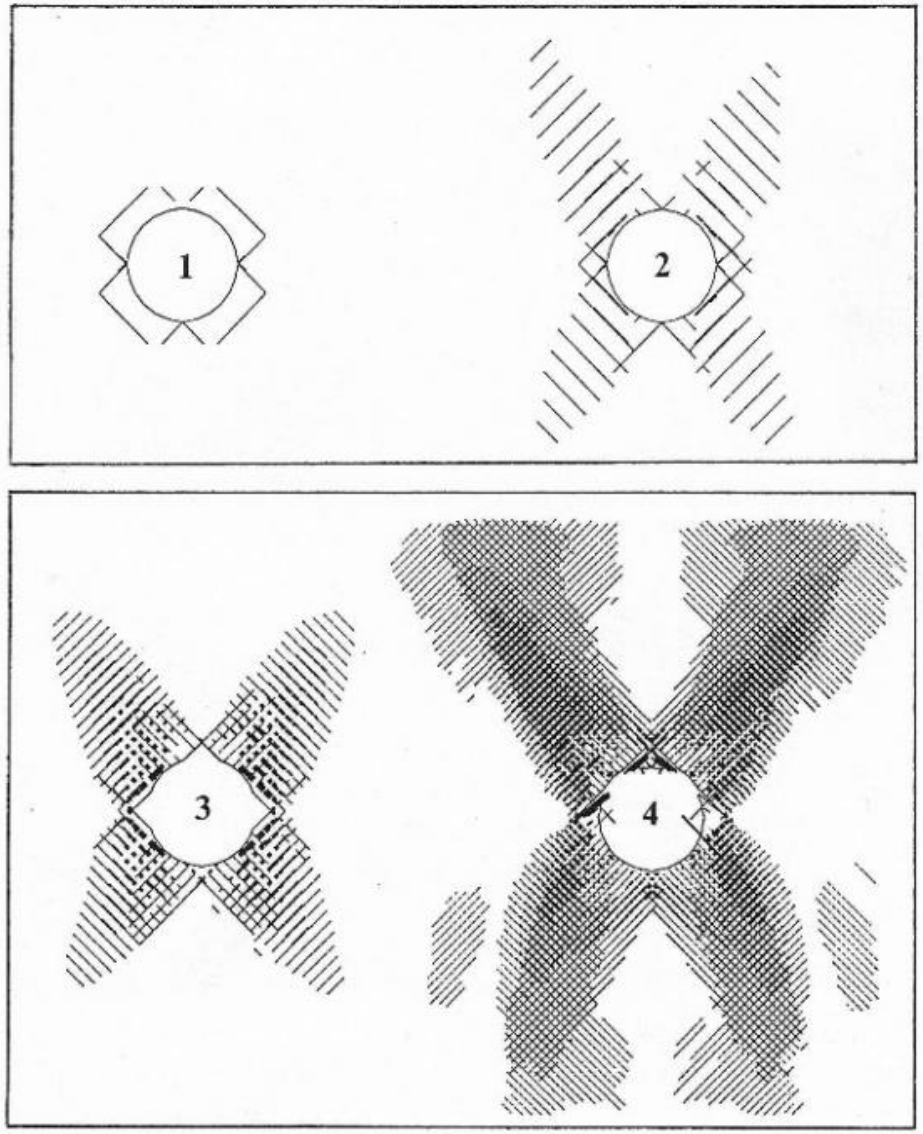
Same tunnel geometry, same modulus.

Which model teaches us something of value?

Blocks are important. Block-size too! EDZ is affected.

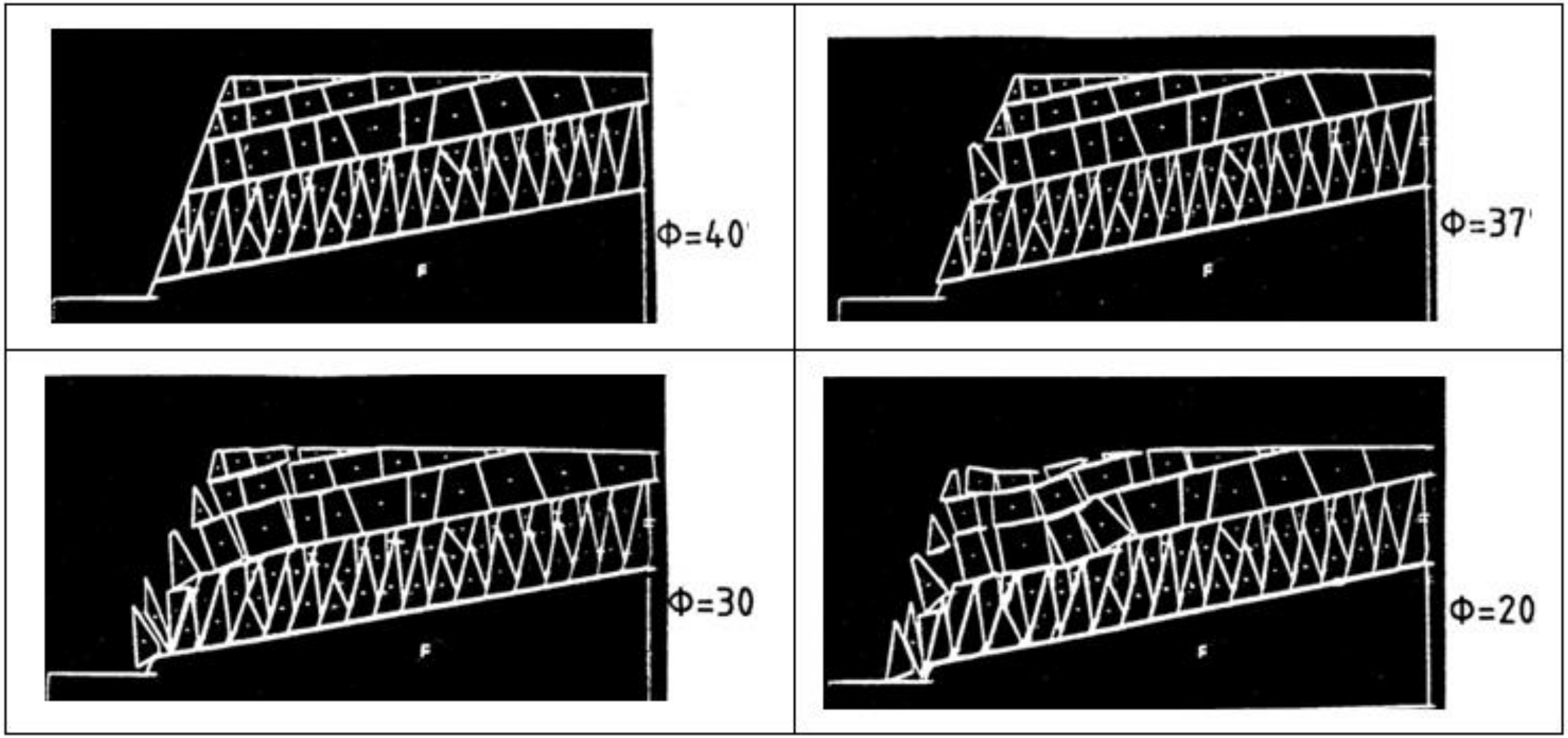
(Of course idealized simple models here. Shen and Barton, 1997)





FROM THE WORLD OF CIVIL ENGINEERING. TUNNELS CAN BE TOO CLOSE IF POOR ROCK CONDITIONS AND/OR HIGH STRESS.

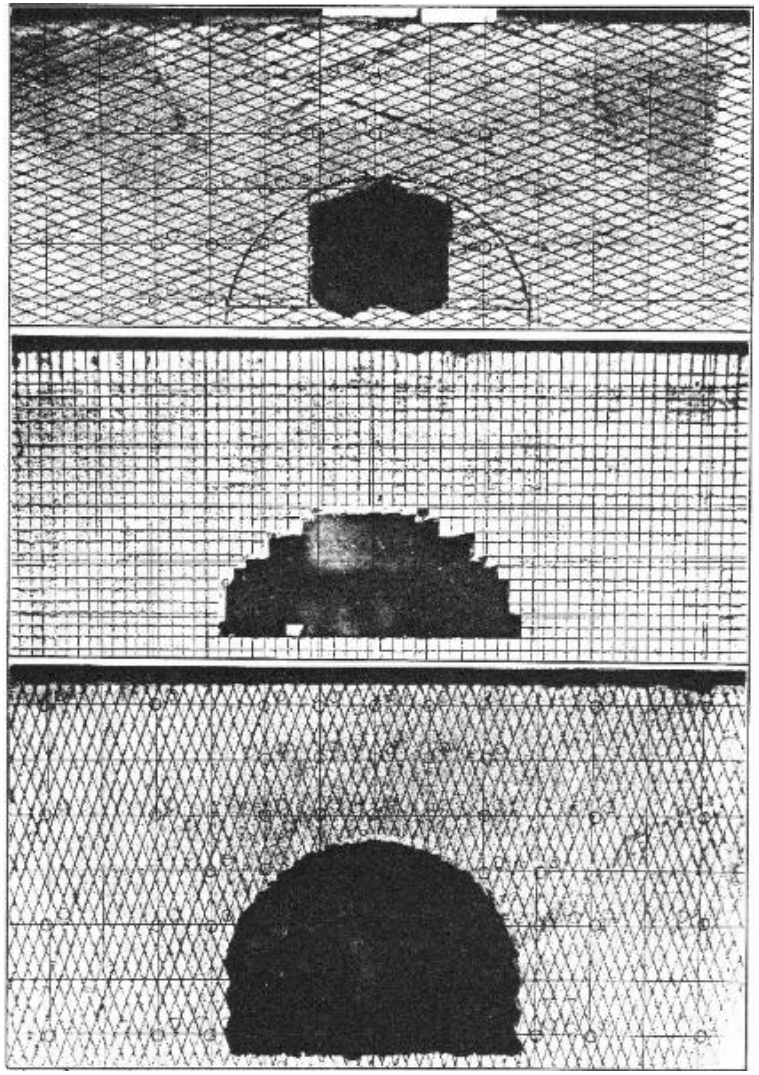
AN EMPIRICAL FINDING!

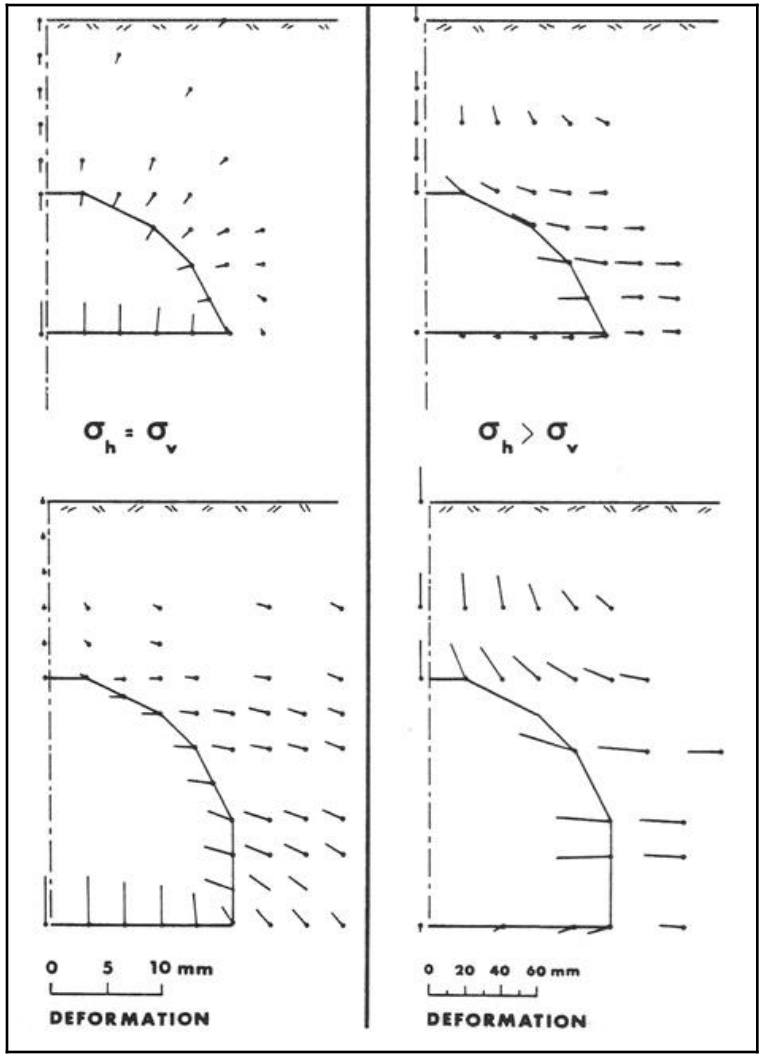


ONCE DECIDING THAT BLOCK MODELLING MAY BE IMPORTANT – WHAT ABOUT BASIC INPUT DATA? (Cundall et al. 1977)

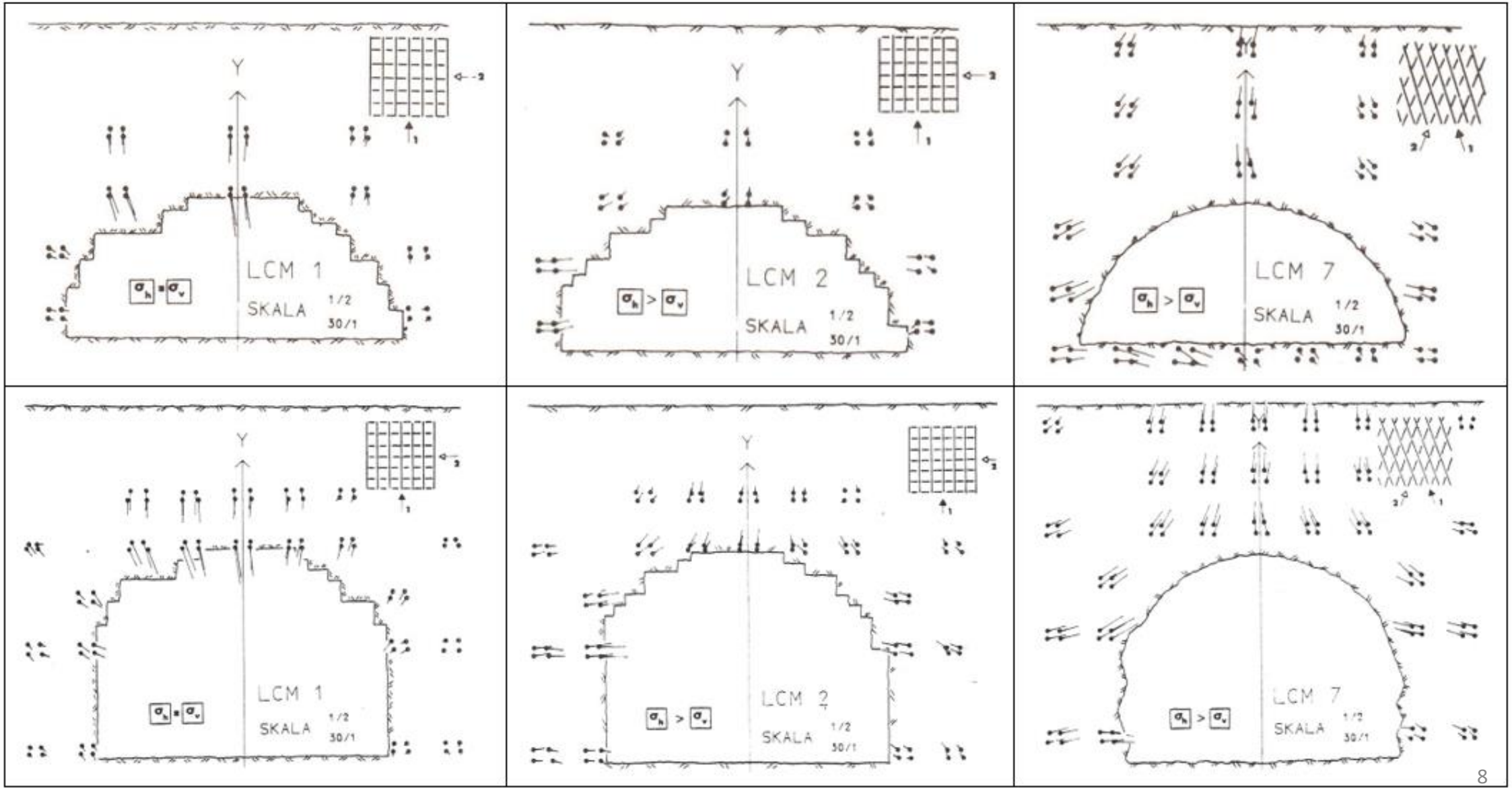
SOME EARLY LESSONS FROM PHYSICAL MODELS

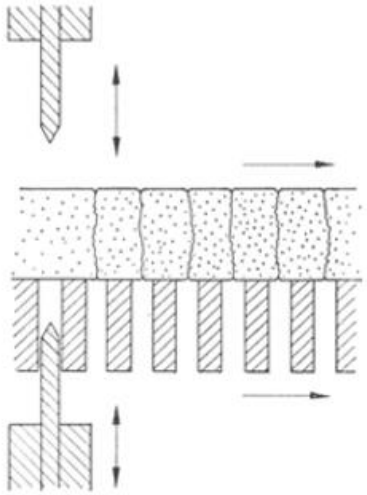
(Barton and Hansteen, 1979)

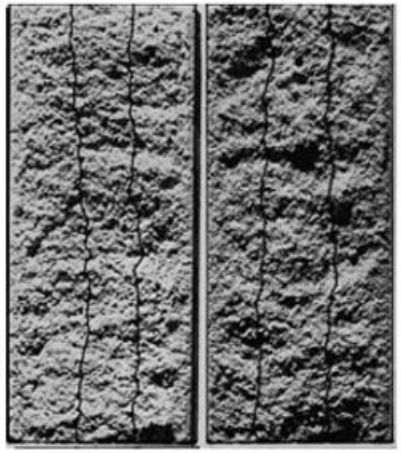


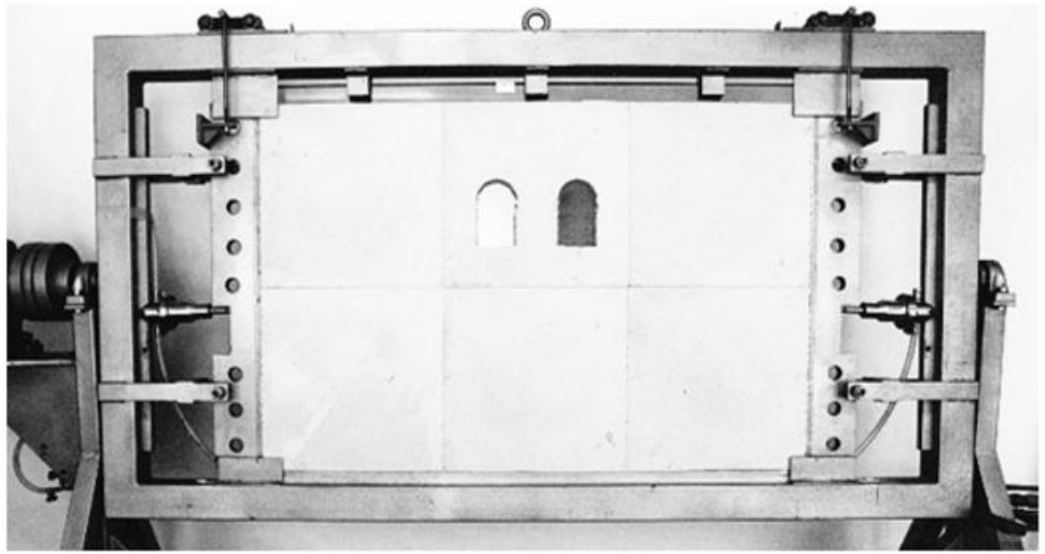


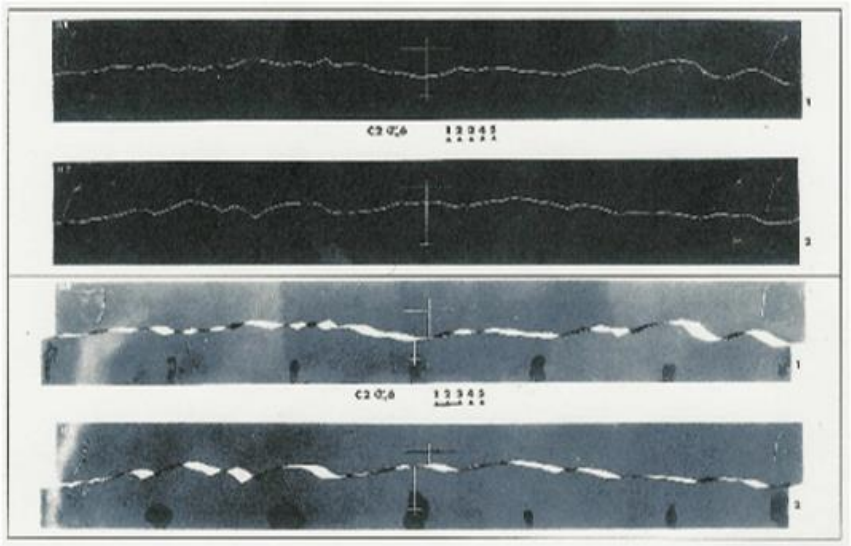
The deformation magnitudes and directions depend on *the joint orientations and on the horizontal stress.*

