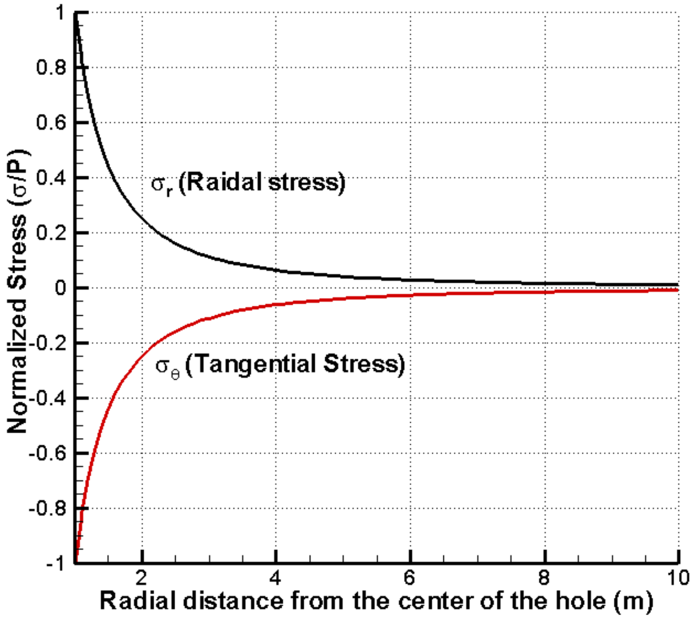
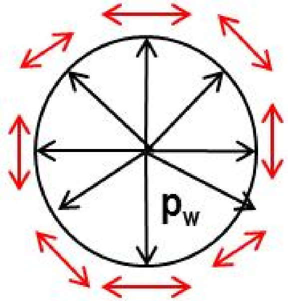
Topics in Energy and Environmental Geomechanics – Enhanced Geothermal Systems (EGS)
Lecture 2. Fundamentals of Geomechanics (2)





Ki-Bok Min, PhD, Associate Professor

Department of Energy Resources Engineering

Seoul National University

Introduction
Contents of the course

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- Week 1 (2 Sept):Introduction to the course/Climate change & Emerging Subsurface Eng Application
- Week 2 (9 Sept): Fundamentals of Geomechanics
- Week 3 (16 Sept):Borehole Stability
- Week 4 (23 Sept): Borehole Stability
- Week 5 (30 Sept): No lecture (business trip)
- Week 6 (7 Oct) : Hydraulic Stimulation (focus on Hydraulic fracturing)
- Week 7 (14 Oct): Hydraulic Stimulation
- Week 8 (21 Oct): Induced seismicity
- Week 9 (28 Oct): Induced seismicity

Introduction
Contents of the course

- Week 10 (4 Nov): Drilling Engineering (invited lecture)
- Week 11 (11 Nov): Well logging (invited lecture)
- Week 12 (18 Nov): EGS Case studies
- Week 13 (25 Nov): EGS Case studies
- Week 14 (2 Dec): Student Conference
- Week 15 (9 Dec): Final Exam (closed book or take-home exam)

Borehole stability problem

- Importance?
  - Economy, Safety, Environment
  - Optimal trajectory and mud weight determination
- Factors
  - In situ stress
  - Injection pressure or mud weight
  - Reservoir rock mechanics properties
  - Anisotropy
  - Thermal effect
  - …

Borehole stability problem

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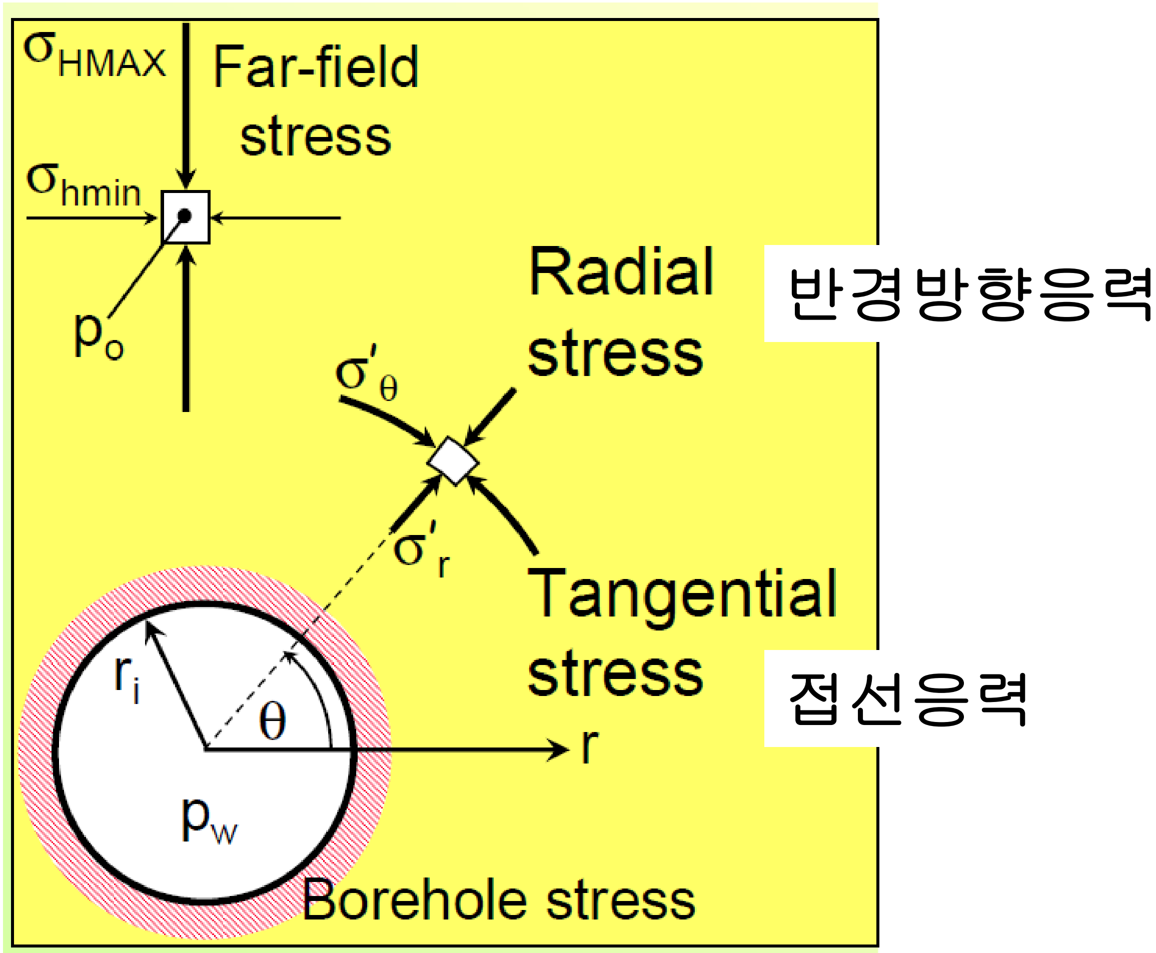
- Definitions – cylindrical coordinate

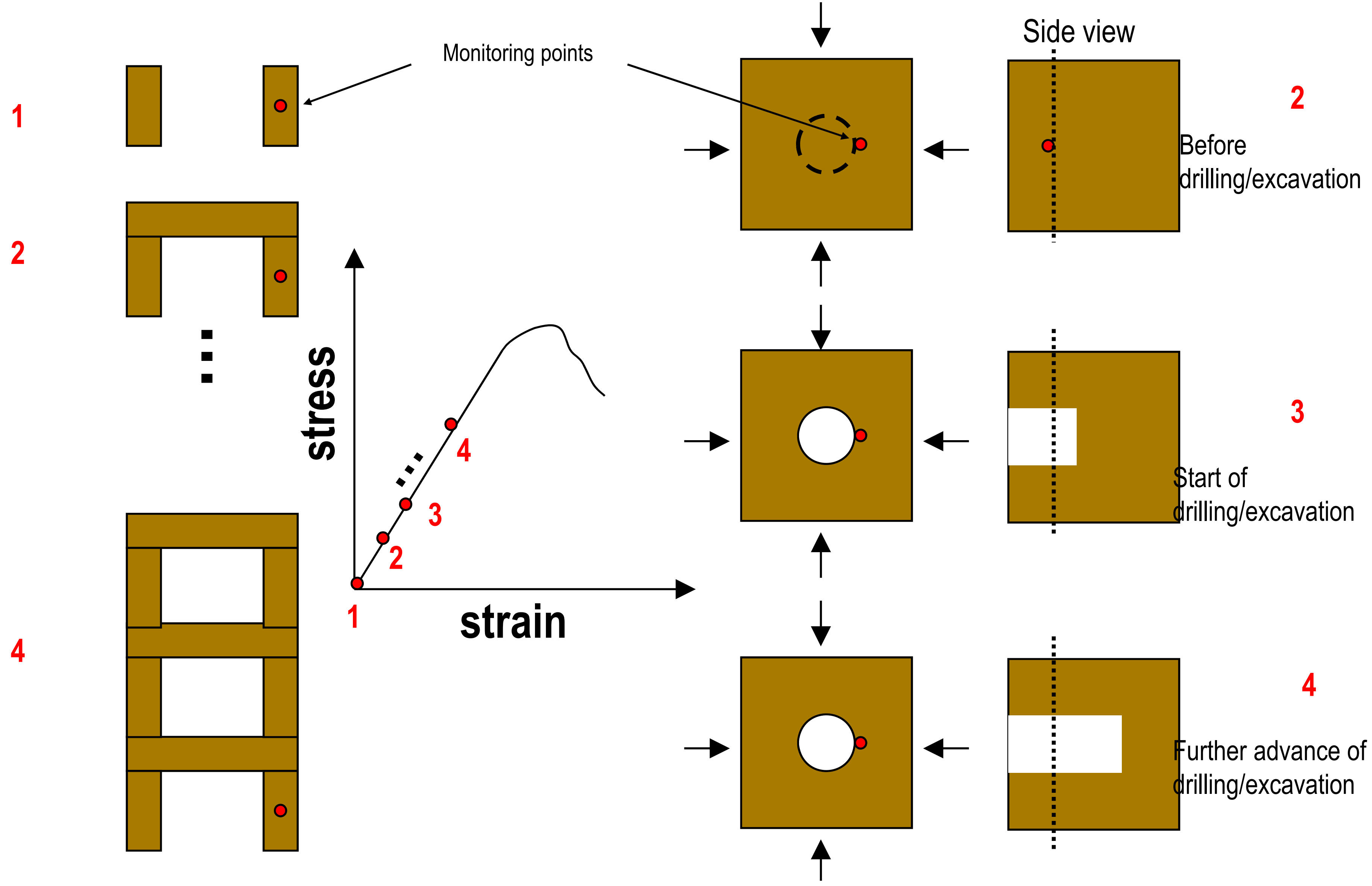


Dusseault, 2012

Nature of Underground Geomechanics

Civil structural problems:
Mechanics of "Addition"

Underground Geomechanics problems:
Mechanics of "Removal"



Borehole stability problem
Kirsch solution (1)

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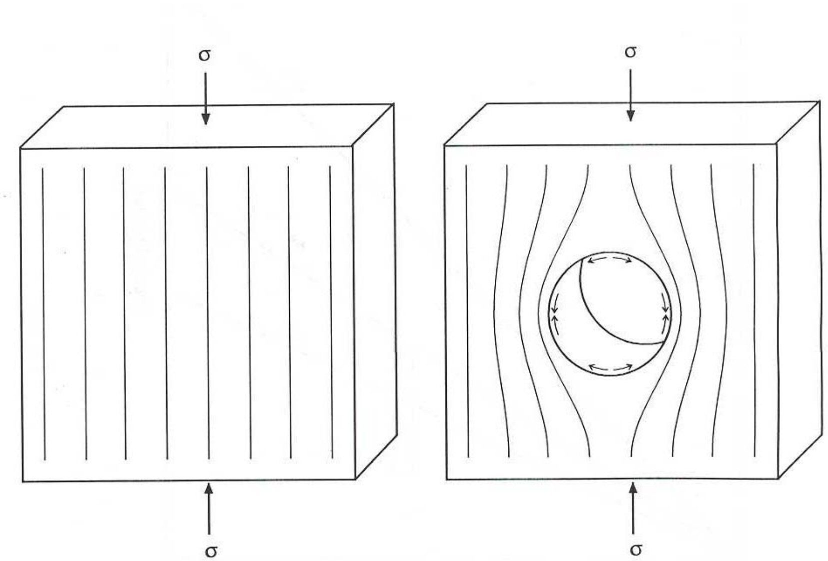
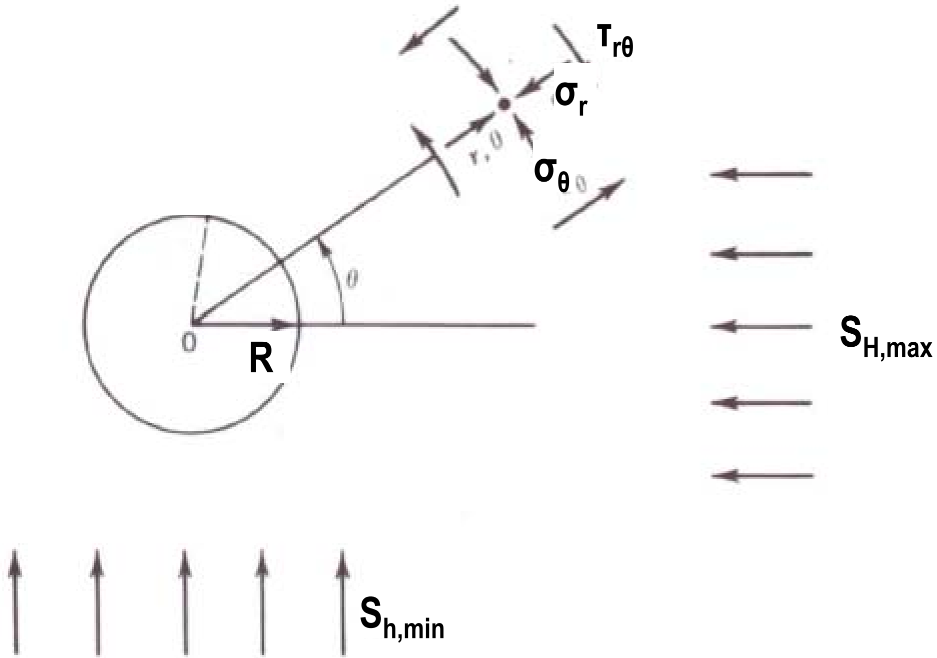
– Stress distribution around circular borehole (Kirsch, 1898)

– Homogeneous, isotropic rock under plane strain condition





Borehole stability problem
Kirsch solution (2)

