# Geothermal Energy (Week 9, 26 Oct)
# - Reservoir Geomechanics

민기복

Ki-Bok Min, PhD

서울대학교 에너지자원공학과 조교수
Assistant Professor, Energy Resources Engineering

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# Homework #3

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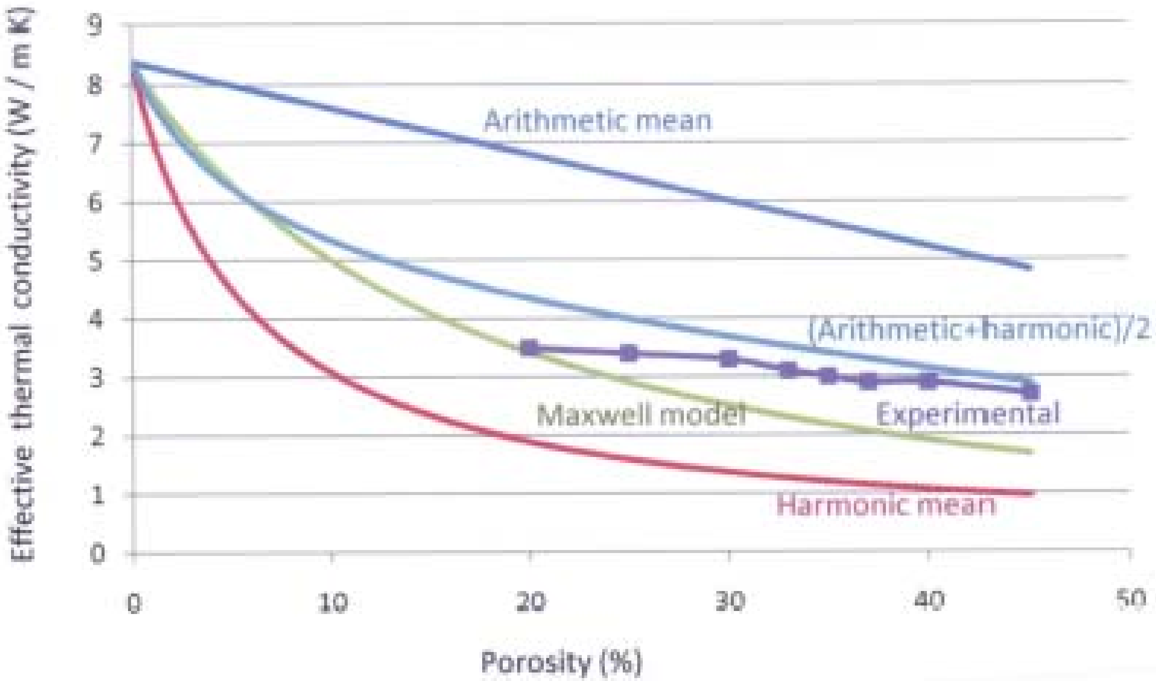
2) 측정된 값은 산술평균과 조화평균의 중간에 위치한다. Maxwell모델 역시 예측오차가 n이 클수록 컸다. 어차피 모델에 오차가 존재한다면 상한과 하한의 평균으로 예측해도 큰 무리가 없을 것이다. 따라서




$k_e = (k_{산술} + k_{조화})/2$

의 식을 이용해 예측하는 제안해보았다. 측정값과 큰 무리 없이 예측되고 있는 것을 확인할 수 있다.

creative! +2

5/5

# Homework #3

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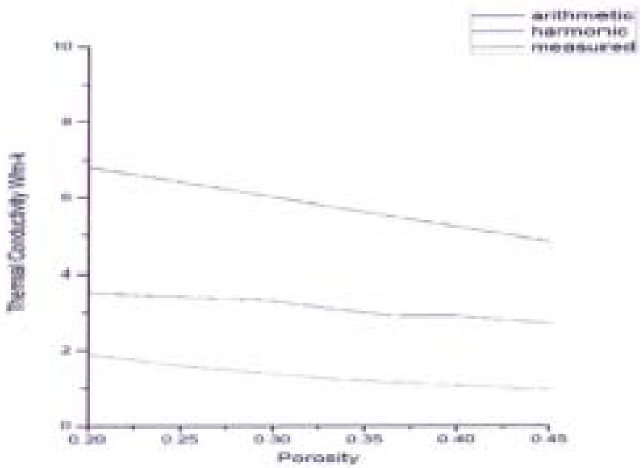
(2) Measured thermal conductivity is plotted in the graph below.




The measured values locate to between the largest and lowest values. Therefore, I think it is a good prediction.

I don't think so.

1/5

# Term Paper
# Progressive Report

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- Submission by 24:00 30 Oct (through email)
- Late submission by 24:00 1 Nov (20% penalty)
- Please use MS Word for writing report (due to track change function)
- Meeting with me (after class on 28 Oct)

| Milestone | Length | Due date | Mark |
|---|---|---|---|
| Proposal | ~1 page | 25 Sept | 10% |
| Progress Report | ~5 pages | 30 Oct | 20% |
| Final Report | ~20 pages | 4 Dec | 35% |
| Presentation | 20 minutes (including questions) | 7 & 9 Dec | 35% |

# Reservoir Geomechanics
## outline

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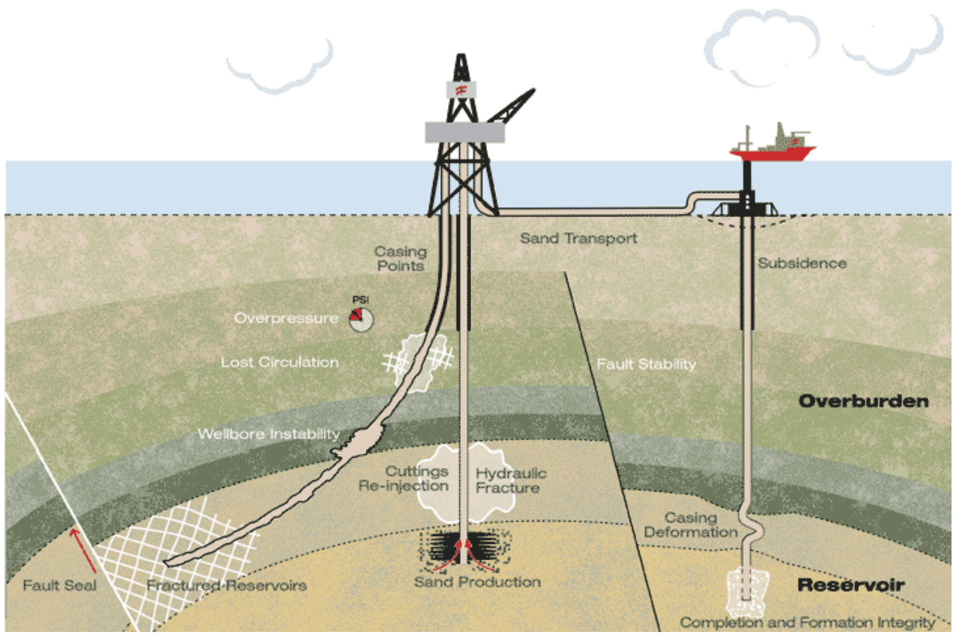
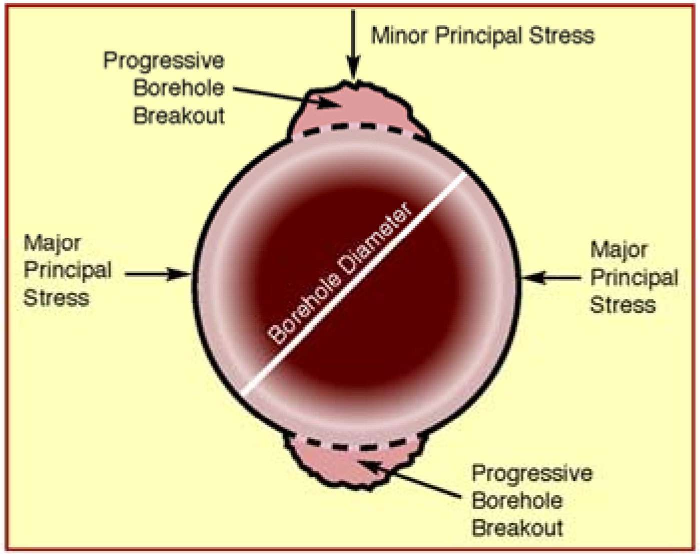
- Fundamentals of rock mechanics
- Borehole stability – stability of geothermal wellbore
- Mechanics of Hydraulic fracturing
- Reservoir Geomechanics




http://www.swri.edu/3PUBS/BROCHURE/D20/geotech/geotech.HTM

http://www.helix-rds.com/EnergyServices/HelixRDS/Capabilities/Geomechanics/tabid/178/Default.aspx