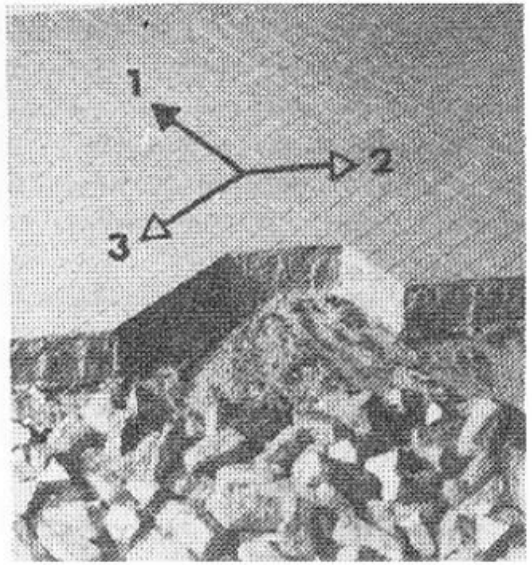


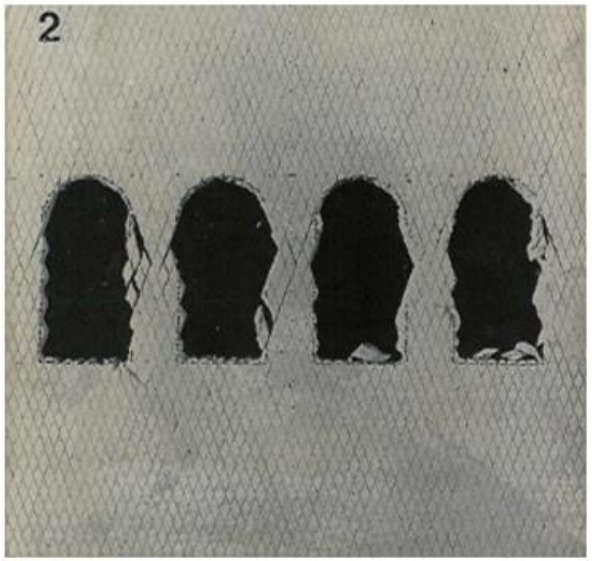


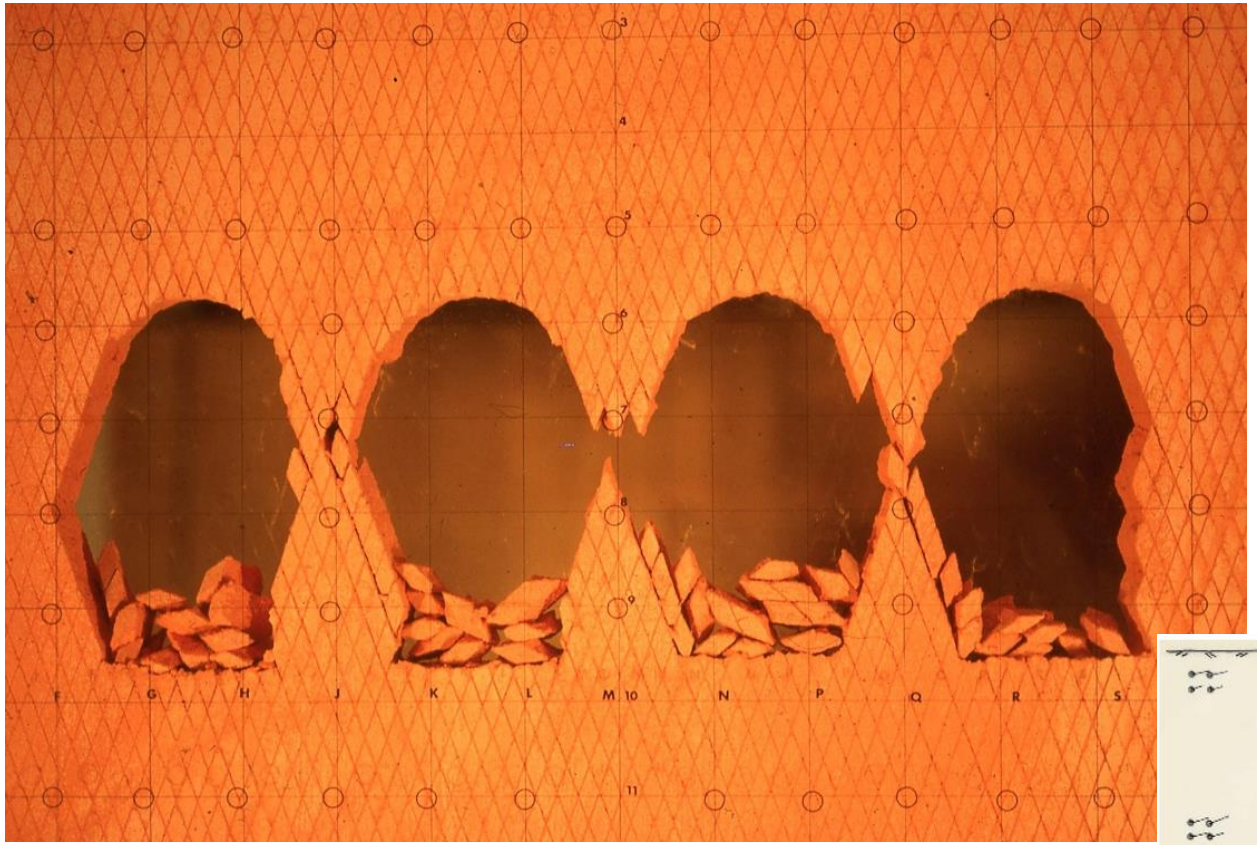




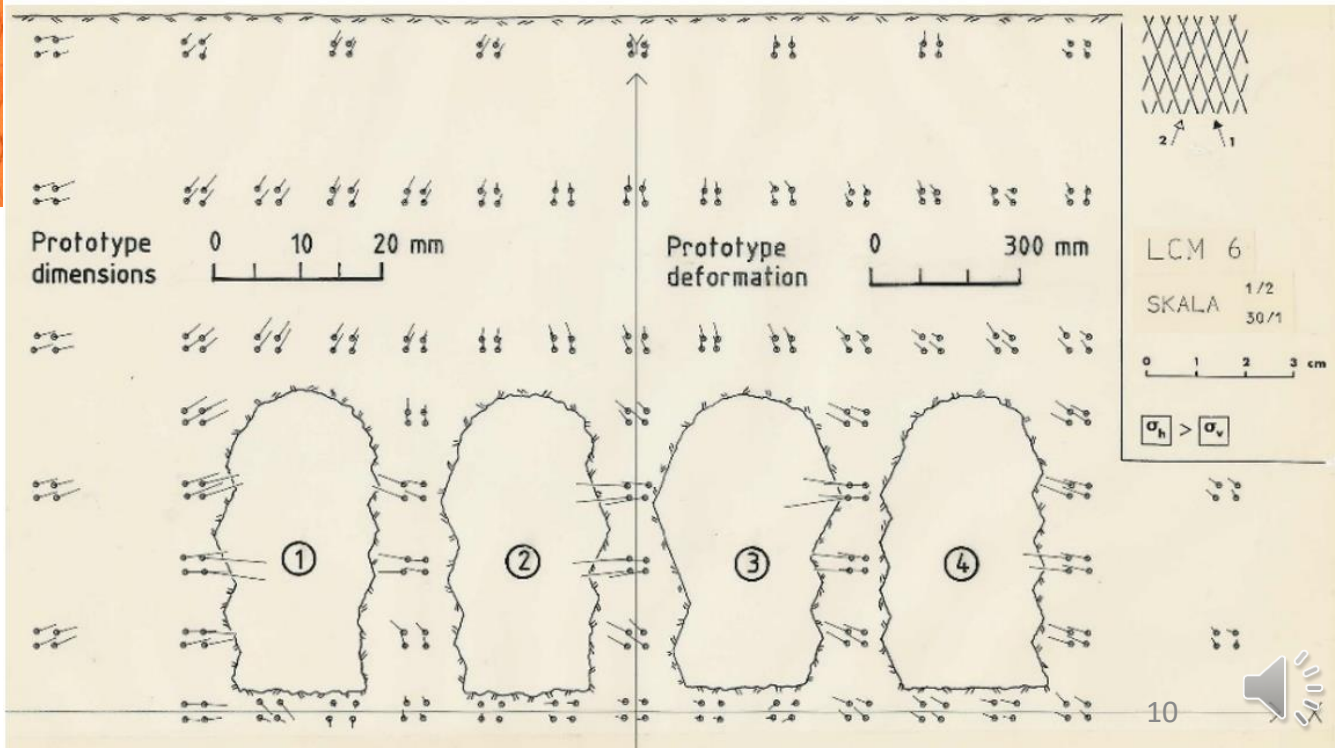



1
2
3


2

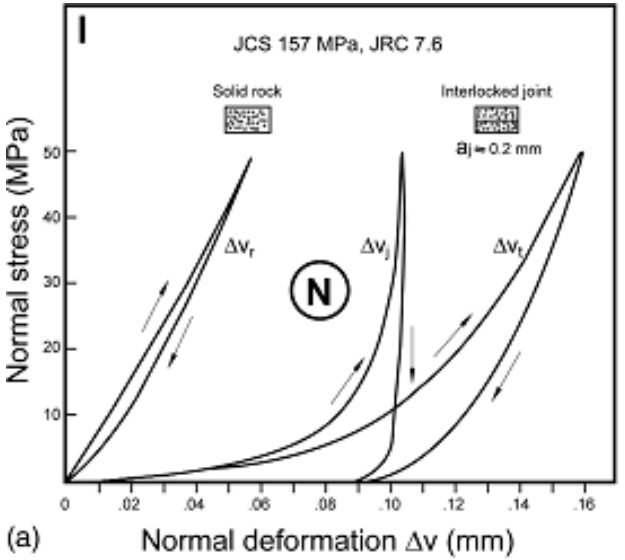


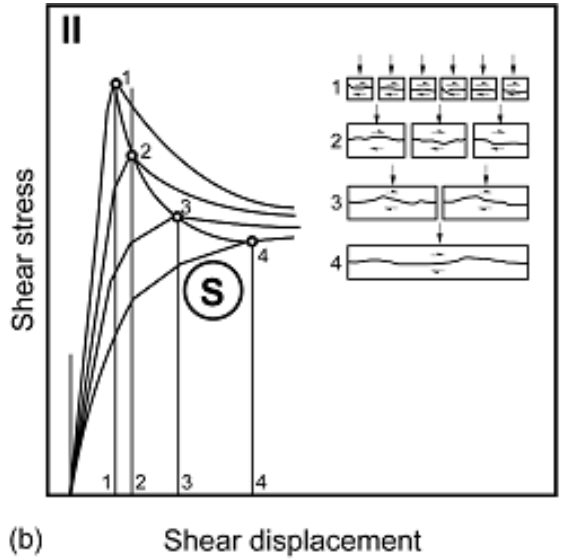
BEFORE UDEC (1980) (but after an ‘earthquake’)

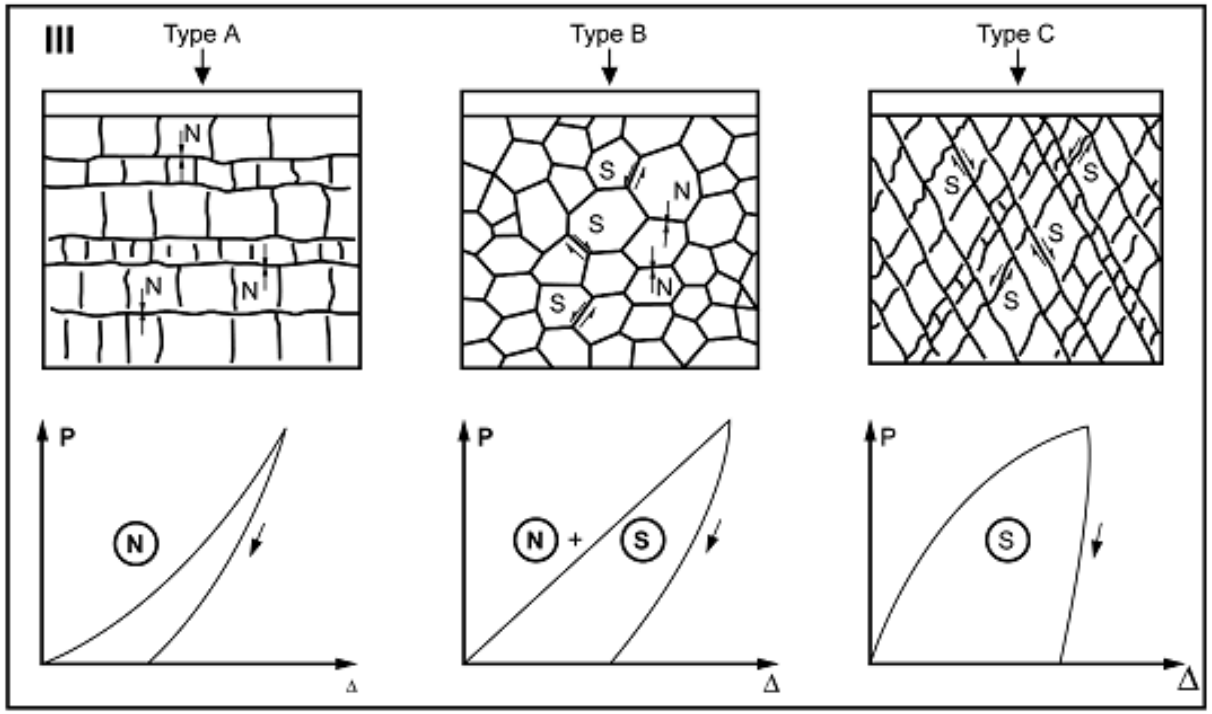


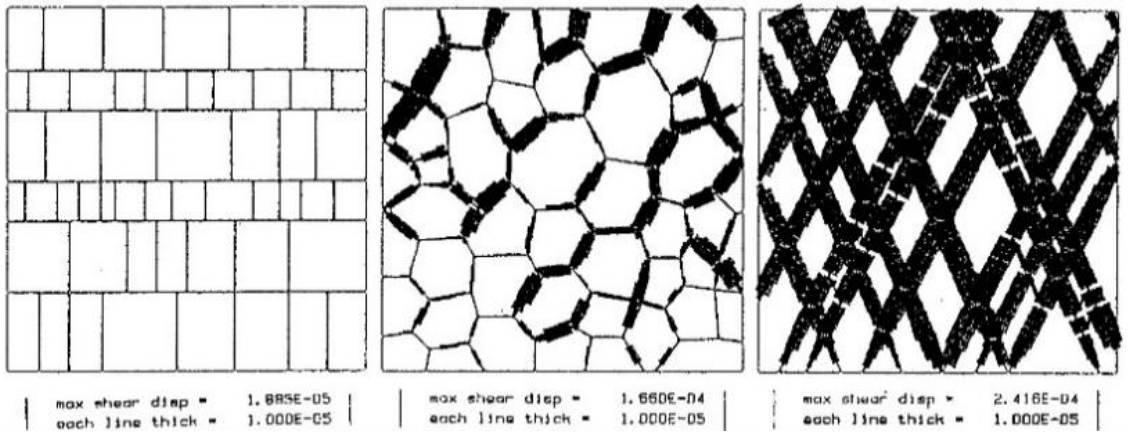
LESSONS ABOUT HYSTERESIS – NON-ELASTIC BEHAVIOUR

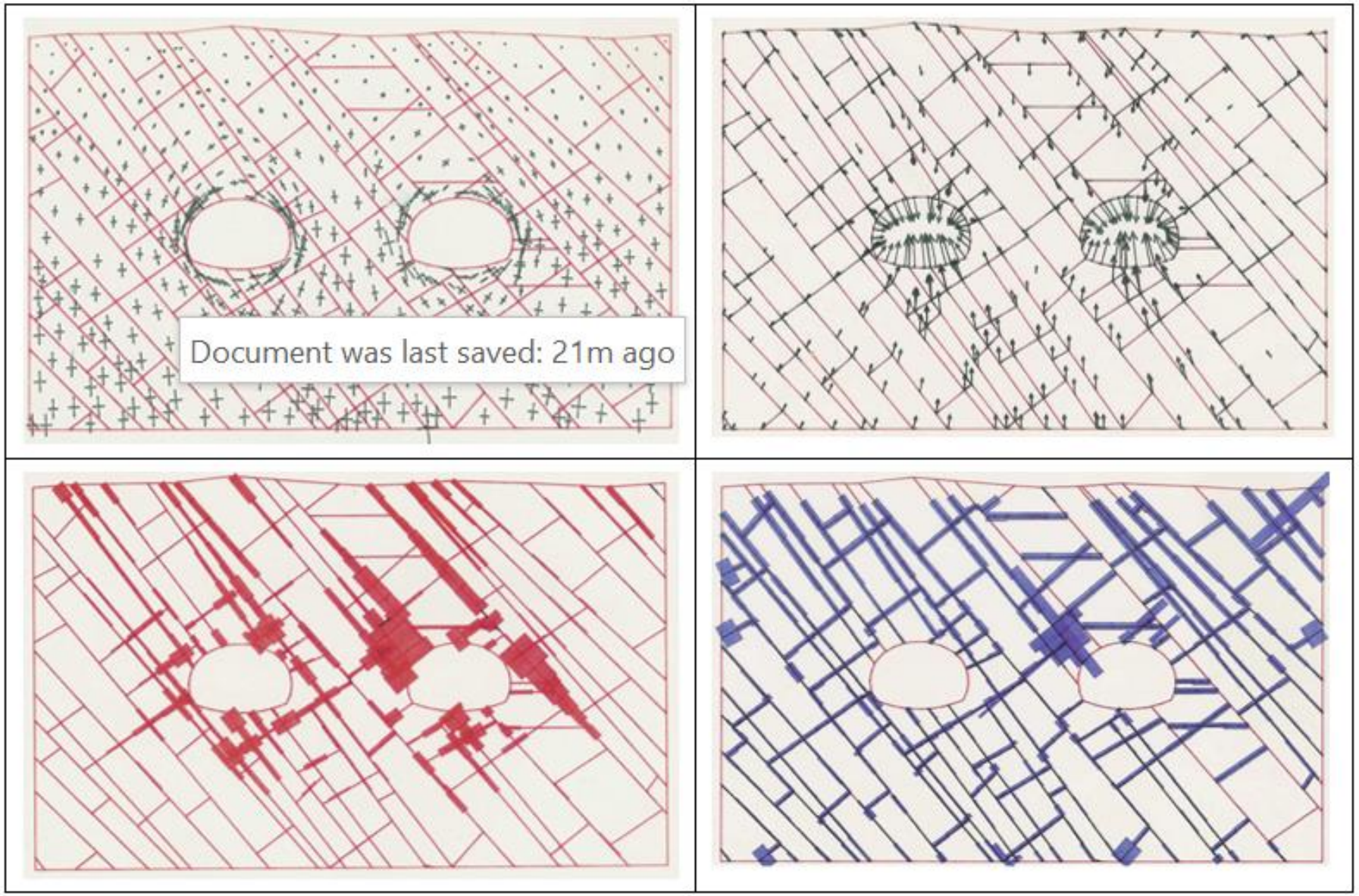
IMPORTANT DETAILS MISSED IN CONTINUUM MODELLING