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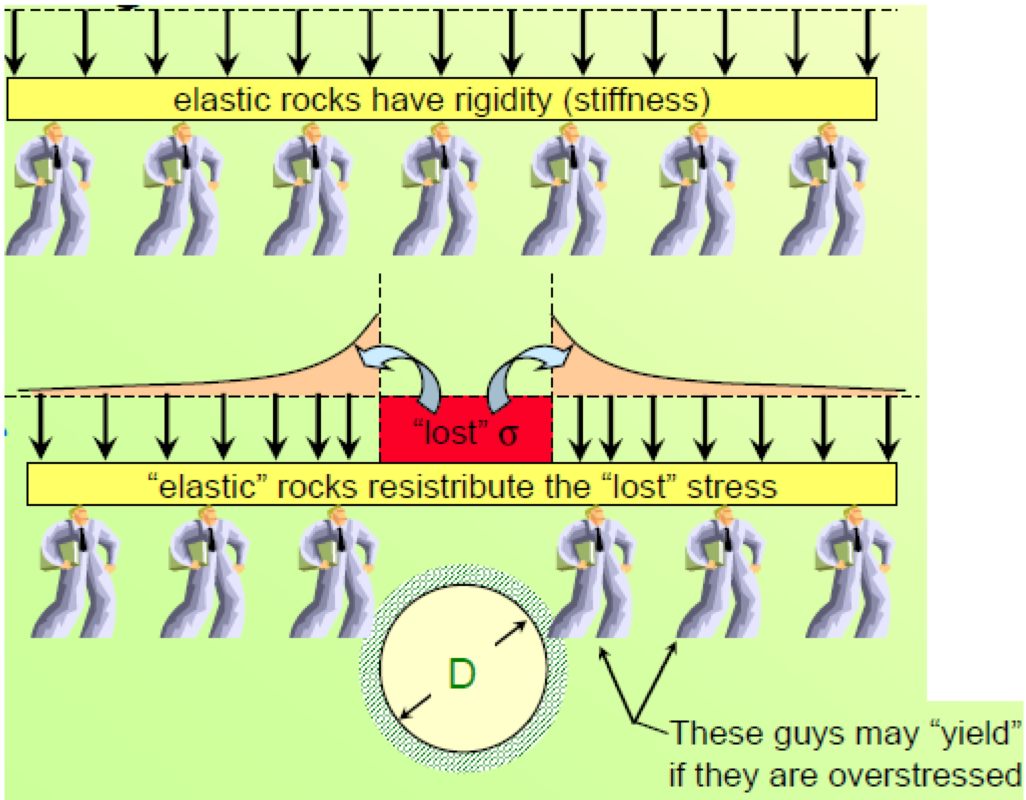
- Stress redistribution(응력 재분배)



Dusseault, 2012

Borehole stability problem
Kirsch solution (3)

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

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

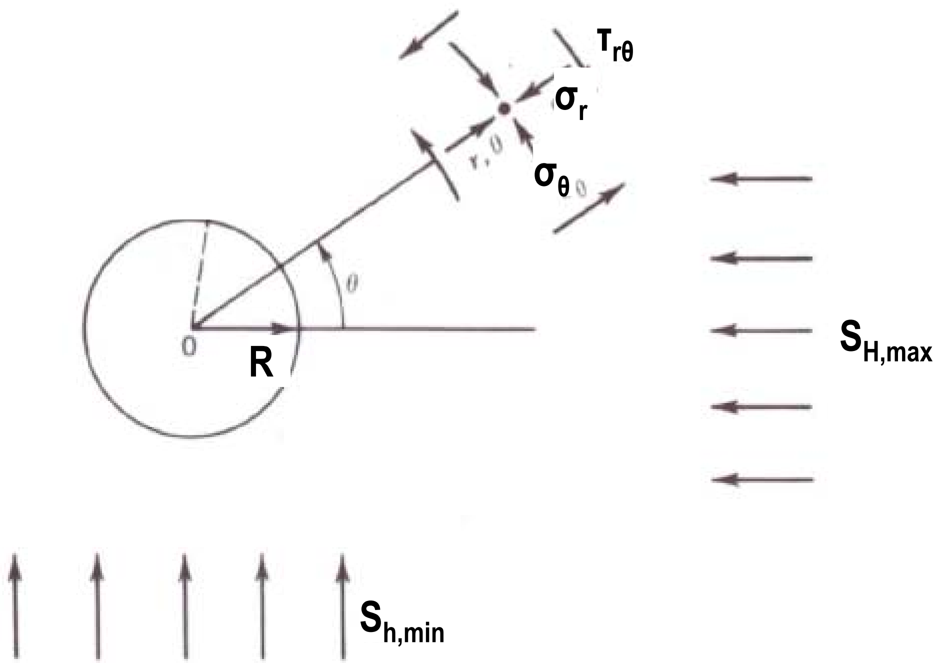
$$\tau_{r\theta} = \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

R: 보어홀의 반경

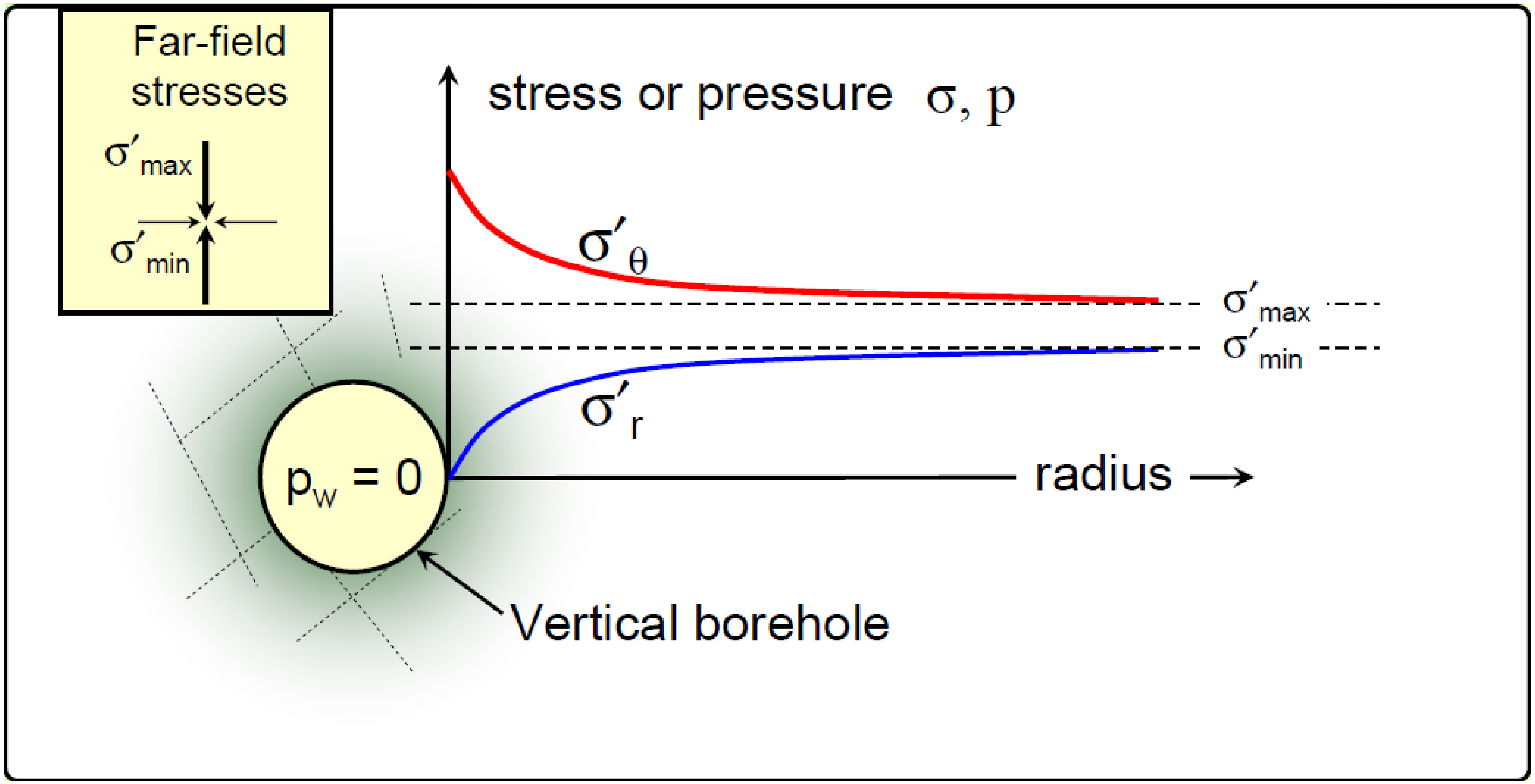
r: 보어홀 중심에서 반경방향의 거리

θ: $S_{H,max}$ 으로부터 반시계 방향으로 측정

$S_{H,max}$, $S_{H,max}$: 최대 및 최소 수평응력



Borehole stability problem
Kirsch solution (4)



Dusseault, 2012

Borehole stability problem
Kirsch solution (5)

- In the borehole surface (R=r)

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

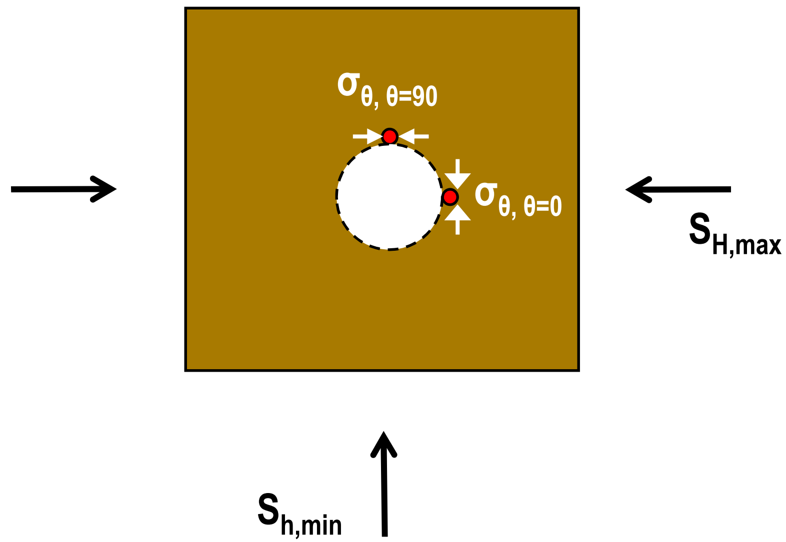
$$\sigma_r = 0$$

$$\sigma_\theta = S_{H\max} + S_{h\min} - 2\left(S_{H\max} - S_{h\min}\right)\cos 2\theta$$

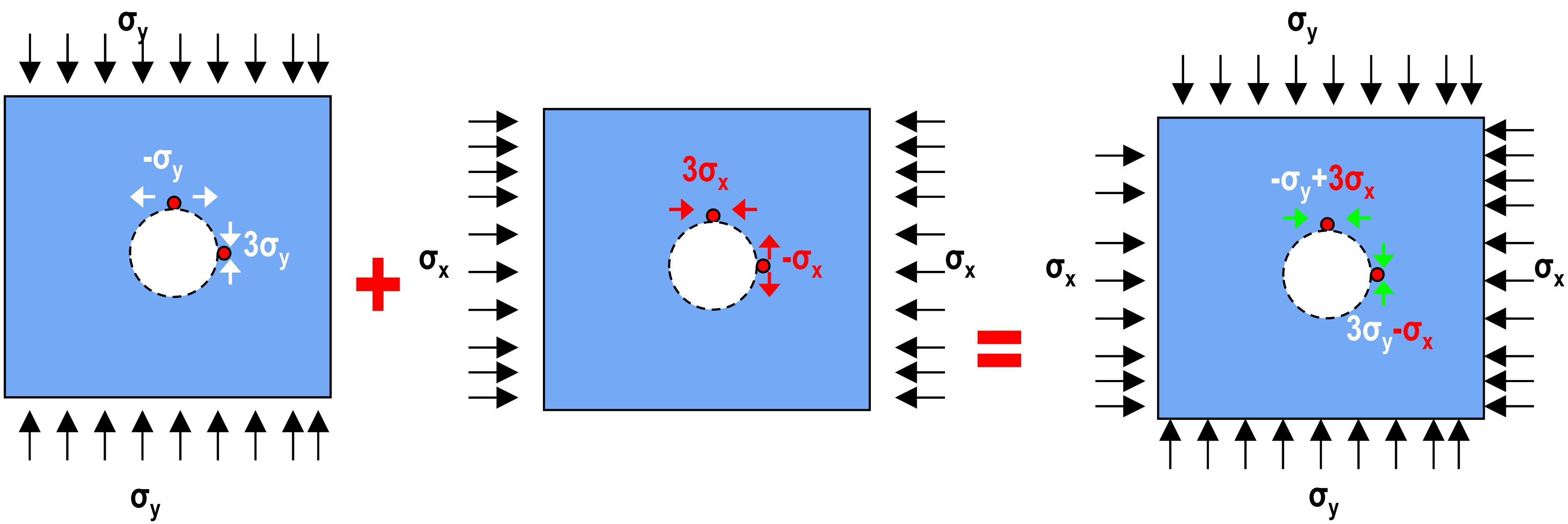
$$\tau_{r\theta} = 0$$

$$\theta = 0, \quad \sigma_\theta = -S_{H\max} + 3S_{h\min}$$

$$\theta = 90, \quad \sigma_\theta = 3S_{H\max} - S_{h\min}$$



Borehole stability problem
Kirsch solution (6)



Under uniaxial stress condition

Maximum Stress concentration 3

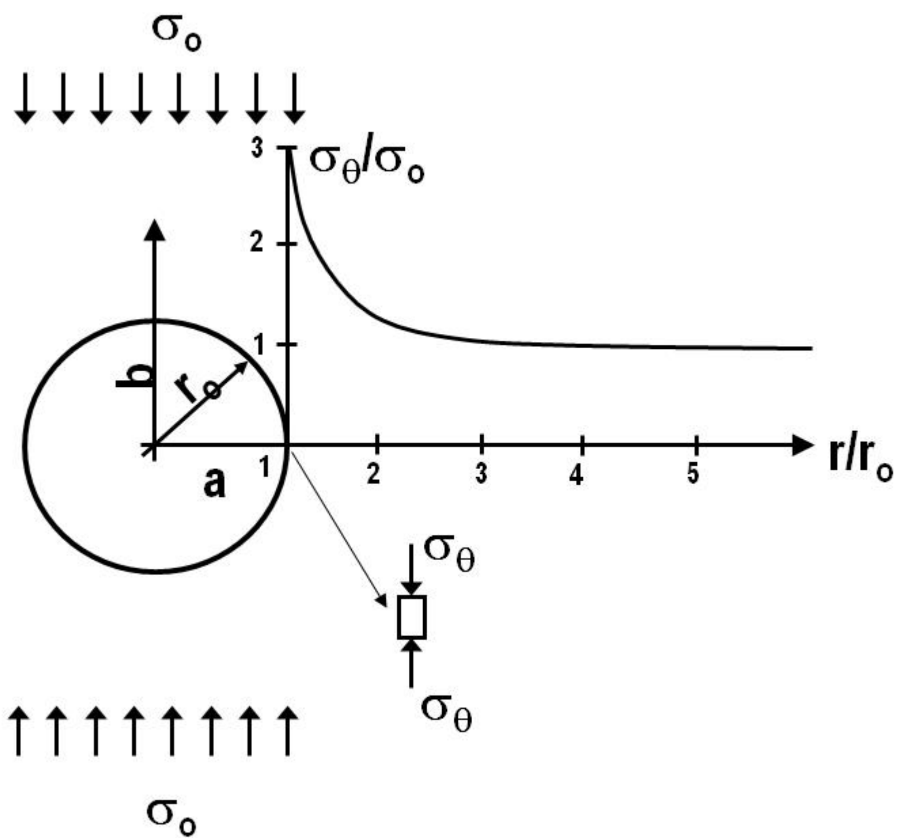
Minimum Stress concentration -1

Biaxial Stress condition:

