SOFT ROCKS THAT ARE JOINTED GIVE EXTRA CHALLENGES

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Macedonia ISRM keynote, OHRID, June 2022

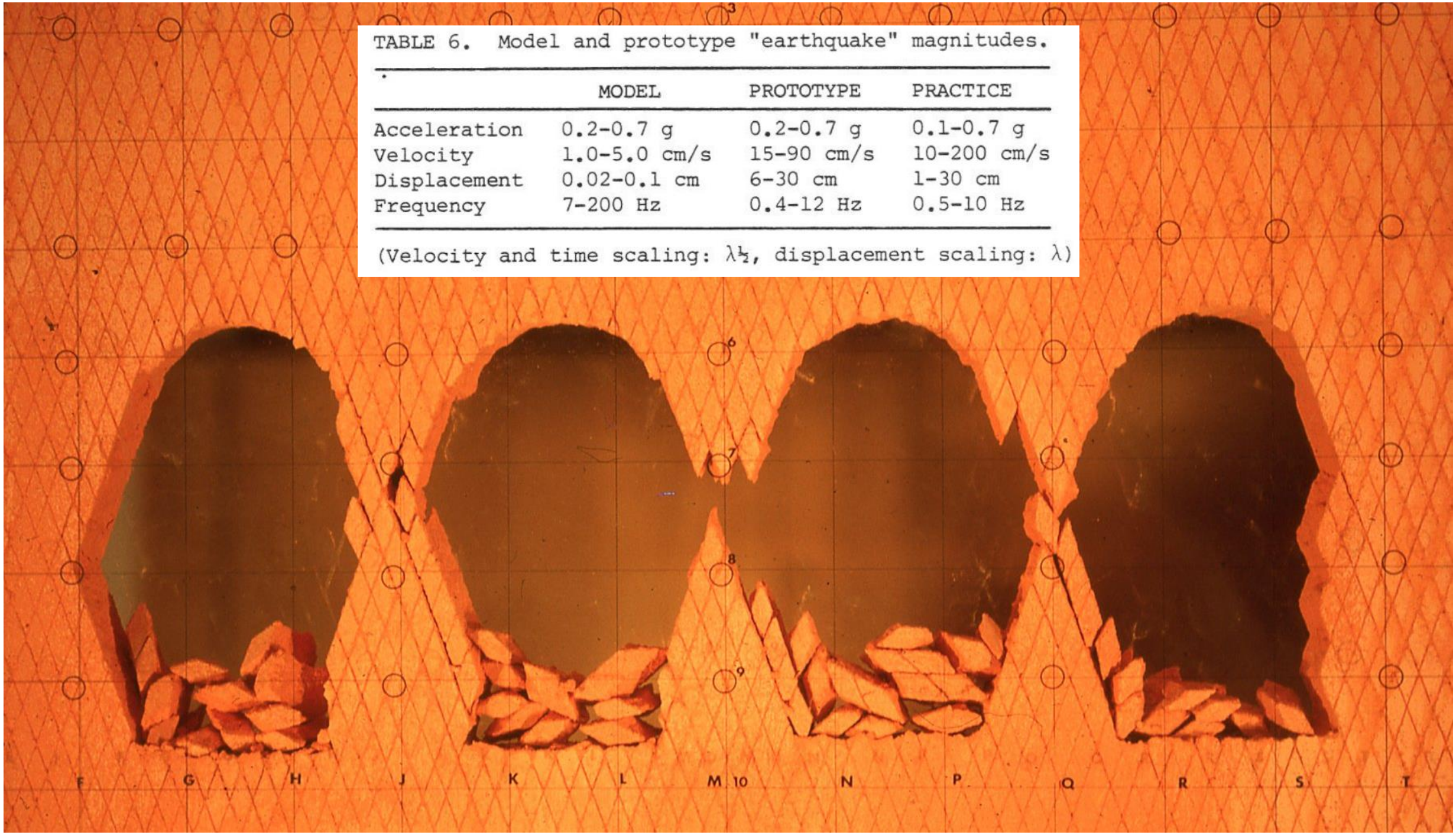
CONTENT of LECTURE

1. WEAK BRITTLE PHYSICAL MODELS WITH FRACTURES, LOG-SPIRALS
2. CHALK MARL AT CHANNEL TUNNEL – CHALLENGES OF JOINTING, WATER
3. PRECEDENT EXPERIENCE IN NEAR-BY TUNNELS – IN CHALK MARL
4. BEAMONT/CAPT. ENGLISH 1880 (!) TBM TUNNEL OF 2.2m DIAMETER
5. FRACOD MODELLING ‘EXPERIMENTS’ TO MATCH TUNNEL FAILURE
6. APPLYING THE Q-SYSTEM’S ‘Q-histogram’ METHODS IN CHALK MARL
7. TML-CONSORTIUM Q-LOGGING AT CHANNEL TUNNEL
8. INDEPENDENT COMPARISON WITH NB&A LOGGING TEN YEARS LATER
9. TBM WORLD RECORDS FOR ‘CHUNNEL’ 8.3m DIAMETER MACHINES
9. THE DANGER OF HIGH WATER PRESSURE AND LOW EFFECTIVE STRESS
10. CONCLUSIONS

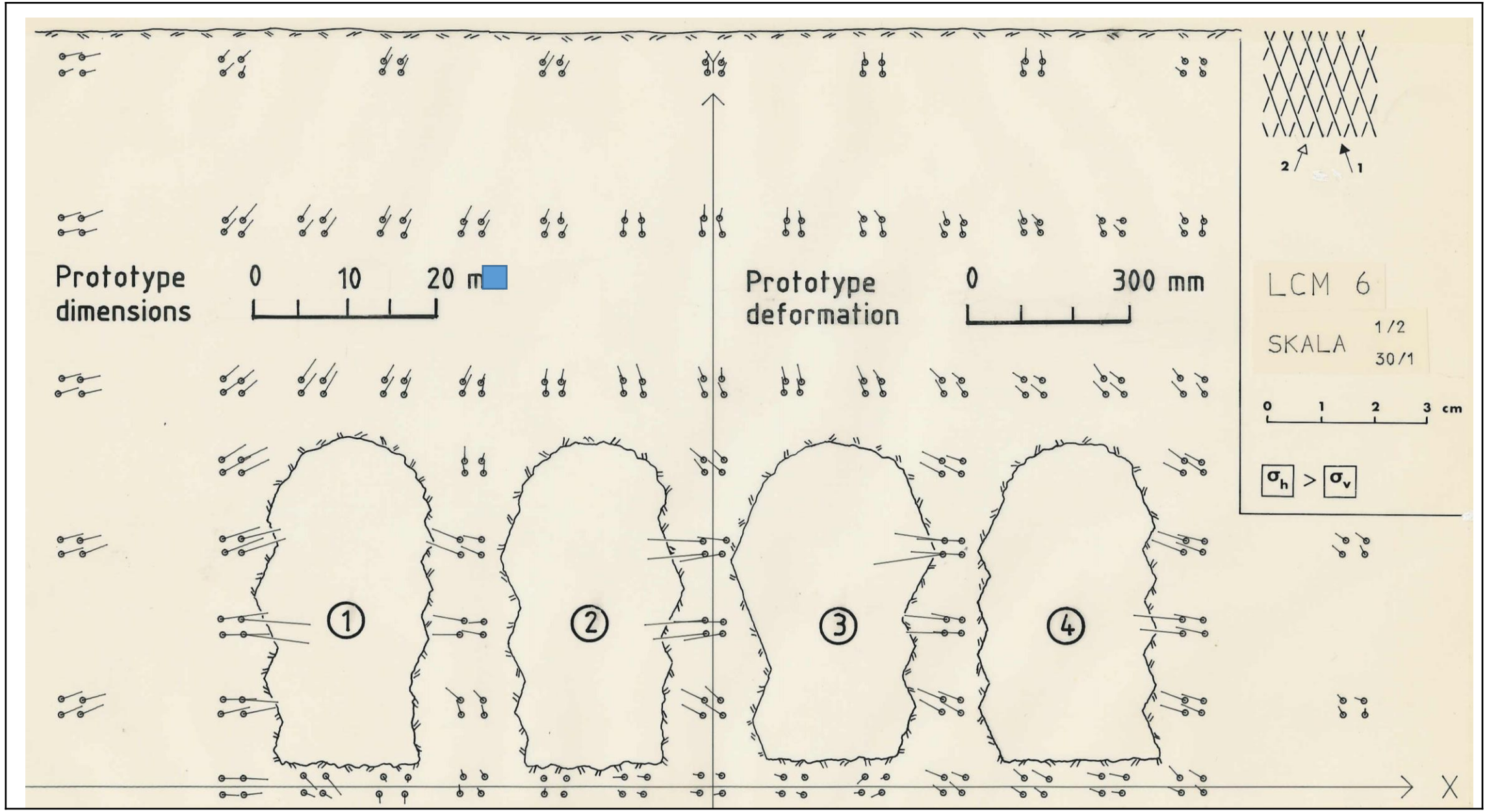
TABLE 6. Model and prototype "earthquake" magnitudes.

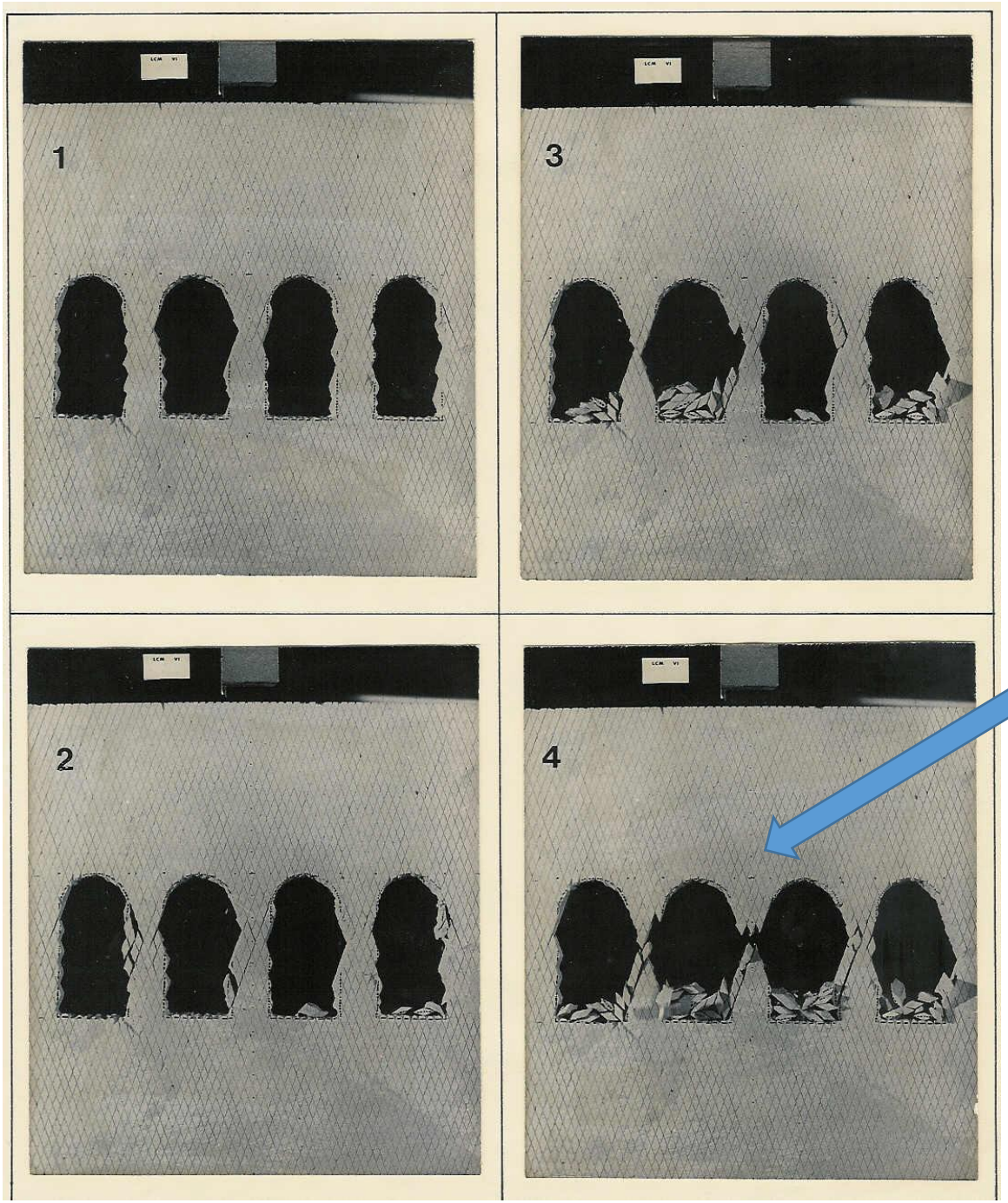
	MODEL	PROTOTYPE	PRACTICE
Acceleration	0.2-0.7 g	0.2-0.7 g	0.1-0.7 g
Velocity	1.0-5.0 cm/s	15-90 cm/s	10-200 cm/s
Displacement	0.02-0.1 cm	6-30 cm	1-30 cm
Frequency	7-200 Hz	0.4-12 Hz	0.5-10 Hz

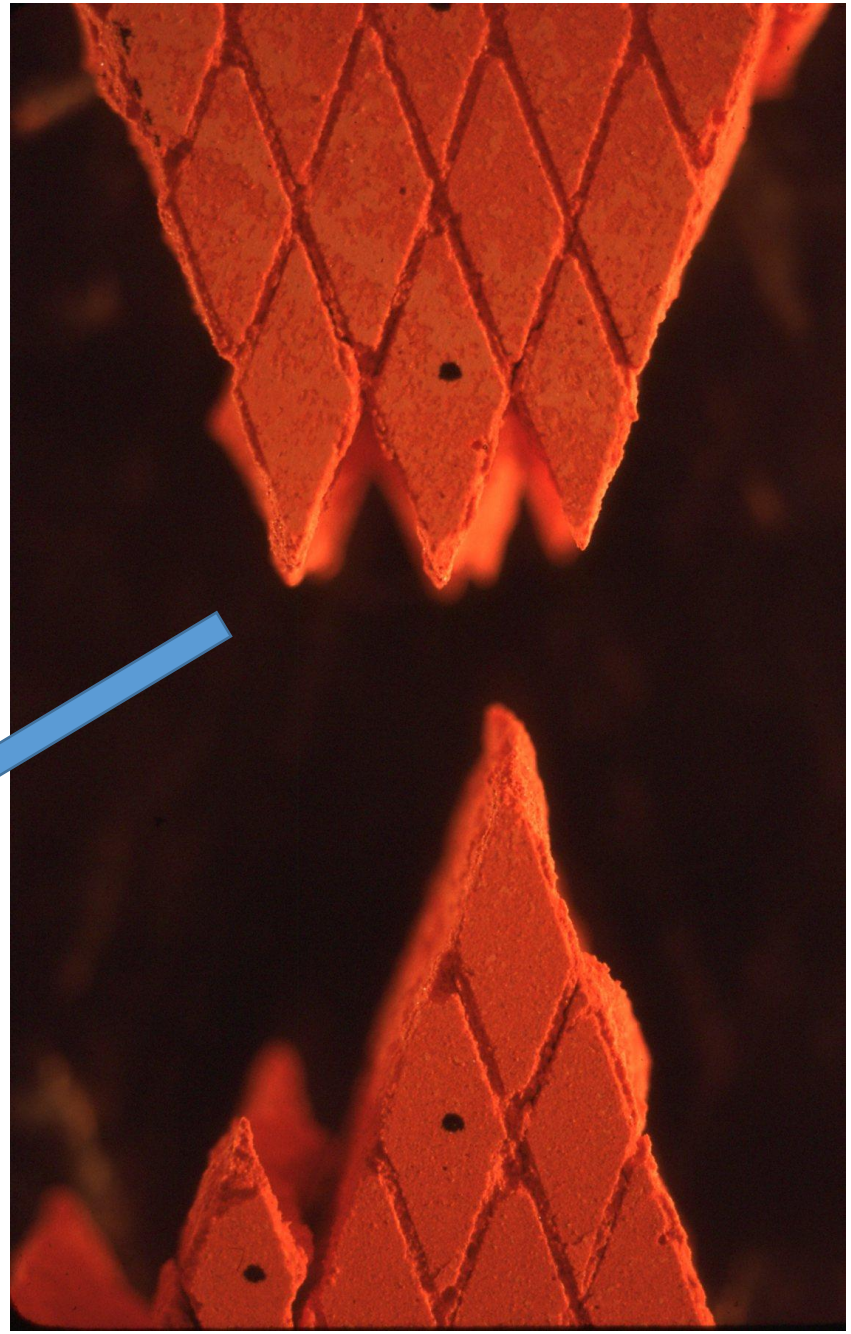
(Velocity and time scaling: $\lambda^{1/2}$, displacement scaling: λ)



Fracture ***over-closure*** from previous stress state: new excavations (1, 2, 3 and 4) do not reverse the deformation direction.(Demonstrates discontinuous, non-elastic behaviour)

