8. Rock mass

Rock mass?

原典不明

Rock or stone (diamond ore)

Rock mass (Suburb of Mudgee, Australia)

Numerous discontinuities!

Rock mass (Suburb of Mudgee, Australia)

Tuff breccia slope at Oshoro

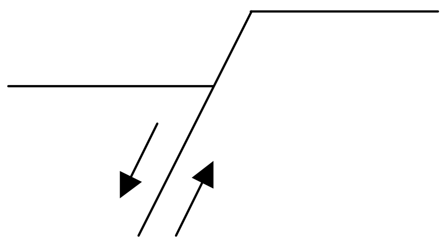
8.1 Classification of discontinuities

- Rock mass contains discontinuities (fractures)
  - No slip: joints
  - Slip: faults

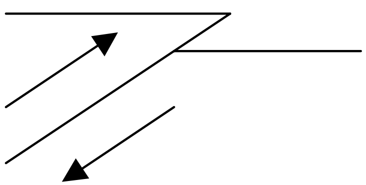
Fault and unconformity at Sunago Coal Mine in Mikasa and Bibai, Hokkaido, Japan（May 11, 1998, Prof. Emeritus Ishijima is standing right low part)

- Discontinuity is not so small that it can be seen by naked eye.
- Roughly speaking, there are many discontinuities in hard rock mass and less discontinuities in soft rock mass.
- Behavior of rock mass consisted of hard rocks often significantly ruled by physical properties of discontinuities.

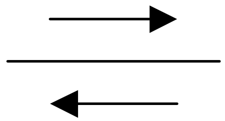
Classification of faults



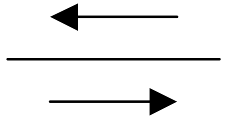
Sectional view of a normal fault (it is called a lag if the dip is less than 45°)



Sectional view of a reverse fault (it is called a thrust if the dip is less than 45°)



Right lateral



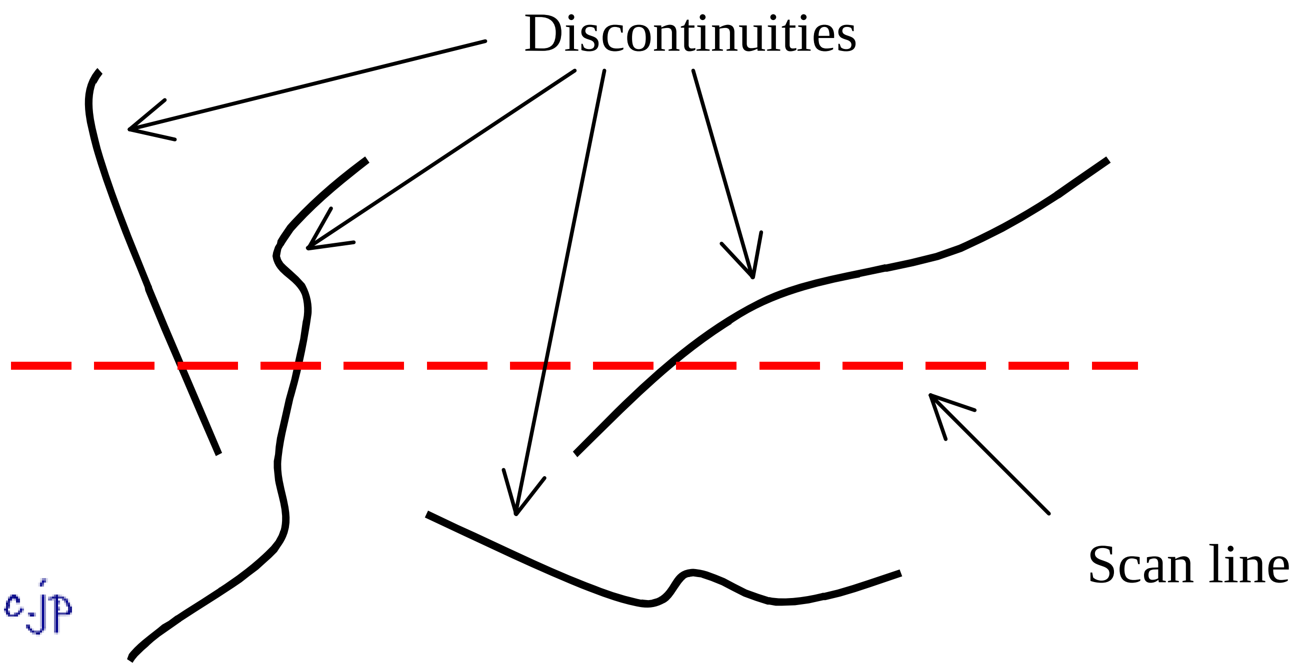
Left lateral

Plan view of a strike-slip fault

8.2 Quantity and orientation of discontinuities

Scan line method (Priest and Hudson, 1981)

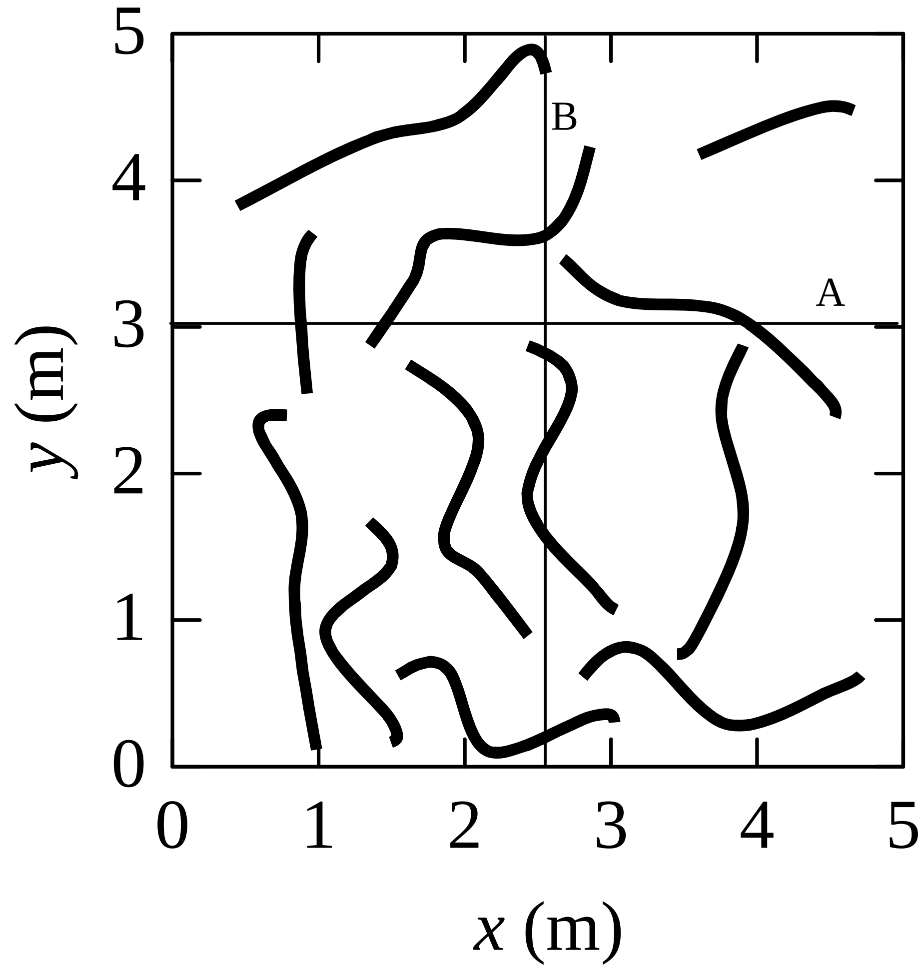
- A scan line is written on the surface of a rock mass.
- Number of discontinuities which cross the scan line per 1 m of scanline is calculated to represent density of dicontinuities.
  - Results depend on the orientation of the scanline.
- Length and orientation are measured for a more precise analysis.