By superposition

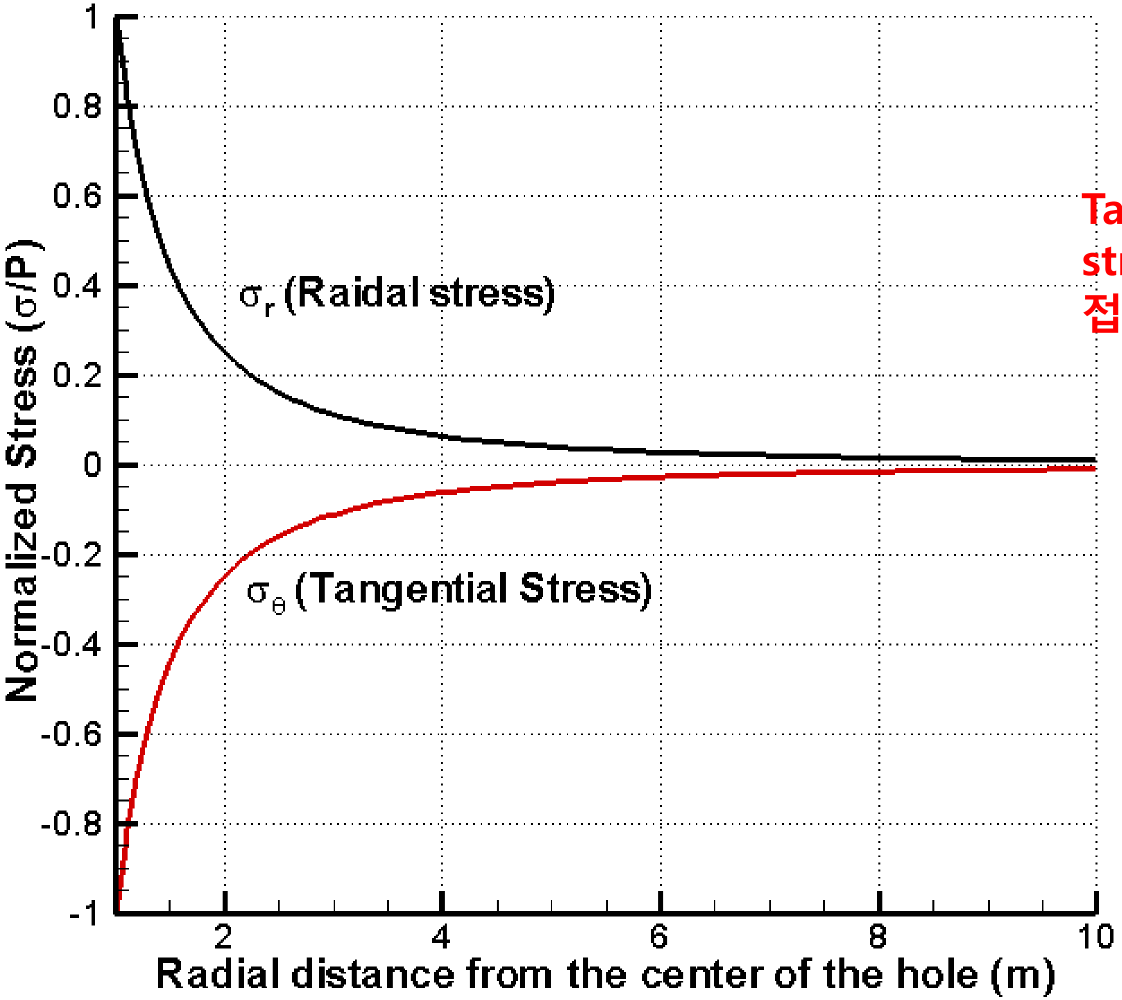
Borehole stability problem
Kirsch solution (7)

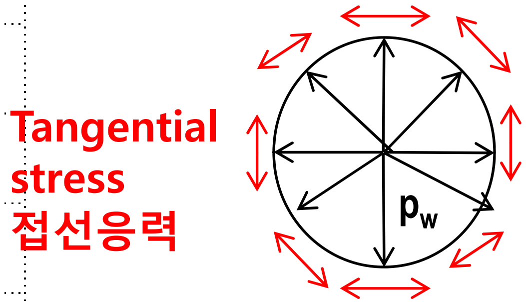
- The area of stress disturbance is within 2~3 times of borehole radius



Borehole stability problem
Internal pressure (1)

- Increase of internal mud/hydraulic pressure





$$\sigma_r = P_w \frac{R^2}{r^2}$$

$$\sigma_\theta = -P_w \frac{R^2}{r^2}$$

Borehole stability problem
Internal pressure (2)

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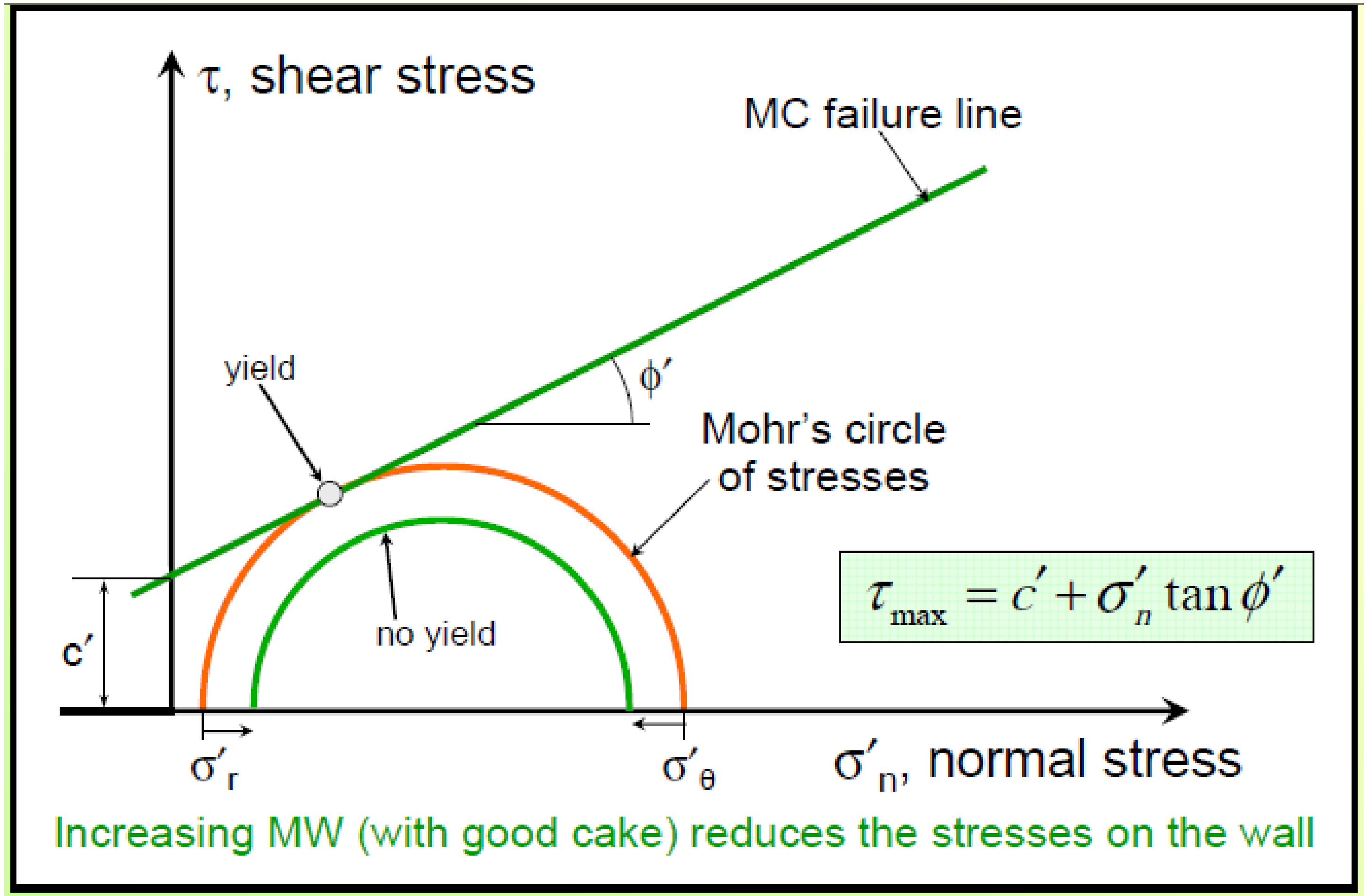
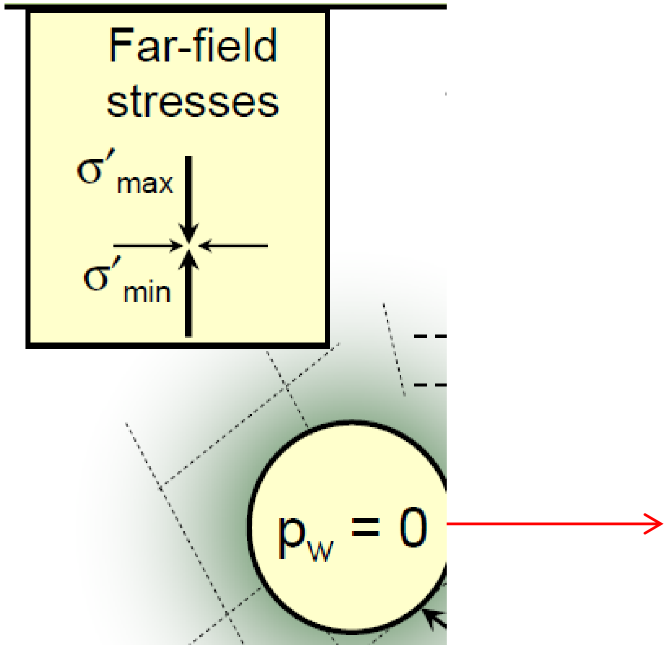
- 이수밀도의 증가 (or 주입압력증가) 는 공벽의 응력을 감소시킴.

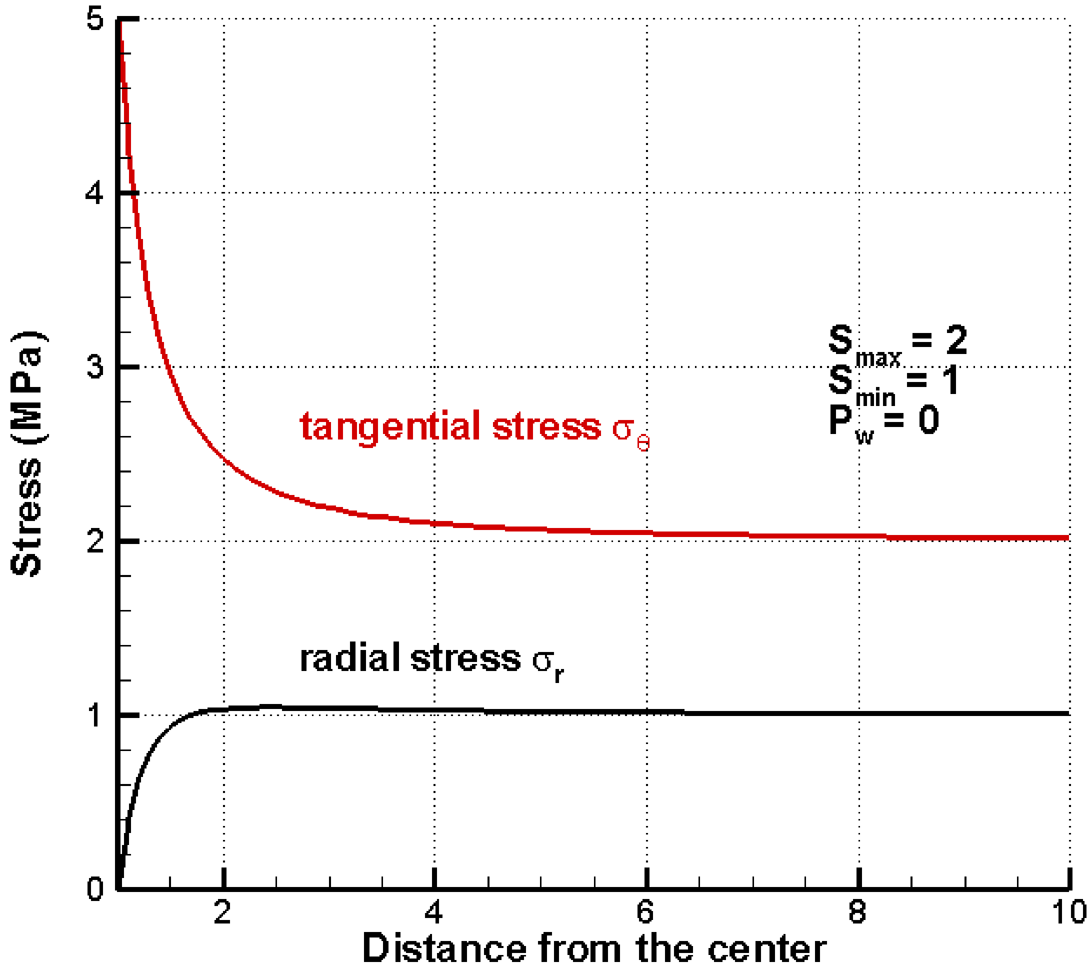


Dusseault, 2012

Borehole stability problem
Example (1)

- Anisotropic Boundary Stress





Borehole stability problem
Example (2)

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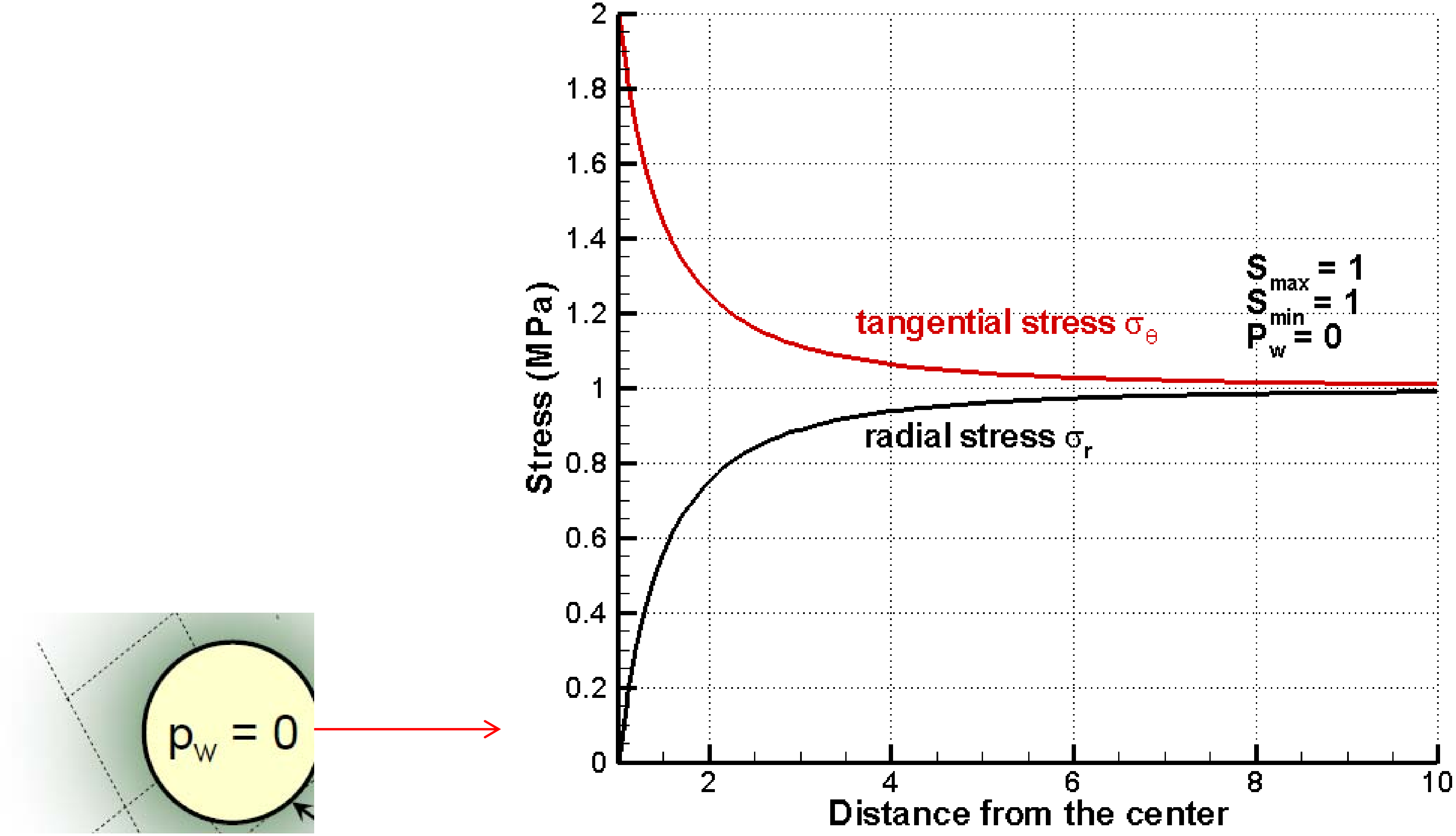
- Isotropic Boundary Stress