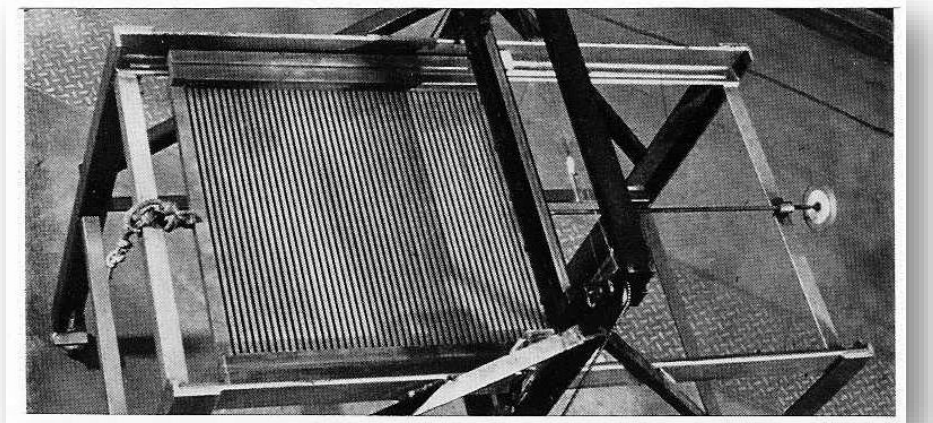


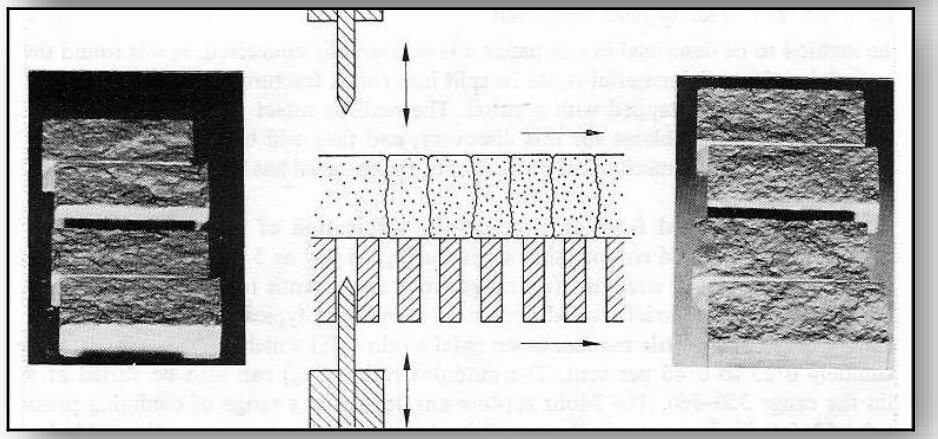




Dynamic modelling of closely spaced caverns

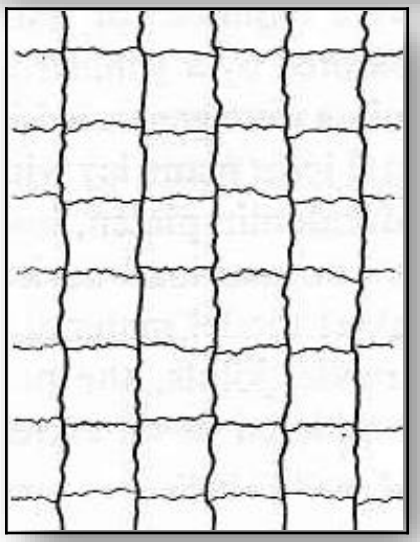
2D JOINTED "ROCK-MASS"

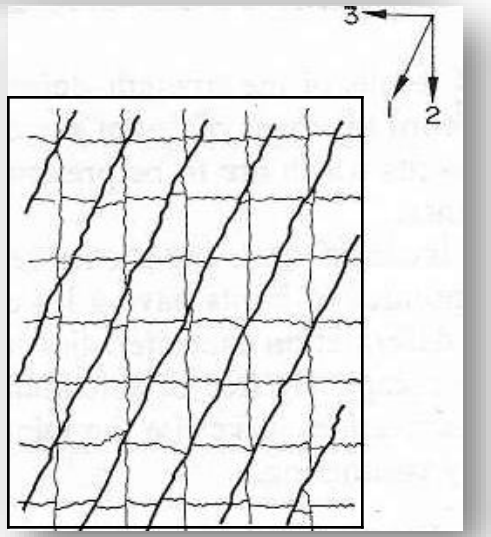


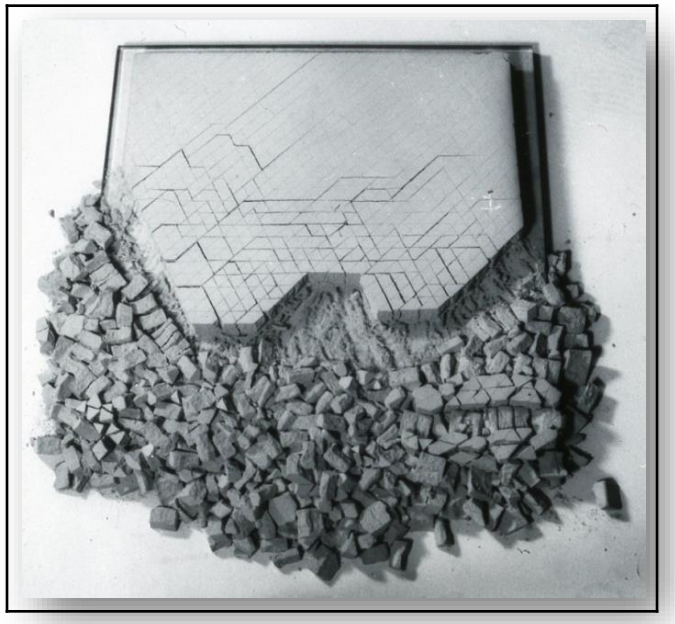


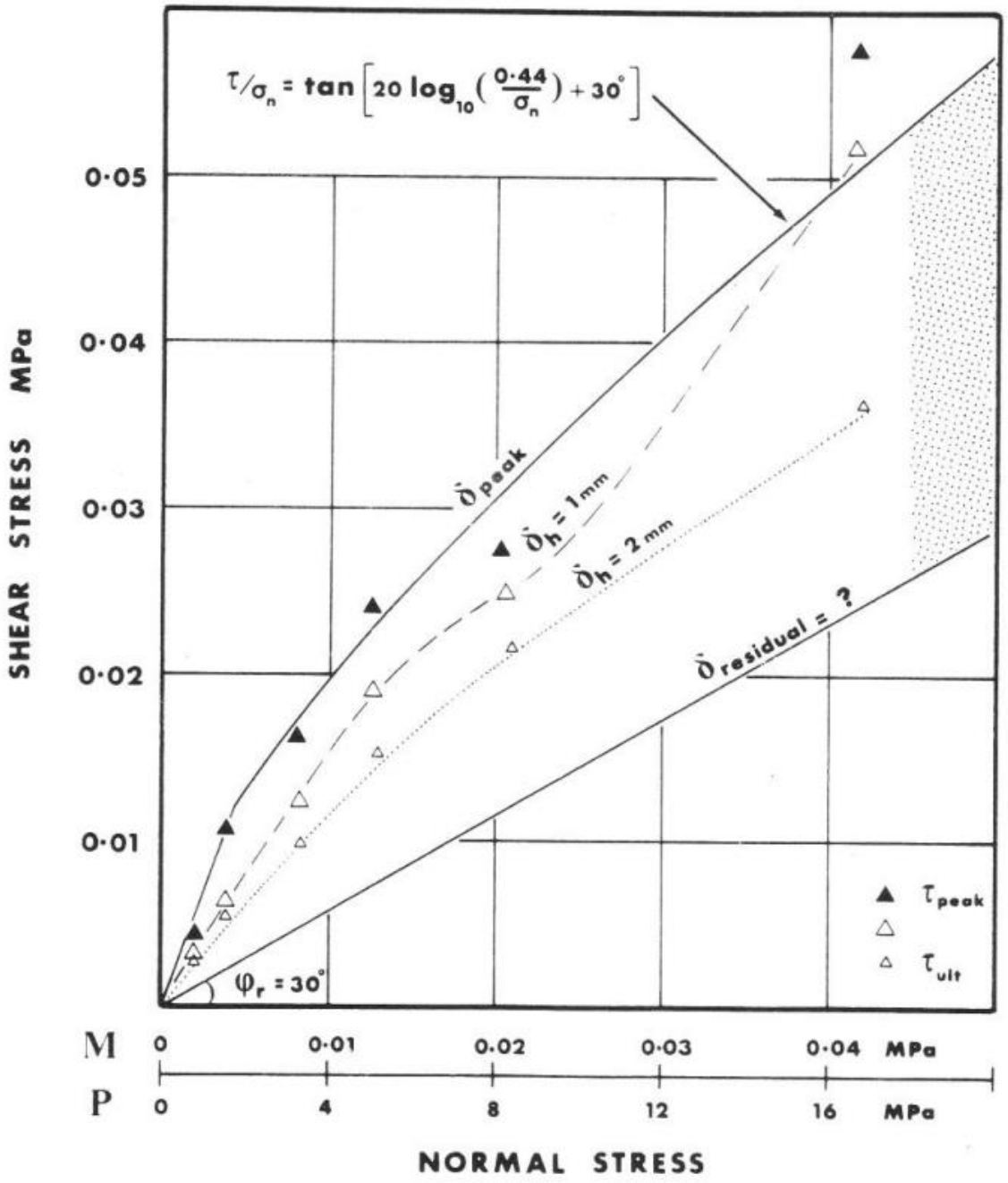
Tension-fracture models used for '*rock slope' studies* (in Ph.D. at Imperial College) 1968-1970.

'Nuclear power plant' *rock cavern* investigations (50m span) (at NGI) 1977-1978 (pre-UDEC)



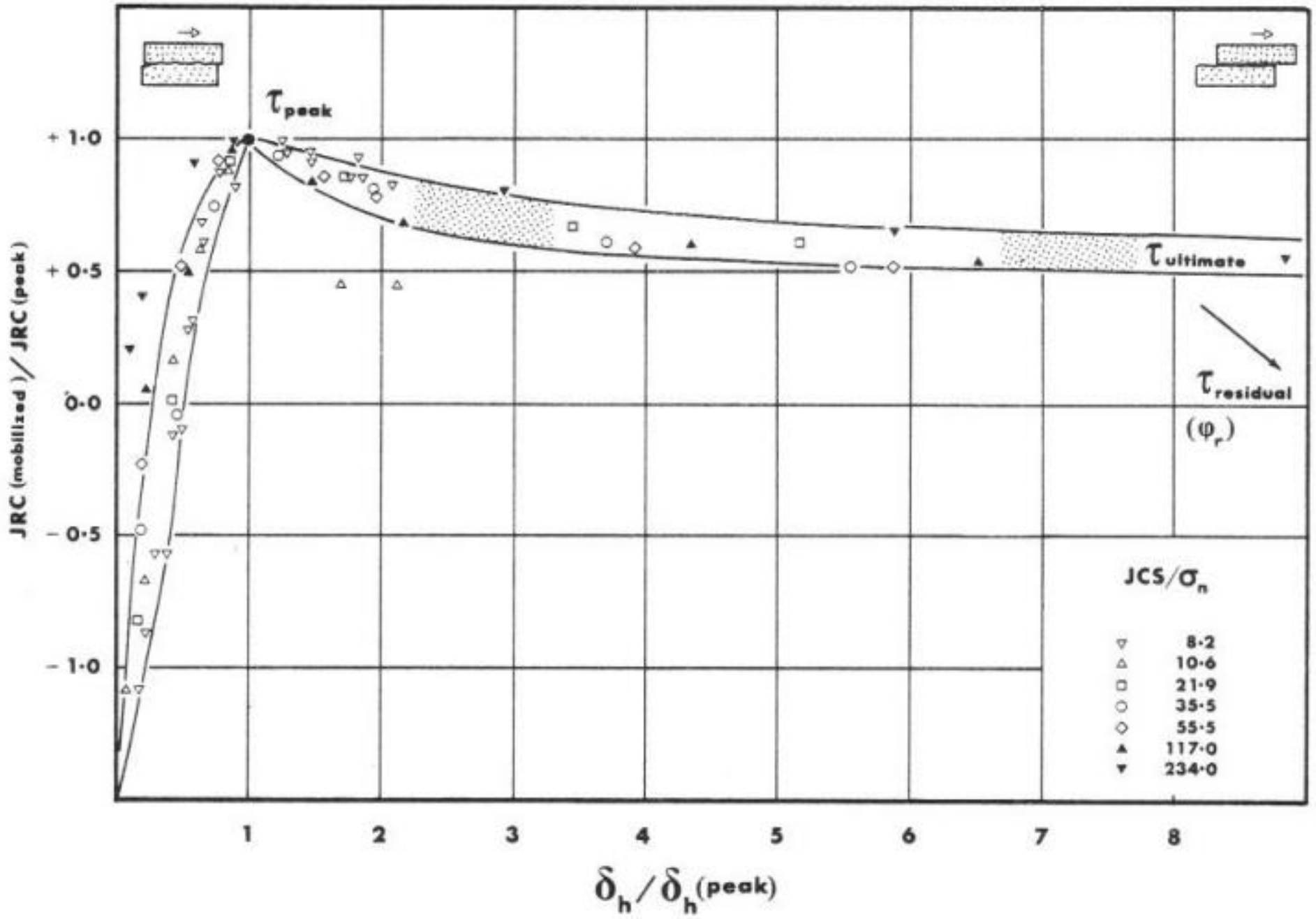




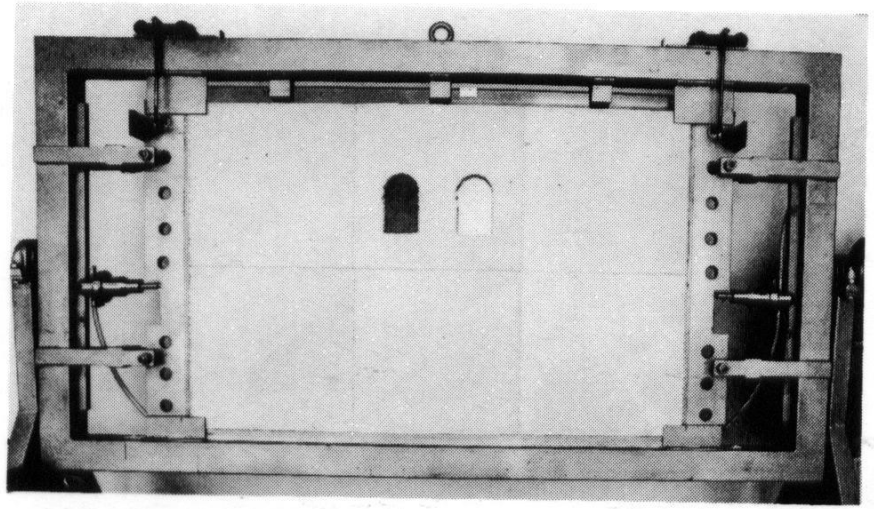


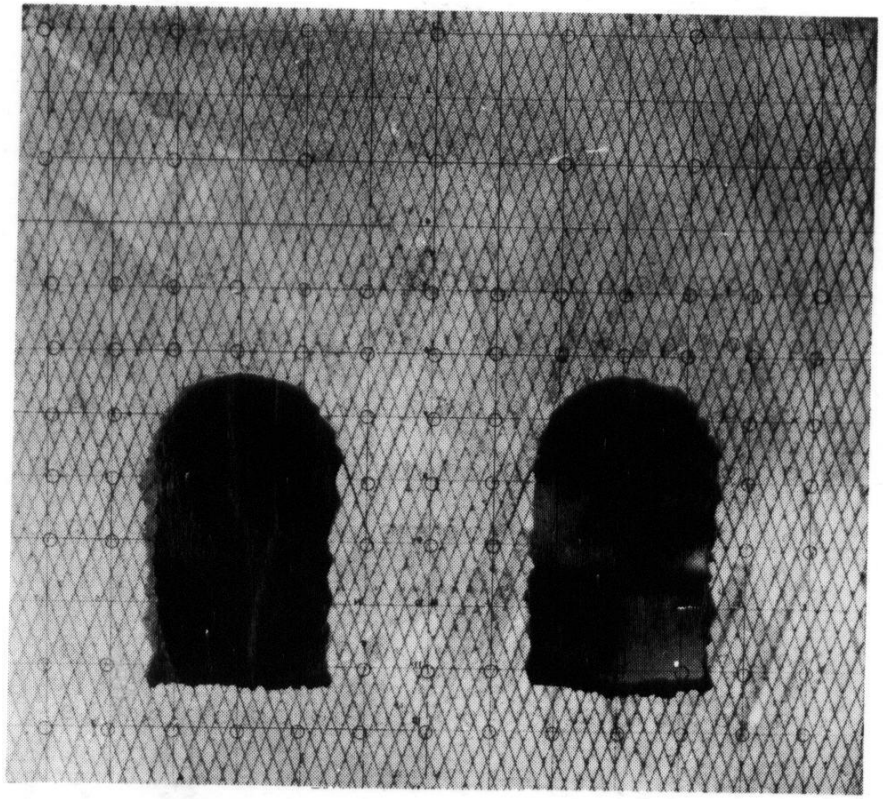
Peak and post-peak shear strength of the tension fractures. (UCS 0.4MPa)

