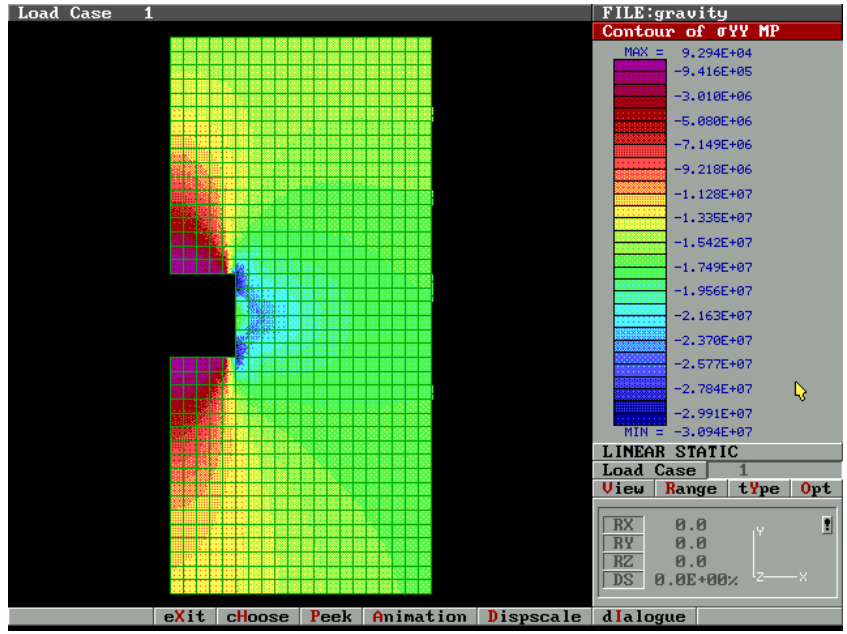
9. Initial stress

- Initial stress
  - Stress state in rock mass without artificial disturbances.
  - One of the basic data in designing rock structure.
  - Competence factor = Uniaxial compressive stress / initial vertical stress is a good index for stability of an opening in rock mass

- Stress state near opening is disturbed
- Disturbed zone is avoided for measurement of initial stress
- Disturbed stress is also measured in some cases where investigating deformation and failure behavior around the opening

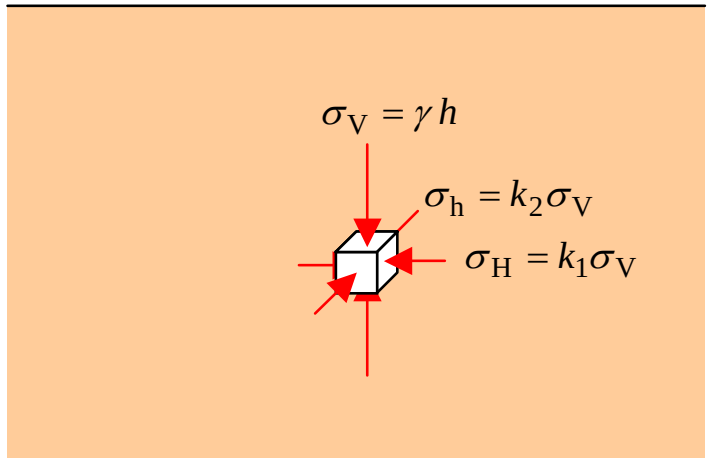


9.1 Initial stress value

Primitive estimation

$$\sigma_V = \gamma h$$

- Initial vertical stress σ_V is equal to the weight of overburden rock (overburden pressure)
  - γ is unit volume weight (ex. 27 kN /m^3)
  - h is the depth (m)
    - Ex. Initial vertical stress at 500 m deep is 13.5 MPa

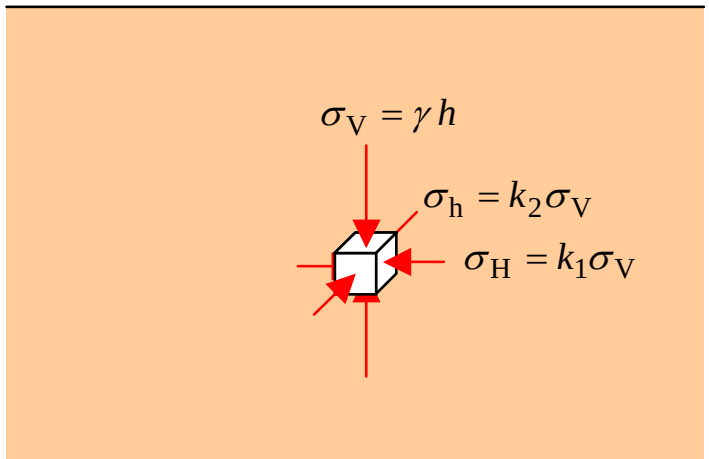


- Initial horizontal stress σ_H at a shallow depth.
- Horizontal stress ε_H is assumed to be zero.

$$E\varepsilon_H = \sigma_H - \nu(\sigma_H + \sigma_V) = 0$$

$$\sigma_H = k\sigma_V$$

$$k = \frac{\nu}{1-\nu}$$



  - E is Young's modulus.
  - ν is Poisson's ratio
  - k is the coefficient for horizontal stress
- k is assumed to be 1 at great depth.

Measured initial stress values

- Initial vertical stress is roughly equal to the primitive estimation

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『Goodman (1980), Introduction to Rock Mechanics, John Wiley and Sons, p. 106, Fig. 4.7a』

を省略させて頂きます。

Goodman, 1980

- Initial horizontal stress is different from the primitive estimation

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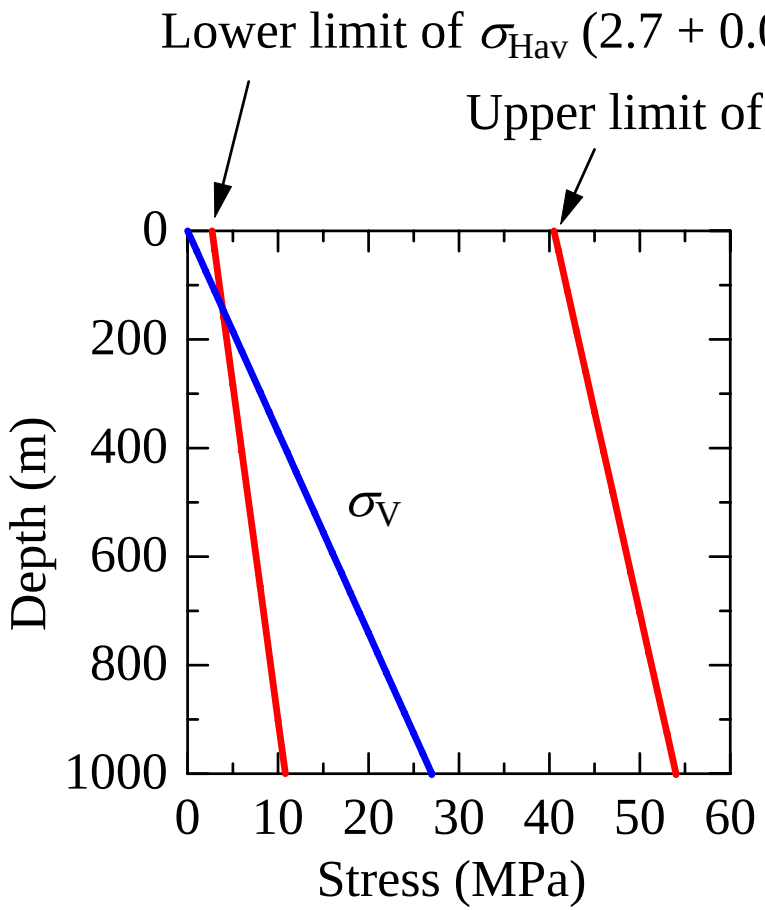
『Goodman (1980), Introduction to Rock Mechanics, John Wiley and Sons, p. 106, Fig. 4.7b』