Borehole stability problem
Example (3)

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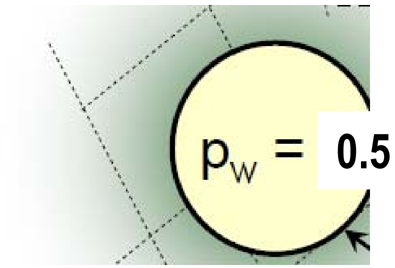
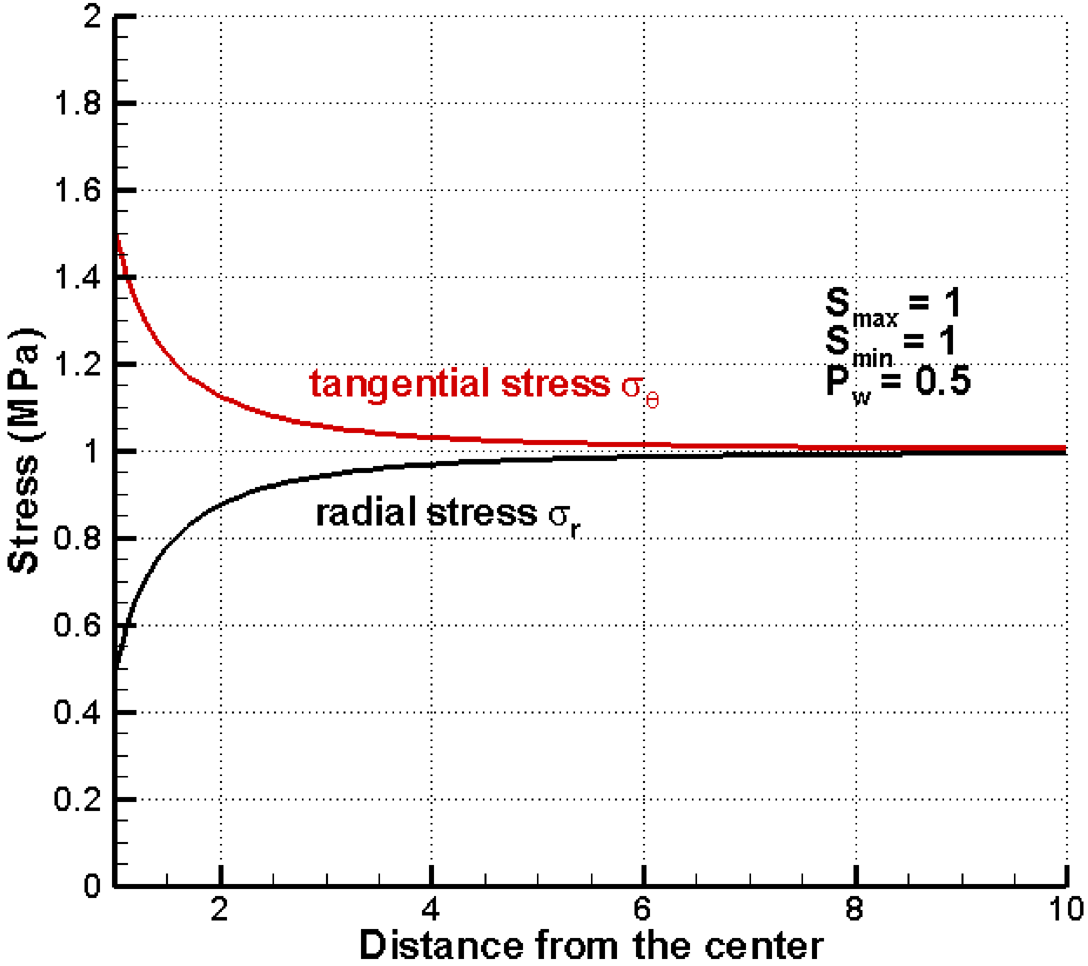
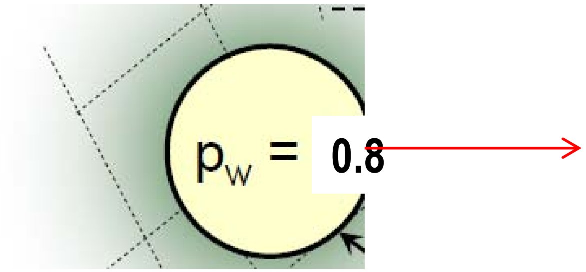
- Isotropic boundary stress + Injection pressure (0.5)

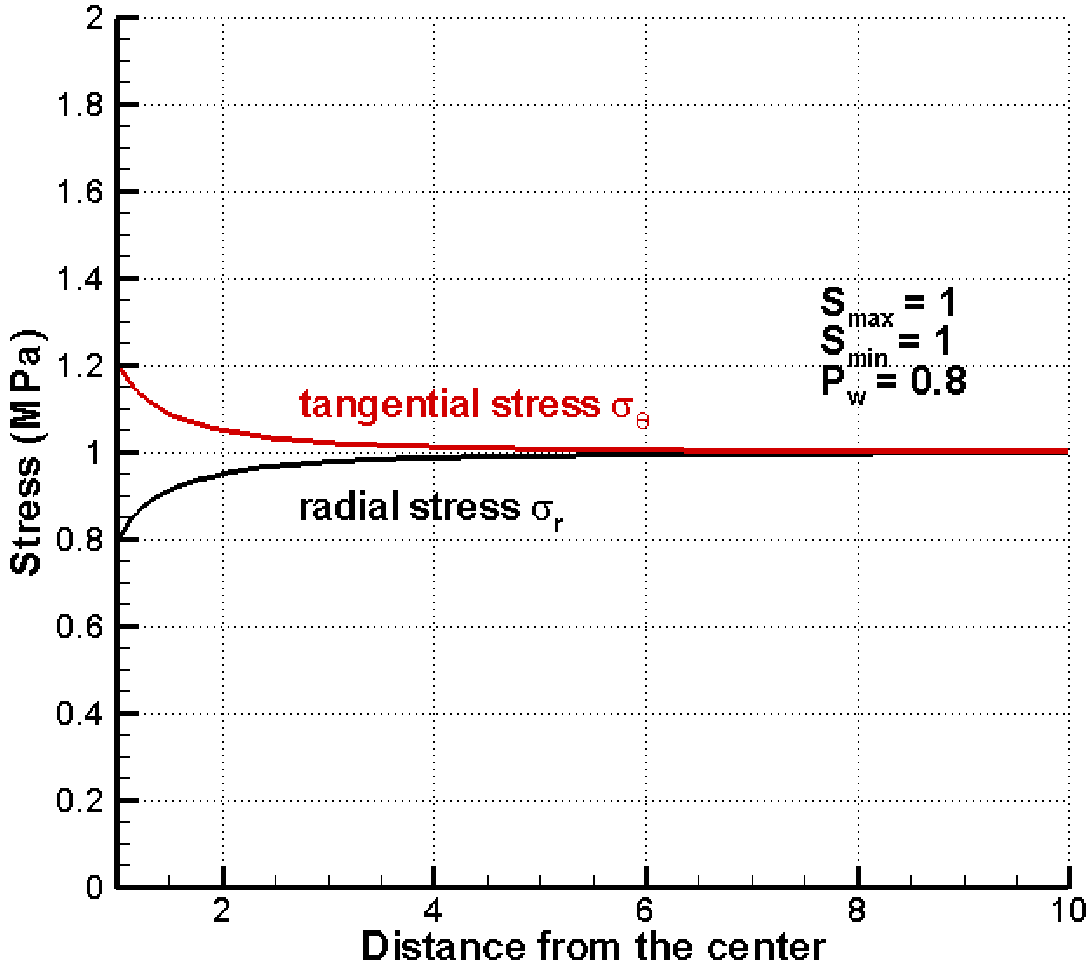




Borehole stability problem
Example (4)

- Isotropic boundary stress + Injection pressure (0.8)

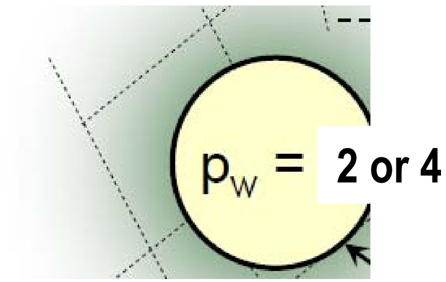


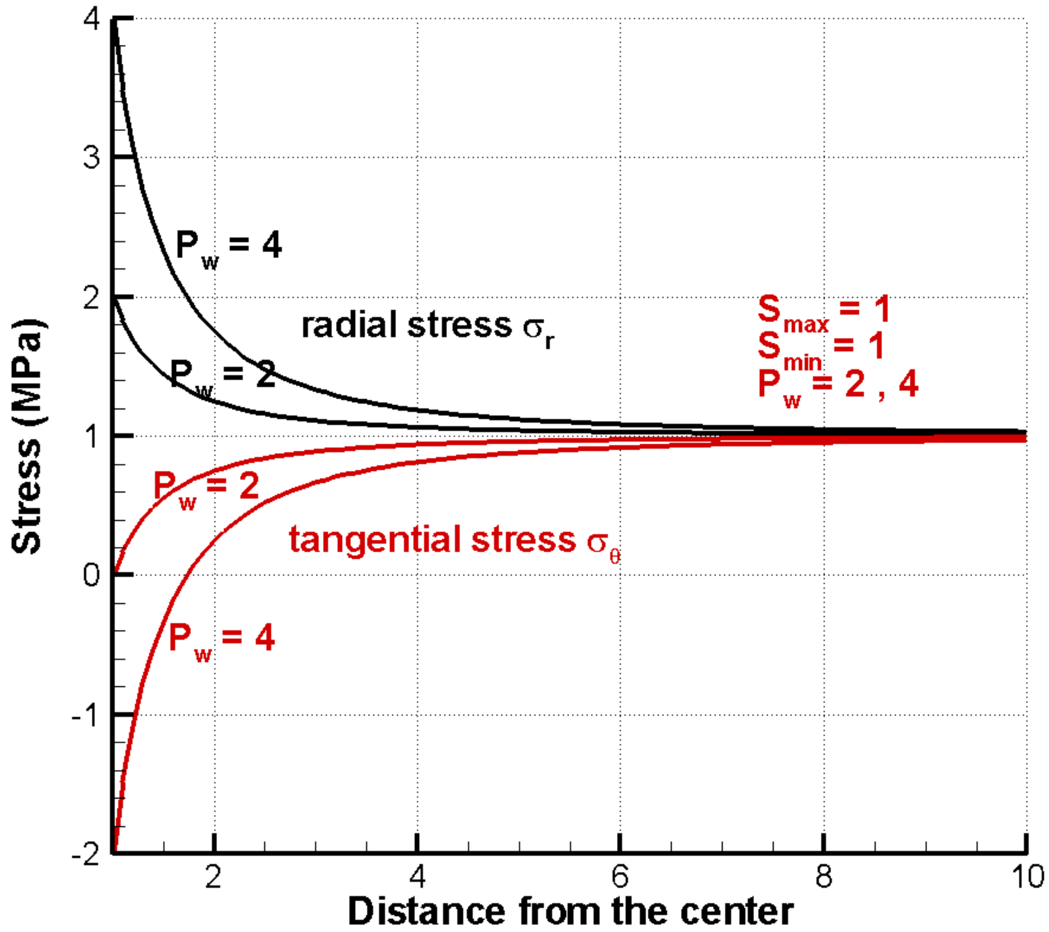


Borehole stability problem
Example (5)

- Isotropic boundary stress + Injection pressure (2-4)

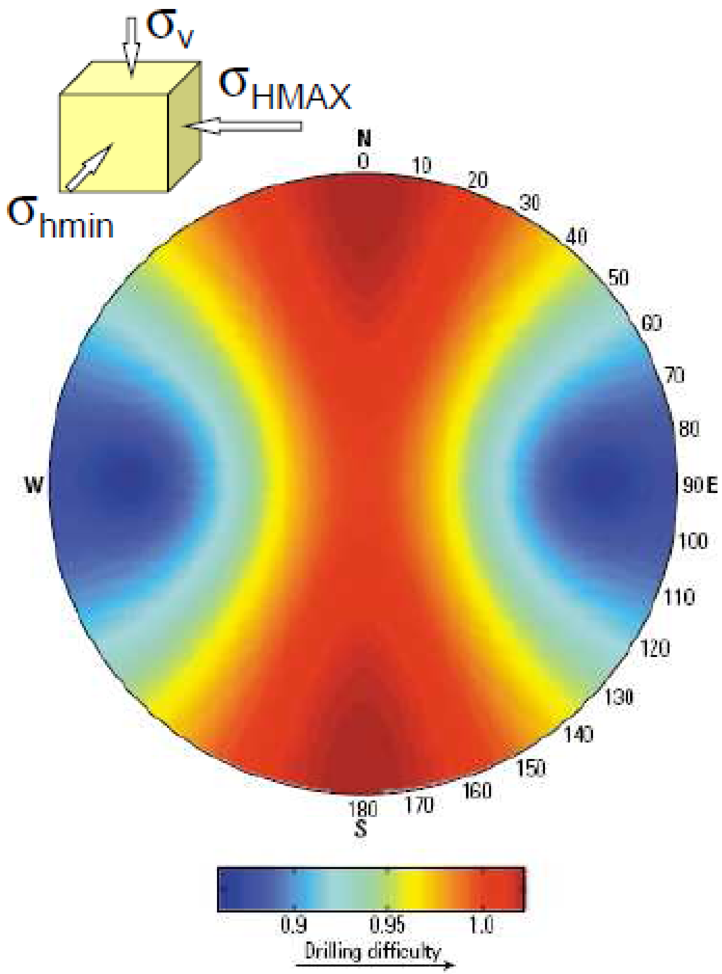
  - Hydraulic Fracturing can occur when internal pressure is big enough





Borehole stability problem
Borehole Trajectory

- Drilling trajectory (최적 시추 궤적 결정)
  - Determine the trajectory that can induce the least stress concentration



Dusseault, 2012

Borehole stability problem
Thermal stress(열팽창 및 열응력)

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- Linear thermal expansion coefficient (unit: /K)

$$\frac{\Delta l}{l} = \alpha \left(T - T_0 \right)$$

- Thermal stress← thermal expansion + mechanical restraint
  - Thermal stress in 1D

