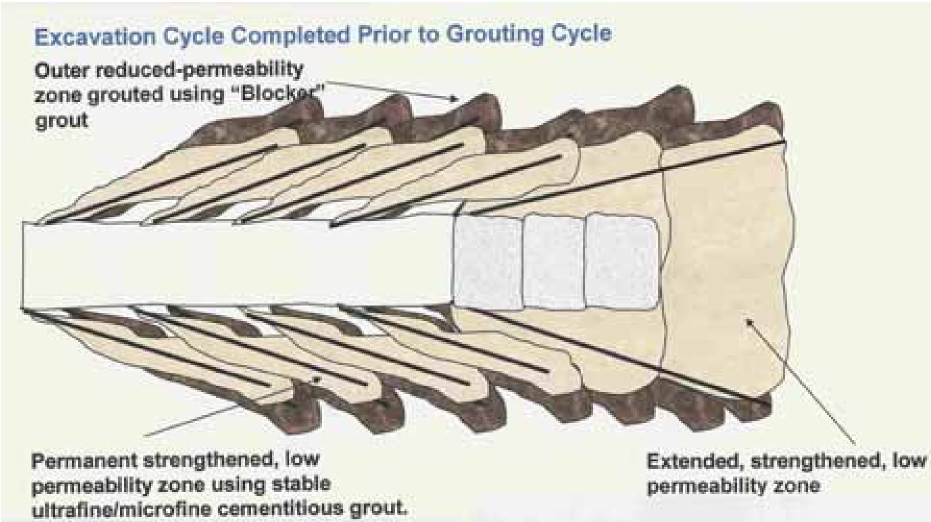
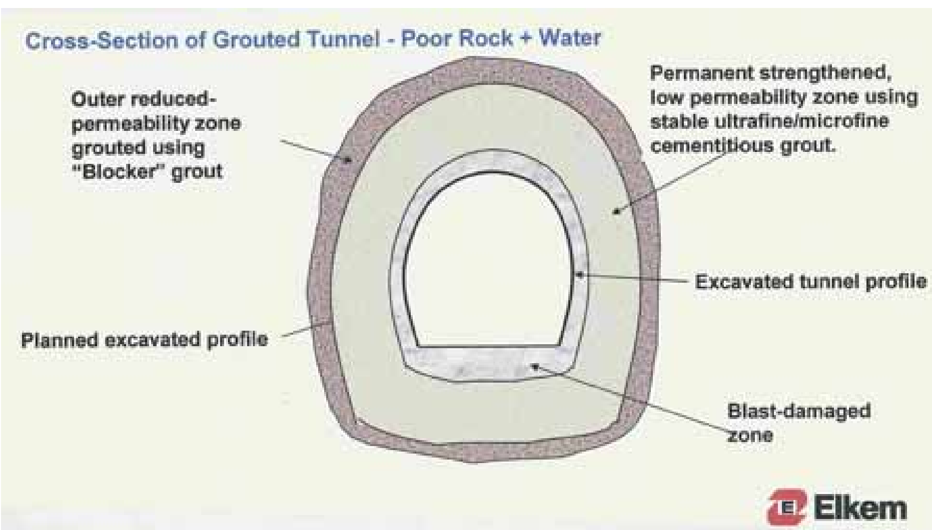
# 6. PRE-GROUTING FOR TUNNELS



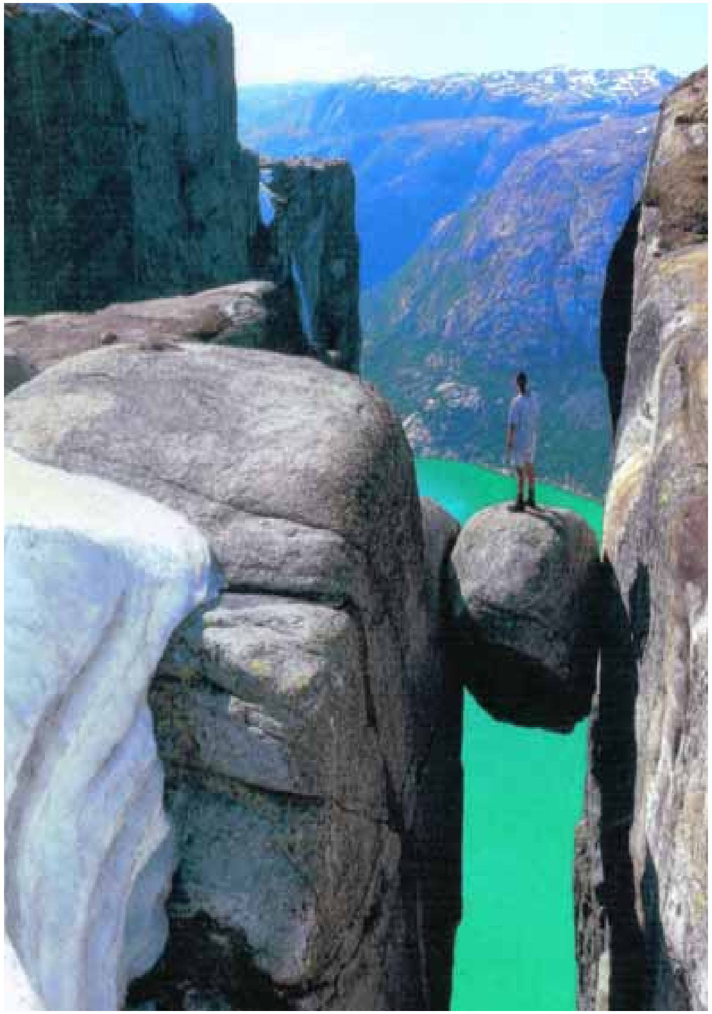

*The practical execution could look like these*



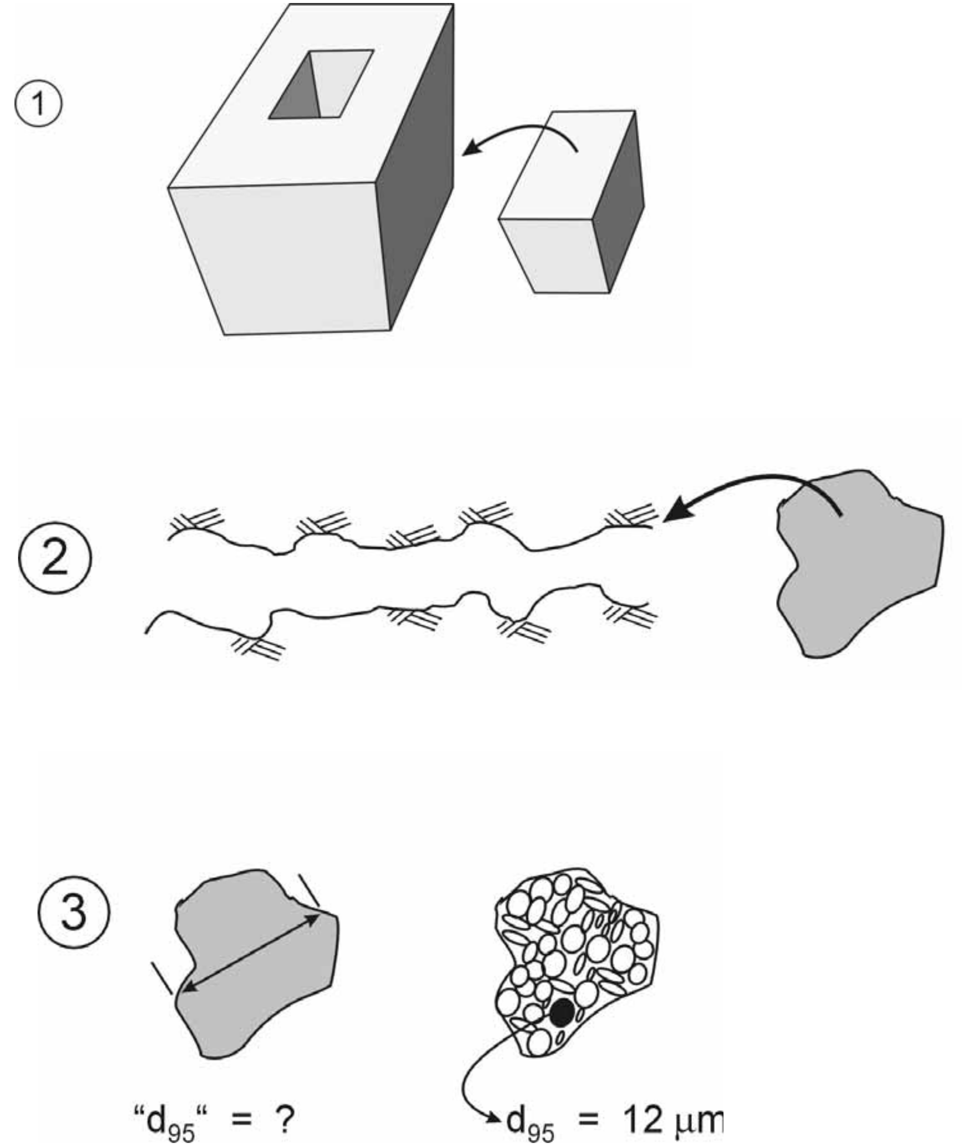

*simplified sketches – but how can it be achieved?*

# SOME PRE-GROUTING HOLES BEING DRILLED TO COVER THE NEXT THREE or FOUR ROUNDS OF TUNNEL ADVANCE

OBVIOUSLY LEAKING JOINTS ARE EASY TO GROUT….. BUT THE TIGHT ONES THAT ALSO LEAK…….?

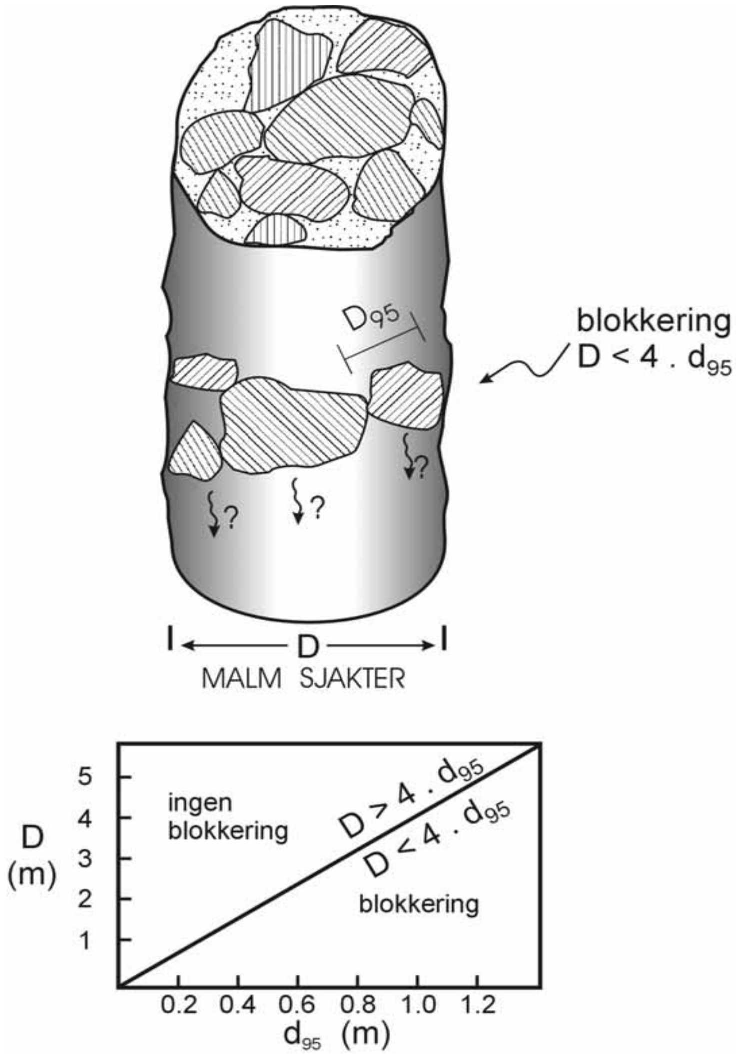


*The dilemma is how to get blocks (i.e. particles) that are too large in joints that are too tight.*




**…..smaller particles! ….. wider joints!**

*Before leaving large blocks and concentrating on cement particles……….note problems with ‘hang-up’ of blocks in mine ore passes!*



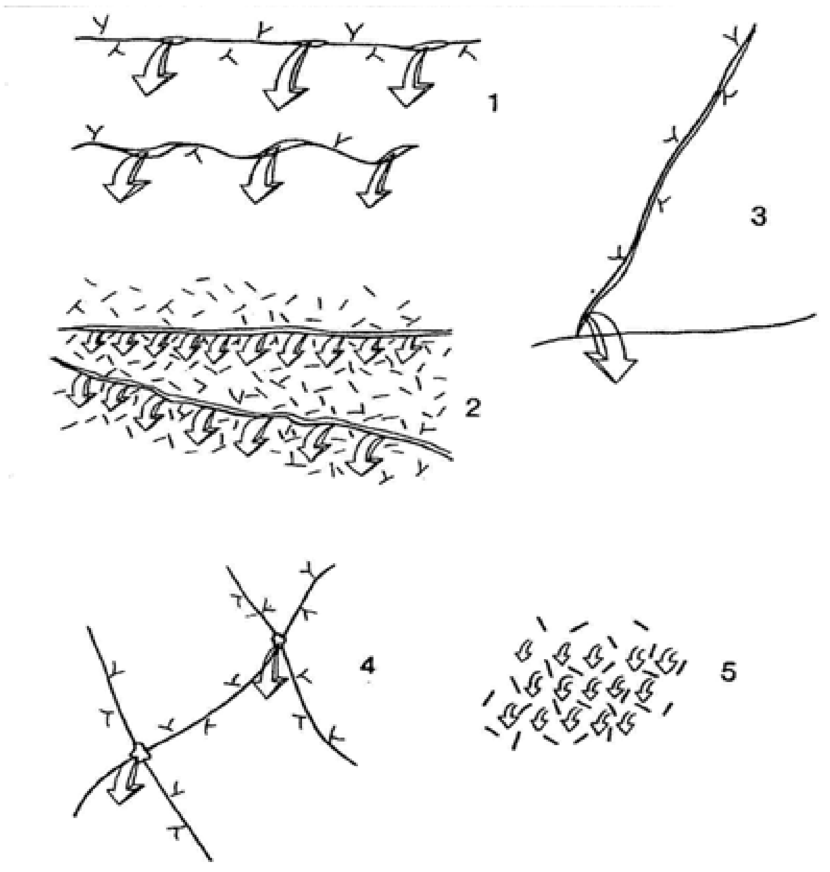

***Ore passes in mines also have problems with large blocks and wall roughness***

Blockage if $D < 4.d_{95}$

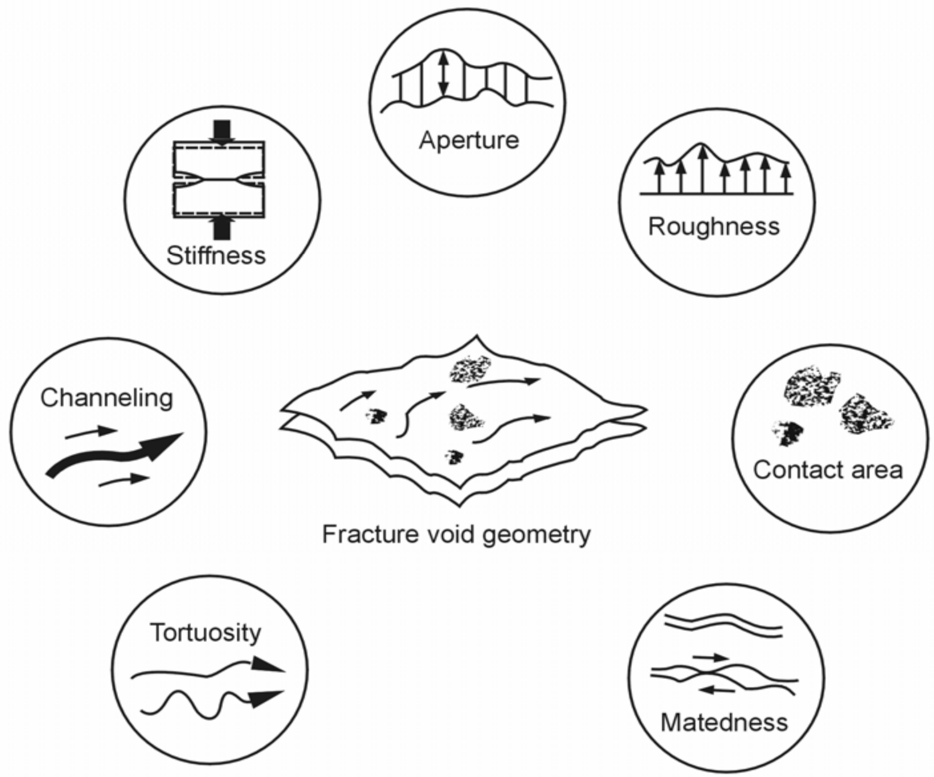
- Boundary layer
- Wall roughness
- ‘Slow’ particles