を省略させて頂きます。

Average initial horizontal stress, Goodman, 1980

Average initial horizontal stress

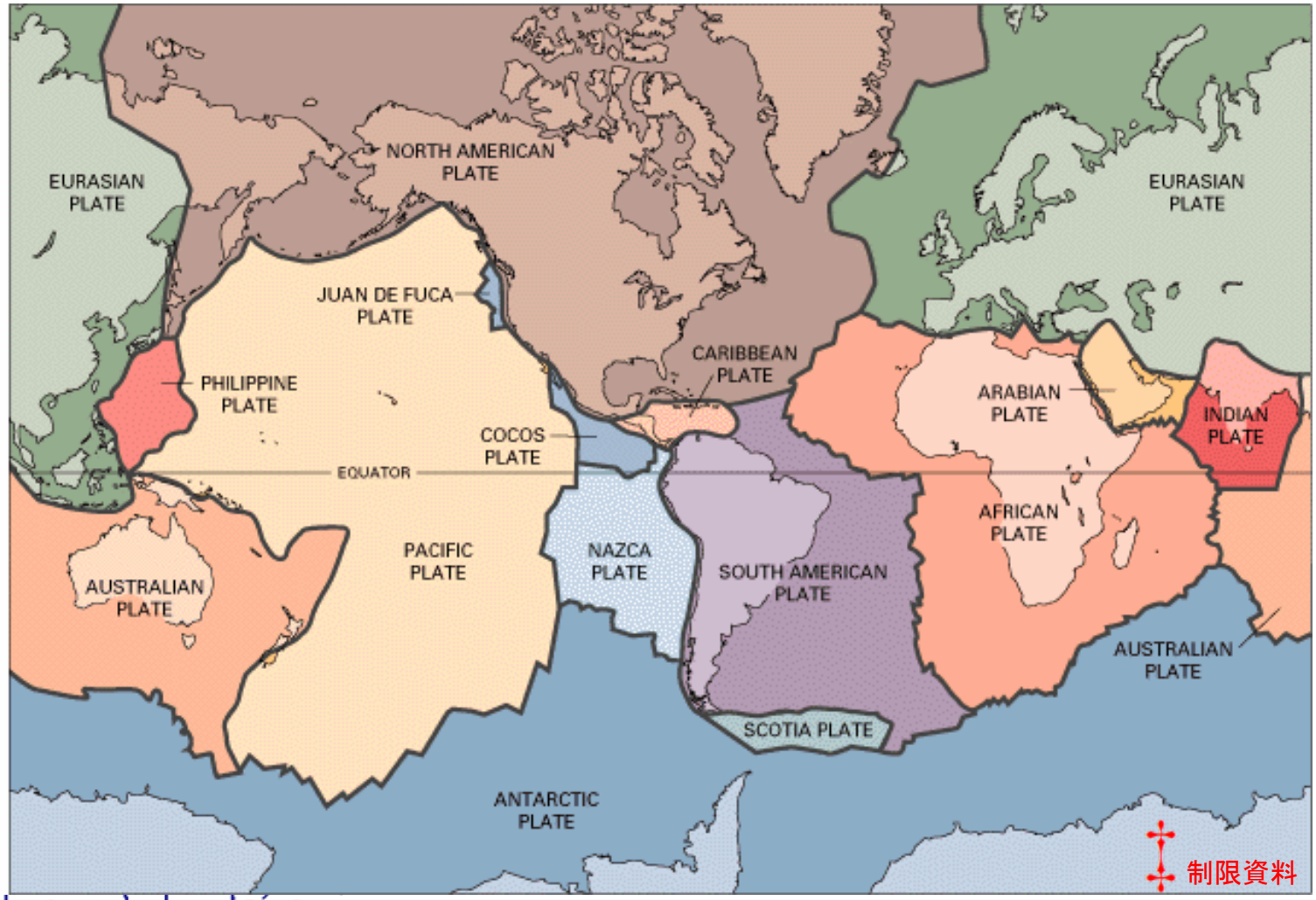


- Average initial horizontal stress = depth independent value + depth proportional value for 0.25 - 0.33 of poisson's ratio

Depth independent value?

- Movement of the tectonic plates
- Spherical shell subsidence model

Tectonic plates



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『Goodman (1980), Introduction to Rock Mechanics, John Wiley and Sons, p. 107, Fig. 4.7』

を省略させて頂きます。

Orientation of the maximum horizontal stress measured by hydraulic fracture method (Goodman, 1980)

- Average focal mechanism of deep earthquakes in and around Japan projected on the upper hemisphere. Arrows show tension and compression axes (Kasahara, 1983)

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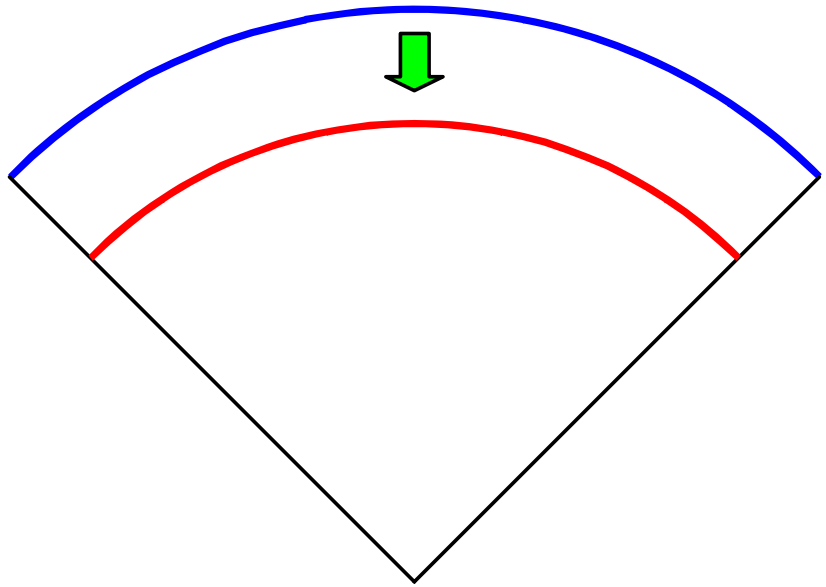
この場所に挿入されていた

『笠原慶一（1983） 地震の力学、鹿島出版会、p. 52, 図3.15』を省略させて頂きます。

Spherical shell subsidence model

- The earth shrinks by gravity force.
- Compressive strain appears by the spherical geometry.