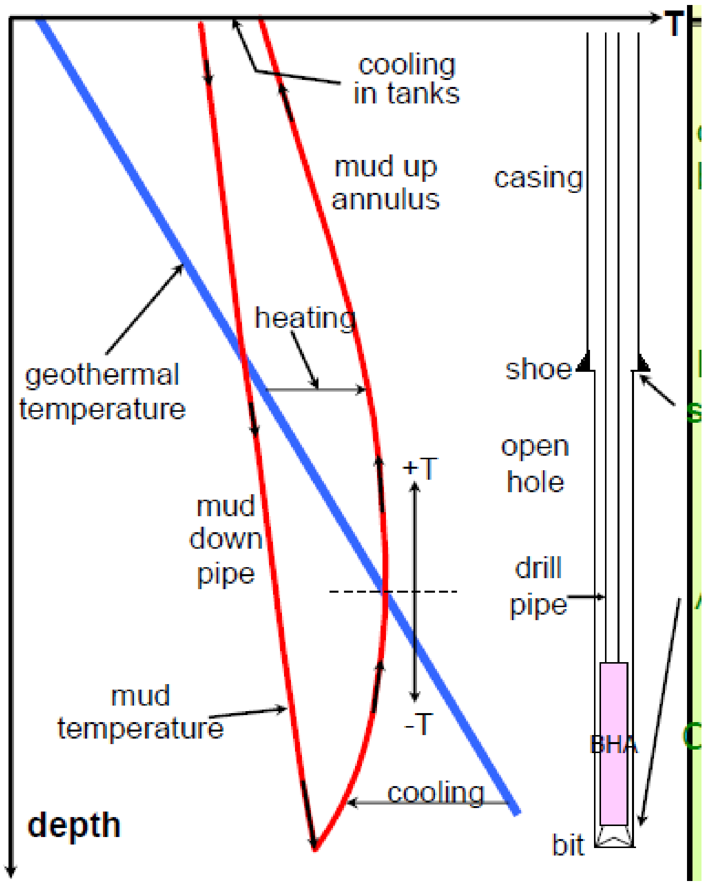
$$\sigma_T = \alpha E \left(T - T_0 \right)$$

  - Thermal stress when a rock is completely (in all directions) restrained

$$\sigma_T = 3\alpha K \left(T - T_0 \right) = \frac{E}{1-2\nu} \alpha \left(T - T_0 \right)$$

Borehole stability problem
Thermal stress(열팽창 및 열응력)

- Downhole : Cooling → stabilize
- Uphole: Heating → can induce failure



Dusseault, 2012

Stress around circular borehole
Generalized Kirsch's solution

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- Boundary stress + internal pressure + temperature;
  - 응력경계 (Principal in situ stress boundary)
  - 내부 주입압력 (Internal pore pressure (mud/water pressure))
  - 온도변화 (Temperature change)

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

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

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

Stress around circular borehole
Generalized Kirsch's solution

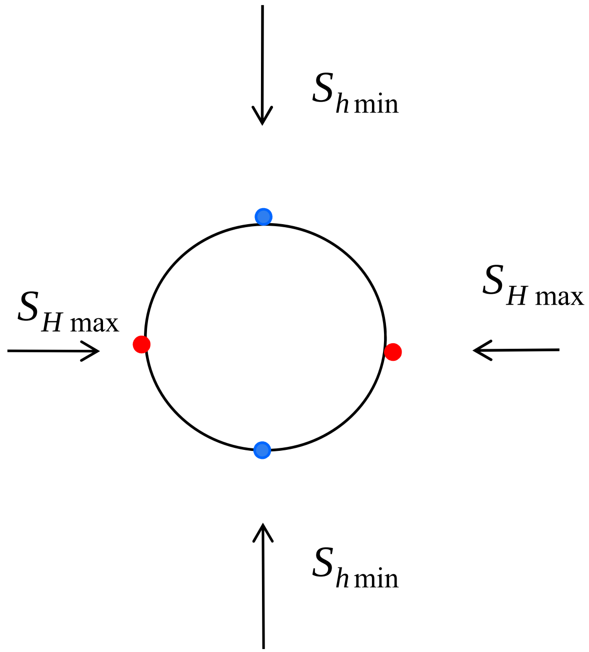
– At the borehole wall (r = R), maximum and minimum hoop stresses are;

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

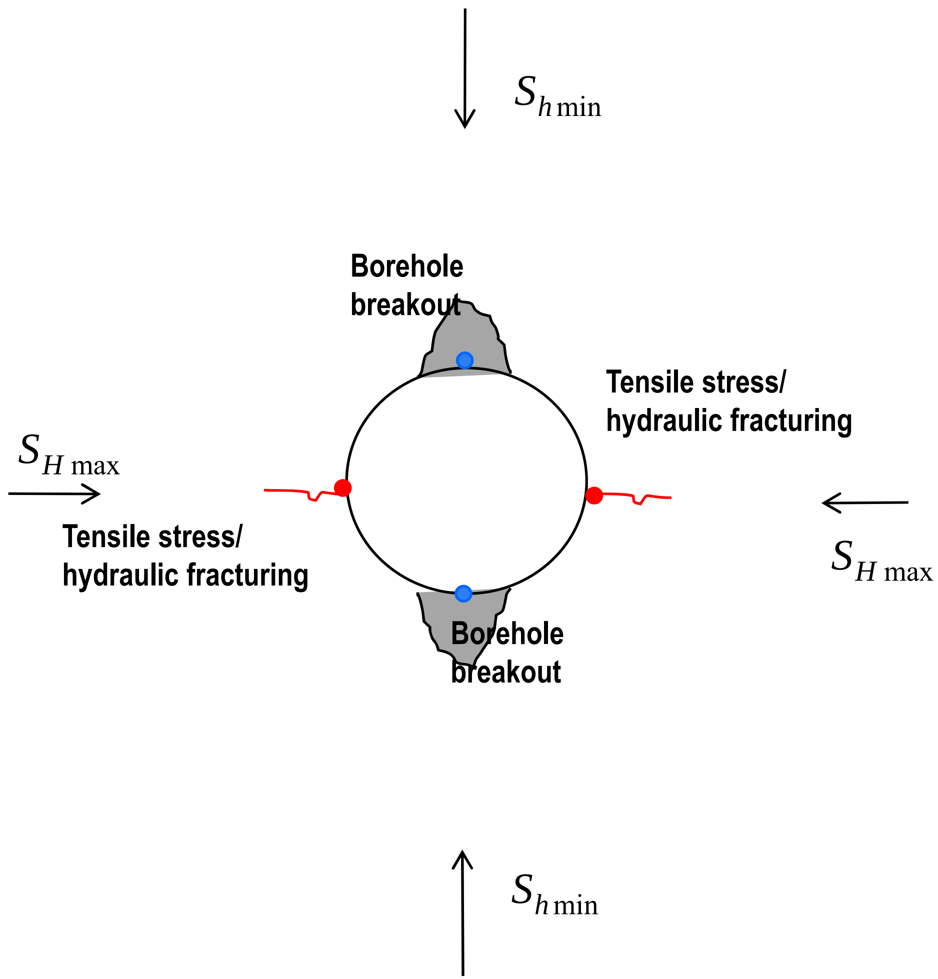
- $\sigma_{\theta,\max} = 3S_{h\max} - S_{h\min} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$

– Without considering temperature change,

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



Stress around circular borehole
borehole breakout vs. hydraulic fracturing



– Required internal pressure to induce tensile stress (neglect T effect);

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

– …. To induce hydraulic fracturing

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

– Required uniaxial compressive strength not to have borehole breakout

- $\sigma_c > 3S_{h\max} - S_{h\min} - P_w$

Borehole breakout

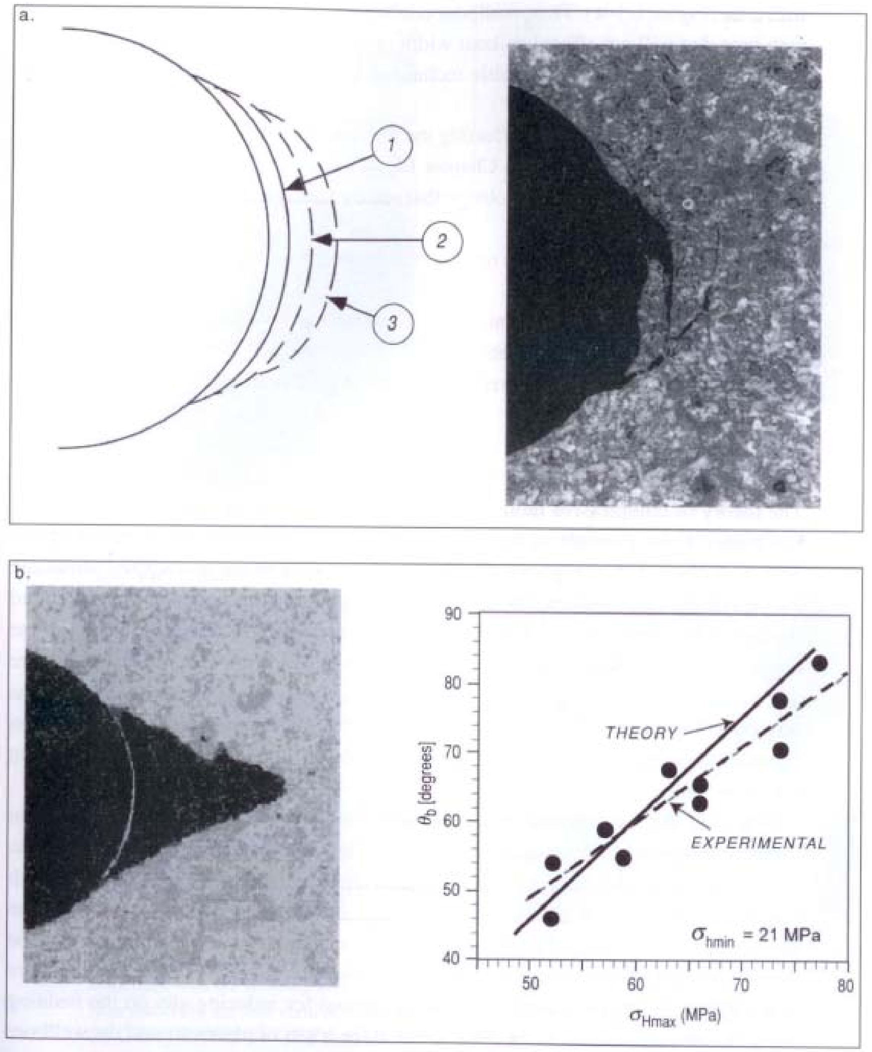
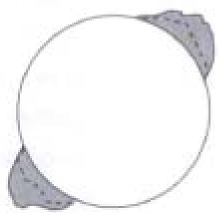


Figure 6.15. After the formation of wellbore breakouts, they are expected to increase in depth, but not width. This is as shown theoretically in (a) after Zoback, Moos *et al.* (1985) and confirmed by laboratory studies (Haimson and Herrick 1989). It can be seen photographically that breakouts in laboratory experiments deepen but do not widen after formation. A shown in (b), measured breakout widths compare very well with those predicted by the simple thoery presented in Zoback, Moos *et al.* (1985) which form the basic for the breakout shapes illustrated in Figures 6.2 and 6.3.

- wellbore enlargements caused by stress-induced failure of a well occurring 180 degree apart
- Induced by compressive failure
- Occur in the direction of minimum horizontal stress



Zoback, 2007

Borehole stability problem
Anisotropy

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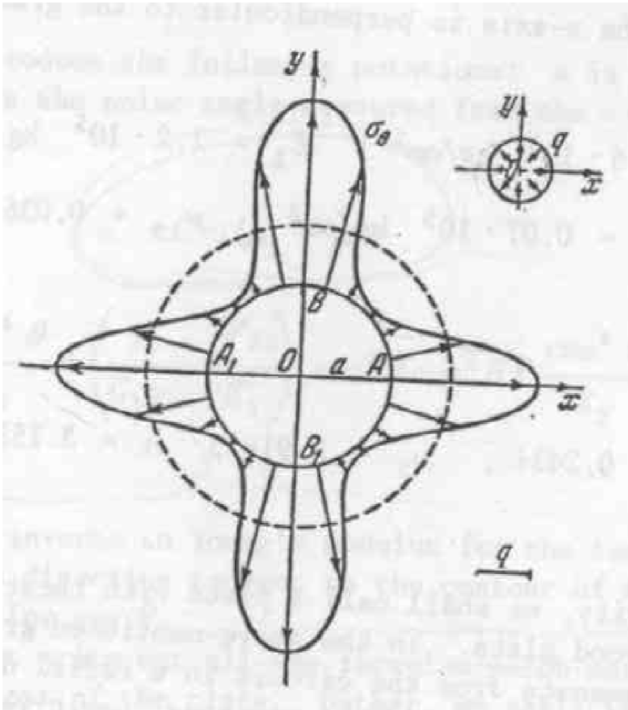
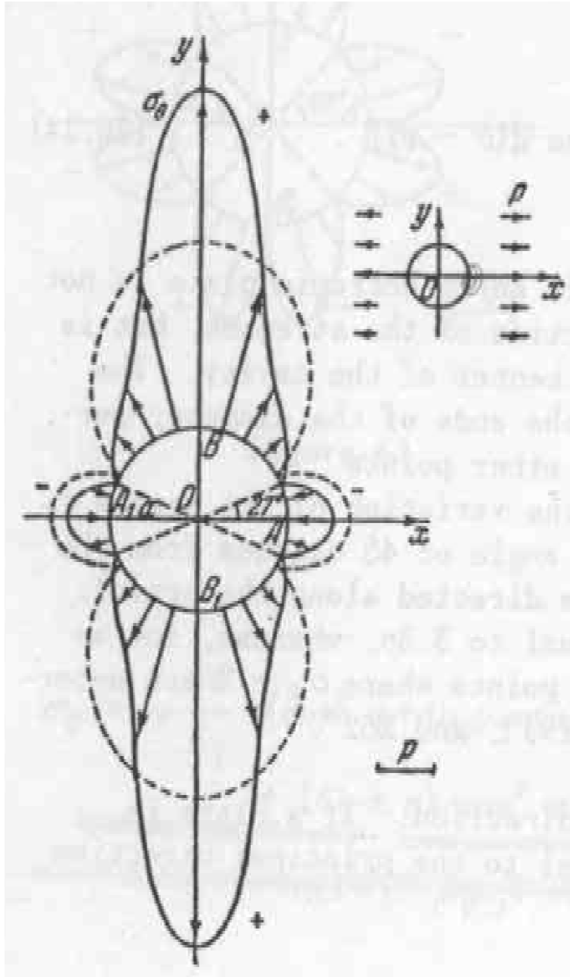
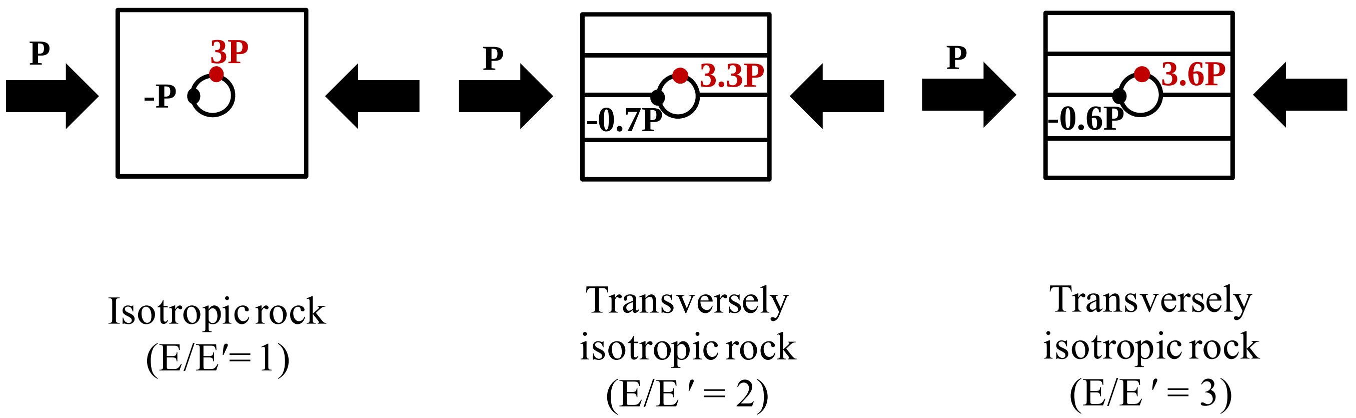
- Some formulae considering anisotropy (internal pressure, uniaxial stress)

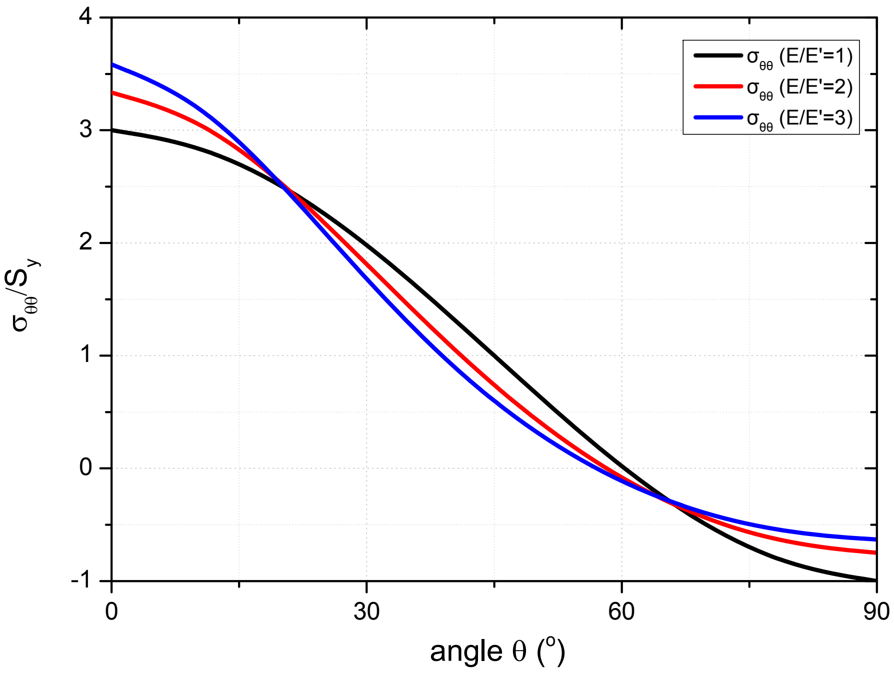




Lekhnitskii, 1963

Borehole stability problem
Anisotropy





- 탄성계수의 이방성에 따라 응력집중의 정도가 달라짐.