## SOME APPEARANCES OF WATER IN TUNNEL WALLS

*How can we reach the channels with grout ???*

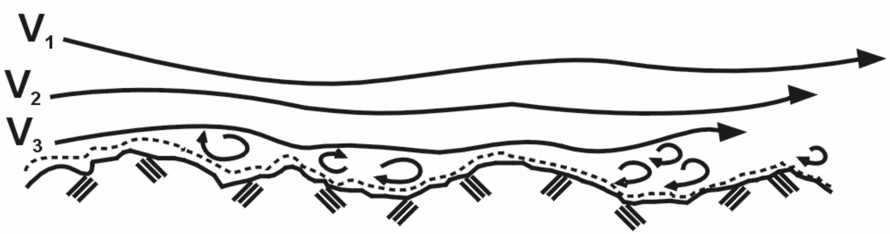


# SOME FUNDAMENTAL PHYSICAL ATTRIBUTES OF ROCK JOINTS

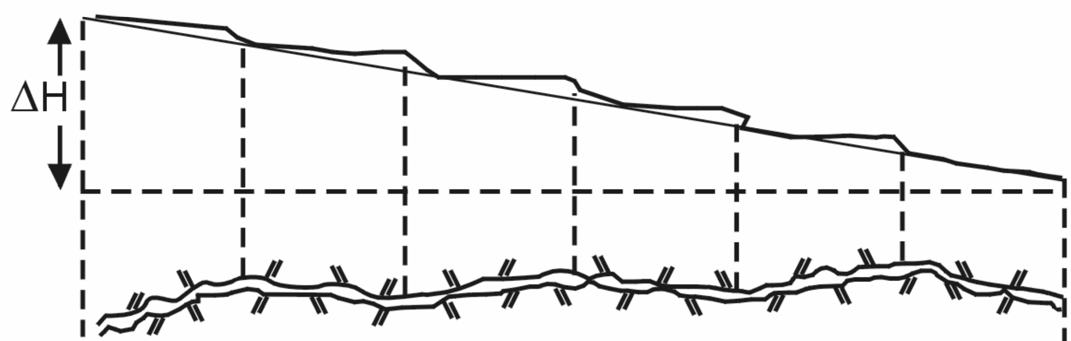



*Hakami 1995*

# HEAD LOSSES IN JOINTS AND BOUNDARY LAYER EFFECTS

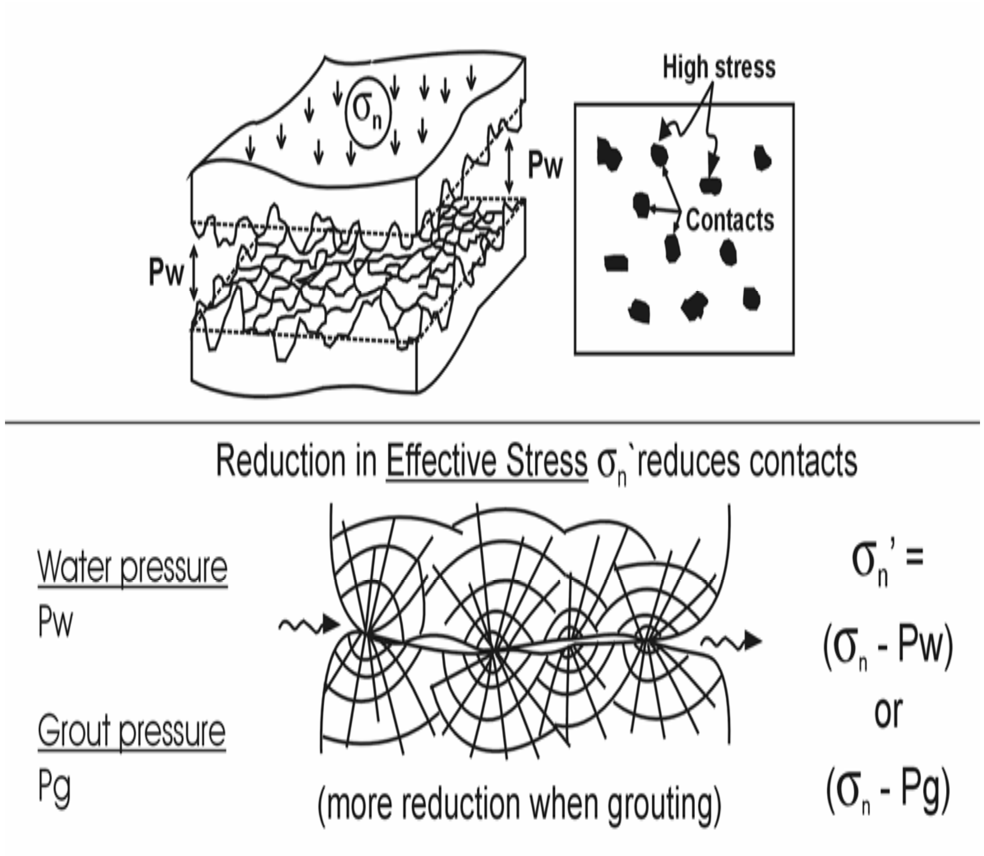



Boundary layer and frictional losses along rough joint walls (after Quadros, 1982)



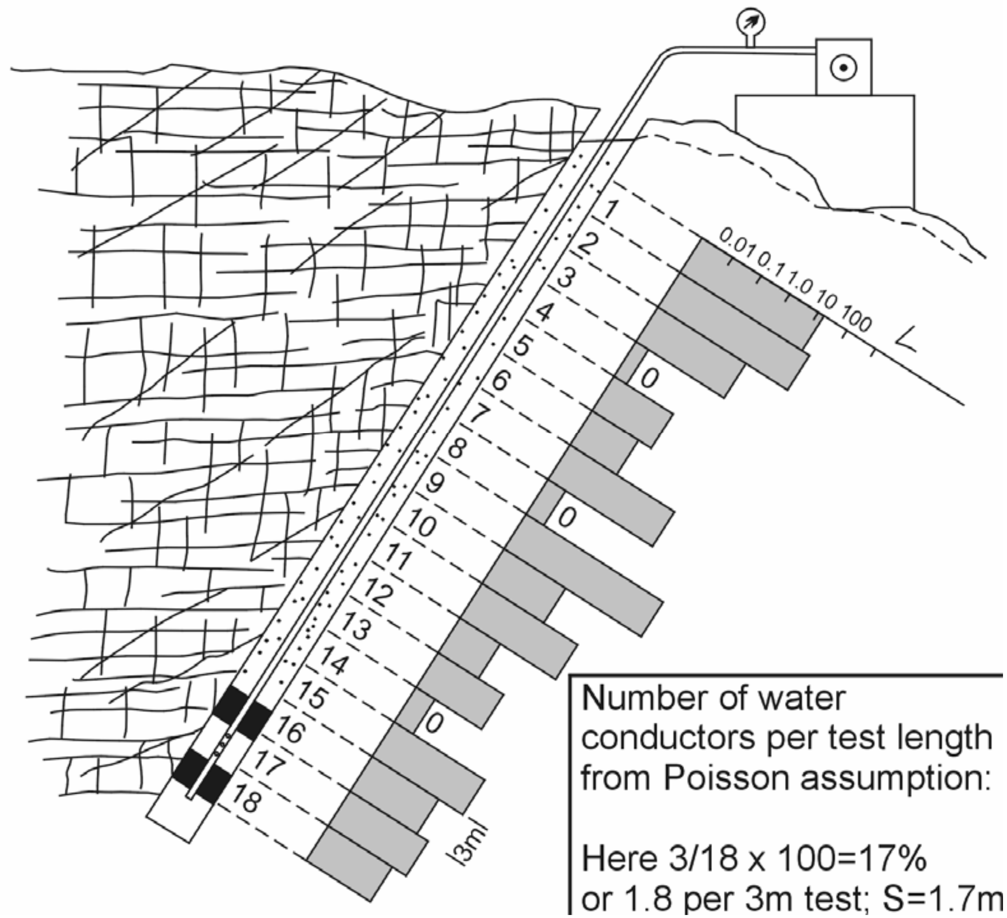

Head losses in rough interlocked joint (Louis,1969)

# EFFECTIVE STRESSES – IN WATER AND GROUT INJECTION




The existing apertures can be changed by fluid pressure – which is very advantageous in grouting!

# WATER INJECTION TESTS – LUGEON METHOD

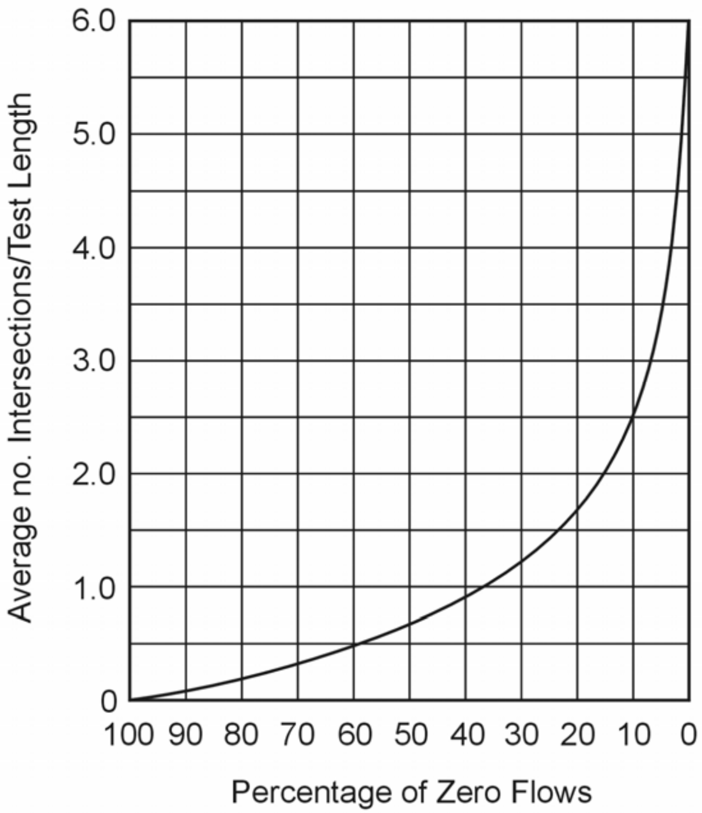



Number of water conductors per test length from Poisson assumption:

Here 3/18 x 100=17%
or 1.8 per 3m test; S=1.7m

***Pay special attention to % of zero flow sections***

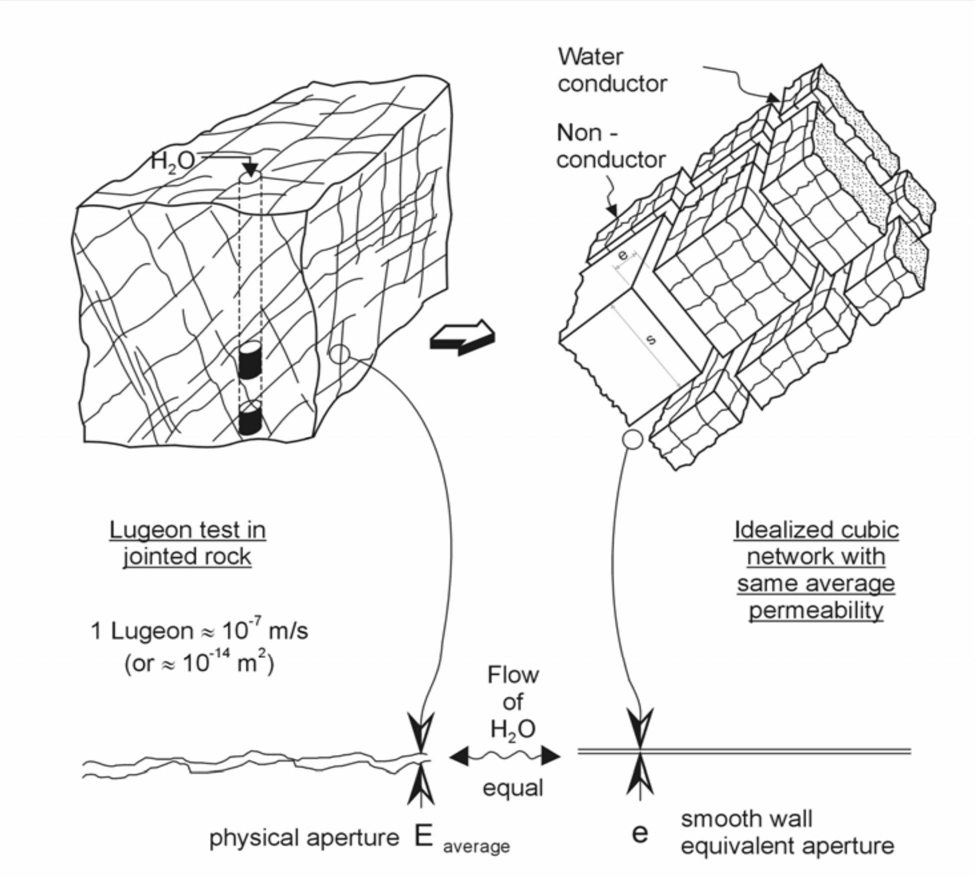
**ASSUMED POISSON DISTRIBUTION – FOR ESTIMATING *<u>AVERAGE</u>* SPACING OF WATER CONDUCTING JOINTS**




**17% of ‘zero’ flow stages means 1.8 conducting joints per test length……on average**

## SOME MORE SIMPLIFICATIONS ARE NEEDED!

## BECAUSE WE ARE ENGINEERS – WE NEED A SOLUTION!

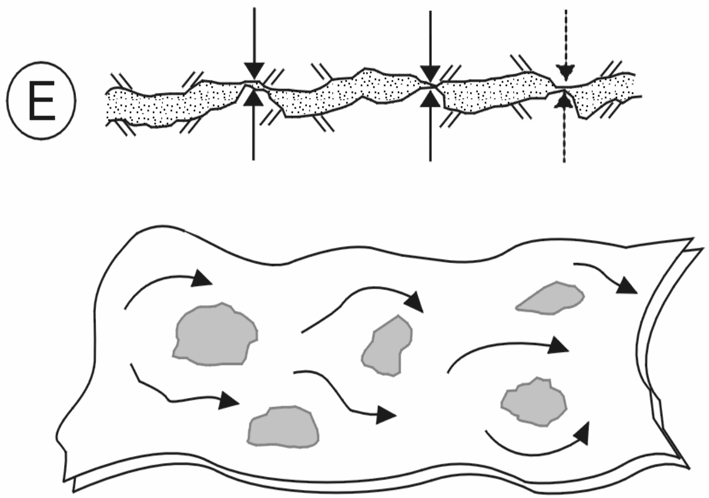



***This is how we ( from Snow, 1968) visualize the conducting network of joints***

# WE WILL NOW WORK WITH TWO DIFFERENT JOINT 'APERTURES'

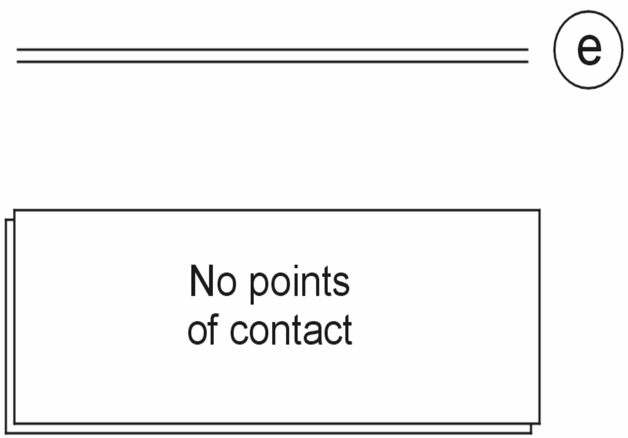
(E) is real and can be grouted

Stress transfer !