- Other representations
  - Number of discontinuities per unit area (m^{-2})
  - Total length of discontinuities per unit area (m/m^2)

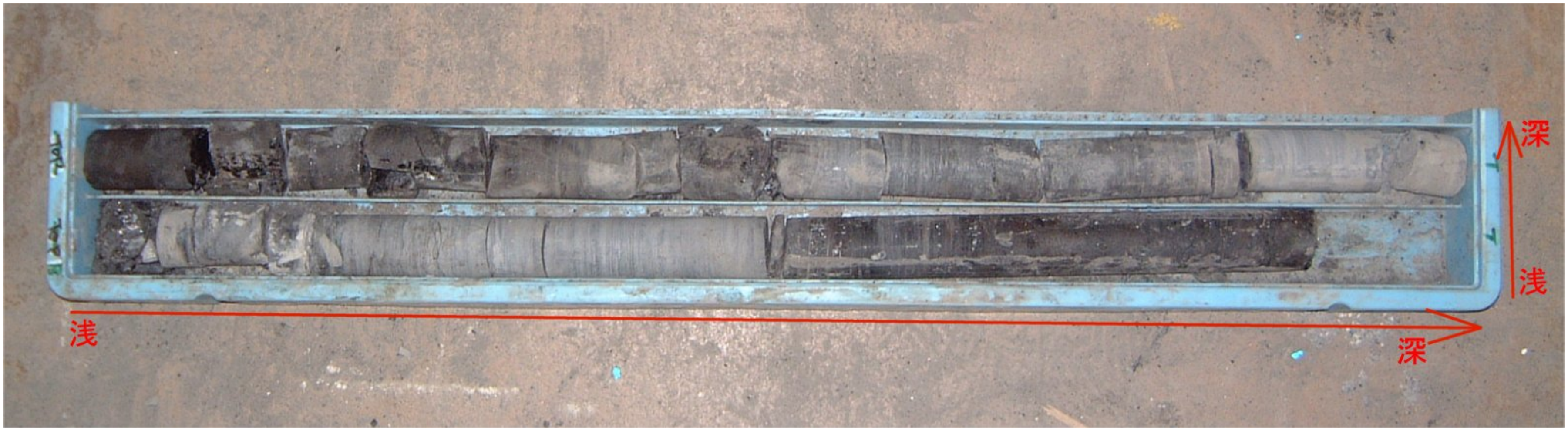
Example

- Calculate density of discontinuity (m^{-1}) along the scan lines A and B, respectively, by using the scan line method.
- Calculate discontinuity density as number of discontinuities per 1 m^2.



RQD（Rock Quality Designation）

- Total length of rock cores whose lengths are more than twice the diameter (ex. 5 cm) is calculated. RQD is obtained as percentage of the total length (ex. 1 m) to a specified length.
  - RQD is originally defined as percentage of the total length of rock cores whose lengths are more than 4 in. to a 60 in. part.



Example of rock core from Kushiro Coal Mine

Example

- Calculate RQD from the photo shown right which are rock cores from a pilot boring at A tunnel

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『Deere, D. U., (1967), AIME, pp. 237-302、p.252, Fig. 6一部修正』
を省略させて頂きます。

Discontinuity density (ft^{-1})

Relationship between discontinuity density and RQD（Deere *et al*., 1967）

$$RQD = 110.4 - 3.68\lambda$$

$$RQD = 115 - 3.3\lambda$$

Relationship between RQD and discontinuity density.

Upper: Priest & Hudson (1981).

Lower: ISRM (1978)

where λ is discontinuity density (m^{-1}) or an inverse of average spacing of discontinuities (m).

Utilization of RQD

- Rock mass clasification
- A close relathionshp between RQD and roadway deformation
  - Ex. Bolted roadway in Taiheiyo Coal Mine
- Related to Young's modulus of rock mass（Zhang & Einstein, 2004）

Fracture coefficient (Ikeda, 1967)

$$K = \left(\frac{V_F}{V_L} \right)^2$$

- V_F is P-wave velocity of rock mass, V_L is that of an intact rock specimen.
- A small K represents high discontinuity density.

Application of the fracture coefficient

- Young's modulus of rock mass used in a numerical analysis for tunnel design is sometimes assumed as follows