# Wednesday

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- Stress distributions around a borehole
- Kirsch solution
- General Kirsch solution considering internal pressure and thermal stress
- Condition for tensile failure
- Condition for compressive failure

# today

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- Borehole Stability (continue)
- Hydraulic Fracturing

# Drilling Video

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# Stresses distribution around a borehole with principal boundary stresses

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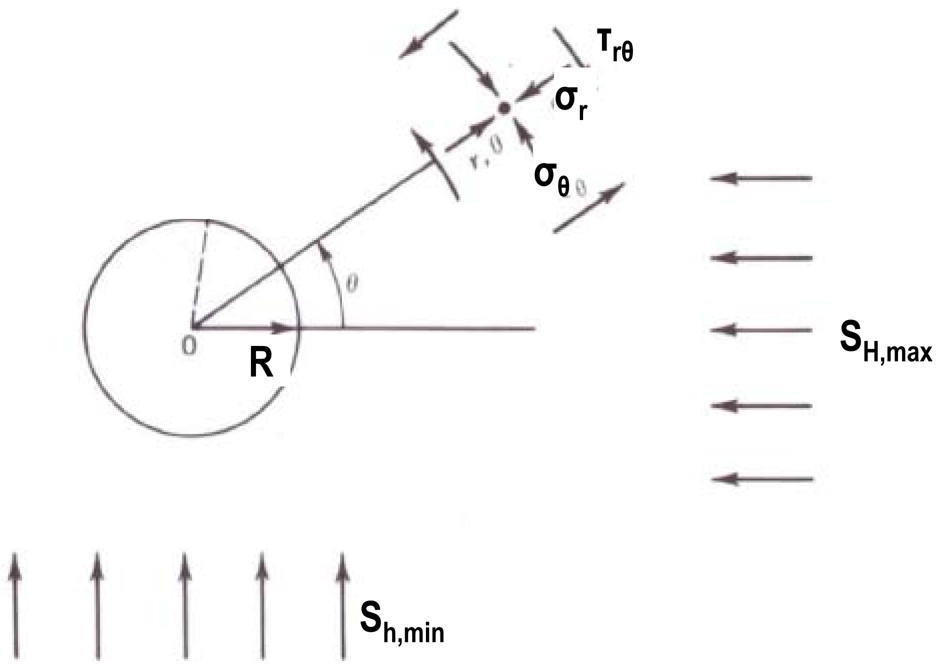
- Problem of stress distribution around a circular borehole was solved by Kirsch (1898)
- Homogeneous rock under plane strain condition within elastic range



# Stresses distribution around borehole with principal boundary stresses

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$$\sigma_r = \frac{S_{H\max} + S_{h\min}}{2}\left(1 - \frac{R^2}{r^2}\right) + \frac{S_{H\max} - S_{h\min}}{2}\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\sigma_\theta = \frac{S_{H\max} + S_{h\min}}{2}\left(1 + \frac{R^2}{r^2}\right) - \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta$$

$$\tau_{r\theta} = \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

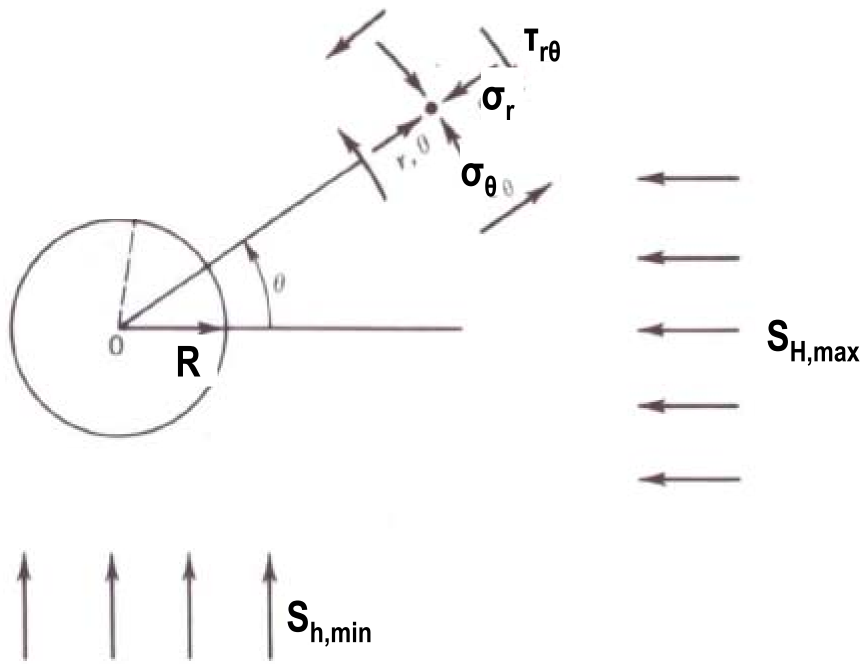
$$\sigma_{zz} = S_v - 2\nu\left(S_{H\max} - S_{h\min}\right)\frac{r^2}{R^2}\cos 2\theta$$

R: radius of well

r: radial distance from the center of the well

θ: measured from $S_{H,max}$

$S_{H,max}$ and $S_{H,max}$: maximum and minimum horizontal insitu stress



# Stresses distribution around borehole
# with principal horizontal stresses

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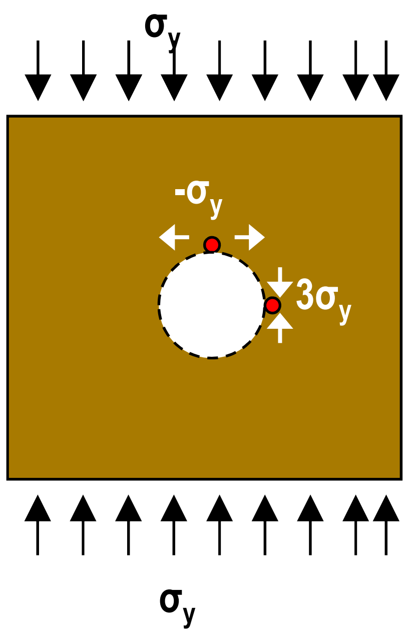
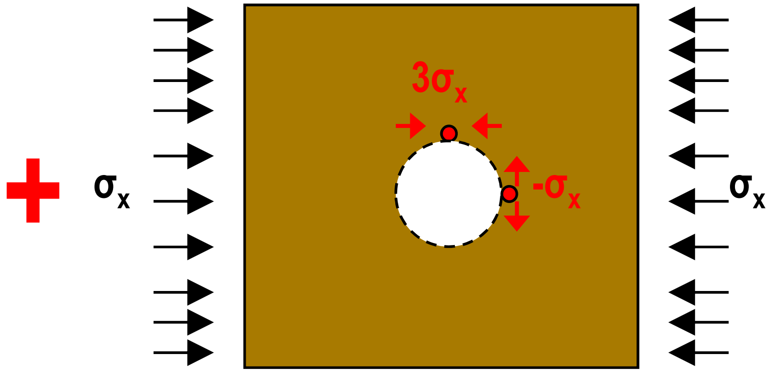
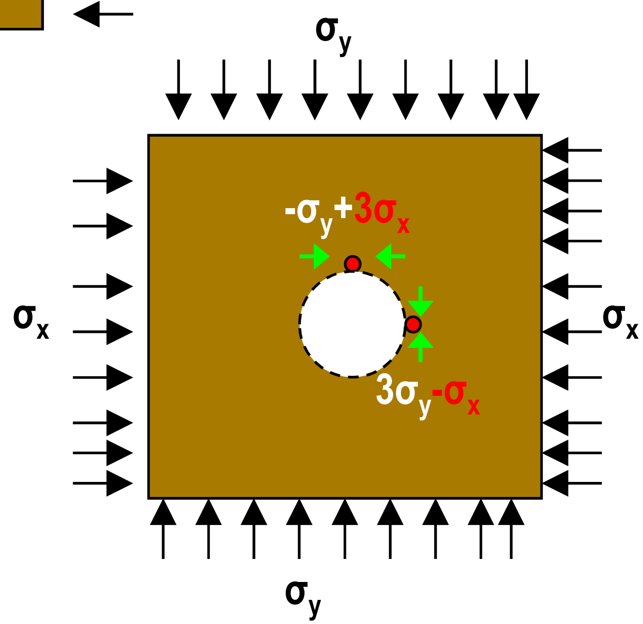



By superimposing two cases, we can obtain stress concentration under biaxial stress field.