Kim H, 2012, MS thesis SNU

Borehole stability problem
Anisotropy

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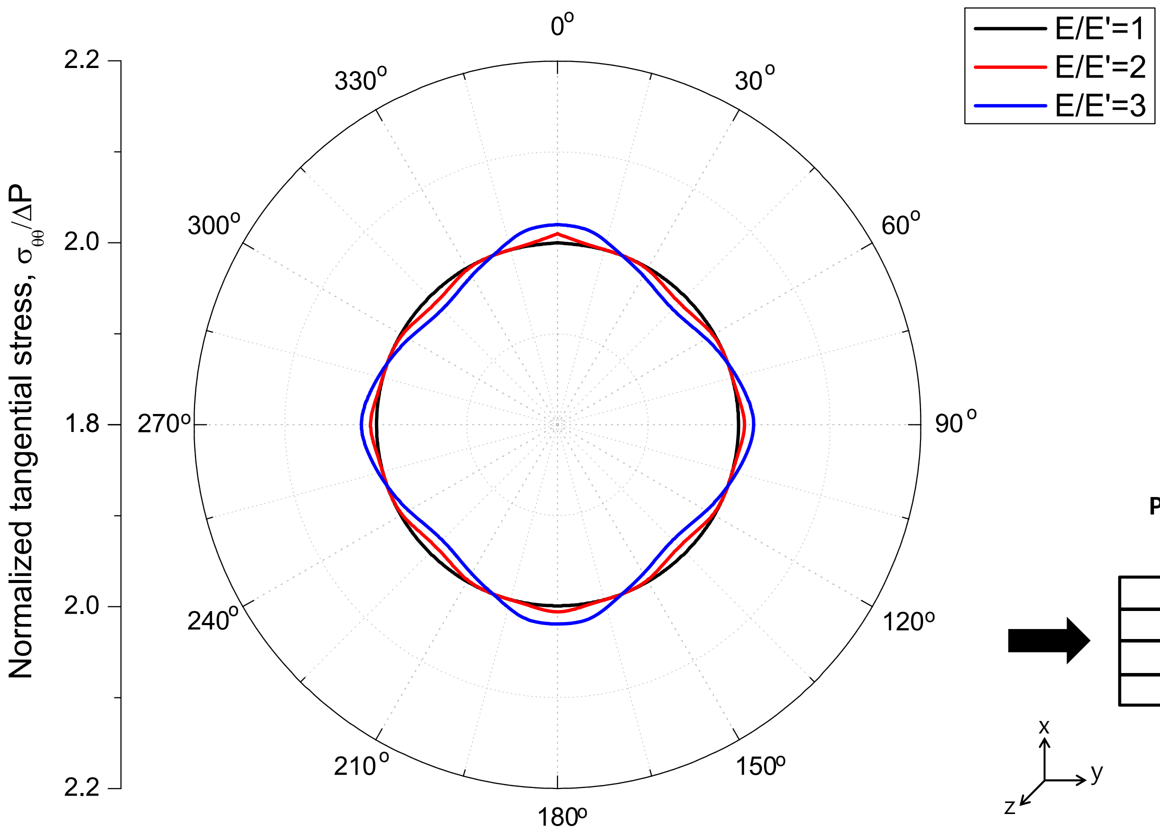
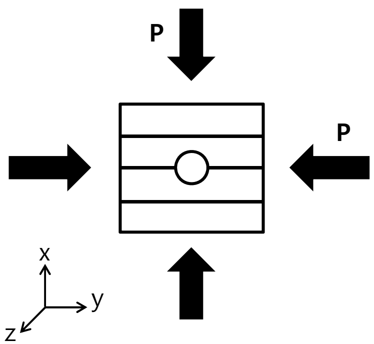
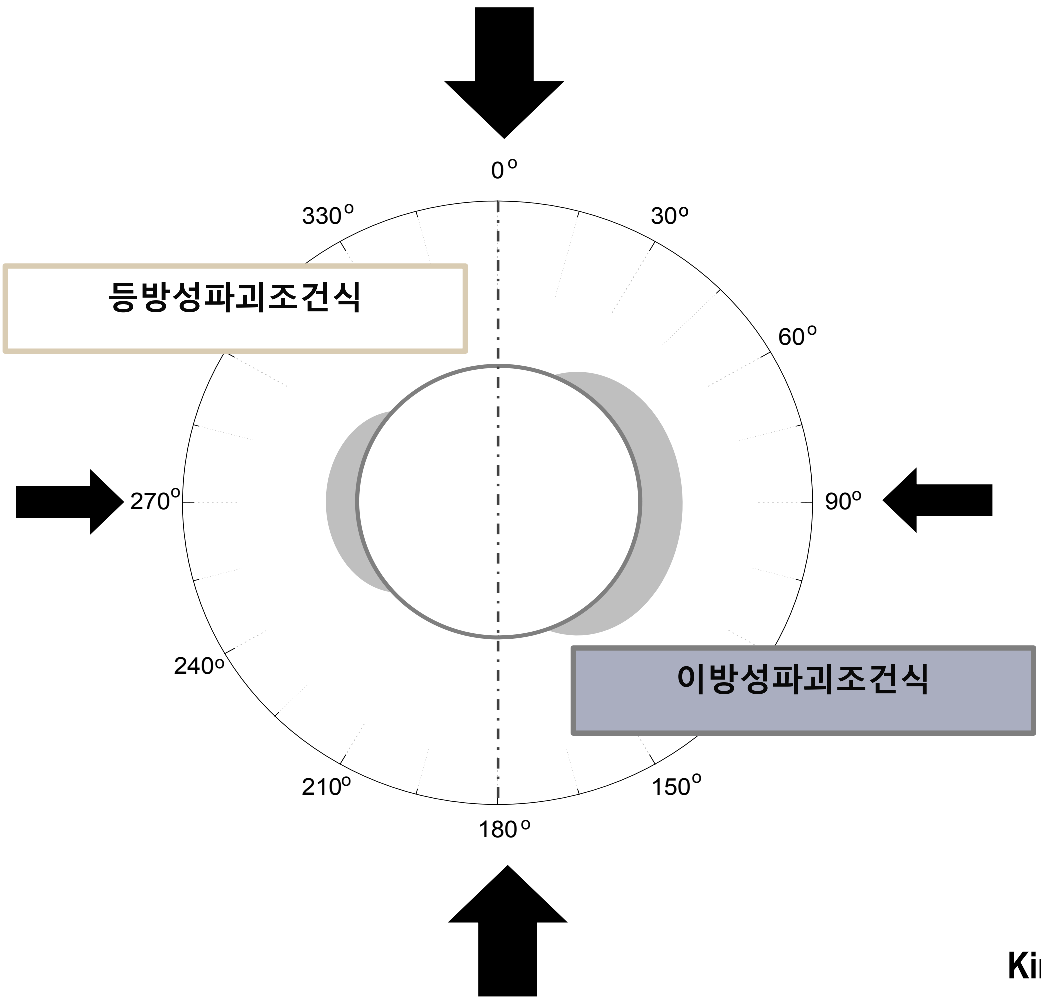




Kim H, 2012, MS thesis SNU

Borehole stability problem
Anisotropy

- 어떤 파괴조건식을 적용하느냐에 따라 파괴범위가 다르게 나타남



Kim H, 2012, MS thesis SNU

Borehole stability problem
Anisotropy – North Sea Example (1)

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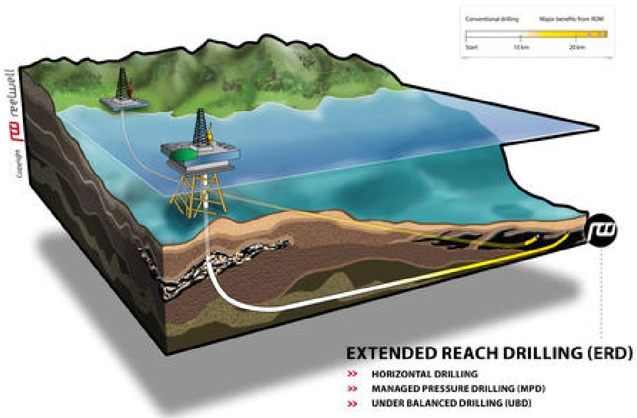
Oseberg in North Sea (Norway)

- Extended Reach Drilling (ERD) has been employed for increasing oil recovery.
- Total Depth = 9,327 m
- Since 1979, total depth for wells has increased steadily.



Okland & Cook, SPE, 1998

Borehole stability problem
Anisotropy – North Sea Example (2)

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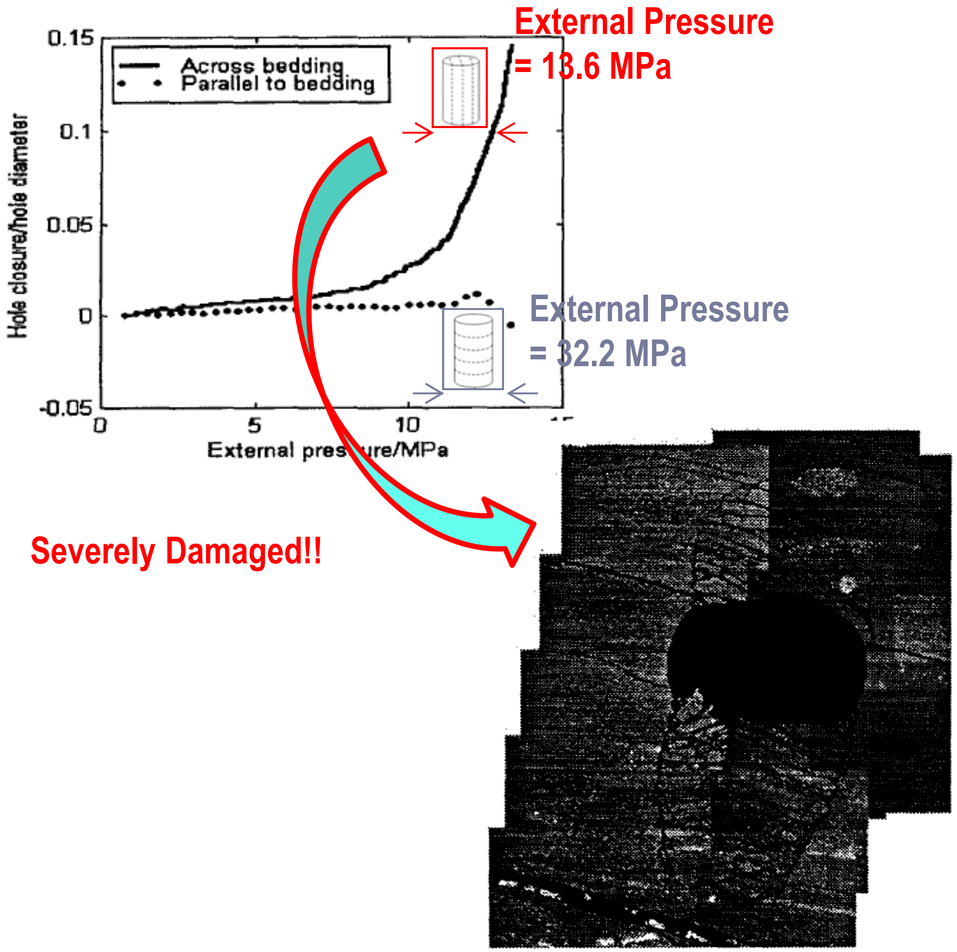
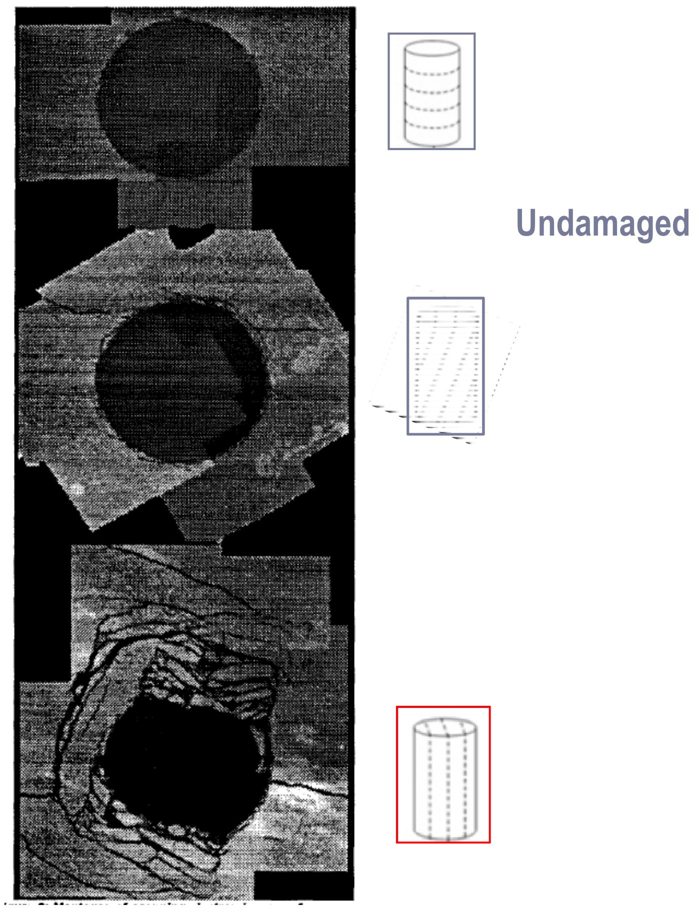
a) Draupne-similar Shale



Severely Damaged!!

b) J_2 (Outcrop shale)