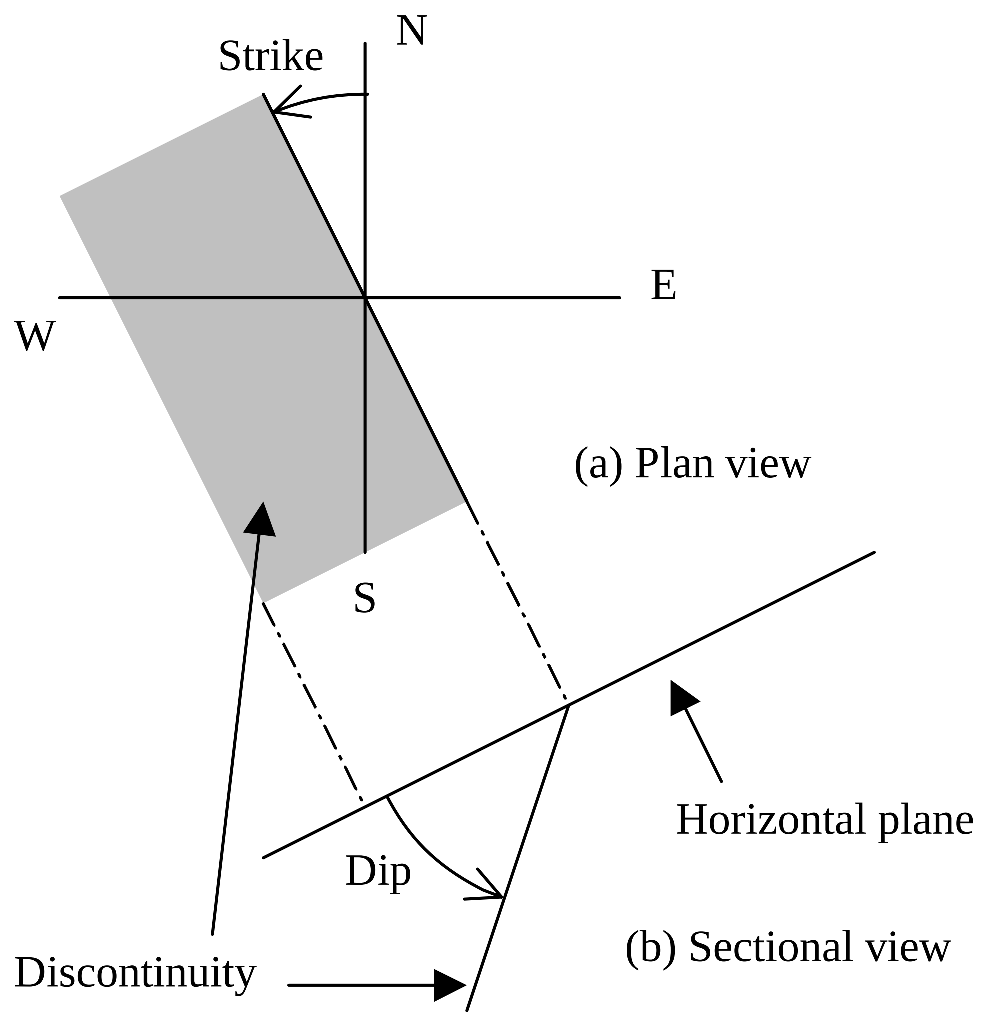
$$E' = KE$$

E' : Young's modulus of rock mass

E : Young's modulus of intact rock specimen

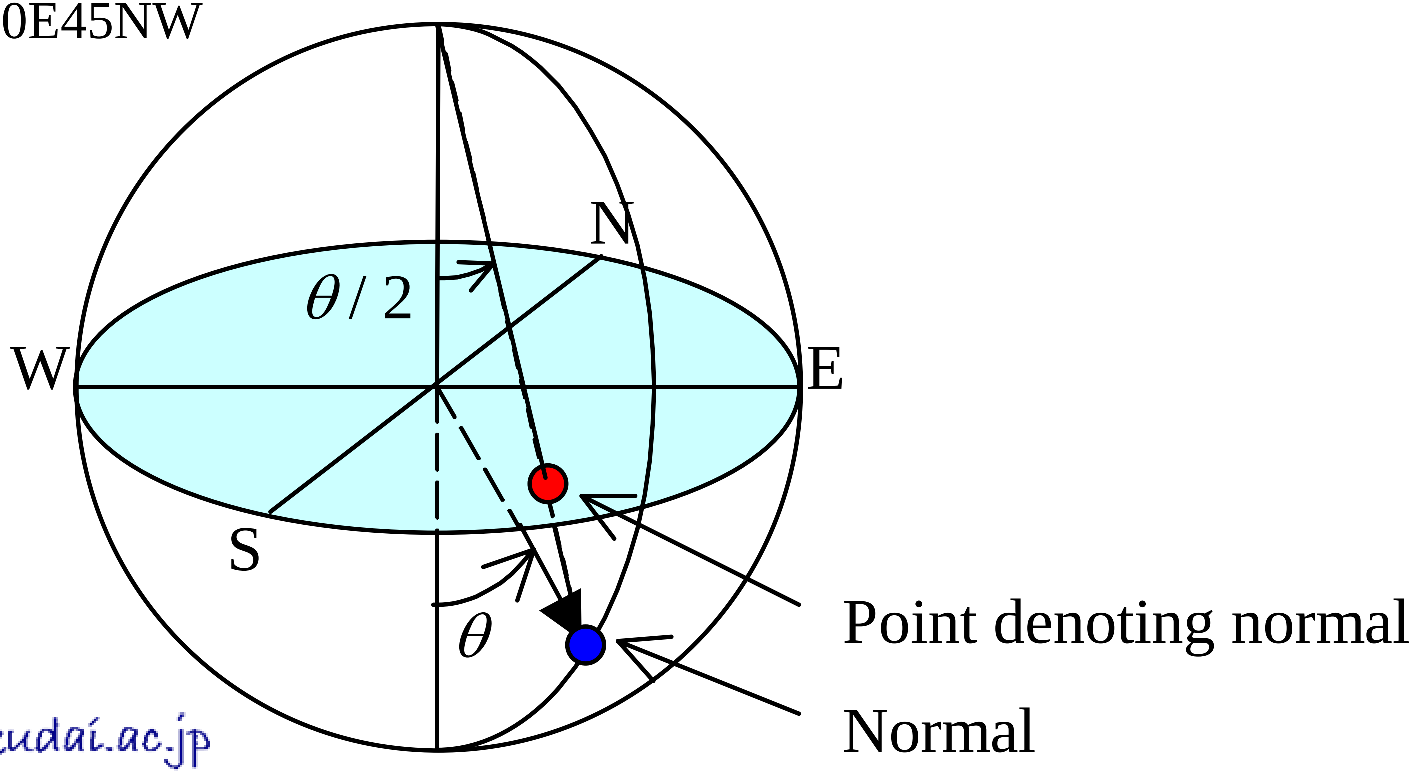
Orientation of discontinuity

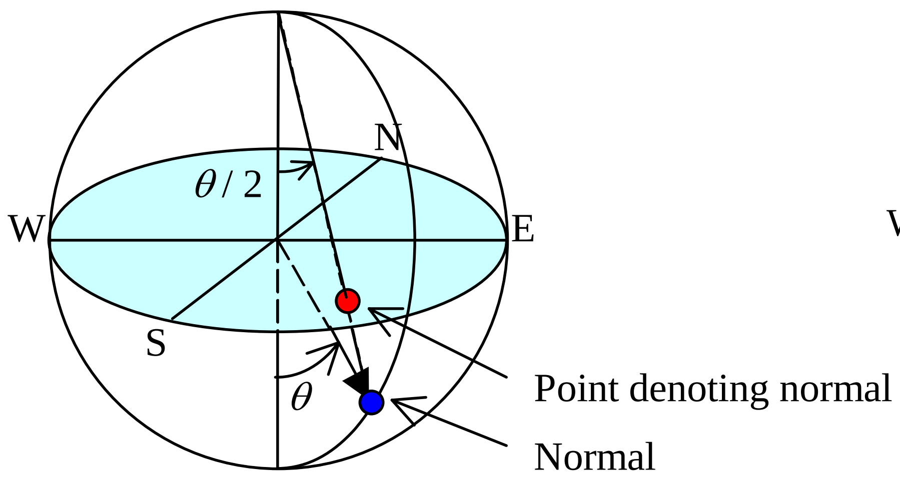
- Ex.
  - Strike: N30W（= S30E）
  - Dip: 45SW
  - Strike and dip: N30W45SW

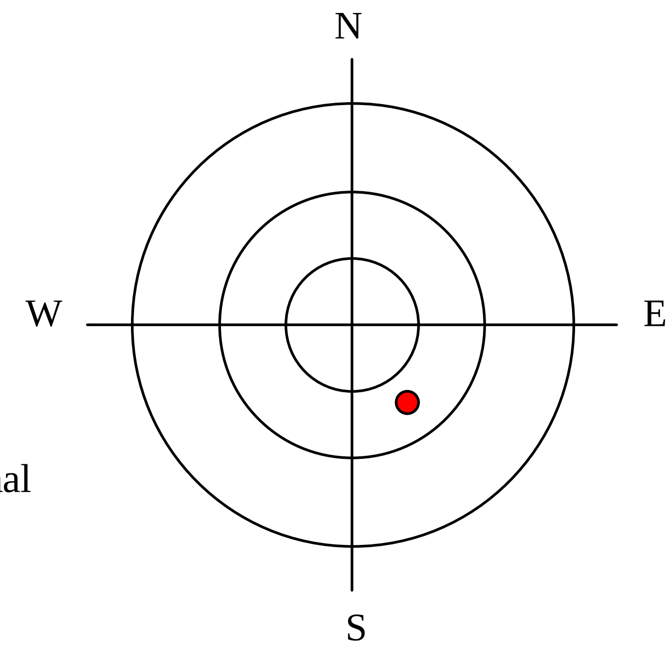


Stereo projection

- Orientation of a normal of a plane can be represented by a point on Wulff net by the lower hemisphere stereo projection technique
  - Ex. N50E45NW