In a uniaxial stress field, the maximum stress concentration is 3 (compressive) and minimum is -1 (tensile)

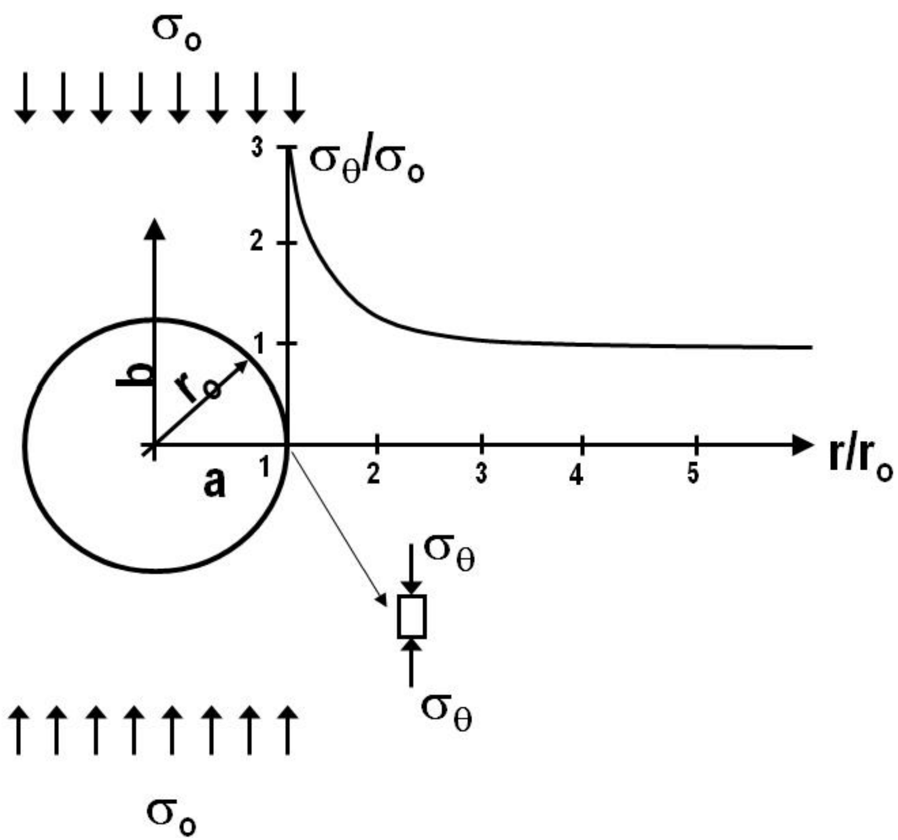
=



# Stresses distribution around borehole with principal horizontal stresses



- Influence of borehole is within 2~3 times of radius



# Stresses distribution around borehole
## General solution

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- Stresses distribution around a borehole with;
  - Principal in situ stress boundary
  - Internal pore pressure (could be mud pressure)
  - Temperature change

$$\sigma_r = \frac{S_{H\max} + S_{h\min}}{2}\left(1 - \frac{R^2}{r^2}\right) + \frac{S_{H\max} - S_{h\min}}{2}\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta + P_w \frac{R^2}{r^2}$$

$$\sigma_\theta = \frac{S_{H\max} + S_{h\min}}{2}\left(1 + \frac{R^2}{r^2}\right) - \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta - P_w \frac{R^2}{r^2} + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

$$\tau_{r\theta} = \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

$$\sigma_{zz} = S_v - 2\nu\left(S_{H\max} - S_{h\min}\right)\frac{r^2}{R^2}\cos 2\theta + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

# Stresses distribution around borehole
# General solution

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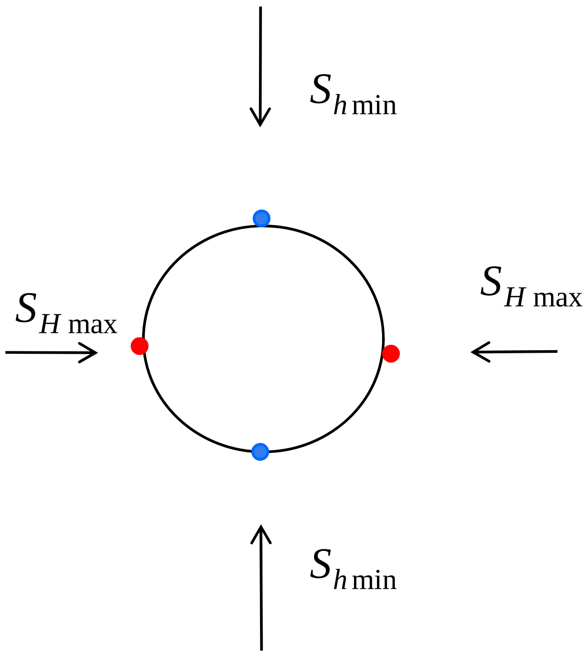
– At the borehole wall (r = R), maximum and minimum hoop stresses are;

- $$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

- $$\sigma_{\theta,\max} = 3S_{H\max} - S_{h\min} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$




– Without considering temperature change,

$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w$$
$$\sigma_{\theta,\max} = 3S_{H\max} - S_{h\min} - P_w$$

# Stresses distribution around borehole
## General solution

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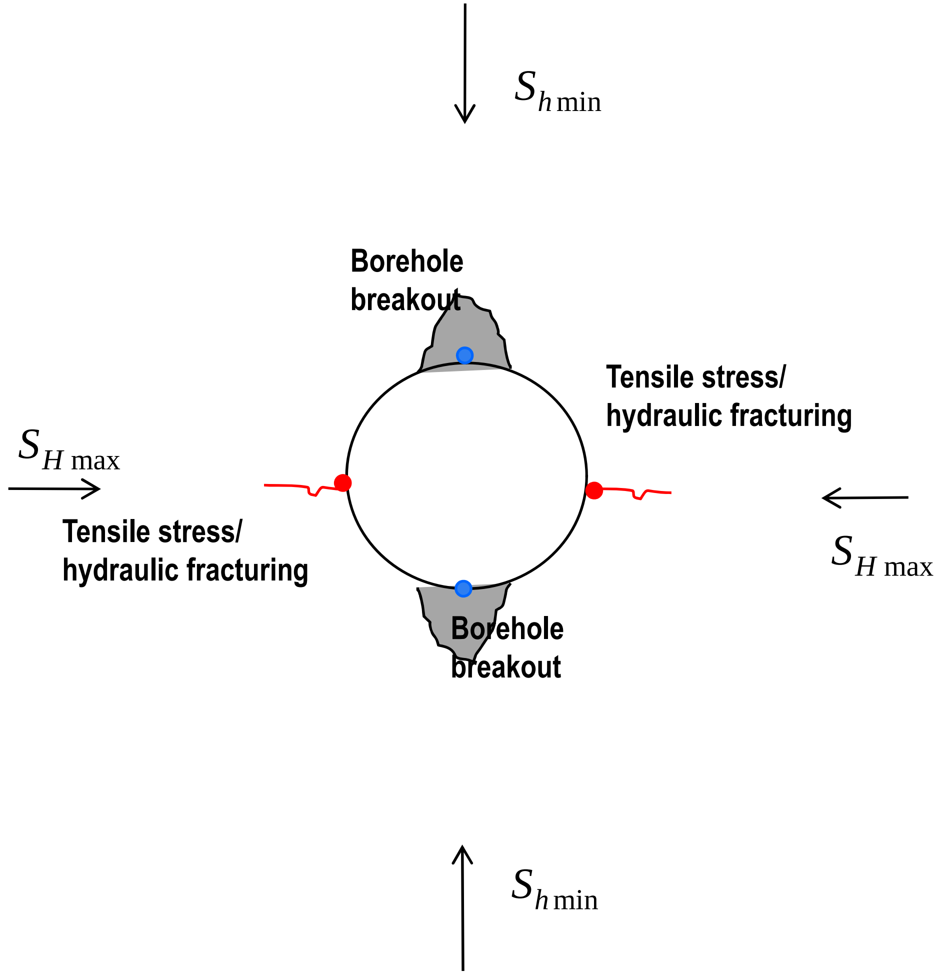