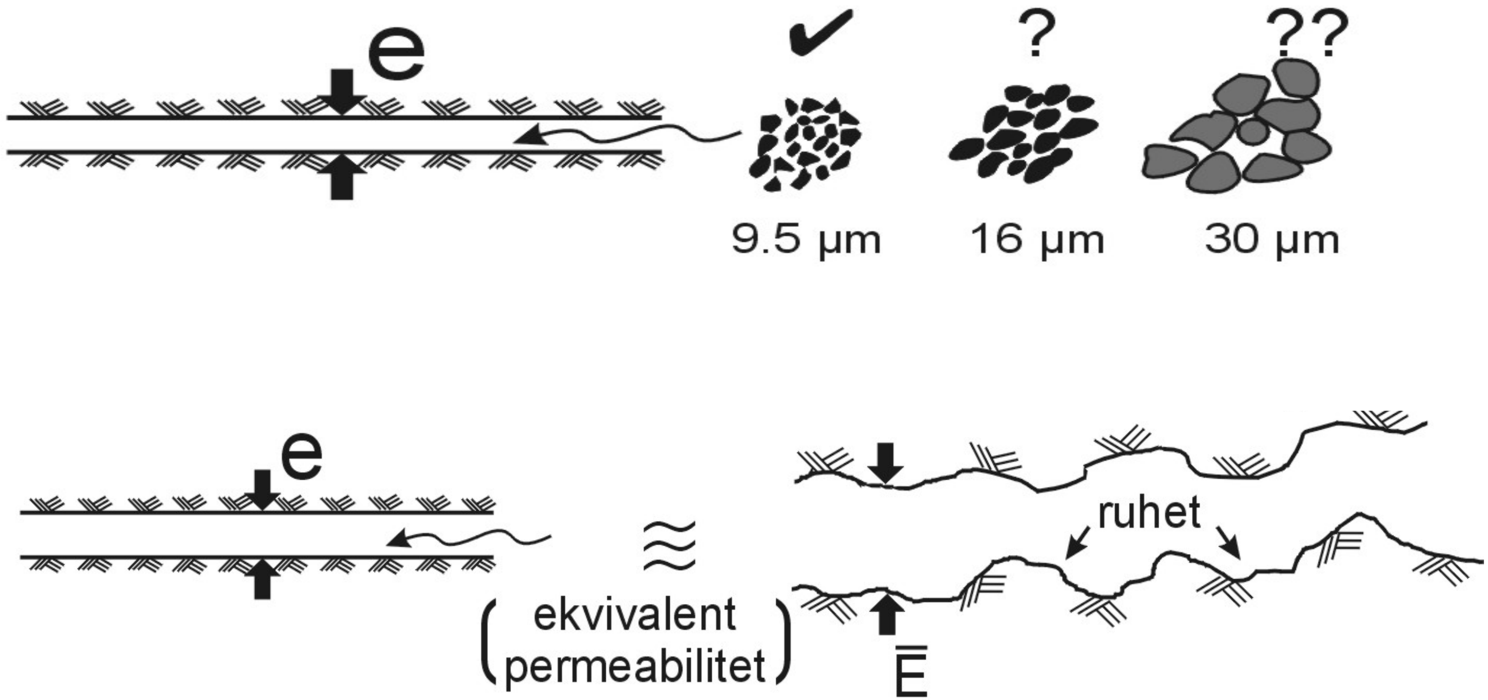



(e) is imaginary and ungroutable

Both E and e respond to injection pressure



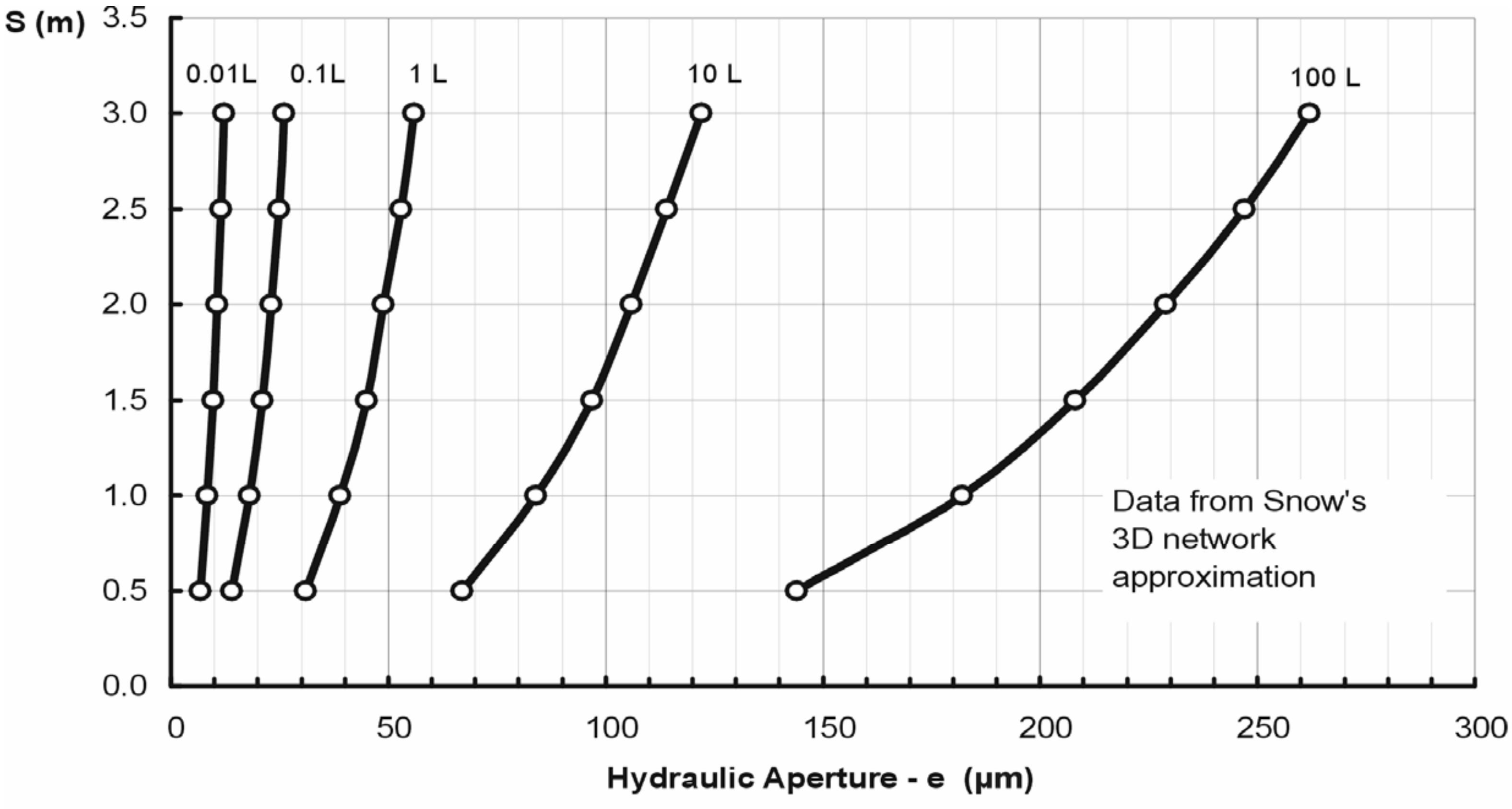
## BECAUSE (e) << (E), larger cement particles than expected can often be used



## *THEORETICAL INTERPRETATION (IN 3D) OF LUGEON RESULTS*

- based on Snow (1968), and the hydraulic theory of Louis 1967 :
- permeability of one smooth parallel plate : **$k = e^2/12$**
- permeability of 1 set of parallel plates : **$K_1 = e^2/12 \times e/S$**
- permeability of 'the conducting rock mass' ( 3 sets) : **$K_{mass} \approx 2\ e^3/12\ S$**
- 1 Lugeon ≈ $10^{-7}$m/s, $10^{-7}$m/s ≈ $10^{-14}$ m$^2$, laminar flow
- 3D interpretation of Lugeon tests **$e \approx (6LS \times 10^{-8})^{1/3}$**
- (e) and (S) in millimeters, L is average Lugeon value…each apply to the local domain, rock type, or borehole depth

The equation $e \approx (6LS \times 10^{-8})^{1/3}$ looks like this for typical S-values of 0.5 to 3.0m




*Obviously it is difficult to inject cement particles into e.g. < 0.1 Lugeon rock masses ……unless E ( the physical joint aperture ) >> e ( the hydraulic aperture )*

# SOME OPTIONS FOR INJECTING TIGHT JOINTS

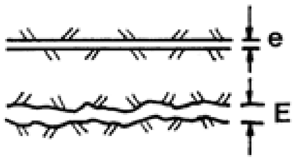
- **It helps to start injection with a high water/cement ratio (i.e. about 1.0)**
- **It helps to use ultrafine or micro cements (with micro silica and plasticisers)**
- **It helps to use up to 5 MPa higher grouting pressure ($P_G$), than water pressure ($P_W$)**

**i.e. $P_G >> P_W >> 1$ MPa**

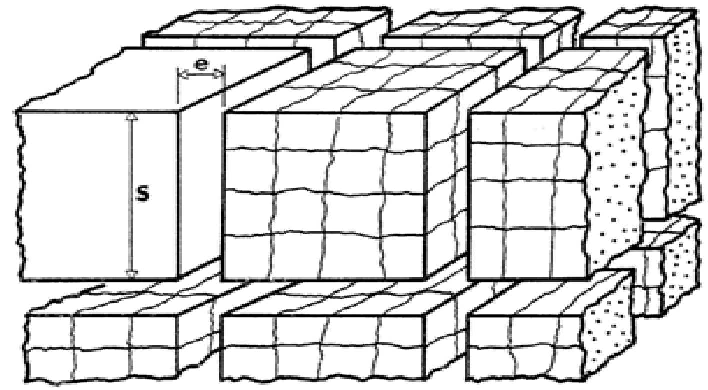
In Norway we use final grouting pressures in the range 5 to 10 MPa (50 to 100 bars), when pre-injecting ahead of tunnels, successively reducing the w/c ratio. The grouts are stable (little shrinkage or water separation).

BUT FIRST WE MUST INVESTIGATE IF WE NEED HIGH PRESSURE GROUTING – what physical apertures do we have??

| Depth zones | S(m) | e( μm) | E( μm) |
|---|---|---|---|
| 5 - 15m | 0.3 | 150 | 218 |
| 15 - 25m | 0.4 | 110 | 186 |
| 25 - 45m | 0.6 | 80 | 159 |
| 45 - 60m | 0.7 | 60 | 138 |

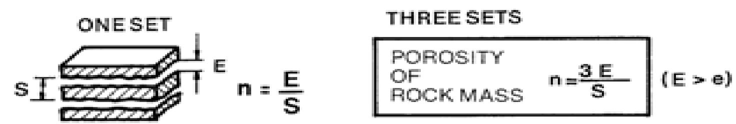



$$E = \sqrt{e.\ JRC^{2\cdot5}}$$




Grout-Take Estimates / 1m³ rockmass

| Depth zone | 5 - 15m | 15 - 25m | 25 - 45m | 45 - 60m |
|---|---|---|---|---|
| Grout (litres) | 2.2 | 1.4 | 0.8 | 0.6 |



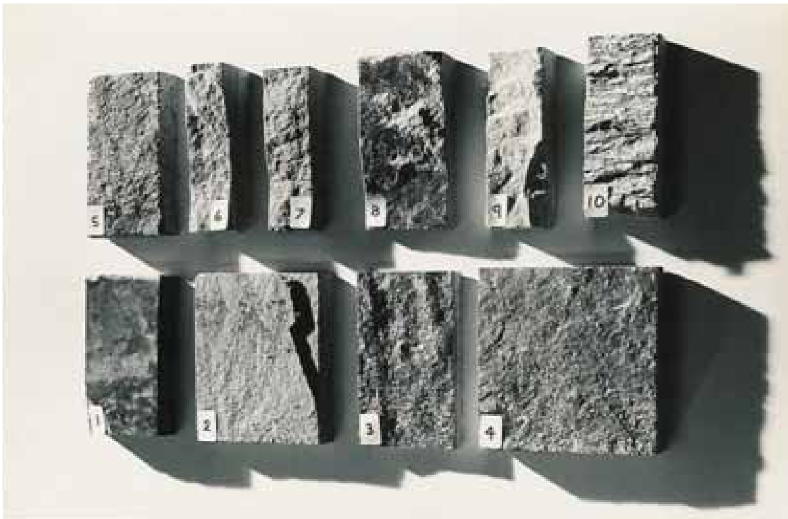

*Here we have Lugeon results from 4 depth zones at a permeable dam site*

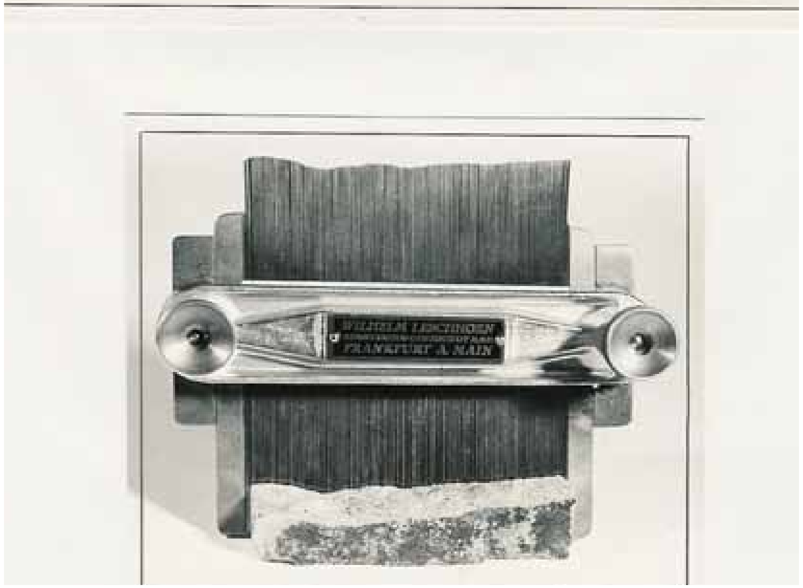
- *(e) and (S) have been interpreted as previously explained*
- *(e) is converted to (E) using JRC (the joint roughness coefficient)*
- *Note that the 'Grout-Take' estimate (from this 1978 example) assumes the same grout pressure as the Lugeon test…….. i.e. $\Delta P_W$ = 1 MPa*

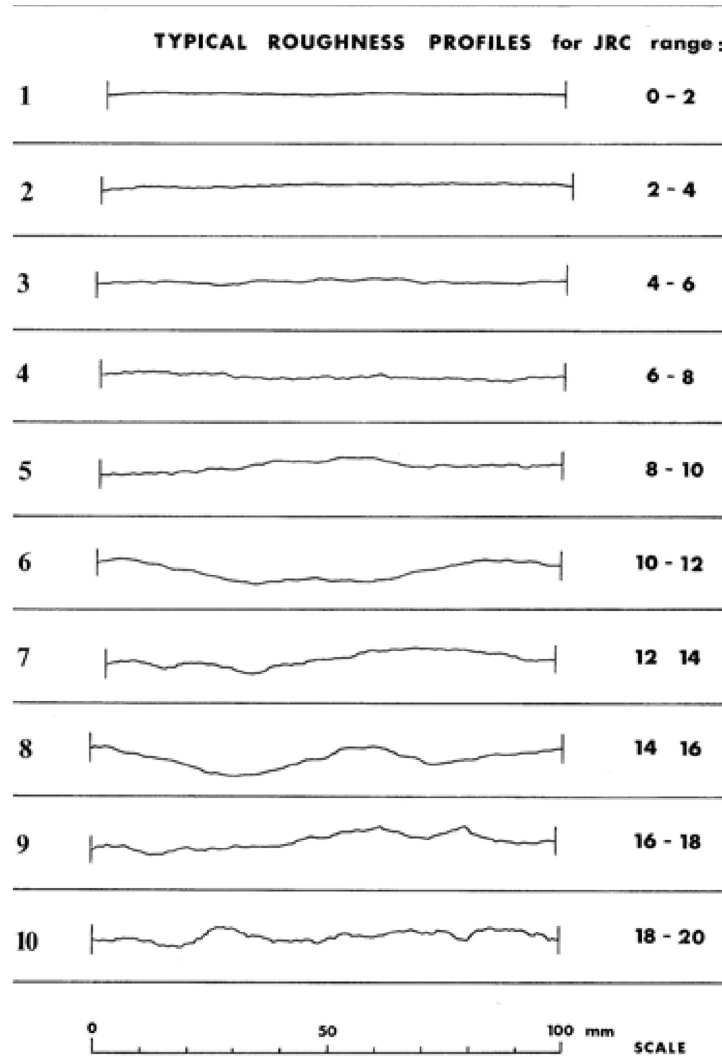
# HOW TO ESTIMATE JRC – THE JOINT ROUGHNESS COEFFICIENT


*Can be done on core from ahead of the face, or in the tunnel close to the face*

# JRC estimation from profile matching

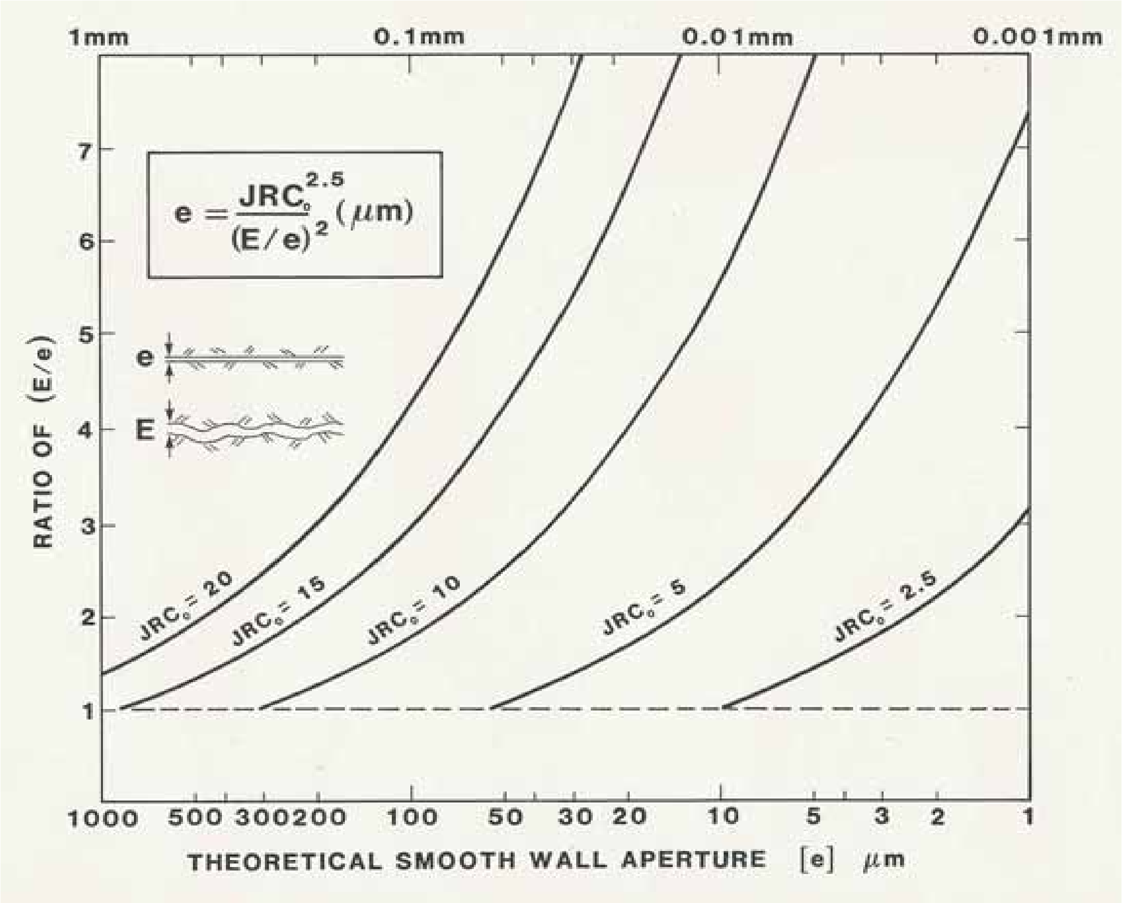




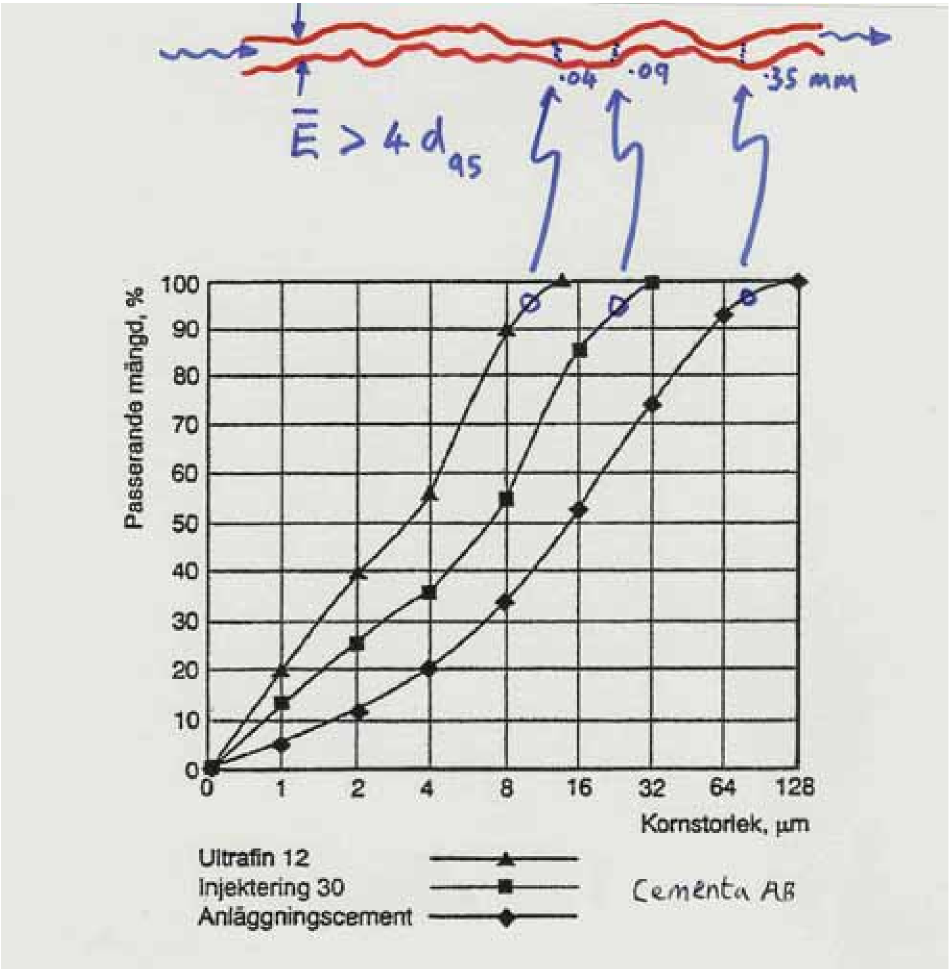


*JRC value ranges derived from tilt tests and direct shear tests*

CONVERSION BETWEEN (e) and (E) USING $JRC_0$ (100mm scale)

