Rock Mechanics & Experiment
암석역학 및 실험

Lecture 6. Fractures – geometrical and mechanical properties/Fractured rock
Lecture 6. 균열의 기하학적 및 역학적 성질/균열암반

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Outline
Geometrical and mechanical behavior of fractures

- Fractures (Discontinuities)
- Geometrical properties of fractures
    - Orientation
    - Spacing (and frequency)
    - Rock Quality Designation (RQD)
    - Persistence, Roughness and Aperture
- Mechanical properties of fractures
    - Normal and shear stiffness
    - Strength

Geometrical properties

- Fractures (Discontinuities)

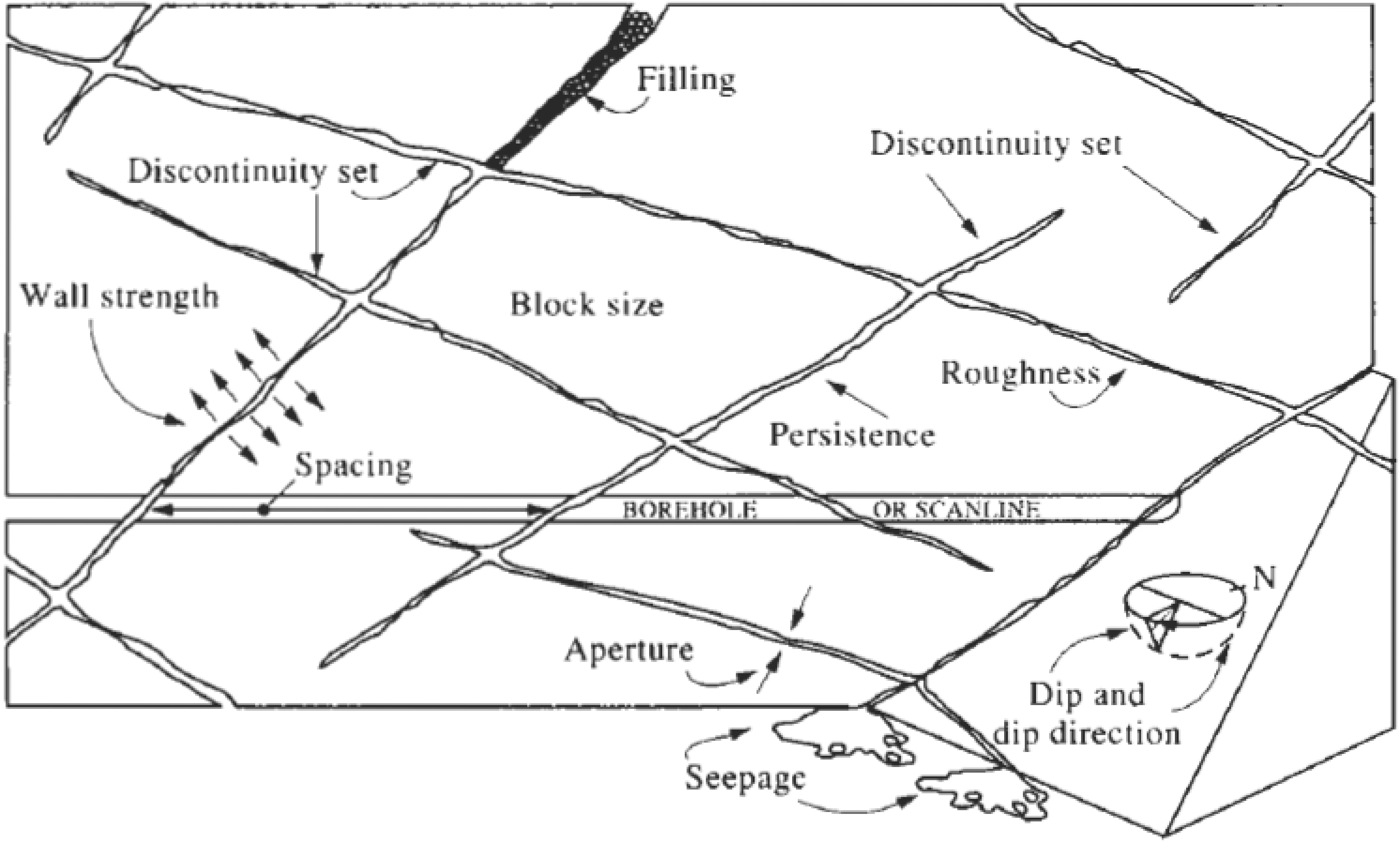
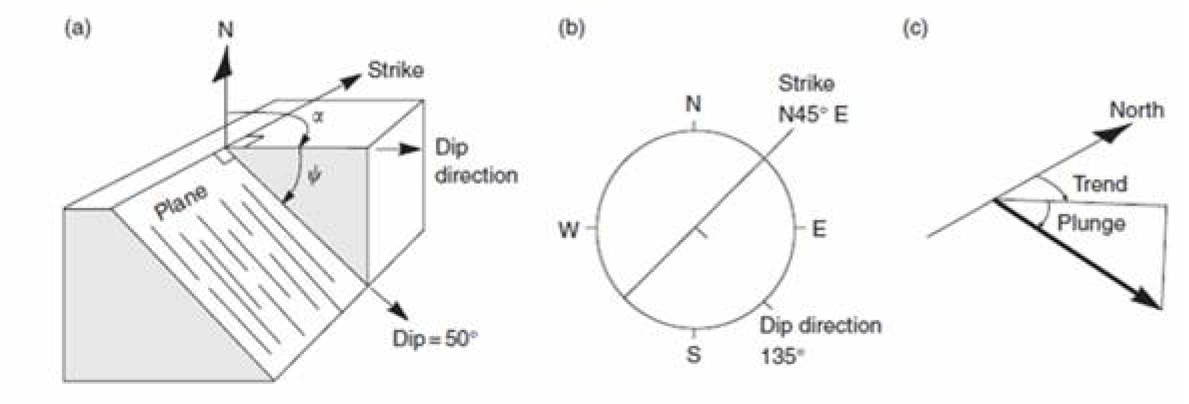


Figure 7.3 Schematic of the primary geometrical properties of discontinuities in rock (from Hudson, 1989).

Geometrical properties
Orientation - definition

- Plane
  - Dip (경사) & Dip direction (경사각)
    - Dip angle: angle between the steepest line and horizontal plane
    - Dip direction: bearing of this steepest line measured from North (clockwise)
    - Ex) 130/50 (dip direction/dip)
  - Or Dip & Strike (주향)
    - Ex) strike N40E, dip 50SE
- Line
  - Trend & Plunge



Geometrical properties
Orientation – hemispherical projection

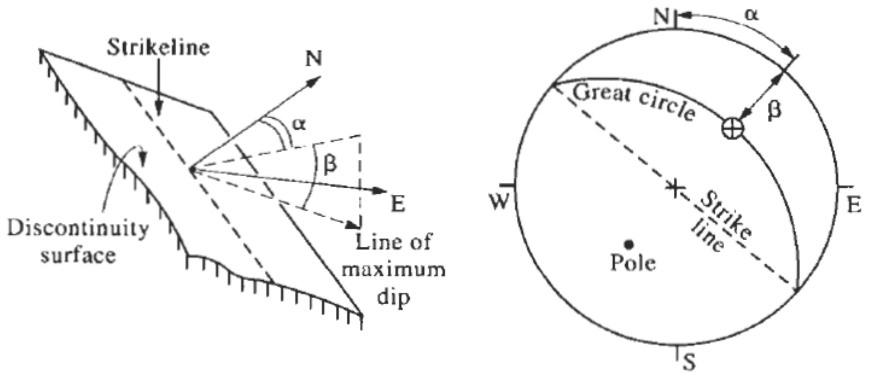
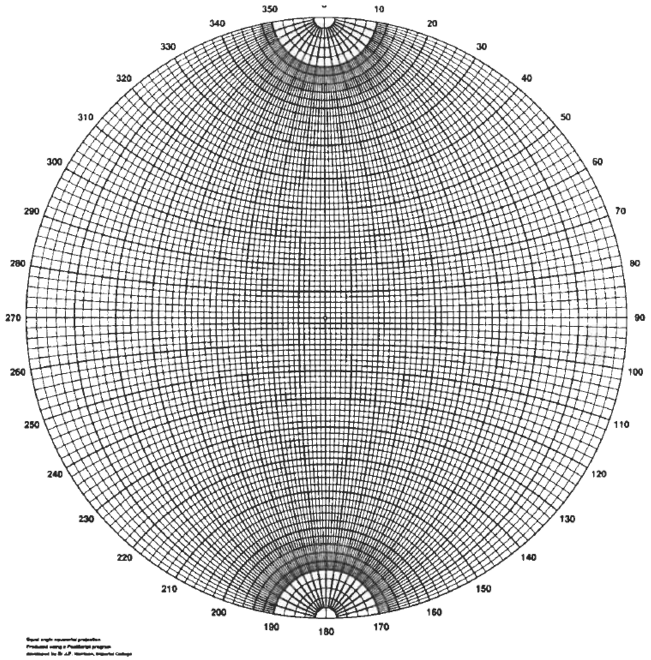
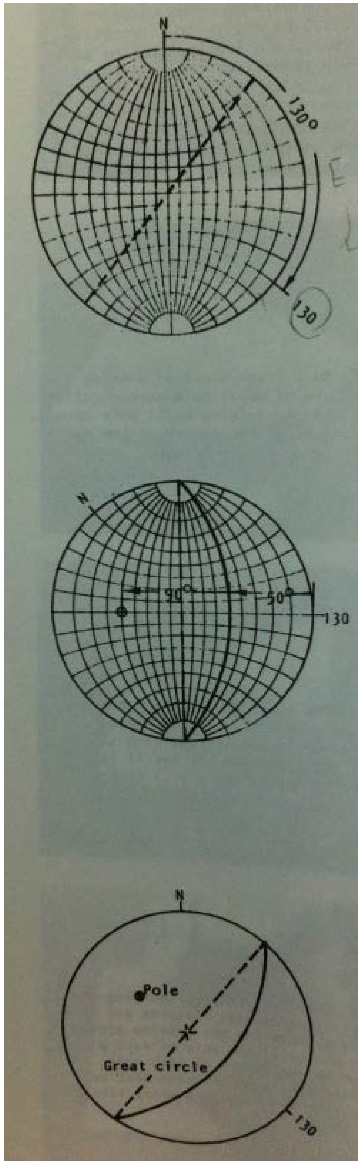