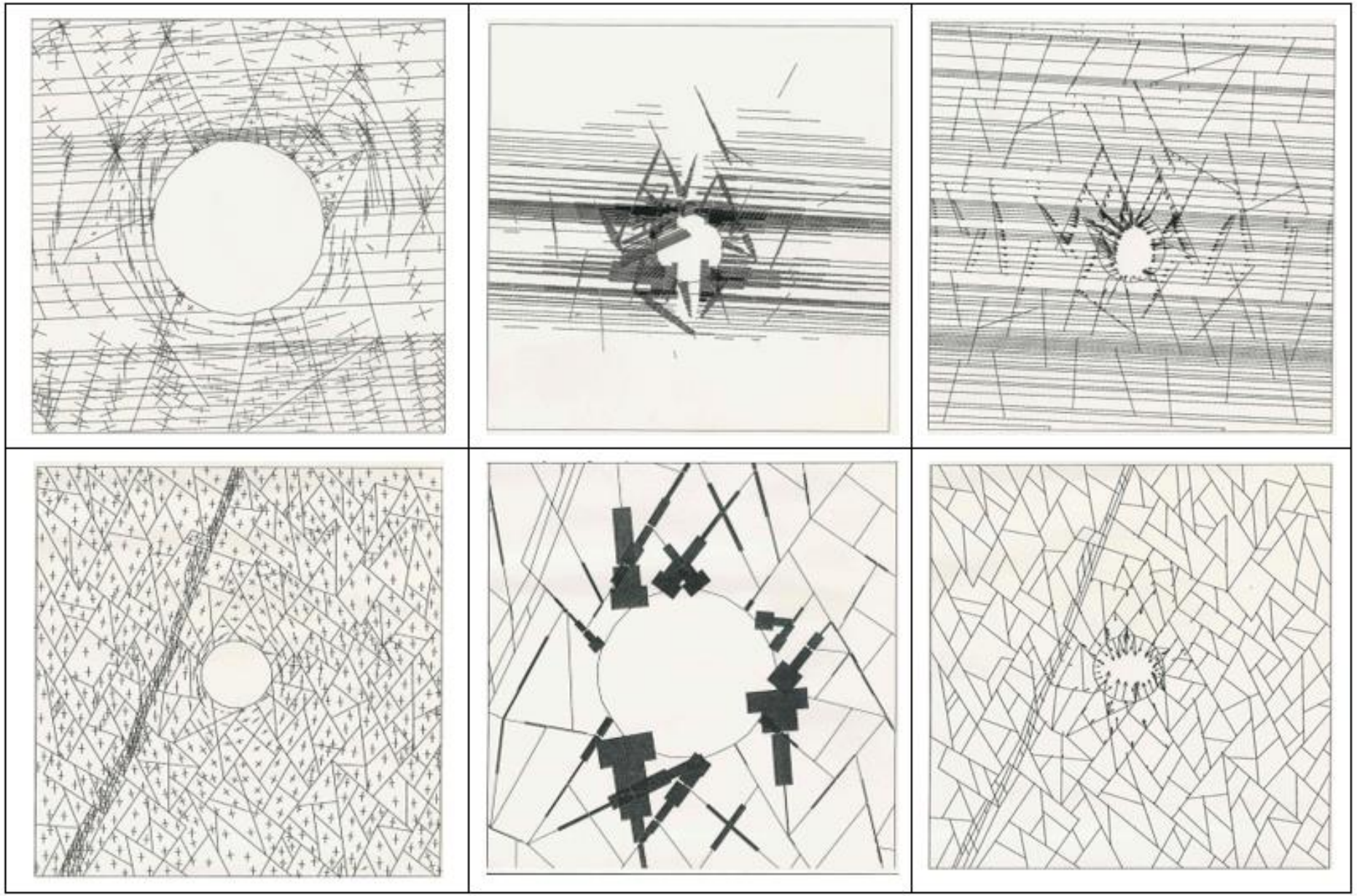




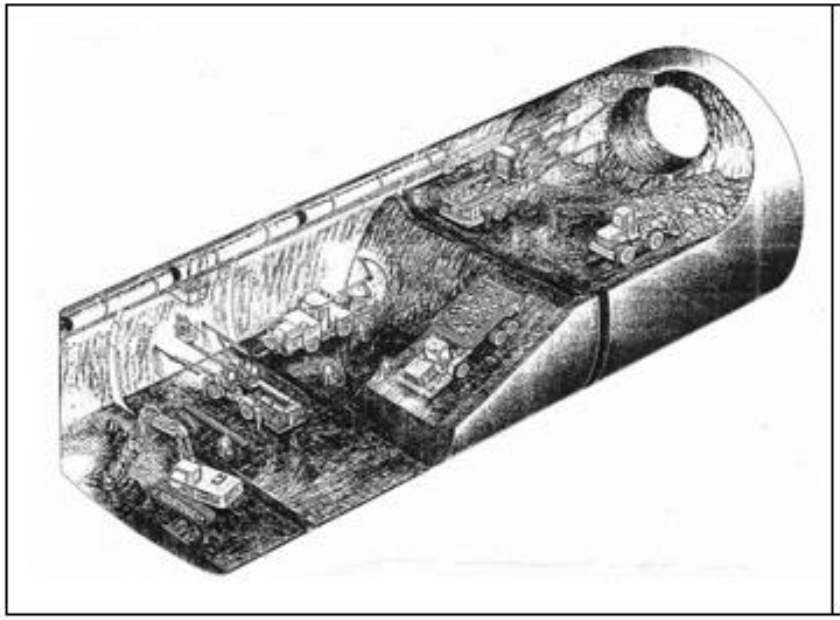


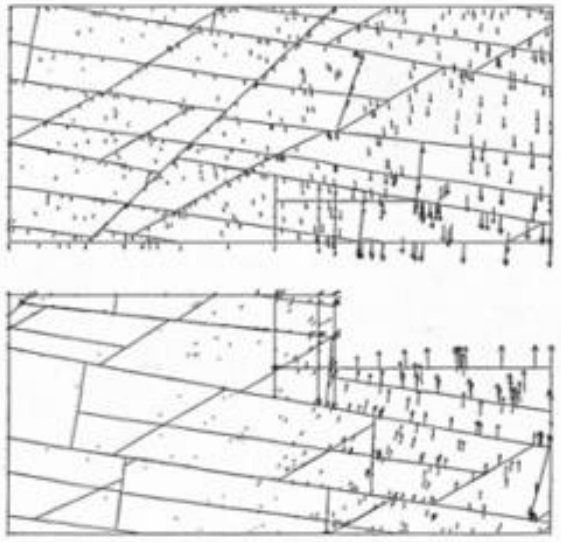


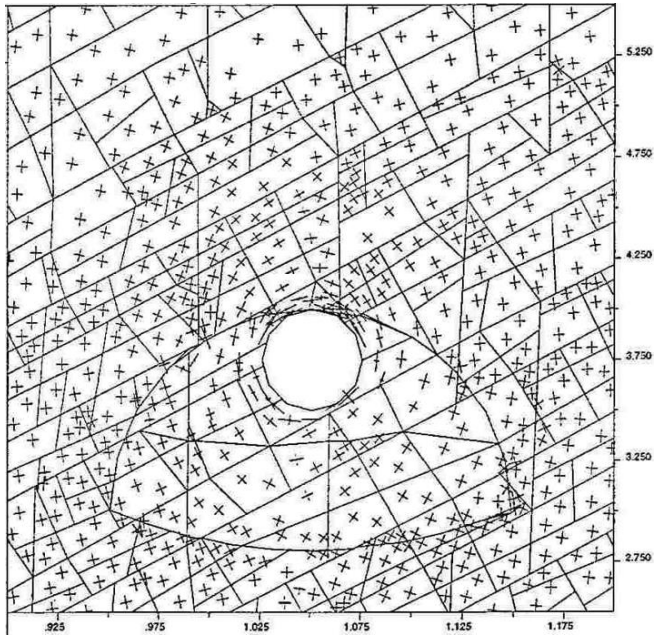
Cundall's UDEC with BB non-linear model of rock joint behaviour.

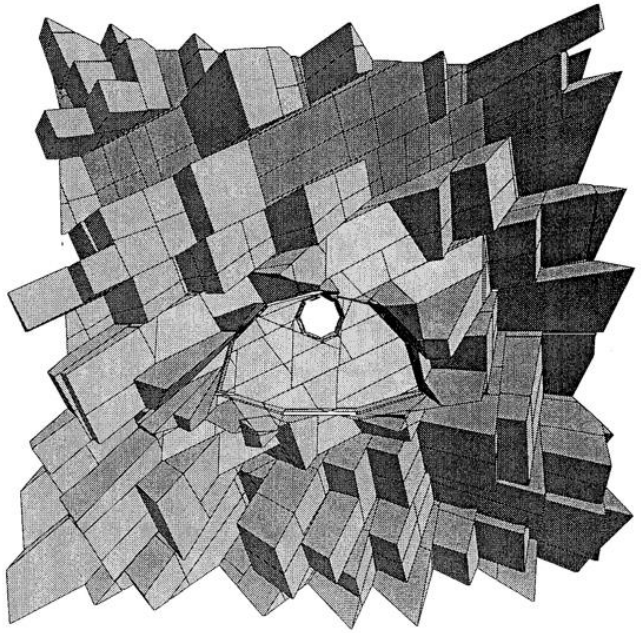


‘Geologic’ details give different behaviour – *much less so in continuum models*

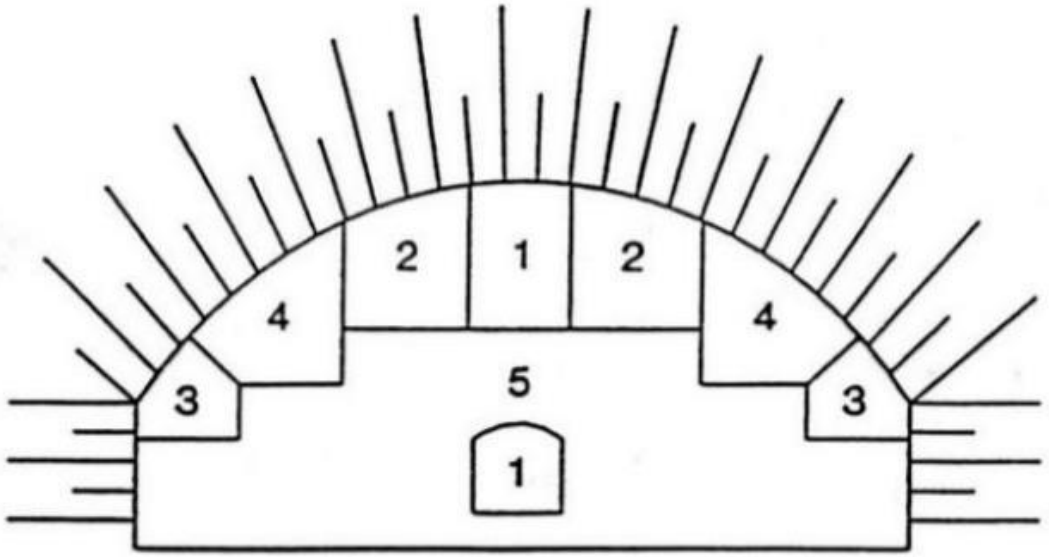


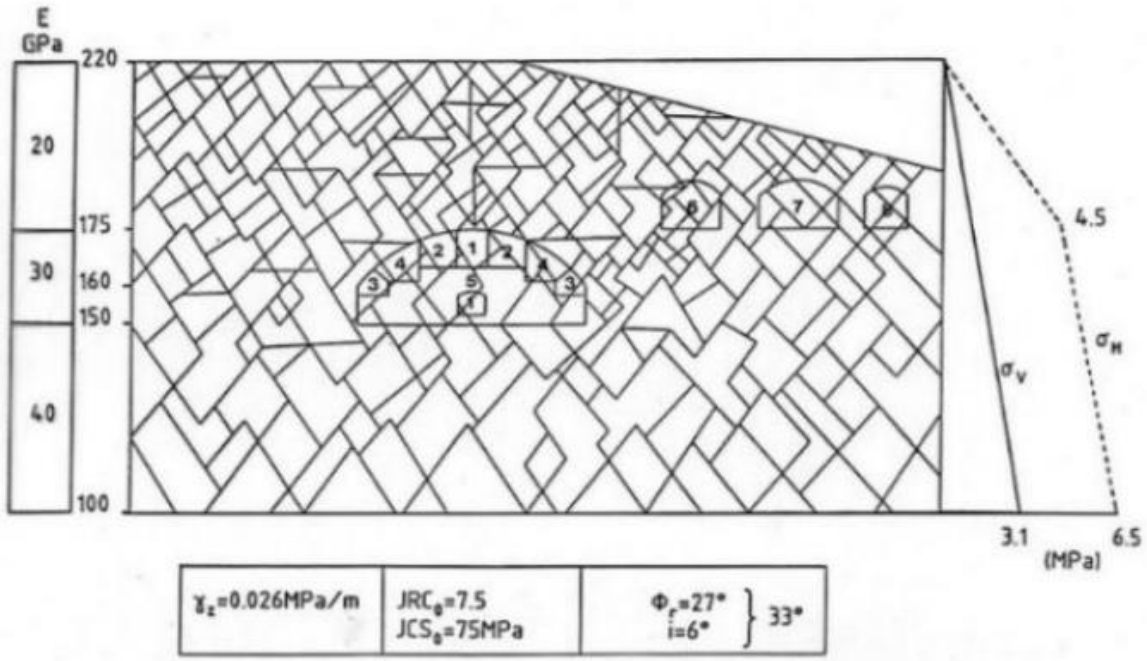


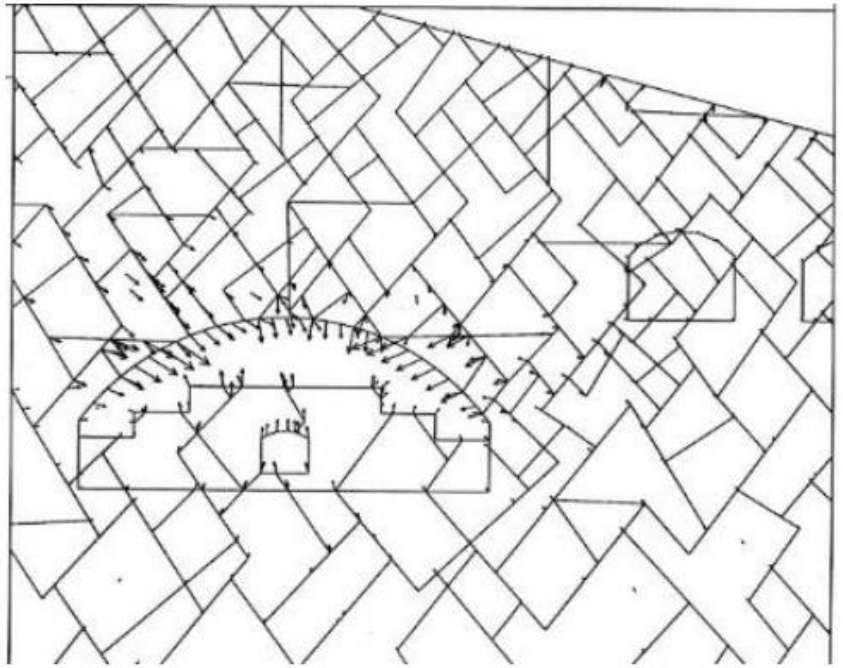




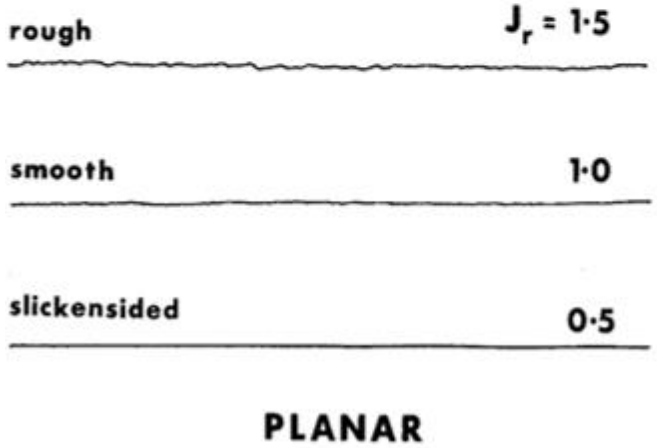
UDEC is 2D
3DEC is needed sometimes

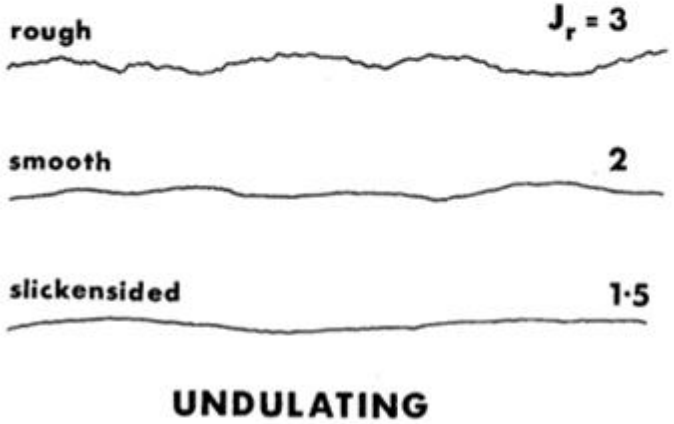

2
1
2
4
4
3
5
3
1

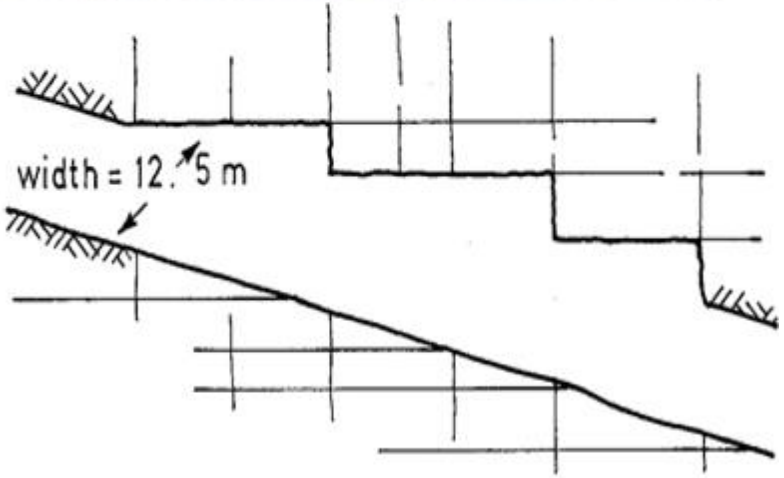

E
GPa
220
20
175
30
160
150
40
100
4.5
σ_H
σ_V
3.1
6.5
(MPa)
γ_z=0.026MPa/m
JRC_0=7.5
JCS_0=75MPa
Φ_r=27°
i=6°
33°



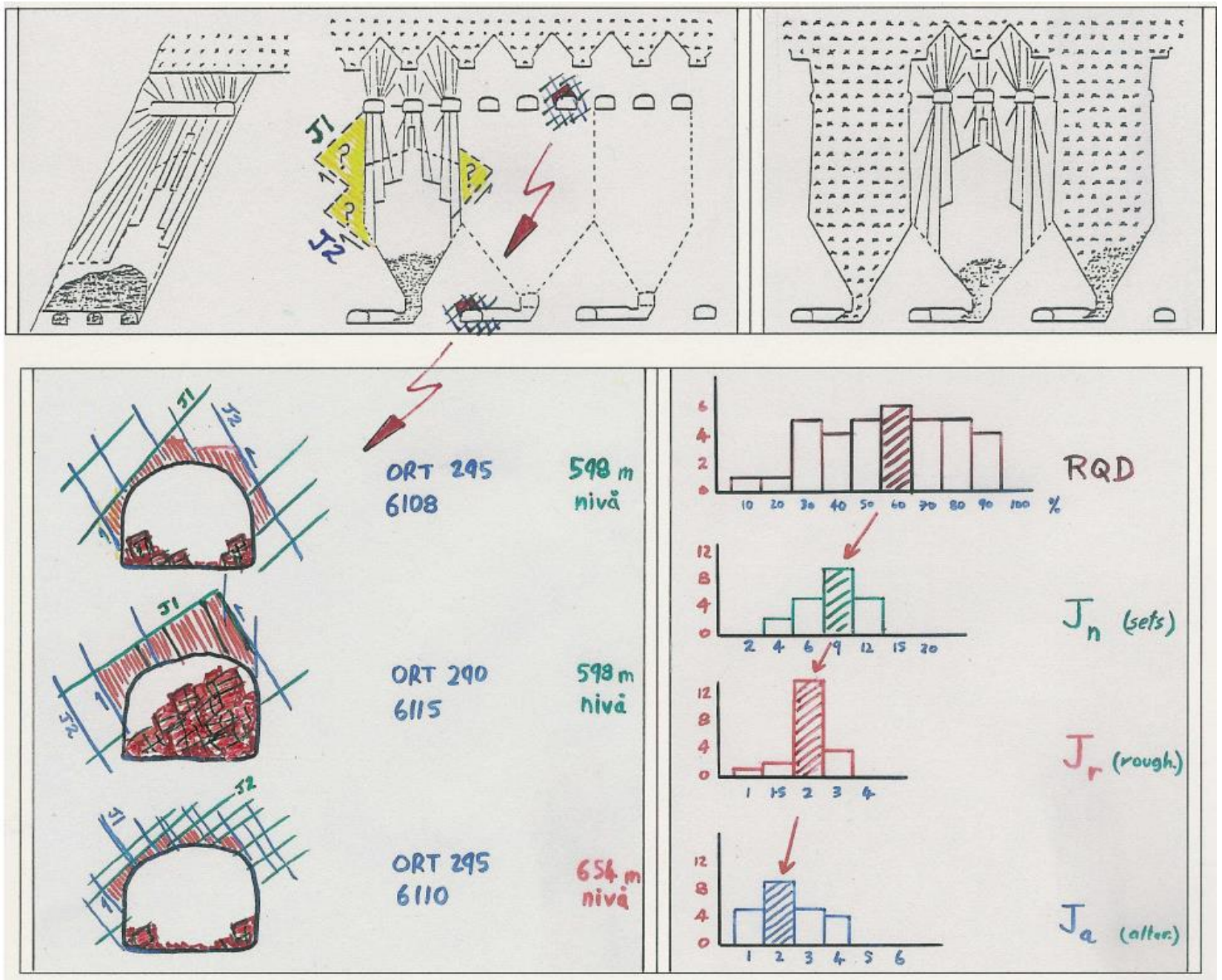
EARLY SCOPING STUDIES TO SEE THE POSITIVE EFFECT OF HORIZONTAL STRESS WHEN SPANS ARE SO LARGE (62m)