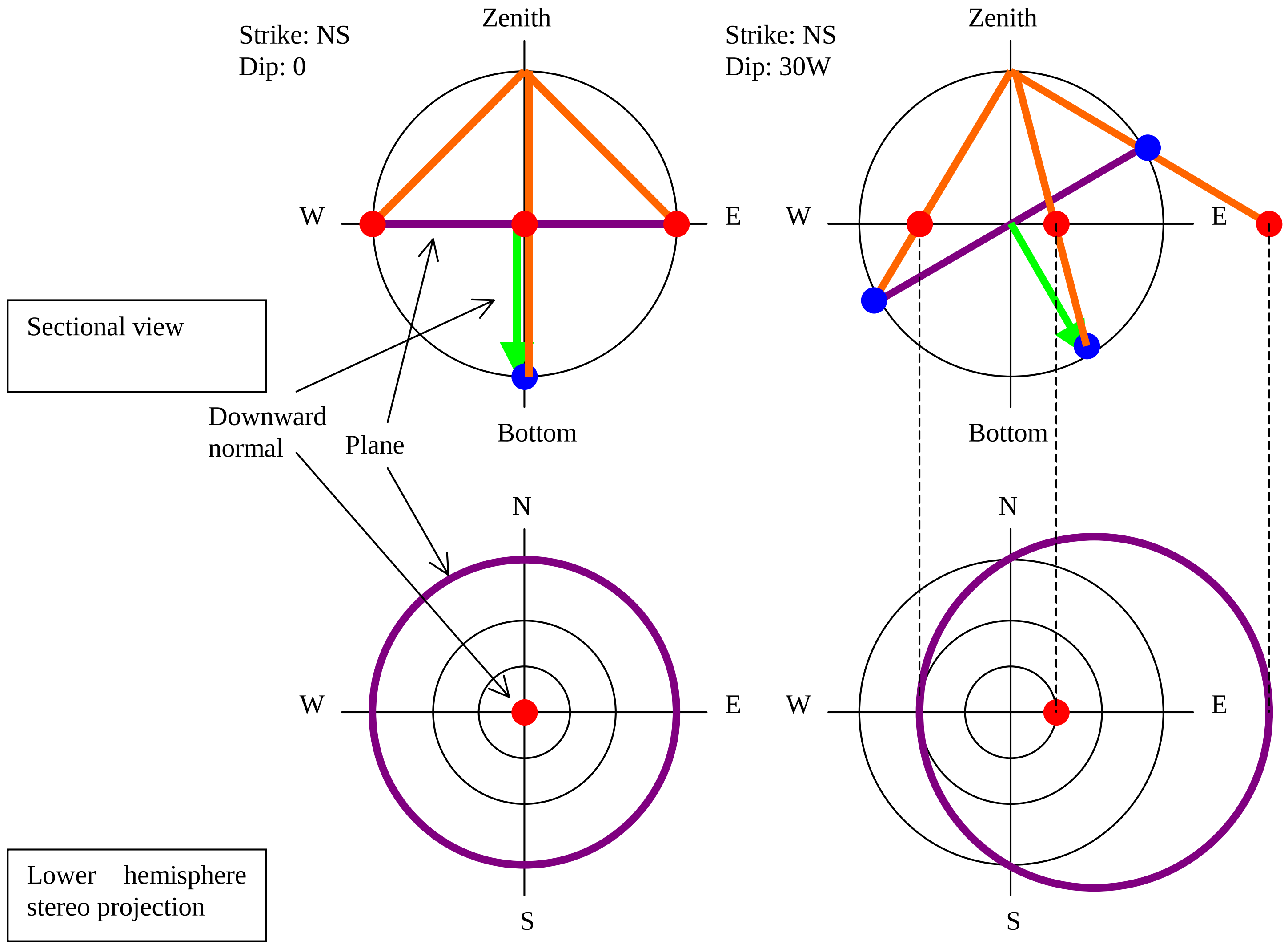






- The hatched plane is draw as the right figure

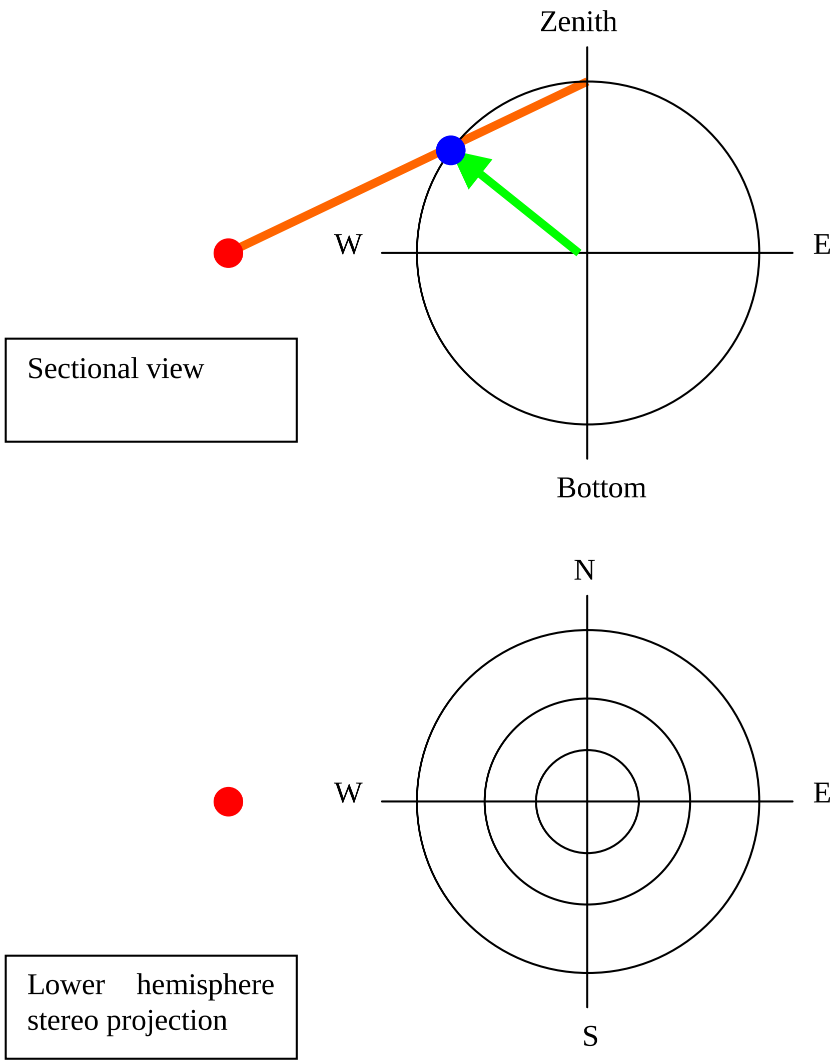
Example for the case where strike is NS



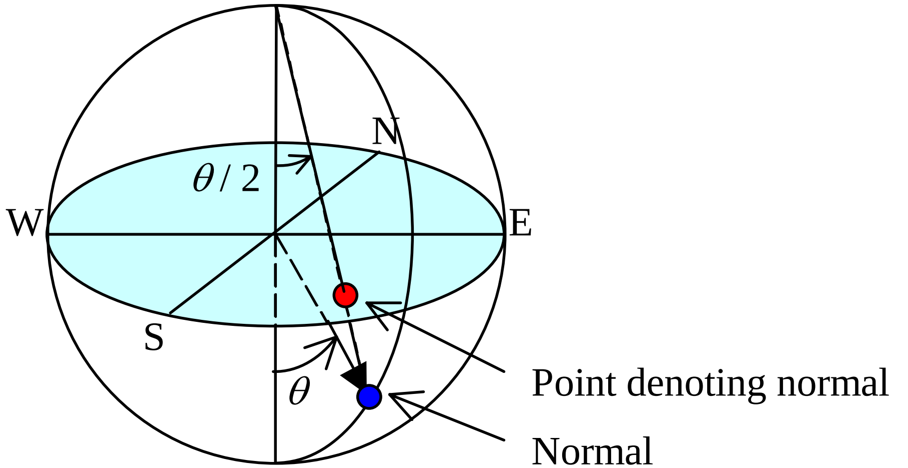
- Vector is represented by a point

- A plane is represented by a great circle

- When we want to represent an upward direction.

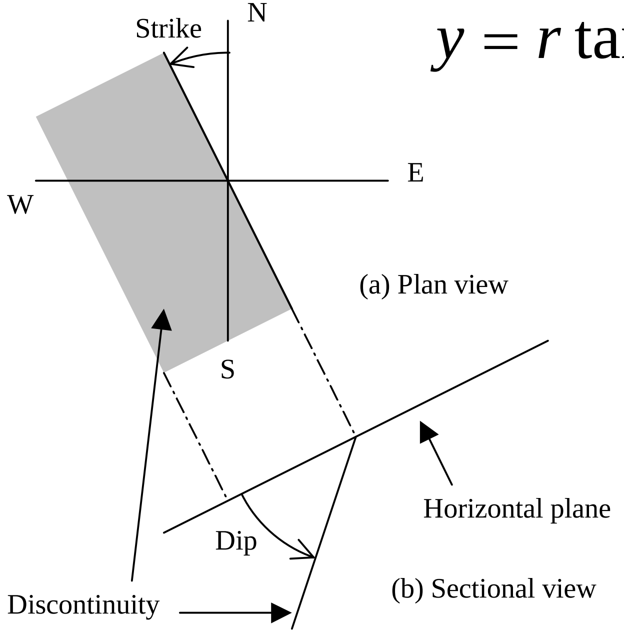


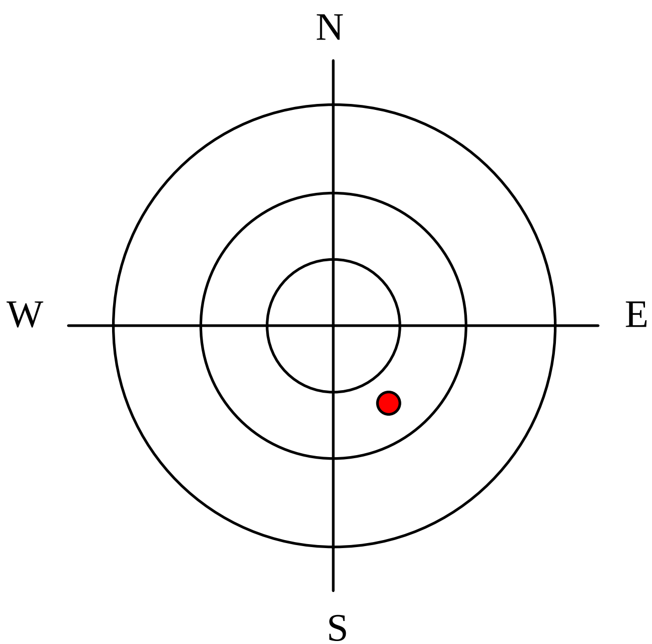
- Coordinate of the point representing a point
  - Strike ϕ, dip θ、radius r.
  - x 、y toward E, N, respectively.



$$x = r\tan\frac{\theta}{2}\cos\phi$$

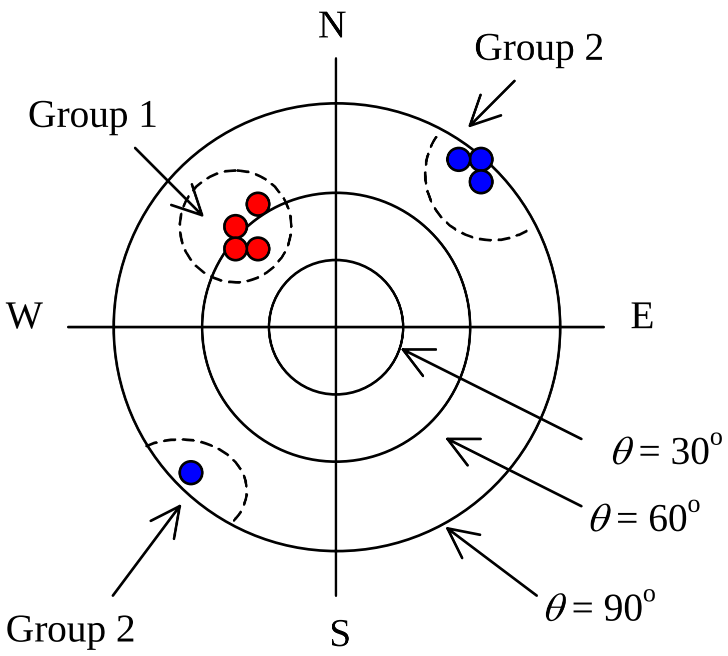
$$y = r\tan\frac{\theta}{2}\sin\phi$$