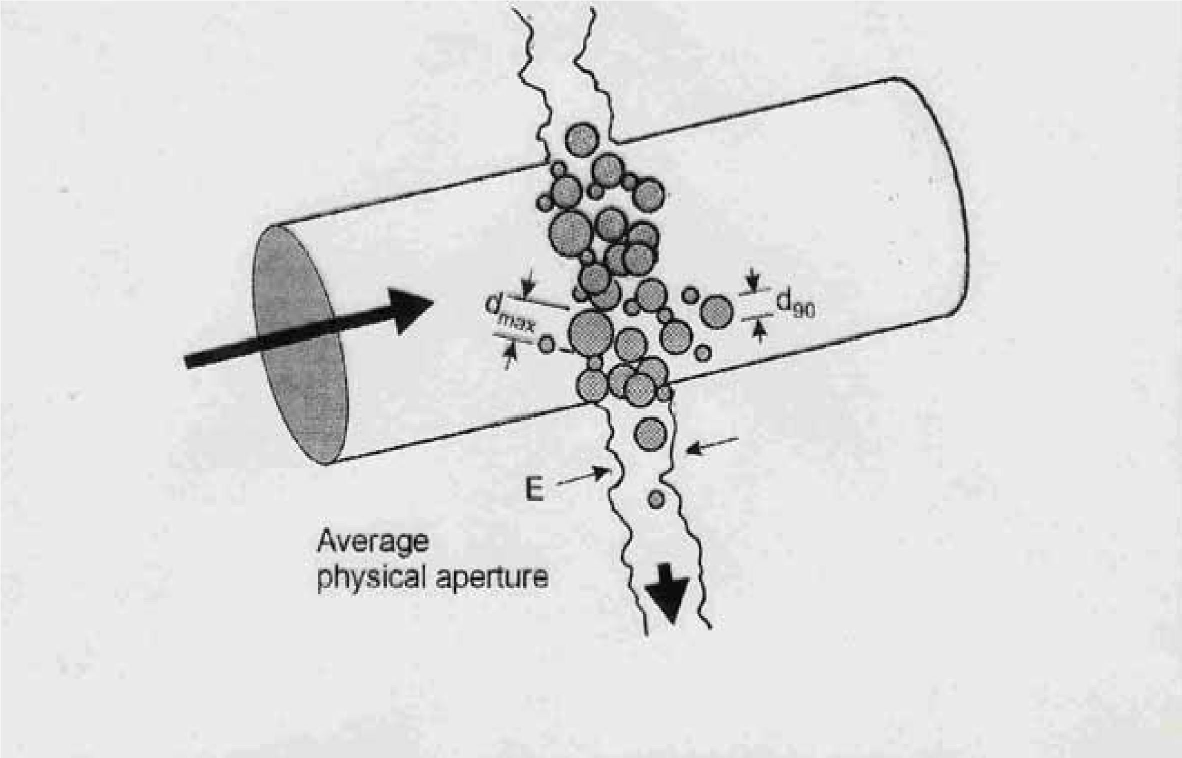


THE (approx.) LIMITS FOR INJECTION of *ULTRAFINE*, *MICRO* and industrial cement



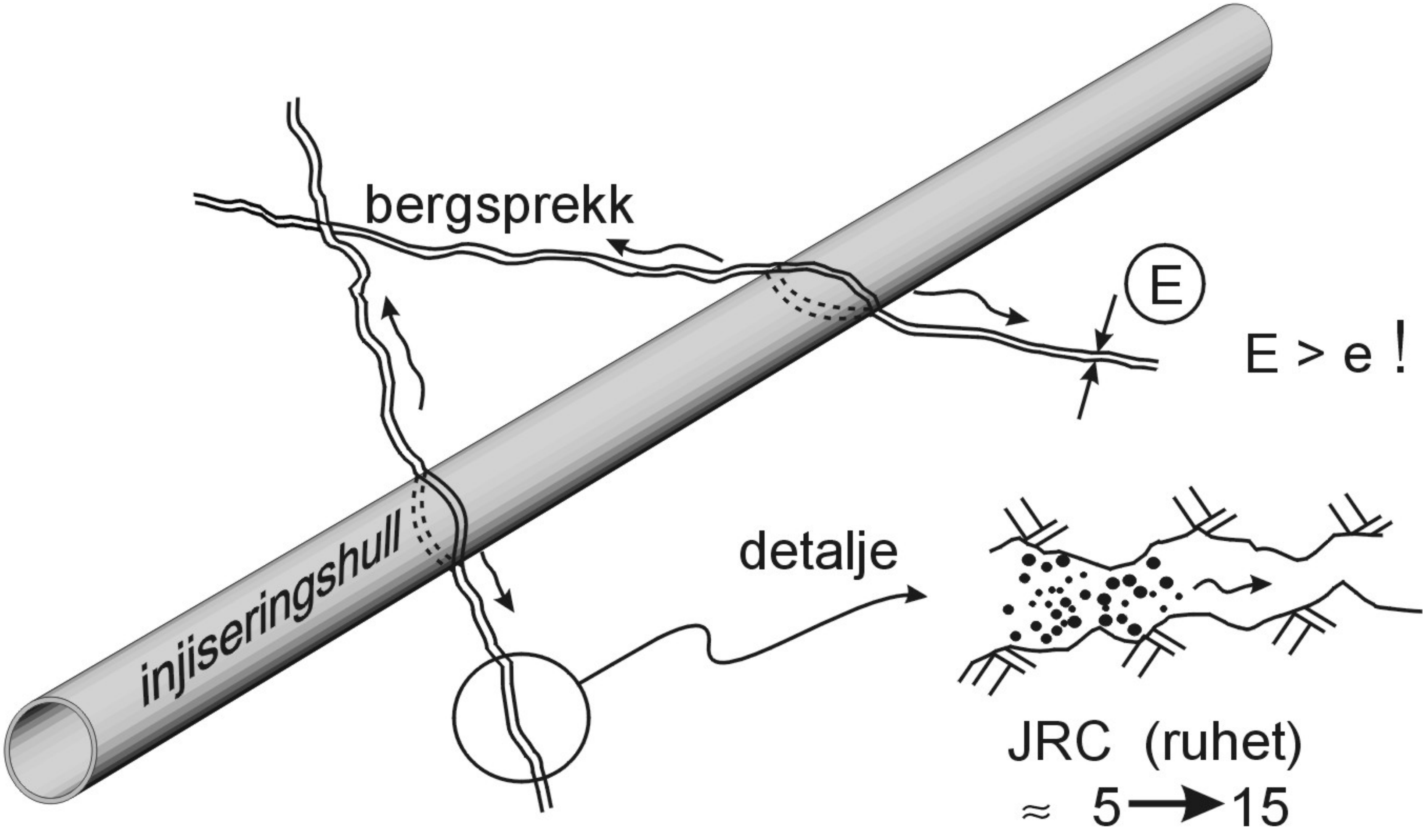

50, 100 and 400µm limits are simpler to remember

IF THE AVERAGE APERTURES (E) ARE NOT LARGE ENOUGH ? ………then (very exaggerated)……… the pressure must be increased!

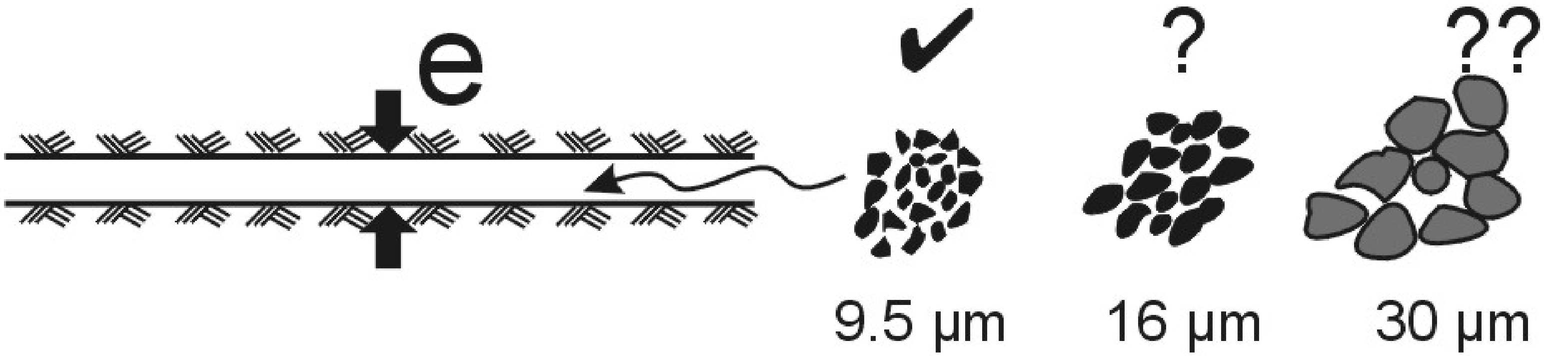



*Local aperture increase (0.1 to 0.3mm ?) with higher pressure*

# GROUTING *BETWEEN* THE JOINT SETS IS ACHIEVED WITH HIGHER PRESSURES

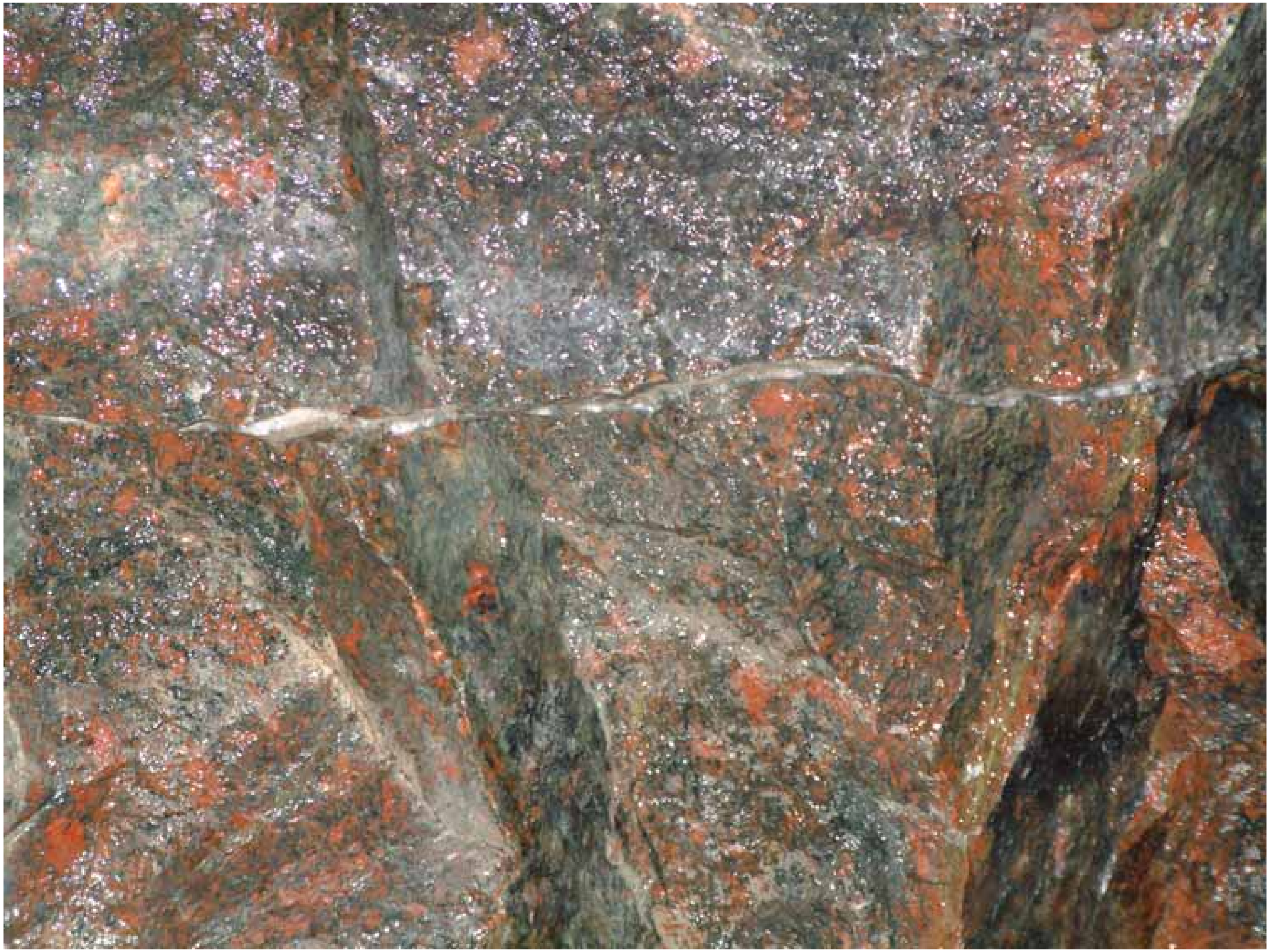


*Even this is possible (all 3 cements can be injected) due to E>e*




*If the joints were smooth this would be* impossible *without higher pressures*

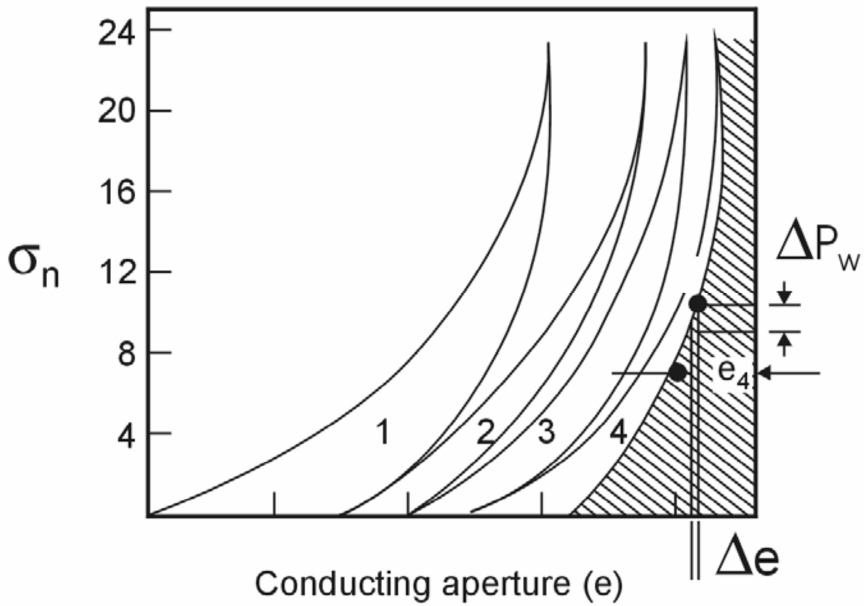
# WHEN GROUTING PRESSURE IS TOO LOW…ONLY 1 SET IS INJECTED?