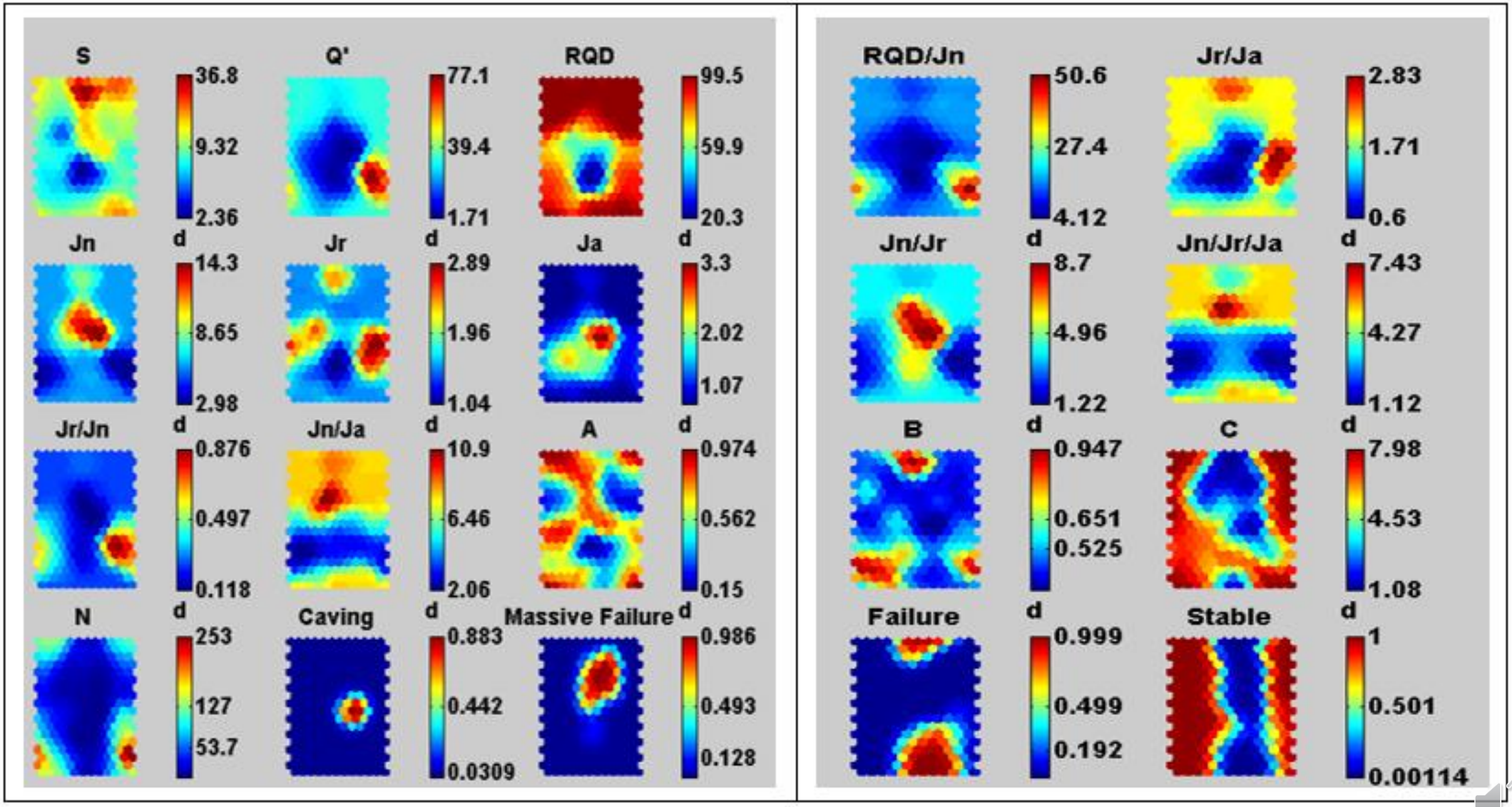
4/2, 6/2, 9/2, 9/3, 12/3, 15/3…….6/1, 9/1.5, 12/2, 15/2 (Jn/Jr ≥ 6)

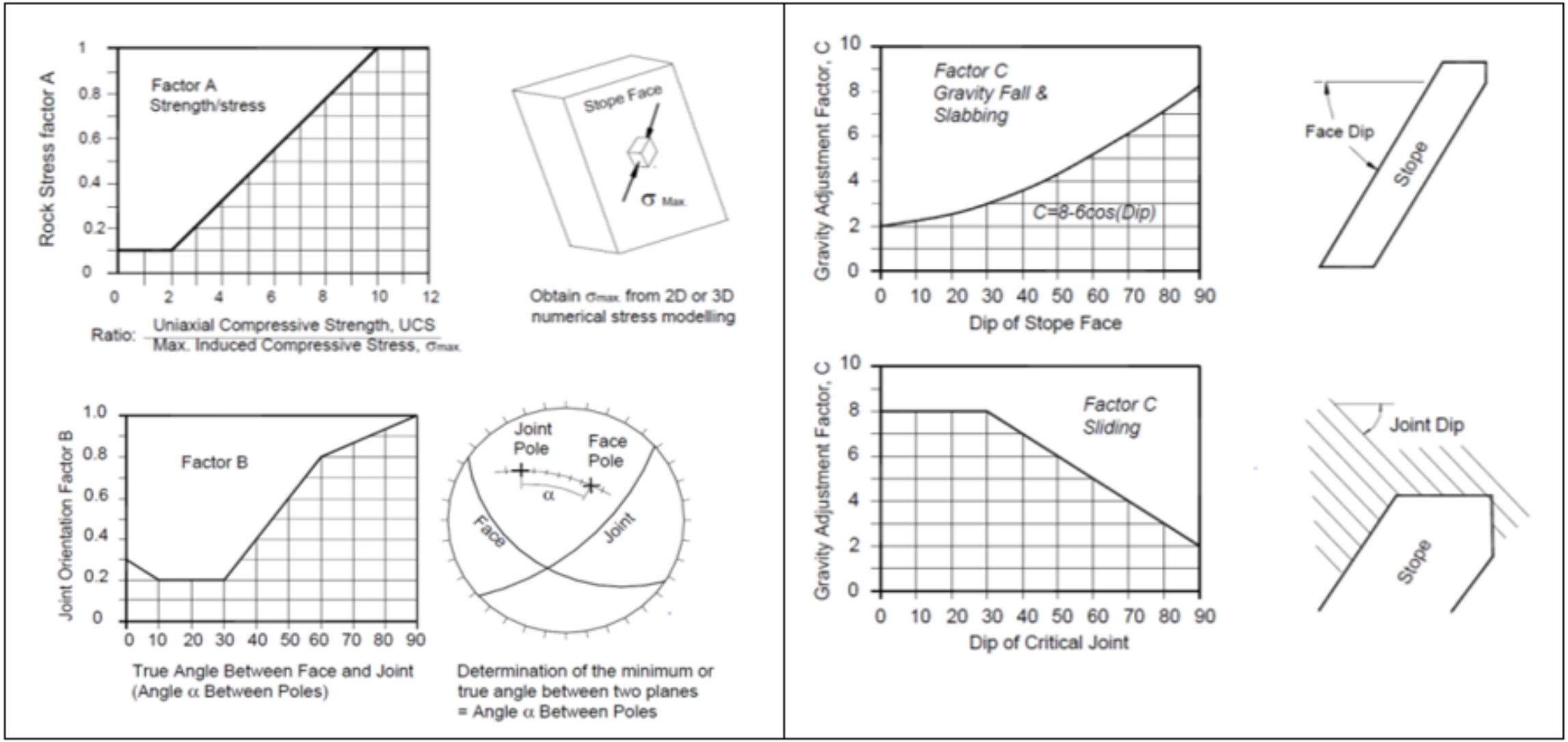


Oscar Project
LKAB, N. Sweden

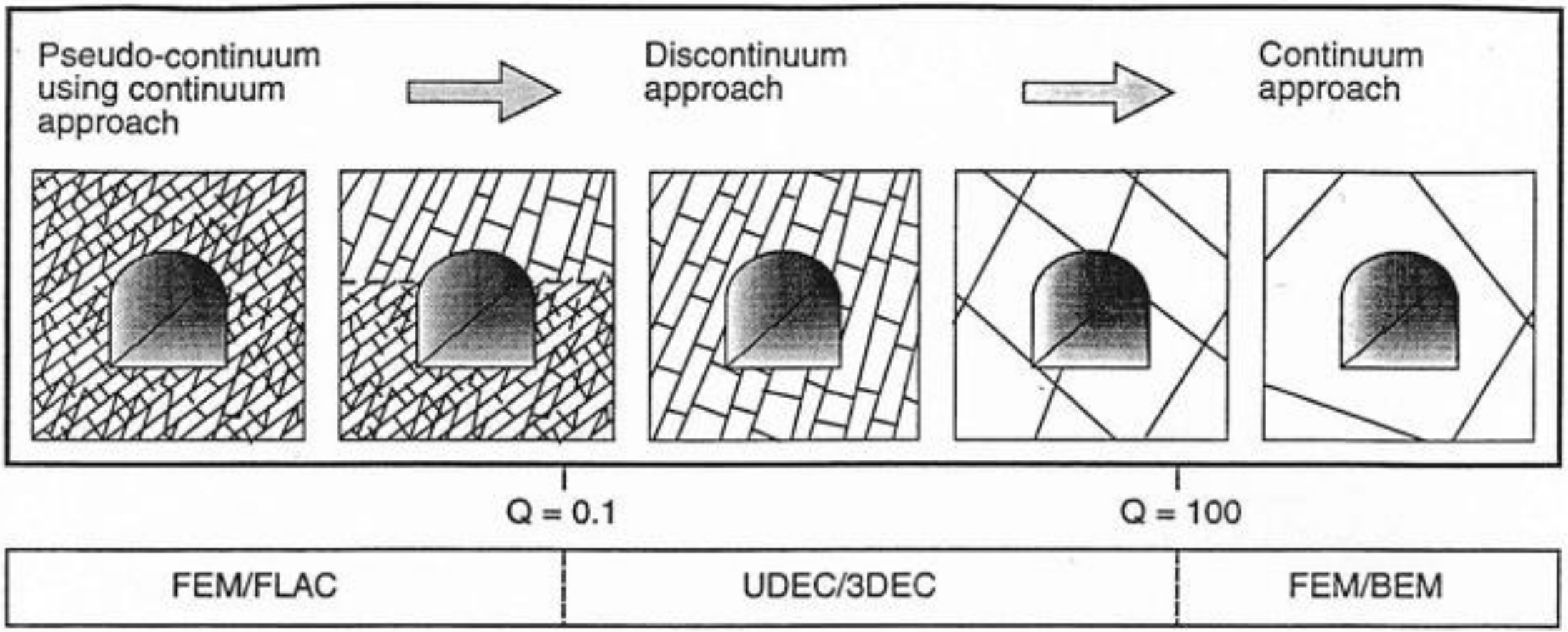
Over-break investigation in long-hole drilling drifts (and in draw-points).

Some extreme values of Jn/Jr explain the major over-break. Ja assists too.


S
36.8
9.32
2.36
Q'
77.1
39.4
1.71
RQD
99.5
59.9
20.3
Jn
14.3
8.65
2.98
Jr
2.89
1.96
1.04
Ja
3.3
2.02
1.07
Jr/Jn
0.876
0.497
0.118
Jn/Ja
10.9
6.46
2.06
A
0.974
0.562
0.15
N
253
127
53.7
Caving
0.883
0.442
0.0309
Massive Failure
0.986
0.493
0.128
RQD/Jn
50.6
27.4
4.12
Jr/Ja
2.83
1.71
0.6
Jn/Jr
8.7
4.96
1.22
Jn/Jr/Ja
7.43
4.27
1.12
B
0.947
0.651
0.525
C
7.98
4.53
1.08
Failure
0.999
0.499
0.192
Stable
1
0.501
0.00114

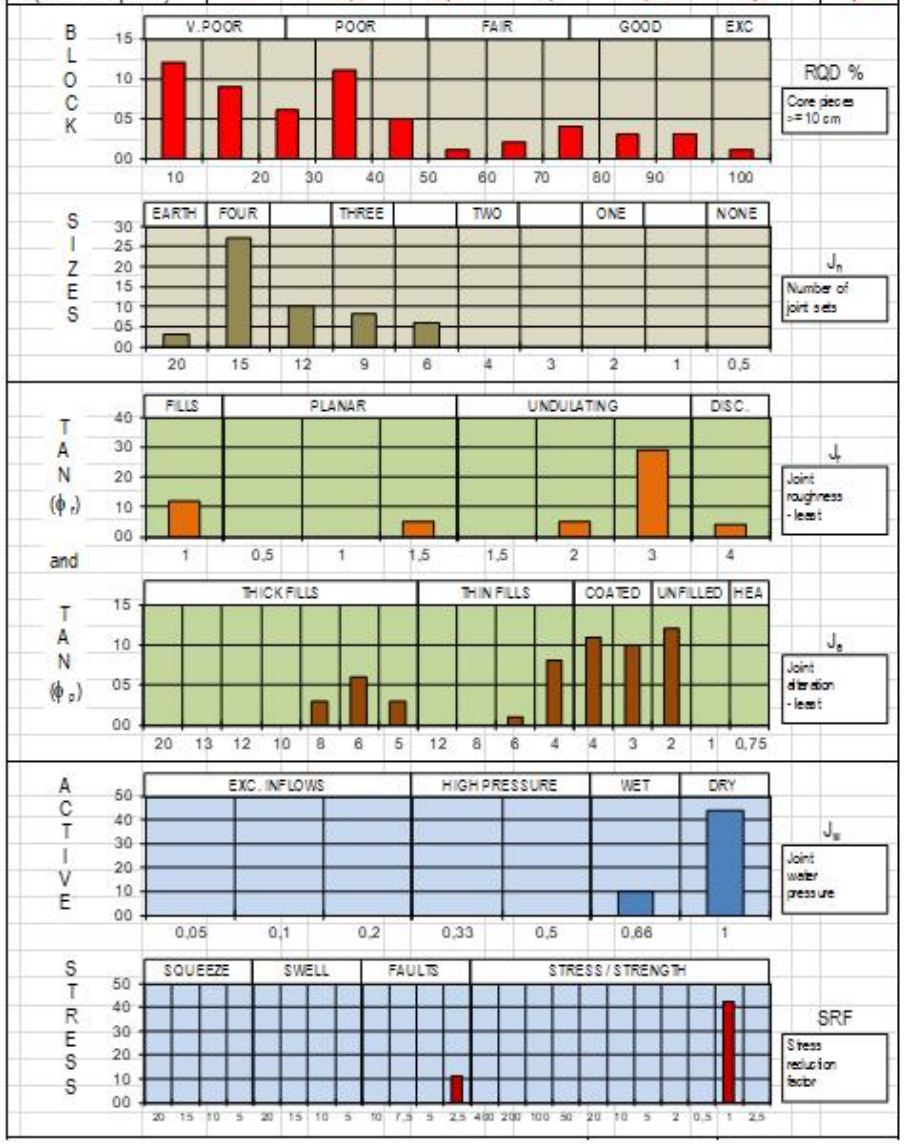


Factors A, B and C for qualifying use of Q' in stope design



- **Heavily jointed weak rock = continuum (FEM)**
  Jointed/faulted rock = discontinuum (UDEC/3DEC) ...see examples
  Massive rock that may fracture = FRACOD...see examples

