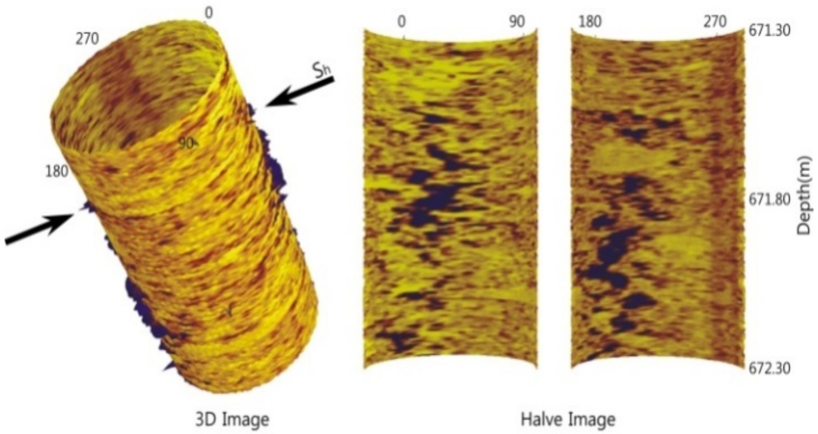
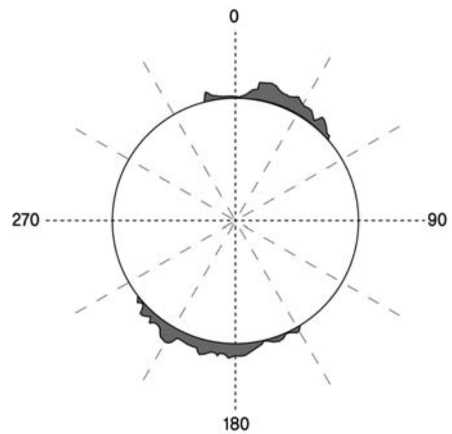
Topics in Energy and Environmental Geomechanics – Enhanced Geothermal Systems (EGS)
Lecture 3. Borehole Geomechanics
(16, 23 Sept 2013)





Imaage log and borehole breakout at Pohang H-5 hole

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Introduction
Contents of the course

- 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)

outline

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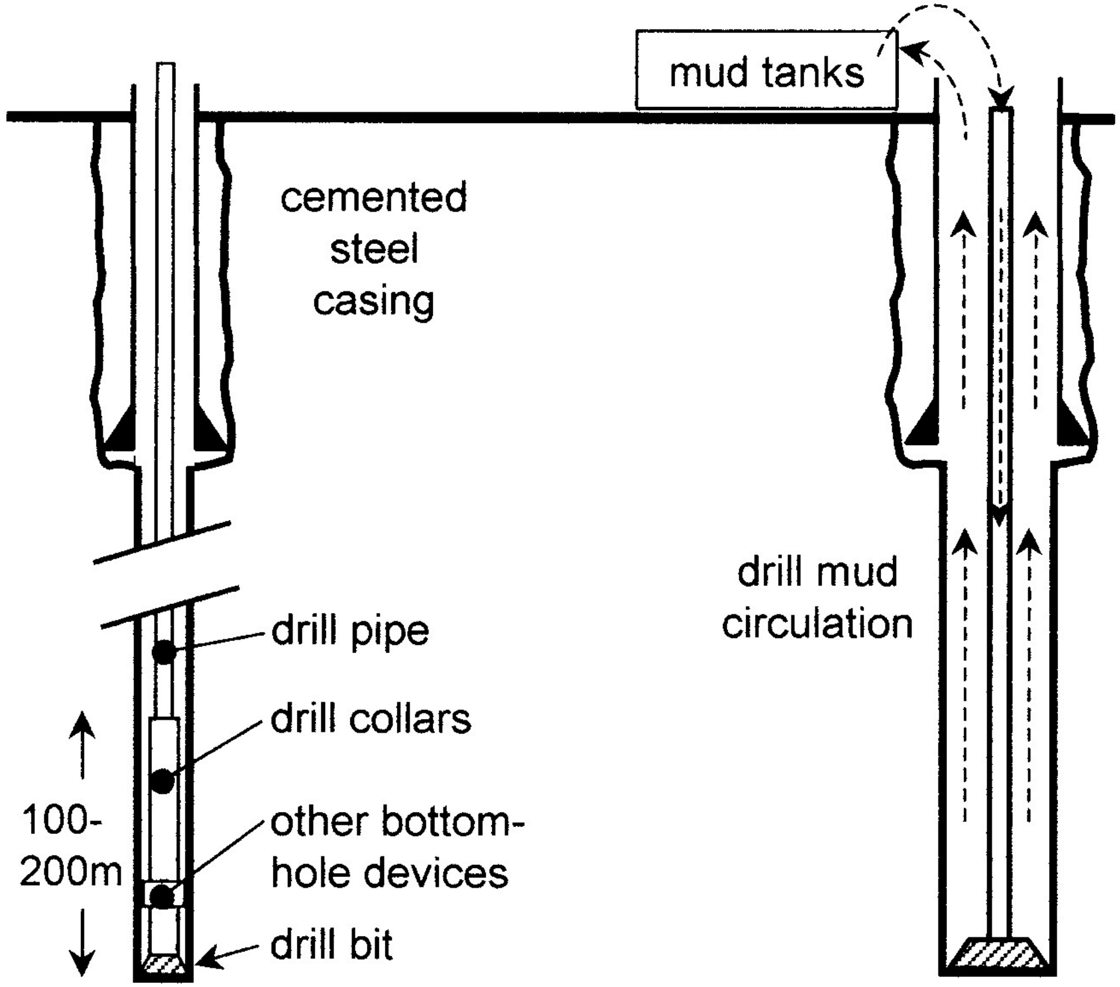
- Motivation for borehole geomechanics
  - Importance
- Theoretical background
  - Stress/strain, constitutive relation, stress equilibrium equation, governing equation
  - Strength and Failure criteria
  - Stresses around a borehole
    - In situ stress, injection pressure, pore pressure, thermal stress
    - Elastic analysis, Elastoplastic analysis
    - Stresses in hollow cylinder
    - Stresses in deviated borehole