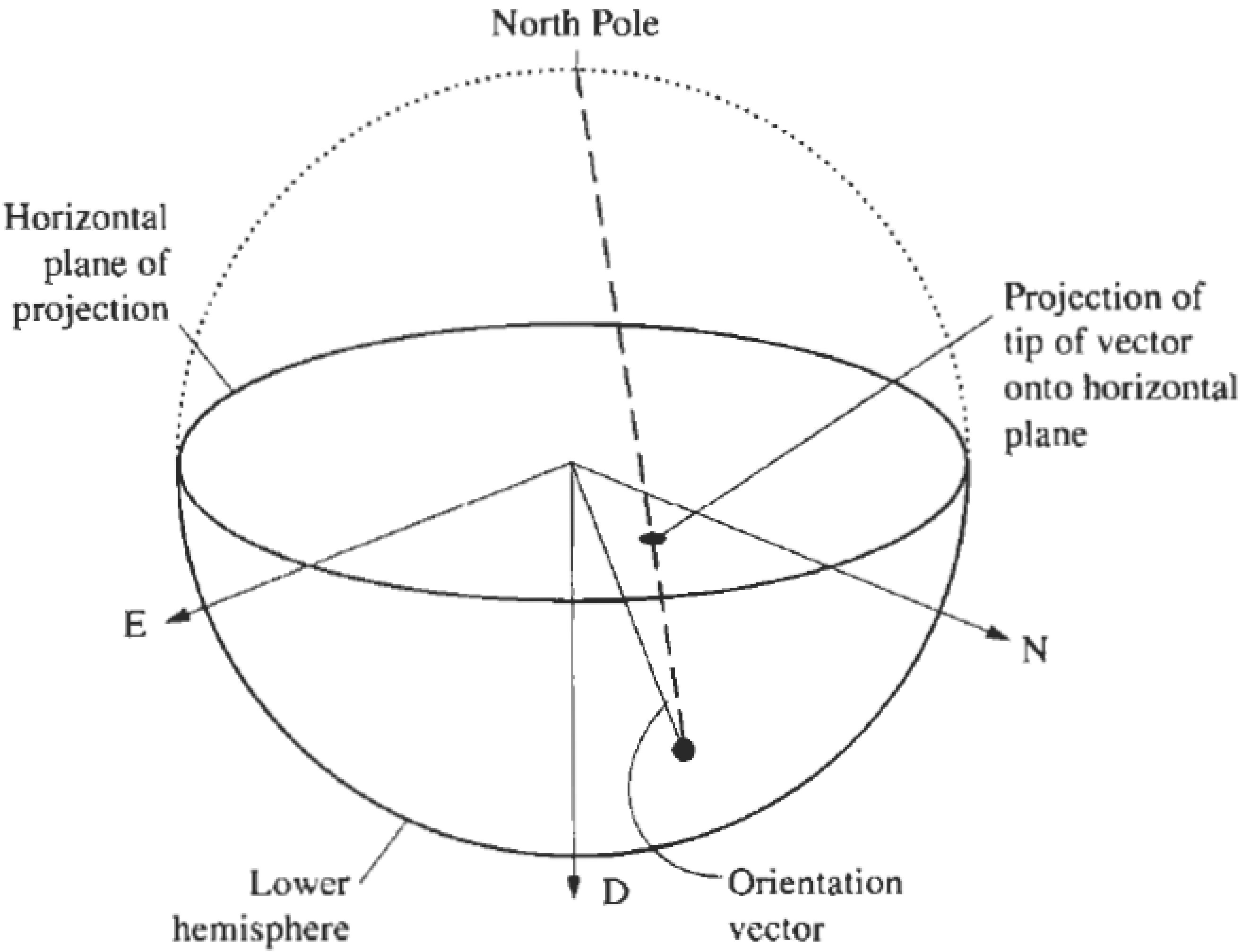
Figure 7.12 Discontinuity plane and the associated hemispherical projection.



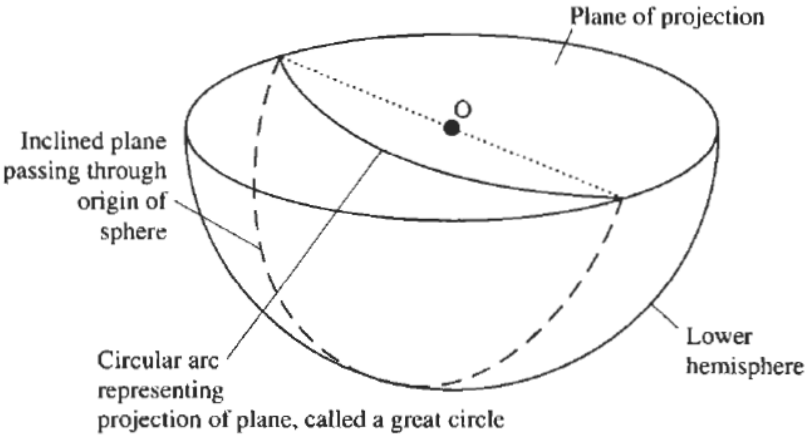


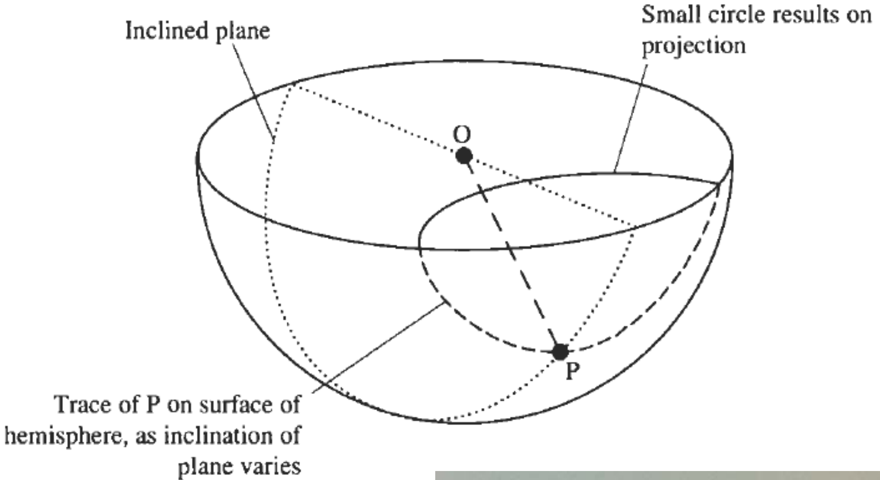
130/50의 예

Hemispherical projection
projection of a line onto two dimensions

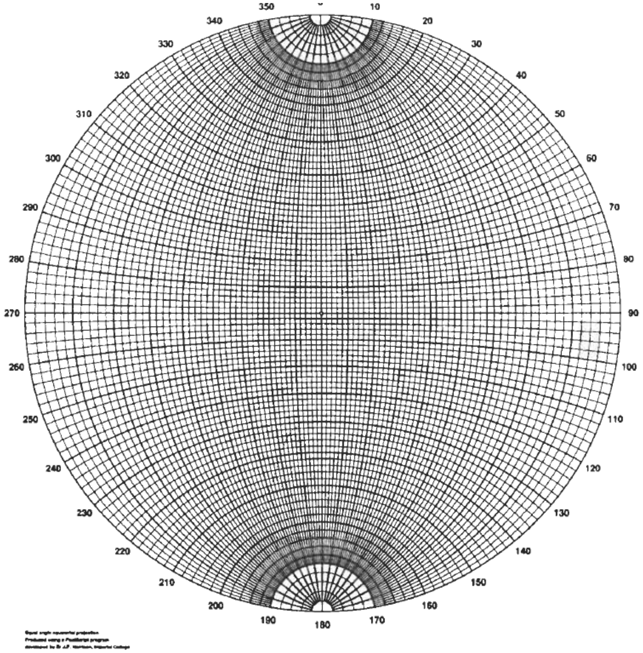


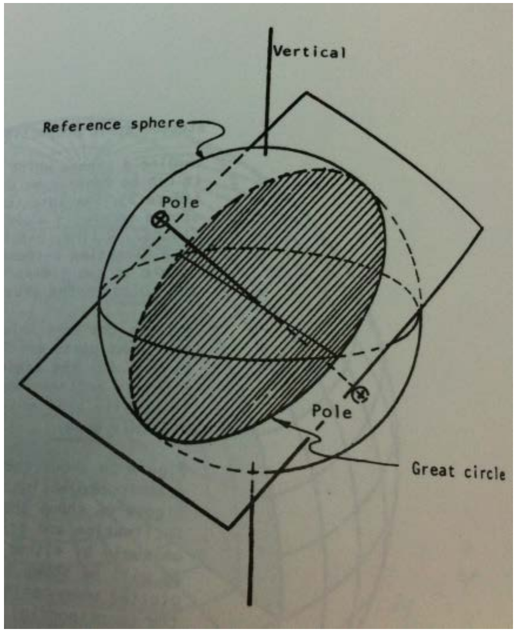
Hemispherical projection
projection of a plane: great circles & small circles





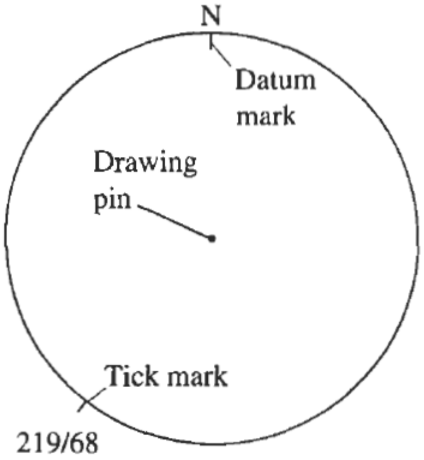
Hemispherical projection net
(반구투영망)





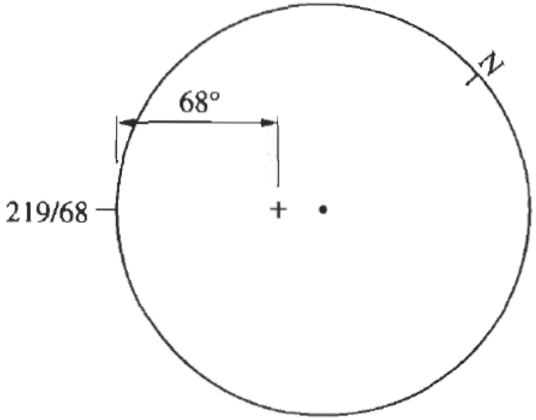
Hemispherical projection
plotting vectors

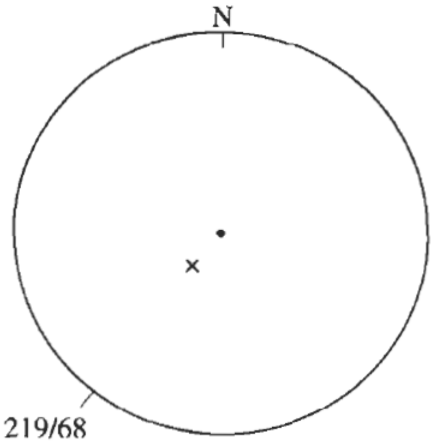
- Trend/plunge: 219/68



Mark, with a tick on the perimeter of the net at the correct azimuth, the vector to be plotted. Write on the projection the orientation. **Only write on the tracing paper, not the net.**

Rotate the tracing paper so that the tick is on the E–W line. Count in an amount equal to the dip of the vector. Mark the position of the vector. **Only write on the tracing paper, not the net.**



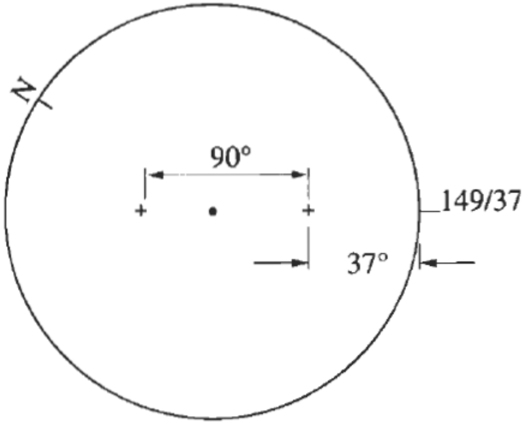


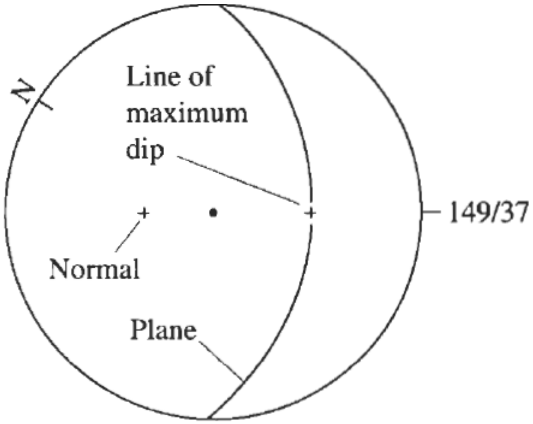
Rotate the tracing paper back to the datum: the position of the vector is now correct relative to north.

Hemispherical projection
plotting planes

- Dip direction/dip 149/37

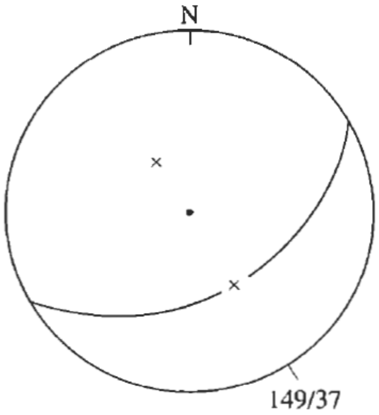
Rotate the tracing paper so that the tick lies on the E–W line, and count in an amount equal to the dip amount of the plane. Count a further 90° along the E–W line, and mark this new position.





Trace the great circle that passes over the first point: this represents **the plane**. The second point represents **the normal to the plane** (i.e. the vector that is perpendicular to the plane). The first point represents the **line of maximum dip**; the second point is termed the **pole**.