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

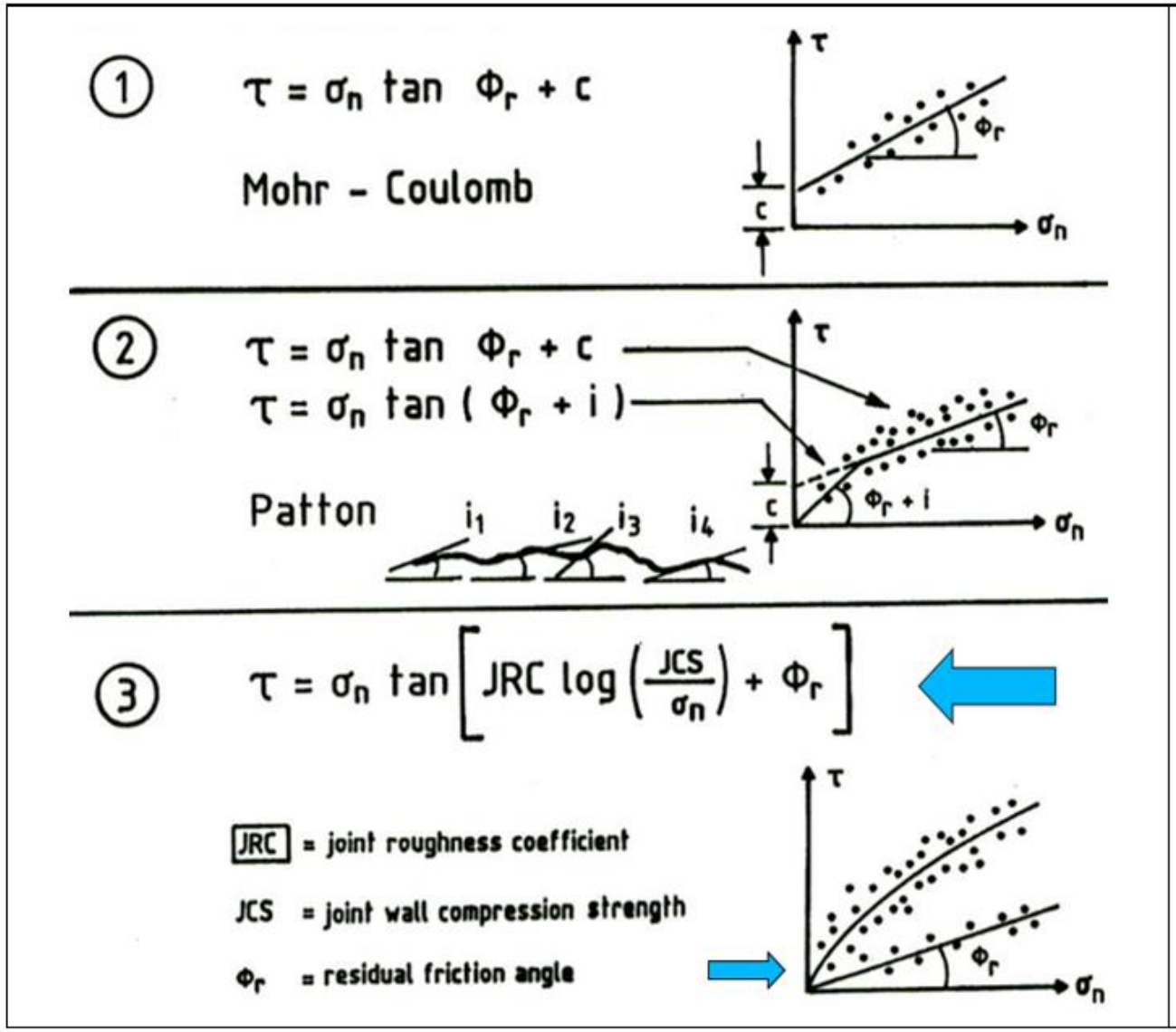


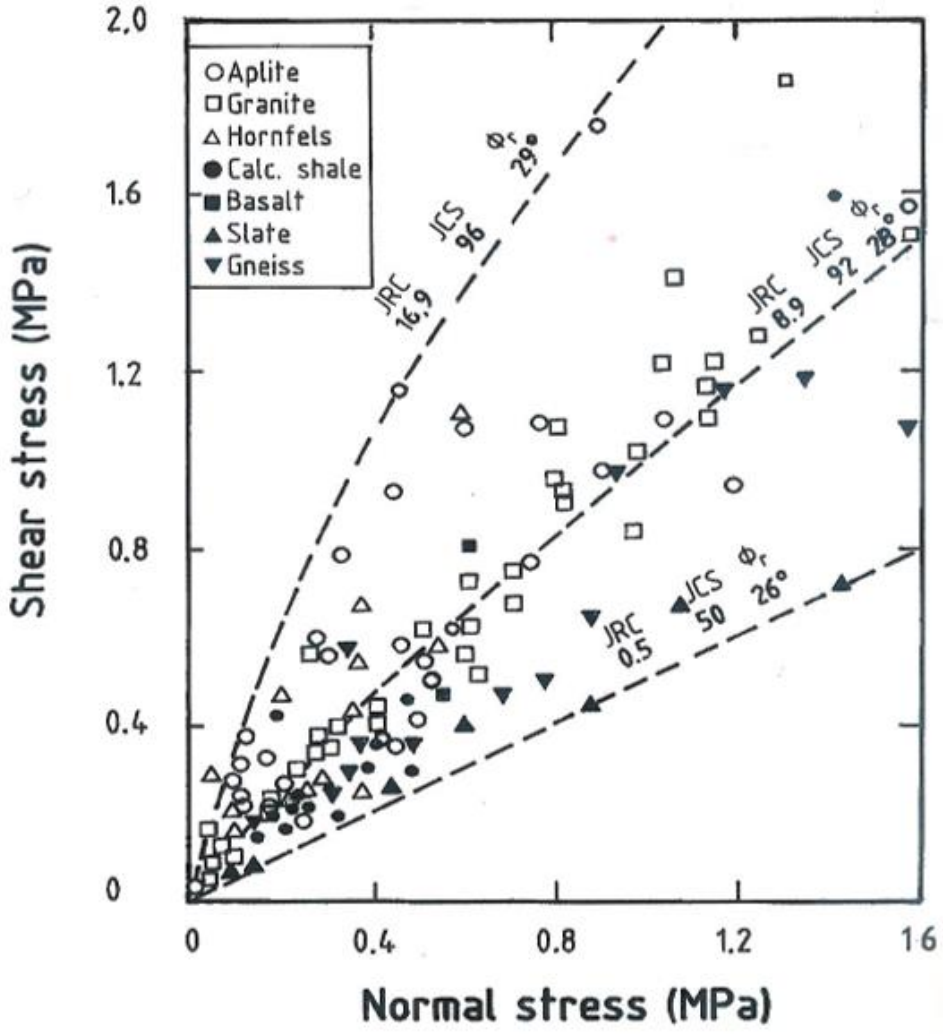
Q IS ONLY PART OF A ROCK MASS DESCRIPTION EXERCISE.

I	ROCK MASS STRUCTURE				
1	RQD	Deere et al., 1967)		block size	Q
2	J_n	= joint set number			Q
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)			
II	JOINT CHARACTER				
9	J_r	= joint roughness number		shear strength	Q
10	J_a	= joint alteration number			Q
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			
III	WATER, STRESS, STRENGTH				
16	J_w	= joint water reduction factor		active stress	Q
17	SRF	= stress reduction factor			Q
18	K	= rock mass permeability (m/s)			
19	σ_c	= compressive strength			
20	σ_1	= major principal stress			

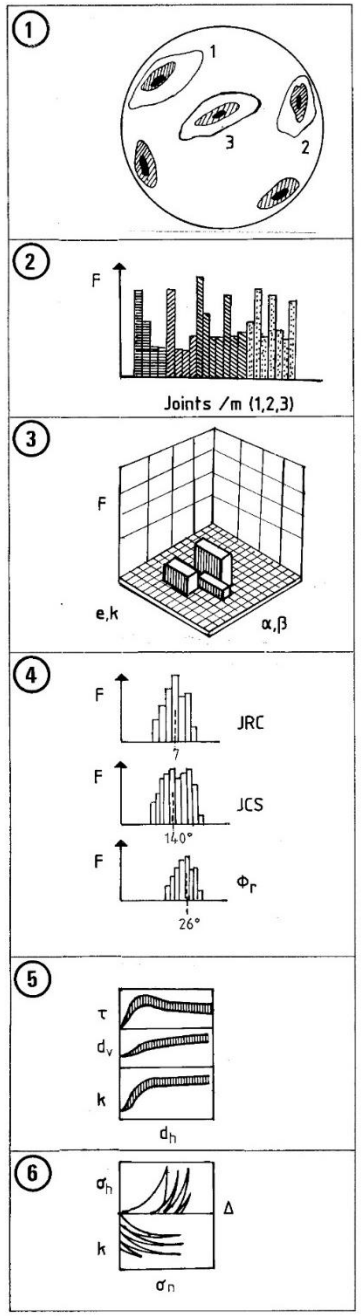
IF THE DECISION IS A DISCONTINUUM MODEL

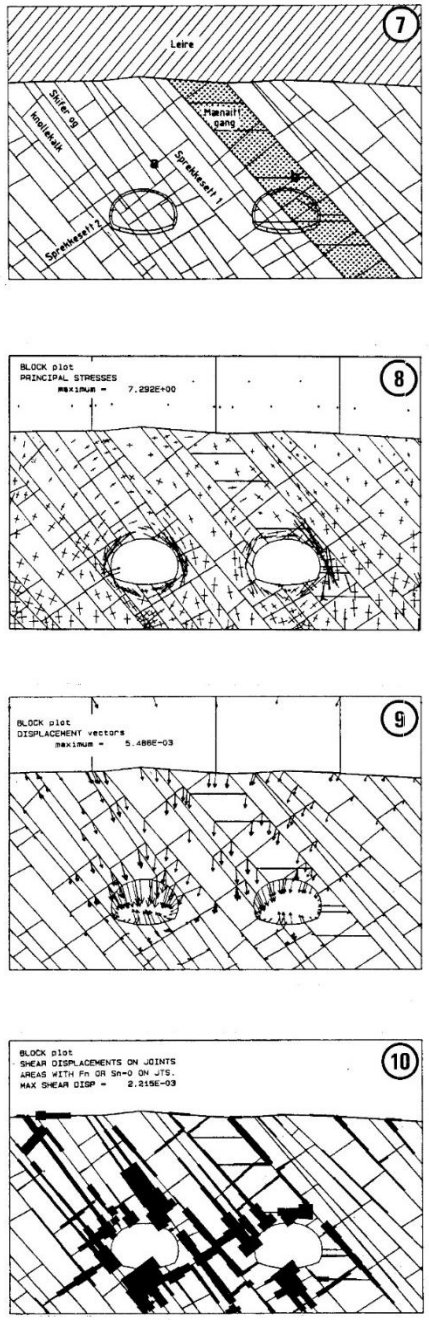
WE WILL NEED A WAY TO DESCRIBE
THE PROPERTIES OF THE ROCK JOINTS





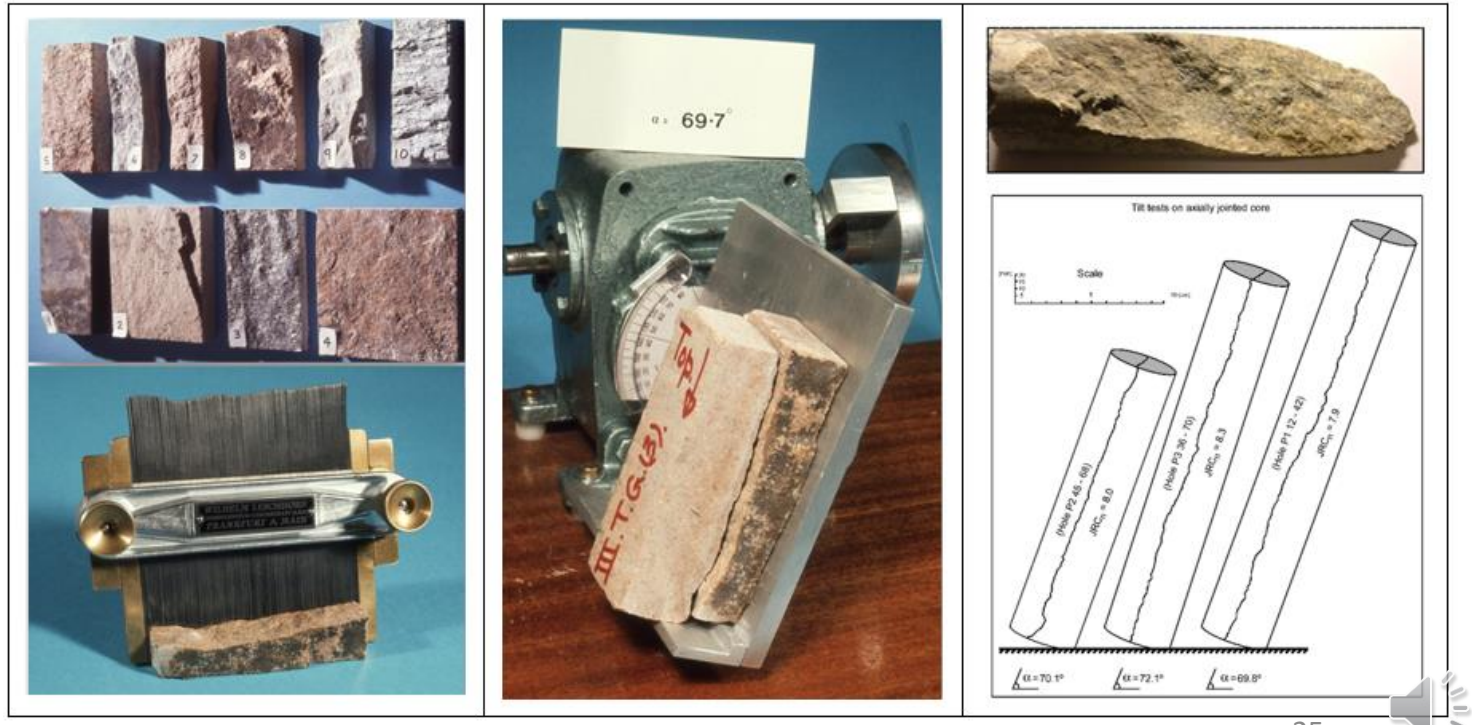
UDEC-BB (jointed model) needs BB parameters JRC, JCS

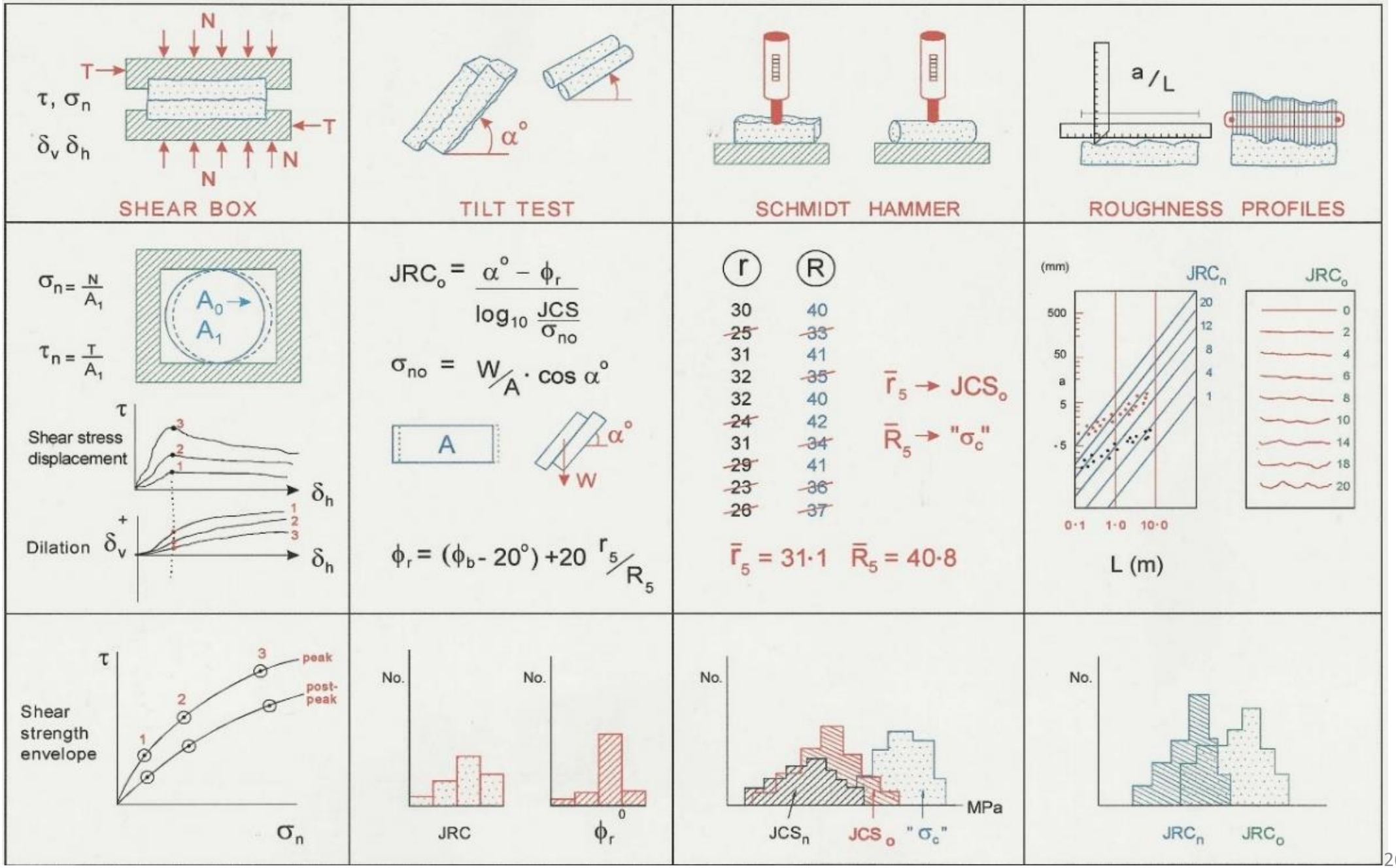




SOME INPUT DATA NEEDS FOR DESCRIBING THE JOINTS: JRC, JCS.

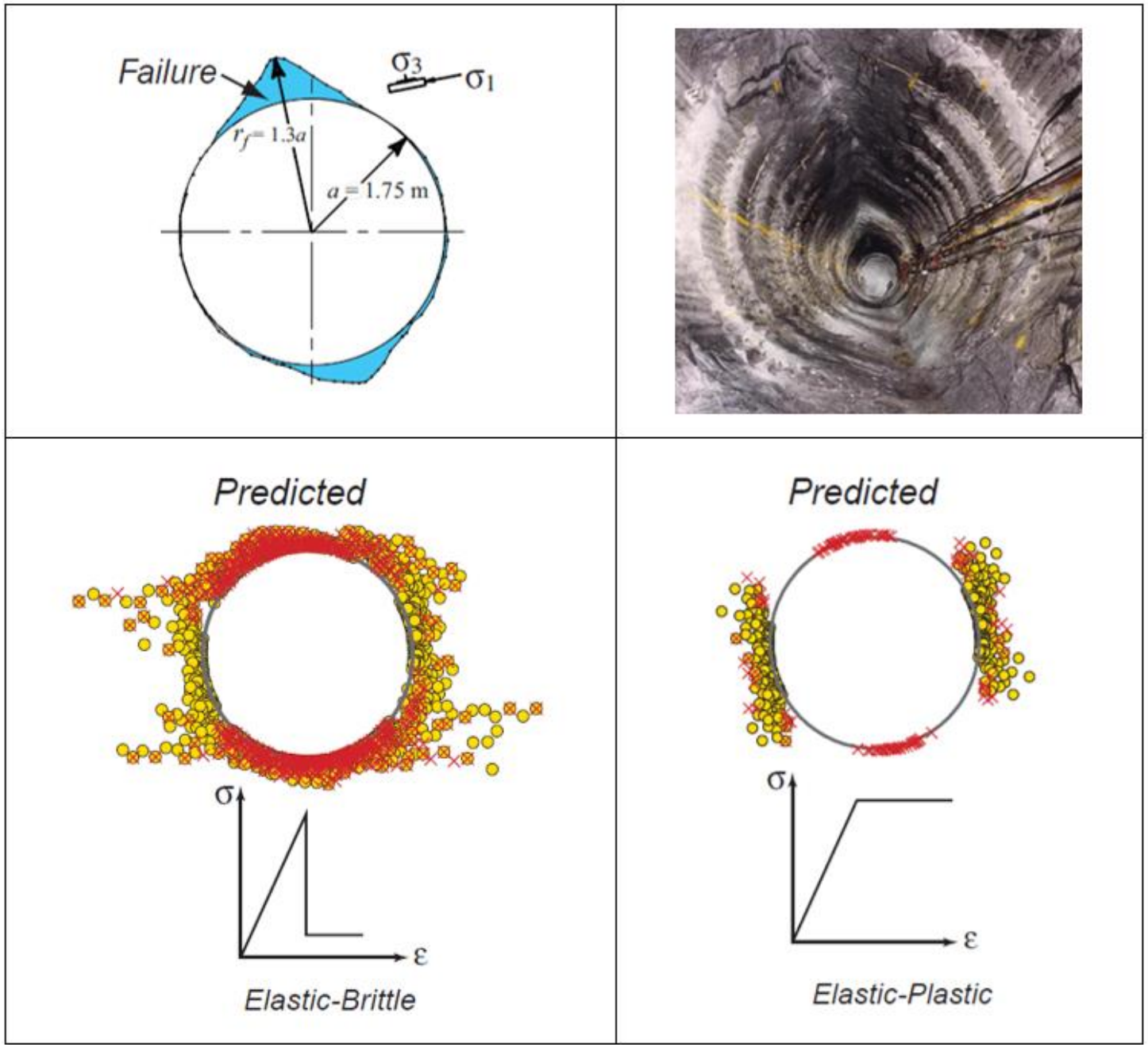
PROFILING OR TILT TESTS ON CORE



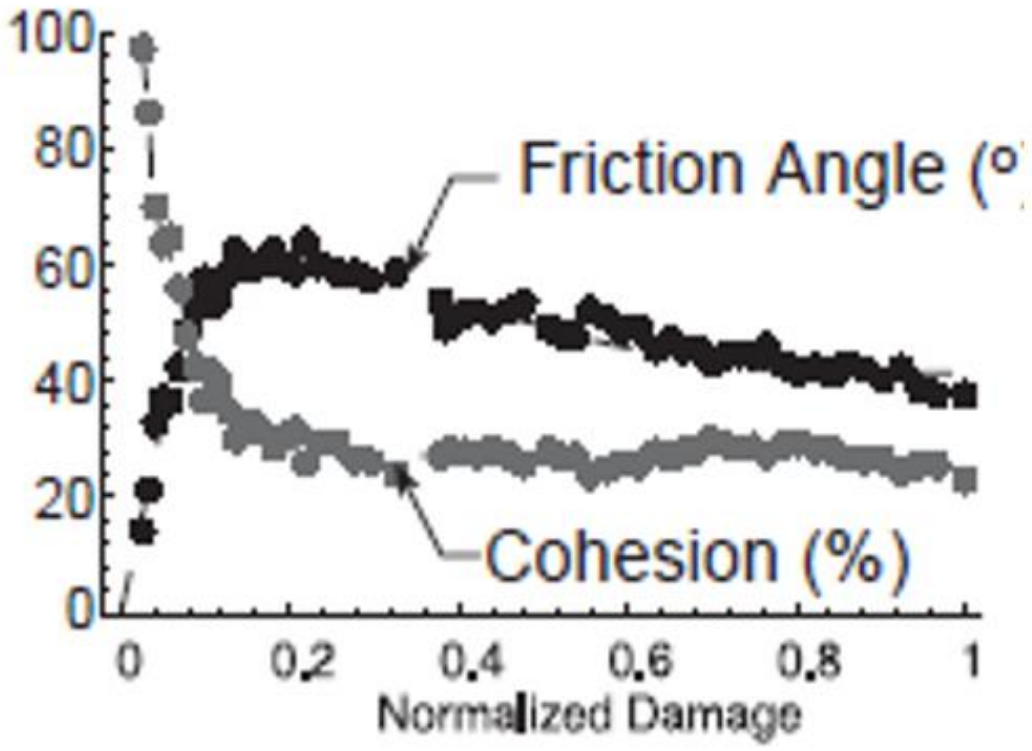

N
T
τ, σn
δv δh
SHEAR BOX
α°
TILT TEST
SCHMIDT HAMMER
a / L
ROUGHNESS PROFILES
σn = N/A1
τn = T/A1
A0
A1
τ
Shear stress displacement
δh
Dilation δv
JRCo = (α° − φr) / log10 (JCS/σno)
σno = W/A · cos α°
A
α°
W
φr = (φb - 20°) + 20 r5/R5
r
R
30 40
25 33
31 41
32 35
32 40
24 42
31 34
29 41
23 36
26 37
r̄5 → JCSo
R̄5 → "σc"
r̄5 = 31·1 R̄5 = 40·8
(mm)
JRCn
JRCo
L (m)
Shear strength envelope
peak
post-peak
σn
No.
JRC
φr
JCSn
JCSo
"σc"
MPa
JRCn
JRCo