outline

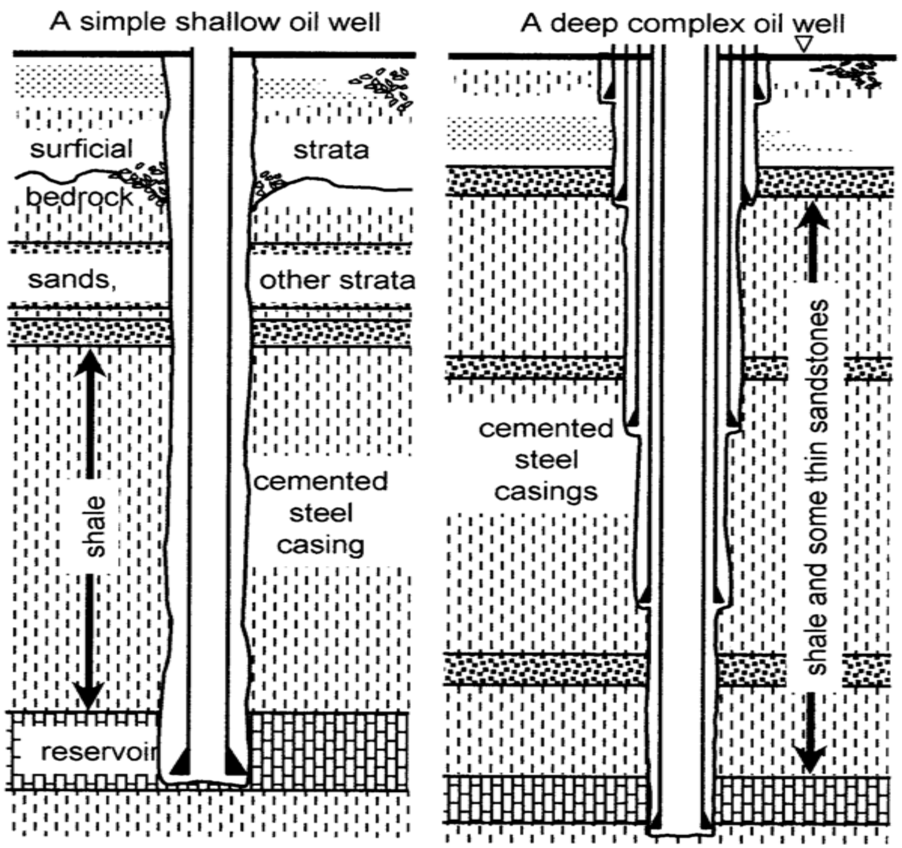
- Borehole stability Analysis
  - Borehole breakout
  - Stress estimation from borehole observation
  - Drilling induced tensile failure
  - Borehole stability problems
    - Tight hole/stuck pipe
    - Lost circulation/mud losses
  - Stability during drilling
    - Mud weight window
  - Other topics