**ONE, or perhaps TWO SETS ARE INJECTED…..**
**BUT THE ROCK MASS IS STILL WET!**

# THE MECHANISM OF JOINT OPENING WITH REDUCED EFFECTIVE STRESS……. i.e. WITH INCREASED GROUTING PRESSURE…….. SEE BB-MODELLING EXAMPLES

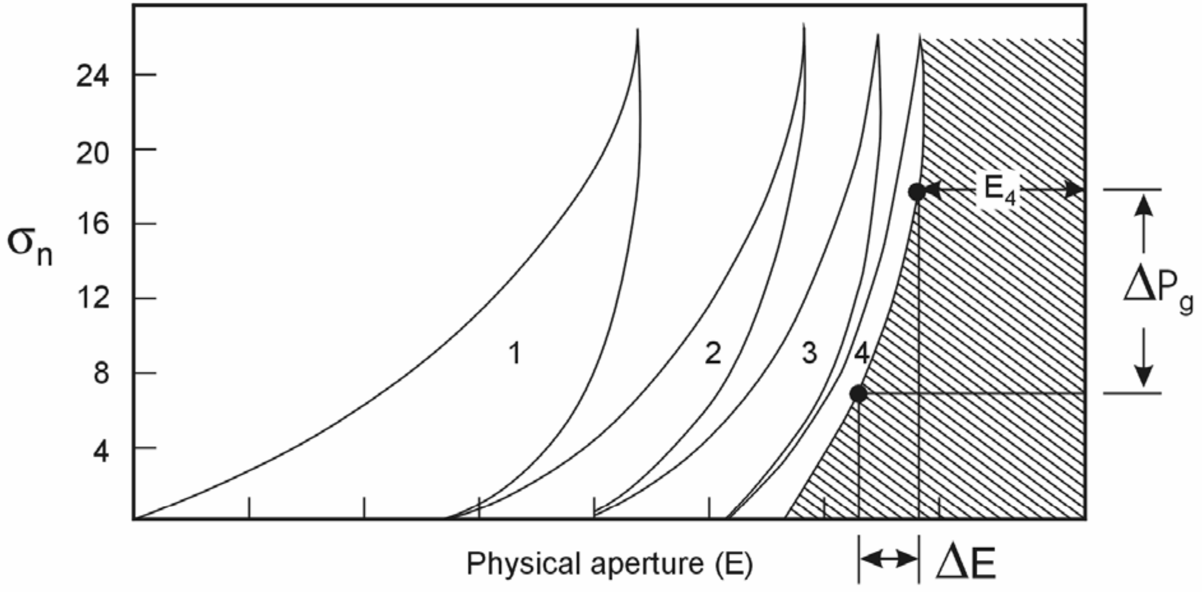
## a) Hydraulic aperture changes




- Assume $e_4$ (hydraulic aperture) represents in situ permeability at existing stress state
- The Lugeon test pressure of $P_w$ (e.g. 0.2, 0.5, 0.7 MPa) is controlled so that $e_4$ changes little during a flow test.

## b) Physical aperture changes

- Assume $E_4$ represents the in situ joint aperture at existing stress state




- In state-of-the-art pre-injection, $\Delta P_g$ is deliberately increased to ensure that $E_4$ increases to allow grout particle penetration.

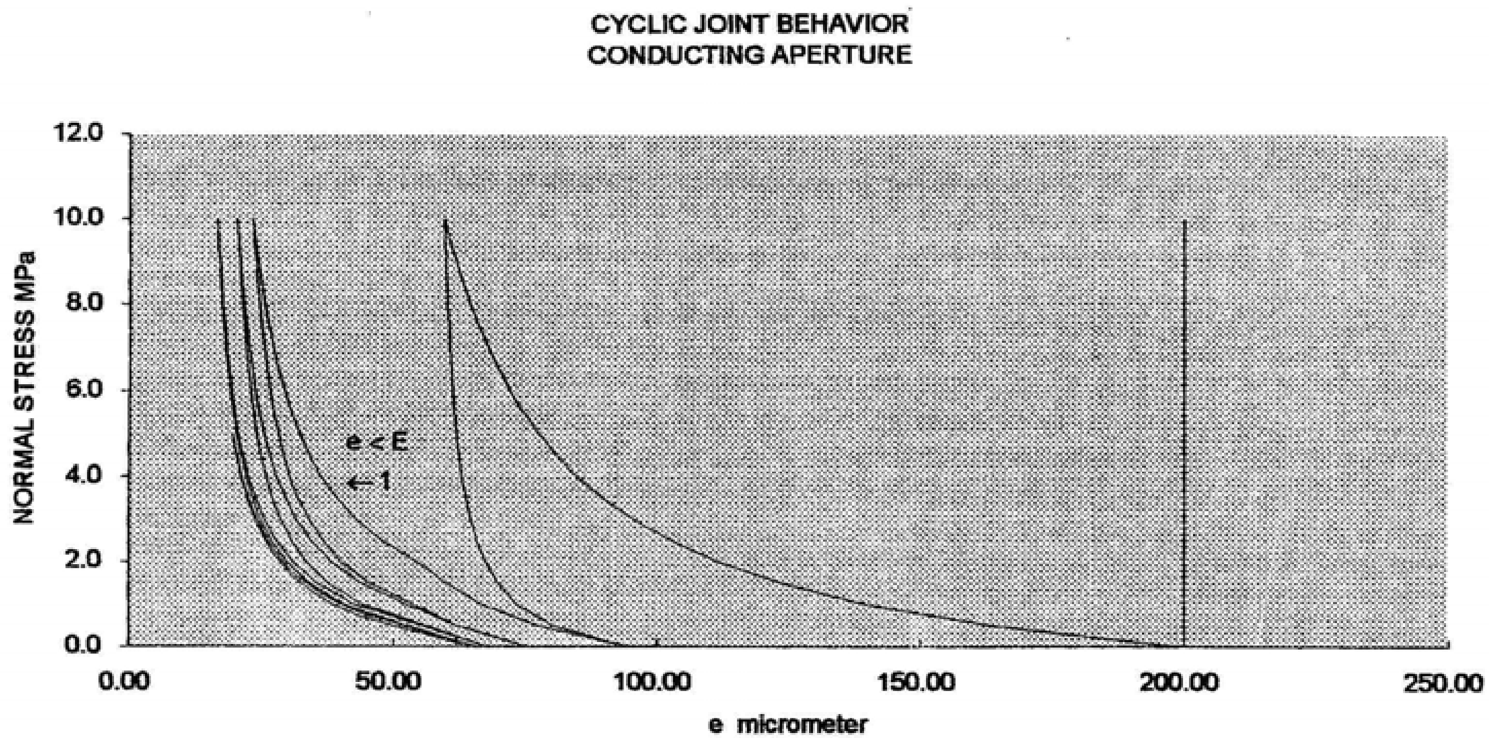
# EXAMPLE OF INPUT DATA AND INITIAL CALCULATIONS WITH BB-EXCEL

| Barton Bandis Joint Model | | | NORMAL CLOSURE CALCULATION | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| INPUT PARAMETERS | | | SNORM | CYCLE 1 | CYCLE 2 | CYCLE 3 | CYCLE 4 | CYCLE 5 | |
| JRC | 5 | | LOAD | 10 | 10 | 10 | 10 | 5 | MPa |
| JCS | 100 | | UNLOAD | 0 | 0 | 0 | 0 | 0 | MPa |
| SIGMAC | 150 | | APERTURE | 0.200 | 0.095 | 0.076 | 0.068 | 0.066 | mm |
| | | | KNP * | 4.8E+02 | 1.4E+03 | 2.3E+03 | 2.6E+03 | 8.1E+02 | |
| CALCULATED PARAMETERS | | | | | | | | | |
| | | LOAD | KNI | 10.49 | 20.34 | 25.14 | 27.77 | 28.55 | MPa/mm |
| | | | VMI | -0.165 | -0.067 | -0.047 | -0.042 | -0.040 | mm |
| | | | AJ | 0.095 | 0.049 | 0.040 | 0.036 | 0.035 | |
| | | | BJ | 0.578 | 0.736 | 0.851 | 0.861 | 0.865 | |
| | | UNLOAD | KNI' | 20.34 | 25.14 | 27.77 | 28.55 | 29.22 | MPa/mm |
| | | | VIRR | -0.105 | -0.019 | -0.008 | -0.002 | -0.002 | mm |
| | | | DSM | -0.105 | -0.124 | -0.132 | -0.134 | -0.136 | |
| | | | SIRR | -0.105 | -0.124 | -0.132 | -0.134 | -0.105 | |
| | | | AJ' | 0.049 | 0.040 | 0.036 | 0.035 | 0.034 | |
| | | | BJ' | 1.286 | 0.907 | 0.952 | 0.886 | 0.894 | |
| | | | VMI' | -0.038 | -0.044 | -0.038 | -0.040 | -0.038 | |

The initial *unstressed physical aperture* is estimated from an empirical equation :

$$E_0 = JRC_0/5(0.2\sigma_c/JCS_0 - 0.1) \text{ mm}$$

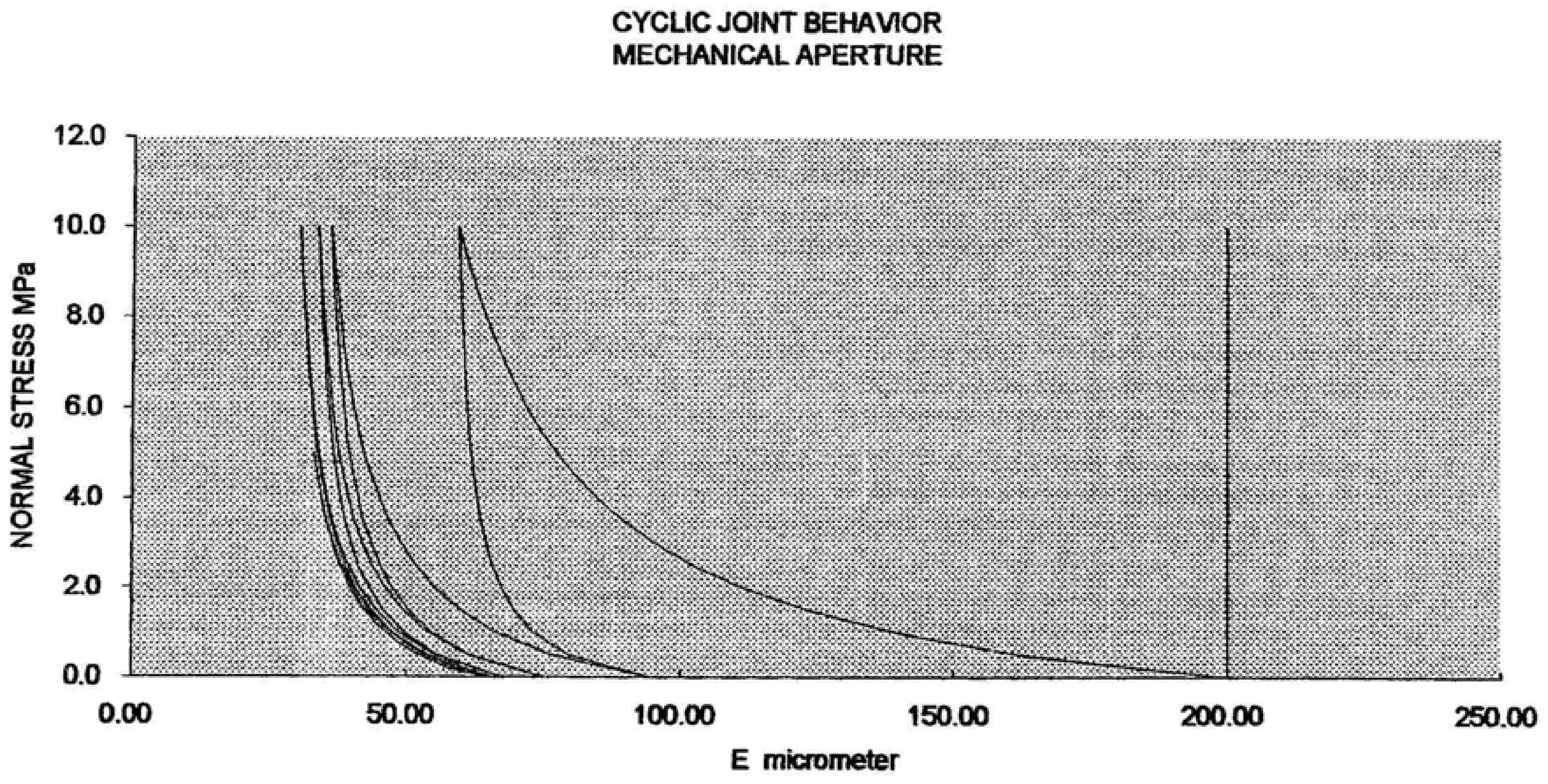
# THE ADVANTAGE OF AN INCREASE IN PRESSURE ON $\Delta e$




CYCLIC JOINT BEHAVIOR

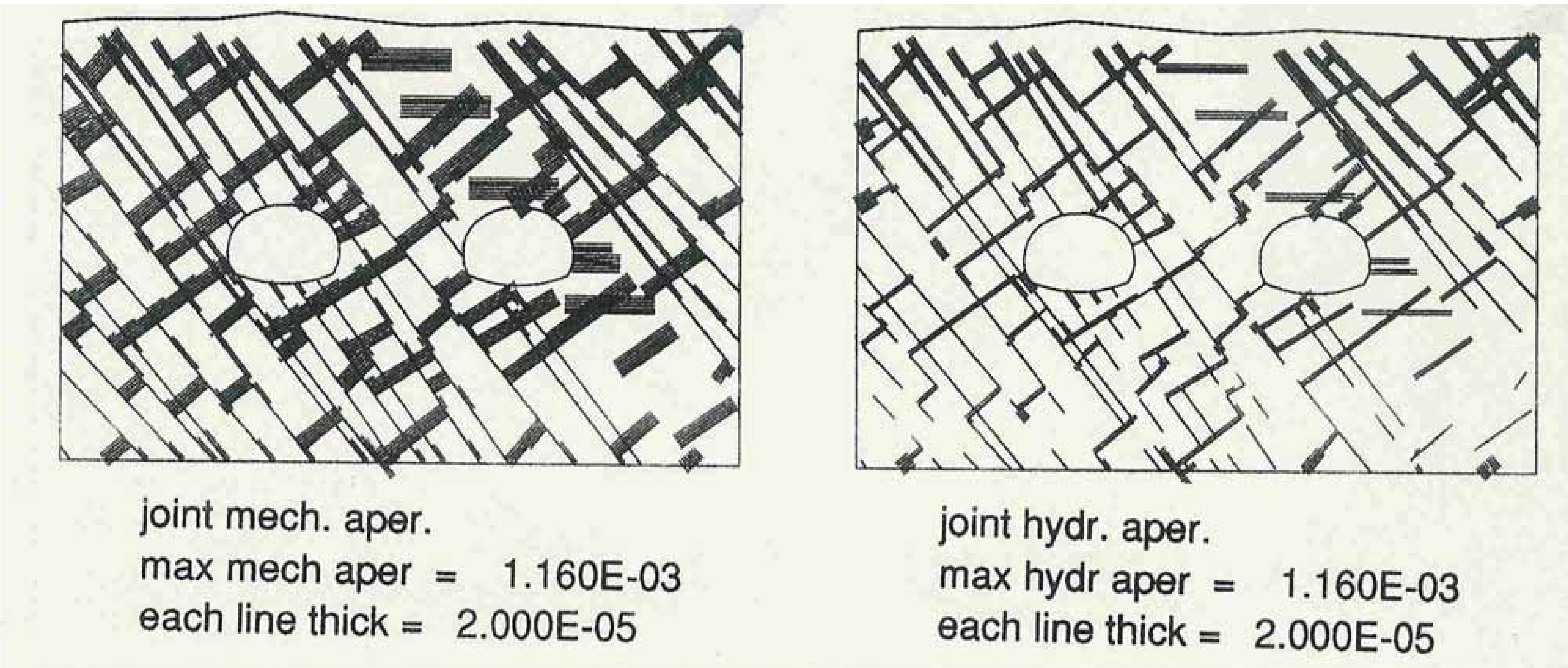
*BUT…. a false idea of permeability will be given with too high water pressure testing*