IF THE DECISION IS A CONTINUUM MODEL

WE WILL NEED A WAY
TO DESCRIBE THE YIELD FUNCTION



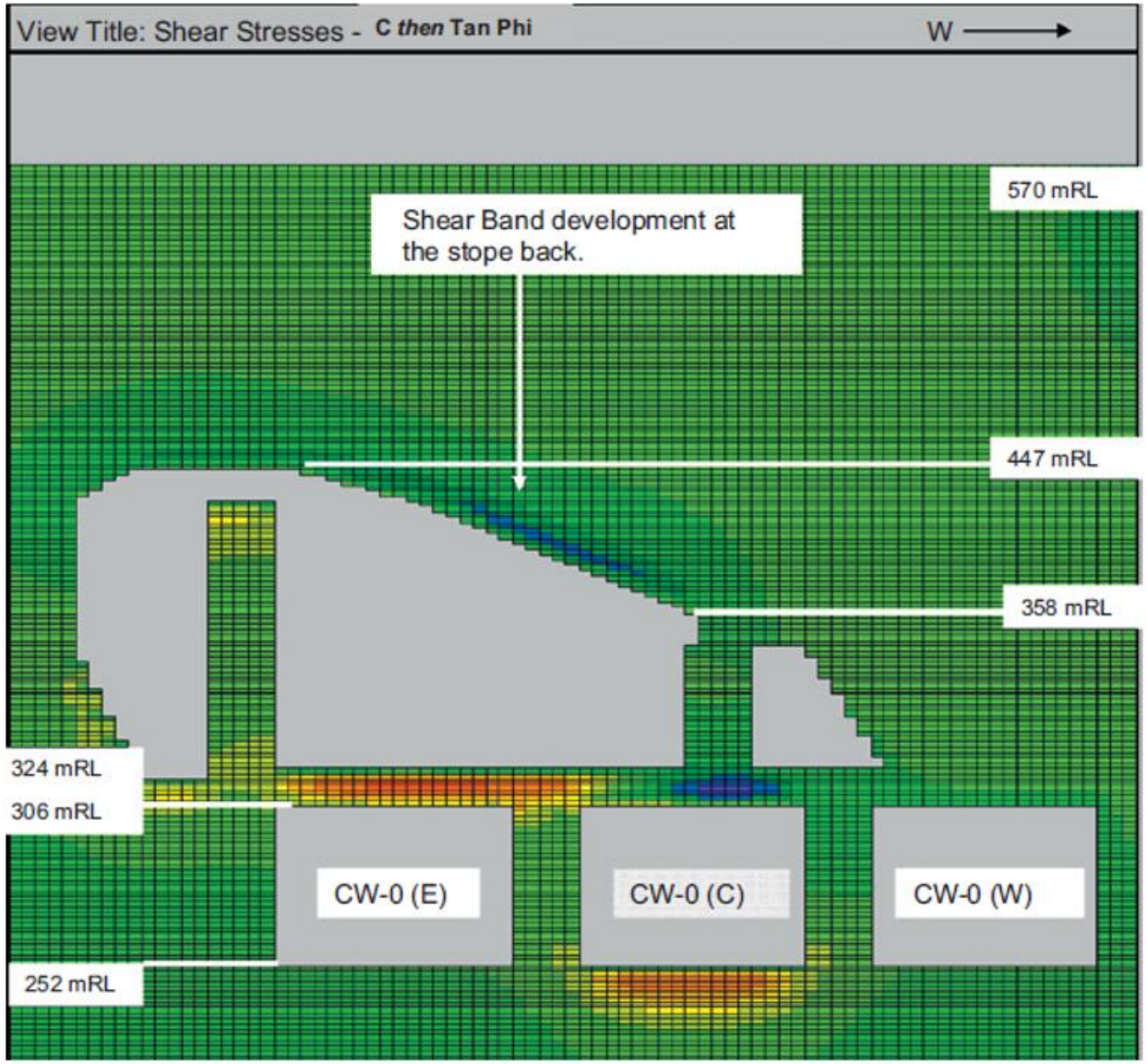
HERE WE START TO SEE THE PROBLEMS WITH CONTINUUM MODELLING

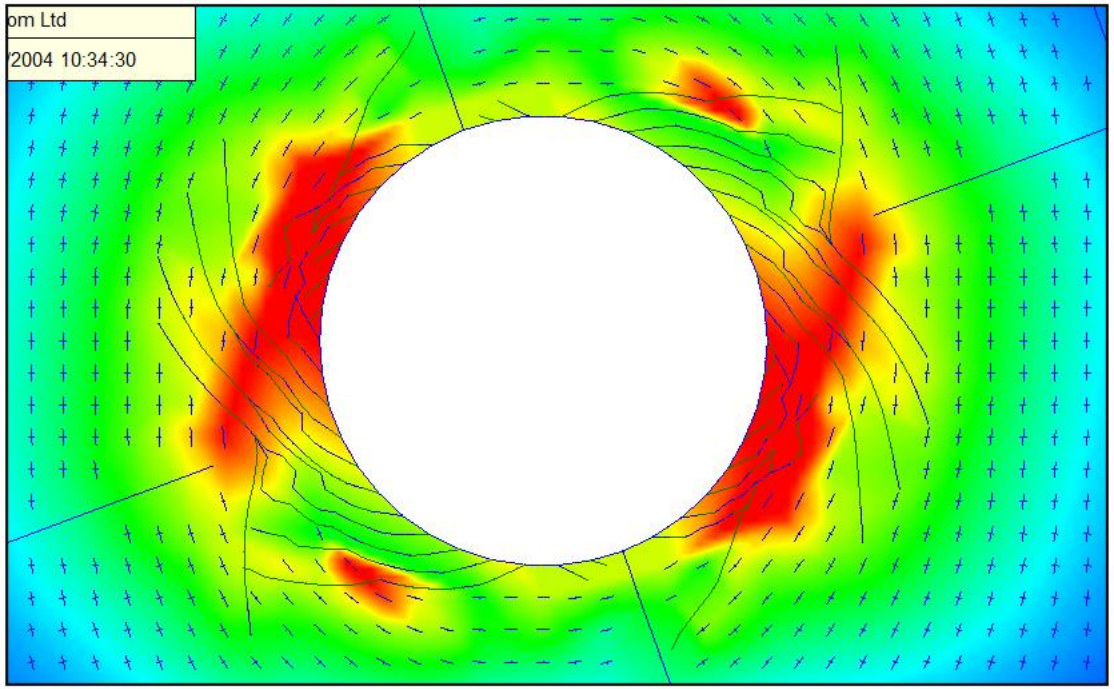


A GREATLY IMPROVED RESULT USING A ***CWFH*** (COHESION WEAKENING FRICTION HARDENING) APPROACH. HAJIABDOLMAJID, MARTIN AND KAISER, 2000.

PANDEY and BARTON, 2011 USED THIS ***CWFH*** APPROACH USING Q-BASED INPUT DATA CC AND FC (COHESION COMPONENT, FRICTION COMPONENT)

Left: FLAC-3D with CSFH. (Pandey and Barton, 2011). Right: FRACOD (Shen, 2008). The latter allows potential fracturing to be modelled.



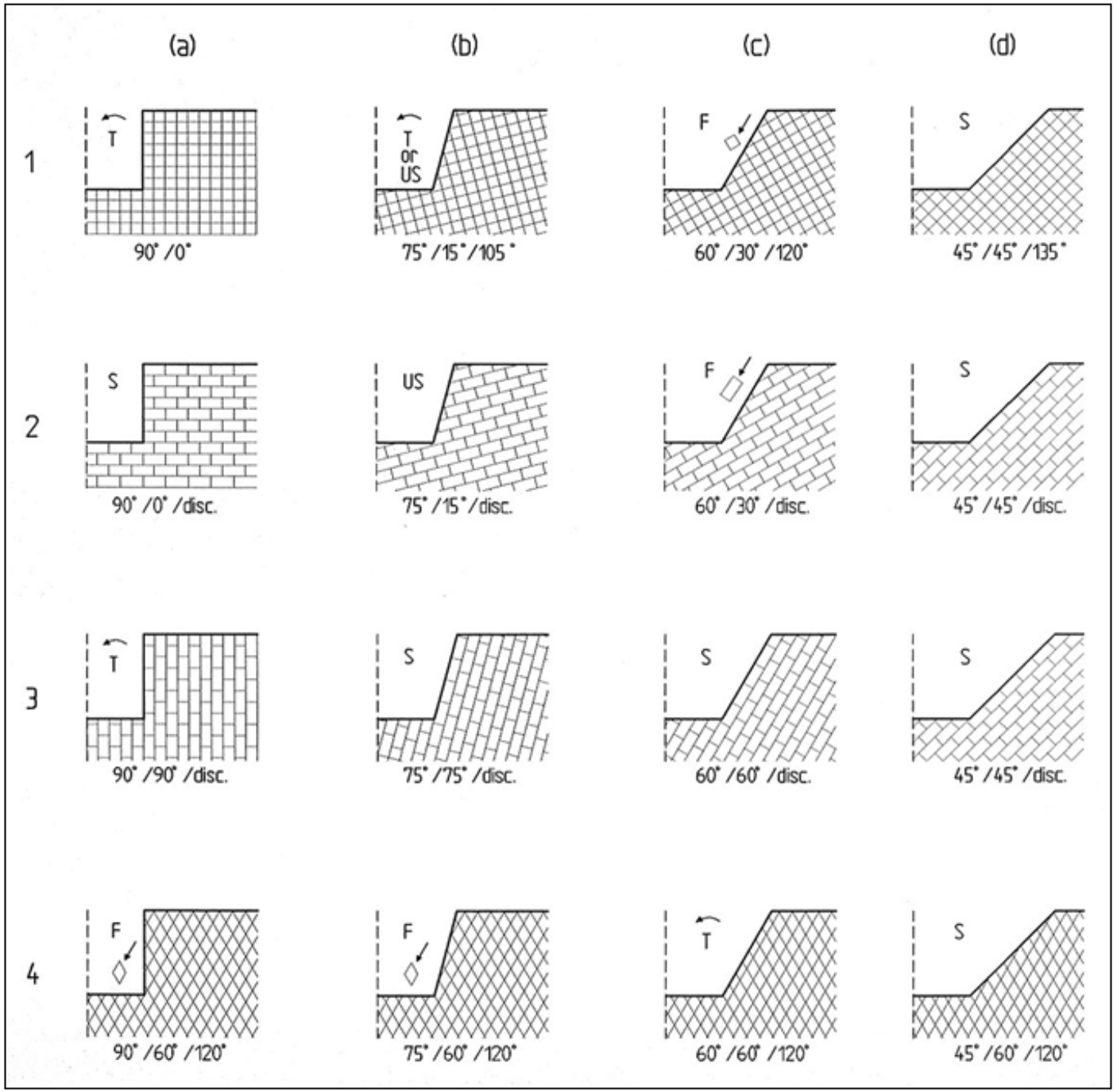


Rock slopes – and details that will never be captured in continuum modelling

A valley of rock slopes: Indian Kashmir, Northern Rail.

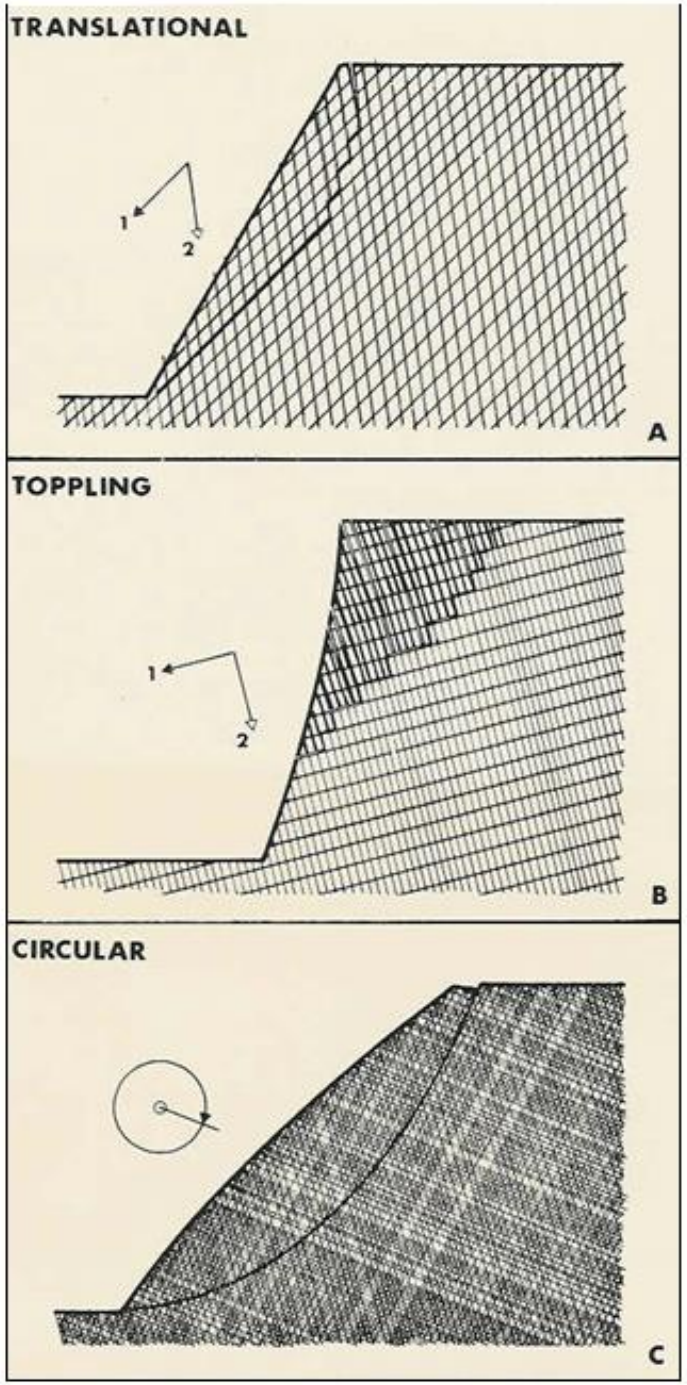
Are we supposed to ‘homogenize’ to a model material?

WHERE is ONE-JOINT-SET, or TWO-JOINT-SETS in GSI (or RMR)?



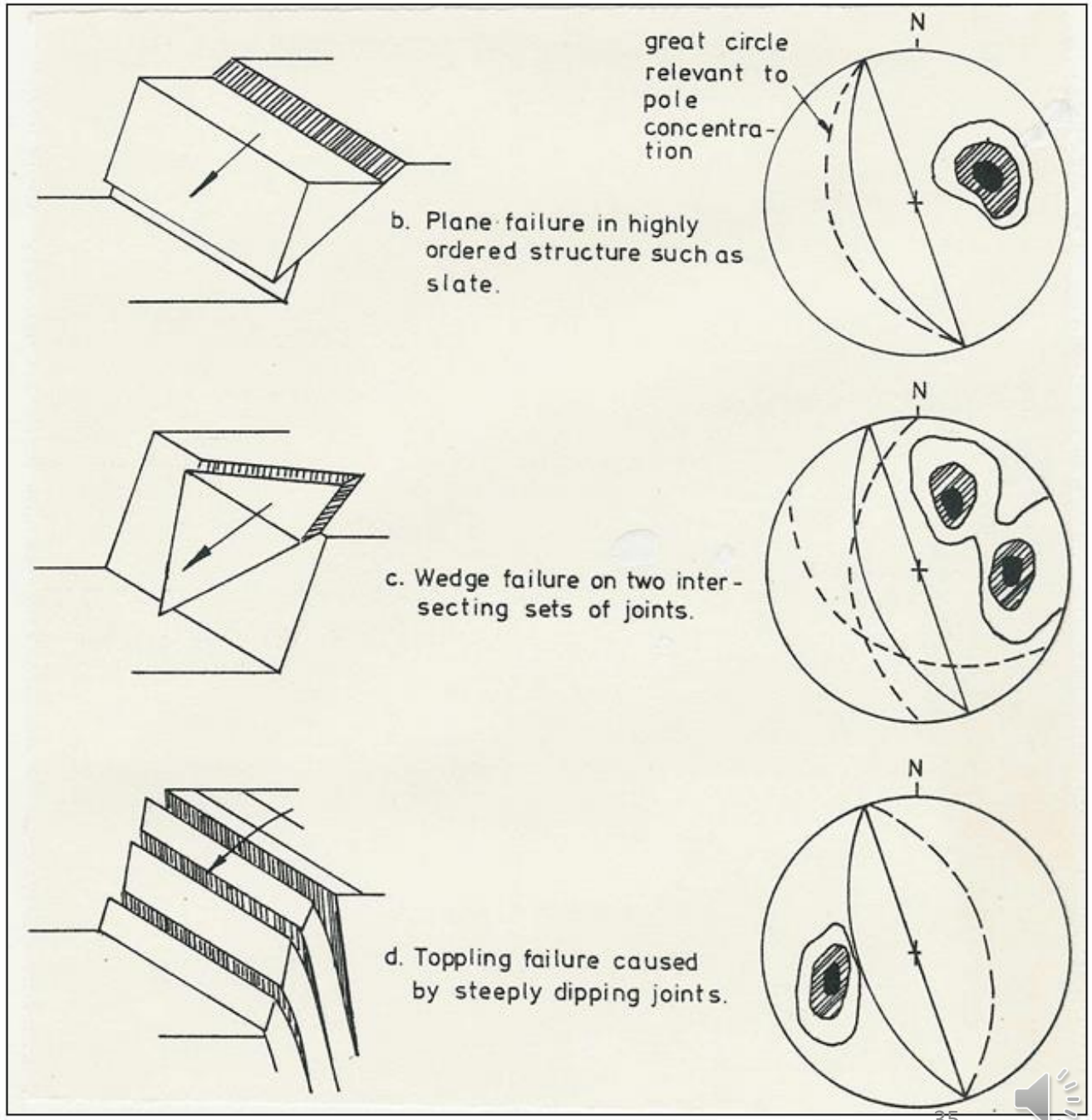
Some fundamentals (if modelling with joints):

S: stable (6)
US: unstable (2)
F: failure (4)
T: toppling (4)