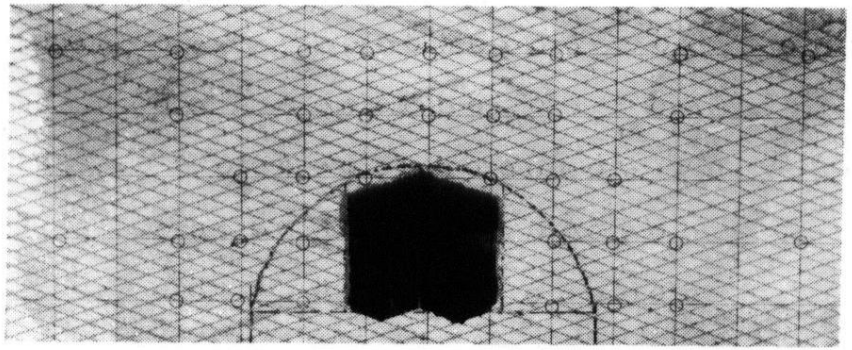
SYMBOL	MODEL	UNITS	PROTOTYPE
σ_c	0.44	Mpa	175
σ_c/σ_t	8(approx.)	-	8(approx.)
E(intact)	87	Mpa	35 000
ρ	19	kN/m^3	25

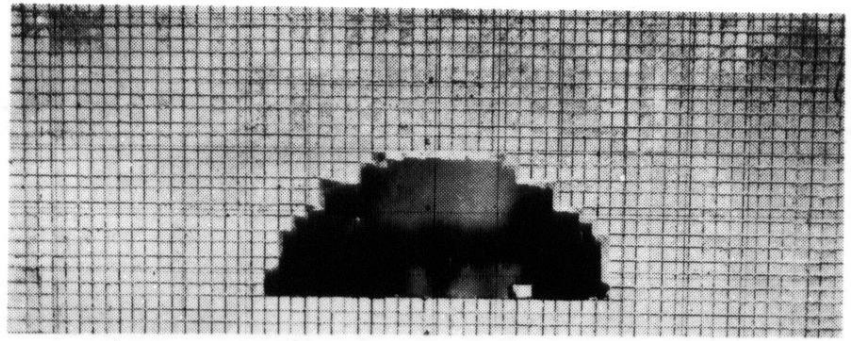


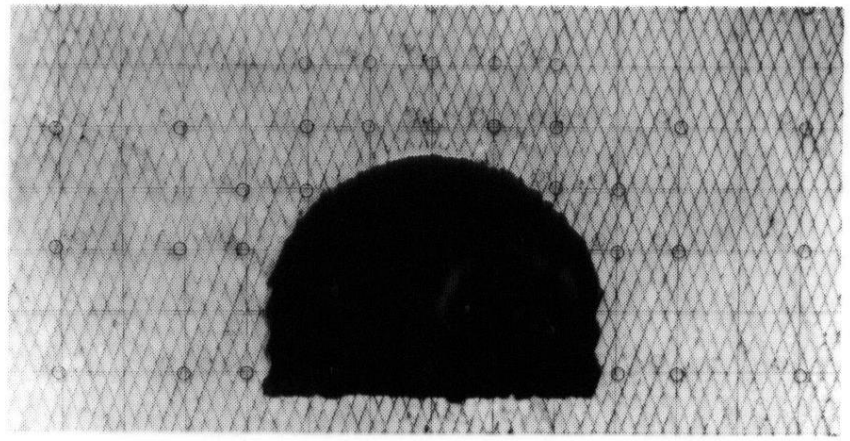
First application of JRCmobilized



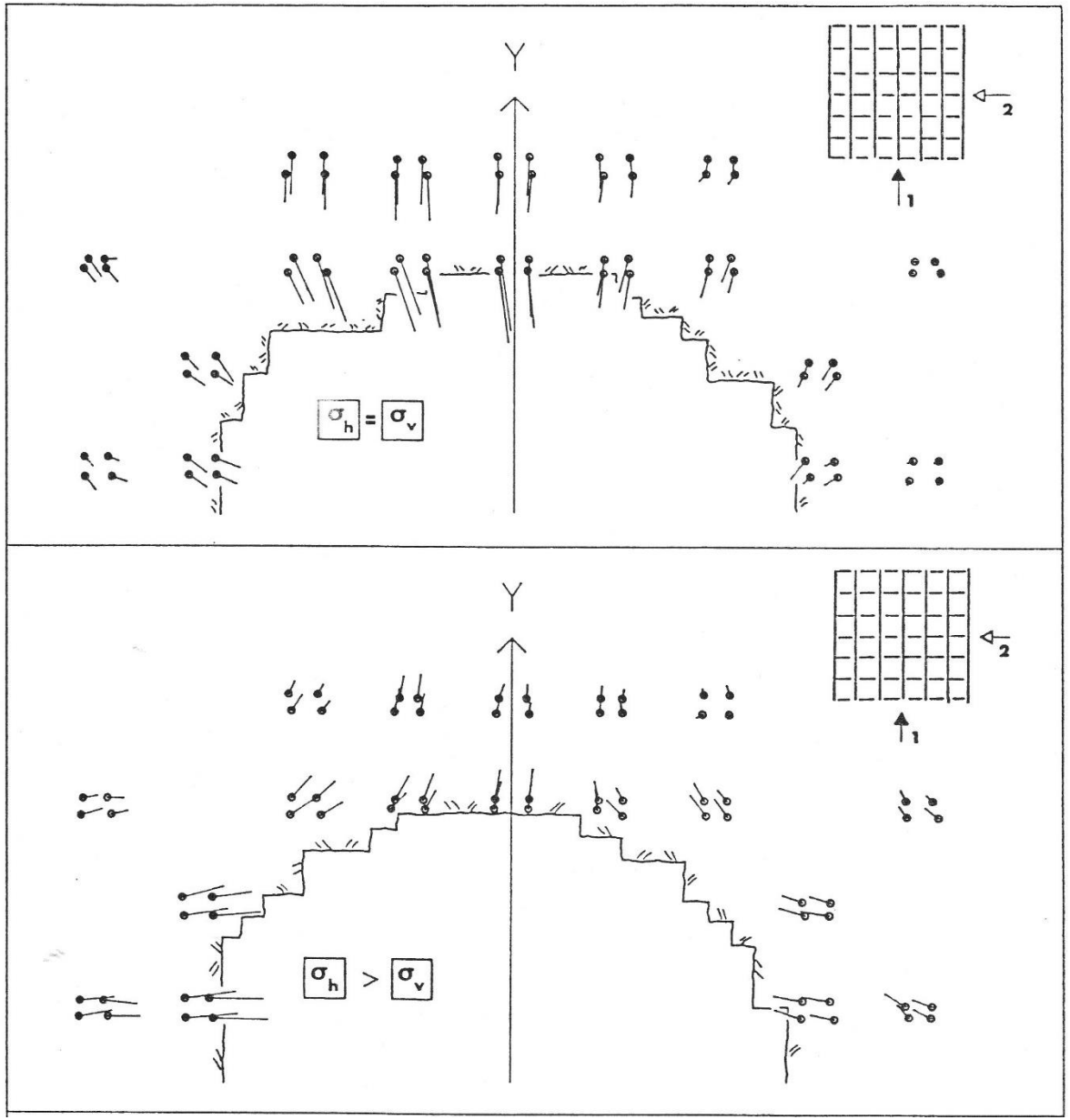


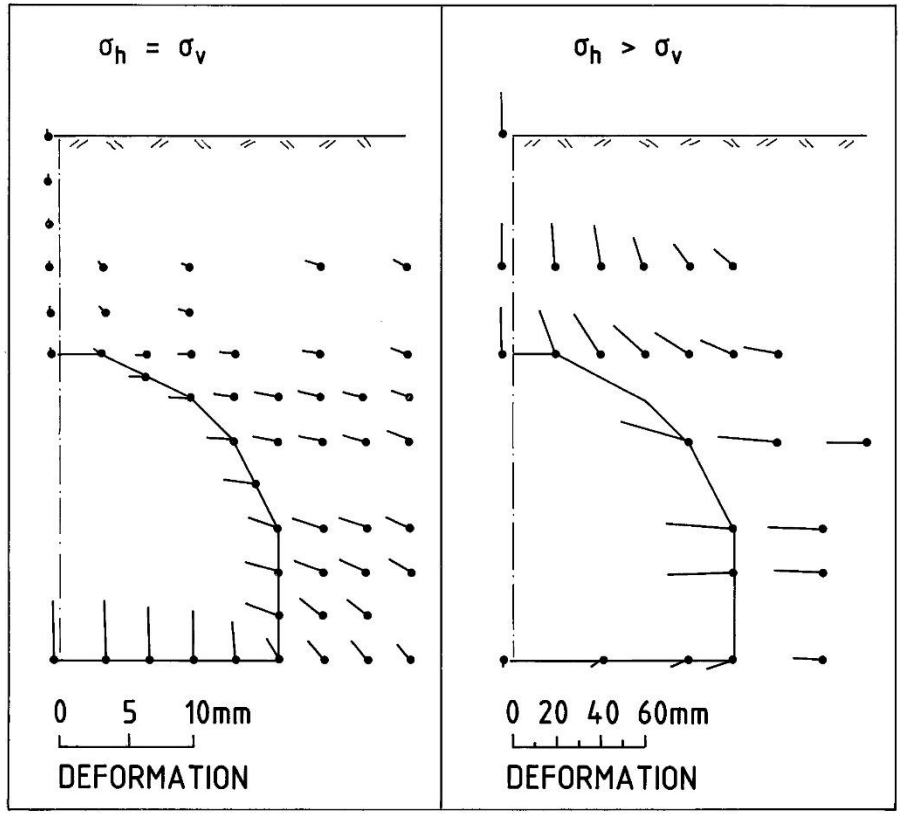






Pre-UDEC (1978) limitations when modelling fractures

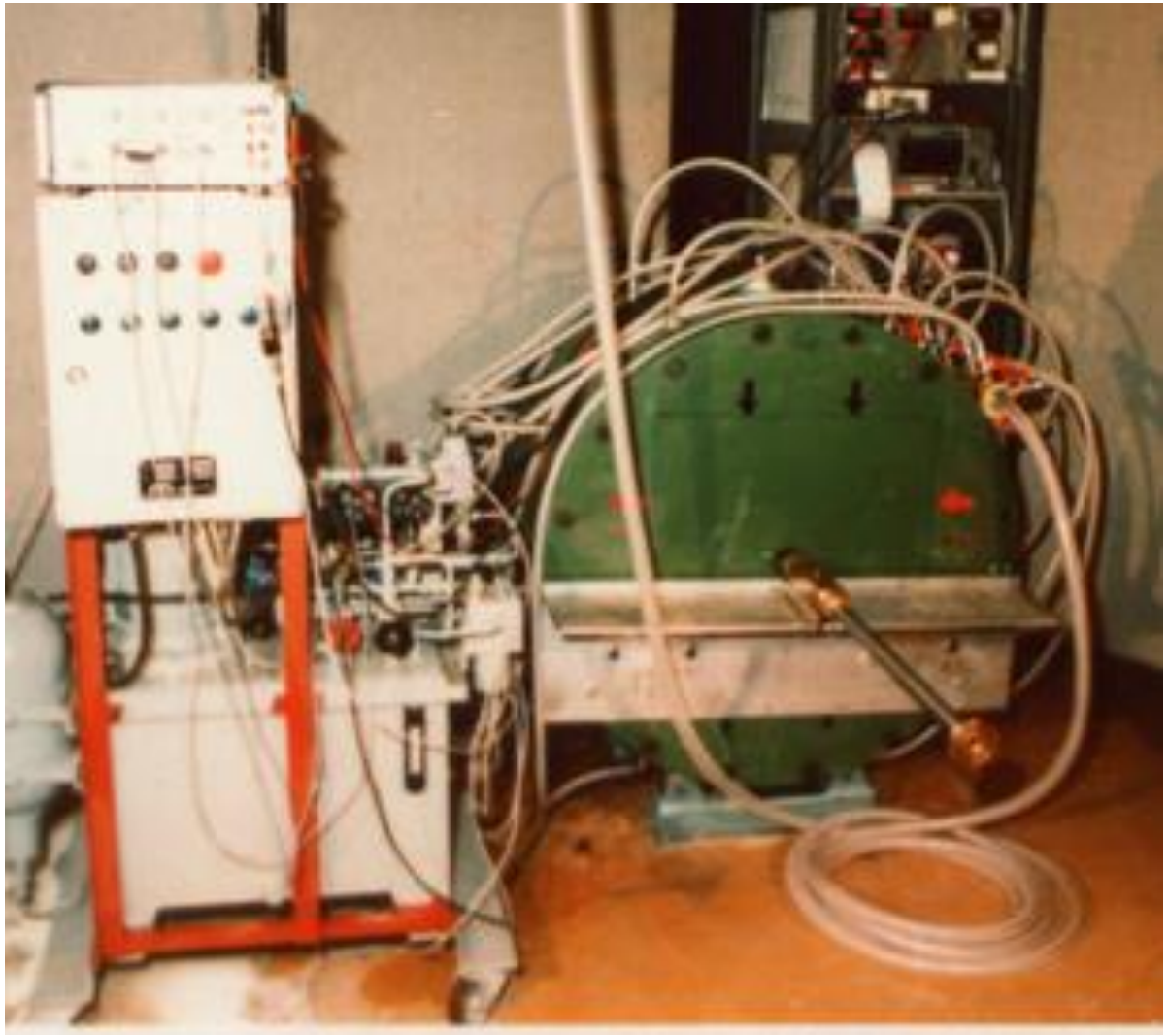


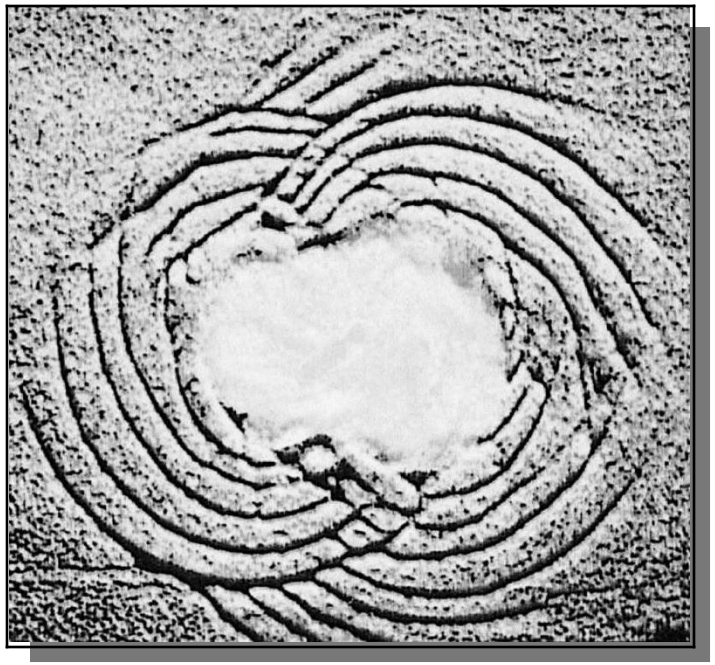


Physical and FEM modelling (Barton and Hansteen, 1979) suggested possible 'heave' resulting from large-cavern construction near the surface.....depended on jointing-or-not, and on joint pattern and horizontal stress level in the physical models.

DRILLING IN SOFT ROCK SIMULANT

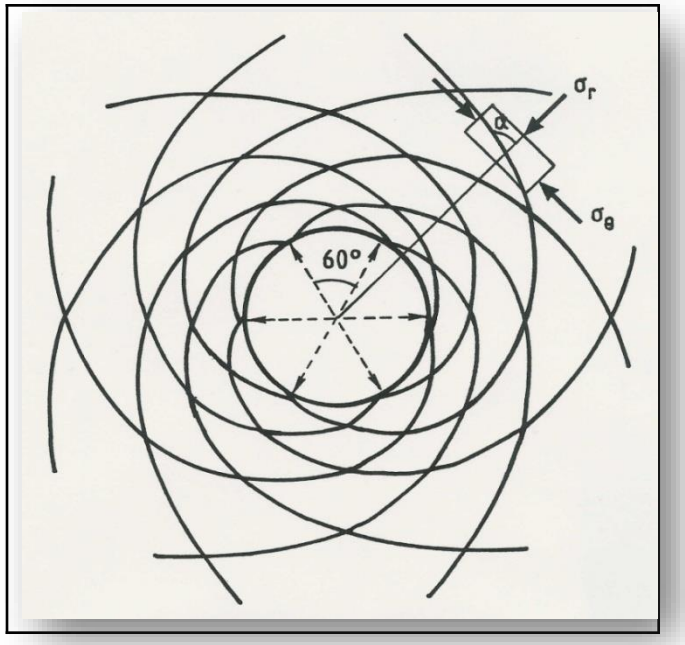
Flat-jack loaded 3D blocks. Drilled while stressed. Could have $\sigma_1 > \sigma_2 > \sigma_3$ with drilling non-parallel to principal stresses if desired. (NGI 1987-1988, Addis et al. 1990, SPE).