– Required internal pressure to induce tensile stress;

- $P_w > 3S_{h\min} - S_{H\max} + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$

– Required uniaxial compressive strength not to have borehole breakout

- $\sigma_c > 3S_{h\max} - S_{h\min} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$

# Stresses distribution around borehole
## General solution

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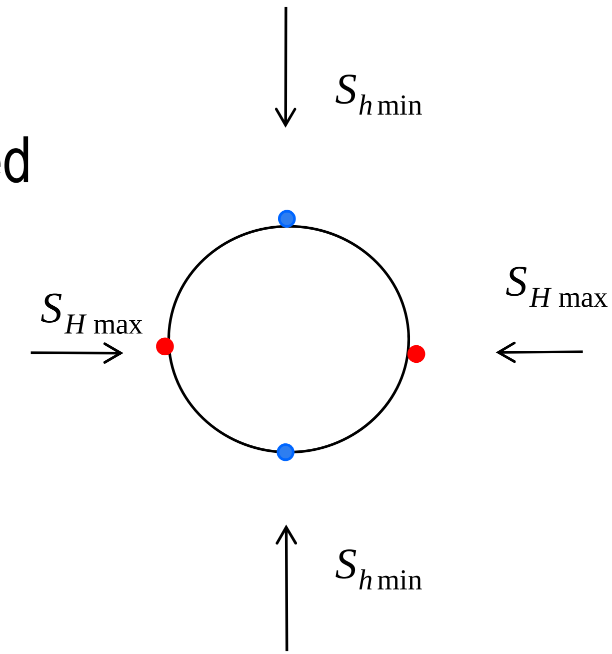
- A more general case around the borehole can be considered.
- And regions where r>R can be also analyzed using failure criteria such as Mohr-Coulomb failure criteria.



# Failure Criteria
## Friction coefficient

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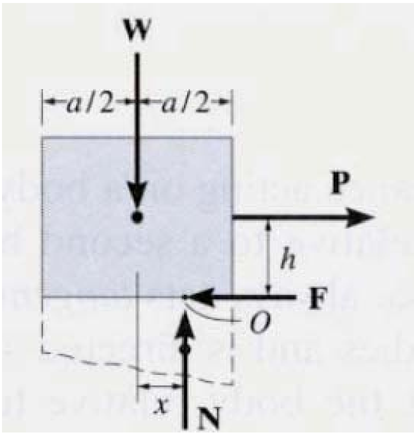
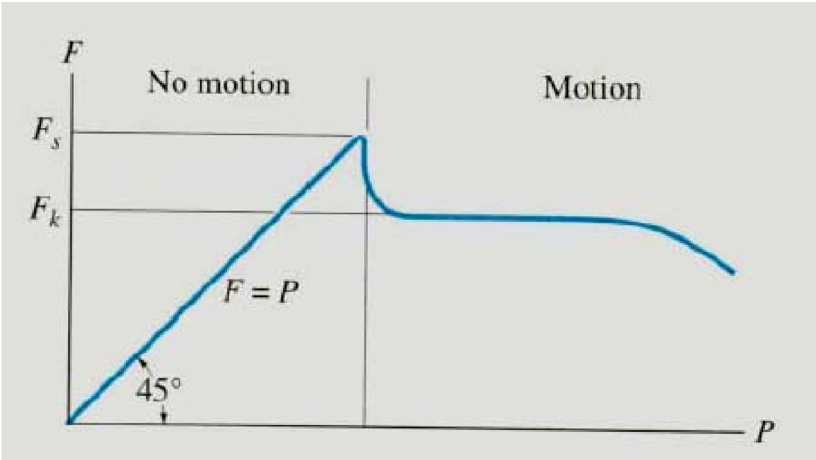
- Friction : force of resistance acting on a body which prevents or retards slipping of the body relative to a second body.
- Frictional forces act tangent (parallel) to the contacting surface in a direction opposing the relative motion or tendency for motion.
- Maximum frictional force, $F_s = \mu N$
- μ: coefficient of (static) friction



# Failure Criteria
# Friction coefficient

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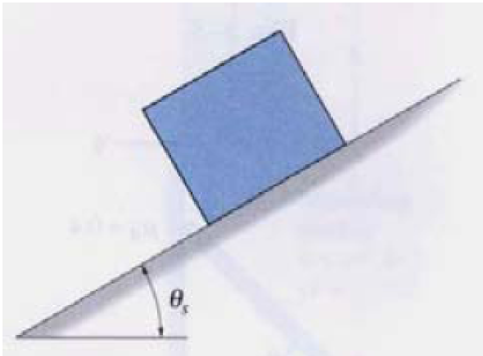
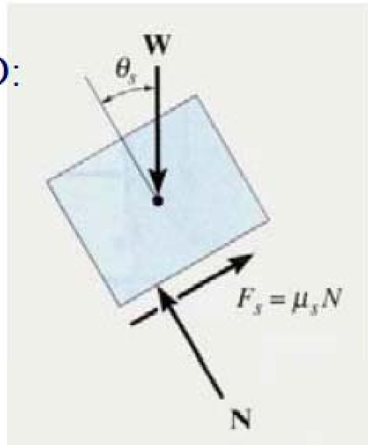
## DETERMING $\mu_s$ EXPERIMENTALLY




A block with weight **W** is placed on an inclined plane. The plane is slowly tilted until the block just begins to slip.

The inclination, $\theta_s$, is noted. Analysis of the block just before it begins to move gives (using $F_s = \mu_s N$):

FBD:




$$\nwarrow + \quad \sum F_y = N - W\cos\theta_s = 0$$

$$\nearrow + \quad \sum F_X = \mu_S N - W\sin\theta_s = 0$$

Using these two equations, we get $\mu_s$ = ($\mathbf{W}\sin\theta_s$) / ($\mathbf{W}\cos\theta_s$) = $\tan\theta_s$

This simple experiment allows us to find the $\mu_S$ between two materials in contact.

# Failure Criteria
## Mohr-Coulomb Failure criteria

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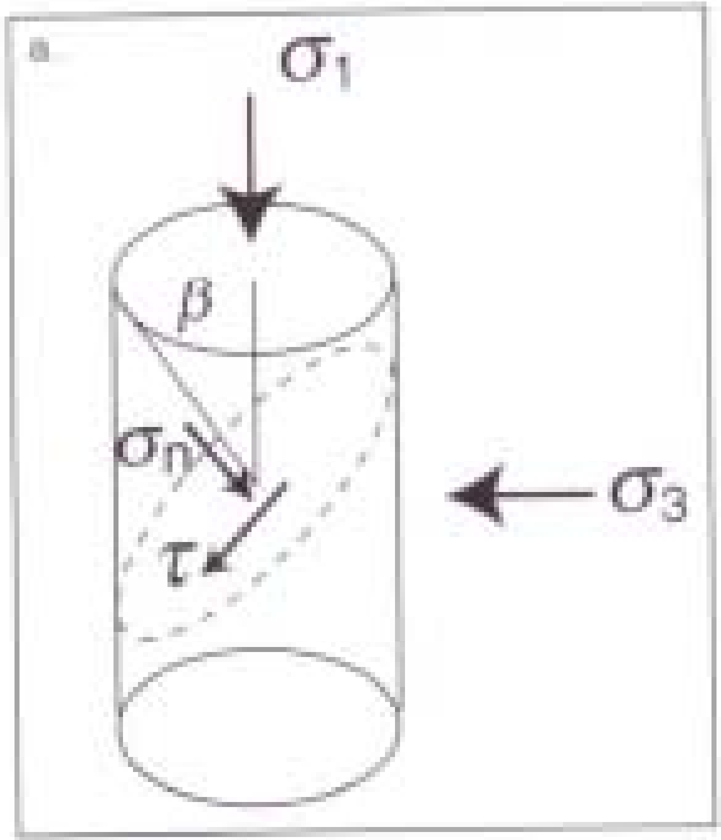


$$\tau = S_0 + \sigma_n \mu_i$$

- τ: Shear stress
- $S_0$=cohesion (or cohesive strength)
- $\sigma_n$: normal stress
- $\mu_i$: coefficient of internal friction