9.2 Method to measure initial stress

Need for initial stress measurement

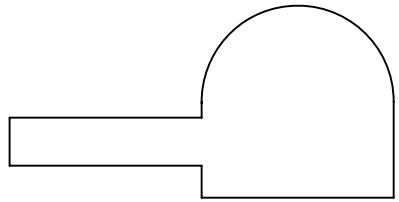
- Initial stress can roughly estimated by the primitive method
- Measurement is required for precise values
  - Initial stress can be affected by such geological phenomena as fold, faults, intrusion of magma etc.

Method	Description	Feature
Stress relief method	A borehole is drilled to desired depth. A probe is installed in the hole. Stress around he probe is relieved by usually overcoring.	Three dimensional stress state can be estimated by one overcoring in most methods. It takes costs and time. There are many results. The hole is drilled usually from a roadway.
Stress compensation method	Stress is relieved measuring displacement or strain. Stress is applied until the displacement or strain recovers to the values before the stress relief. Necessary stress is regarded as initial stress.	Measurement is usually carried out at rock surface. It is difficult to estimate three dimensional stress state. Elastic constants are not required to estimate rock stress.
Hydraulic fracturing method	A borehole is drilled from the ground surface or a roadway. Initial stress is estimated from hydraulic fracturing data.	Only horizontal stresses are usually estimated. It can be apllied up to several km deep. There are any results.
Methods using oriented core	Material tests in laboratory are carried out for rock cores. Initial stress is estimated from such data as stress-strain curves.	Results similar to other methods are often obtained although the mechanisms are not well understood.
Method based on fault earthquake data	Orientation of initial stress is estimated based on the focal mechanism of fault earthquakes.	Enormous data can be used although the stress magnitude can't be estimated.

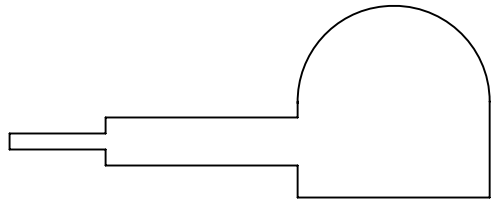
9.3 Stress relief methods

Stress relief method

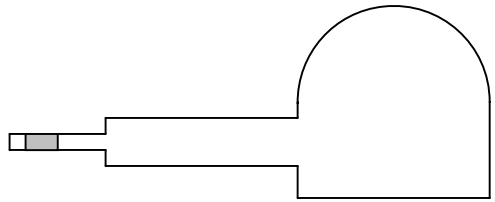
- A borehole is drilled usually from a roadway. The borehole should be longer than the roadway width to avoid areas where stress concentrates.
- A pilot hole is drilled from the borehole top.
- A probe is installed in the pilot hole.
- Overcoring is carried out measuring deformation and/or strains.



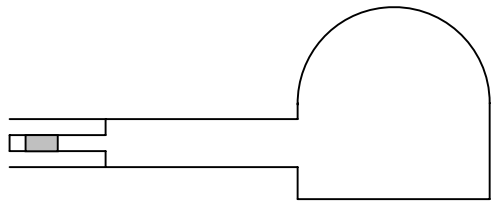
(1)



(2)



(3)



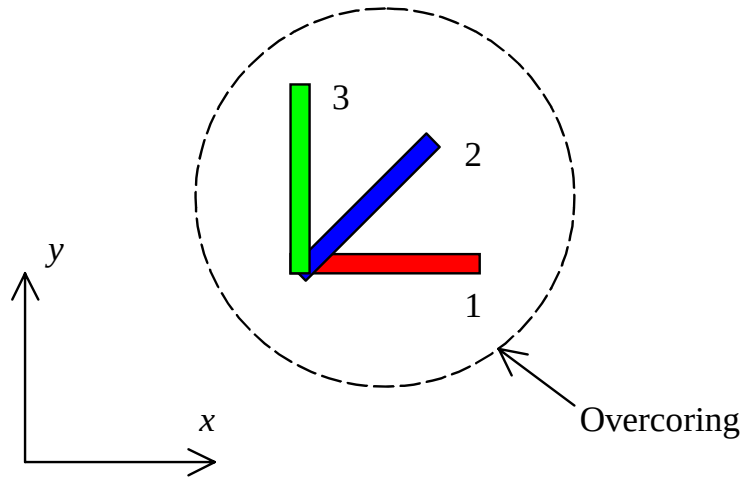
(4)

Principle of stress relief method

- No stress exists in the hollow cylinder formed by overcoring.
- Magnitude of strain and/or deformation with overcoring are equal to that when the pilot hole is drilled under the initial stress state with an inverted sign.
  - The strains and/or deformations can be obtained by analytical methods or numerical methods assuming an elastic medium.
- Initial stress can be estimated by solving the simultaneous equations.

Example

- A rosette gage was atacched to a rock surface and overcoring was carried out around the gage. Represent change in strains of the gauges 1, 2 and 3 by E, ν, σ_x, σ_y τ_{xy}.



$$\sigma_\alpha = \sigma_x \cos^2 \alpha + \sigma_y \sin^2 \alpha + 2\tau_{xy} \cos\alpha \sin\alpha$$

Example of stress relief method

- Conical bottom strain method (Sakaguchi et al., 1994)