Borehole Stability Problems
Drilling operation



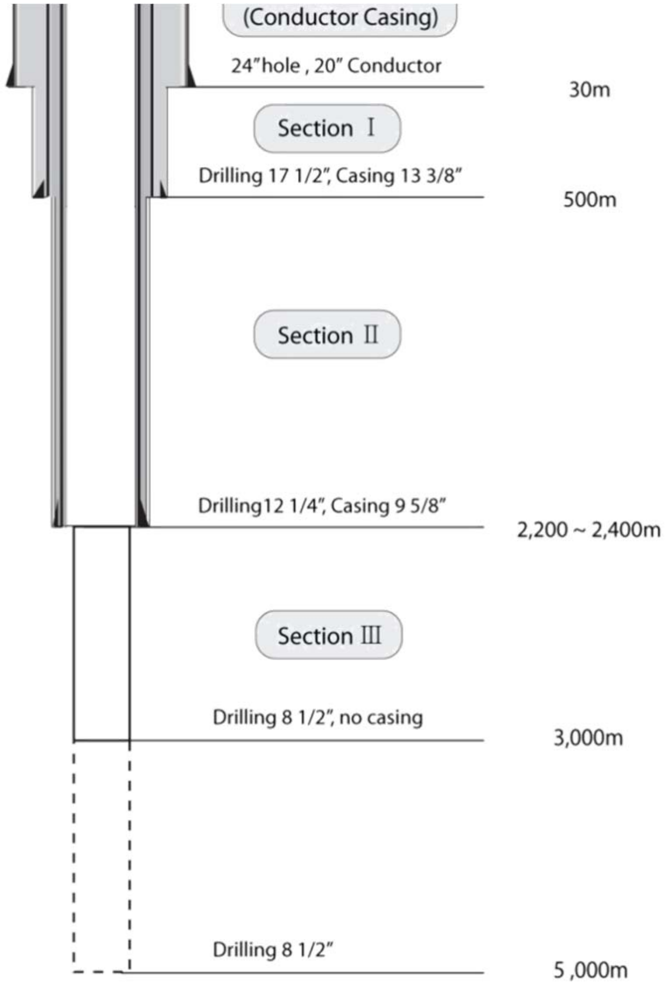
Drilling equipment and mud circulation (Vincent, 2006)

Borehole Stability Problems
Drilling operation



Well casing profiles in the oil industry

(Vincent, 2006)



Well Plan in Pohang EGS site

Borehole stability problem

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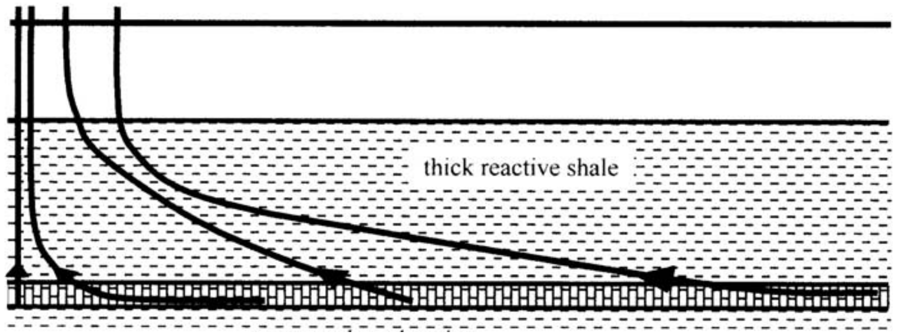
- Importance?
  - Borehole instability cause substantial problems – can cause 5-10% of drilling cost. Mainly mechanical collapse
  - Instability usually occur in shale or mudstone.
  - Demand ↑ for more sophisticated well trajectories – highly deviated, horizontal, deep wells.
  - Environmental impact due to lost circulation
  - Safetv issue too from kick/borehole blow out in petroleum industry



Various well profiles (Vincent, 2006)

Borehole stability problem

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- Factors
  - In situ stress
  - Injection pressure or mud weight
  - Reservoir rock mechanics properties
  - Anisotropy of rock properties
  - Thermal effect
  - Chemistry (especially shale/mudstone)

Borehole Stability problem

- Borehole problem is problematic because (Fjaer et al., 2008);
  - Drill bit may be > 1,000s m away, visual observation not possible (cf. tunneling excavation)
  - Large variation in reservoir in stress (depleted reservoir/non-depleted shale, drilling through faults). In situ stress measurement difficult
  - Large variation/uncertainty in formation properties. Coring is costly.
  - Many mechanisms contribute; mud chemistry, stress, temperature, pore pressure…
  - Operational condition is complex
- Sound understanding on theory and insightful engineering judgment should be combined.