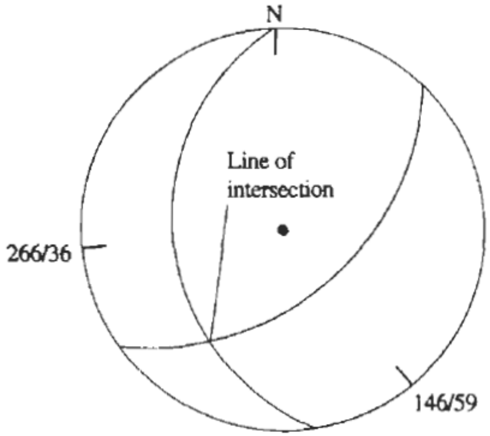
Rotate the tracing paper back to the datum: the positions of the plane and the normal are now correct relative to north.

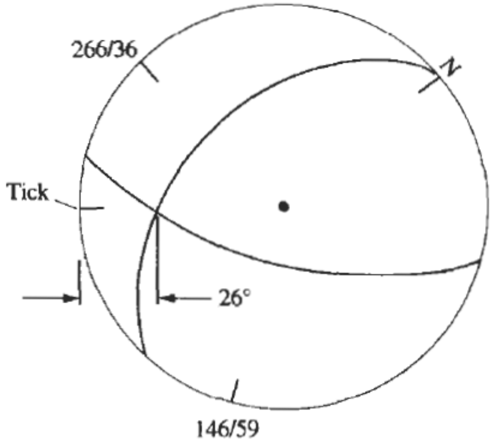


Hemispherical projection
Determining the line of two intersection of two planes

- 266/39 & 146/59

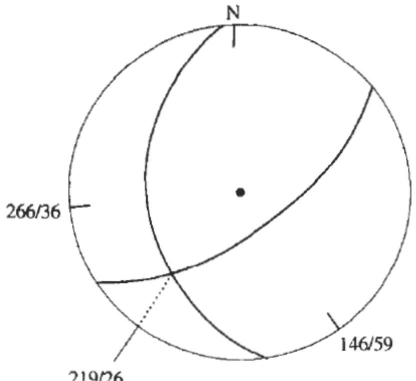
For any pair of planes, there is a line of intersection: it is where the two great circles cross. Finding its orientation is easy.





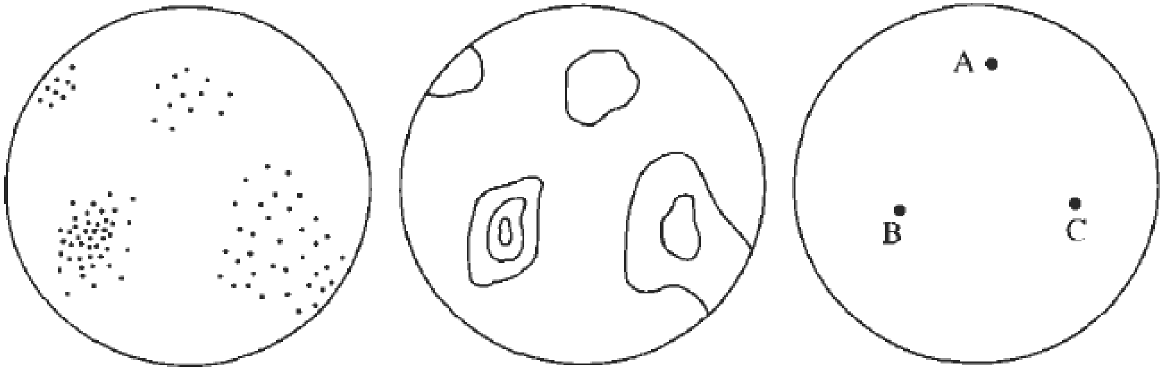
Rotate the tracing paper so that the intersection of the great circles lies on the E–W line. Mark the azimuth of this with a tick on the perimeter of the projection. Measure the plunge of the line by counting in from the perimeter, along the E–W line.

Rotate the tracing paper back to the datum, and measure the azimuth of the intersection. Thus we can see that the planes 266/36 and 146/59 have an intersection of 219/26. You should be able to measure graphically all such angles to the nearest degree.



Geometrical properties
Orientation

- Fracture sets
  - Fractures with similar orientations are identified as a ‘set’



(a) Raw data (b) Contoured data (c) Main discontinuity sets

Figure 7.13 Discontinuity orientation data plotted on the lower-hemispherical projection.

Geometrical properties
Spacing (frequency)

- Spacing
  - Distance between adjacent fracture intersections with the measuring scanline
- Frequency
  - Number of fractures per unit distance (reciprocal of spacing)
  - P_{10}: number of fracture per unit length of scan line
- Intensity
  - 2D, P_{21}: length of fracture traces per unit area of sampling surface
  - 3D, P_{32}: area of fractures per unit volume of rock mass

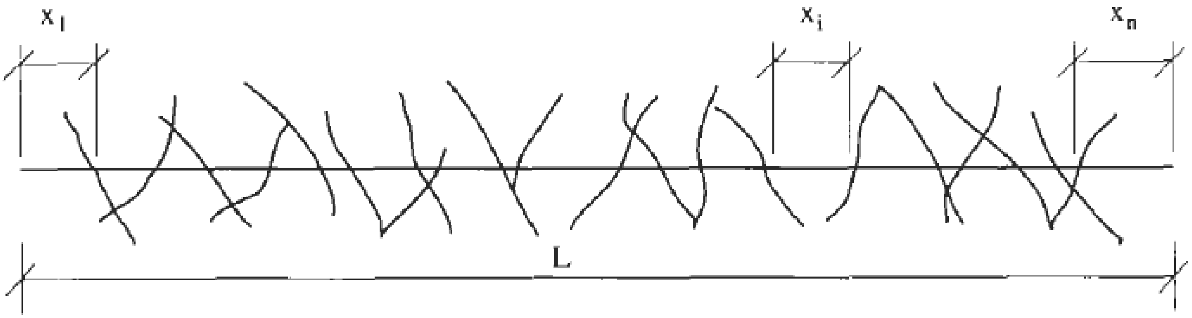


Figure 7.4 Quantifying discontinuity occurrence along a sampling line.

Geometrical properties
Spacing (frequency)

- Geological Survey

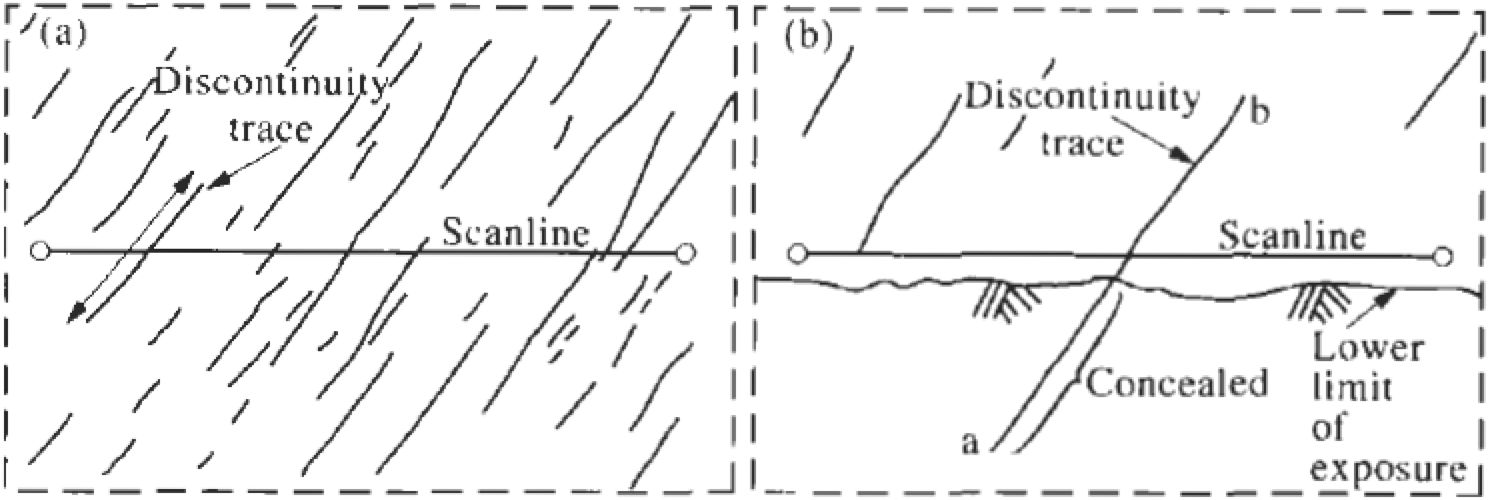


Figure 7.15 Diagrammatic representation of discontinuity traces intersecting a scanline set up on a rock face.

Geometrical properties
RQD

- Rock Quality Designation (RQD)
  - Percentage of the sampling line (cores) consisting of spacing values greater than 10 cm.

$$\mathrm{RQD} = 100 \sum_{i=1}^{n} \frac{x_i}{L} \%$$

where x_i = spacing values greater than 0.1 m, and n is the number of these intersected by a borehole core or scanline of length L.

Geometrical properties
Persistence, roughness and aperture

- Persistence (연속성)
  - Lateral extent of a discontinuity plane
  - Dimension (length, area) of fracture + connectivity
  - Dimension
    - Trace length
    - Area
- Aperture
  - The distance between adjacent walls of a discontinuity. Openness of the discontinuity
  - Important for hydraulic and mechanical behavior
  - Has distribution

Geometrical properties
Discrete Fracture Network (DFN)

- Measurement of Aperture
  - Direct measurement
    - Insertion of feeler gauge (steel with different thickness)
    - Impression packer
    - Borehole camera
  - Indirect measurement
    - Back calculation from the flow rates

$$Q = \frac{\rho_w g \overset{\text{unknown}}{\boxed{e^3}}}{12\mu}\frac{\partial h}{\partial x} \qquad e = \left(\frac{12\mu Q}{\rho_w g} / \frac{\partial h}{\partial x}\right)^{1/3}$$

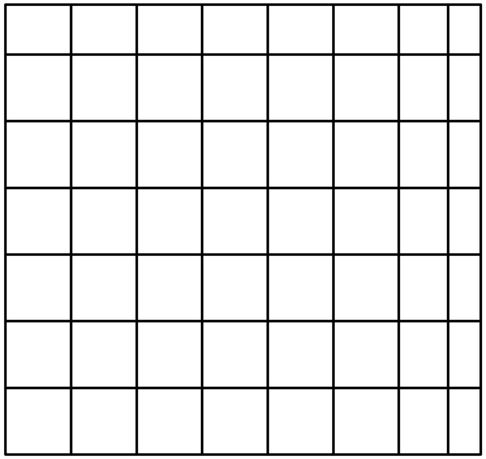
www.wikipedia.org

Geometrical properties
Discrete Fracture Network (DFN)

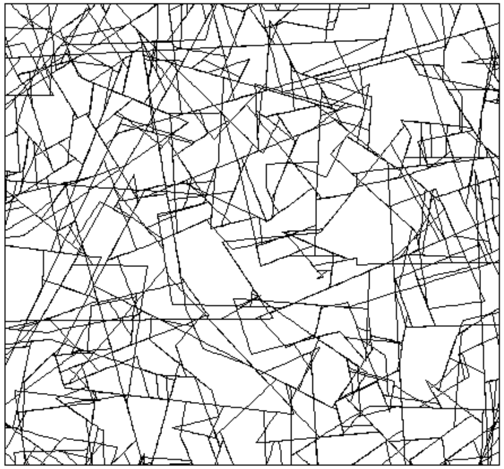
- Geometrical properties of fractures
  - Orientation (dip and dip direction), size (trace length in 2D), intensity (spacing in parallel infinite fracture), location, aperture, roughness
- Characterization method
  - Exposed rock faces
    - scanline sampling: line-based sample, use measuring tape (줄자).
    - Window sampling: area-based sample, rectangle of measuring tapes
  - Borehole sampling
- We then need to construct a geometric model of fractured rock – deterministic or stochastic generation of fractures
  - Monte Carlo Simulation

Geometrical properties
Discrete Fracture Network (DFN)