Application of stereo projection

- Analysis of joint sets, joints which orientations are similar with each other.
- Orientation of principal stresses
- Analysis of rock slope failure



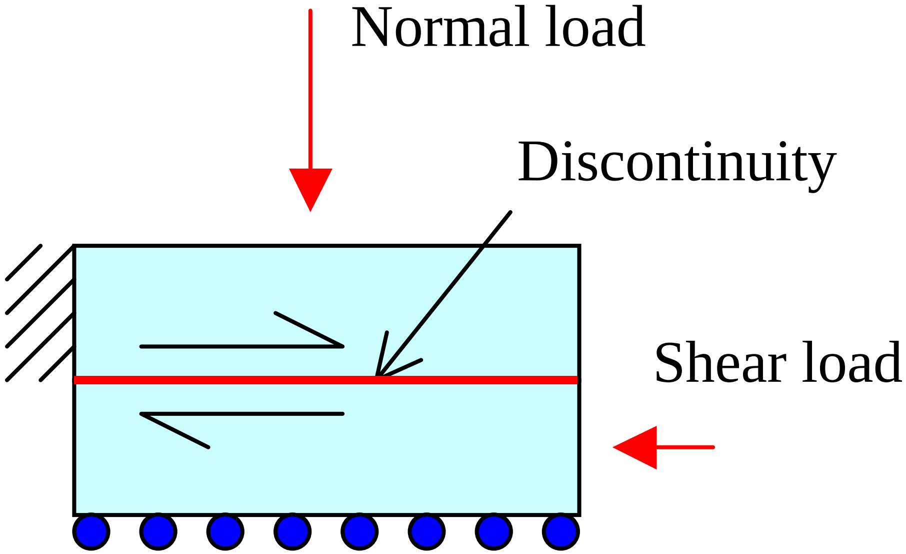
8.3 Strength of discontinuity

$$|\tau| \leq C + \sigma \tan\phi$$

$$\sigma \geq -T_0$$

- τ and σ is shear and normal stress acting on discontinuity, respectively, C is cohesion, ϕ is friction angle, T_0 is tensile strength.
- Cohesion and friction angle is said to be 0～7 MPa and 27～35°, respectively (Yamaguchi and Nishimatsu, 1991)
- Tensile strength of discontinuity is considered nearly zero without detailed research.