Borehole Stability Problems
nature of the problem

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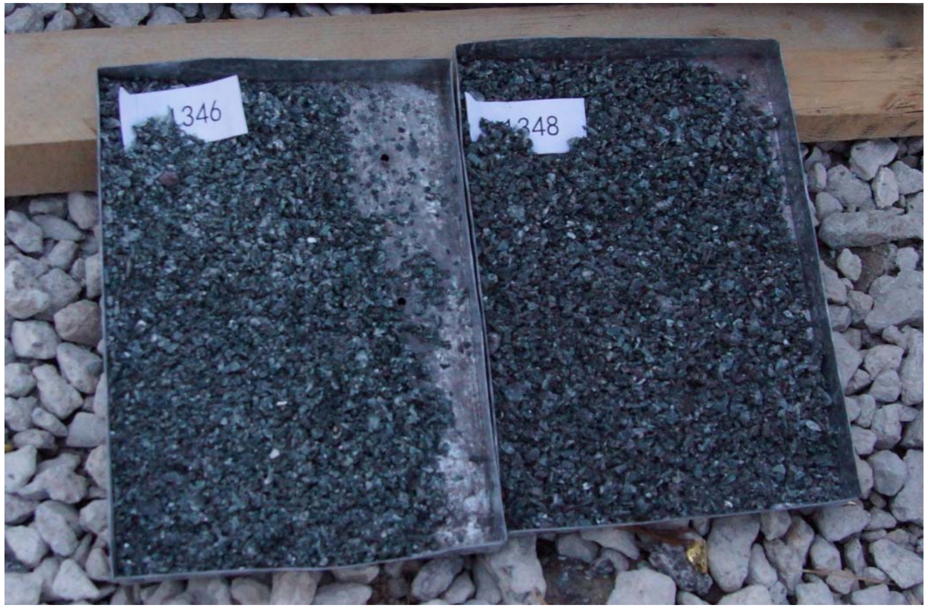

Rock cutting from Pohang EGS site. ~few mm

↑

REALITY

DREAM

↓

One of the biggest rock core in the world at AECL URL in Canada (2002). ~ 1m

Borehole stability problem
Work Flow chart

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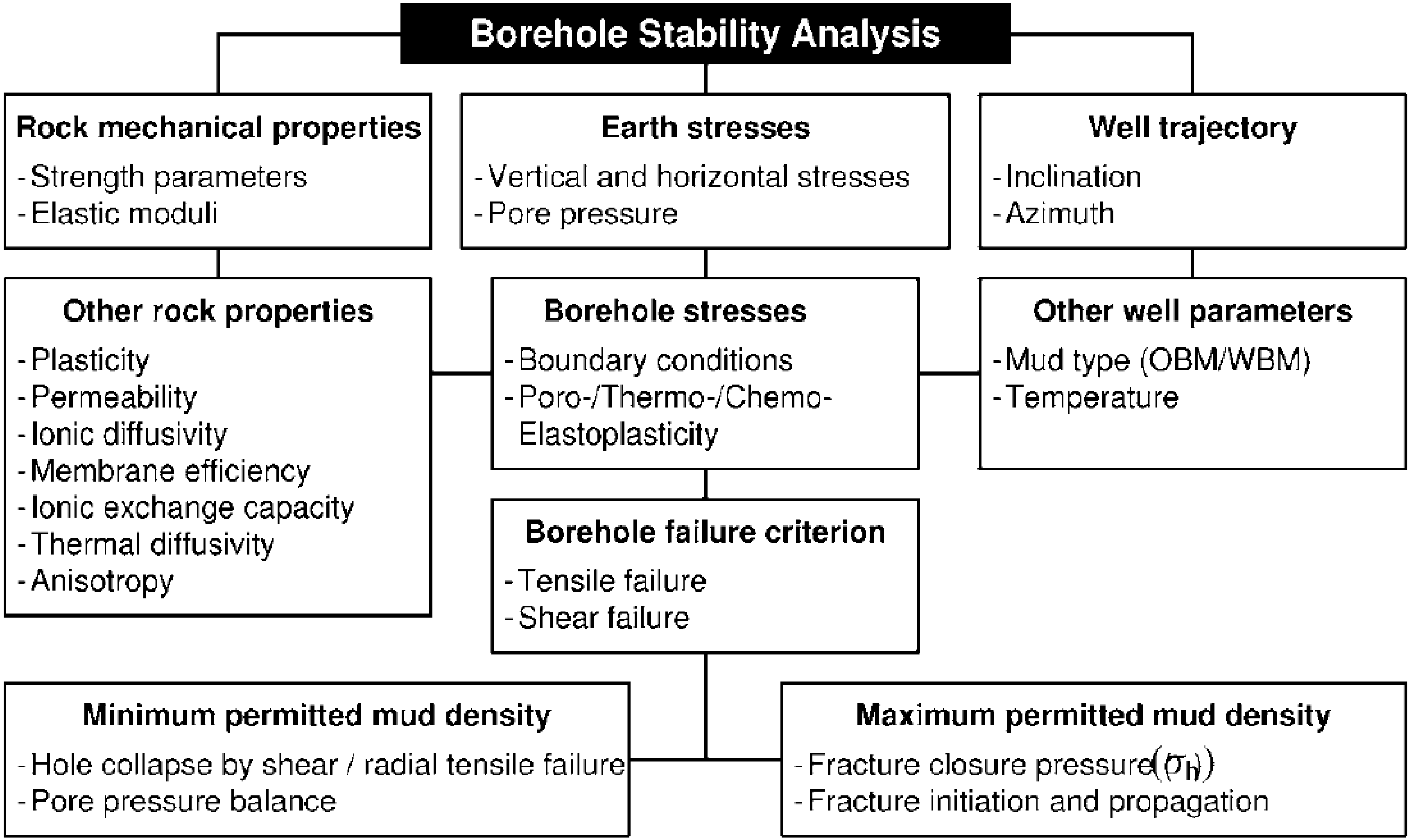