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この場所に挿入されていた

『坂口清敏他、資源と素材. 110(4) [1994.04]資源素材学会、p. 332, Fig. 2』を省略させて頂きます。

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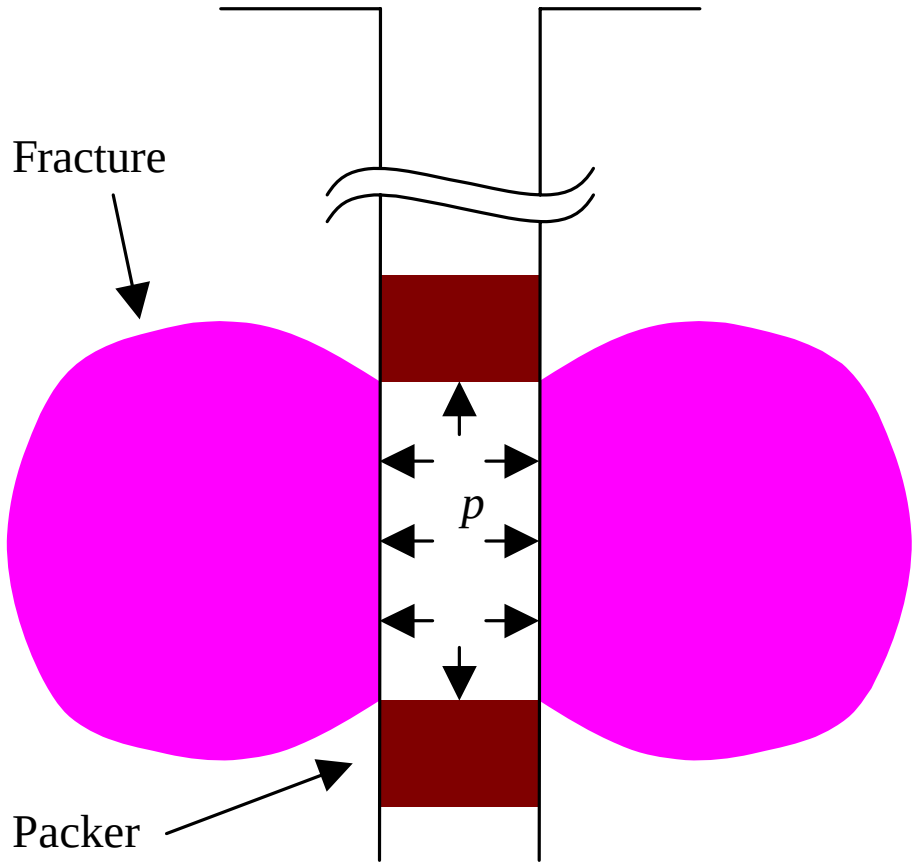
『坂口 清敏 他、資源と素材. 110(4) [1994.04]資源素材学会、
p. 333, Fig. 3 』を省略させて頂きます。

Sakaguchi et al., 1994

9.4 Hydraulic fracturing

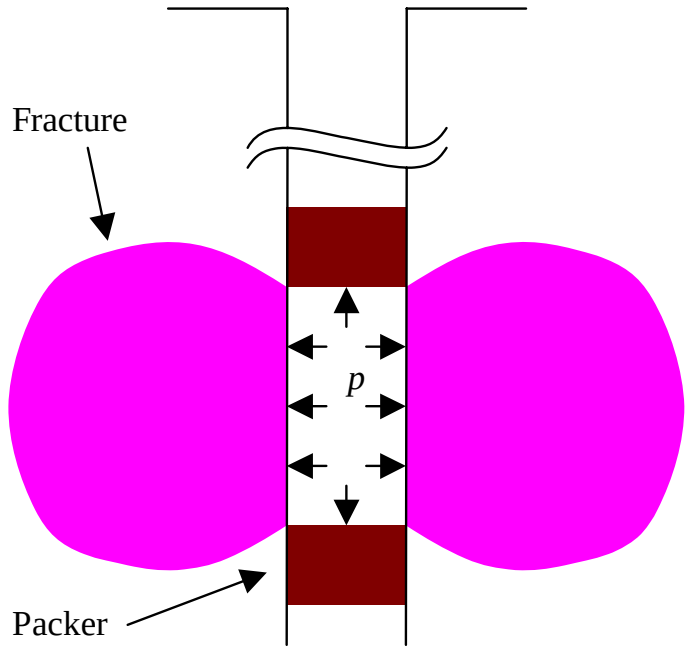
Hydraulic fracturing method

- Often used method.
- Originally developed for wells for petroleum and geothermal energy to measure stress and to enhance the prodcution
- There are some cases in which hydraulic fracturing is carried out from an existed roadway.



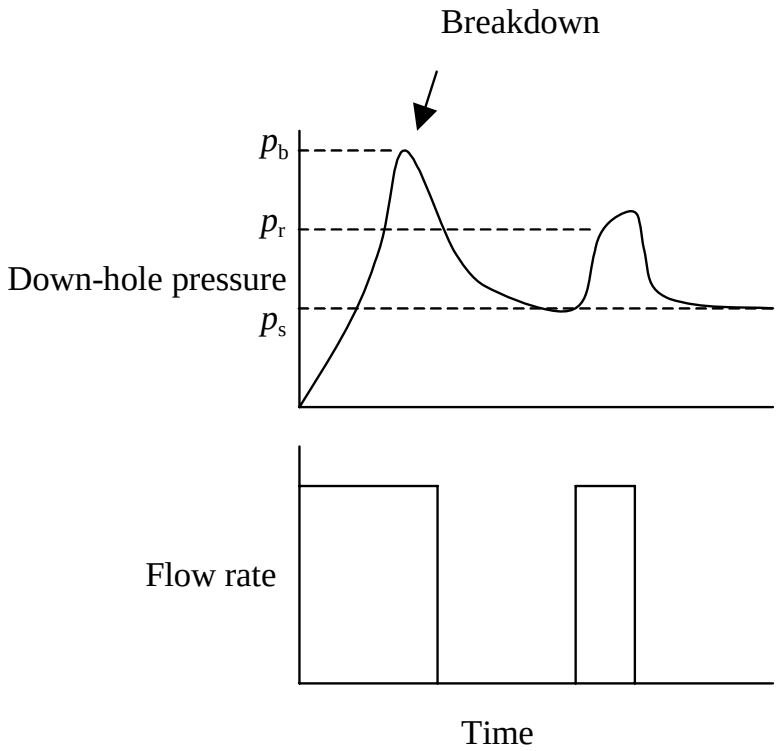
Hydraulic fracturing

- A borehole is drilled.
- Packer and a water pipe is installed.
- Water is injected measuring pressure and flow rate.