Loaded and unloaded
at approximately 20 MPa



Okland & Cook, SPE, 1998

Borehole stability problem
Work Flow chart

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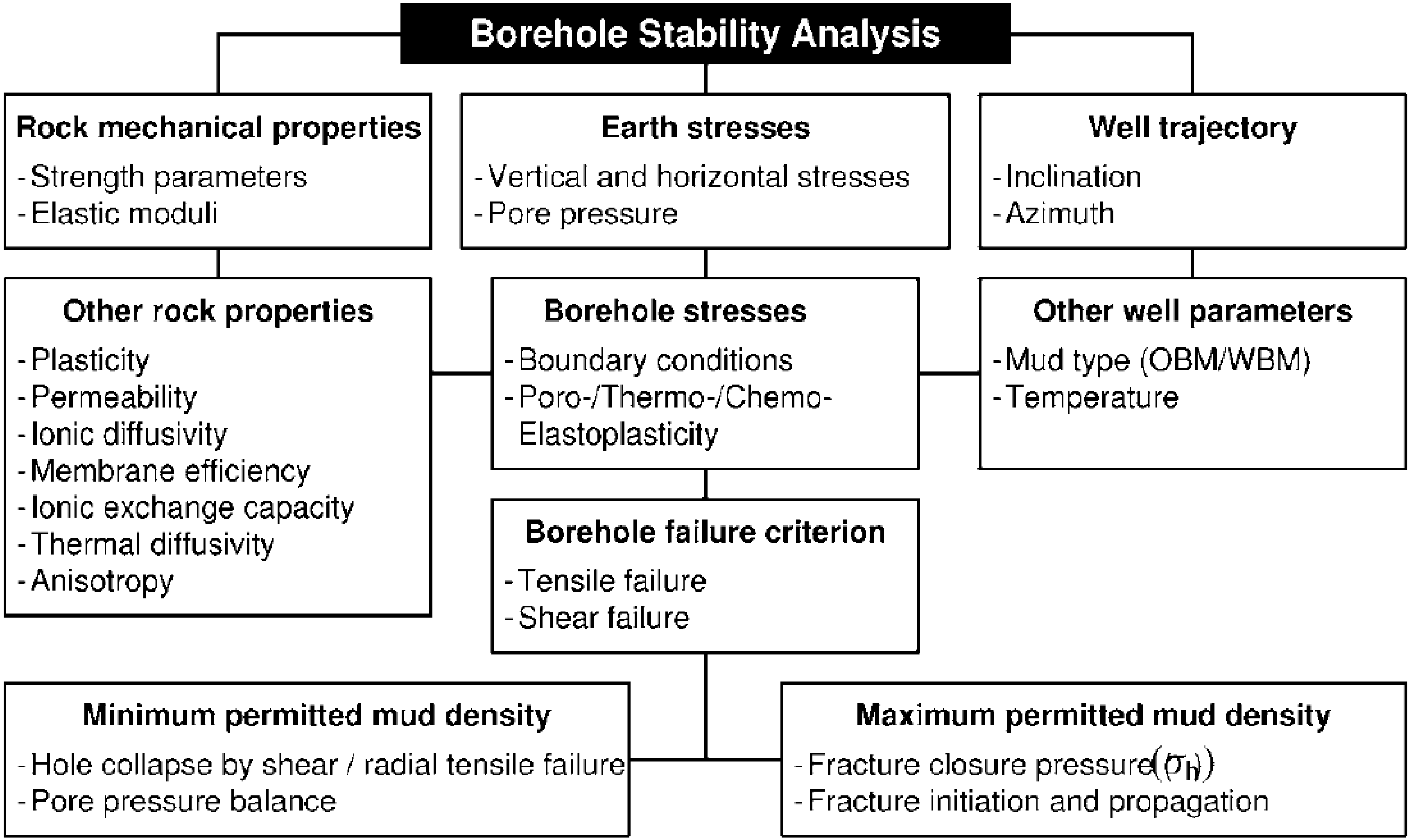

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Reservoir subsidence (저류층 침하)
Mechanism

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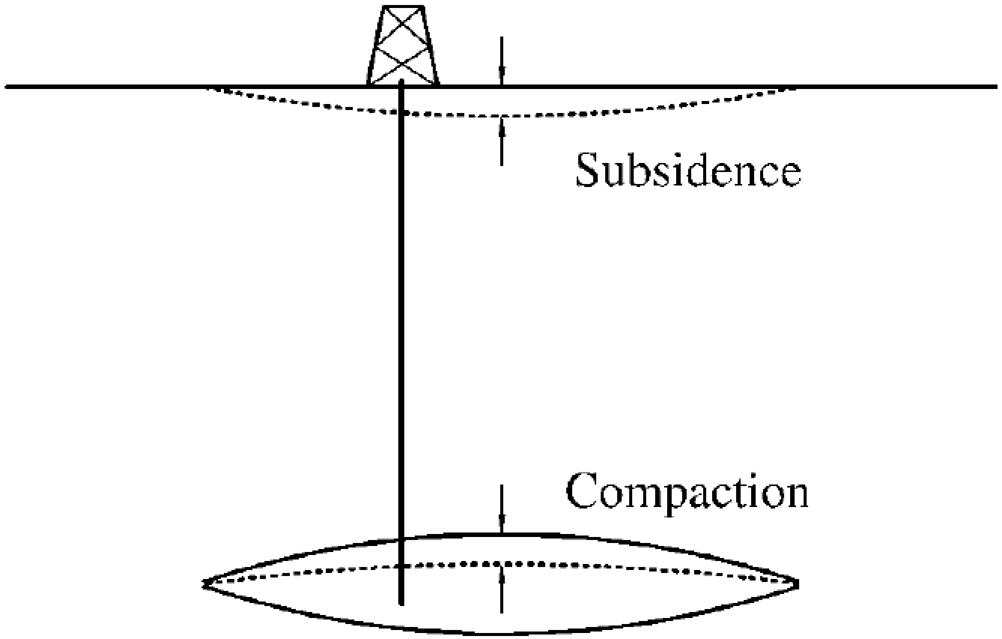
- Subsidence induced by the decrease of reservoir formation pressure
- P ↓ → effective stress ↑ → compression



Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Reservoir subsidence (저류층 침하)
Mechanism

- More serious when;
  - Bigger reservoir formation pressure decrease
  - Thick reservoir
  - Compressible reservoir
  - E.g.) Wilmington field in California: 9 m subsidence (Fjaer, 2008)

Reservoir subsidence (저류층 침하)
Poroelastic stress change

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- Change of horizontal stress due to pore pressure change

$$\Delta S_h = \alpha \frac{(1-2\nu)}{(1-\nu)} \Delta p_p = k \Delta p_p$$

S_h :수평방향응력(horizontal stress)

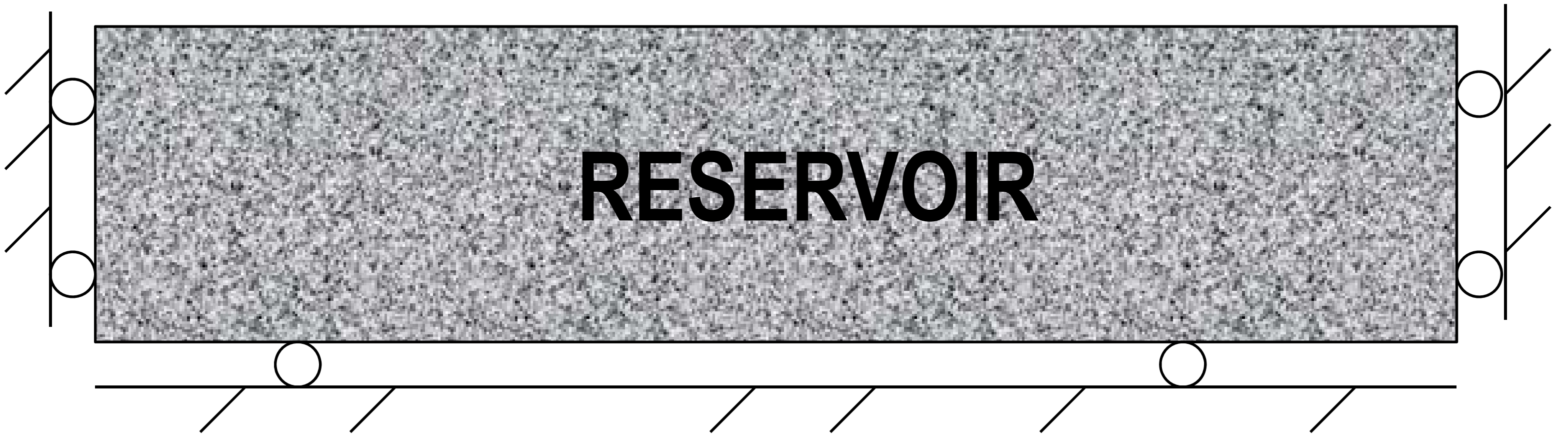
ν:암석의 포아송비(Poisson's ratio)

k:응력경로계수(stress path factor, SPF)

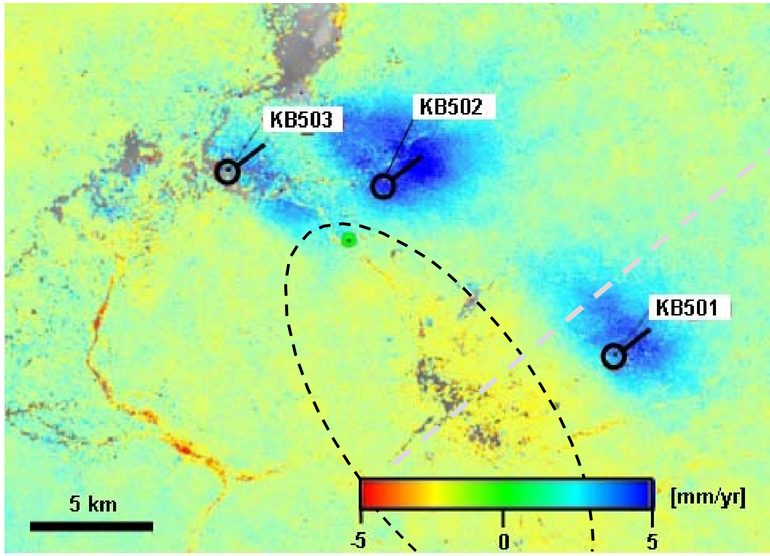
Reservoir subsidence (저류층 침하)
Uniaxial compaction model

- Compaction coefficient or unaxial compressibility, Cm;

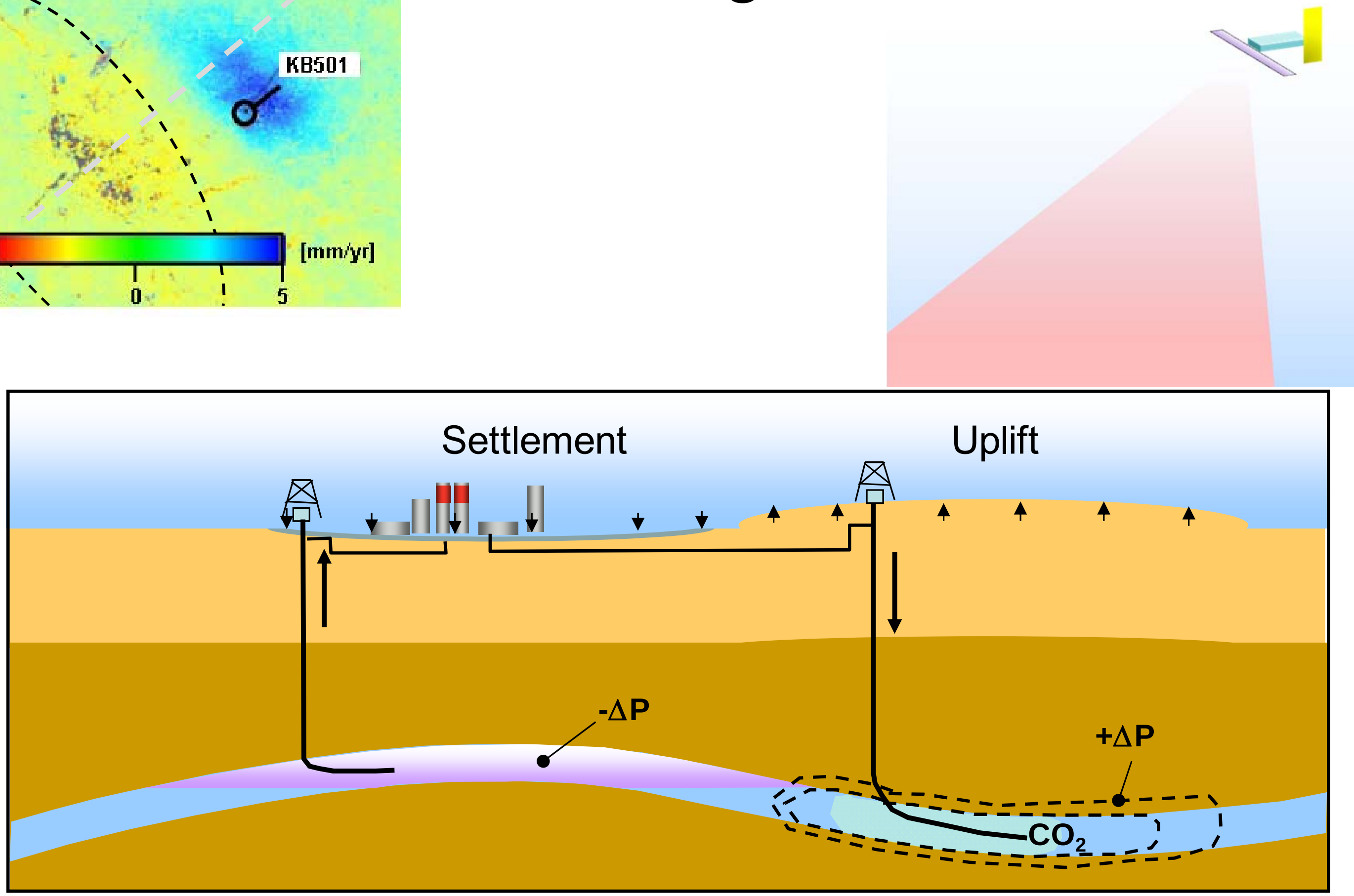
$$\frac{\Delta h}{h} = -C_m \alpha \Delta p = -\frac{1}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu}\alpha \Delta p$$



Reservoir subsidence (저류층 침하)
Example(2): In Salah (Gas/CO2 storage)