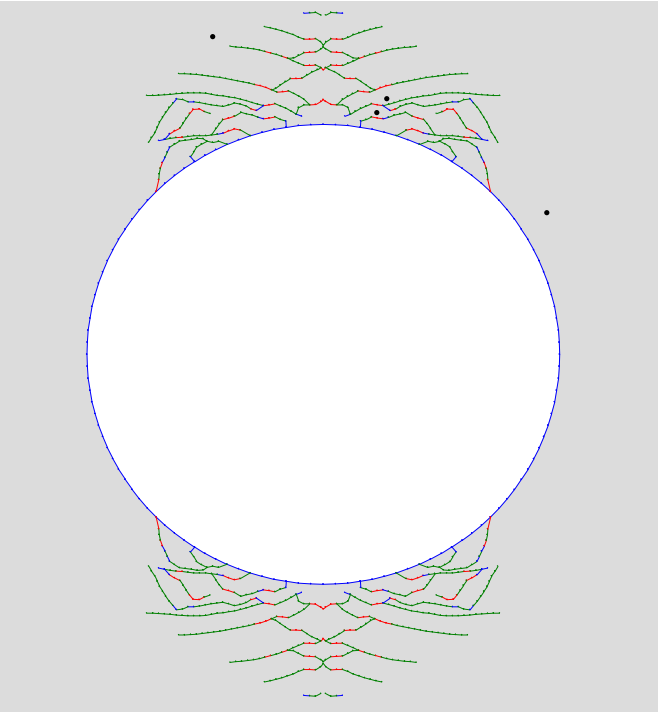


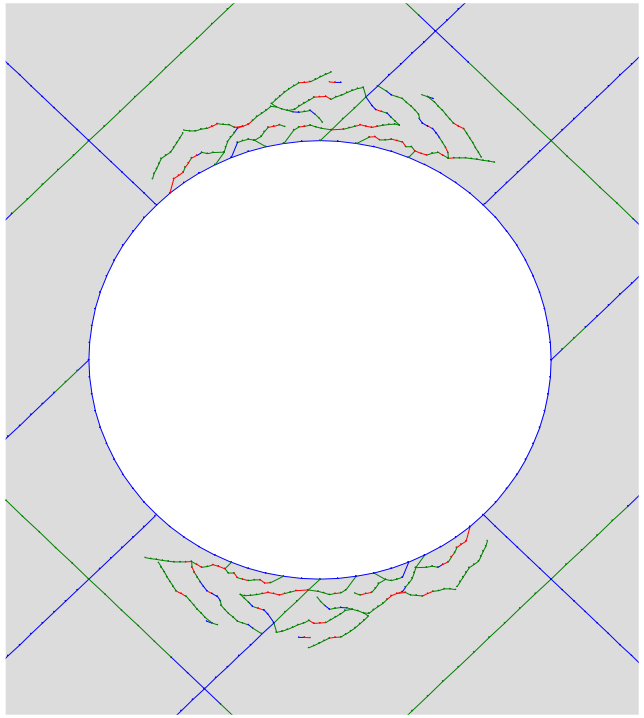
Borehole stability studies at NGI.

(Joint Industry Project). Addis et al., SPE, 1990.



Drilling into $\sigma_1 > \sigma_2 > \sigma_3$ loaded cubes 0.5 x 0.5 x 0.5 m of model sandstone





Physical models

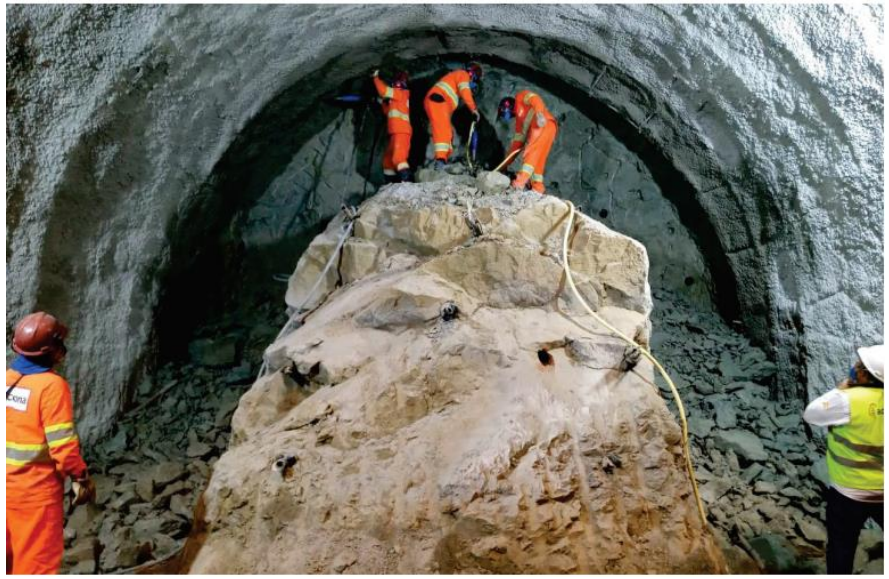
(*UCS = 0.5MPa)*

Numerical models:

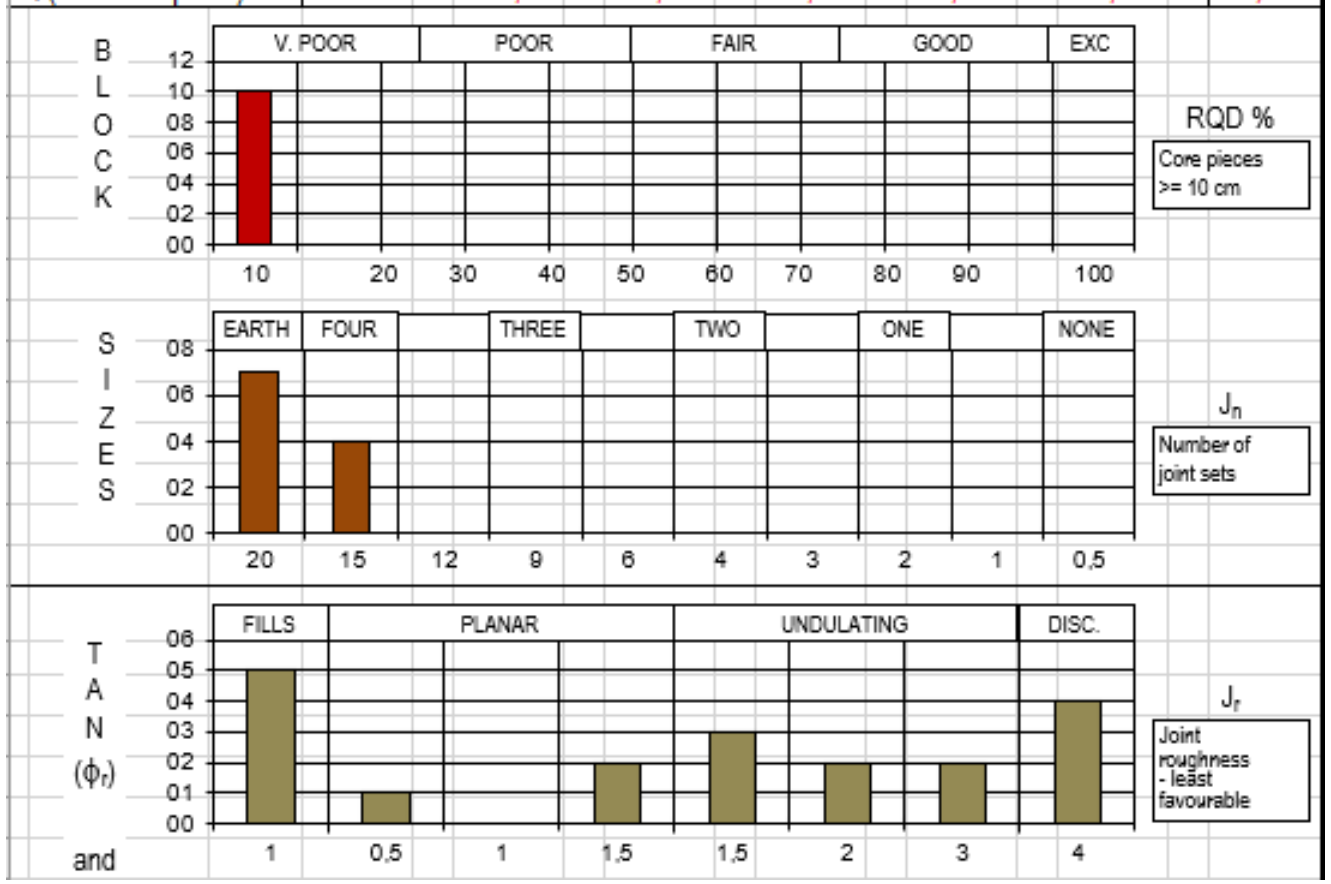
(Hard rock, 1000m depth simulation with FRACOD.

Shen and Barton, 2018)

Natural, weak materials (over-consolidated clay) can also have fractures – both slickensided and planar. UCS = 1 to 2MPa.



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20,0	*	1,5	/	6,0	*	1,00	/	2,0	=	0,063
Q (typical max)=	10	/	15,0	*	4,0	/	4,0	*	1,00	/	1,0	=	0,7
Q (mean value)=	10	/	18,2	*	2,1	/	5,6	*	1,00	/	1,3	=	0,16
Q (most frequent)=	10	/	20,0	*	1,0	/	6,0	*	1,00	/	1,0	=	0,08



An over-consolidated clay with fractures. Has a Q-value!

Even 1MPa does not prevent slickensided blocks

ONE OF WORLD'S LARGEST TUNNEL PROJECTS

- CHANNEL TUNNEL
- UK to FRANCE (English bias)
- FRANCE to UK (French bias)

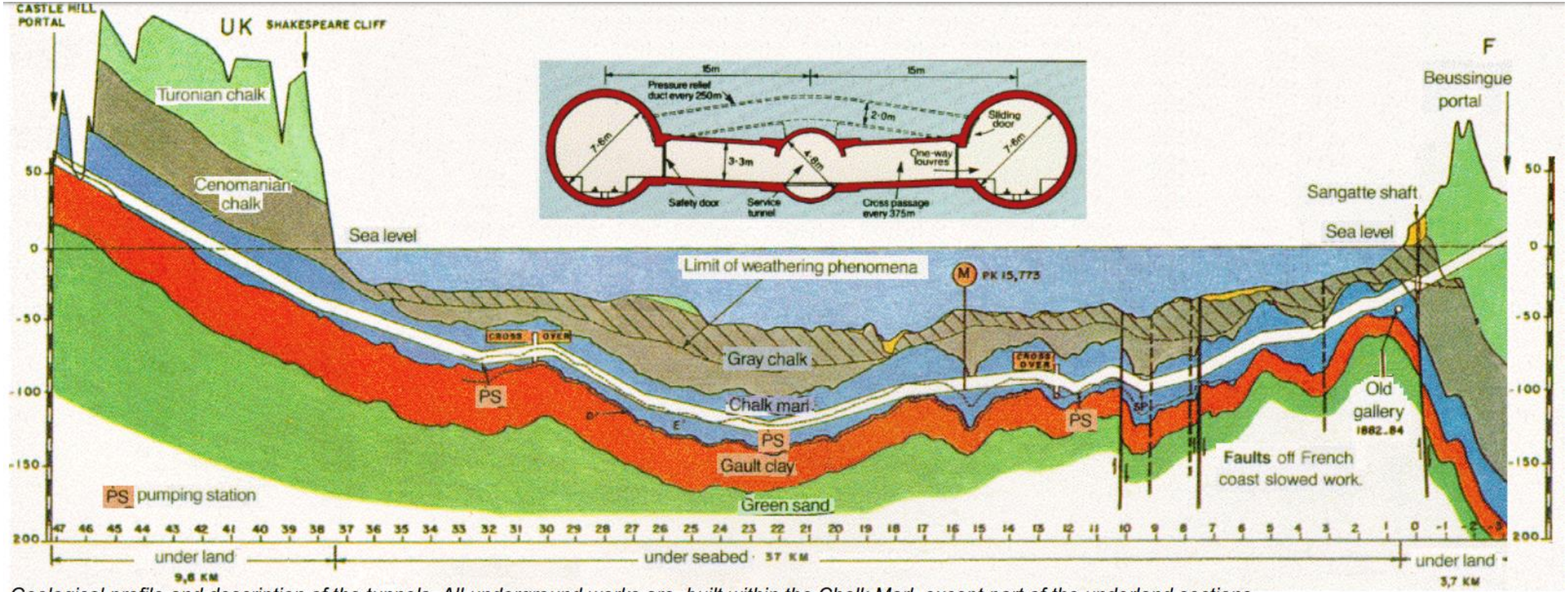
- How much did it cost to build the Channel Tunnel? It took just under six years and 13,000 workers to build the Channel Tunnel. The total cost came at an eye-watering £4.65 billion which would be the equivalent of **£12 billion** in today's money (Google – thank you).

UK to France, France to UK……

……..

BREAK-THROUGH!

December 1st 1990

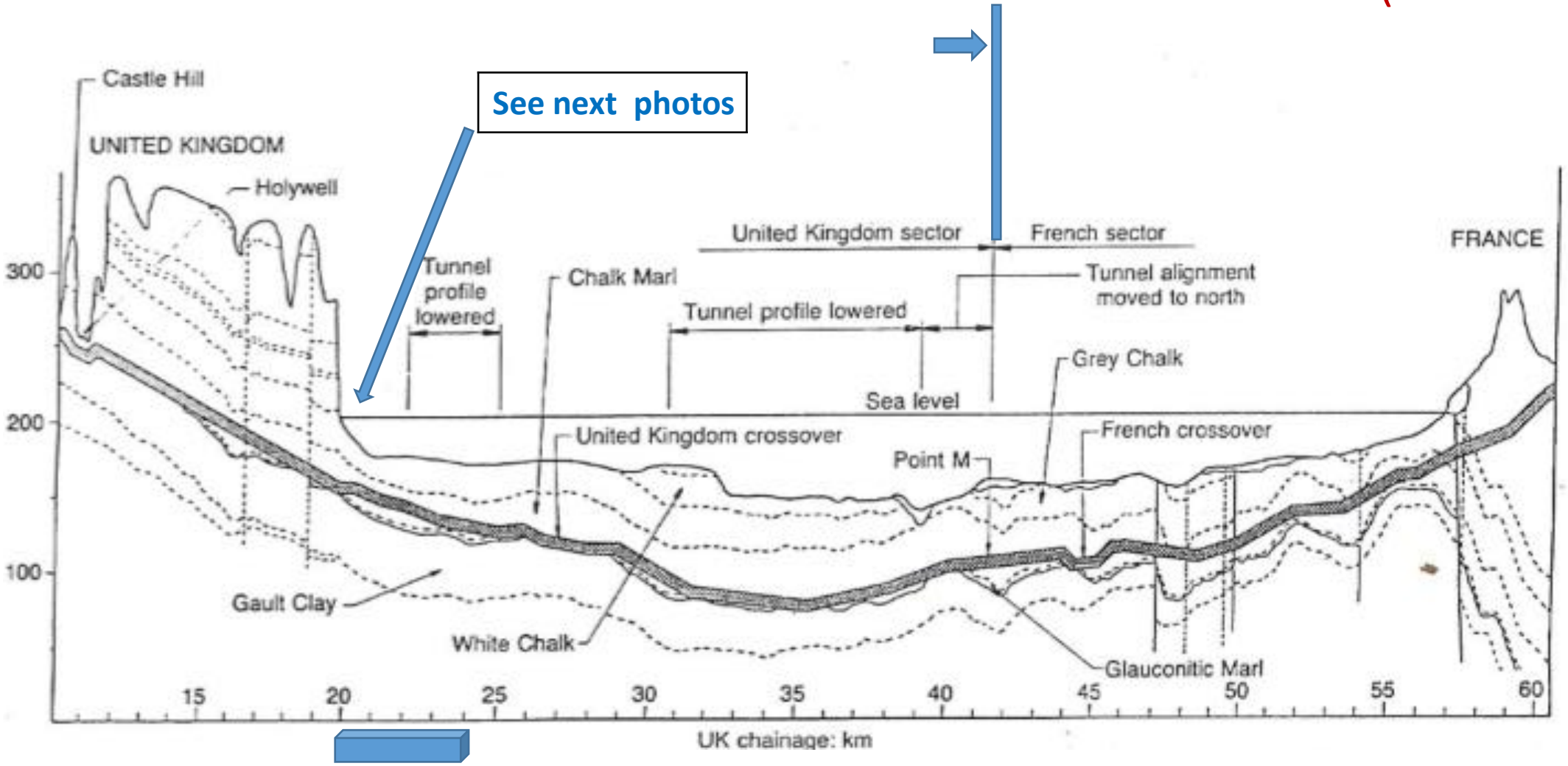


Geological profile and description of the tunnels. All underground works are built within the Chalk Marl, except part of the underland sections.

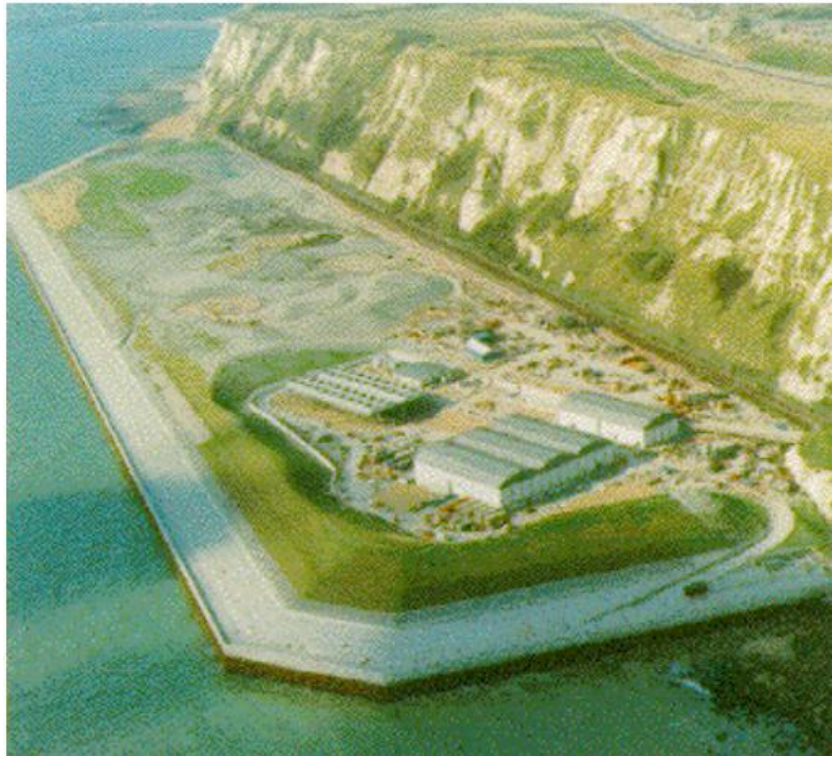
Jointing not expected in the 4 to 9 MPa UCS of the (blue) Chalk Marl.