# Failure Criteria

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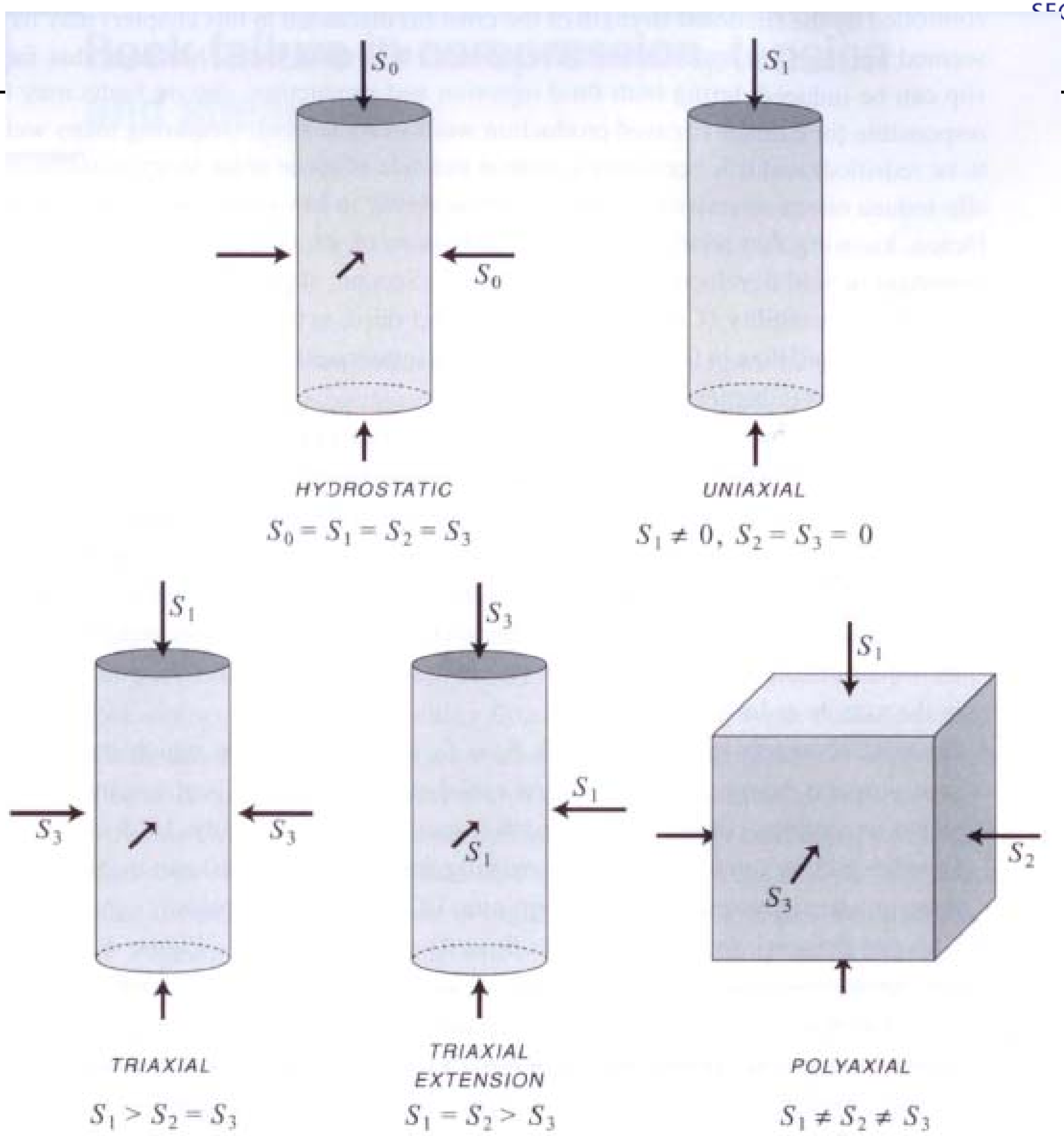

# Failure Criteria
## Mohr-Coulomb Failure criteri

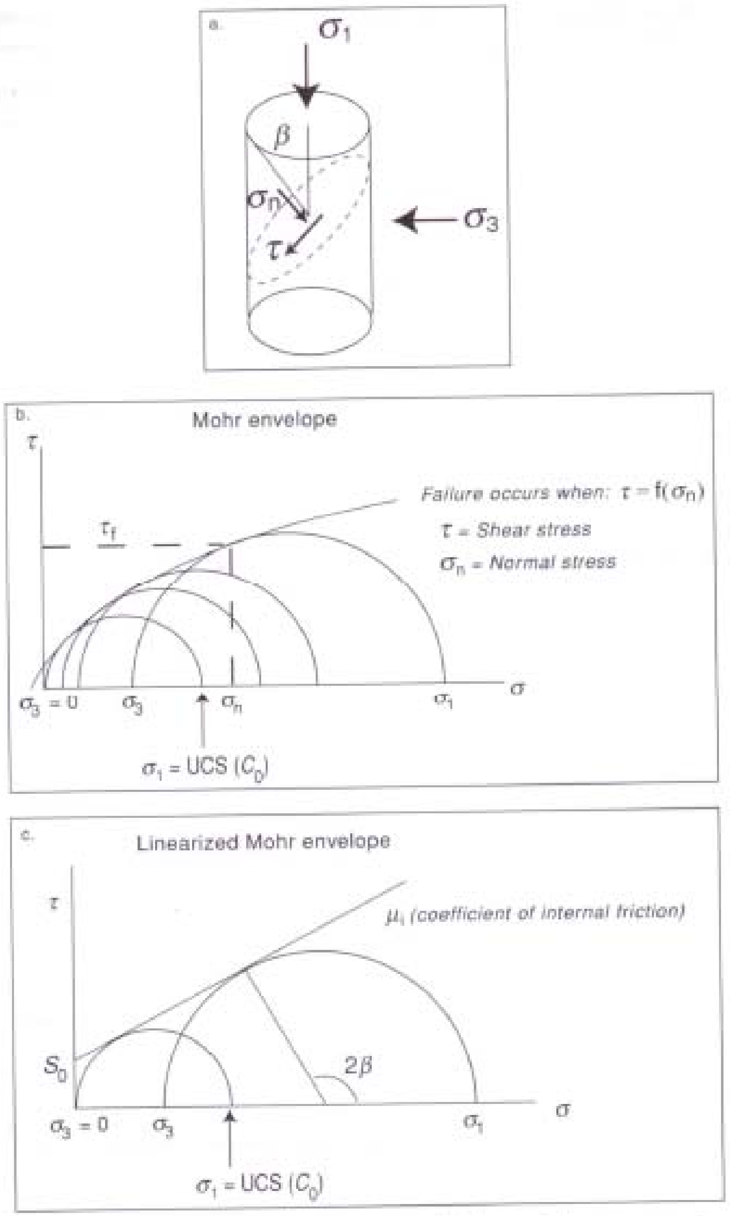


**Figure 4.2.** (a) In triaxial strength tests, at a finite effective confining pressure $\sigma_3$ ($S_3$–$P_0$), samples typically fail in compression when a through-going fault develops. The angle at which the fault develops is described by $\beta$, the angle between the fault normal and the maximum compressive stress, $\sigma_1$. (b) A series of triaxial strength tests at different effective confining pressures defines the Mohr failure envelope which typically flattens as confining pressure increases. (c) The linear simplification of the Mohr failure envelope is usually referred to as Mohr–Coulomb failure.