- Geometrical models based on the characterisation



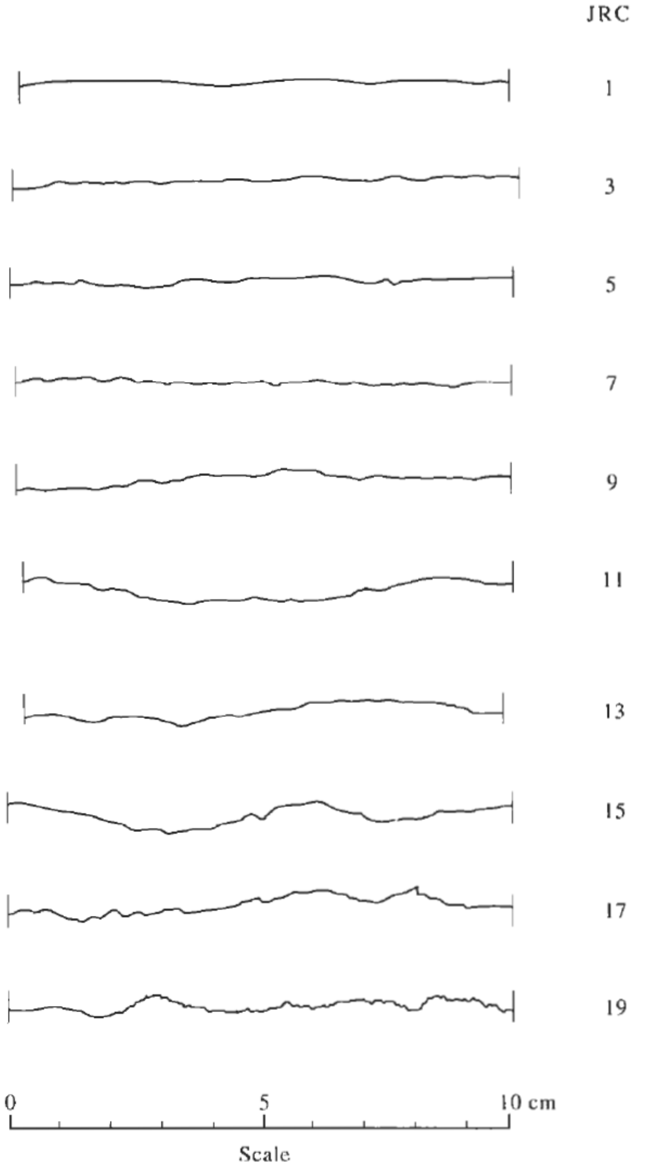
Idealized regular fracture model



Discrete Fracture Network
(암반균열망)

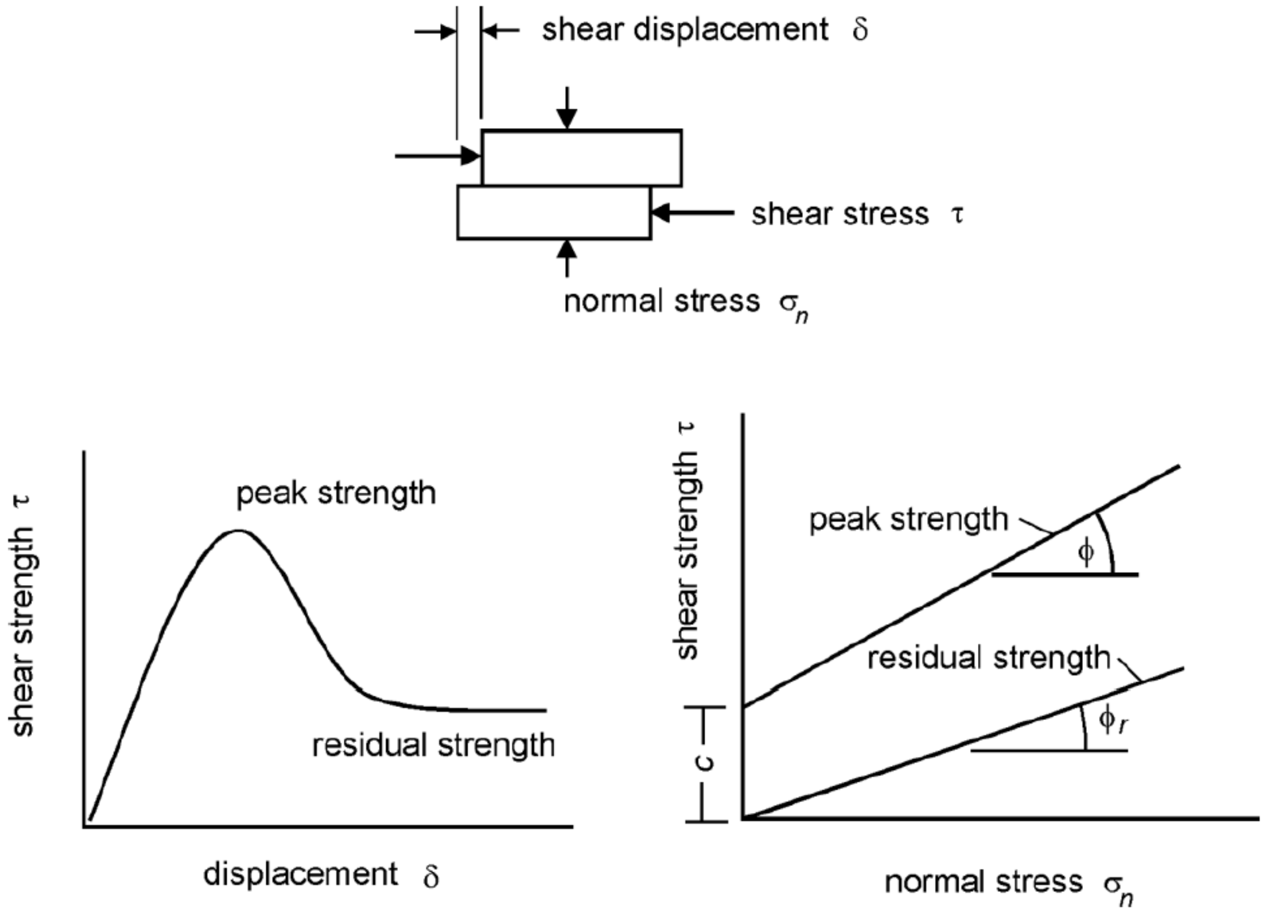
Geometrical properties
Persistence, roughness and aperture

- Roughness (거칠기)
  - Deviation of a discontinuity surface from perfect planarity
- Joint Roughness Coefficient (JRC)
  - Compare the profiles of discontinuity surface with standard roughness profile and assign numerical values.
  - Developed by Nick Barton (1977)
  - Not robust way but practically very important for mechanical and hydraulic properties of fractures



Mechanical properties

- Shear testing of fractures

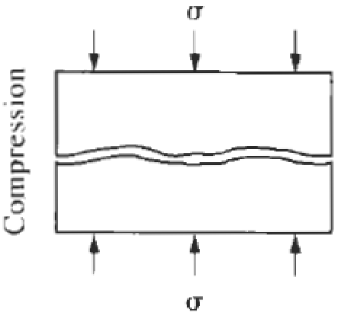


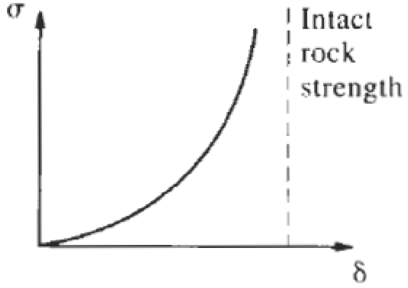
Hoek E, 2007, Practical Rock Engineering, ,https://www.rocscience.com/learning/hoek-s-corner/books

Mechanical properties
Stiffness

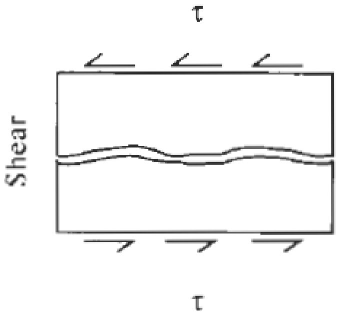
- Normal stiffness
  - Unit: Stress/length (MPa/m)
  - Linear model $\sigma_n = K_n \delta_n$
  - Non-linear model

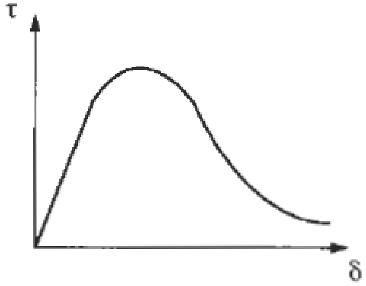
$$\delta_n = \frac{\sigma_n}{c + d\sigma_n}$$





- Shear stiffness
  - Unit: Stress/length (MPa/m)
  - Linear model $\sigma_s = K_s \delta_s$

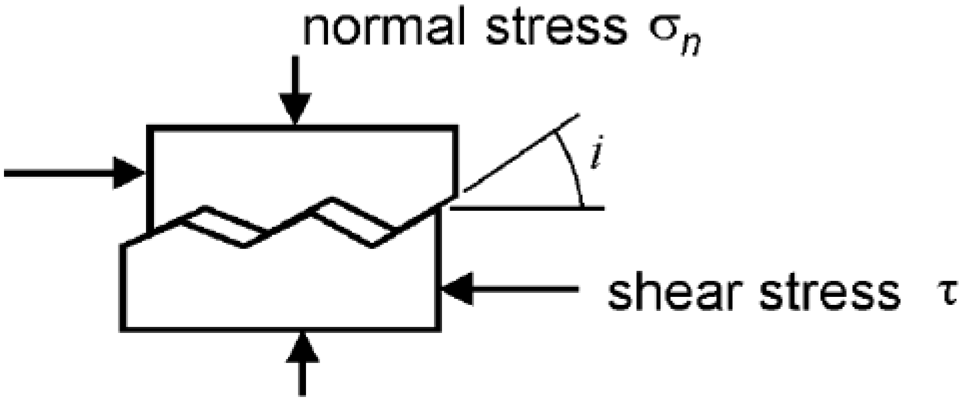


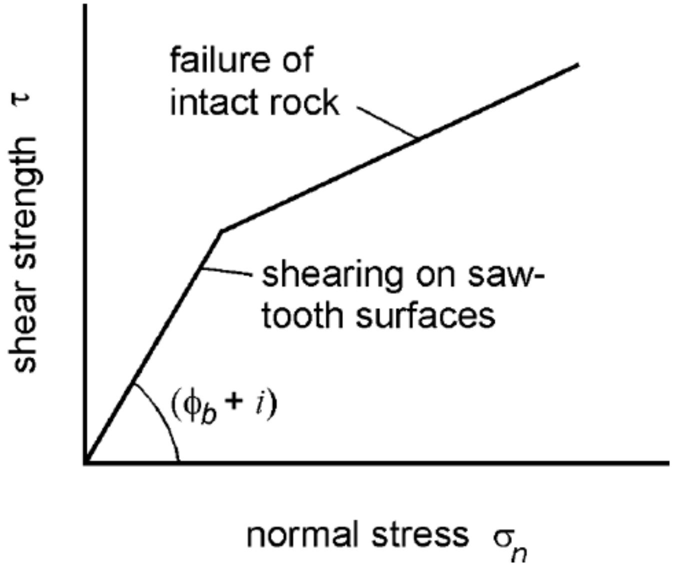


  - Non-linear model: e.g., Barton's equation (strength + full path)

Mechanical properties
Strength

- Patton's law (1966) for fracture friction angle





$$\tau = \sigma_n \tan(\phi_b + i)$$

where ϕ_b is the basic friction angle of the surface and
i is the angle of the saw-tooth face.