(Figure: P-J Pompée) **Note 'chainage' from French side. 37km under water.**

CHANNEL TUNNEL: UK to FRANCE (≈ 60km)

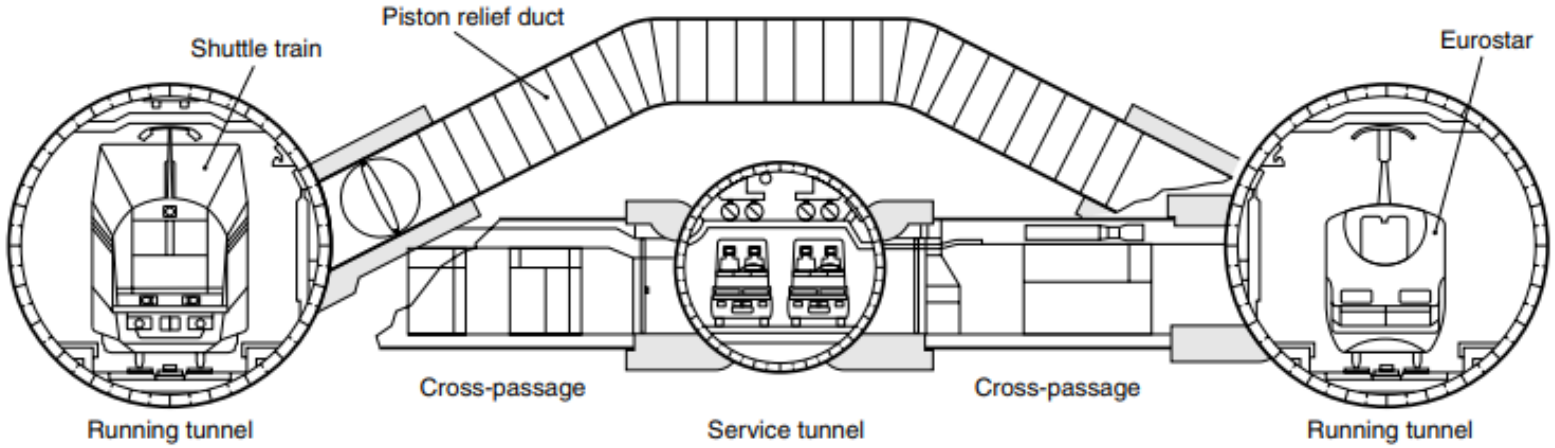


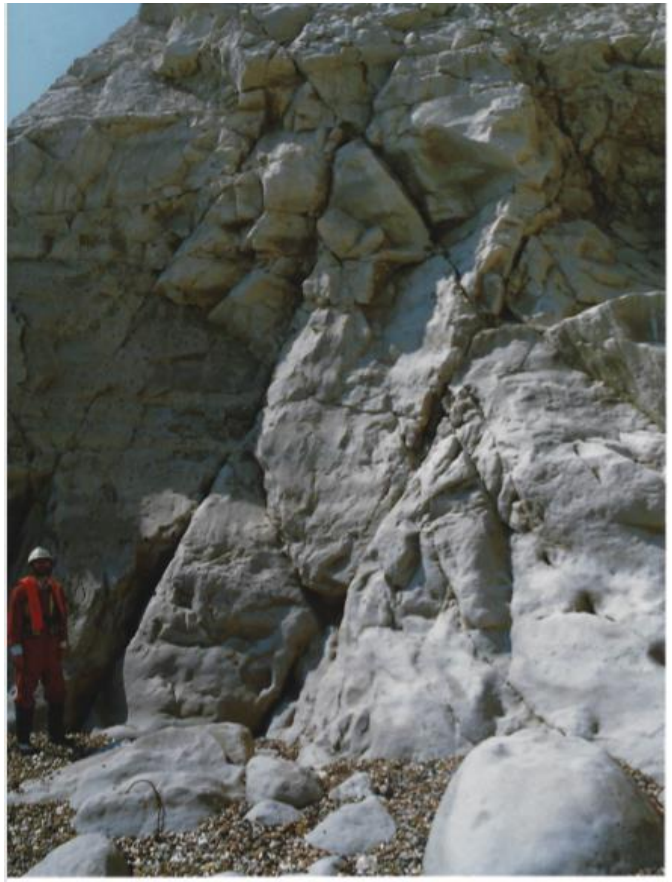
Chalk Marl expected to be the perfect, soft, unjointed (??) medium, ideal for record TBM advance. Ch. 20-24 proved the opposite!



Shakespeare Cliffs

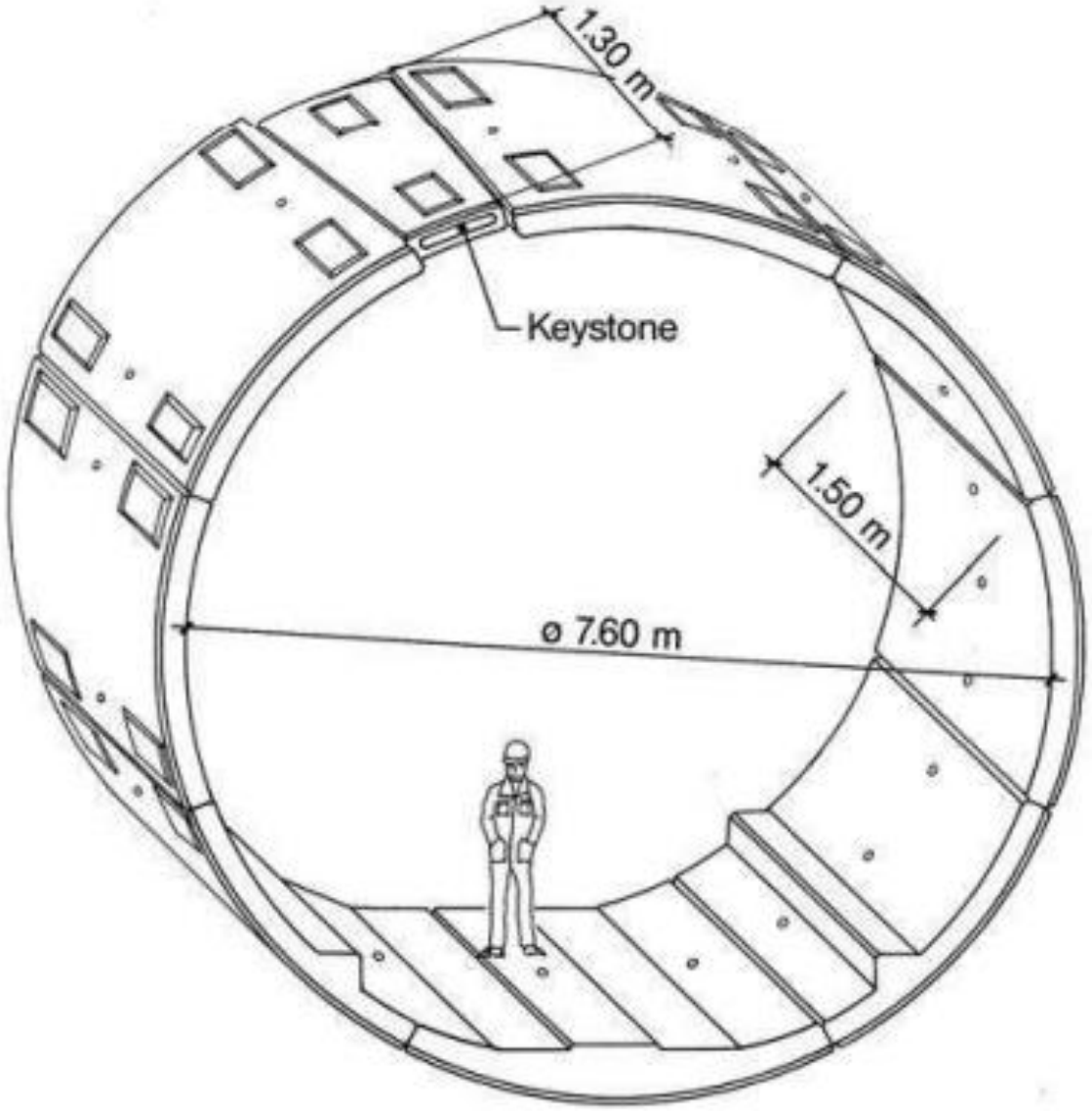
- Jointed Chalk forms the cliffs
- Chalk Marl seen at low tide





The Jointed Chalk of the cliffs

The softer Chalk Marl (UCS = 4 to 9 MPa)……was expected to be unjointed!



Over-break due to jointing 'not expected'……therefore *unbolted PC elements (UK side)*

(Sea-water infiltration onto / into TBM, also not expected).

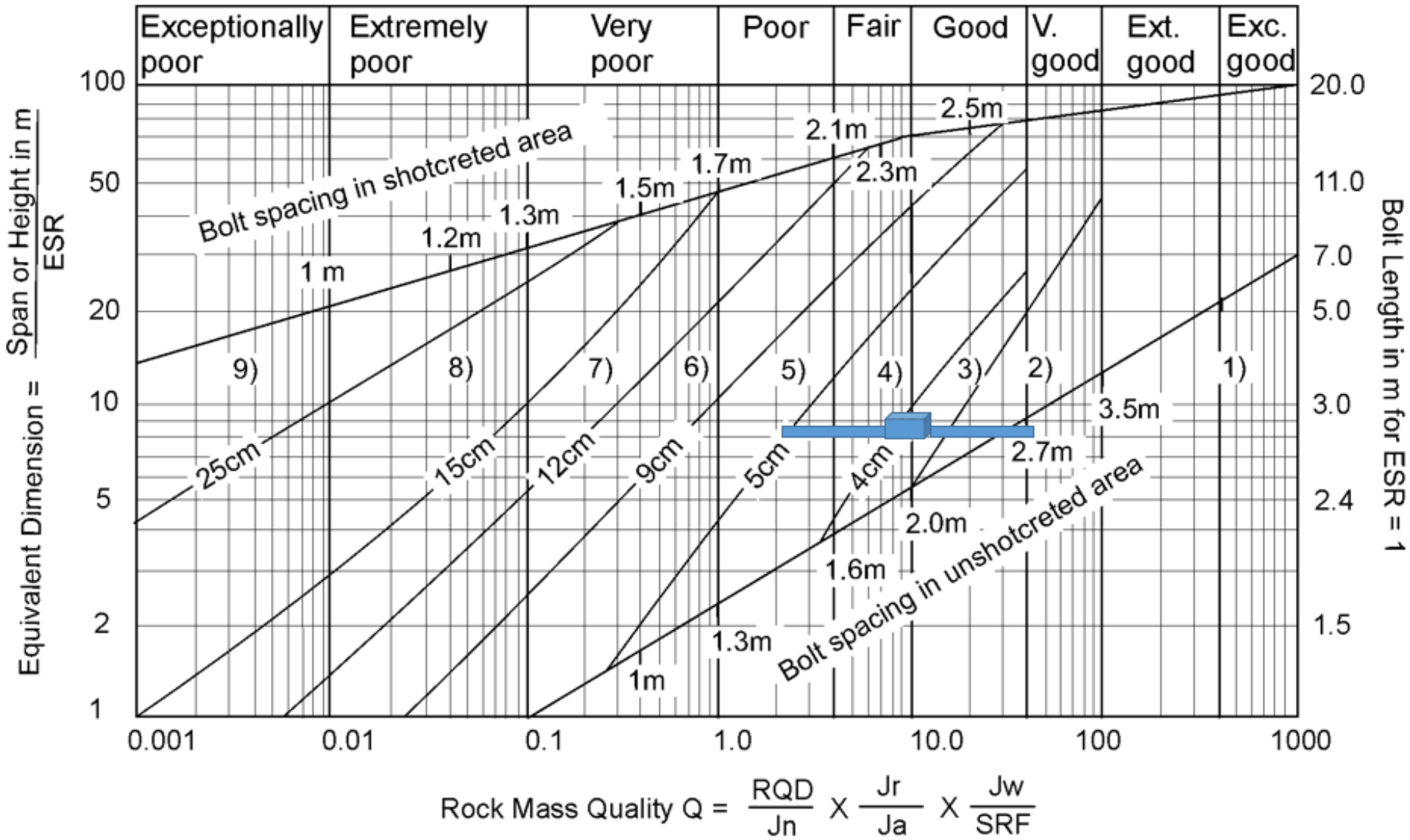
MAJOR PROBLEM:
Unsupported tunnel lengths of 17 and 18m for the marine service (MST) and marine running tunnels (MRT).

This means approx. 3.5 and 2 diameters of *unsupported rock mass* with Q of about 8 (range 1 to 50).

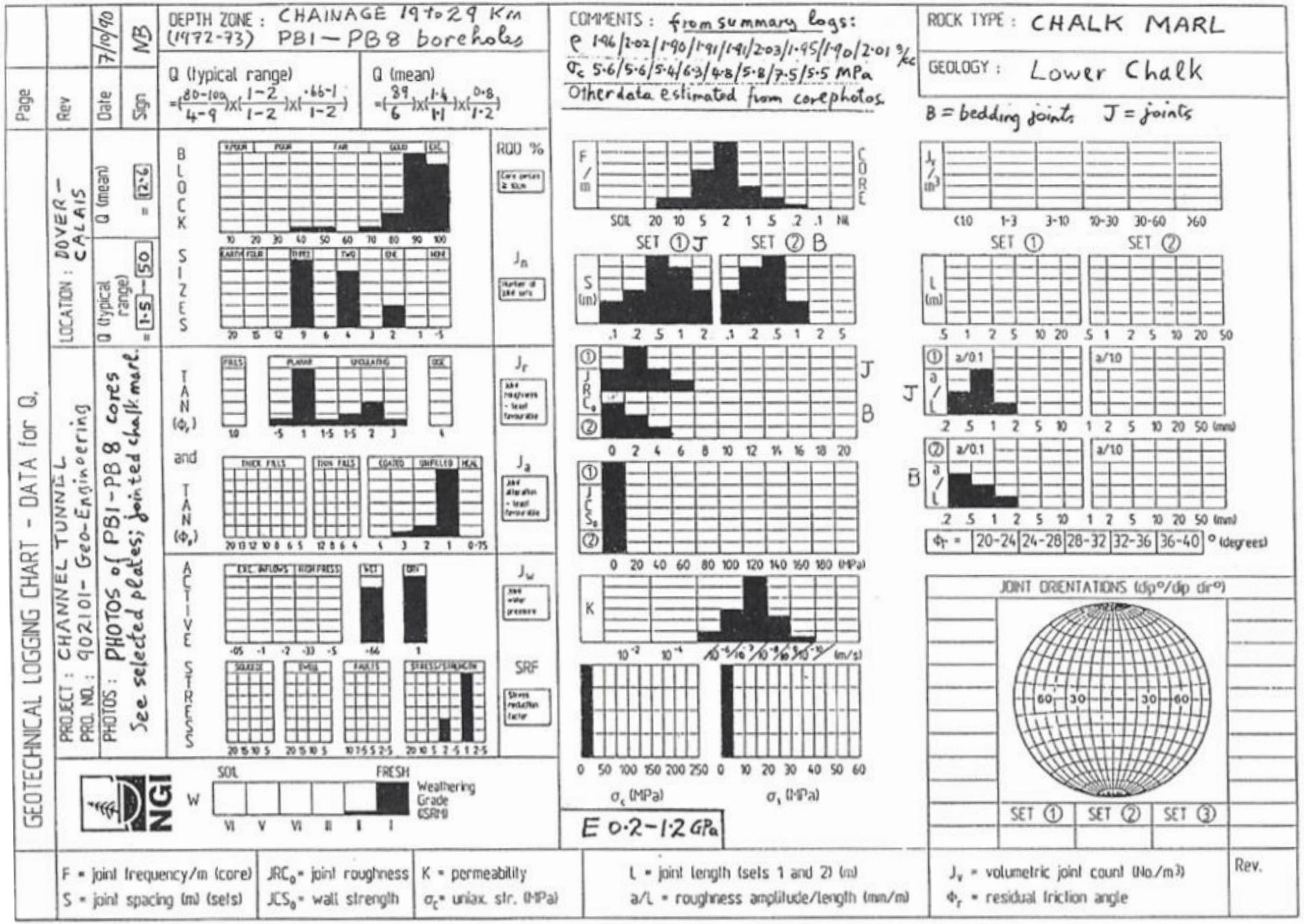
Tunnels of 8.4 and 5.3m span require Q = *40* and *10* (respectively) for no support to be required (Q data base).