# Failure Criteria
## Mohr-Coulomb Failure criteria (Example)

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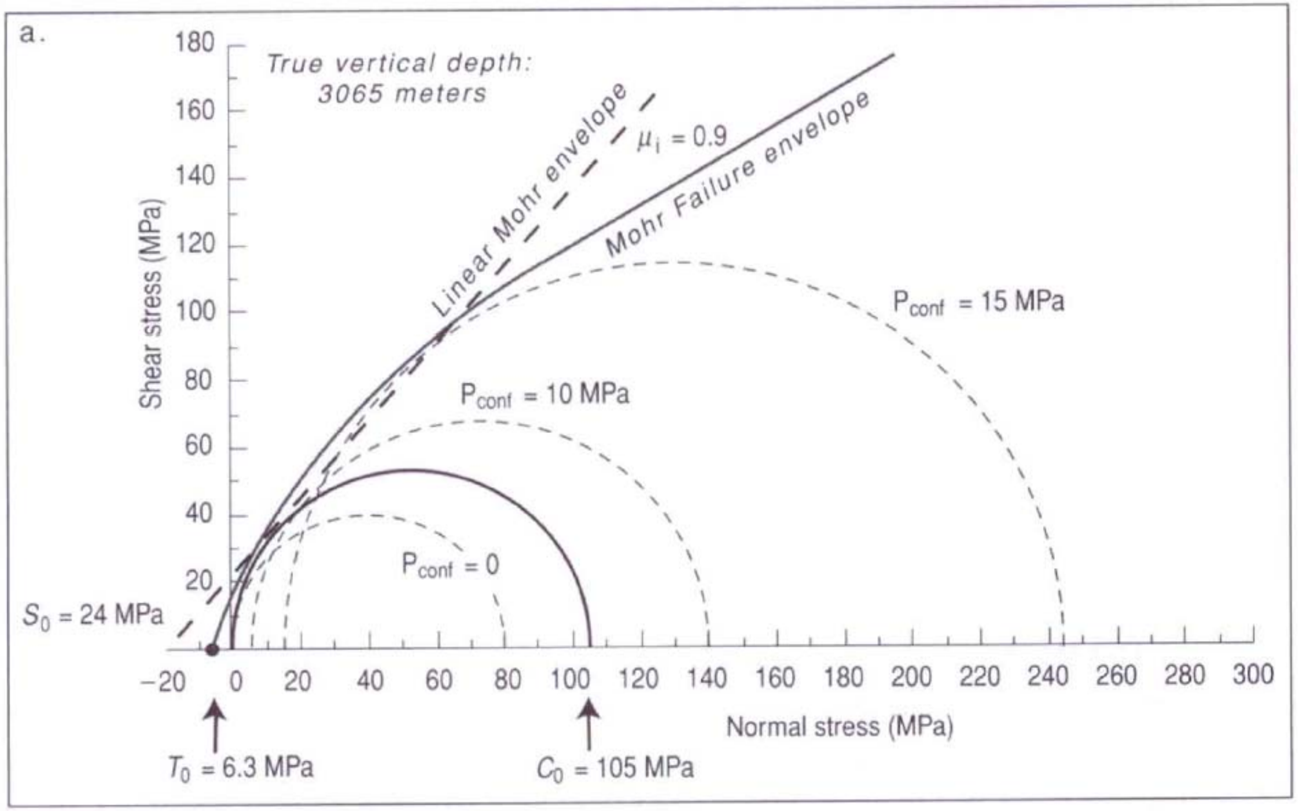
- Sandstone from 3065 m depth in southeast Asia (Zoback, 2007)
- $S_0$=24MPa, UCS=105MPa, $\mu_i$=0.9



# Failure Criteria
## Mohr-Coulomb Failure criteria (Example)

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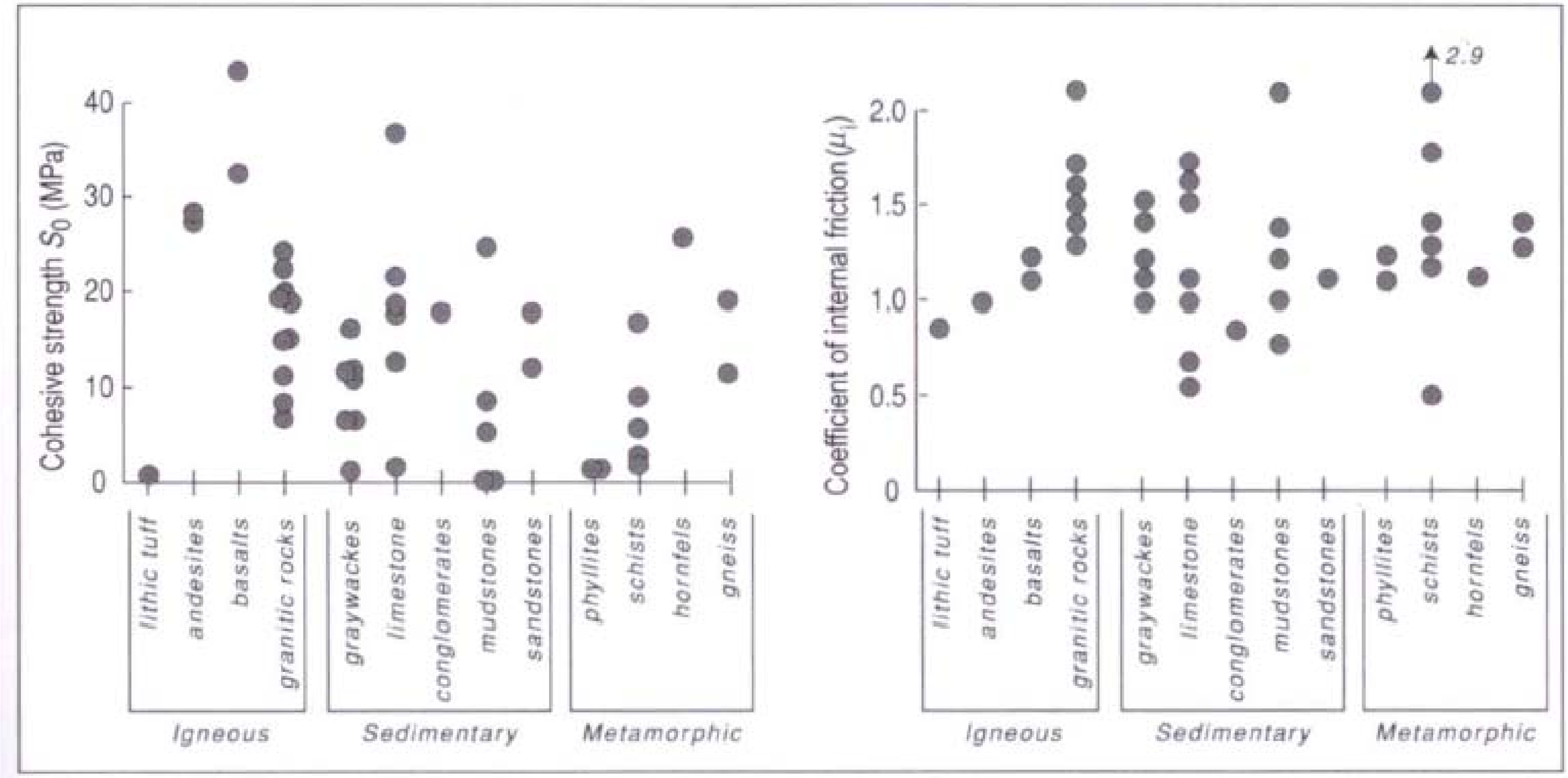
– Examples of measured cohesive strength (cohesion) and coefficient of internal friction