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Borehole stability problem
Example

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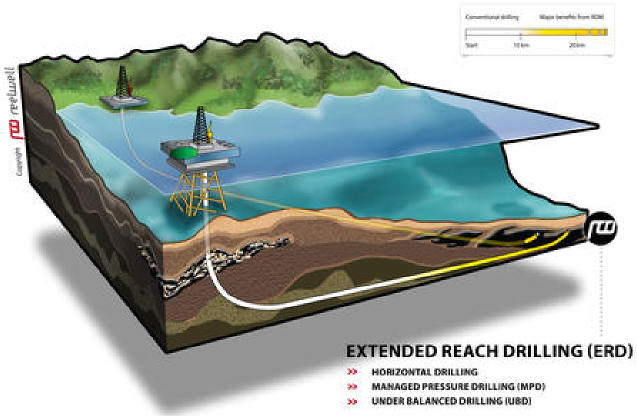
Oseberg in North Sea (Norway)

- 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
Example

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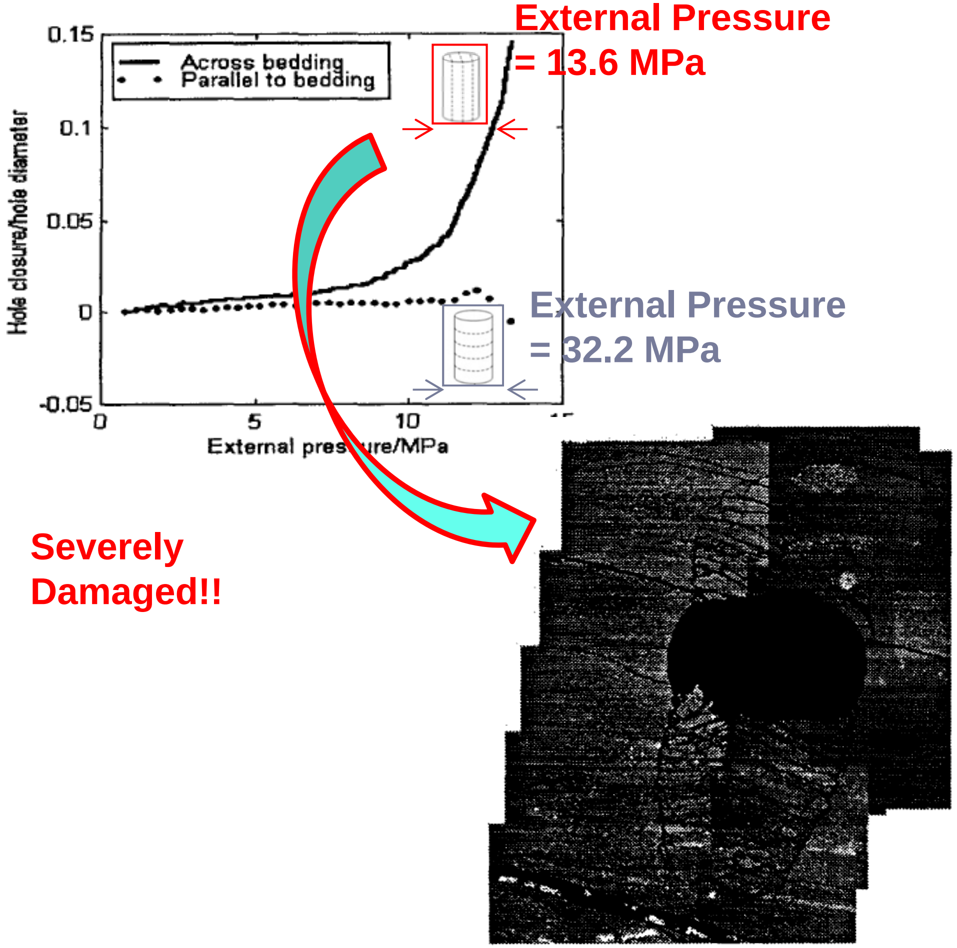
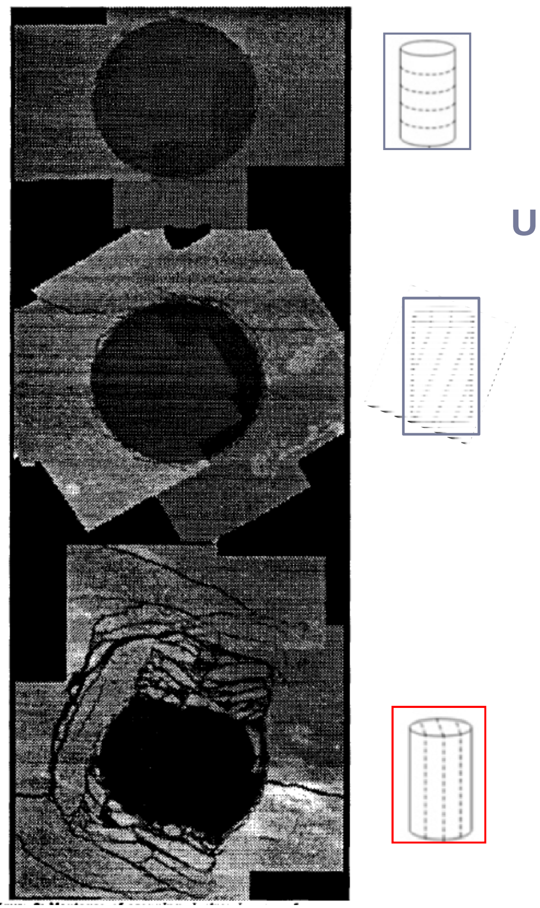
a) Draupne-similar Shale