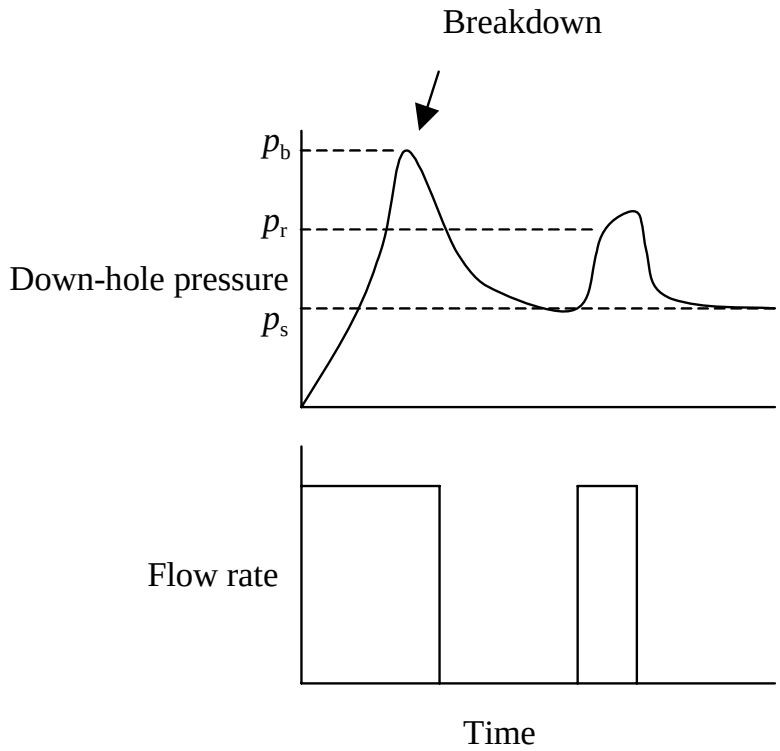
Hydraulic fracturing

- Water valve is closed after breakdown which is a decrease of water pressure and represents that a fracture appears at the borehole wall. The pressure at the breadown is called p_b.
- Water is injected again.
  - Decrease of the slope of the water pressure-time curve represent reopening, namely, the fracture is opened again. The pressure at re-opening is called re-opening pressure p_r.
  - Injection is continued for a while and then the valve is shut.Water pressure will converge. The converged pressure is called shut-in pressure p_s.



Hydraulic fracturing

- Packer etc. are removed and fracture orientation is observed by a borehole camera or impression packer.

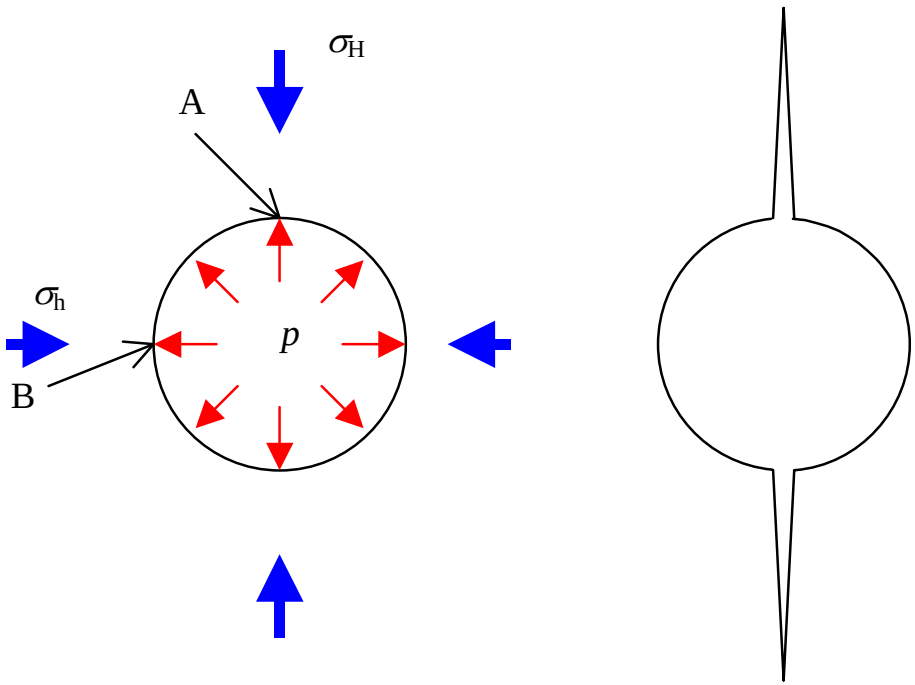


Principle of hydraulic fracturing

- Tangential stresses σ_A, σ_B at points A and B when internal pressure p acts to a circular hole under maximum principal stress σ_H and minimum principal stress σ_h (pore pressure is ignored for convenience).

$$\sigma_A = 3\sigma_h - \sigma_H - p$$

$$\sigma_B = 3\sigma_H - \sigma_h - p$$



$$\sigma_A = 3\sigma_h - \sigma_H - p$$

$$\sigma_B = 3\sigma_H - \sigma_h - p$$

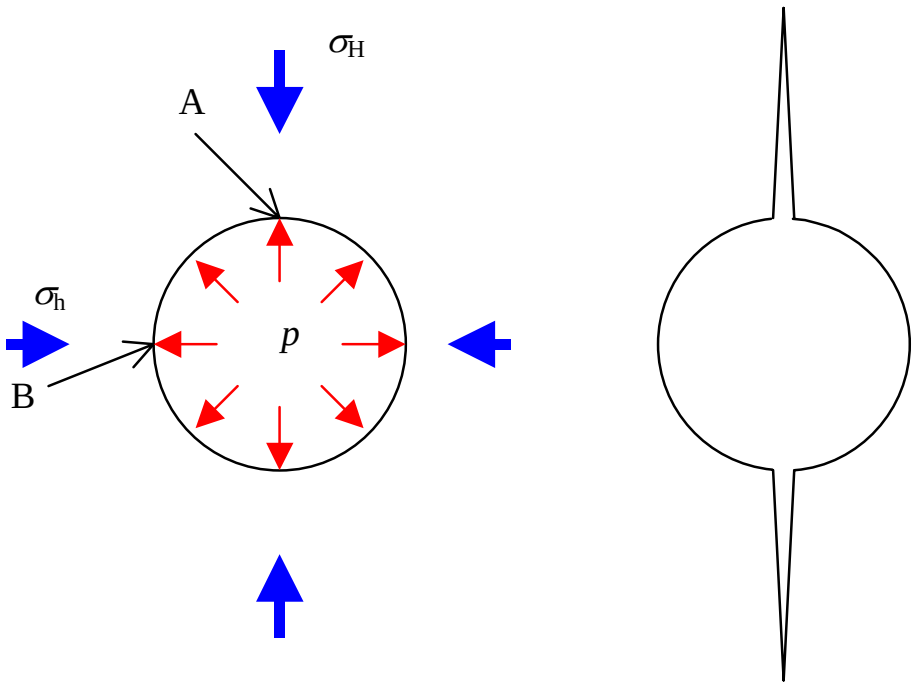
Principle of hydraulic fracturing

- σ_A is smaller than σ_B. A fracture initiate and grows from point A when the following criterion is satisfied.
  - T_0 is tensile strength.

$$T_0 \le -\sigma_A = -3\sigma_h + \sigma_H + p$$

- The following equation is derived for the breakdown pressure p_b.