# Failure Criteria
## Application to a borehole

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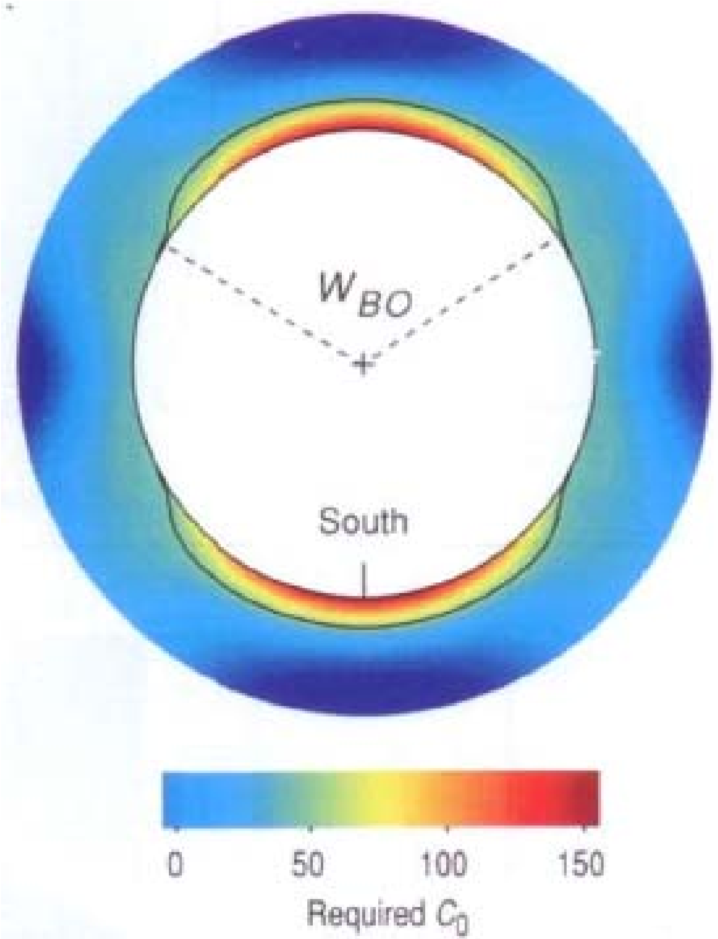
- $S_{hmax}$=90 MPa, $S_{hmin}$=51.5 MPa, $S_v$=88.2 MPa, UCS($C_0$) = 45 MPa, $\mu_i$=1.0
- Region of failure
- Color indicate the required UCS to avoid failure



# Hydraulic Fracturing

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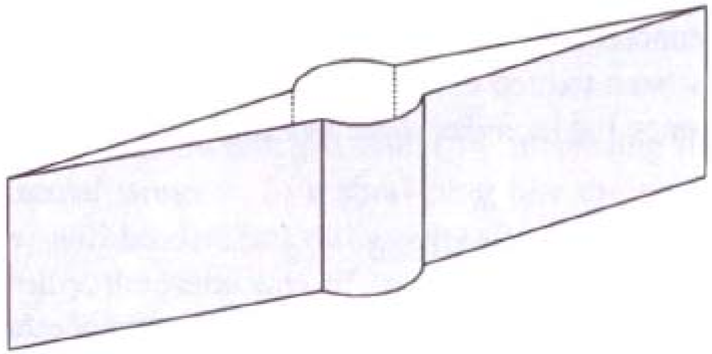
- Fracturing of the rock by fluid pressure for the purpose of altering rock properties, such as permeability.
- Also called ‘hydrofracturing
- Takes place when the fluid pressure within the rock exceeds the smallest principal stress plus the tensile strength of the rock.



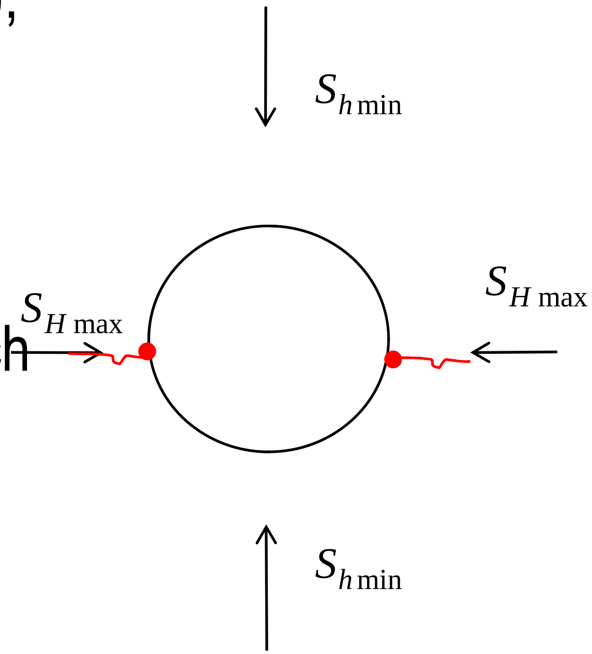
# Hydraulic Fracturing
# Breakdown Pressure



– At the borehole wall (r = R), maximum and minimum hoop stresses are (without considering temperature effect);

$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w$$




– Tensile failure occur when hoop stress reach the tensile strength

$$-T_0 = 3S_{h\min} - S_{H\max} - P_w$$

$$P_b = 3S_{h\min} - S_{H\max} + T_0$$

– $p_b$: breakdown pressure

# Hydraulic Fracturing
# pressure-time response

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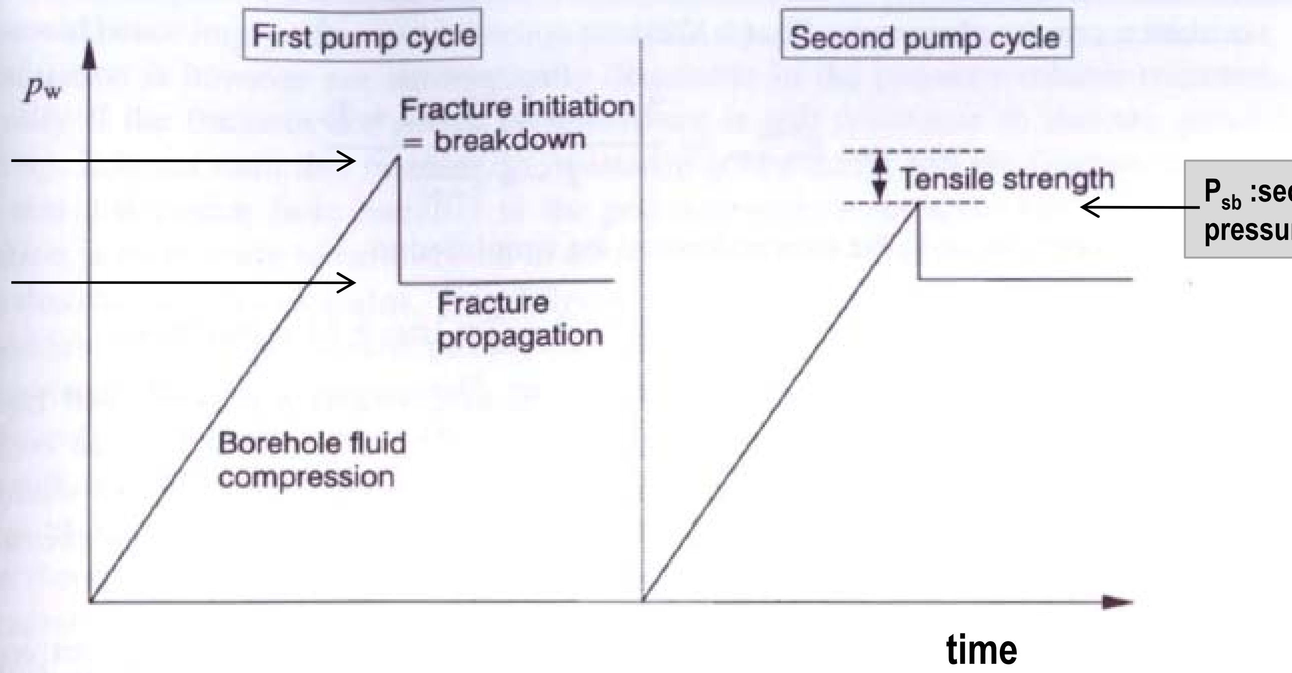
$P_b$ :breakdown pressure

$P_s$: shut-in pressure




$P_{sb}$ :secondary breakdown pressure

Fig. 11.4. Idealized borehole pressure response during hydraulic fracturing of a vertical wellbore. Two pressure cycles are included.