Plane shear test



- Plane shear test is often carried out to investigate shear strength of discontinuity
- It is difficult to use a natural discontinuity
- Rapture plane by splitting is regarded as discontinuity in most cases.

Plane shear test

- Load-shear displacement curve
  - A strain-softening behavior due to locking between discontinuities
- Normal displacement
  - Similar to dilatancy

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図表を省略させて頂きます。

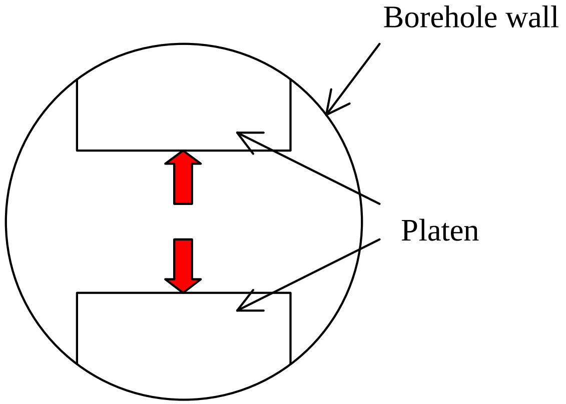
Shear test for a rapture plane by splitting

8.4 Deformation and strength of rock mass

- Deformation behavior of rock mass is significantly affected by discontinuities
  - The behavior is clearer for rock mass consisted of hard rock.
- Young's modulus for in-situ rock mass
  - is smaller than that for an intact rock specimen.
  - is estimated based on
    - The product of the Young's modulus of an intact specimen and the fracture coefficient is sometimes used as Young's modulus of rock mass (Ex. Nihon Tetsudo Kensetsu Kodan, 1996)
    - Young's modulus of rock mass is estimated based on RMR which will be described later (Okabe et al., 2000 in Japanese)
    - Borehole jack test
    - Jack test

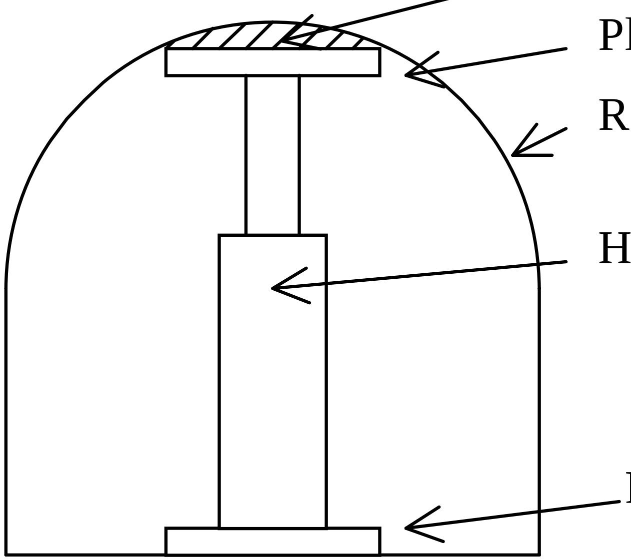
Borehole jack test

- Young's modulus is evaluated from load and displacement of borehole wall when steel platens are pressed against the borehole wall.



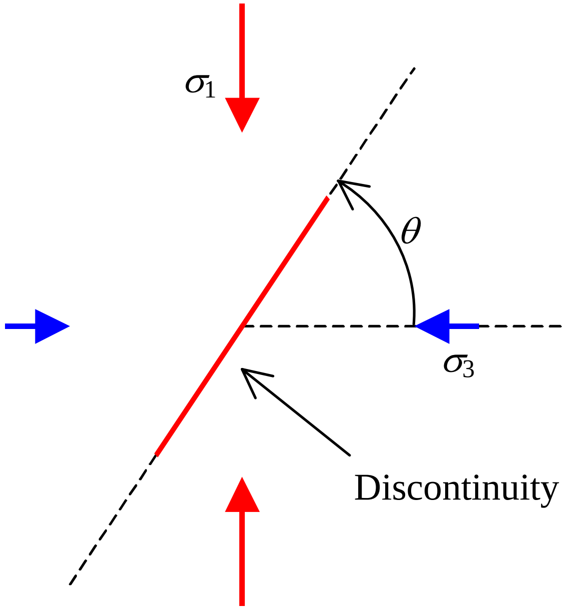
Jack test

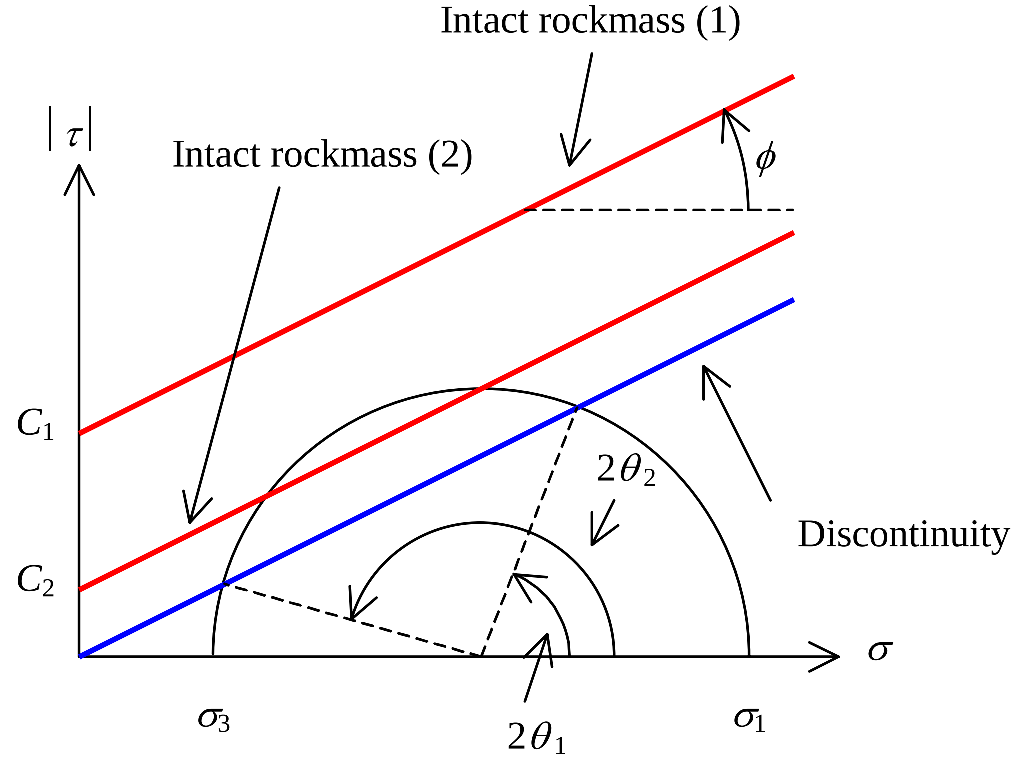
- Young's modulus of rock mass is evaluated from load and displacement when a pair of surfaces are pressed.