Q in *low-cover, sub-sea, ch. 20-24km* was generally below 10 and much below 40. Problems with stability (overbreak) were predictable and inevitable.

Precedent: tunnels, marine core: Q ≈ 8 – 12, but up to 40+ for later km. Undersea ch. 20-24km, Q down to ≈ 2. Over-break problems.

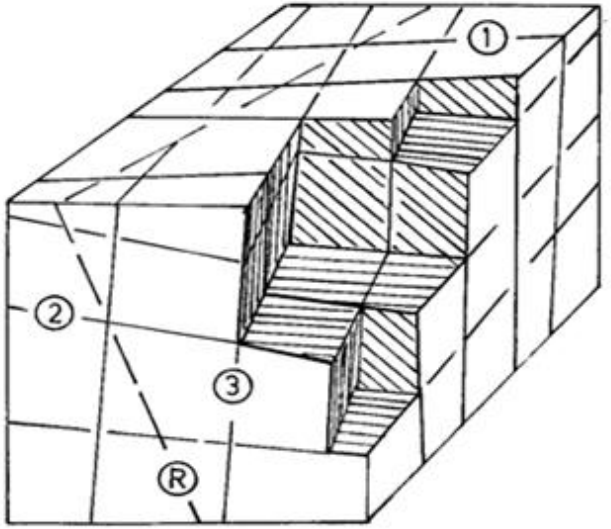


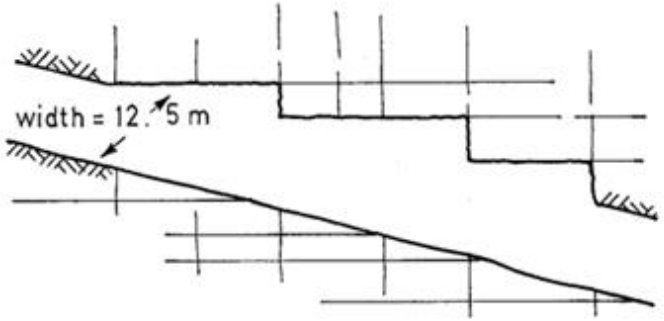
One of the more obvious examples of sub-sea-bed jointing in the chalk marl. For unknown reasons, this did not alert designers to the risk of over-break and the need for *bolted* (TBM) tunnel segments.

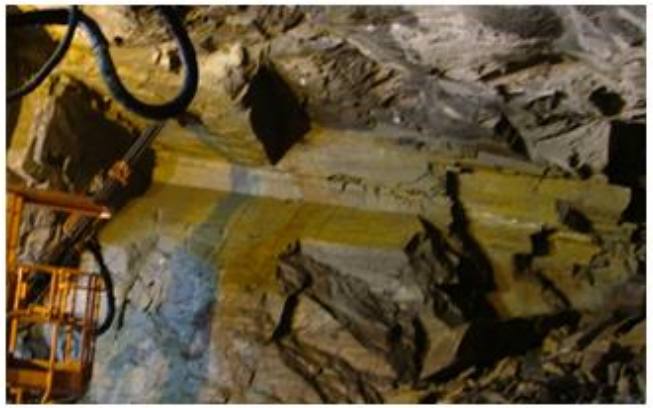


Eight marine borehole cores logged (Q in left column)

Jn/Jr = 9/1 implies over-break







OVERBREAK IF Jn/Jr ≥ 6

Jn = number of sets

Jr = roughness

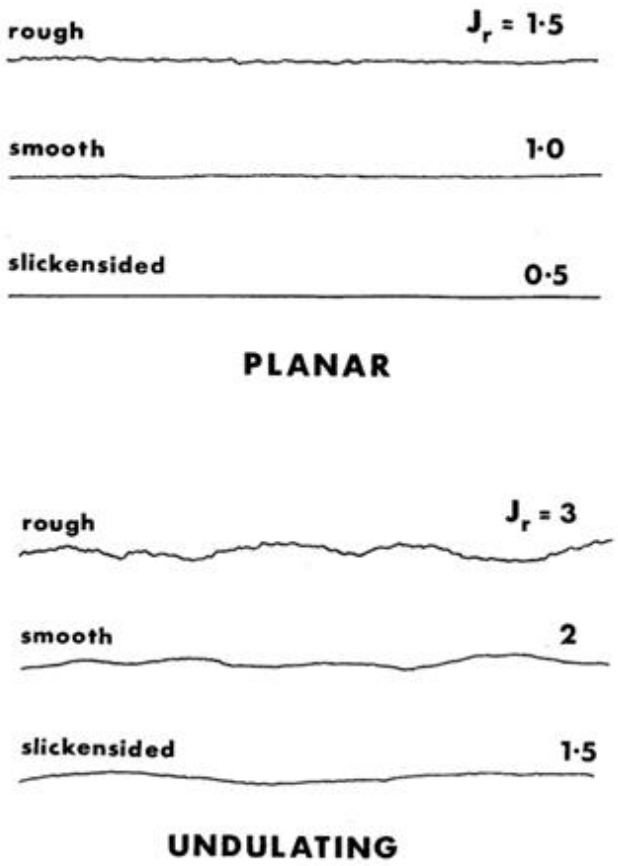
6/1.0 9/1.5

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.

JOINTING *WAS* EVIDENT IN NEAR-BY TUNNELS!

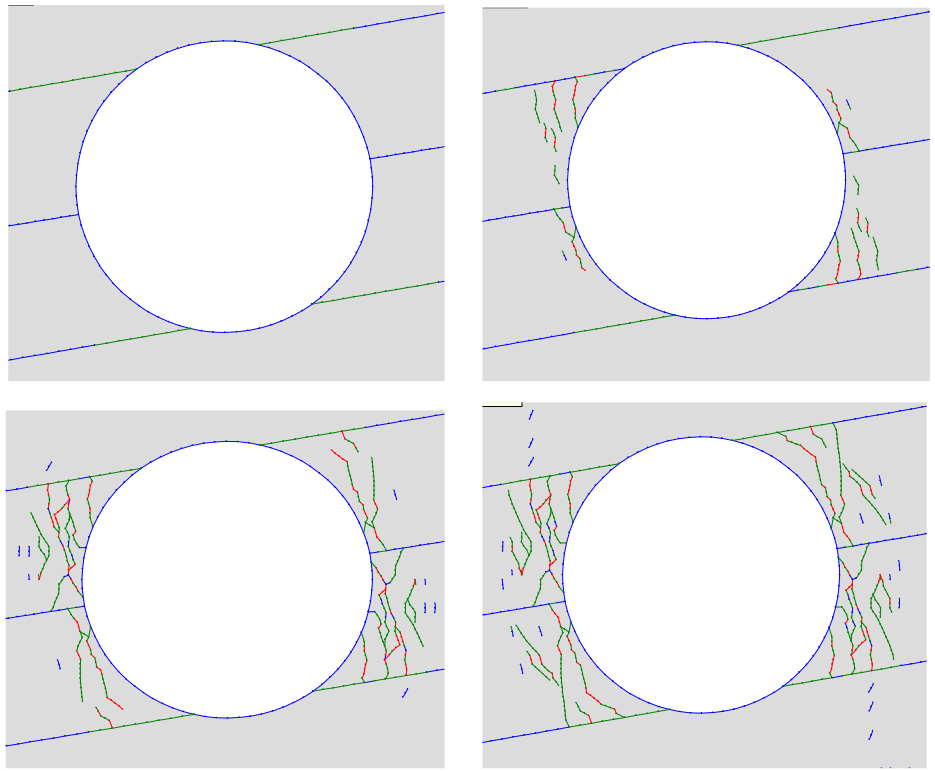
Top-left, clockwise:

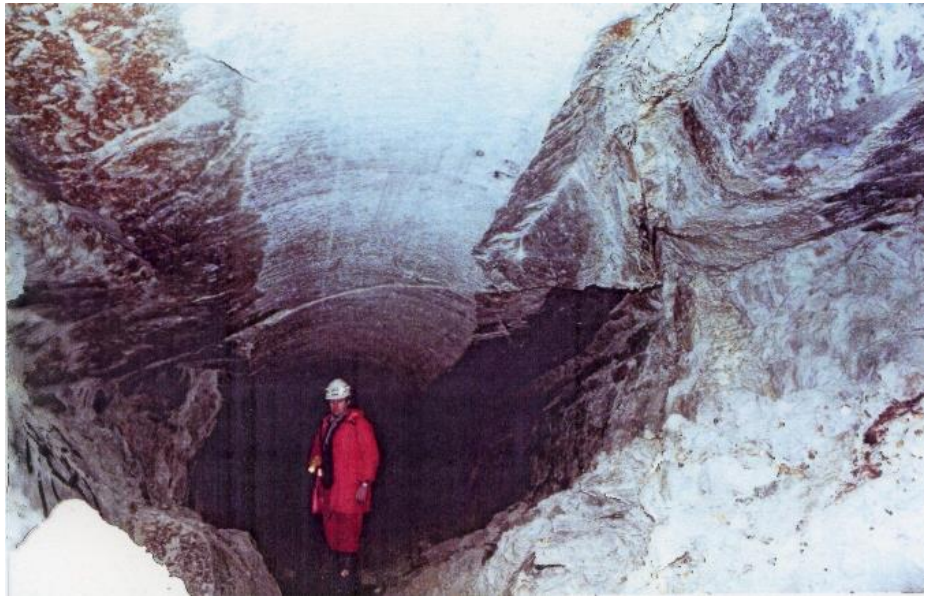
Terlingham Water tunnel,

Beaumont TBM Tunnel, 1880: tidal influence, stress/STRAIN-failure, wedge-failure.

Three photos separated by 150 m

(BOTH TUNNELS CLOSE TO CHANNEL TUNNEL)





CRACKING IS ACTUALLY CAUSED BY EXCEEDING THE ***CRITICAL EXTENSION STRAIN:***

Cracking in tension, then shear:

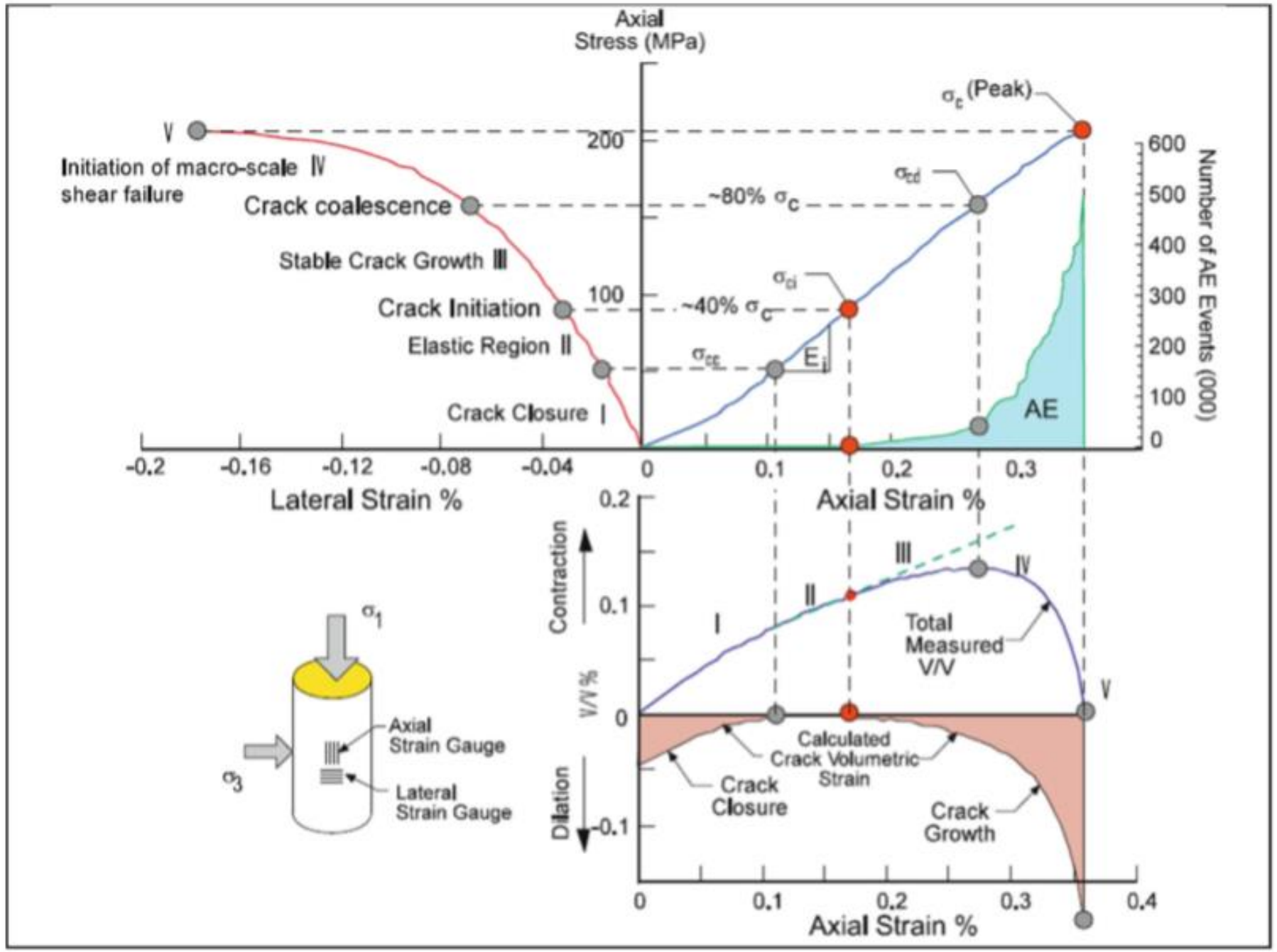
(Not 'compression' failure). FRACOD model)

(Stacey, 1981 and Baotang Shen……Barton and Shen, 2017)

$$\sigma_{critical\ tangential\ stress} \approx (0.4 \times UCS) \approx \sigma_t/\nu$$

(derived from $\varepsilon_3 = [\ \sigma_3 - \nu.\sigma_1]/E$

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



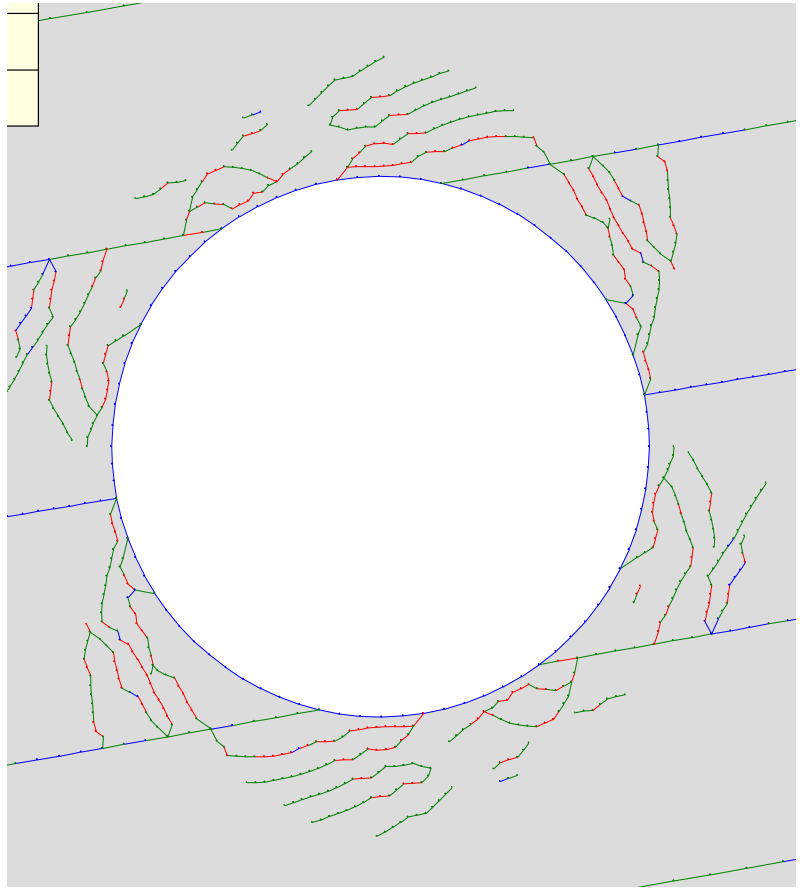
Martin, 1997.

Note: AE also initiates at approx. $\sigma_1 = 0.4\ \sigma_c$

(or when $\sigma_1 = \sigma_t / \nu$)

WHAT IF THE STRESS HAD BEEN MAXIMUM IN THE HORIZONTAL DIRECTION? WHAT TYPE OF FAILURE?

THESE TWO FRACOD MODELS (by Dr. Baotang Shen) 'PROVE' THAT IT WAS THE HIGH VERTICAL STRESS WHICH CAUSED THE FAILURE.