Hoek E, 2007, Practical Rock Engineering, ,https://www.rocscience.com/learning/hoek-s-corner/books

Mechanical properties
Strength

- Barton’s equation (1977)

$$\tau = \sigma_n \tan\left[JRC \log_{10}(JCS/\sigma_n) + \phi_r \right]$$

τ: Shear Strength of a fracture

JRC: Joint Roughness Coefficient

JCS : Joint Wall Compressive Strength

ϕ_r : residual friction angle

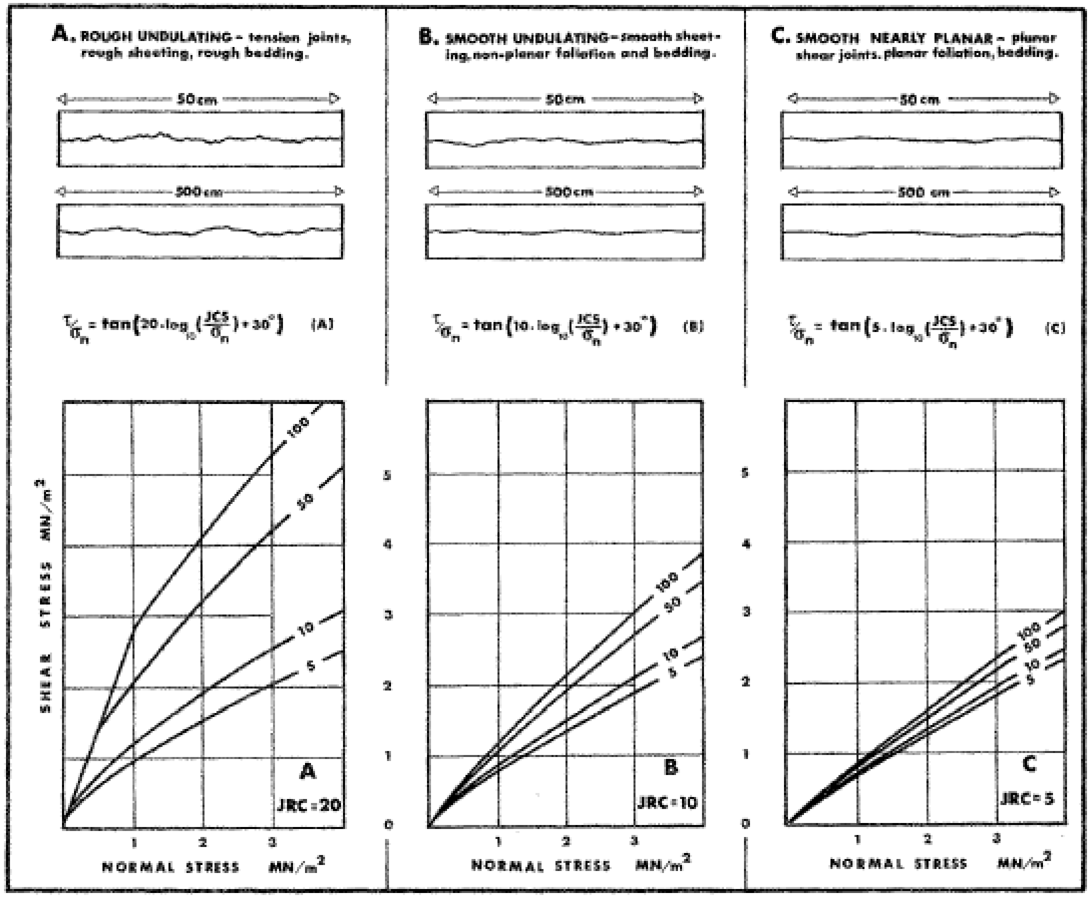


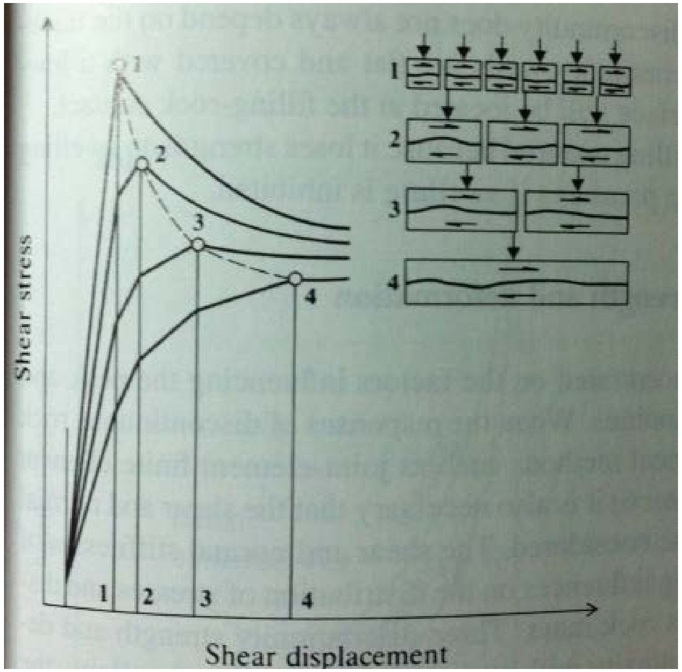
Fig. 1. Empirical law of friction in graphical form. Each curve is numbered with the appropriate *JCS* value (units of MN/m²). The roughness profiles are intended as an approximate guide to the appropriate *JRC* values 20, 10 and 5. Completely smooth planar joints have *JRC* = 0

Barton & Choubey, 1977, The shear strength of rock joints in theory and practice, *Rock Mech Rock Eng*, 10(1-2):1-54

Mechanical properties

Strength

- Size dependent behavior of a fracture



$$JRC_n = JRC_o \left(\frac{L_n}{L_o} \right)^{-0.02 JRC_o} \qquad (8)$$

where JRC_o, and L_o (length) refer to 100 mm laboratory scale samples and JRC_n, and L_n refer to in situ block sizes.

Mechanical properties
Strength

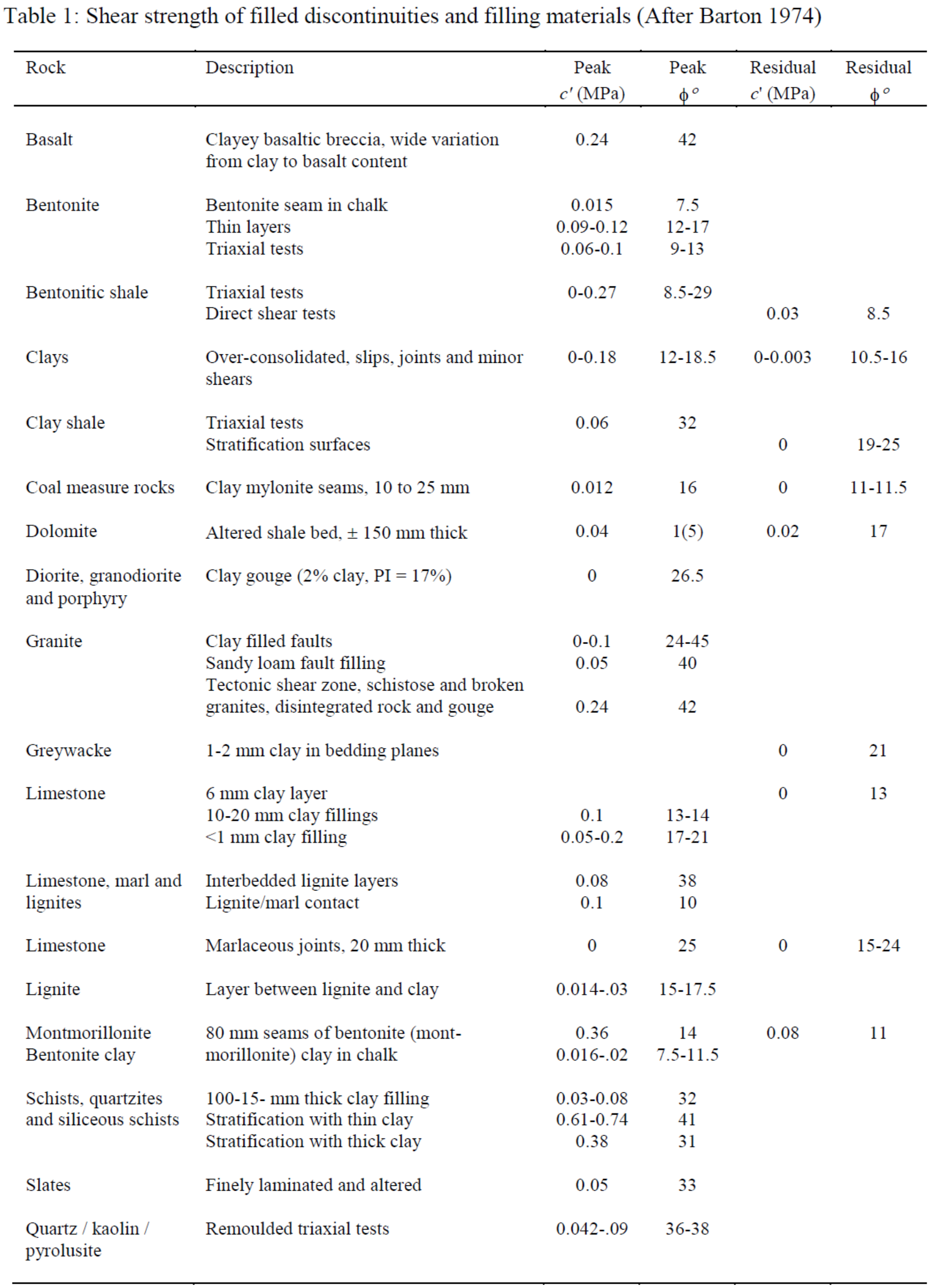


Table 1: Shear strength of filled discontinuities and filling materials (After Barton 1974)

Rock	Description	Peak c' (MPa)	Peak $\phi°$	Residual c' (MPa)	Residual $\phi°$
Basalt	Clayey basaltic breccia, wide variation from clay to basalt content	0.24	42		
Bentonite	Bentonite seam in chalk	0.015	7.5		
	Thin layers	0.09-0.12	12-17		
	Triaxial tests	0.06-0.1	9-13		
Bentonitic shale	Triaxial tests	0-0.27	8.5-29		
	Direct shear tests			0.03	8.5
Clays	Over-consolidated, slips, joints and minor shears	0-0.18	12-18.5	0-0.003	10.5-16
Clay shale	Triaxial tests	0.06	32		
	Stratification surfaces			0	19-25
Coal measure rocks	Clay mylonite seams, 10 to 25 mm	0.012	16	0	11-11.5
Dolomite	Altered shale bed, ± 150 mm thick	0.04	1(5)	0.02	17
Diorite, granodiorite and porphyry	Clay gouge (2% clay, PI = 17%)	0	26.5		
Granite	Clay filled faults	0-0.1	24-45		
	Sandy loam fault filling	0.05	40		
	Tectonic shear zone, schistose and broken granites, disintegrated rock and gouge	0.24	42		
Greywacke	1-2 mm clay in bedding planes			0	21
Limestone	6 mm clay layer			0	13
	10-20 mm clay fillings	0.1	13-14		
	<1 mm clay filling	0.05-0.2	17-21		
Limestone, marl and lignites	Interbedded lignite layers	0.08	38		
	Lignite/marl contact	0.1	10		
Limestone	Marlaceous joints, 20 mm thick	0	25	0	15-24
Lignite	Layer between lignite and clay	0.014-.03	15-17.5		
Montmorillonite	80 mm seams of bentonite (montmorillonite) clay in chalk	0.36	14	0.08	11
Bentonite clay		0.016-.02	7.5-11.5		
Schists, quartzites and siliceous schists	100-15- mm thick clay filling	0.03-0.08	32		
	Stratification with thin clay	0.61-0.74	41		
	Stratification with thick clay	0.38	31		
Slates	Finely laminated and altered	0.05	33		
Quartz / kaolin / pyrolusite	Remoulded triaxial tests	0.042-.09	36-38		

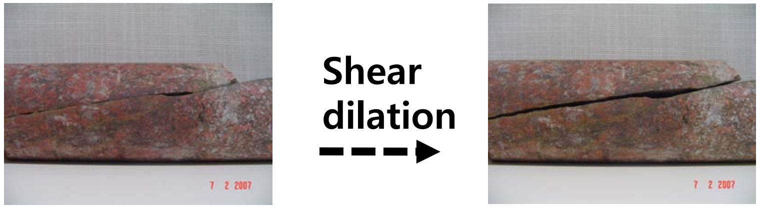
Hoek E, 2007, Practical Rock Engineering, ,https://www.rocscience.com/learning/hoek-s-corner/books