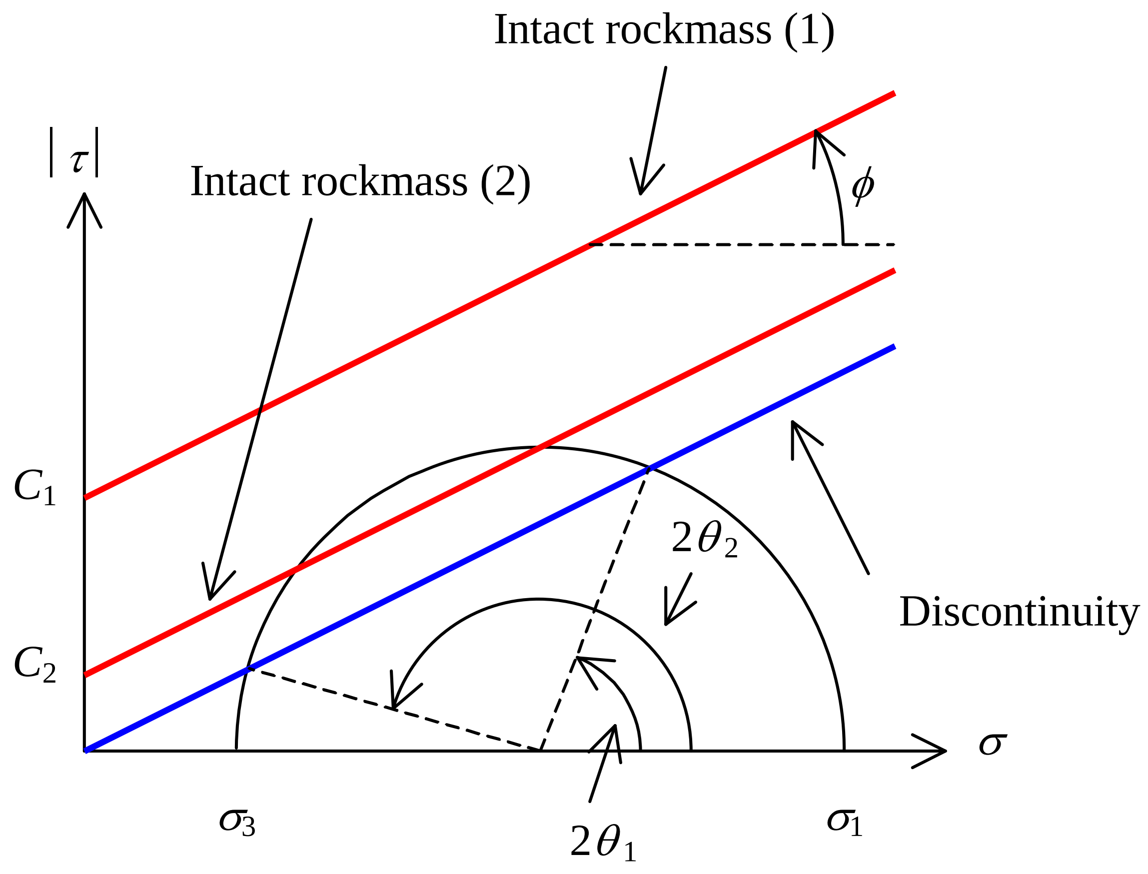
Example of strength of rock mass having a discontinuity

- Cohesion of discontinuity is zero.
- It is assumed for convenience that friction angle of discontinuity and intact rock mass is equal.



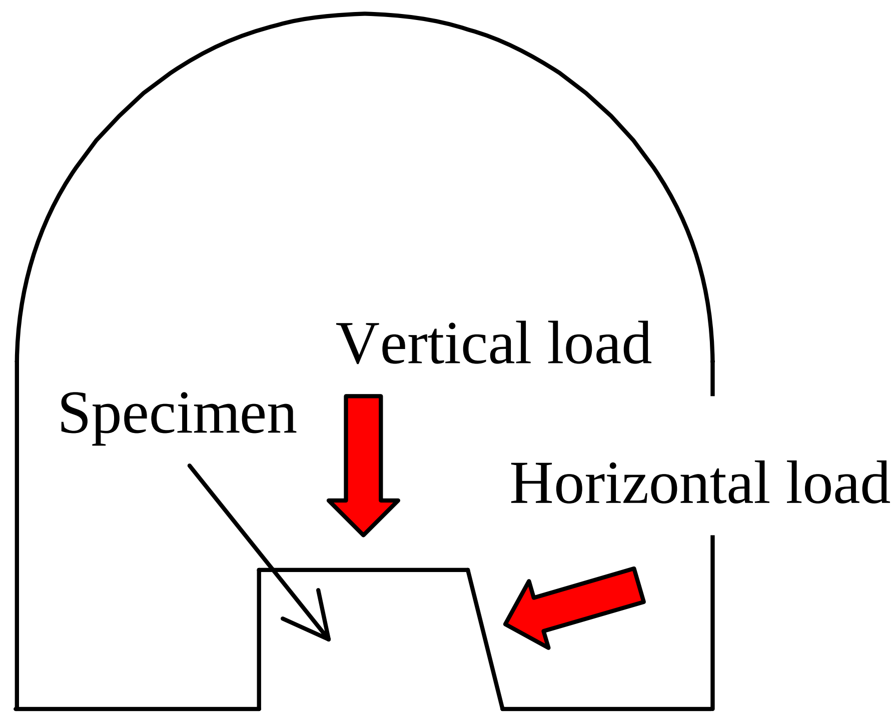


- When cohesion is C_1
  - Rock mass itself does not failure
  - Discontinuity slips when $\theta_1 \leq \theta \leq \theta_2$
    - In a special case, it slips when $\sigma_3 = 0$ and $\theta \geq \phi$
- When cohesion is C_2
  - Rock mass failures
  - Discontinuity does not slip when $\theta \leq \theta_1$ or $\theta \geq \theta_2$, namely, rock mass failures but discontinuity does not slip.