$$T_0 = -3\sigma_h + \sigma_H + p_b$$



$$\sigma_A = 3\sigma_h - \sigma_H - p$$

$$\sigma_B = 3\sigma_H - \sigma_h - p$$

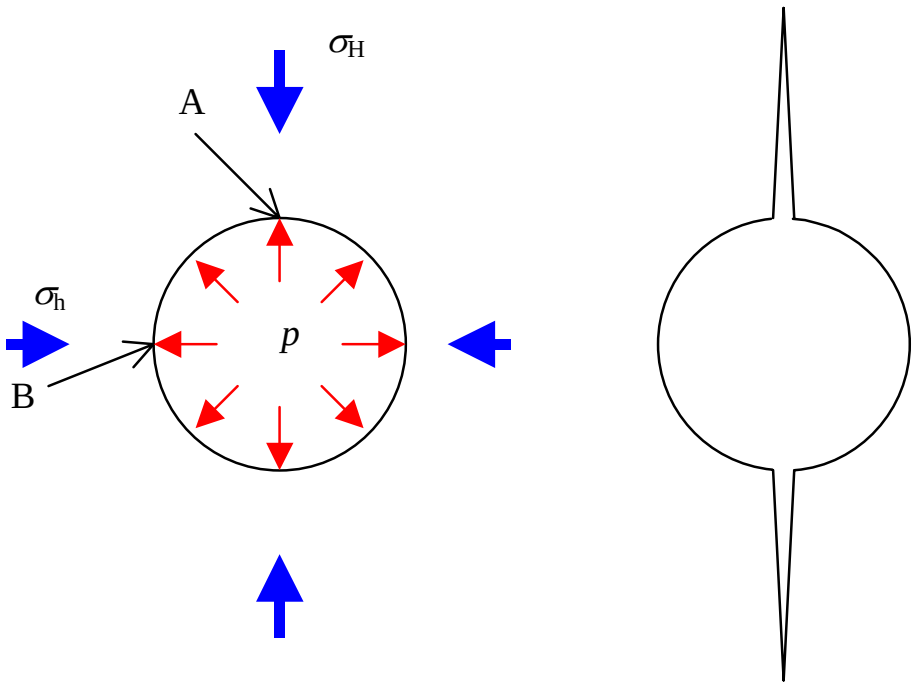
Principle of hydraulic fracturing

- Reopening occurs when the tangential stress at point A becomes tensile.

$$0 \geq 3\sigma_h - \sigma_H - p$$

- Consequently, for reopening pressure,

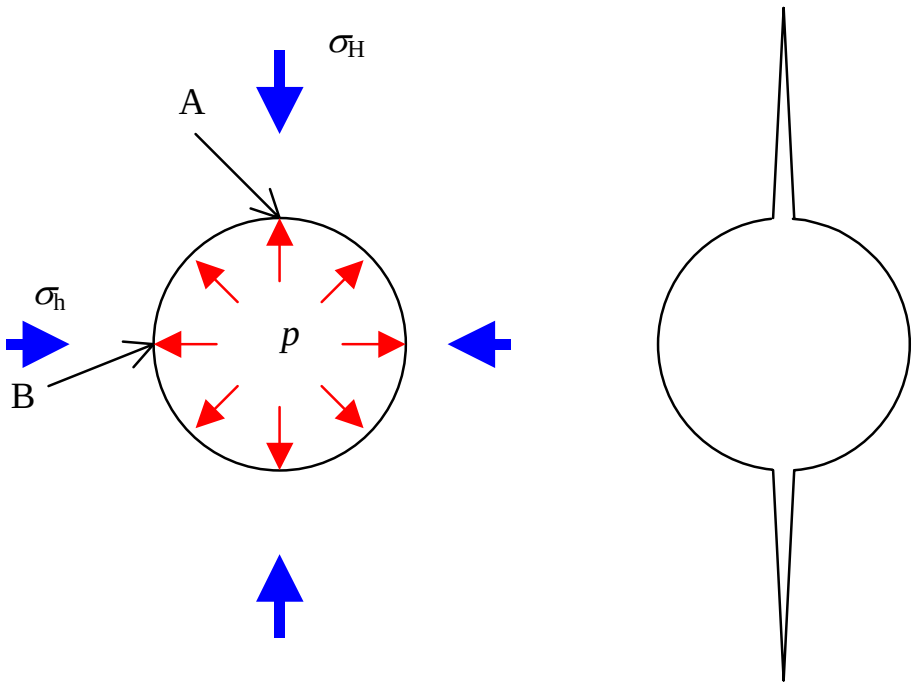
$$0 = 3\sigma_h - \sigma_H - p_r$$



Principle of hydraulic fracturing

- It is said that shut-in pressure is roughly equal to σ_h.

$$\sigma_h = p_s$$



Procedure to estimate initial stress

- Minimum principal stress is estimated from the shut-in pressure

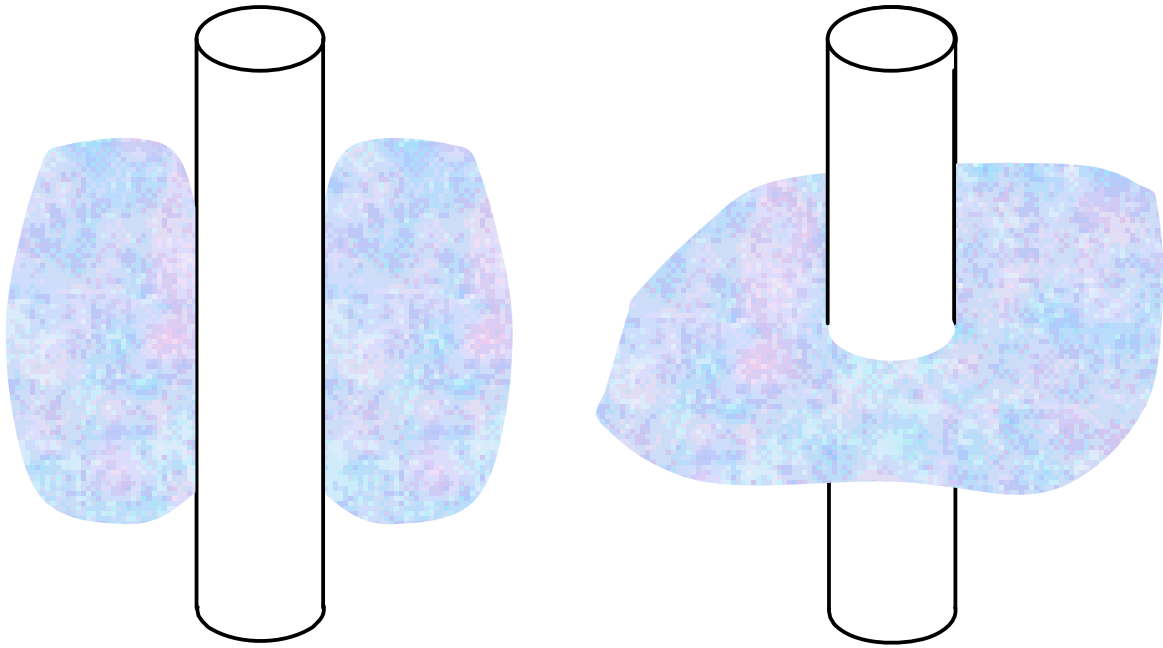
$$\sigma_h = p_s$$

- Maximum principal stress is estimated from the minimum principal stress and the re-opening pressure.

$$0 = 3\sigma_h - \sigma_H - p_r$$

- Orientation of the maximum principal stress is equal to that of the fracture observed by a borehole camera or an impression packer.