Mechanical properties
Strength - dilation

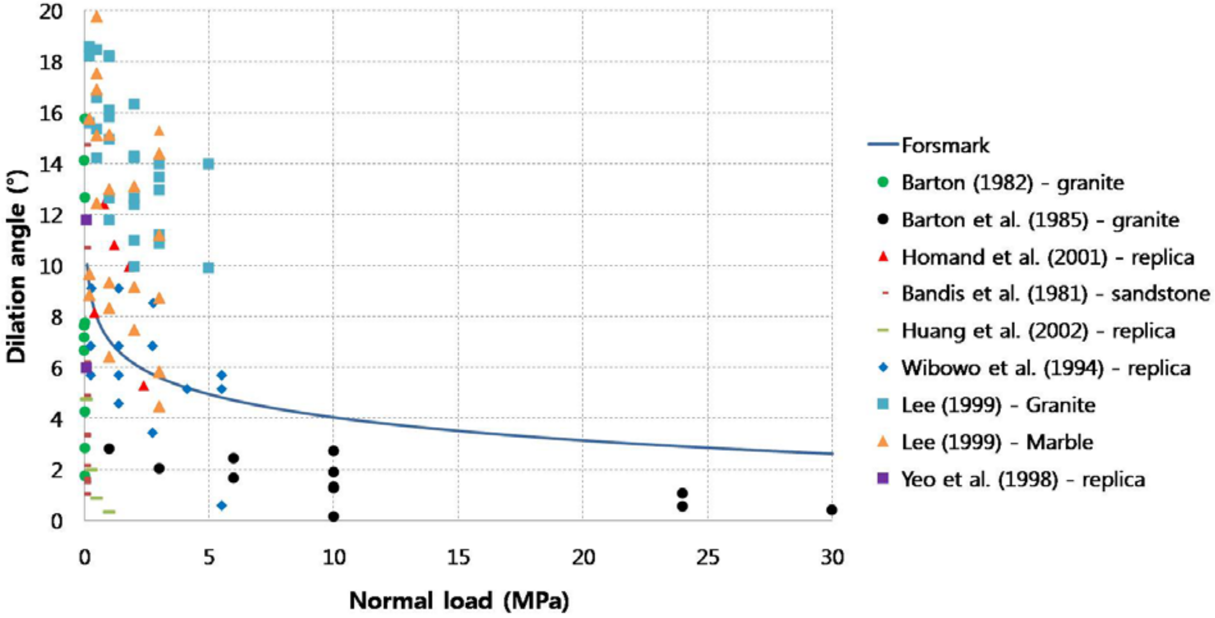
- Fracture dilation during fracture shearing
  - Great implication for geo-environmental engineering

$$\phi_{dilation} = \tan^{-1}\left(\frac{\text{normal dilation}}{\text{shear displacement}}\right)$$

$$\phi_{dilation} = \frac{1}{2} JRC \log\left(\frac{JCS}{\sigma_n}\right)$$



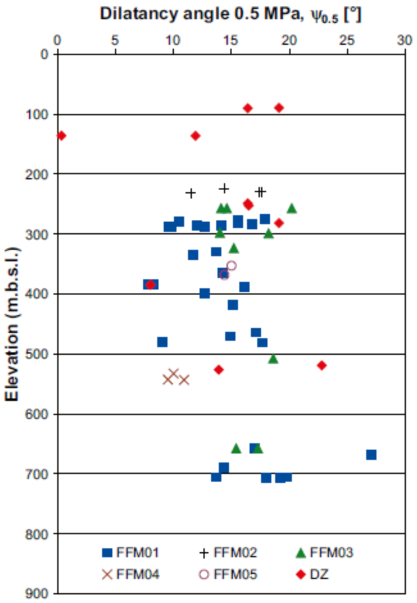
Shear dilation

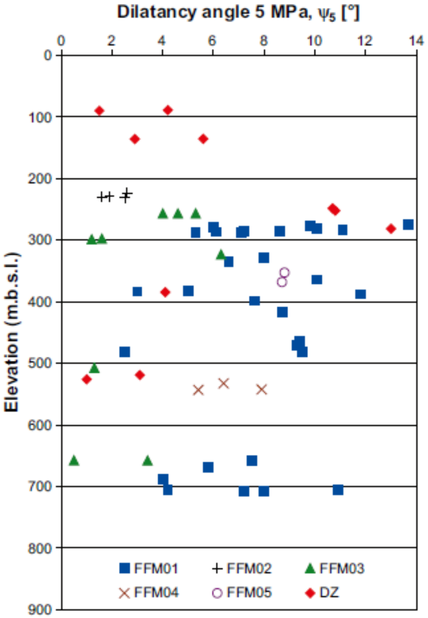


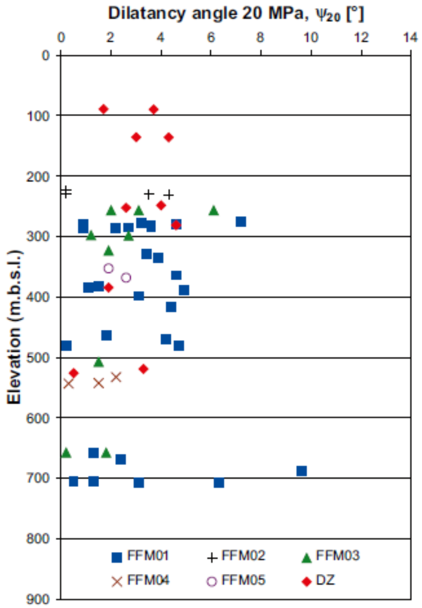
Mechanical properties
Strength-dilation

- Aperture change due to shear dilation (SKB, 2007)
  - 3.2° dilation angle under 20 MPa
  - Dilation angles from direct shear tests for the FFM01 fracture domain

Normal load (MPa)	Mean (°)	Std. dev. (°)	Minimum (°)	Maximum (°)	Uncertainty of mean (%)
0.5	14.6	4.1	7.8	27.1	±10.2
5	7.7	2.7	2.5	13.7	±12.8
20	3.2	2.1	0.2	9.6	±23.9

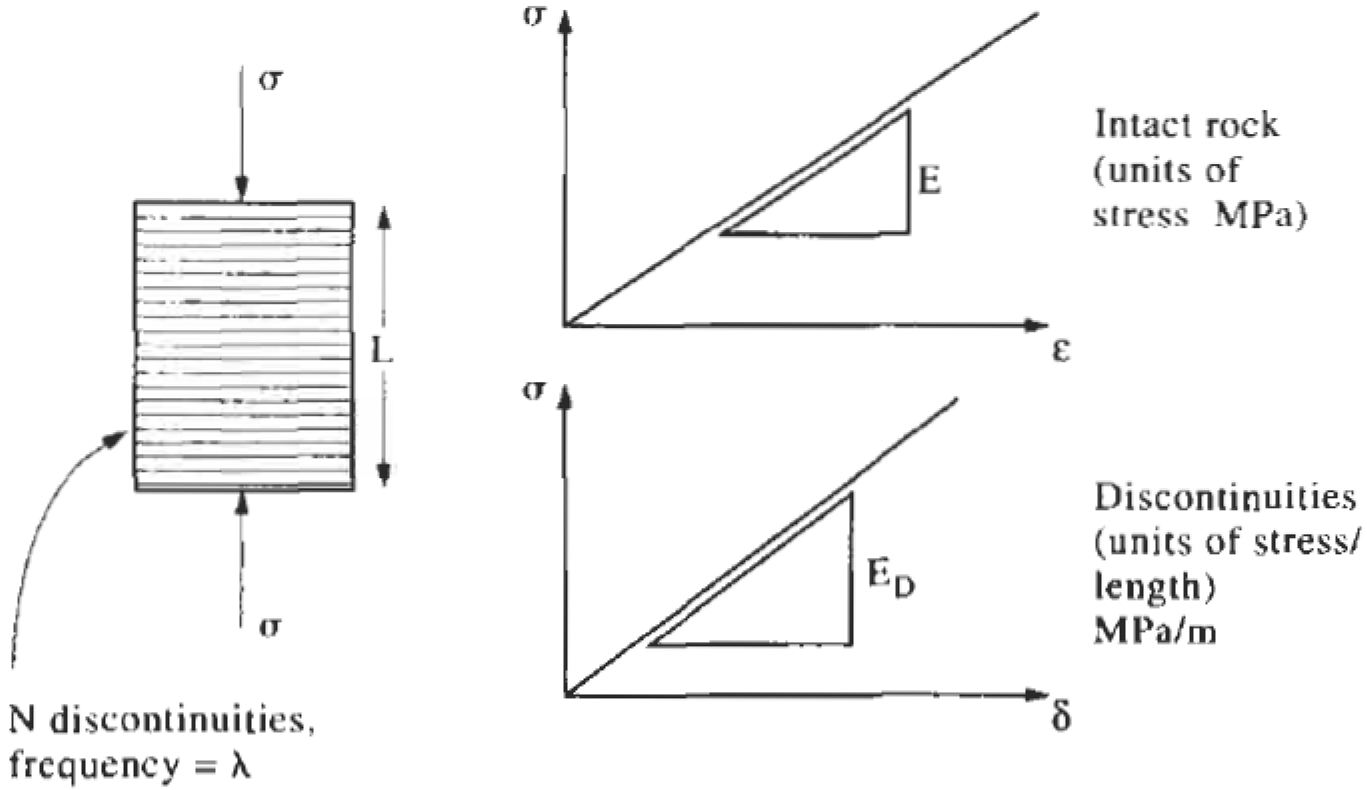






SKB R-7-31

Fractured Rock Masses
Elastic modulus (deformation modulus)



$\delta = 1/\lambda =$ spacing of fractures

Fractured Rock Masses
Elastic modulus (deformation modulus)

- Elastic (deformation) modulus of fractured rock mass

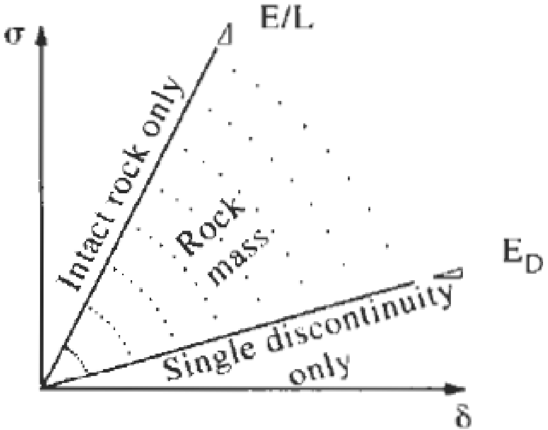
$$\frac{1}{E_m} = \left(\frac{1}{E_i} + \frac{1}{k_n \cdot S} \right)$$

$$\frac{1}{E_m} = \left(\frac{1}{E_i} + \frac{\lambda}{E_D} \right)$$

E_m : Elastic modulus of rock mass

k_n : normal stiffness of a fracture

S : spacing of fractures

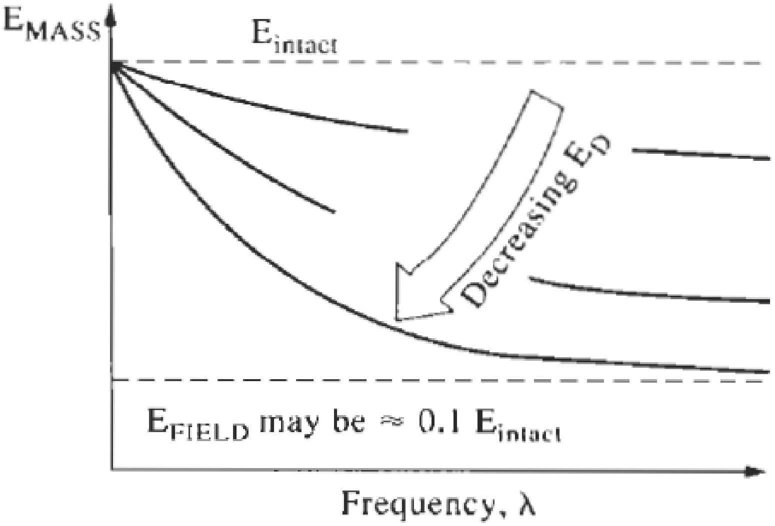


$$\frac{1}{G_m} = \left(\frac{1}{G_i} + \frac{1}{k_s \cdot S} \right)$$

G_m : Shear modulus of rock mass

k_s : shear stiffness of a fracture

S : spacing of fractures



Fractured Rock Masses
Elastic modulus (deformation modulus)