# Hydraulic Fracturing

## shut-in pressure & secondary breakdown pressure

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- Shut-in pressure ($p_s$) is equal to the minimum horizontal stress

$$P_s = S_{h\min}$$

- The difference between breakdown pressure and secondary breakdown pressure equals the tensile strength.

$$P_b - P_{sb} = T_0$$

# Hydraulic Fracturing
# Application to stress measurement

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$$P_b = 3S_{h\,\min} - S_{H\,\max} + T_0$$

$$P_s = S_{h\,\min}$$

$$P_b - P_{sb} = T_0$$

- $S_{hmax}$, $S_{hmin}$ and $T_0$ can be obtained.
- However, above calculation is based on circular borehole and it is not accurate to calculate the maximum principal stress with above method on a deep borehole with borehole breakout.
- Borehole breakout depth??? ~2km???

# Hydraulic Fracturing
## Equipment

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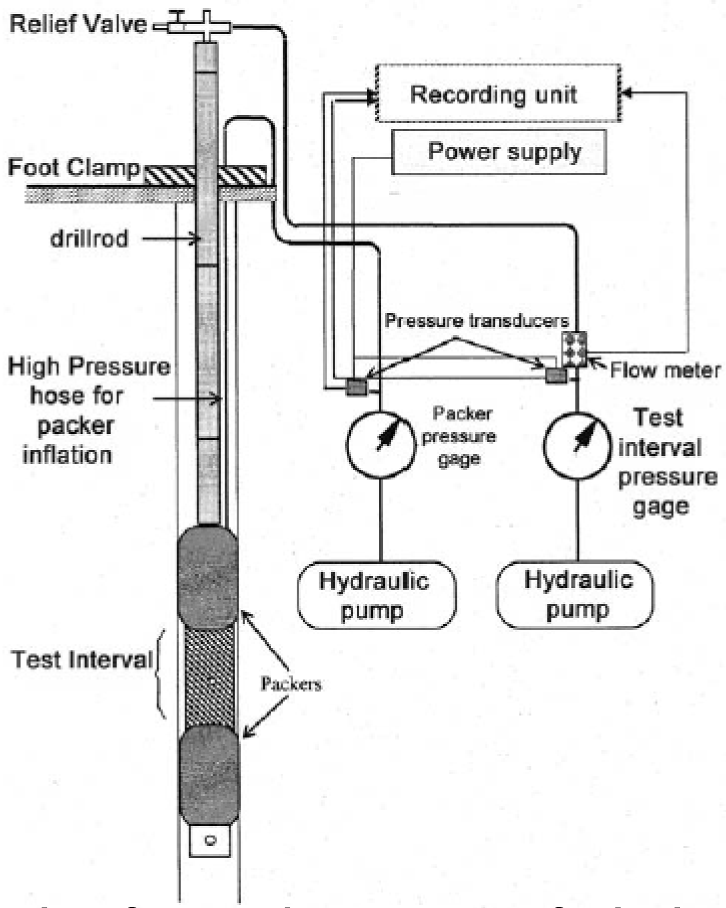


**Schematic downhole and surface equipment set up for hydraulic fracturing (ASTM D 4645-08)**

# Hydraulic Fracturing
## borehole pressure response



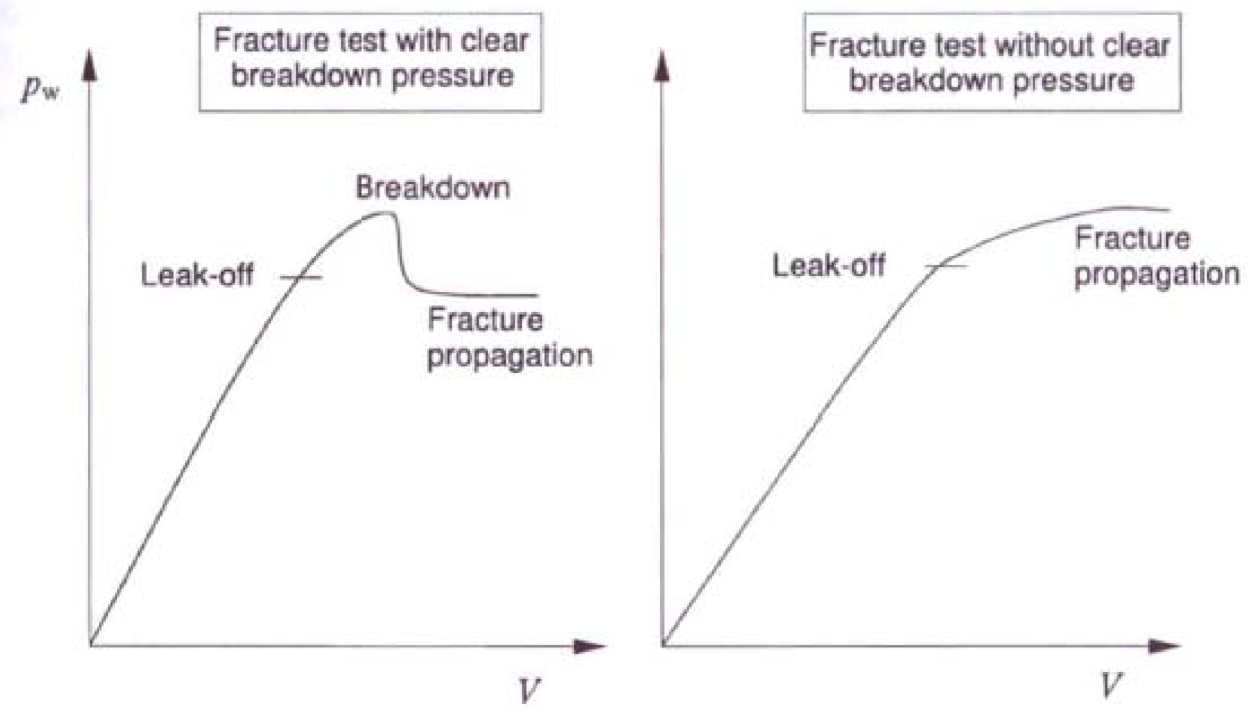


Fig. 11.5. Realistic borehole pressure response during hydraulic fracturing of a vertical wellbore. The example to the left has a distinct breakdown pressure, while this is not the case in the example to the right.

# Hydraulic fracturing
# Proppant

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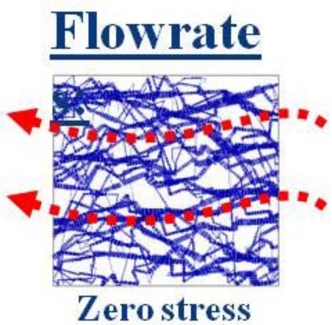
- Sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment.
- In addition to naturally occurring sand grains, man-made or specially engineered proppants, such as resin-coated sand or high-strength ceramic materials like sintered bauxite, may also be used.
- Proppant materials are carefully sorted for size and sphericity to provide an efficient conduit for production of fluid from the reservoir to the wellbore (Schlumberger dictionary).

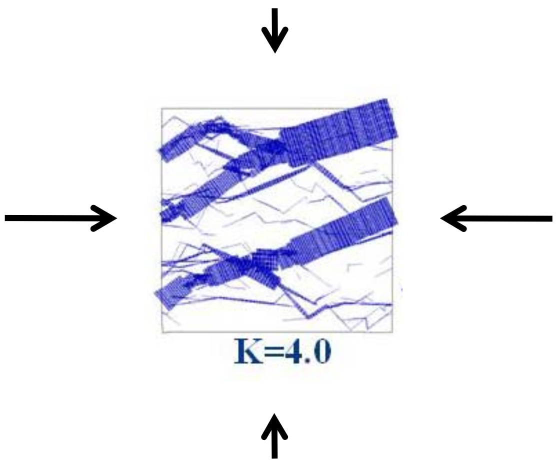
# Hydraulic stimulation



– The fractures created by hydraulic stimulation, which best connect across the reservoir, may not formed through tension. Instead, they are created by shearing on pre-existing joint sets (MIT, 2006).

– Shear failure of fracture occur inclined to the maximum principal stress



# today

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- Borehole Stability (continued)
  - Mohr-Coulomb Failure Criteria
- Hydraulic Fracturing
  - Direction of fracturing
  - Condition for fracture initiation/propagation

# Wednesday

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- Reservoir Geomechanics
- Coupled Process

# References

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- Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press
- Fjaer E et al., 2008, Petroleum-related Rock Mechanics, 2nd Ed., Elsevier
- ASTTM D 4645-08, Standard Test Method for Determination of In-Situ Stress in Rock Using Hydraulic Fracturing Method