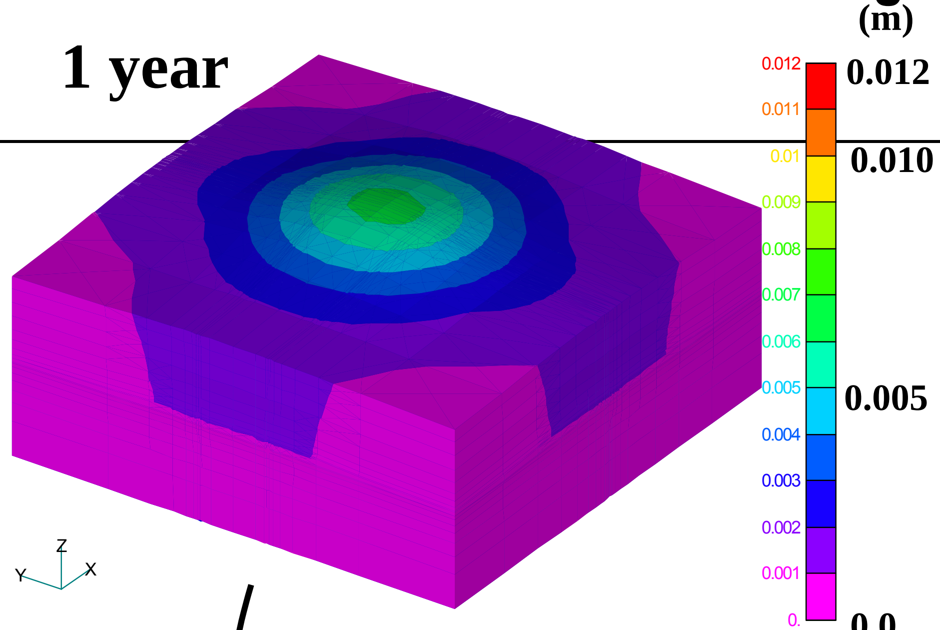


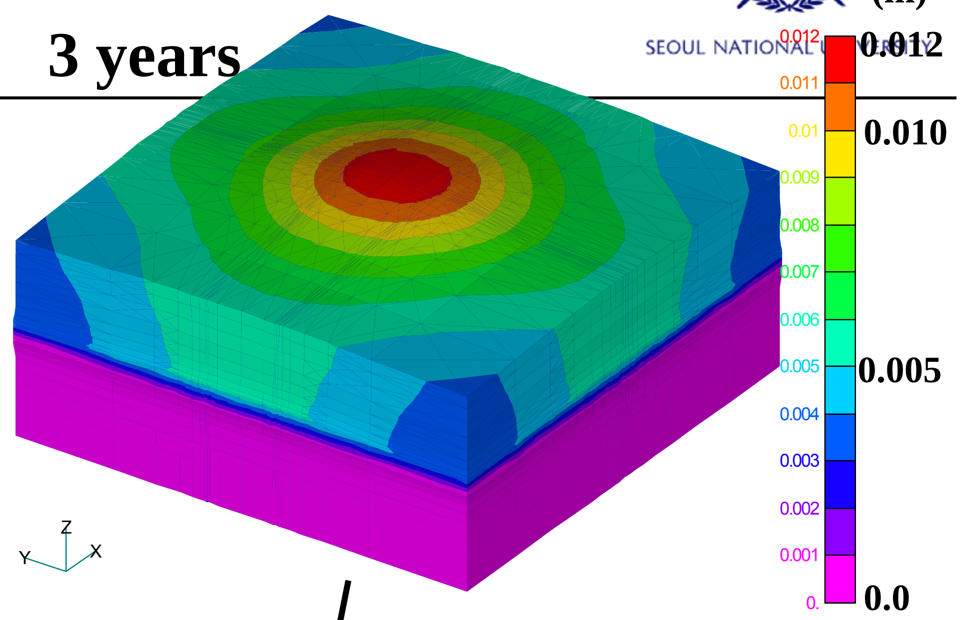
- Annually, 5 mm (above injection holes)
- Heaving and Subsidence

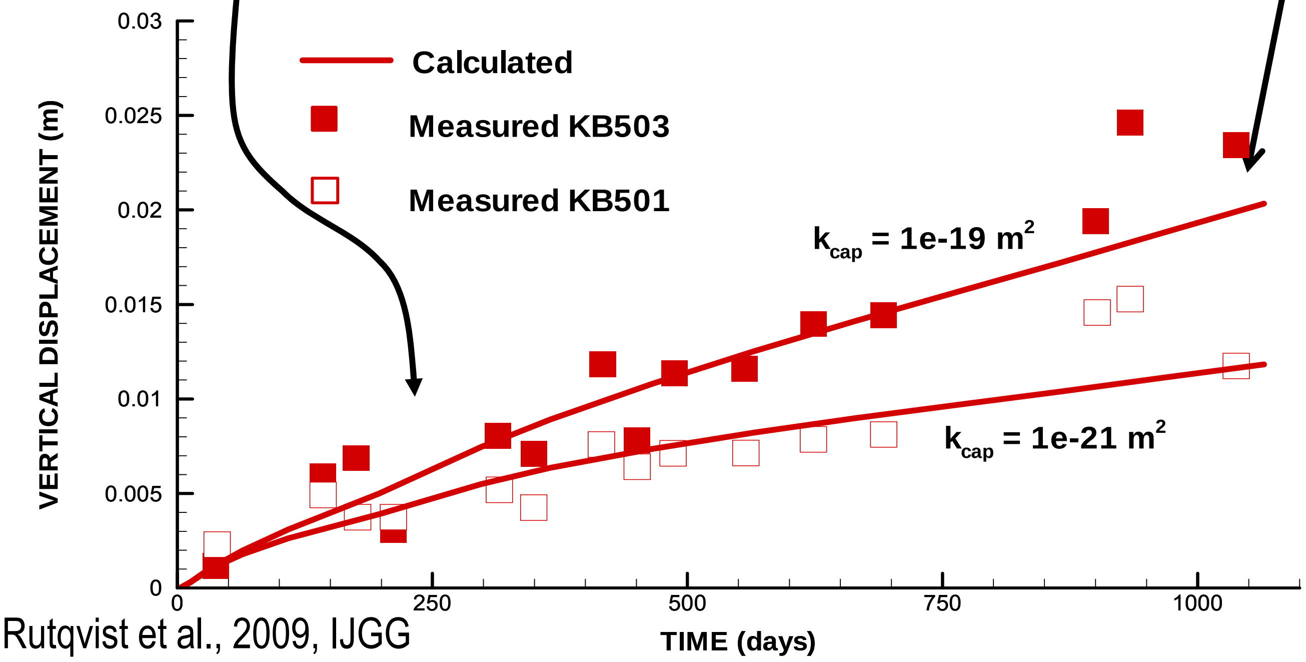


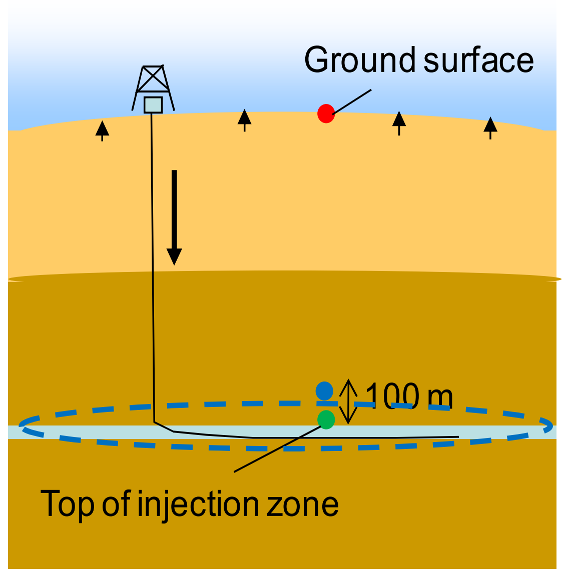
Rutqvist et al., 2009, IJGG

Prediction of Reservoir Heaving



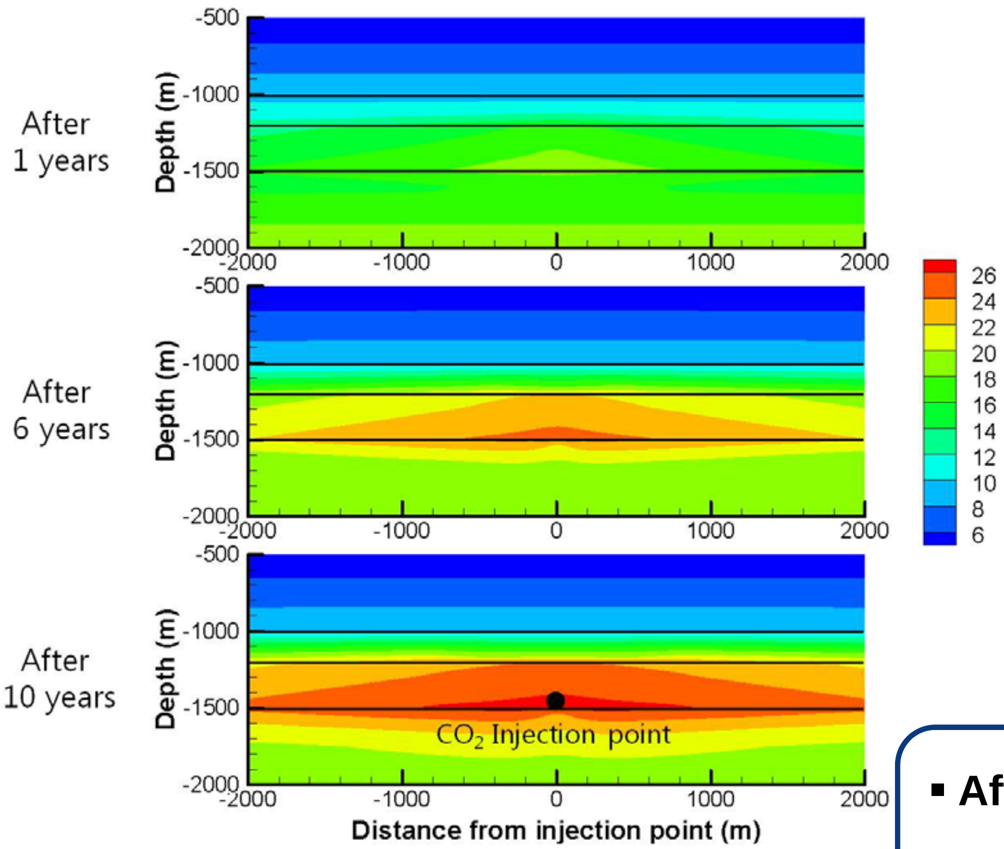




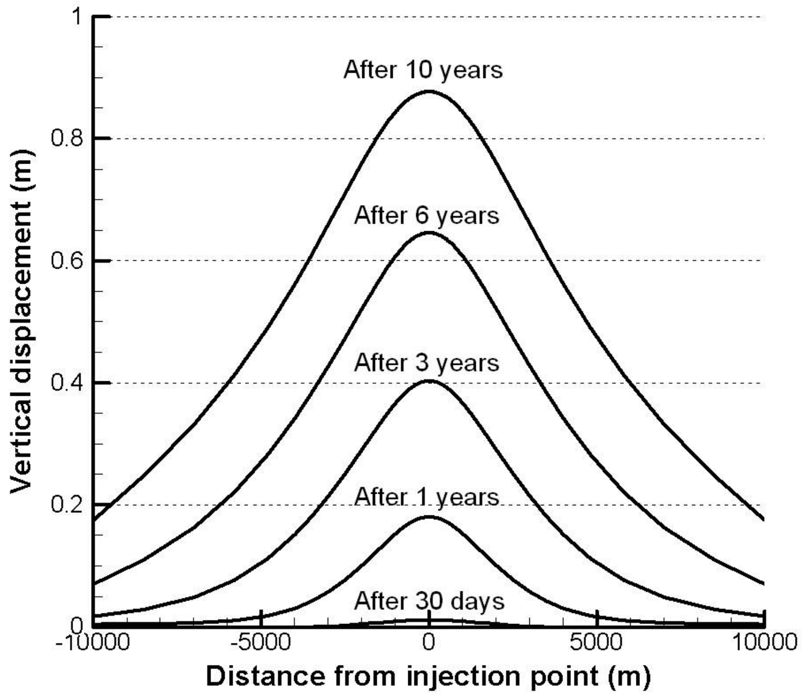


Rutqvist et al., 2009, IJGG

Reservoir subsidence (저류층 침하)
Example(3): Heaving in CO2 storage reservoir



Pressure change with time near the injection point (Units: MPa)



Vertical displacement profile

- **After 10 years**
  - **the pore pressure : about 12 MPa**
  - **the vertical displacement : 0.87 m**

Lee, Min, Rutqvist (2012), RMRE

Example of Reservoir Geomechanics Application
Natural Gas storage in depleted Reservoir

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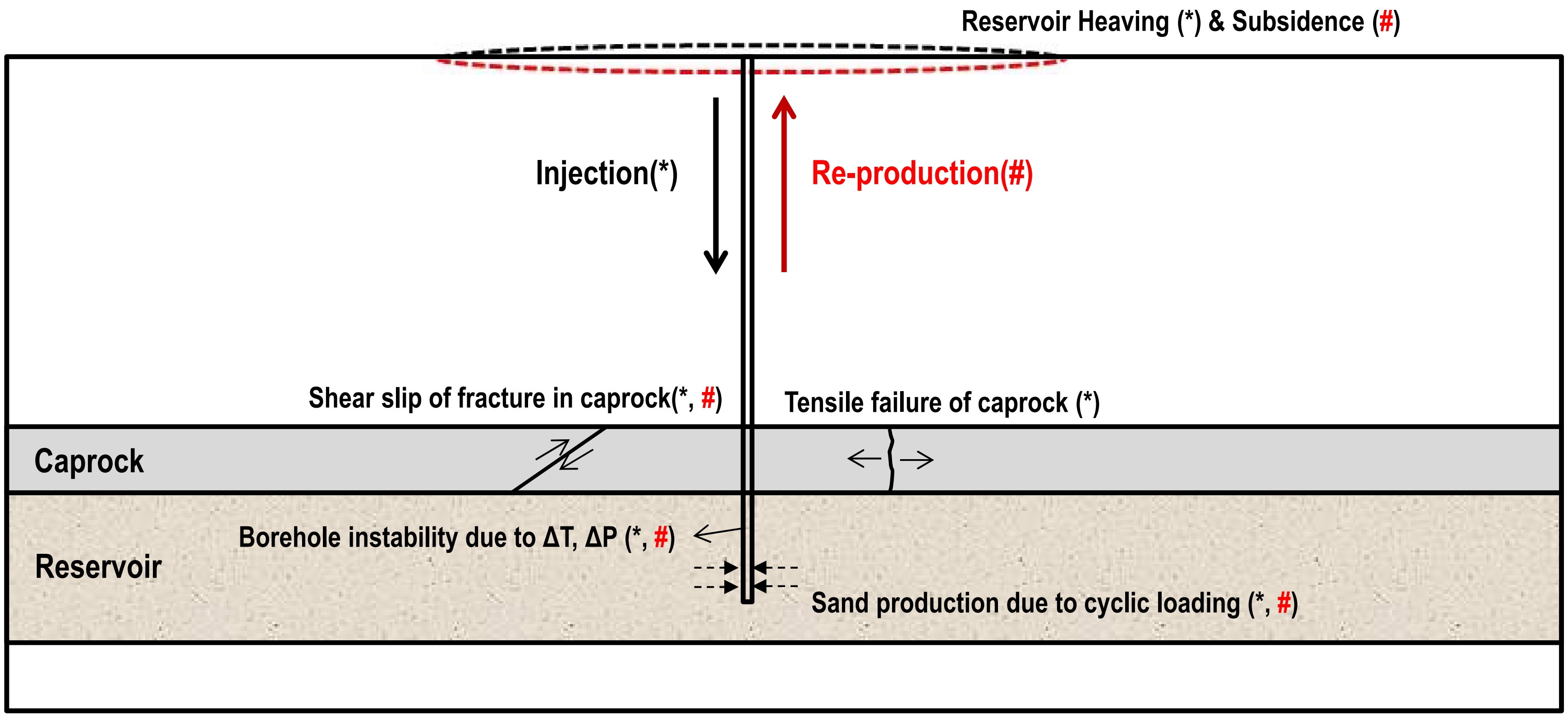
- Natural Gas need to be stored due to unbalanced consumption during summer and winter.



Min, 2013, Geomechanics study for Underground Gas storage of depleted reservoir

Summary
Contents – Applications

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- Fundamentals of Geomechanics
  - Stress
  - Strain
  - Stress-strain relationship
  - Uniaxial, tensile & triaxial strength
  - In situ rock stress
- Stress around a cavities
  - Circular hole
    - Anisotropic case
    - Elastic-plastic rock
  - Penny-shaped cracks

Things to remember

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- Stress (Equilibrium, Principal stress, Transformation)
- Hooke's Law (compare with Darcy's Law)
- Stress concentration around circular hole
  (3 & -1)
- Concept of Effective Stress