Chalk-marl

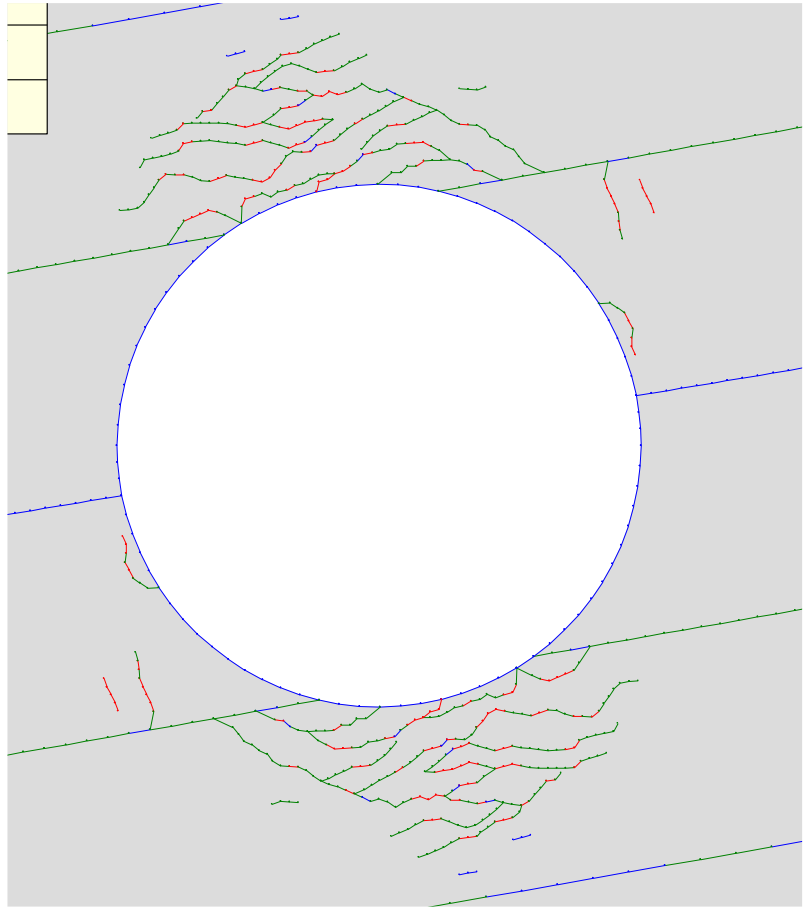
UCS = 6 MPa,

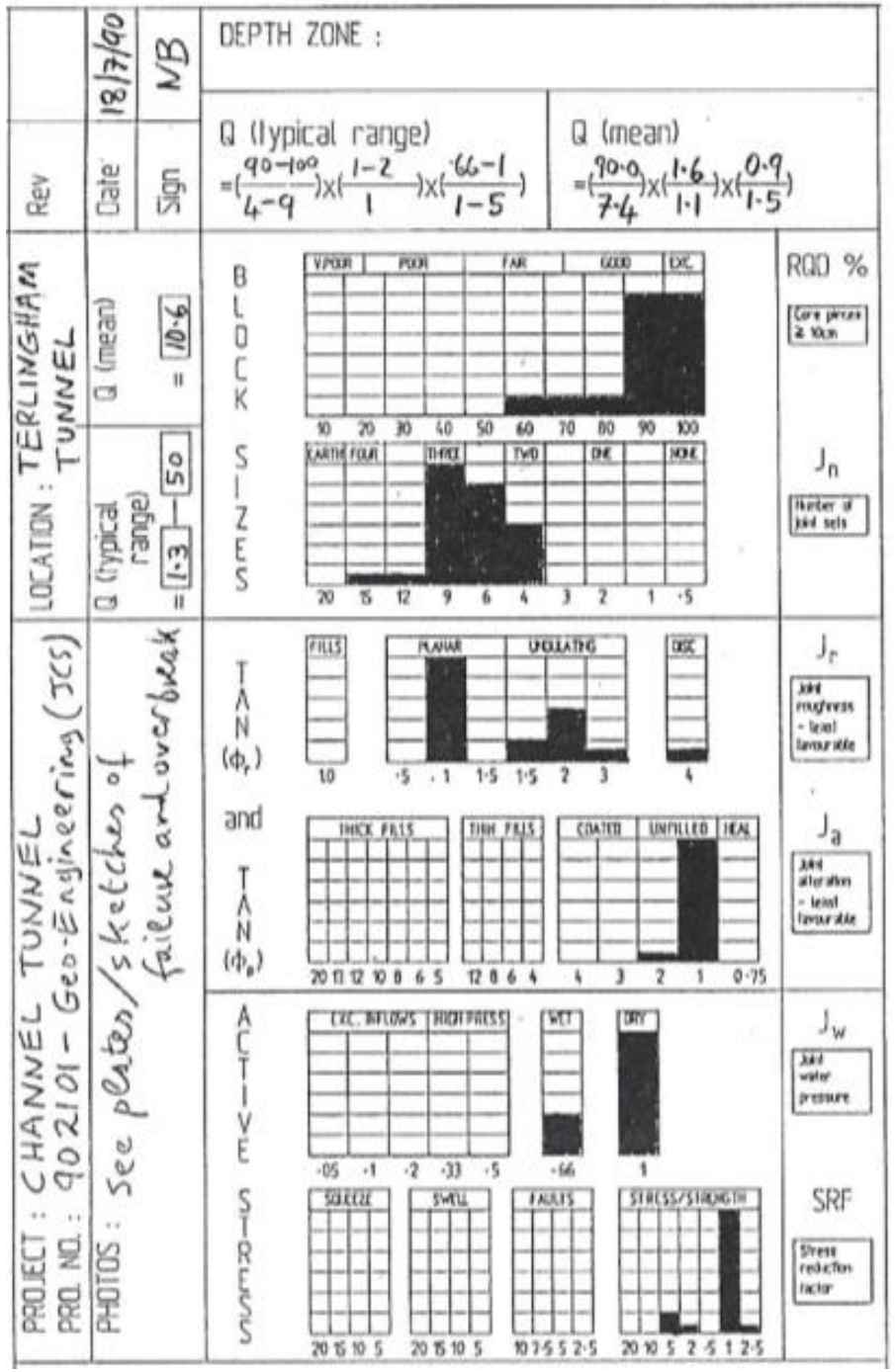
Left: σ_h/σ_v = 1.0

Right: σ_h/σ_v = 2.0

(red fractures show tension/opening)

(green fractures have propagated in shear)

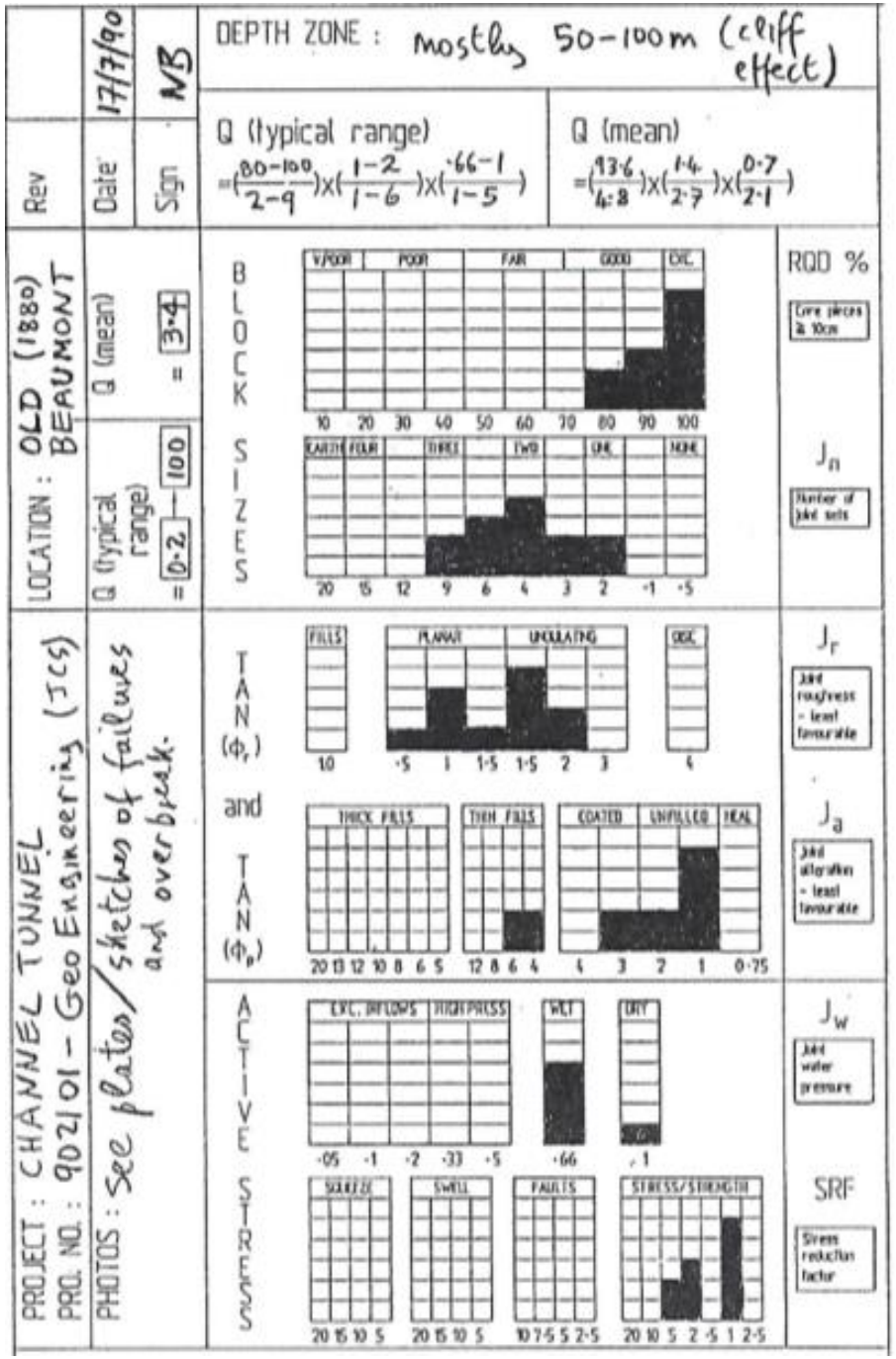


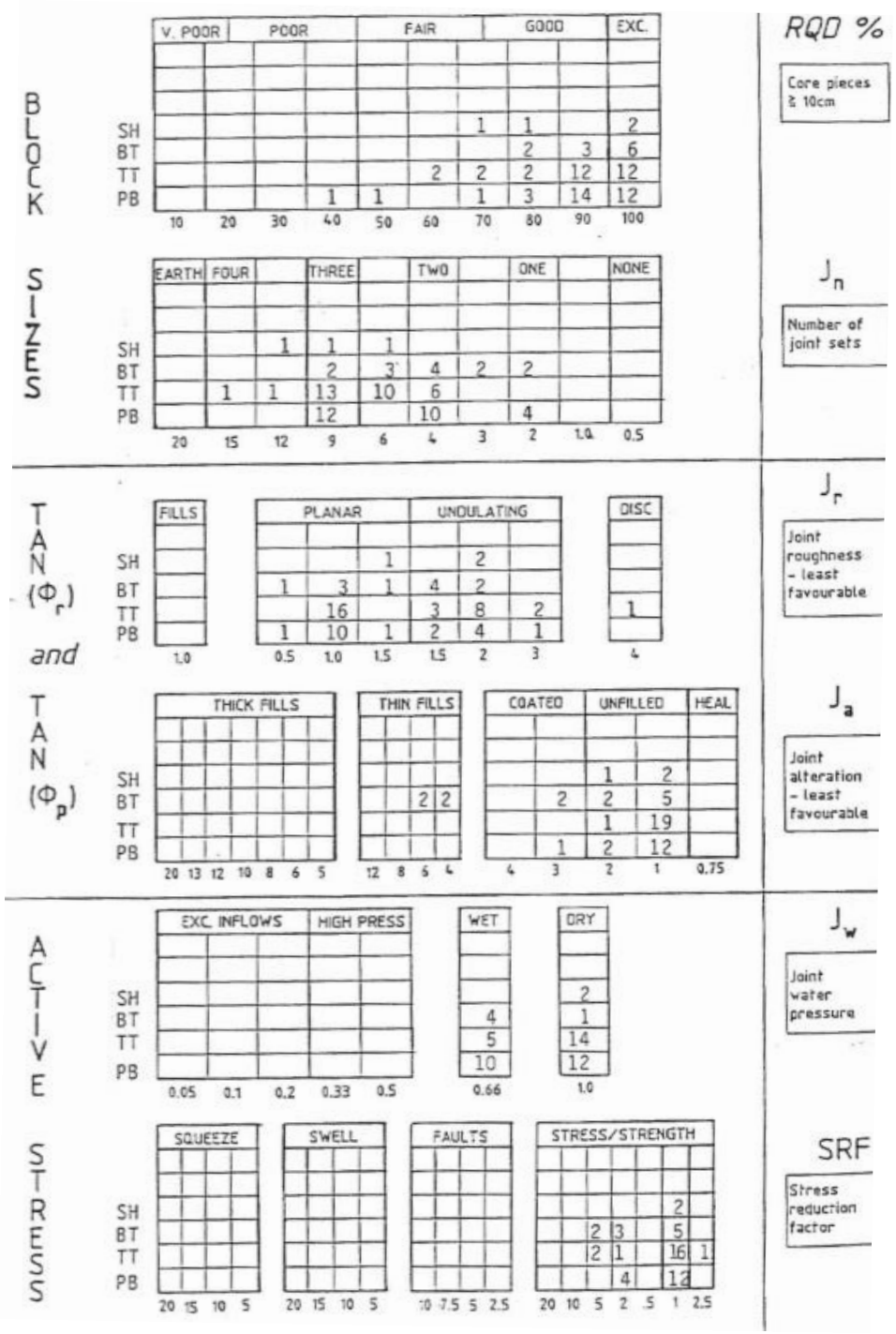


Q-logging in these local tunnels in Chalk Marl

……

Jointing was very obvious





The 'statistics' of Q-logging (NB data).

SH = Shakespeare Cliffs (chalk)

BT = Beaumont Tunnel

TT = Terlingham Tunnel

PB = 8 'PB-series' marine drill-cores

MOST FREQUENT:

RQD = 100

Jn = 9 (three sets)

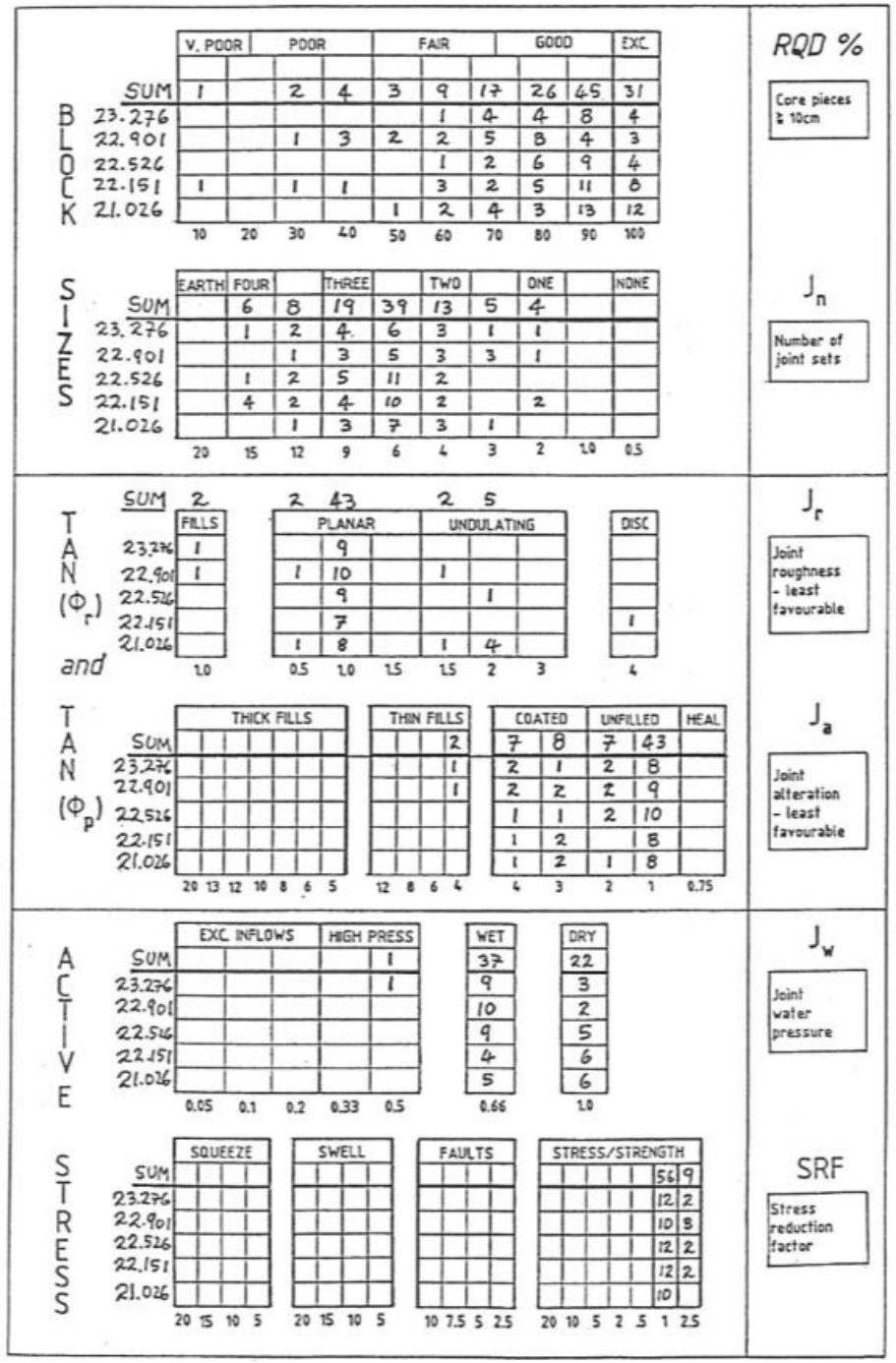
Jr = 1 (smooth, planar)

Ja = 1 (no alteration)

Jn/Jr = 9/1 (i.e. > 6, therefore over-break)

Typical over-break in chalk marl next to one of the TBM (seen in pressure relief ducts).