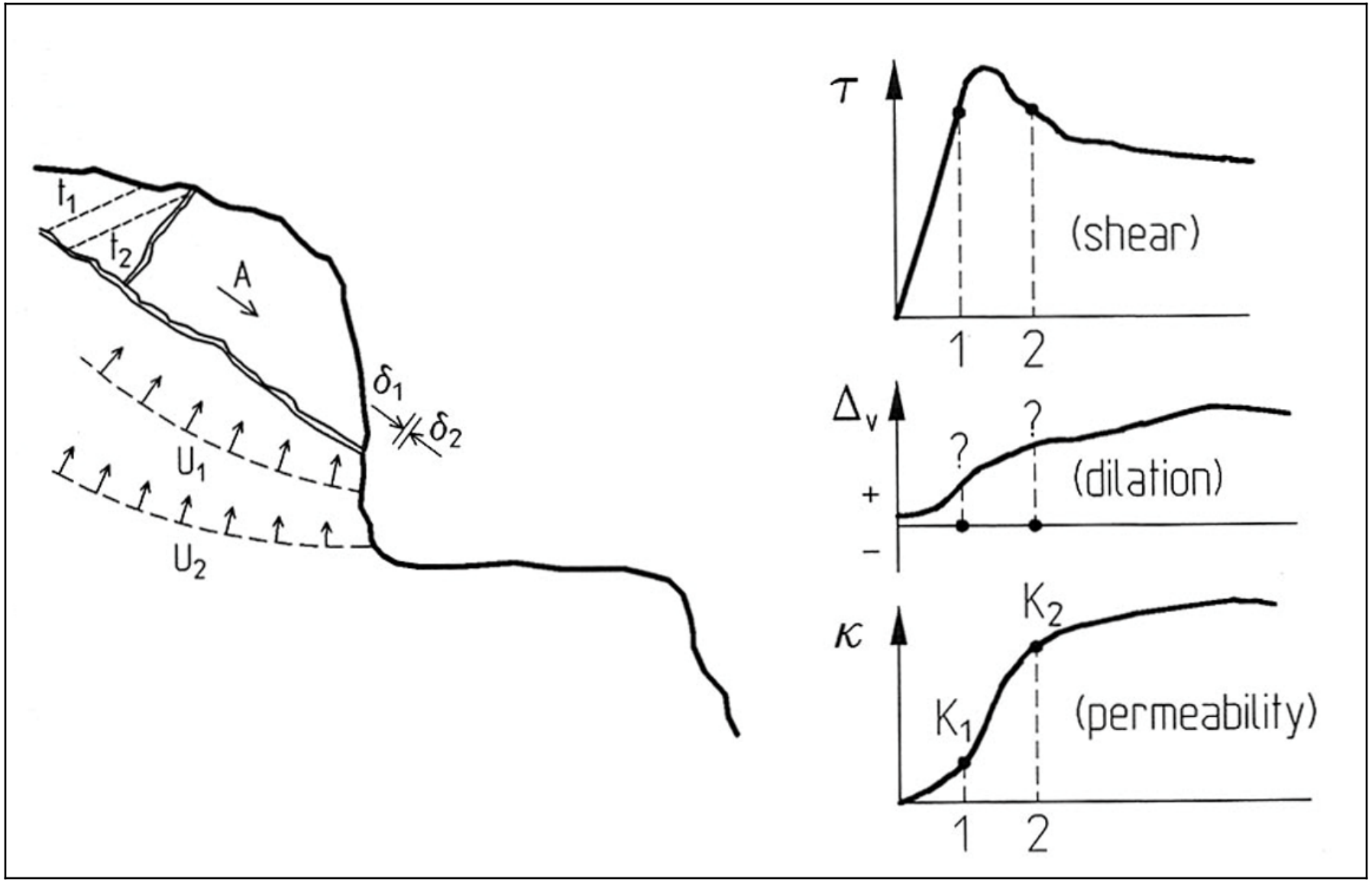


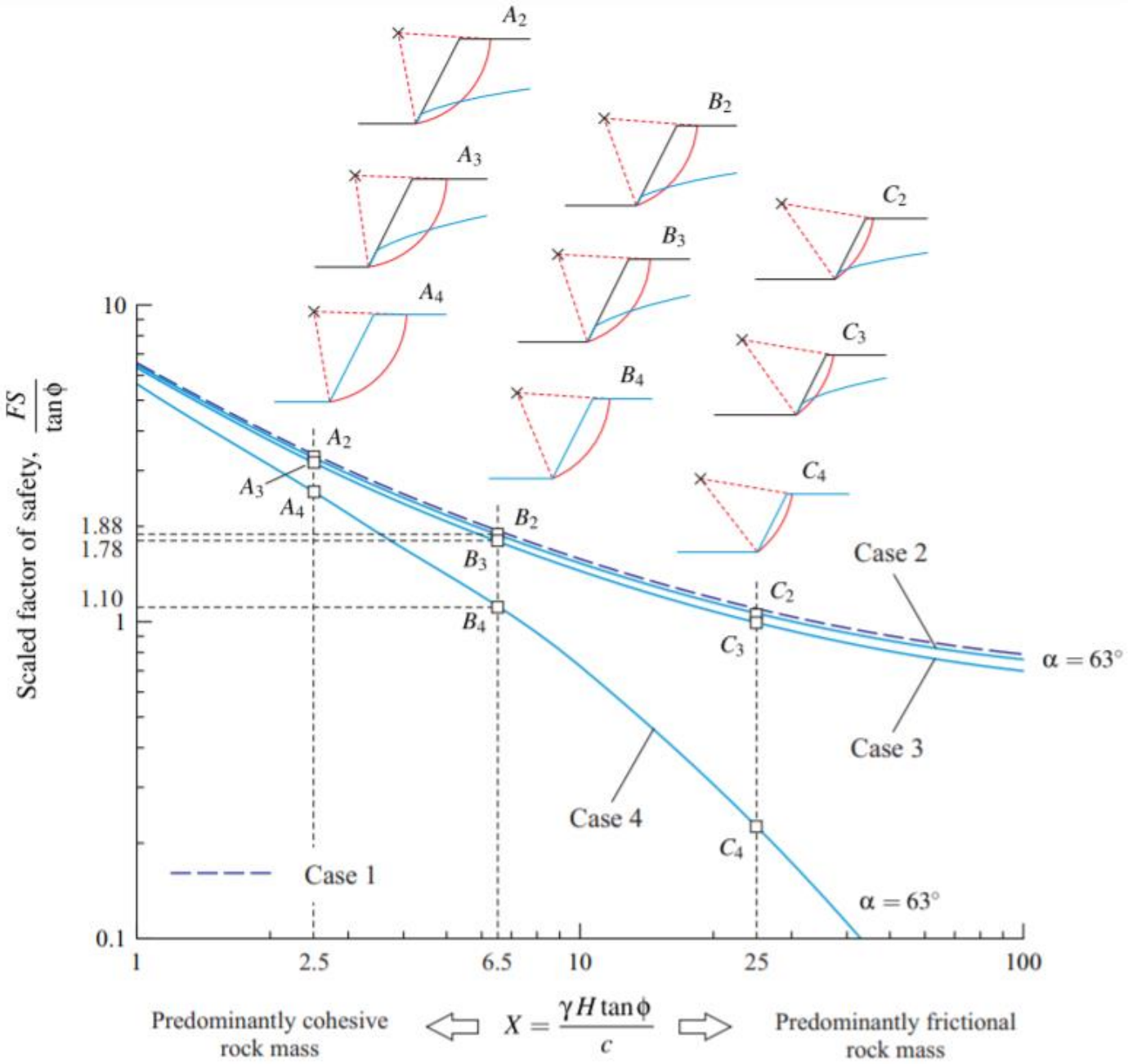
Left: Barton, 1973.

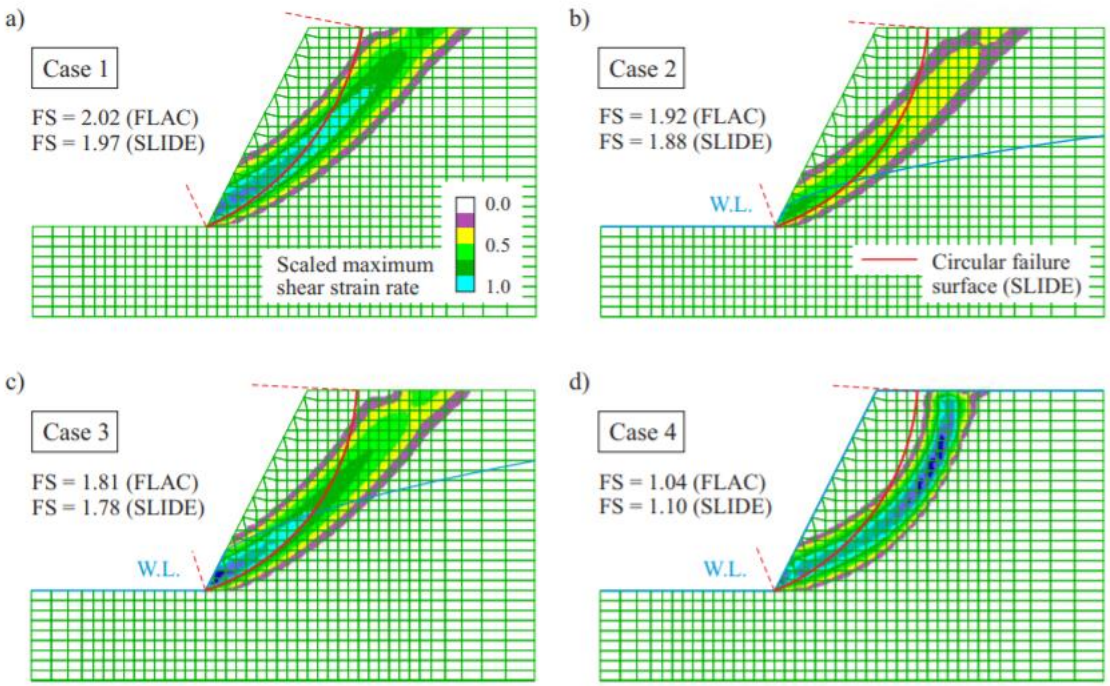
Right: Hoek and Bray, 1976



The reality is more interesting than continuum







Computational tools for the analysis of circular failure of rock slopes

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Do we ever see such failures in rock masses?

International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2020 – Hard Rock Engineering
Trondheim, Norway, 14-19 June

Slope angle versus slope height – the basis of an empirical tool for slope design within fractured rock masses using IUCM

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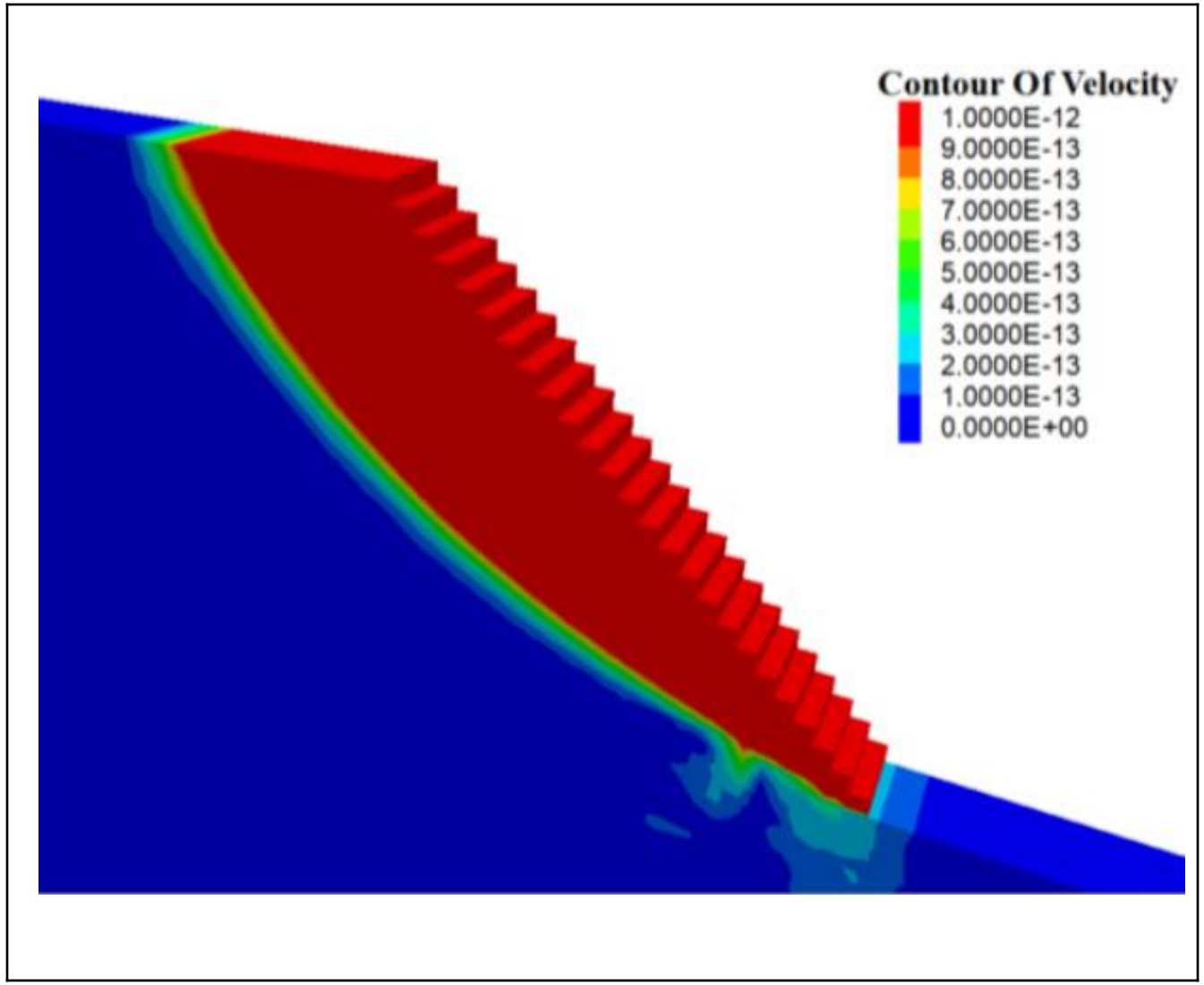
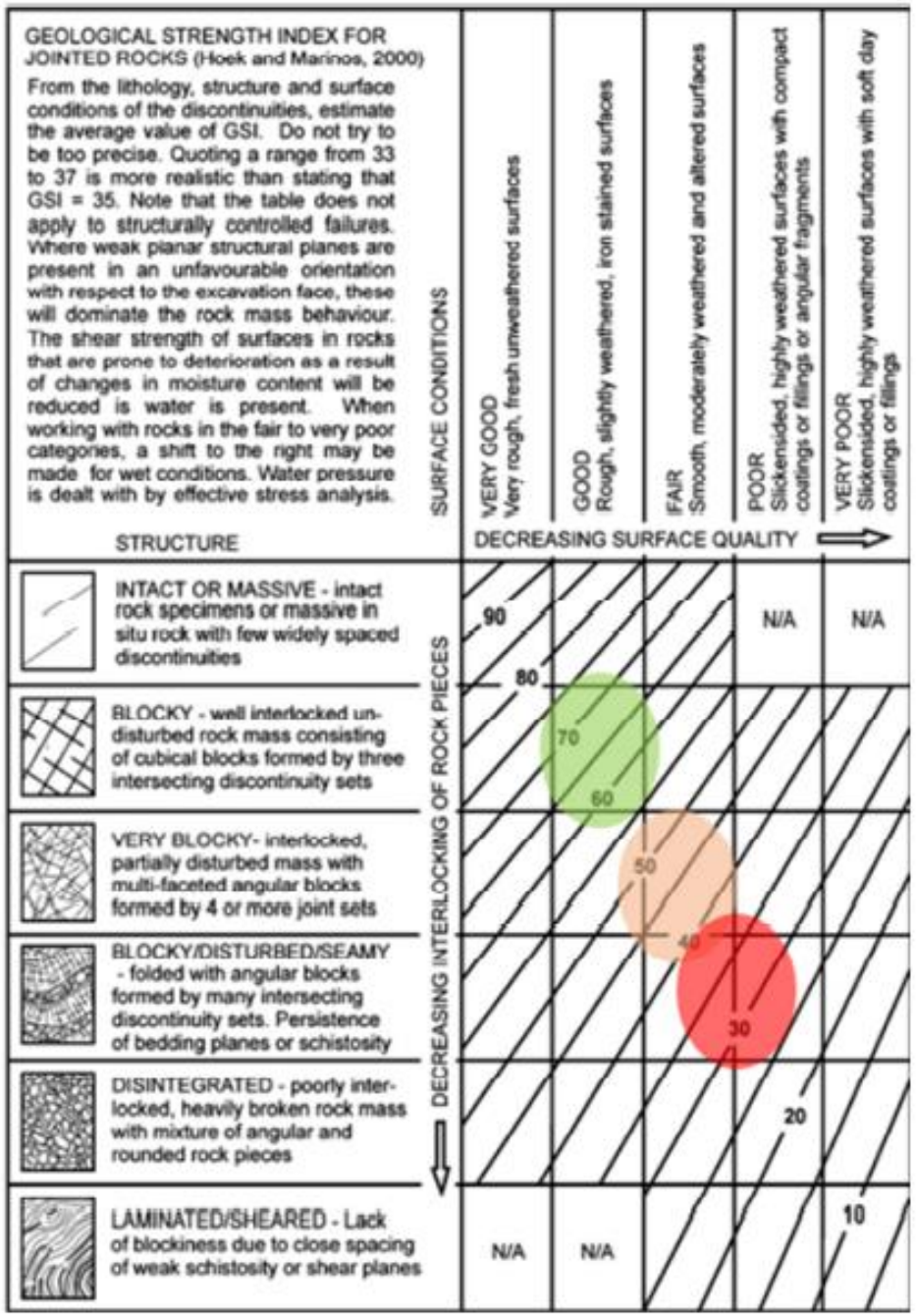
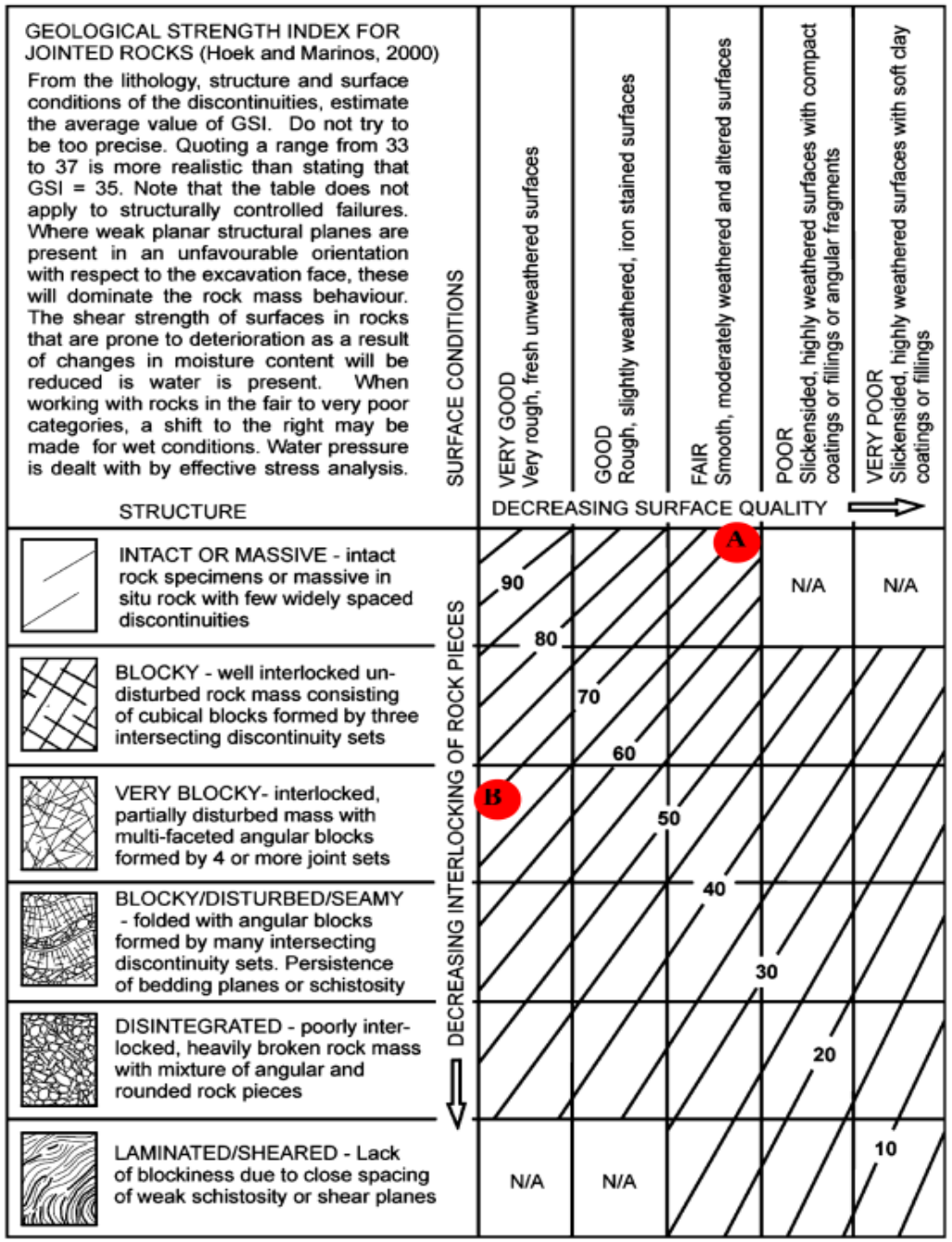


FLAC-3D slice of a 200m high open-pit slope, with IUCM constitutive model. Has anyone ever seen a huge 'spoon-shaped' failure like this in competent jointed rock? UCS 20MPa – OK? But joint effects missed by continuum modelling.