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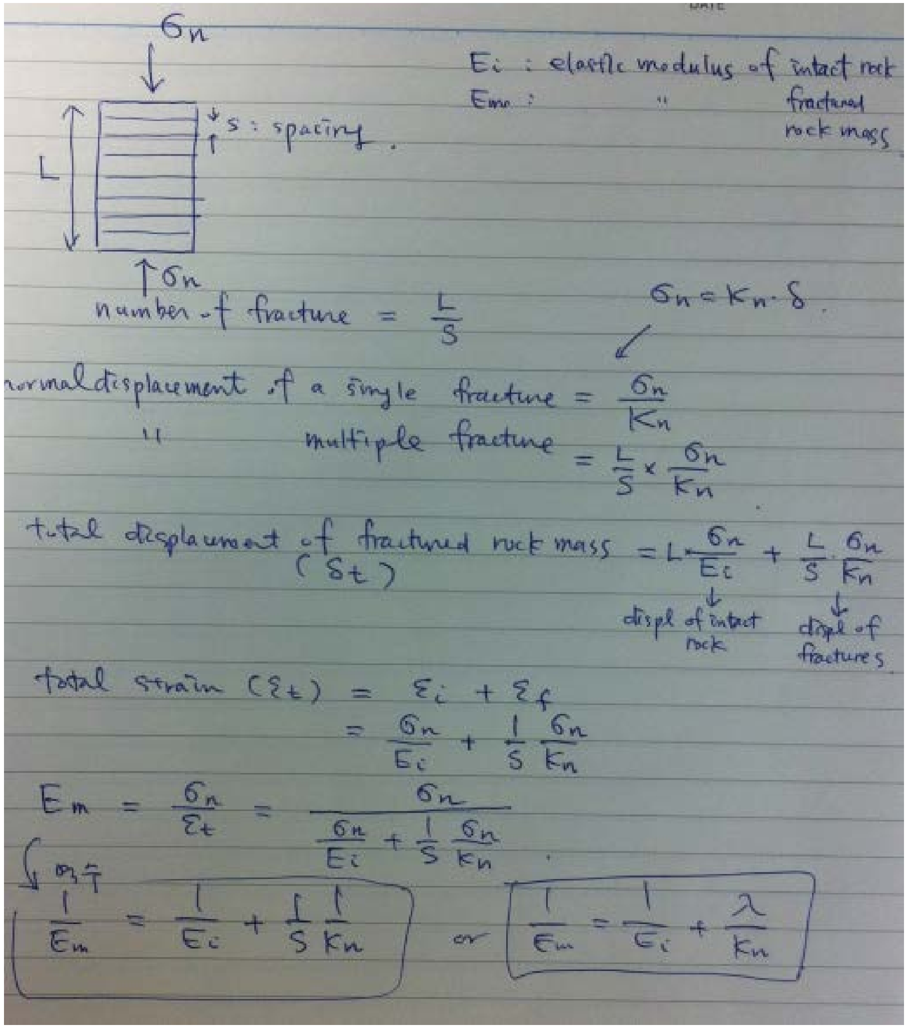
- Derivation



E_i : elastic modulus of intact rock
E_m : " fractured rock mass

number of fracture $= \frac{L}{S}$

$\sigma_n = K_n \cdot \delta$.

normal displacement of a single fracture $= \frac{\sigma_n}{K_n}$

" multiple fracture $= \frac{L}{S} \times \frac{\sigma_n}{K_n}$

total displacement of fractured rock mass (δ_t) $= L \cdot \frac{\sigma_n}{E_i} + \frac{L}{S} \cdot \frac{\sigma_n}{K_n}$

$\frac{\sigma_n}{E_i}$ → displ of intact rock

$\frac{L}{S} \cdot \frac{\sigma_n}{K_n}$ → displ of fractures

$$\text{total strain } (\varepsilon_t) = \varepsilon_i + \varepsilon_f = \frac{\sigma_n}{E_i} + \frac{1}{S}\frac{\sigma_n}{K_n}$$

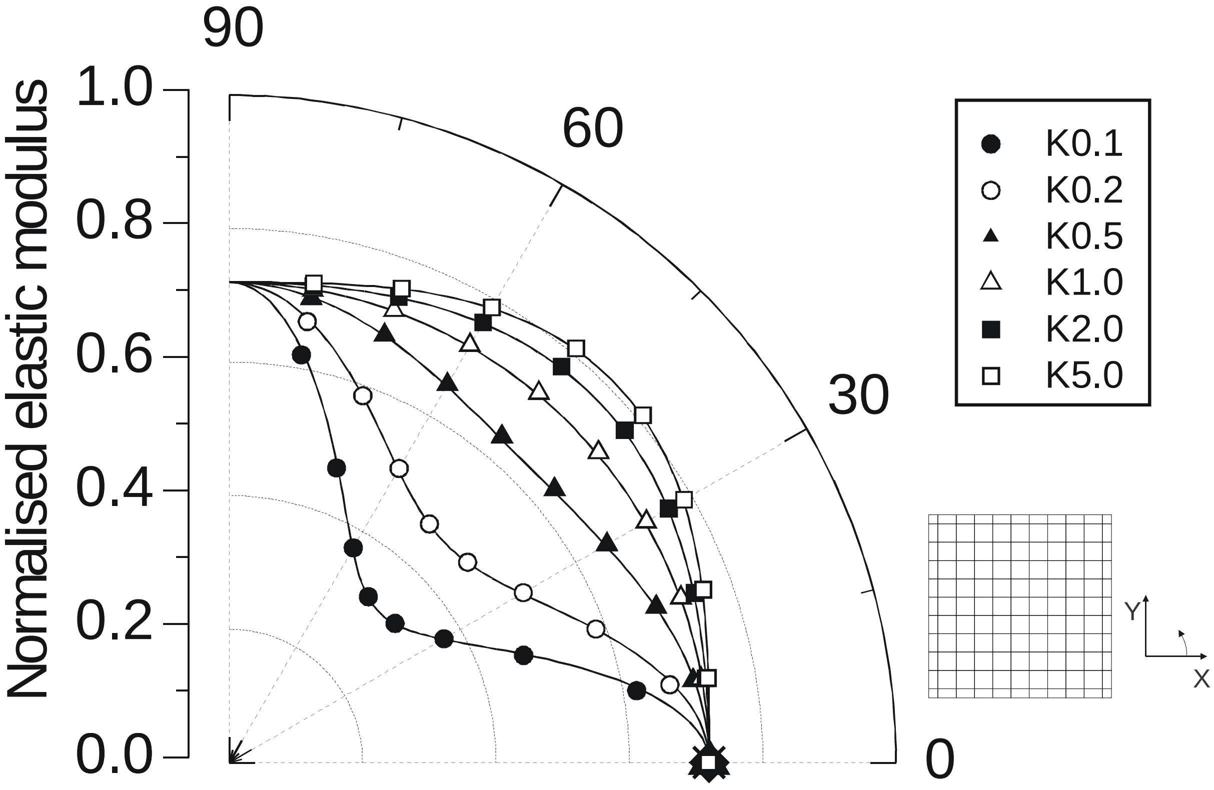
$$E_m = \frac{\sigma_n}{\varepsilon_t} = \frac{\sigma_n}{\frac{\sigma_n}{E_i} + \frac{1}{S}\frac{\sigma_n}{K_n}}.$$

역수

$$\boxed{\frac{1}{E_m} = \frac{1}{E_i} + \frac{1}{S}\frac{1}{K_n}} \quad \text{or} \quad \boxed{\frac{1}{E_m} = \frac{1}{E_i} + \frac{\lambda}{K_n}}$$

Fractured Rock Masses

Elastic modulus (deformation modulus) - anisotropy



Fractured Rock Masses
Data from Forsmark, Sweden

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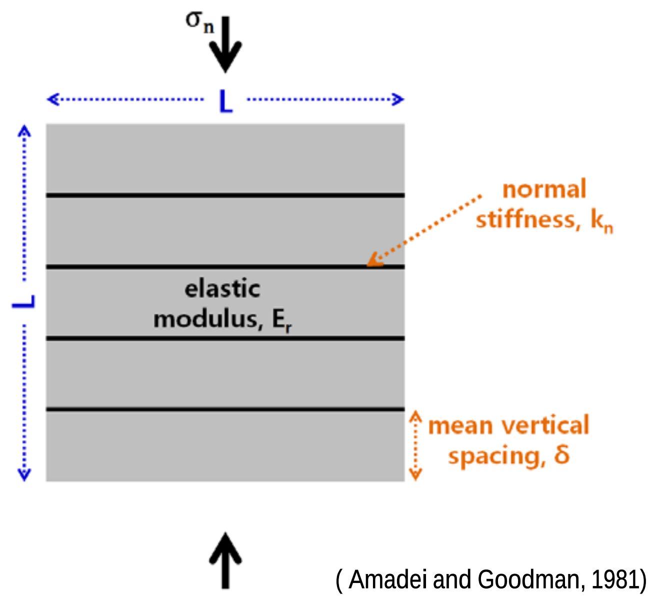
Equivalent Continuum Model



(Amadei and Goodman, 1981)

$$\frac{1}{E_e} = \left(\frac{1}{E_r} + \frac{1}{k_n \cdot S} \right), \qquad \frac{1}{G_e} = \left(\frac{1}{G_r} + \frac{1}{k_s \cdot S} \right)$$

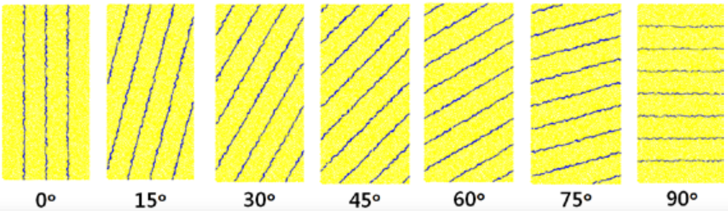
E_e , G_e : equivalent elastic & shear modulus,
E_r, G_r : intact rock elastic & shear modulus,
k_n , k_s : normal & shear stiffness on weak planes,
S : mean vertical spacing

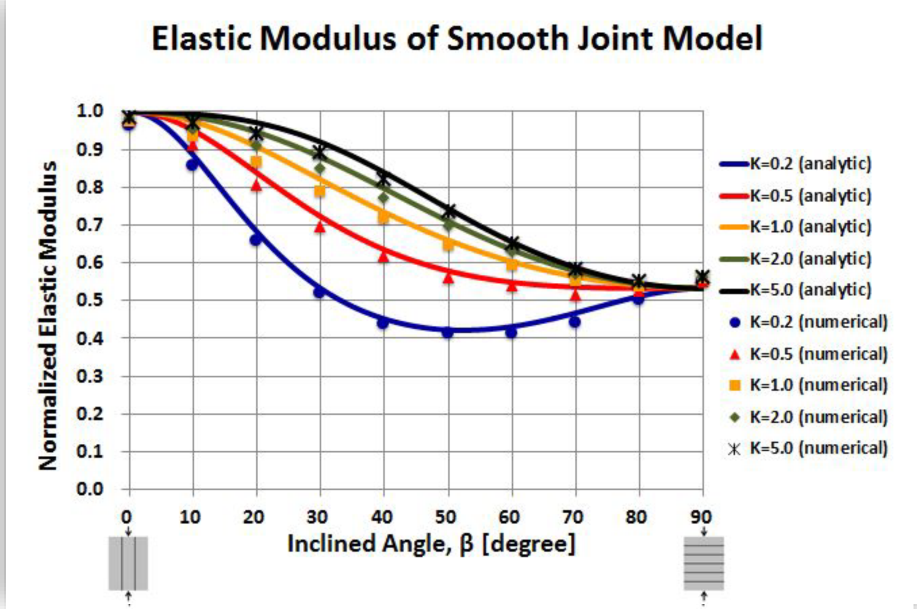
K :shear to normal stiffness ratio

Tensor Transformation

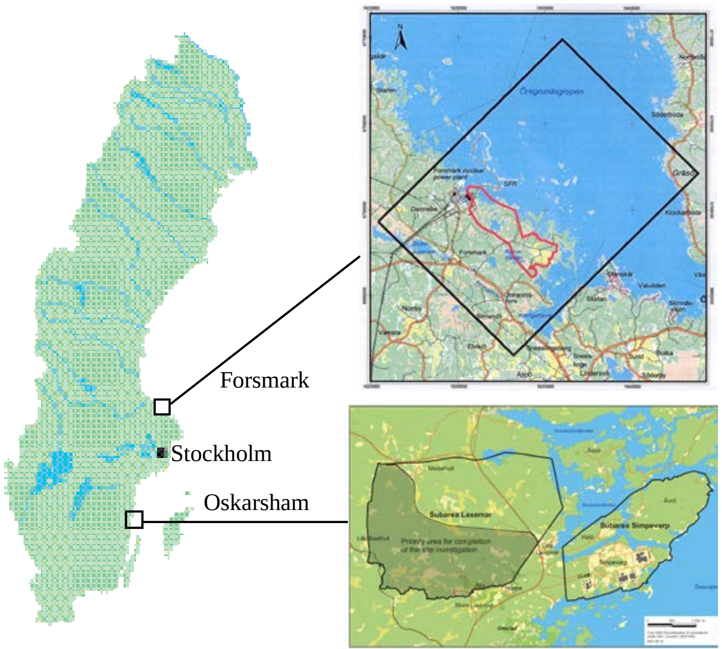
$$\frac{1}{E_\beta} = \frac{1}{E_r} + \cos^2\beta \cdot \left(\frac{\cos^2\beta}{k_n \cdot \delta} + \frac{\sin^2\beta}{k_s \cdot \delta} \right)$$