Severely Damaged!!

b) J_2 (Outcrop shale)

Loaded and unloaded at approximately 20 MPa



Undamaged

Okland & Cook, SPE, 1998

Some Mathematical Equations that capture the important physics

Borehole stability problem
Effect of internal pressure

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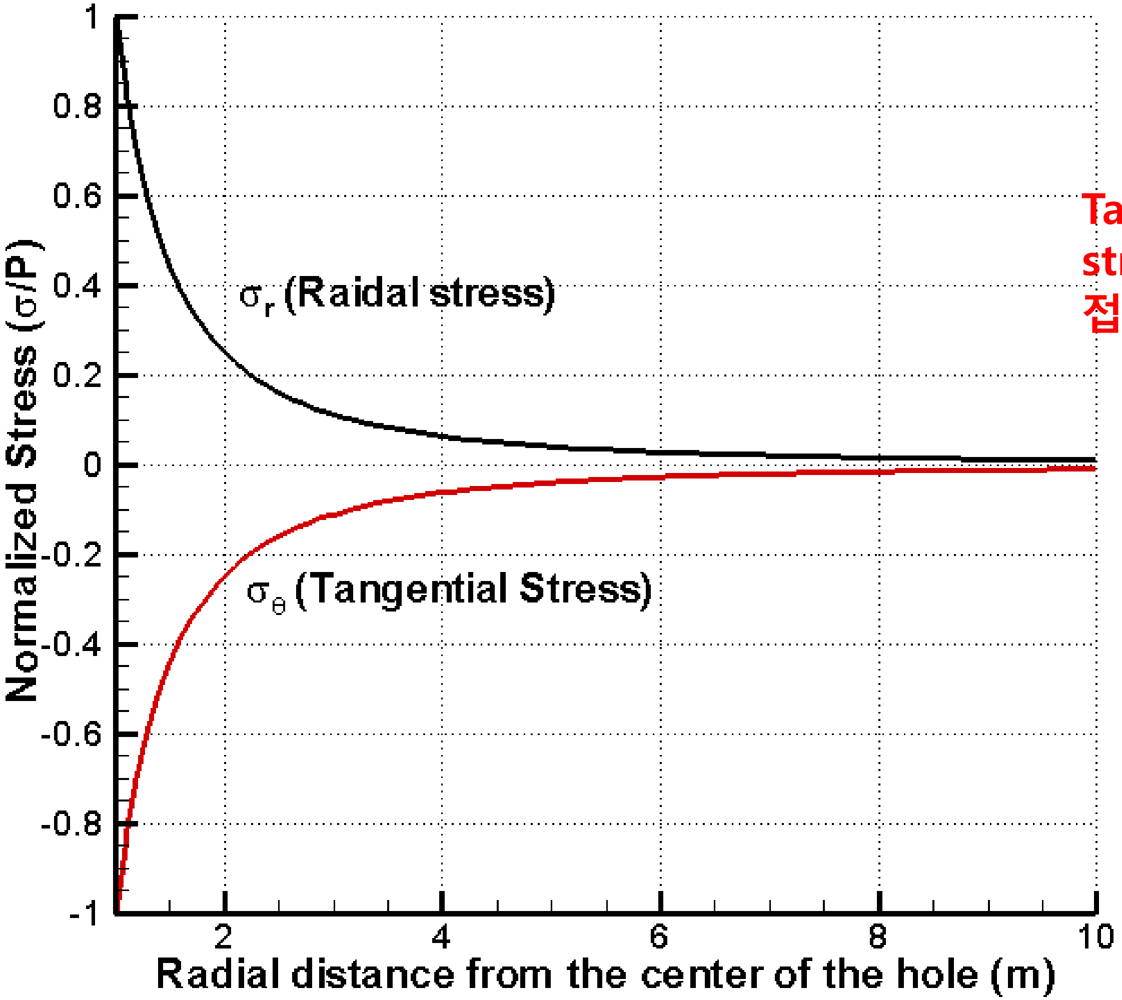
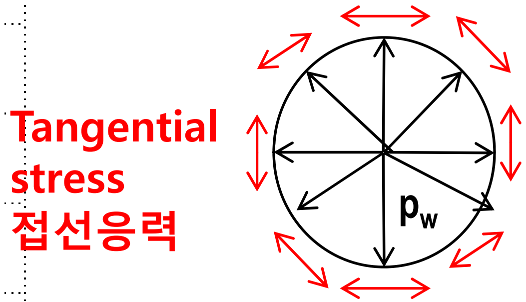
- Increase of internal mud/hydraulic pressure