In-situ shear test

- A rock block whose height and area is 30 cm and 0.36 - 1.5 m^2, respectively, is shaped from the rock floor.
- Horizontal load is increased under a constant normal load until the specimen shows shear failure
  - Stress is not uniform
  - Strength of in-situ rock mass can be roughly obtained
- In-situ tension test (Takada et al, 2000)
- In-situ triaxial test (Tani, 2005)



8.5 Rock mass classification

- Material tests of rock is important as basic data in designing rock structures.
  - However, mechanical behavior of rock mass is affected by discontinuities.
- Rock mass classification
  - Classification of rock mass from engineering view points.
  - There are several methods
  - Rock mass classification is carried out at an designing stage.
    - Data for classification should be obtained through surface investigation and borehole measurement

Rock mass classification for tunnels (JSCE, 1996)

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RMR (Rock Mass Rating, Goodman, 1980)

- Rock mass classification for underground mining
  - Score for compressive strength
  - Score for RQD
  - Score for joint spacing in the most influencing orientation
  - Score for condition of the joint
  - Score for water
  - Score for joint orientation
  - Rock mass is classified according to the total score

Compressive strength

UCS (MPa)	Rating
> 200	15
100 - 200	12
50 - 100	7
25 - 50	4
10 - 25	2
3 - 10	1
< 3	0

RQD

RQD (%)	Rating
91 - 100	20
76 - 90	17
51 - 75	13
25 - 50	8
< 25	3

Joint spacing in the most influencing orientation

Joint spacing (m)	Rating
> 3	30
1 - 3	25
0.3 - 1	20
0.005 - 0.3	10
< 0.005	5

Condition of joint

Description	Rating
Very rough surfaces of limited extent; hard wall rock	25
Slightly rough surfaces; aperture less than 1 mm; hard wall rock	20
Slightly rough surfaces; aperture less than 1 mm; soft wall rock	12
Smooth surfaces, OR gouge filling 1 - 5 mm thick, OR aperture of 1 - 5 mm thick; joints extend more than several times	6
Open joints filled with more than 5 mm of gouge, OR open more than 5 mm; joints extend more than several meters	0

Water inflow

Inflow per 10 m tunnel length (*l* / min) OR	Joint water pressure divided by major principal stress OR	General condition	Ratin g
None	0	Completely dry	10
< 25	0.0 - 0.2	Moist	7
25 - 125	0.2 - 0.5	Water under moderate pressure	4
> 125	0.5	Severe water problems	0

Joint orientation

Assessment of influence of orientation on the work	Rating increment for tunnels	Rating increments for foundations
Very favorable	0	0
Favorable	-2	-2
Fair	-5	-7
Unfavorable	-10	-15
Very unfavorable	-12	-25

Classification

RMR (sum of rating increments from the above tables)	Class	Description of rock mass
81 - 100	I	Very good rock
61 - 80	II	Good rock
41 - 60	III	Fair rock
21 - 40	IV	Poor rock
0 - 20	V	Very poor rock

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『Goodman (1980), Introduction to Rock Mechancs,
John Wiley and Sons, p. 239, Fig. 7.13』を省略させて頂きます。

Application of RMR for estimation of unsupported span (Goodman, 1980)

Example

- Classify a moist rock mass whose uuniaxial compressive strength is 60 MPa, RQD is 52%, joint spacing is 50 cm, jint orientation is very favorable, joint aperture is 2 mm.

- Answer: III、Fair rock

8.6 Permeability of rock mass

Rock	Permeability (m^2)		Porosity
	Laboratory	In-situ	
Sandstone*	3×10^{-12} to 8×10^{-17}	1×10^{-12} to 3×10^{-17}	
Navajo sandstone*	2×10^{-12}		
Berrea sandstone*	4×10^{-14}		
Graywacke*	3.2×10^{-17}		
Rodessa sandstone**	3.3×10^{-13}		30.2%
Wilcox sandstone**	1.9×10^{-13}		17.5%
Shale*	10^{-18} to 5×10^{-22}	10^{-17} to 10^{-20}	
Pierre shale*	5×10^{-21}	2×10^{-18} to 5×10^{-20}	
Limestone, dolomite*	10^{-14} to 10^{-22}	10^{-12} to 10^{-16}	
Salem limestone*	2×10^{-15}		
Indiana limestone***	4×10^{-15}		12.2%
Elenberger dolomite**	1.3×10^{-12}		5.4%
Hugoton dolomite**	1.4×10^{-14}		13.5%
Basalt*	10^{-21}	10^{-11} to 10^{-16}	
Granite*	10^{-16} to 10^{-20}	10^{-13} to 10^{-18}	
Schist*	10^{-17}	2×10^{-16}	
Fissured schist*	1×10^{-13} to 3×10^{-13}		
Hyaloclastite			
Toyohama hyaloclastite****	1.1×10^{-13} to 1.3×10^{-13}		22%

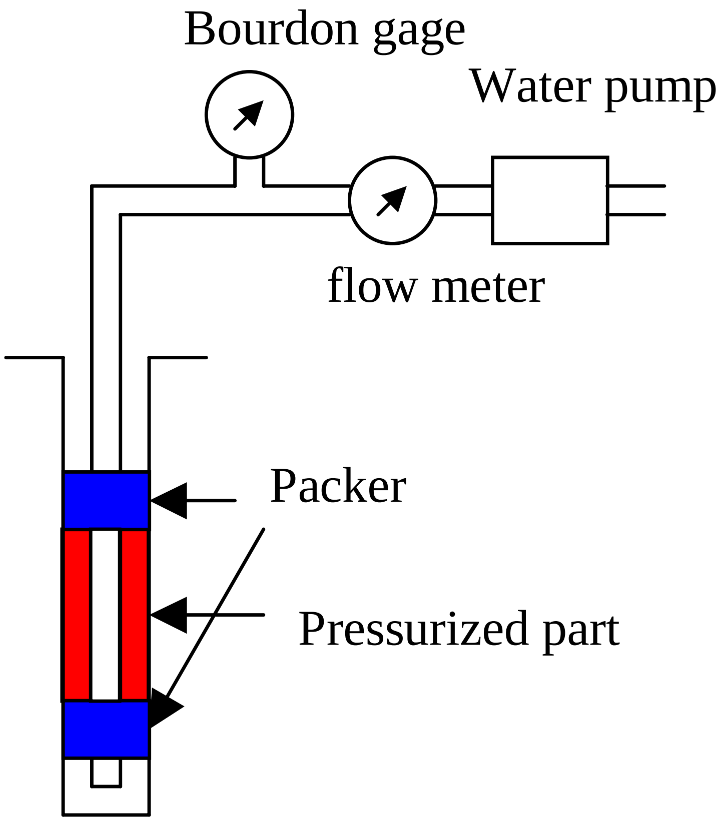
- Permeability of rock mass is significantly affected by discontinuities.
  - Permeability of an intact rock specimen and that of rock mass are different with each other in most cases

Measurement of permeability of rock mass

- Lugeon test
- Vacuum air test (Yamada et al., 1999)

Lugeon test

- A part of drill hole is shielded by a pair of packers
- Water pressure is applied to the part
- Water pressure and water inflow are recorded



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Evaluation of hydraulic conductivity

- Lugeon value

$$L_u = \frac{10Q}{P\,l}$$

  - Q : Water inflow (l / min)
  - P : Water pressure (kgf / cm^2, 10 kgf / cm^2 is standard)
  - l : Length of the pressurized part (m, 5 m is standard)

- Hydraulic conductivity (cm/s)

$$k = \frac{L_u \ln \frac{l}{R}}{1000 \times 60 \times 2\pi}$$

  - R : Radius of drill hole (m)

8.7 Failure of rock mass

- Conventional concept: conjugate shear planes
- Recent concept: fractures which are parallel to the free surface

Sheeting joint at V-shaped valley of Ponbetsu River in Ikushunbetu, Mikasa.