Vertical fracture (left) and horizontal fracture (right)



Criterion for horizontal fracture

- Vertical stress σ_v at borehole wall is

$$\sigma_v = \sigma_V - 2p$$

- Criterion for horizontal fracture is

$$\sigma_v < 3\sigma_h - \sigma_H$$

- Another method has to be used in he case where horizontal fracture occurs.

More detail

- Consideration on pore pressure and fracture mechanics（Nihon Kikai Gakkai, 1989)
- Determination of three dimensional stress state based on data from one borehole (Nihon Kikai Gakkai, 1989)
- Statistical consideration (Shin & Okubo, 1999)
- Estimation of initial stress measuring strains (Sato et al., 1999b、Itoh et al., 2001)
- Detailed consideration on re-opening pressure (Ito et al., 1999b)

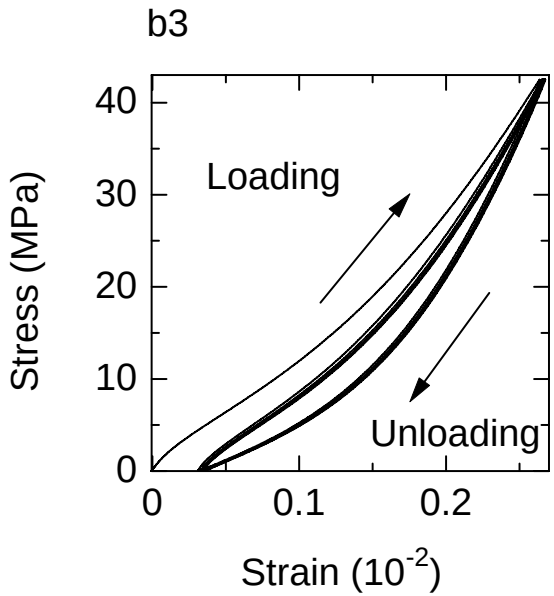
Example

- Calculate breakdown, re-opening and shut-in pressures for a rock mass whose tensile stress is 10 MPa. Maximum and minimum horizontal stresses are 25 MPa and 20 MPa, respectively.

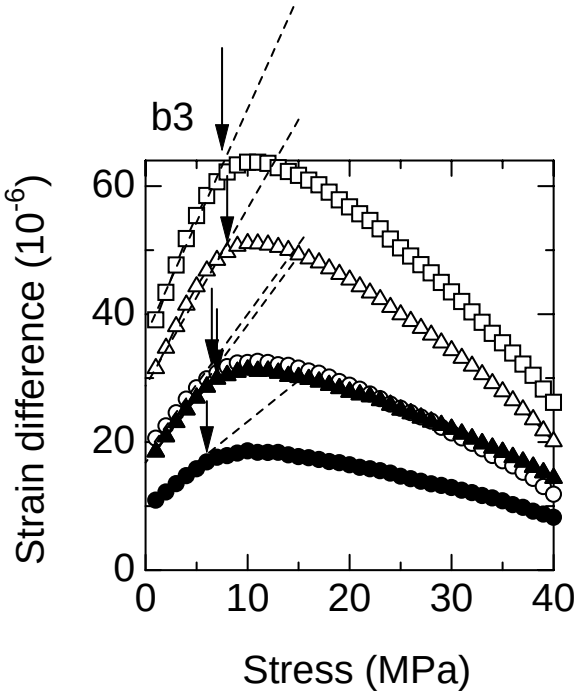
9.5 Methods using oriented cores

- Estimation of initial stress from laboratory test on oriented cores (Ex. Nihon Kikai Gakkai, 1989)
  - AE mehod (Lavrov, 2003)
  - DSCA method (Oikawa et al.,1995, Yamaguchi et al., 1991, Matsuki et al., 1995)
  - DRA mehod
  - ASR method
  - *Mehod utilizing P-wave velocity*
- Results similar to such reliable methods as stress relief method and hydraulic fracturing method are often obtained.
- Principle is not well known. There are many points which should be clarified. For example, how long rock core maintain the stress memory is not well known.

Example of DRA method



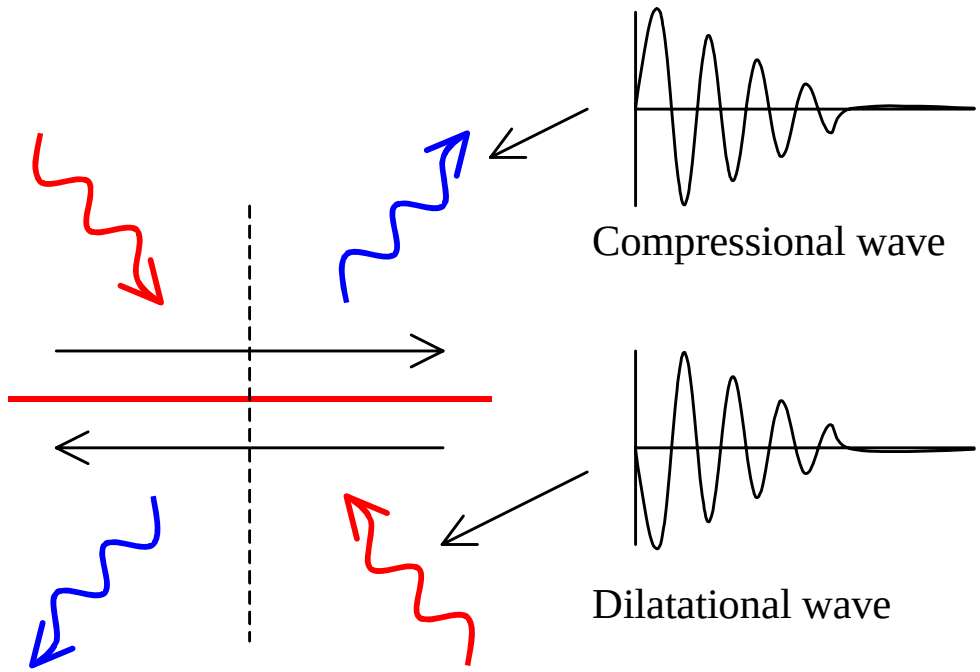
Stress-strain curves



Strain difference function

9.6 Method based on fault earthquakes

- Sign and amplitude of elastic wave from fault slip depends on orientation to the observatory.
- Compressional and dilatational wave can be observed for P-wave, for example.



- Compression and tensile axes can be obtained by projecting polarity of P-wave on the direction of observatory.
- Directions of compression and tension axes are sometimes regarded as those of the maximum and minimum principal stress, respectively.