# THE ADVANTAGE OF AN INCREASE OF PRESSURE ON *ΔE*



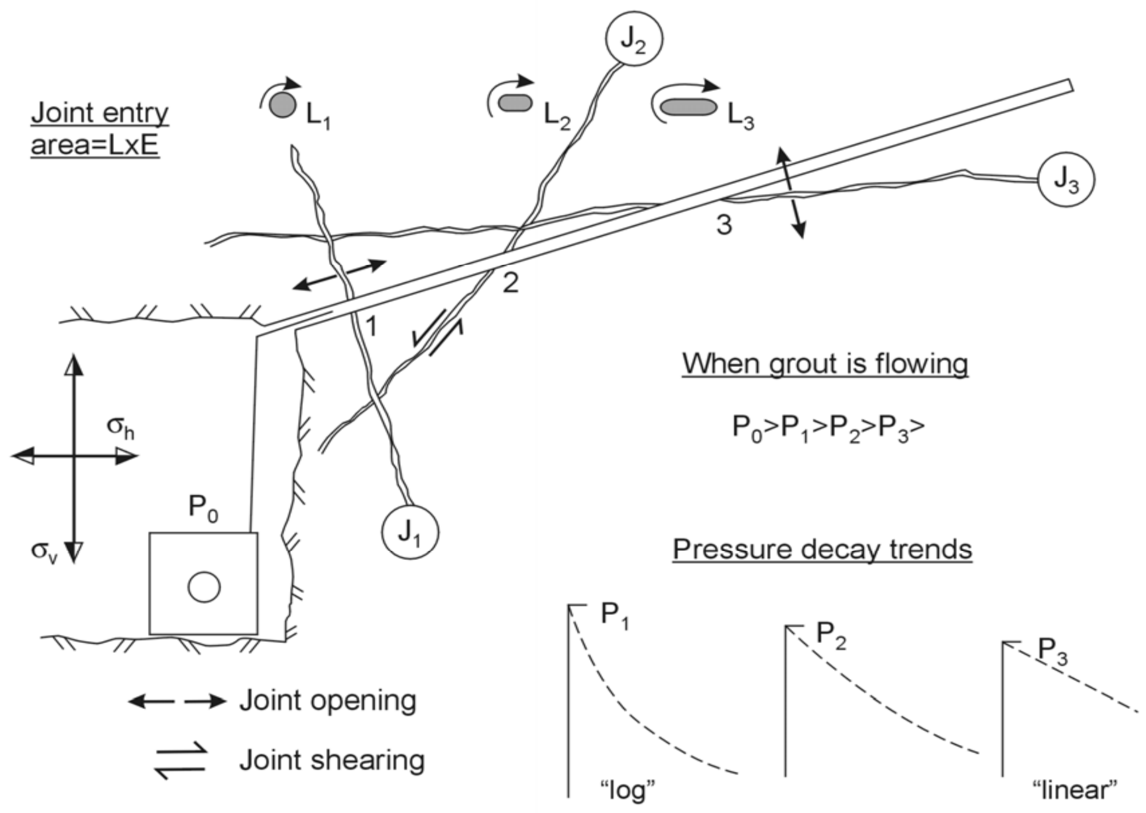

*Note that E can be almost doubled from 30 to 60μm…… now OK for ULTRAFINE?*

*The difference between E and e in a UDEC-BB model (Makurat, 1988: Oslo Tunnel)*

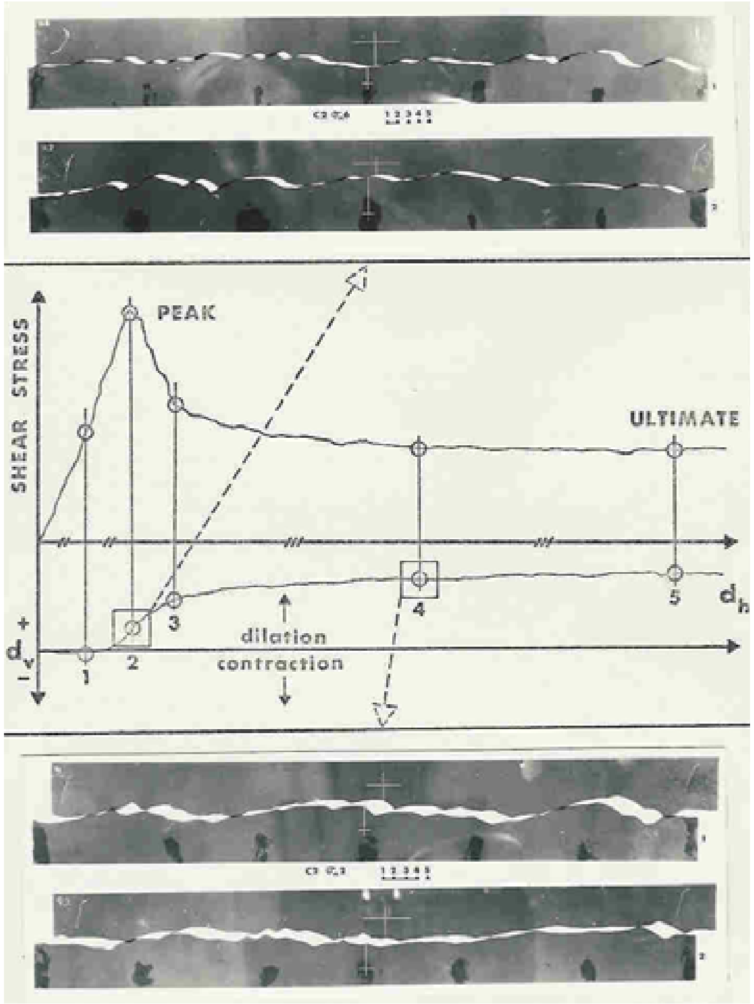


BUT ROCK MASSES ARE VERY VARIABLE……WHAT ABOUT SHEARING ???

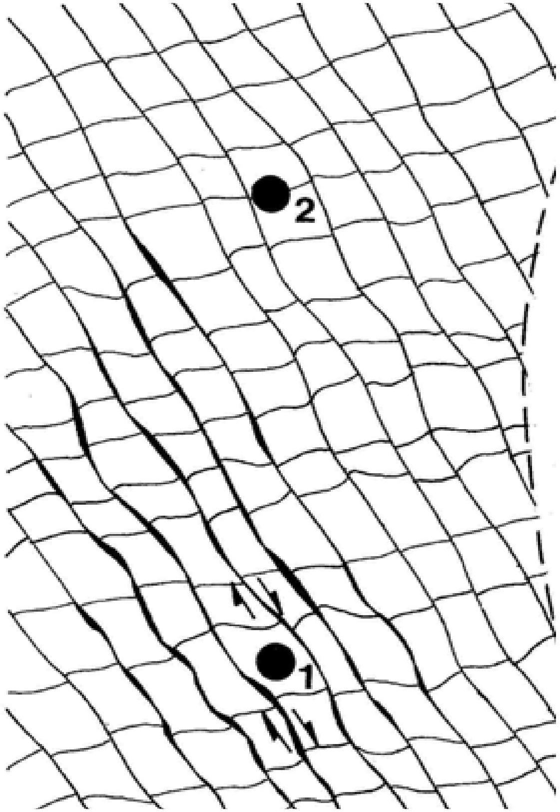
HERE THERE IS POTENTIAL SHEARING ON THE INCLINED JOINT SET ……IF THE STRESSES ARE ANISOTROPIC



# LOCAL SHEARING CAUSES LOCAL DILATION AND EASIER GROUT PENETRATION IN JOINTS THAT MAY HAVE BEEN TOO TIGHT

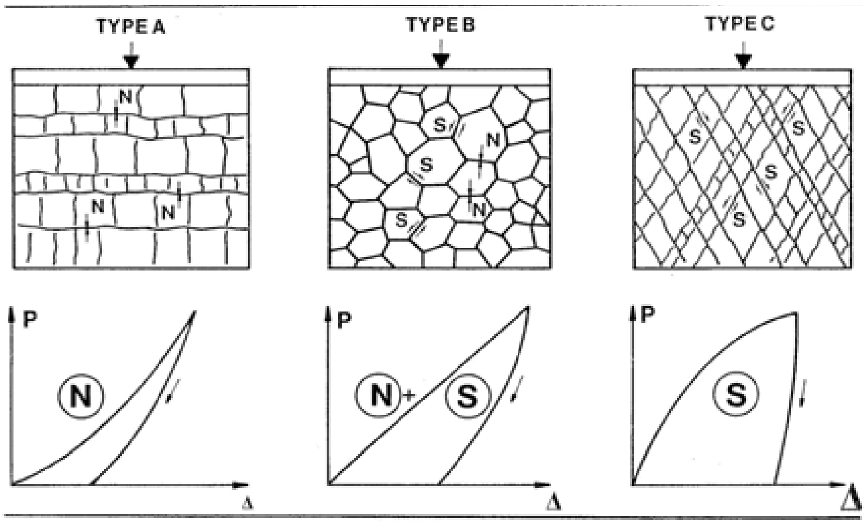


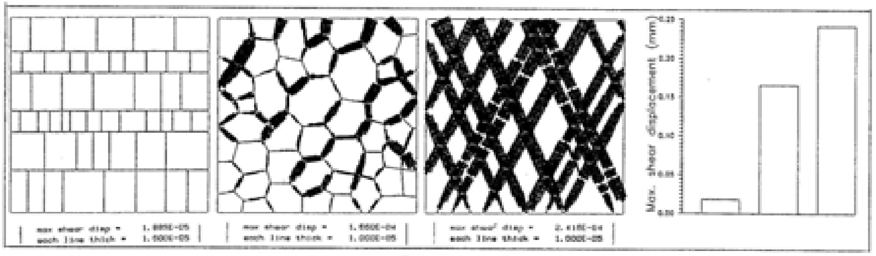
# A TYPICAL SITUATION WHERE JOINT SHEAR AND DILATION MIGHT OCCUR DURING HIGH PRESSURE PRE-GROUTING




*Future tunnel wall on right…principal stress vertical….but no hydraulic fracturing*

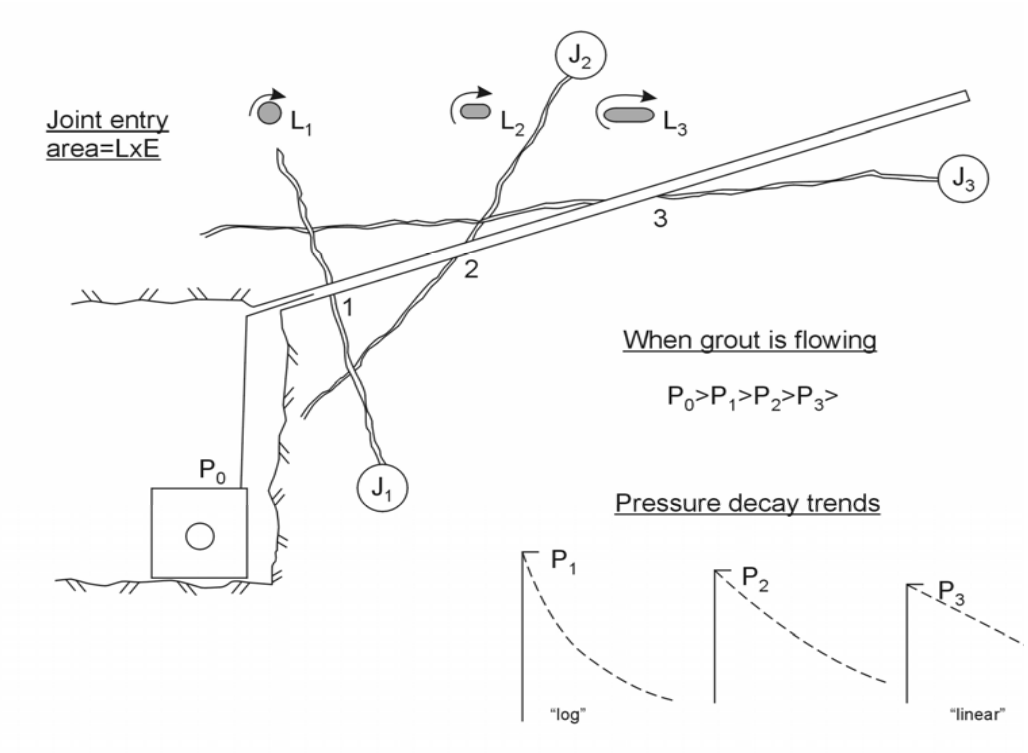
DIFFERENT JOINT DEFORMATION MECHANISMS CAN OBVIOUSLY OPERATE (LOCALLY) DURING HIGH PRESSURE INJECTION…..
due to the reduced local effective stresses



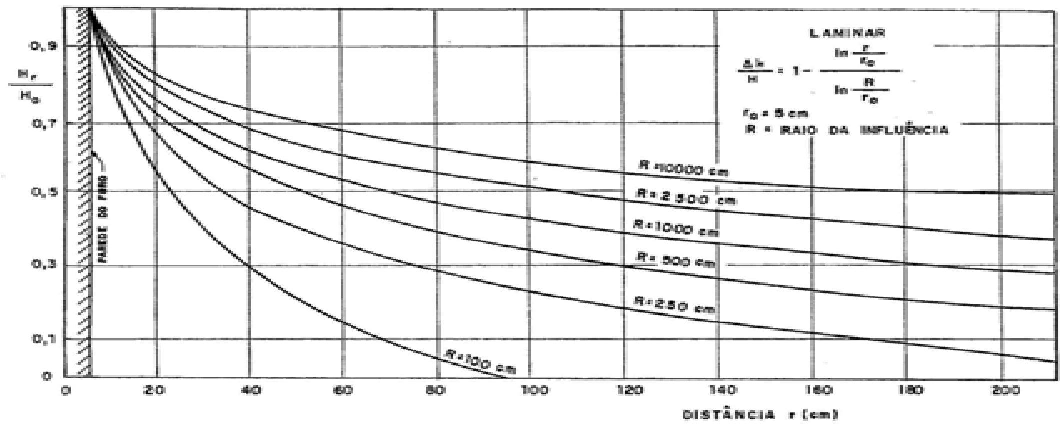



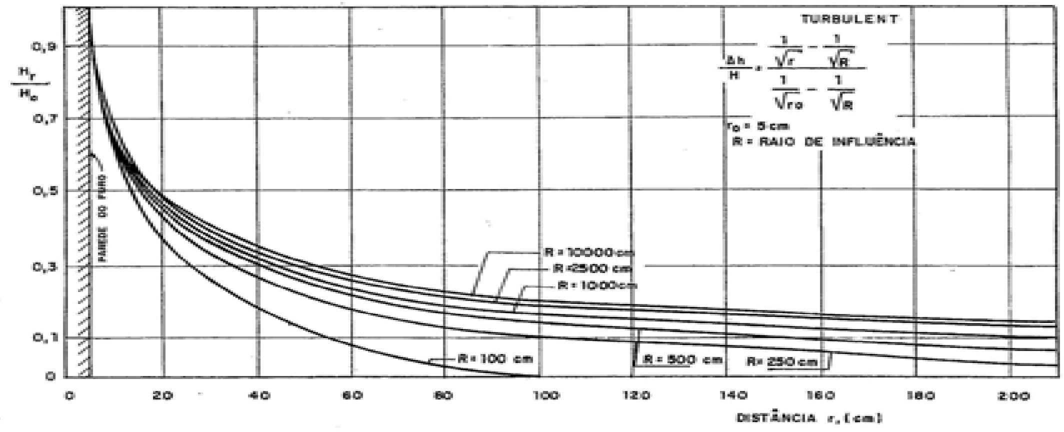
BUT HIGH PRESSURE GROUTING IS ***UNLIKELY*** TO CAUSE UNWANTED DEFORMATION i.e. uncontrolled hydraulic opening…….

due to pressure decay mechanisms even stronger than for Newtonian fluids



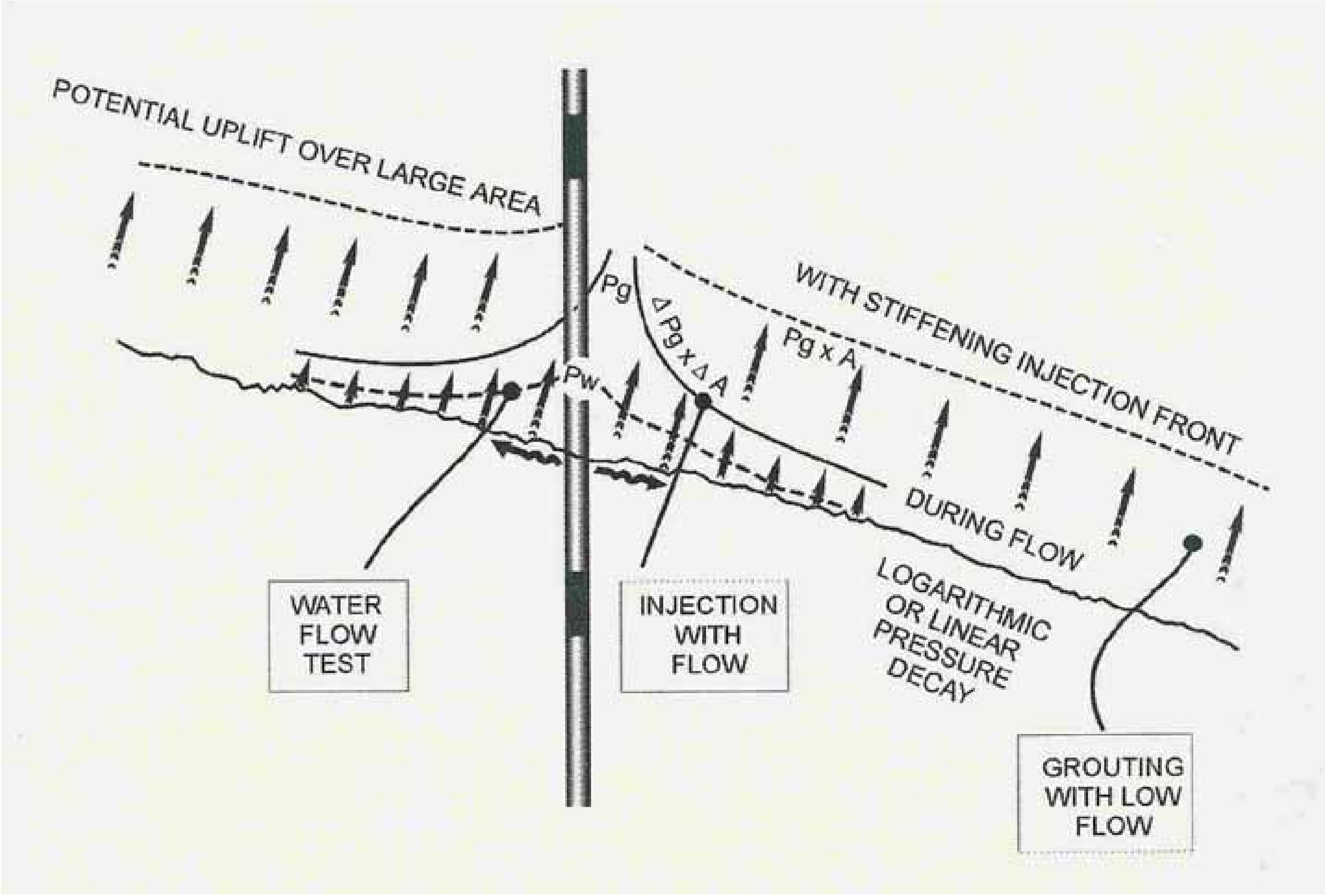

THE LOGARITHMIC PRESSURE DECAY IS A 'SAFETY MECHANISM' for high pressure grouting…….while flow is still occurring….. and is extra effective with cohesive + frictional fluids like grout