Parameter		Rock Mass B
Density	ρ (t/m^3)	2.7
Intact Young's Modulus	E_i (GPa)	28.2
Geological Strength Index	GSI	40
Hoek Brown Constant	m_i	10
Intact uniaxial compressive strength	UCS (MPa)	20

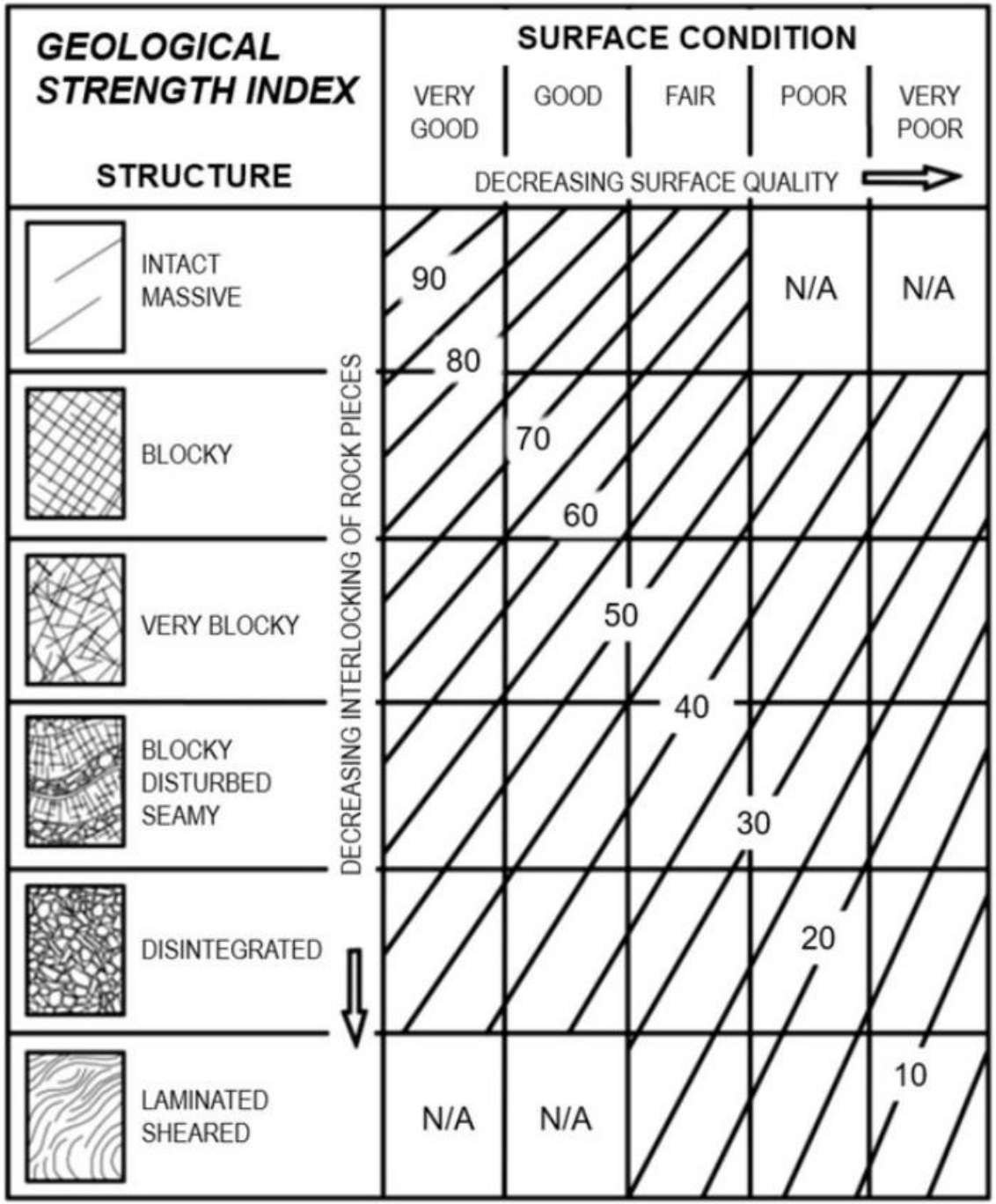
The recently developed **'Improved Unified Constitutive Model' (IUCM).** 'This takes the best parts of Mohr-Coulomb and Hoek-Brown'. ***But something is not correct here.***



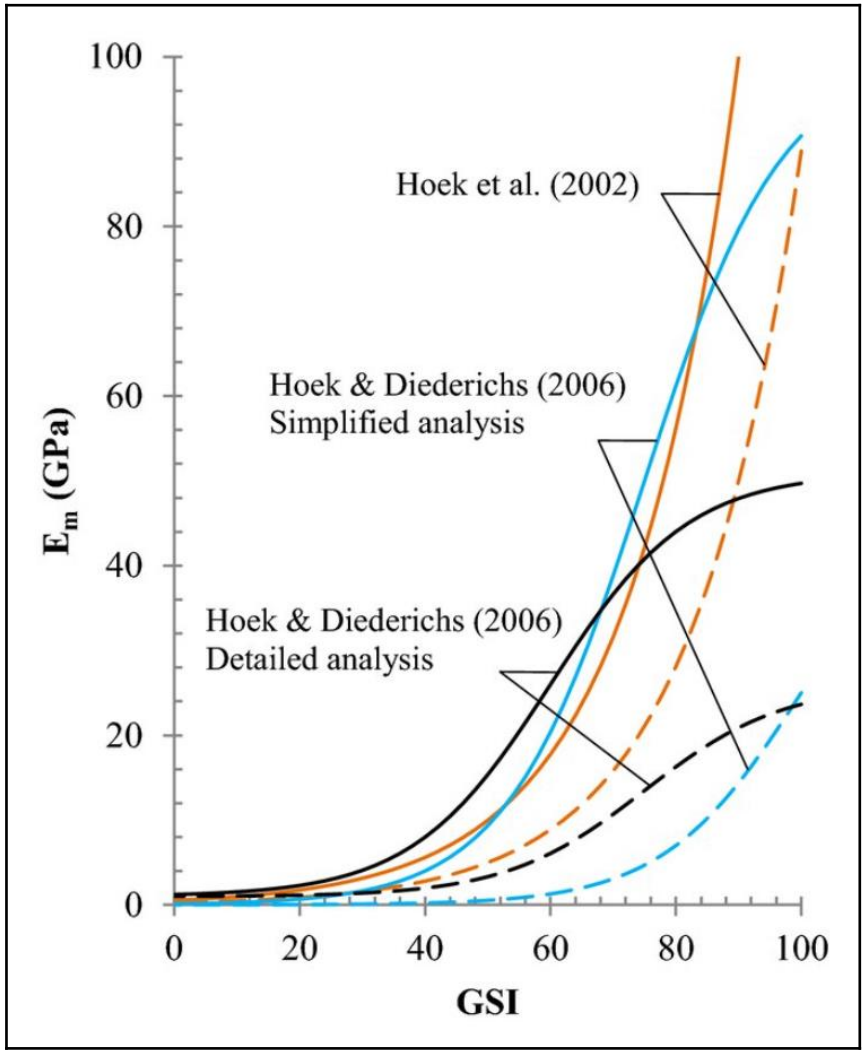


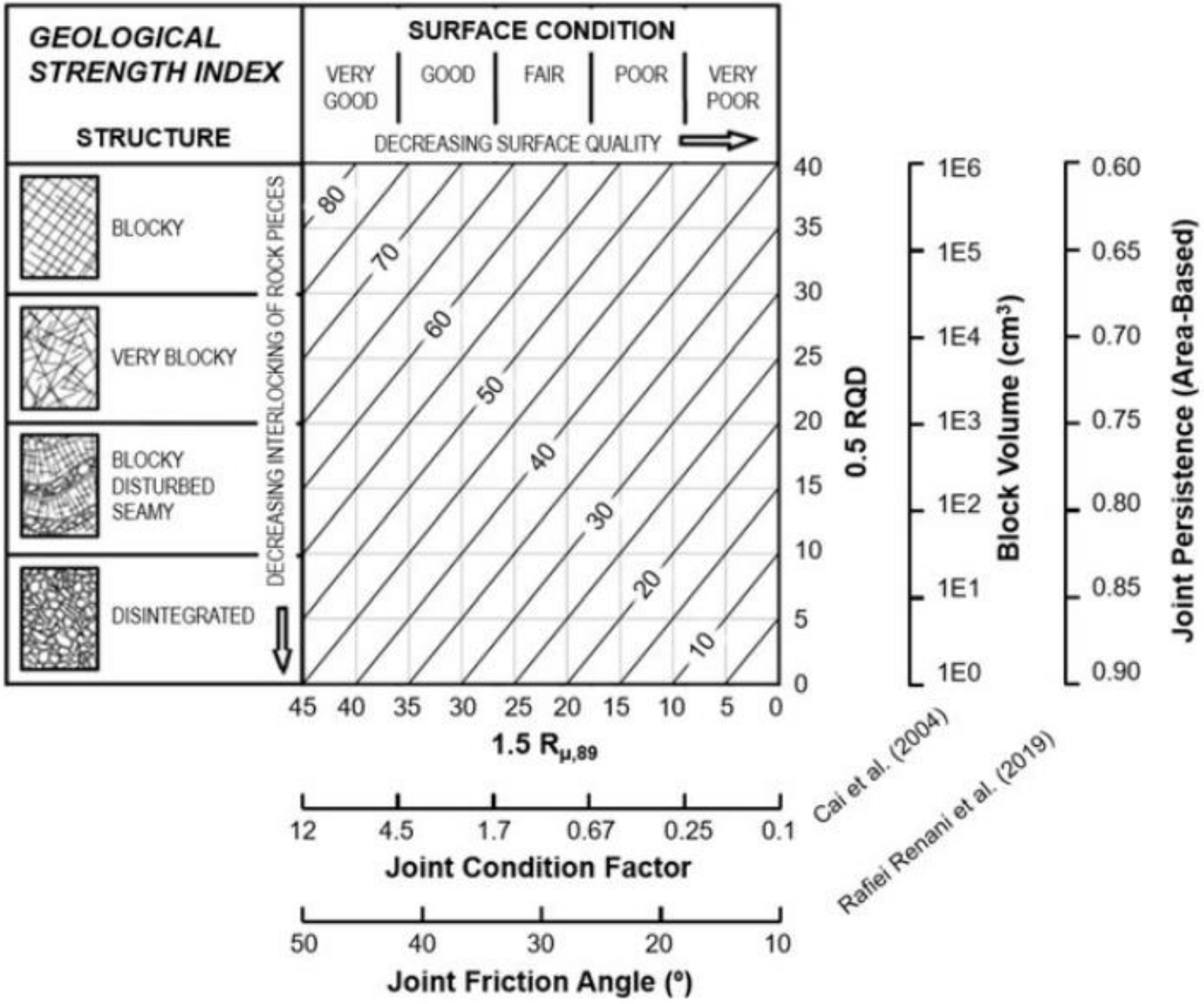
In the opinion of the lecturer it is rather remarkable that so many young (and not so young) people have adopted the Rocscience-promoted and of course Hoek-promoted GSI, with the associated Hoek-Brown equations (see following screens).

It starts to look as if ‘geology’ is involved. Then all goes into a continuum blender – and ‘geology’ is lost.



The GSI chart stripped of its author's instructions. The hopeless deformation modulus advice.





Some creative additions for 'better' quantifying GSI.

[Forty-Year Review of the Hoek–Brown Failure Criterion for Jointed Rock Masses.]

Renani and Cai, 2021

$GSI1 = RMR - 5 = R1+R2+R3+R4+R5(=15) - 5$	(1)
$GSI2 = 1.5\ R4 + 0.5\ RQD$	(2)
$GSI_3 = 15 \log\left(\frac{RQD}{Jn}\frac{Jr}{Ja}\right) + 50$	(3)
$GSI_4 = 9 \ln\left(\frac{RQD}{Jn}\frac{Jr}{Ja}\right) + 44$	(4)
$GSI_5 = \frac{52Jr/Ja}{(1+Jr/Ja)} + 0{,}5RQD$	(5)
$GSI_6 = \frac{26{,}5 + 8{,}79\ln Jc + 0{,}9\ln Vb}{1 + 0{,}0151\ln Jc - 0{,}0253\ln Vb}$	(6)
$GSI_7 = 153 - \frac{165}{\left[1+\left(\frac{Jp}{0{,}19}\right)^{0{,}44}\right]}$	(7)

A selection of some equations used to improve the quantification of GSI.

Why a published method should require so much improvement is not clear.

Ván & Vásárhelyi, 2014.

$$C_m = \frac{\sigma_{ci}\left((1+2a)s + (1-a)m_b\sigma_{3n}\right)\left(s + m_b\sigma_{3n}\right)^{a-1}}{(1+a)(2+a)\sqrt{1 + \left(6am_b\left(s + m_b\sigma_{3n}\right)^{a-1}\right)/(1+a)(2+a)}}, \quad (1)$$

$$\phi_m = \sin^{-1}\frac{6am_b\left(m_b\sigma_{3n} + s\right)^{a-1}}{2(1+a)(2+a) + 6am_b\left(m_b\sigma_{3n} + s\right)^{a-1}}, \quad (2)$$

$$\sigma_{3n} = \frac{0.47\sigma_{cm}^{0.06}(\gamma H)^{0.94}}{\sigma_{ci}}, \quad (3)$$

$$m_b = m_i \exp\frac{\mathrm{GSI} - 100}{28 - 14\,D}, \quad (4)$$

$$\sigma_{cm} = \sigma_{ci} \cdot \frac{\left(m_b + 4s - a\left(m_b - 8s\right)\right)\left(m_b/4 + s\right)^{a-1}}{2(1+a)(2+a)}, \quad (5)$$

$$E_{rm}(MPa) = 100.000\,\frac{1 - D/2}{1 + e^{(75+25D-GSI)/11}} \quad (6)$$

$$E_{rm}(MPa) = E_i\left(0.02 + \frac{1 - D/2}{1 + e^{(60+15D-GSI)/11}}\right) \quad (7)$$

The remarkable set of opaque equations that represent the Hoek-Brown formulation of the shear strength (and moduli) of rock masses.

- **YOUR LECTURER REJECTS CONTINUUM MODELLING!**

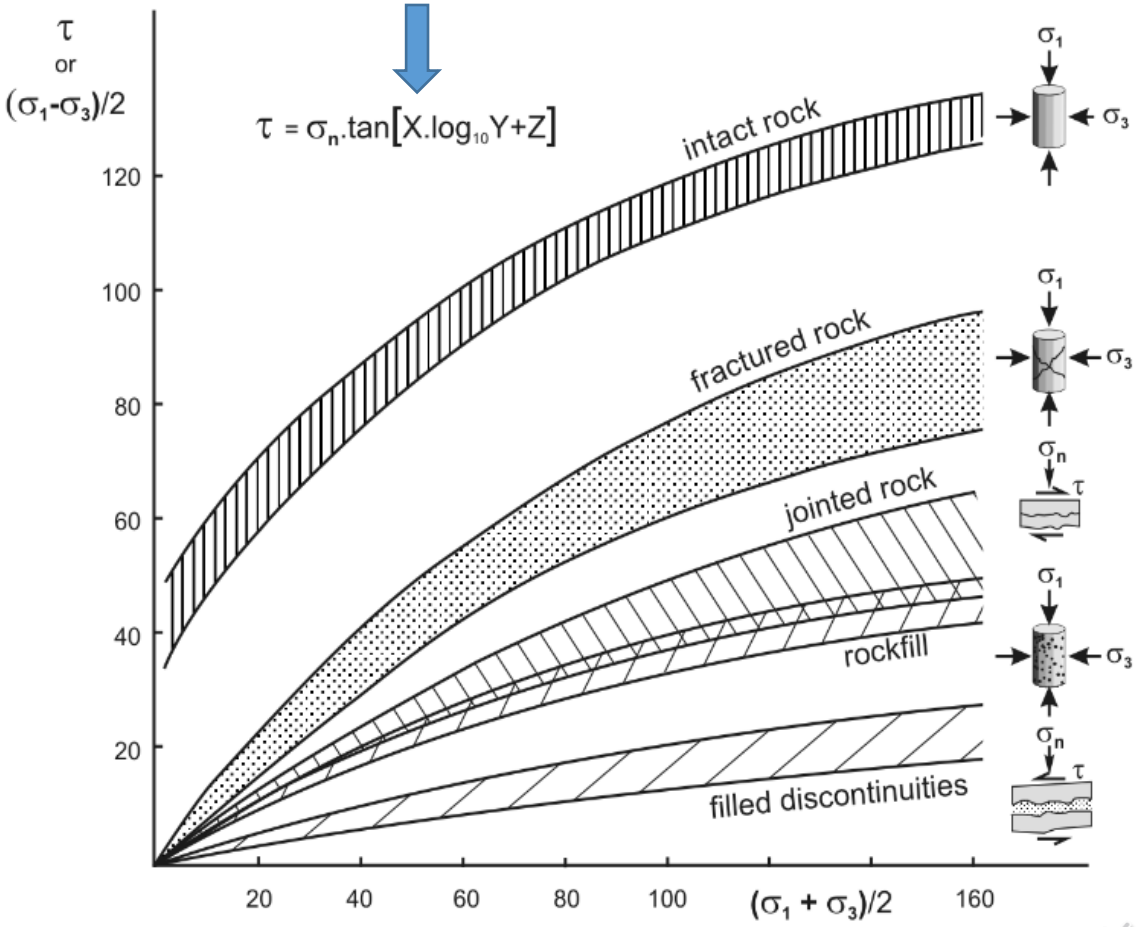
- **THE GSI HOEK-BROWN RS2 (FEM) METHOD IS USUALLY GIVING FALSE (CONTINUUM) RESULTS.**

- **ROCK *MASSES* ARE MORE INTERESTING (and more complex) THAN THIS!**

- **REAL BEHAVIOUR WILL CONSTANTLY BE A SURPRISE IN RELATION TO CONTINUUM PREDICTIONS.**

WHAT IS HELPING TO PREVENT SUDDEN COLLAPSE?

Progressive failure of components: **CcSs: crack, crunch, scrape, swoosh**



Bingham Pit: No casualties. Monitored. Progressive failure....i.e. ‘τ = c *then* σn tan ϕ’

SLIDING ON A BASAL FAULT PLANE WITH WEDGE EFFECT SEEN TO THE LEFT. NO ‘SPOON-SHAPED’ FAILURE AS WITH CONTINUUM ANALYSES.

CONCLUSIONS

1. Continuum modelling concepts and results may be misleading many.
2. Mohr-Coulomb and Hoek-Brown (based on GSI) are part of the problem.
3. Real rock masses are usually jointed and sometimes faulted.
4. The jointing (and faulting) can be in rock with UCS as low as 5MPa.
5. Modelling rock masses as discontinua is of course more difficult.
6. Joints have stress-dependent shear strength and exhibit dilation.
7. UDEC-BB may be the most realistic method if 2D approximation is OK.
8. 3DEC with a smaller number of key joint sets is complex but may be needed.
9. An open-pit mine is not a cheap affair. Modelling cannot be cheap either.
10. Rock slopes with joints do not show spoon-shaped failure, like models.
11. An open pit will often fail (if it is possible) by combined fault and joint wedges.

Nick Barton obtained a London University B.Sc. in Civil Engineering from King's College in 1966, and a Ph.D. concerning shear strength and rock slope stability from Imperial College in 1971. He worked for two long periods at NGI in Oslo, and for four years at TerraTek in Salt Lake City. Since 2000 he has had his own international rock engineering one-man consultancy, Nick Barton & Associates, based in Oslo and São Paulo. He has consulted on several hundred rock engineering projects in a total of 40 countries during 50 years, has 270 publications as first or single author, and has written two books, one on TBM prognosis, the other linking rock quality and seismic attributes of rock masses at all scales. He is currently writing a book with Bandis: Engineering in jointed and faulted rock (expected 2023). He has twelve international awards including the 6th Müller Lecture of ISRM. **He developed the widely used Q-system for classifying rock masses, and for selecting rock tunnel and cavern single-shell support in 1974. He was originator of the rock joint shear strength parameters JRC and JCS and co-developer of the resulting Barton-Bandis constitutive laws for rock joint coupled M-H modelling in 1982, which was incorporated as a sub-routine in UDEC-BB in 1985.** He has also developed the Q*tbm* prognosis method and Q*slope* for selecting maintenance-free rock cutting and bench-face angles. His chief areas of consulting activity have been in hydropower tunnelling and cavern construction and performance, nuclear waste disposal site characterization, metro tunnels and caverns, and site characterization assistance at high dams. He has given more than forty keynote lectures in international conferences.