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

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

Borehole stability problem
Elastic Stress distribution

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

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

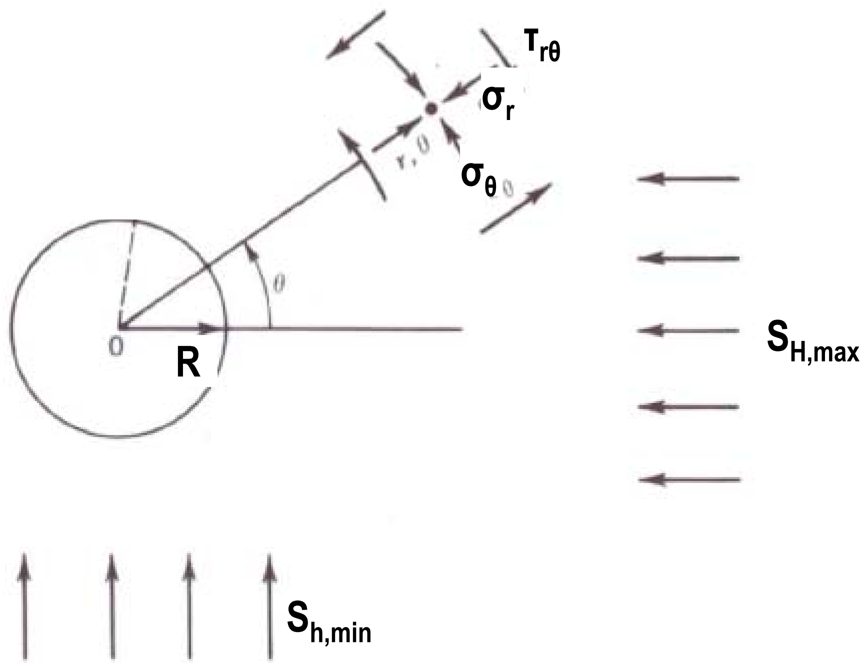
$$\tau_{r\theta} = \frac{S_{H\max} - S_{h\min}}{2}\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