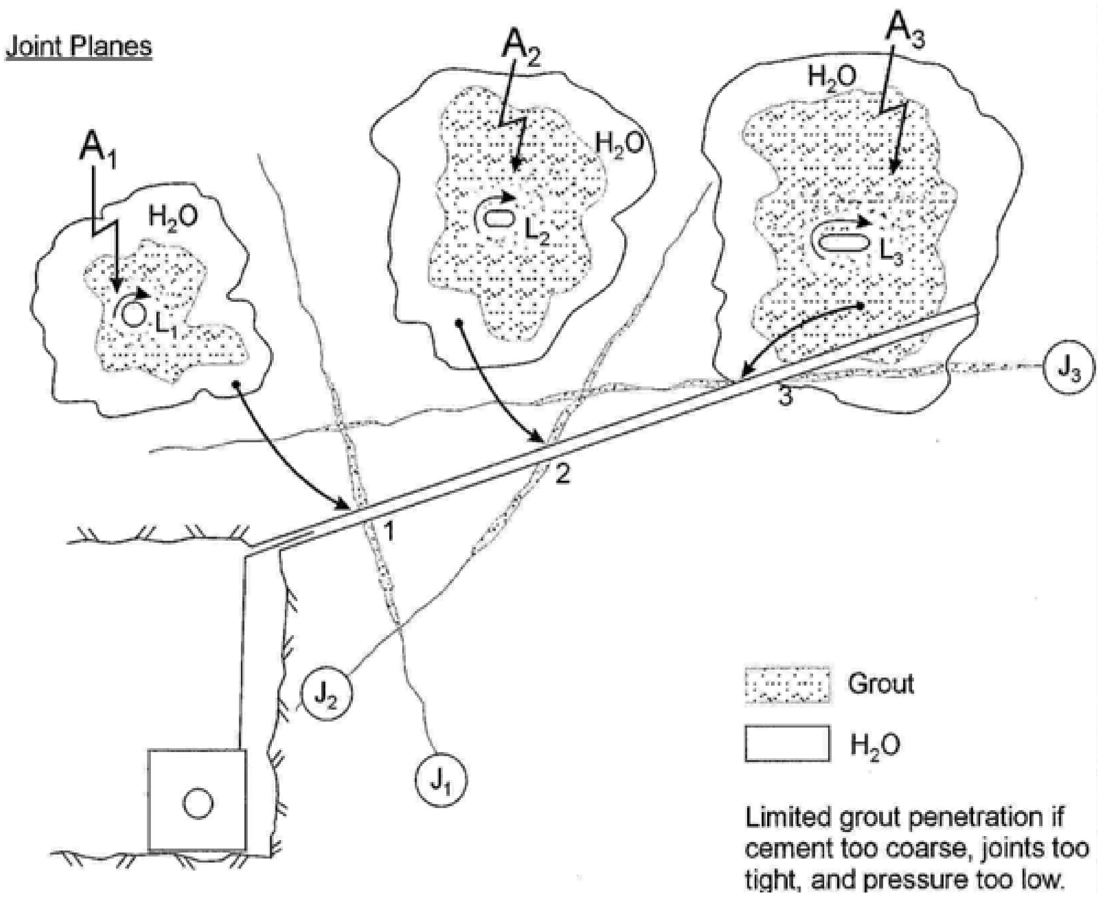




*Logarithmic pressure decay with radial, laminar or turbulent flow (e.g. Cruz, 1979) for the case of Newtonian fluids*

IT IS IMPORTANT TO BE AWARE OF UPLIFT (OR TUNNEL FACE) DEFORMATION THAT MAY OCCUR IF FLOW HAS CEASED AND PRESSURE IS MAINTAINED

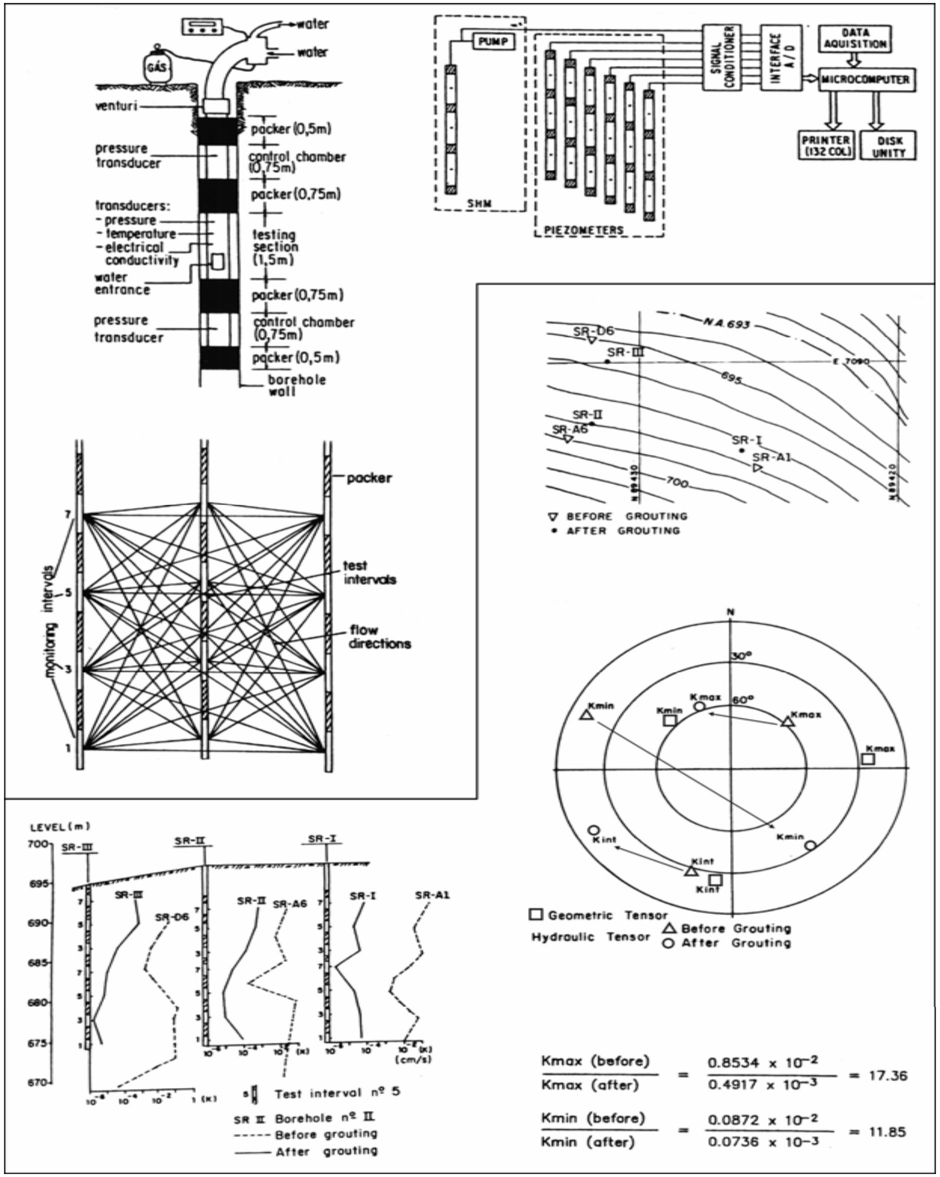


# WHAT HAPPENS WITH TOO LOW PRESSURE, TOO TIGHT JOINTS, TOO LARGE CEMENT PARTICLES…..AND UNSTABLE GROUTS…… THAT BLEED WATER?



WE CALL THIS WATER-SICK ROCK......MORE WATER AFTER THAN BEFORE

*BUT……THE NEXT SCREEN SHOWS WHAT SEEMS TO OCCUR WHEN DOING SUCCESSFUL INJECTION – when the grout penetrates as expected*




IPT multi-probe-multi-hole measurement of grouting
(Quadros and Correa Filho, 1995)

- In summary the 3 principal permeability tensors have rotated and reduced in magnitude due to grouting
- Single hole interpretation shows from 1 to 4 orders of magnitude improvement e.g. $10^{-7}$ to$10^{-8}$ m/s up to $10^{-4}$ to $10^{-8}$ m/s
- With 3D interpretation across 4 to 8 m of rock mass (this was the hole spacing), the improvement is 1/17 for $K_{max}$, and 1/11 for $K_{min}$
- This emphasises the need for closer spacing (e.g. split-spacing) of holes
- The results suggest that individual joint sets are successively injected
- Norwegian experiences suggest ‘pressure plateau’ …. as each joint set is injected?
- Can we take this further and think of *rock mass property improvement ???*

Suppose the following small improvements occur to individual Q-parameters

Improvement of rock mass properties with pre-grouting

| | | | | | |
|---|---|---|---|---|---|
| effective | RQD | increases | e.g. | 30 to 50% | |
| effective | $J_n$ | reduces | e.g. | 9 to 6 | |
| | $J_r$ | increases | e.g. | 1 to 2 | (changed set)* |
| | $J_a$ | reduces | e.g. | 2 to 1 | (changed set)* |
| | $J_w$ | increases | e.g. | 0.5 to 0.66 | (perhaps Jw = 1 is achieved) |

SRF would reduce only near surface e.g. 2.5 to 1

(* it may be appropriate to qualify with the word "perhaps" in several cases here)

Before pre-grouting $Q \approx \frac{30}{9} x \frac{1}{2} x \frac{0.5}{2,5}$

$\approx 0.3$

After pre-grouting $Q \approx \frac{50}{6} x \frac{2}{1} x \frac{0.66}{1 or 2.5}$

$\approx 11$ (or 4·4)

These could give the following improvements in rock mass properties ……?

| *Before pre-grouting* | *After pre-grouting* | *(alternative)* |
|---|---|---|
| Q ≈ 0.3 | Q ≈ 11 | (Q ≈ 4·4) |
| $V_p$ ≈ 3.0 km/sec | Vp ≈ 4.5 km/sec | ($V_p$ ≈ 4·1) km/sec |
| L ≈ 3 (3x$10^{-7}$ m/s | L ≈ 0·1 ($10^{-8}$ m/s) | (L ≈ 0·2) 2 x $10^{-8}$ m/s |
| M ≈ 7 GPa | M ≈ 22 GPa | (M ≈ 16) GPa |
| $P_r$ ≈14 tnf/$m^2$ | Pr ≈ 4·5 tnf/$m^2$ | ($P_r$ ≈ 6·1) tnf/$m^2$ |
| Δ ≈ 33 mm | Δ ≈ 0·9 mm | (Δ ≈ 2·3) mm |

| *Without pre-grouting* | *With pre-grouting* | *(alternative)* |
|---|---|---|
| B 1·5 m/sec | B 2·4 m c/c | B 2·1 m c/c |
| S (fr) 12 cm | S (fr) 4 cm | S (fr) 5 cm |

SOME OF THE EMPIRICAL EQUATIONS RELATING Q-value and rock mass property estimates

$$Q_c = Q \times \sigma_c / 100$$

$$(\text{km/s})\ V_p \approx \log Q_c + 3.5 \quad (+\text{depth effect})$$

$$(\text{GPa})\ E_{mass} \approx 10\, Q_c^{1/3} \quad (+\text{depth})$$

$$SIGMA_{cm} = 5\gamma\, Q_c^{1/3}\ (\text{MPa})$$

$$P_r \approx 0.1\, Q^{-1/3} \approx \frac{10^{-3}}{E_{mass}}\ (\text{MPa})$$

$$L \approx 1/Q_c$$

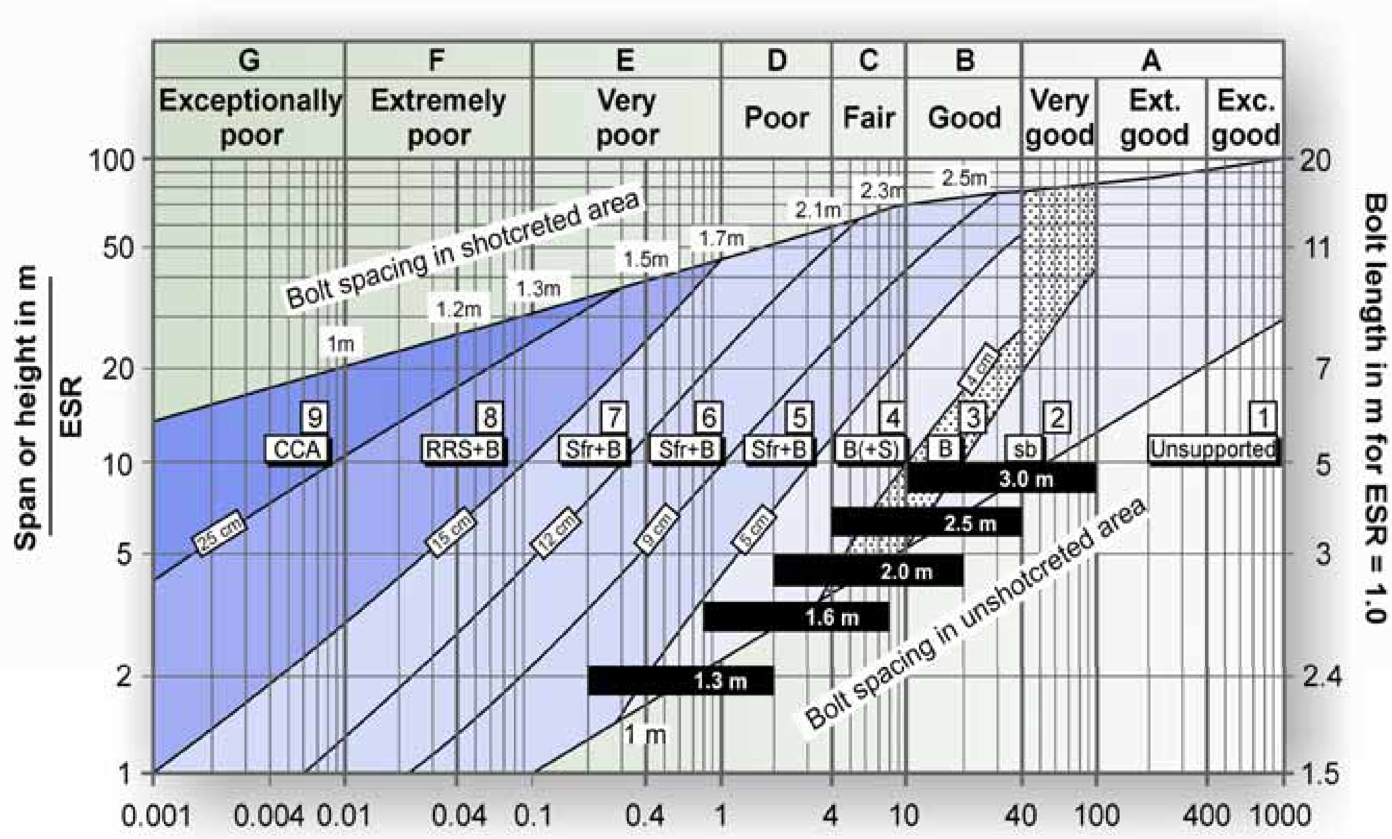
$$K \approx 10^{-7} \times L\ (\text{m/s})$$

$$\Delta_{mm} \approx SPAN(m)/Q$$

$$FC = \tan^{-1}\left(J_r/J_a \times J_w\right)^{\circ}$$

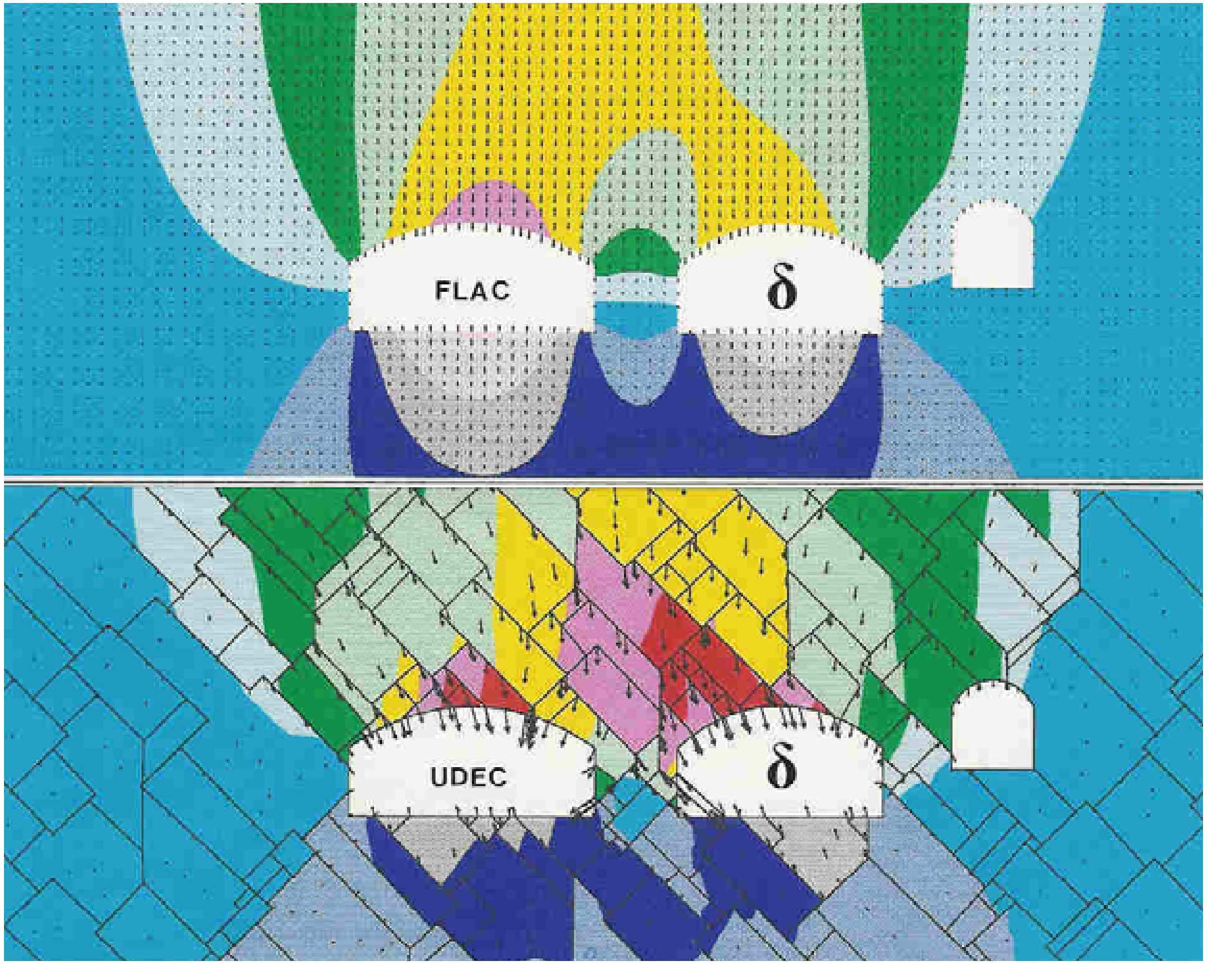
$$CC = RQD/J_n \times 1/SRF \times \sigma_c/100\ \text{MPa}$$