(E_β varies with respect to inclination, ***β***)

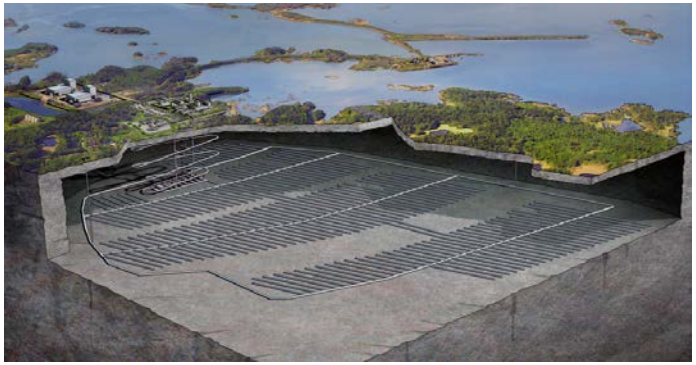




Fractured Rock Masses
Elastic modulus (example from Forsmark, Sweden)

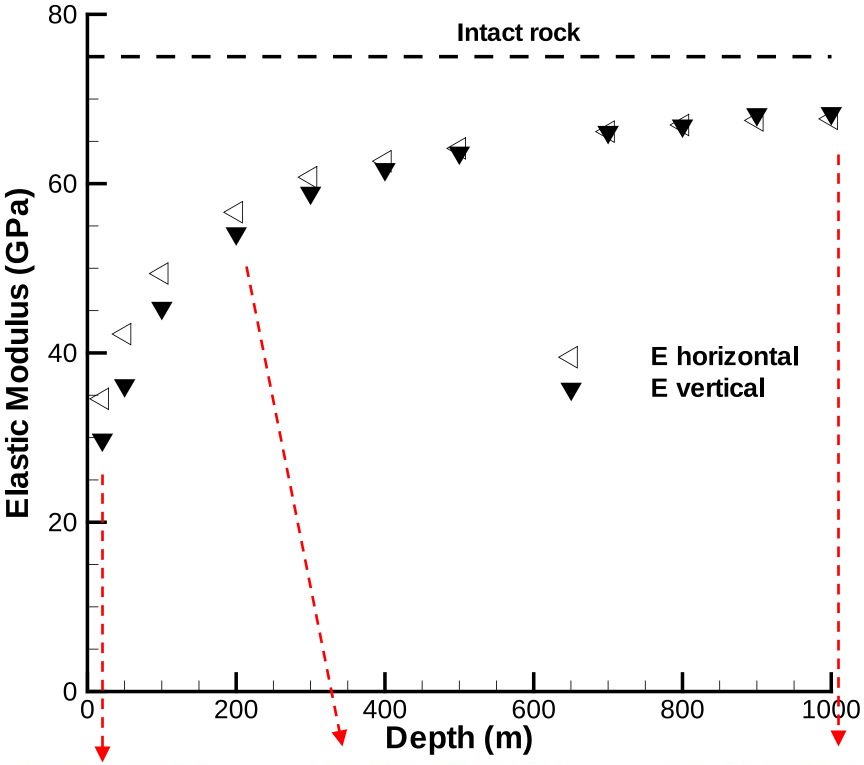


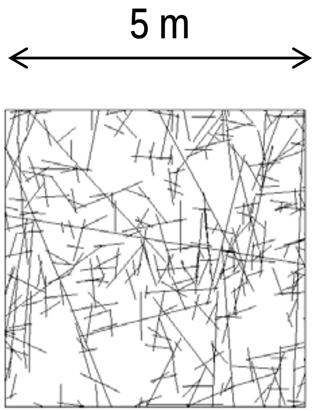
Map of Sweden

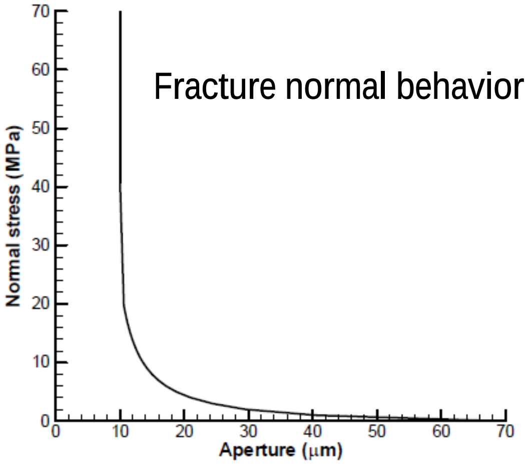


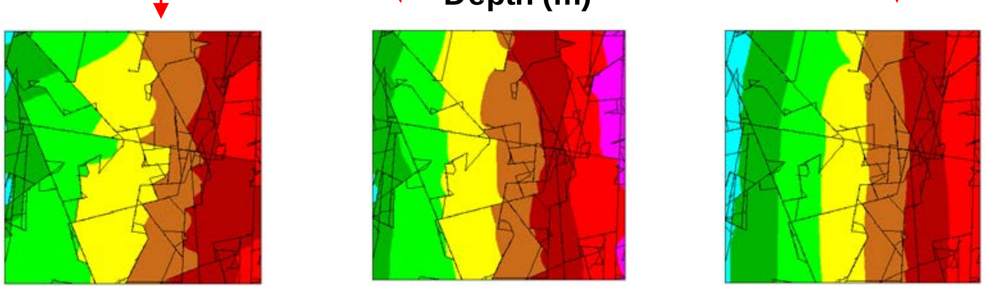
- Swedish geological repository of nuclear waste
- Forsmark and Oskarshamn, two candidate sites for Swedish Program.
- 2002-2009: site investigation.
- 2009: Forsmark, as the final site
- 2011: License application
- 2015: decision (?)
- 2025: Operation

Fractured Rock Masses
Elastic modulus (example from Forsmark, Sweden)









Displacement distribution

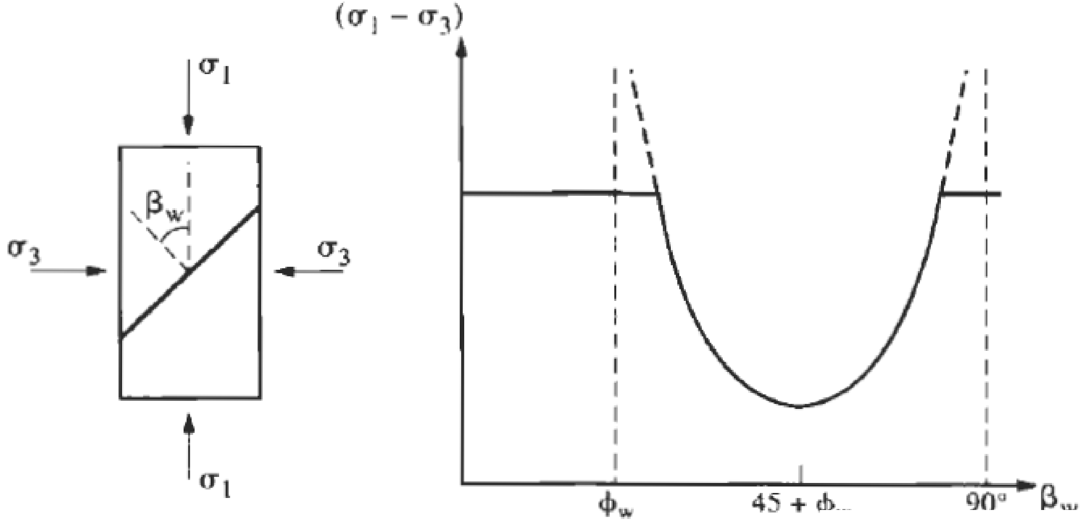
Elastic moduli of fractured rock is lower than those of intact rock

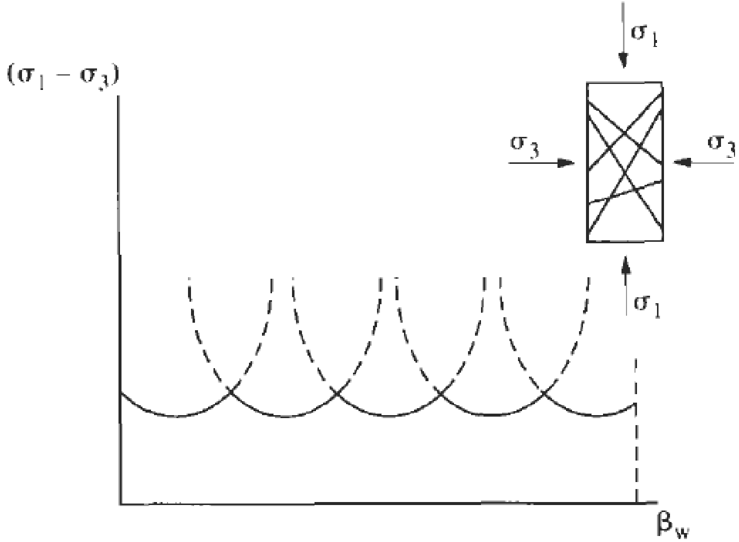
Elastic moduli ↑ with stress ↑
- highly stress-dependent

Effect of fracture/stress is more evident in low stress condition.

Min KB, Stephansson O, The DFN-DEM Approach Applied to Investigate the Effects of Stress on Mechanical and Hydraulic Rock Mass Properties at Forsmark, Sweden, *Tunnel & Underground Space: Journal of Korean Society for Rock Mechanics*, 2011;21(2):117-127

Fractured Rock Masses
Strength





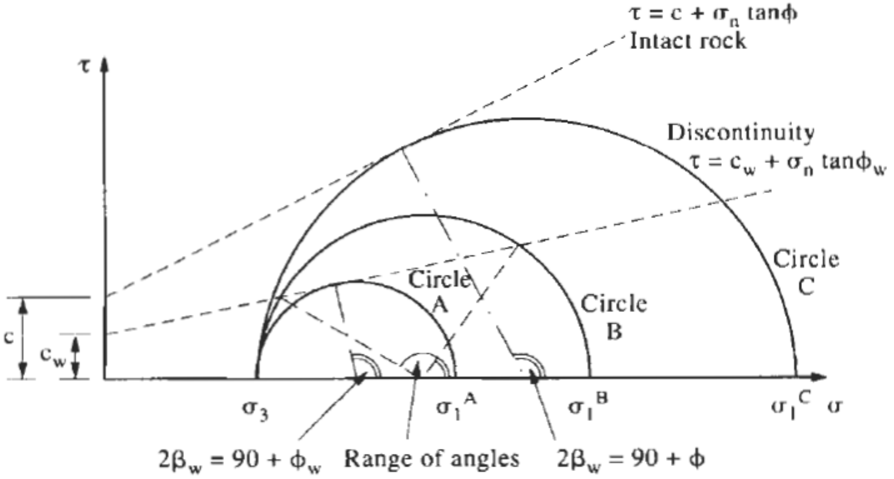


Figure 8.5 Mohr's circle representation of the possible modes of failure for rock containing a single plane of weakness.