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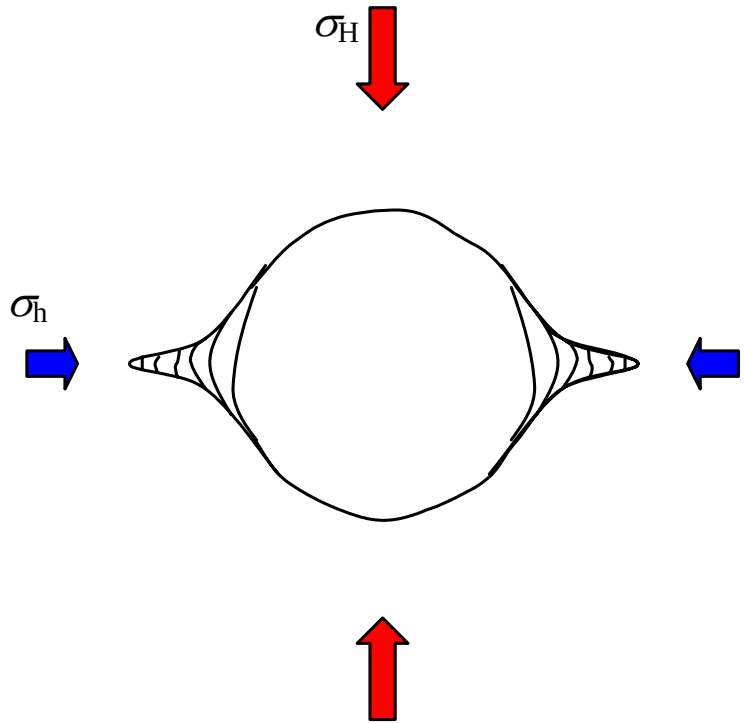
『笠原慶一（1983） 地震の力学、鹿島出版会、p. 52, 図3.15』を省略させて頂きます。

- Compression and tension axes represents stress change due to fault slip and their directions should not be always coincides to those of initial stress. However, similar results to stress relief method and hydraulic fracturing method are often obtained.
- The directions of initial stress can be easily estimated from enormous fault earthquake data although the magnitude of initial stress can't be estimated.

9.7 Other methods

Borehole breakout

- Failure phenomena which are observed at sidewall of petroleum and geothermal wells
- Failure zones of dog ear-shape grow in the direction of the minimum principal stress
- Initial stress magntude can be estimated from the shape of the failure zone.
- For detail, refer Brudy & Zoback (1999), Cuss et al. (2003), Haimson & Lee (2004)



Core discing

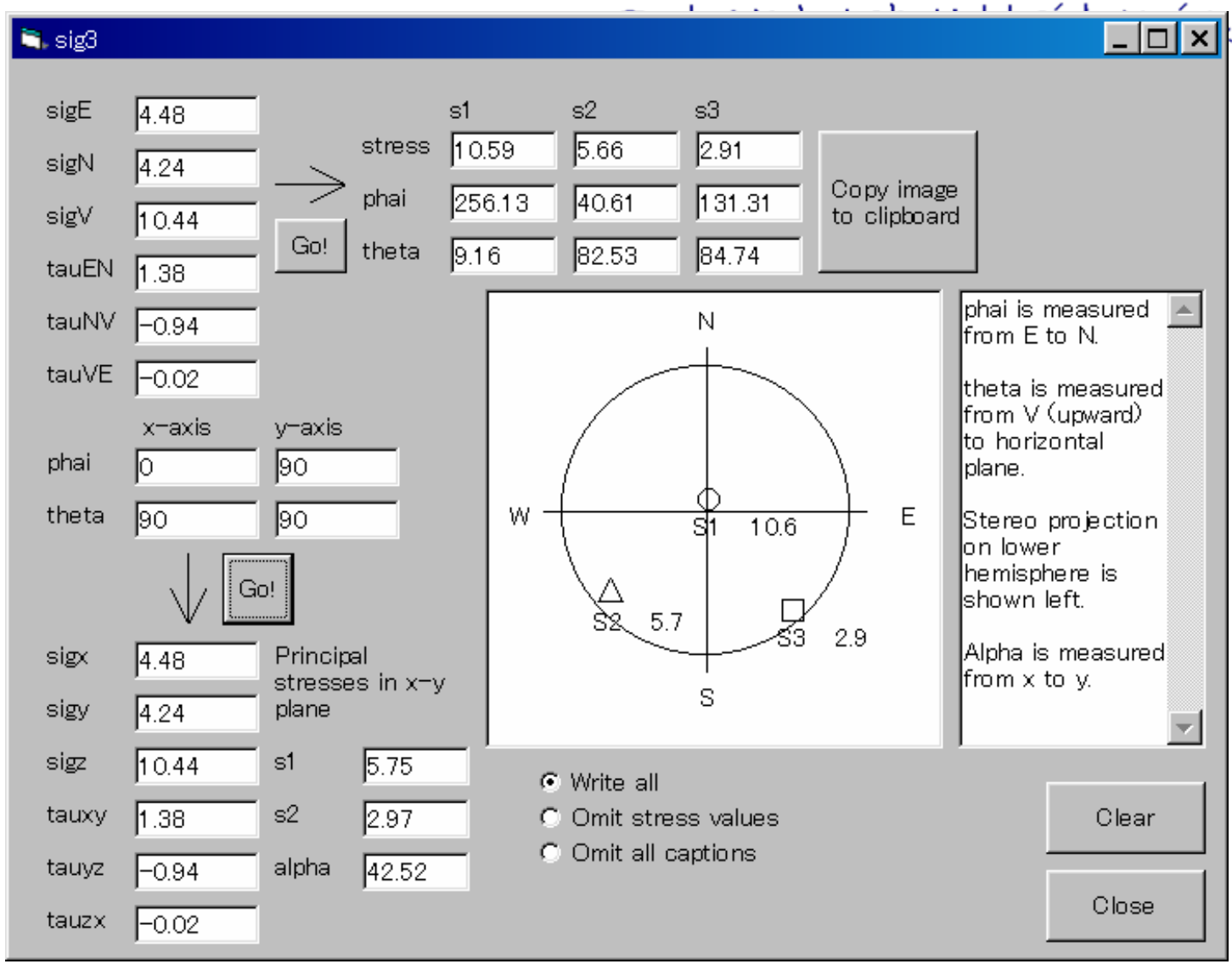
- Rock core breaks in a many discs when a borehole is drilled to a high pressure zone.
- Relationship between stress state and disc shape is investigated (ex. Obara et al., 1998).
- Initial stress state can be roughly estimated.

Core discing which was observed at Kamaishi Mine

Other other other

- Calcite twins（Kang *et al*., 1999）
- Sub-crater of volcano (Karino and Murata, 1998）
- Electric resistivity (Ito *et al*., 1999a）
- etc.....

9.8 Example result of initials stress measurement



Example of results at Ikeshima Coal Mine. Depth is 416 m.

http://rock.eng.hokudai.ac.jp