# HERE WE SEE THE POTENTIAL FOR REDUCED TUNNEL SUPPORT ……. IF THE EFFECTIVE Q-VALUE CAN BE IMPROVED

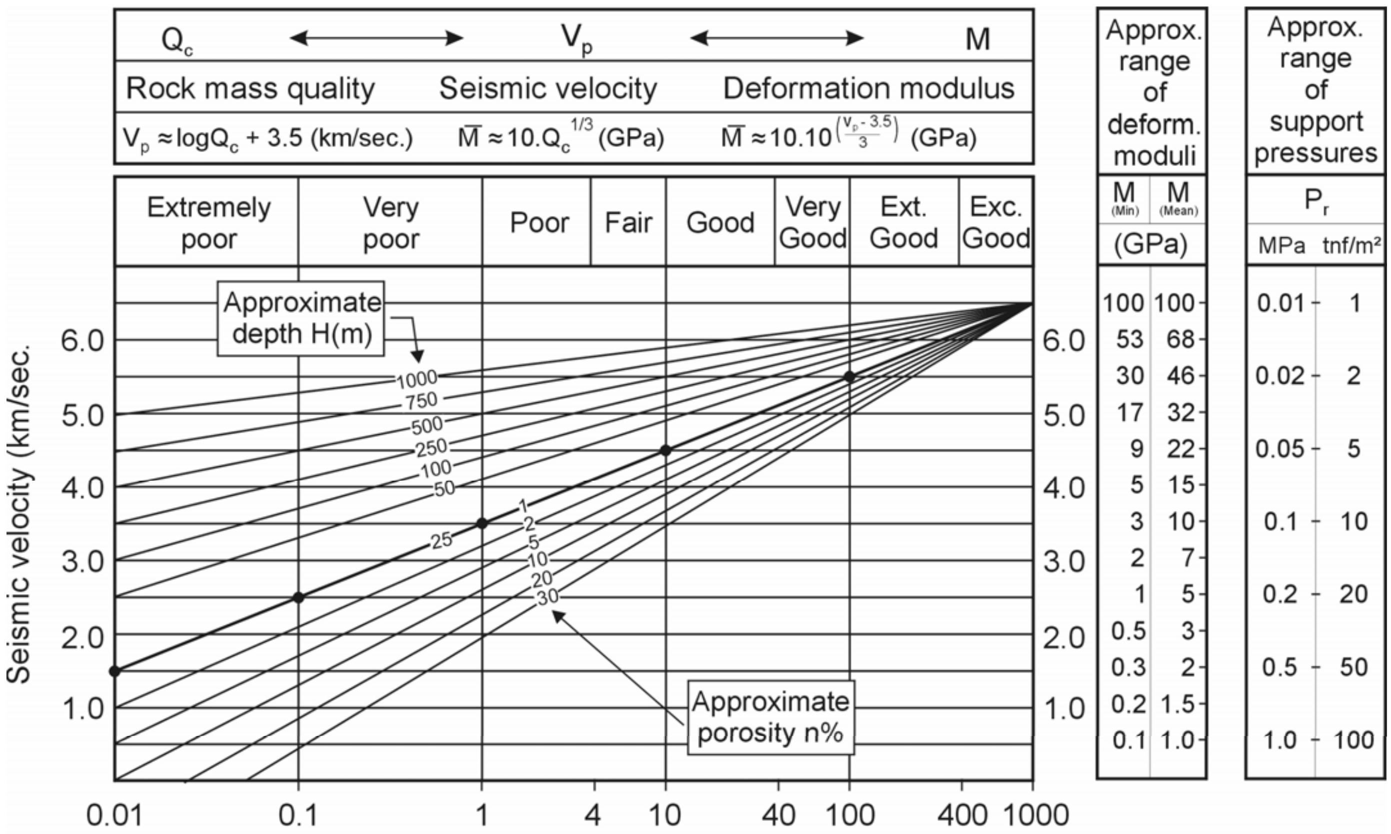



Rock mass quality $Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$

# REDUCED TUNNEL DEFORMATION…. WOULD ALSO BE SEEN IN MODELS



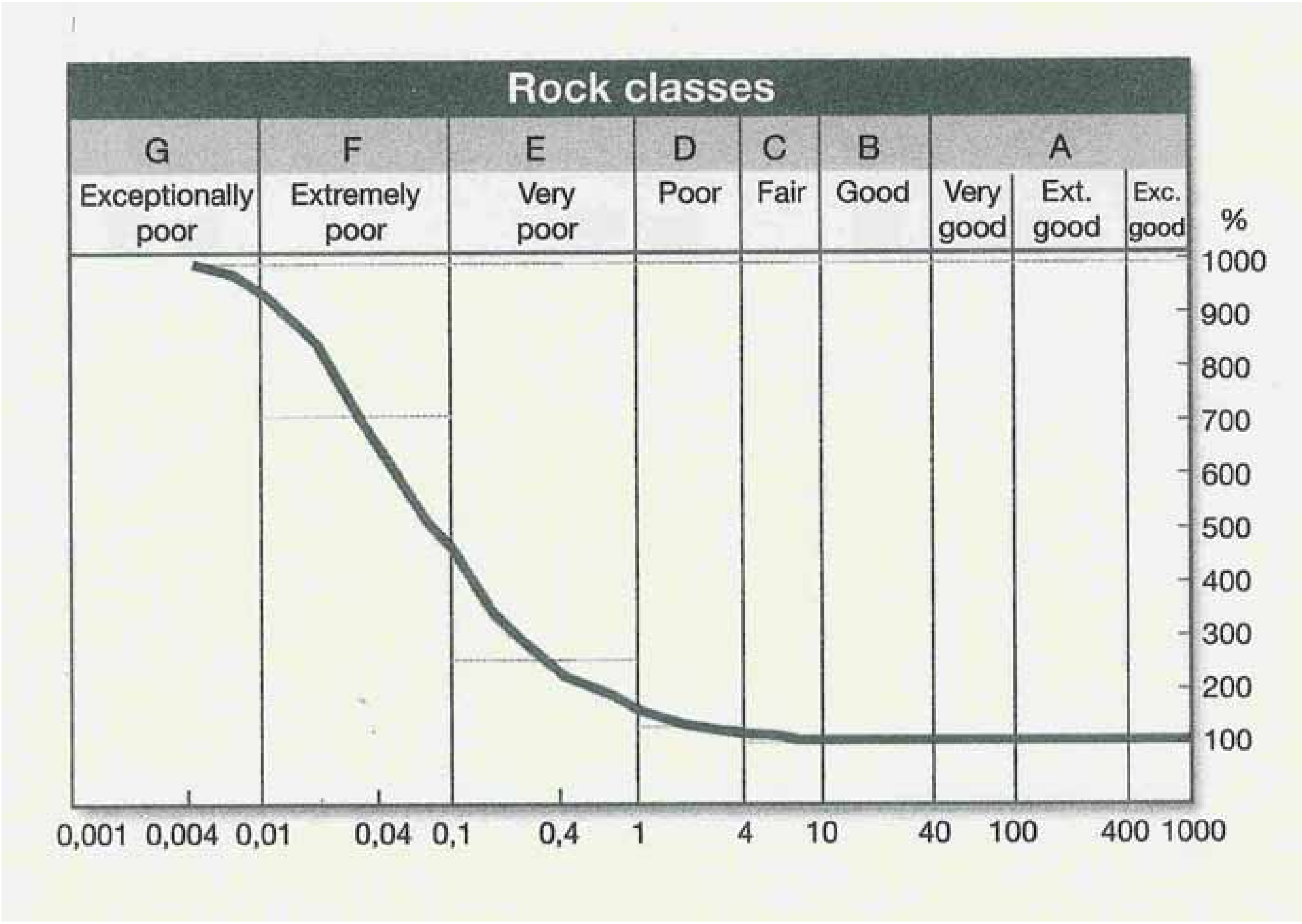
# IF Q-VALUES CAN BE IMPROVED…… SO TOO WILL SEISMIC VELOCITY…… AND MODULUS OF DEFORMATION…… AND SUPPORT PRESSURE NEEDS




$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}\right] \frac{\sigma_c}{100}$$

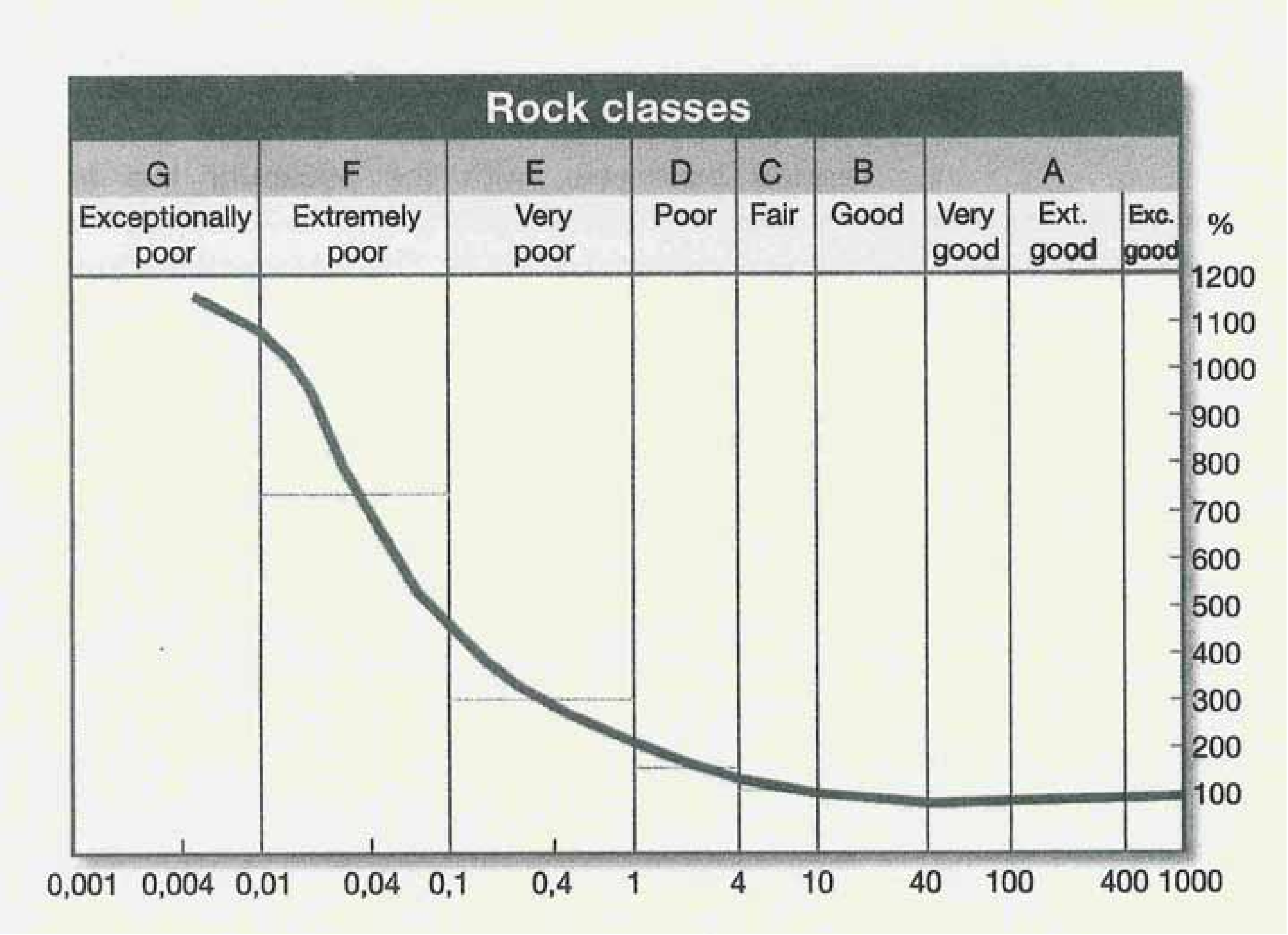
# RELATIVE ***TIME*** FOR TUNNEL EXCAVATION AND SUPPORT

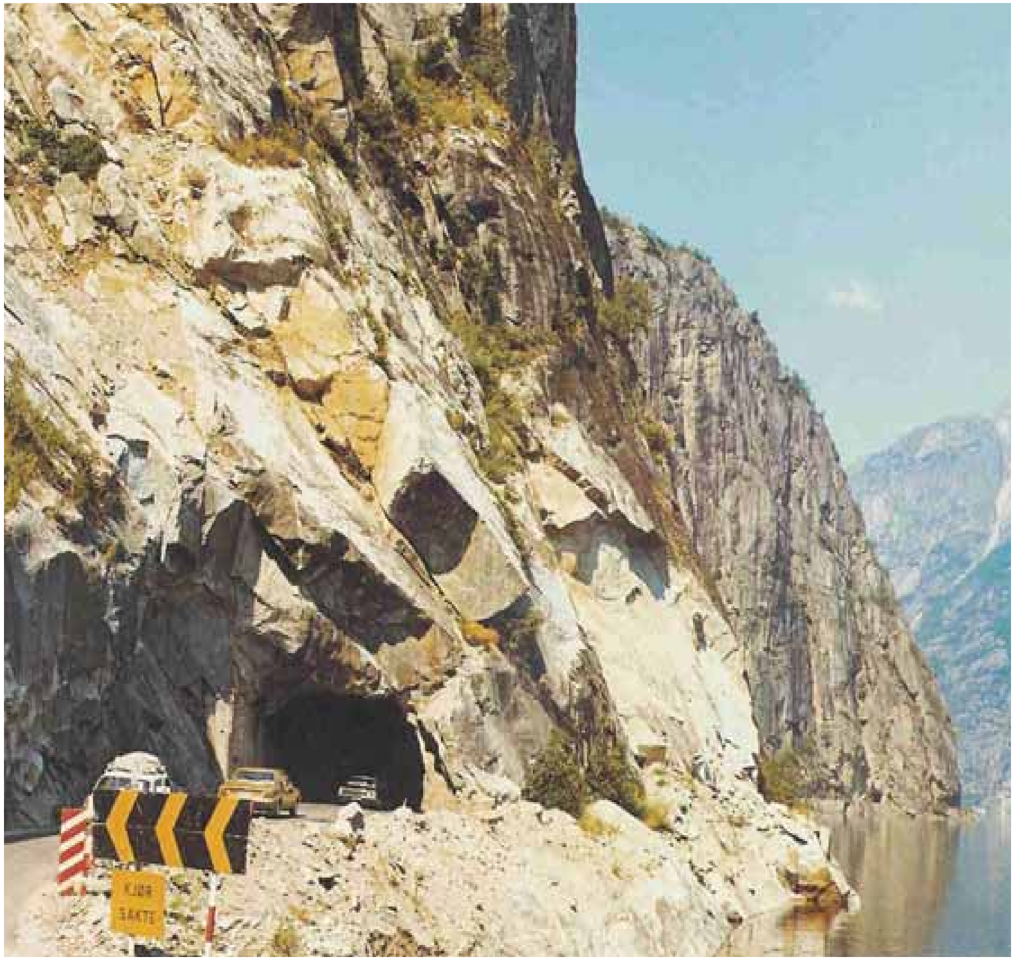
………potential benefits of pre-grouting, especially if $Q \approx 0.1$



RELATIVE ***COST*** FOR TUNNEL EXCAVATION AND SUPPORT

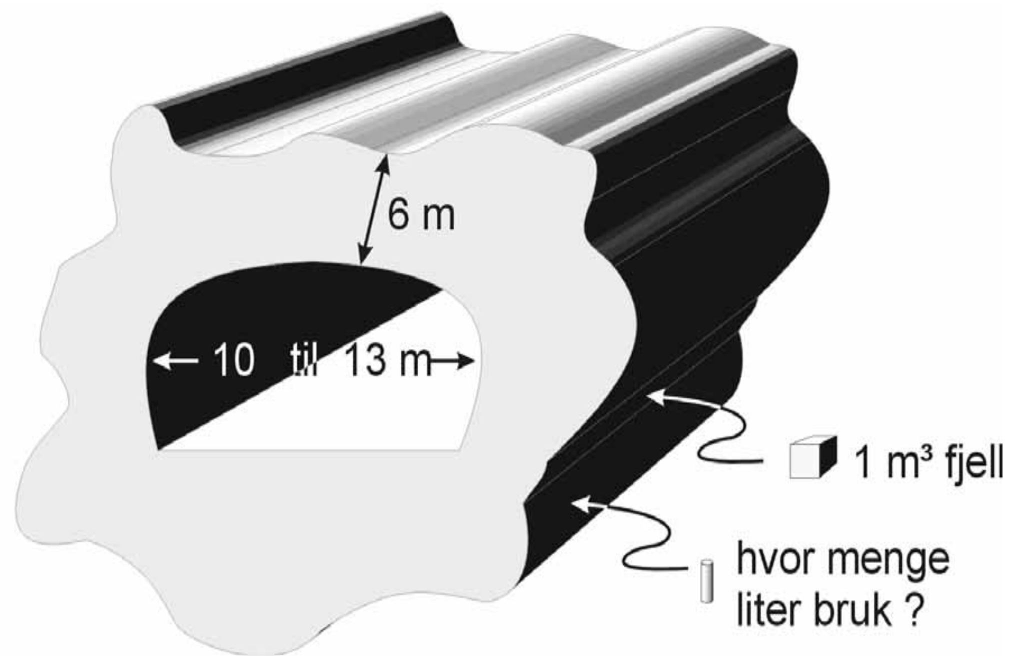
………potential benefits of pre-grouting, especially if Q ≈ 0.1





Take care if cover (depth to surface ) is limited !

One of nature's examples of 'pre-injection' (i.e. hydrothermal fluids…. calcite)




*How many litres of grout per m³ of rock mass? …… with 6m cylinder assumption usually 1 to 5 liters/m³.*