THIS CAUSED PROBELMS/DELAYS WITH (PC-ELEMENT) ‘RING-BUILDING’



Q-logging by the contractor consortium, TML, *of five of the poorest Channel Tunnel chainages in sub-sea, permeable, and partially weathered sections.*

(Barton and Warren, 1996) …….(Ch 20-24km)

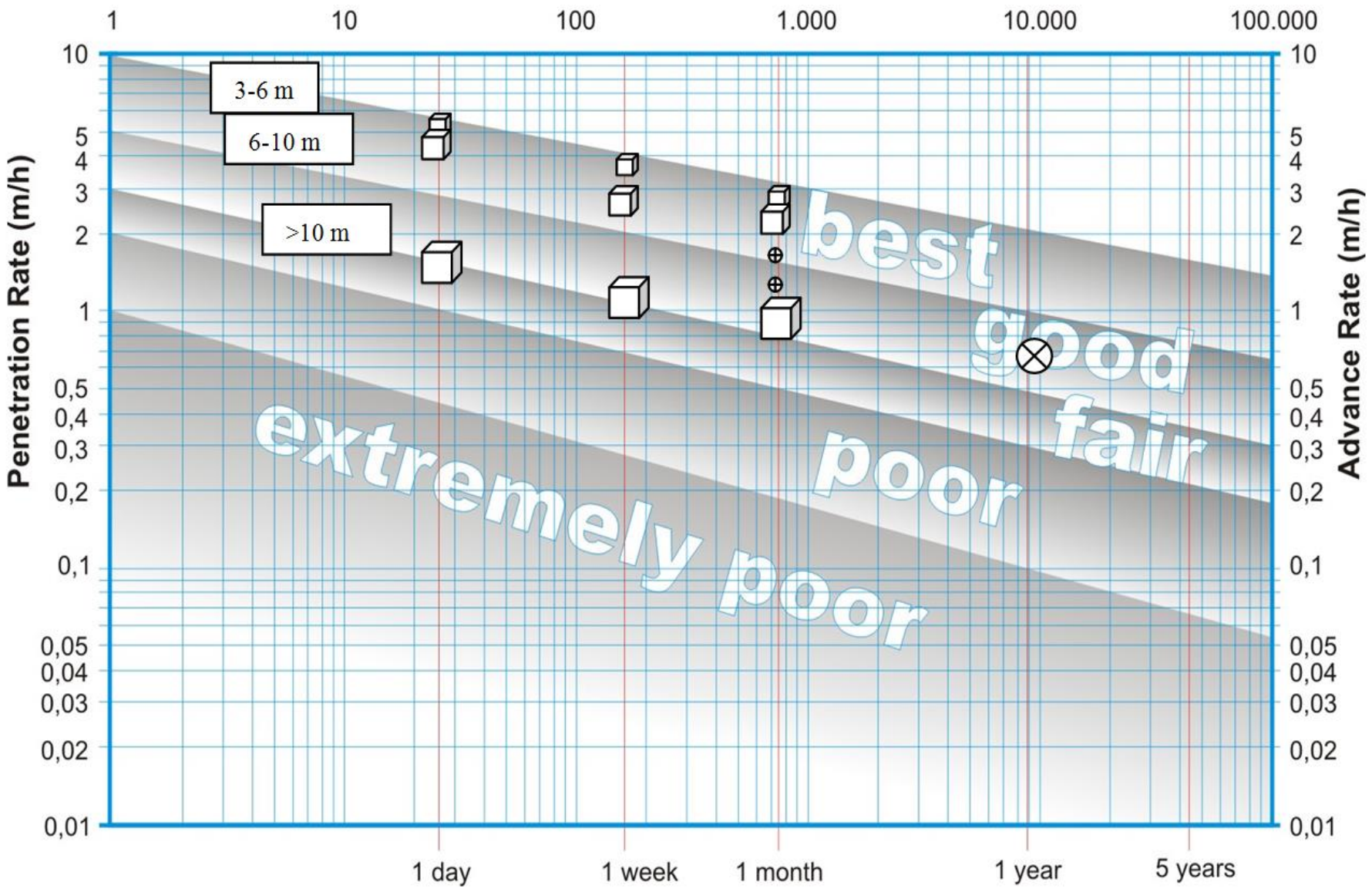
Data from:	Most Frequent	Next most frequent	Possible problem ground
Predicted Conditions	Q = 11.1	Q = 7.4	Q = 1.7-3.3
(Pre-construction data)	$\left(\frac{100}{9}\right)\times\left(\frac{1}{1}\right)\times\left(\frac{1}{1}\right)$	$\left(\frac{90}{4}\right)\times\left(\frac{2}{2}\right)\times\left(\frac{0.66}{2}\right)$	$\left(\frac{90}{9}\right)\times\left(\frac{1}{2}\right)\times\left(\frac{0.66}{1\text{-}2}\right)$
Encountered conditions	Q = 13.2	Q = 2.6	Q = 1.8-4.3
(typical: km 20-24)	$\left(\frac{90}{5.8}\right)\times\left(\frac{1}{1}\right)\times\left(\frac{0.9}{1}\right)$	$\left(\frac{88}{6.6}\right)\times\left(\frac{1.4}{2.5}\right)\times\left(\frac{0.8}{2.3}\right)$	$\left(\frac{88}{6.6}\right)\times\left(\frac{1}{2.5}\right)\times\left(\frac{0.8}{1\text{-}2.3}\right)$
Encountered conditions	Q = 10.0	Q = 3.0	Q = 0.9-2.2
(Poorest: km 20-24	$\left(\frac{90}{6}\right)\times\left(\frac{1}{1}\right)\times\left(\frac{.66}{1}\right)$	$\left(\frac{100}{9}\right)\times\left(\frac{2}{3}\right)\times\left(\frac{1}{2.5}\right)$	$\left(\frac{90}{9}\right)\times\left(\frac{1}{3}\right)\times\left(\frac{0.66}{1\text{-}2.5}\right)$

COMPARISON of NB and TML logging in MST and MRT between Ch. km 19.8 and km 27.2

Chainage (±50m)		Author's estimates of Q		TML estimates of Q	
		Q (range)	Q (mean)	Q (range)	Q (mean)
1	19,824 km	7.5 – 50	17.6	2.4 – 80	28.9
2	19,925 km	0.9 – 25	7.5	1.7 – 40	11.4
3	20,651 km	1.0 – 100	7.8	1.6 – 40	11.7
4	21,026 km	1.7 – 50	9.4	4.4 – 13.2	7.4
5	22,151 km	1.2 – 17	5.7	2.4 – 19	7.0
6	22,526 km	1.2 – 17	5.6	3.0 – 6.7	4.9
7	22,901 km	0.5 – 20	2.6	1.8 – 10.7	4.9
8	23,276 km	0.5 – 25	3.7	1.1 – 8.2	4.0
9	23,651 km	1.5 – 25	5.7	2.5 – 13.3	7.9
10	27,025/167 km	9.9 – 133	12.4	3.0 – 80	16.2

WORLD RECORDS BY TBM – ASSEMBLED BY ROBBINS: *RESULTS WHEN SIZES ARE COMBINED TO REDUCE SCATTER.*

Assume 24 hrs/day, 168 hrs/week, 720 hrs/month. *(Barton, 2013).*



World record drill-and-blast Svea Tunnel:

5.8 km 54 weeks, from one face.

NOTE:THE WORLD RECORD TBM ALSO SHOW *(-)m* gradient

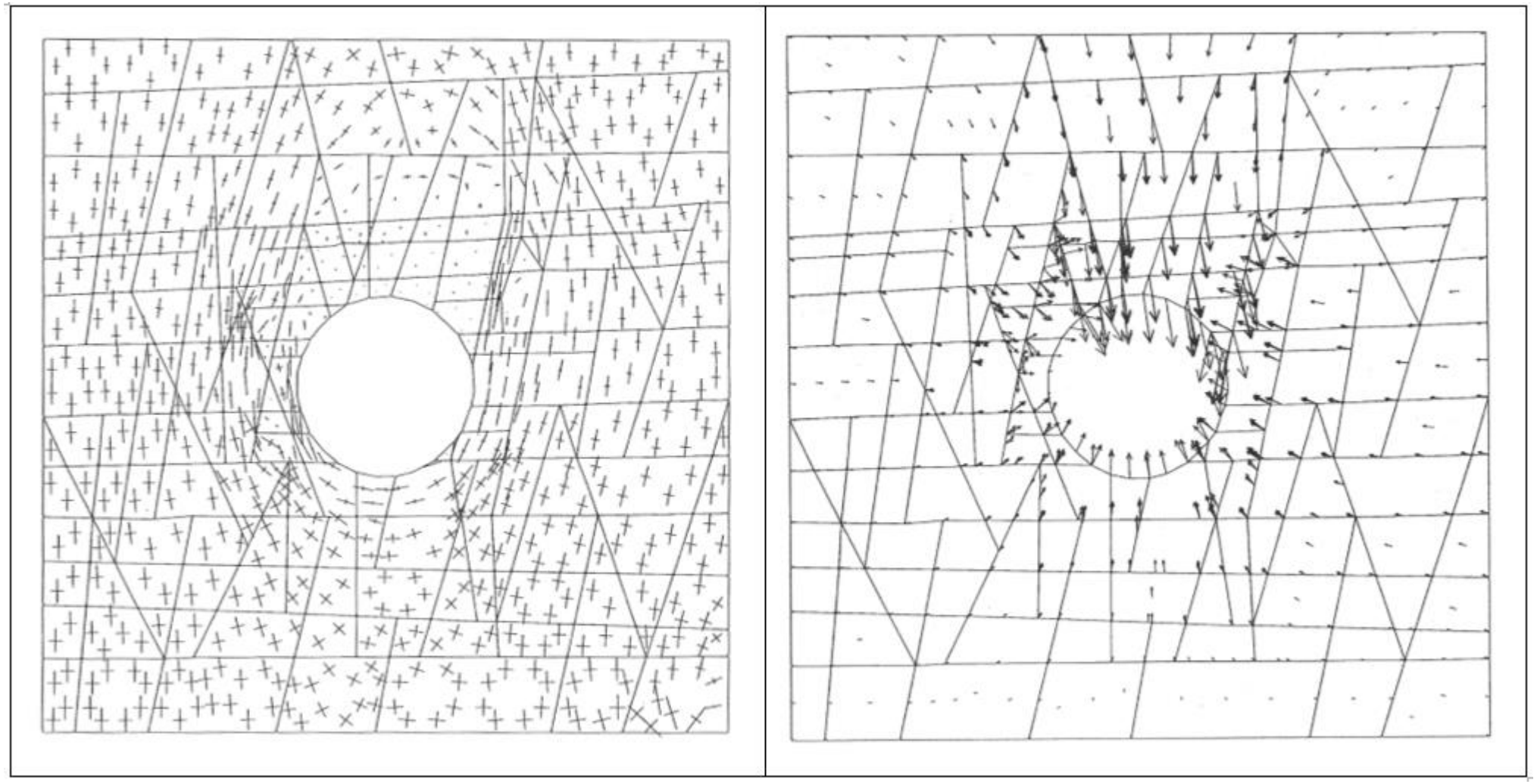
DIAMETER	7 - 8 m	8 - 9 m
BEST DAY	115 m Robbins Karahnjukar Iceland	75 m Robbins Channel Tunnel UK
BEST WEEK	428 m Robbins Karahnjukar Iceland	428 m Robbins Channel Tunnel UK
BEST MONTH	1482 m Robbins TARP Chicago USA	1719 m Robbins Channel Tunnel UK
MONTHLY AVERAGE FOR PROJECT	770 m Robbins TARP Chicago USA	873 m Robbins Channel Tunnel UK

SOME OF THE WORLD RECORDS ARE FROM THE UK

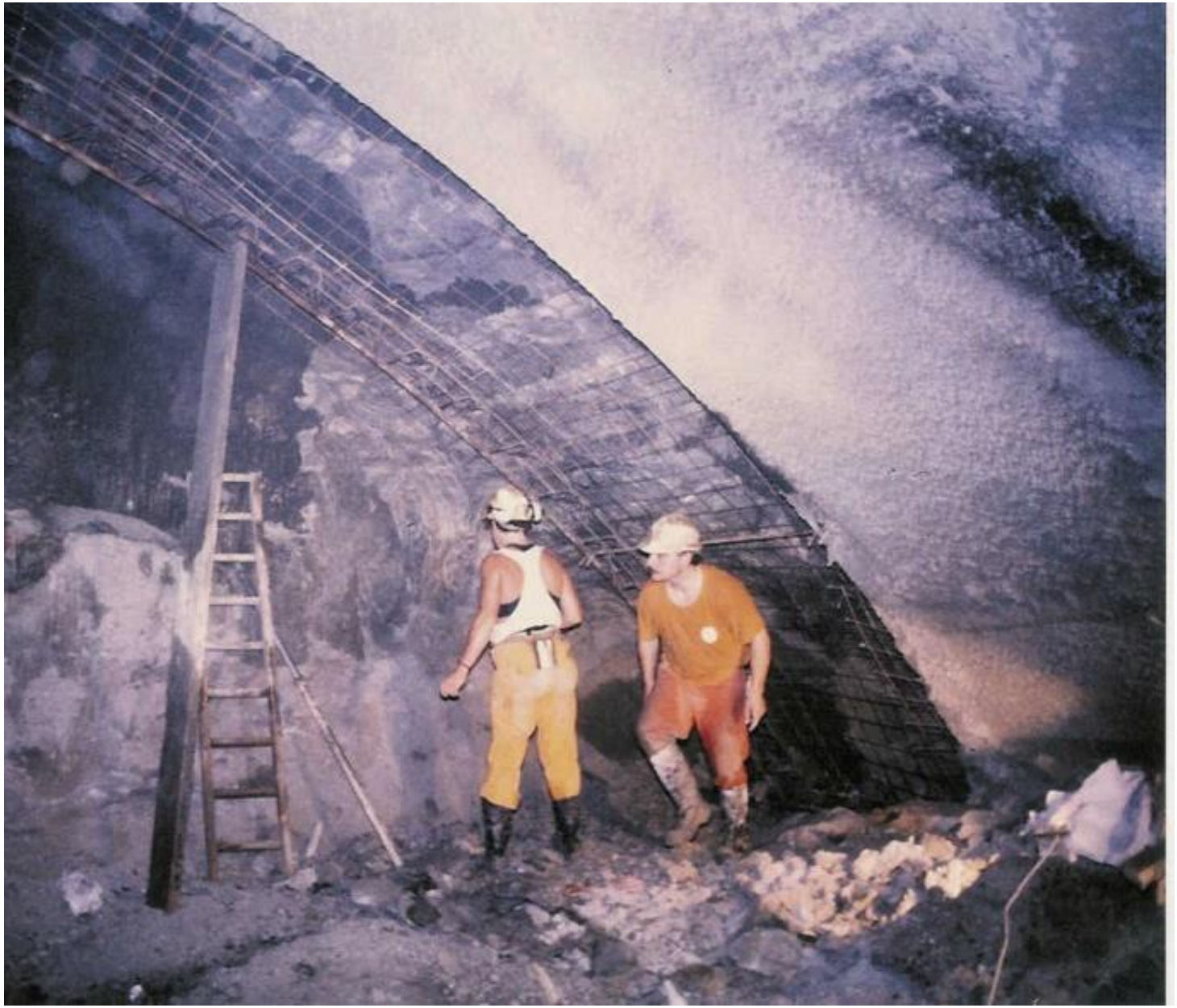
HALF OF THE CHANNEL TUNNEL (chalk marl)

UCS 4 to 9MPa

PROBLEMS CAUSED BY WATER PRESSURE – SUB-SEA



Low effective stresses in the horizontal direction, combined with the low JRC meant that predicted vertical deformation, and maximum joint shearing could be several millimeters. (A 50m deep sub-sea-bed simulation of the 5.3m diameter Service Tunnel. UDEC-BB model, pers. comm. Makurat, 1990).



The temporary support phase of NATM (if including lattice girders) is not PARTICULARLY STABLE. Where is the stiffness? And no bolting. (Cross-over cavern, mid-Channel)

EUROTUNNEL:

SUB-SEA CROSS-OVER CAVERN

FINAL CCA STABLE – OF COURSE

(INTERNET PHOTO).

CONCLUSIONS

1. **Soft rocks, soft model materials (sand and gypsum), and hard (OC) clays can all bear fractures, even with UCS in the range 0.5 to 2MPa.**

2. **Despite the *weakness* (4 to 9MPa) the Channel Tunnel *chalk marl* was systematically jointed in some sub-sea kilometers and caused problems for the TBM: over-break hindered PC-element assembly, and salt water inflows prejudiced electrics/electronics on the TBM.**

2. **The contractor consortium TML utilized the Q-system for rock mass characterization. Their detailed characterization of some difficult sub-sea kilometers saw Q-values sinking towards Q = 2 ('poor') – in a medium that designers thought would be unjointed since so weak.**