R: 보어홀의 반경

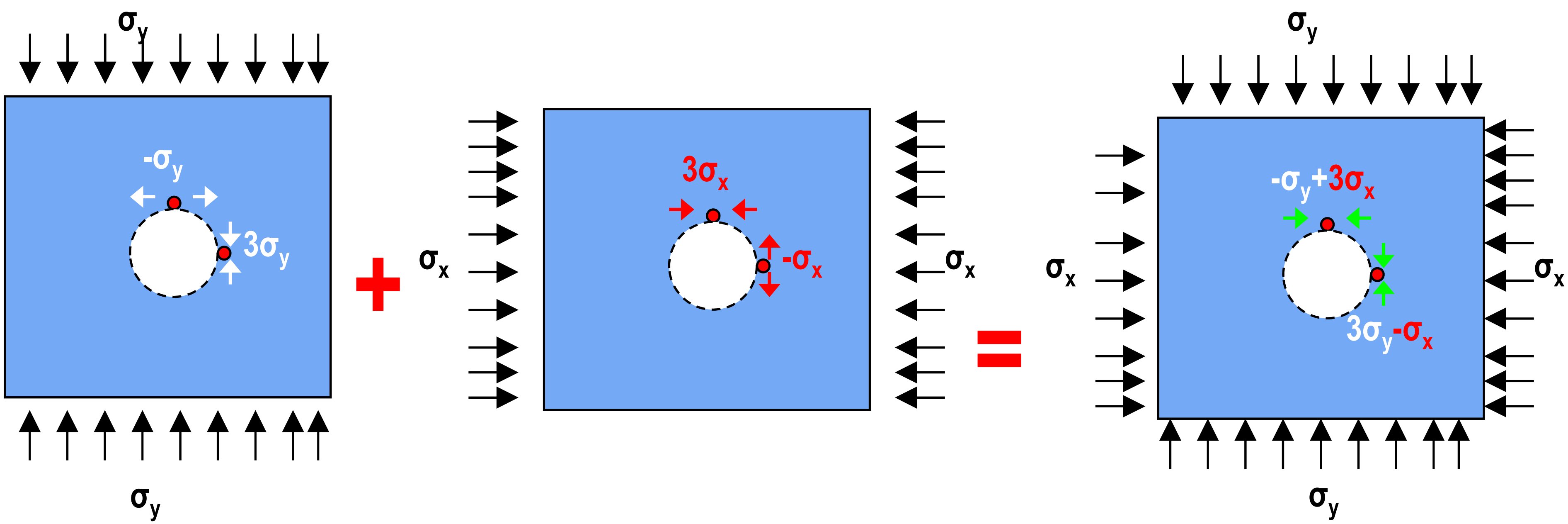
r: 보어홀 중심에서
반경방향의 거리

θ: $S_{H,max}$ 으로부터 반시계
방향으로 측정

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



Borehole stability problem
Elastic Stress distribution



Under uniaxial stress condition

Maximum Stress concentration 3

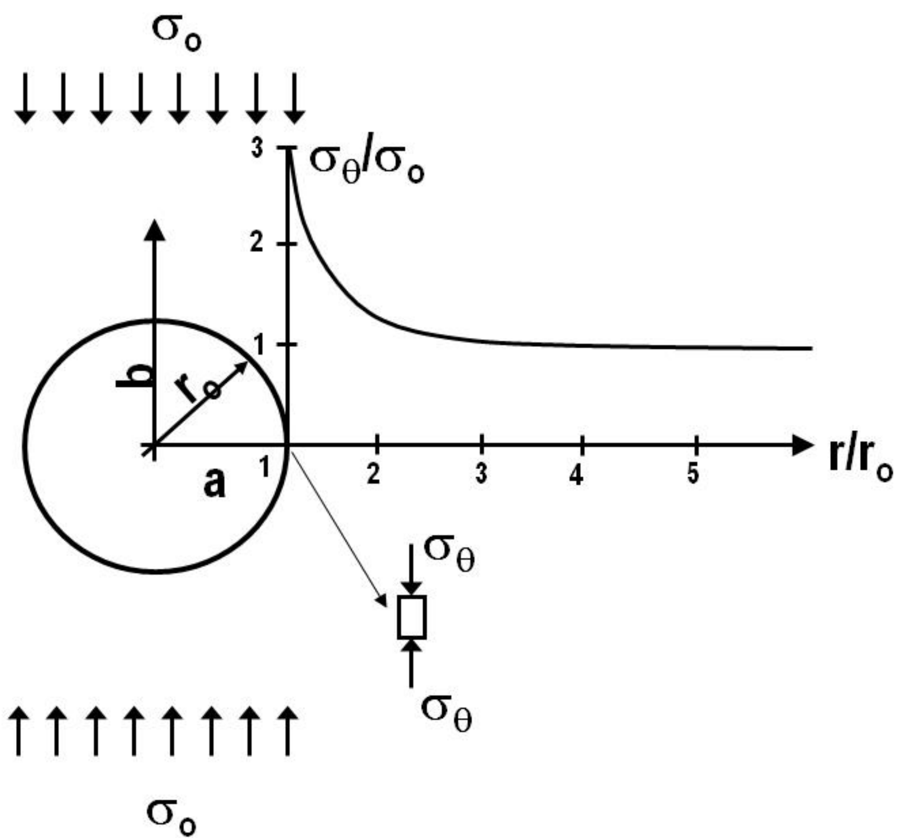
Minimum Stress concentration -1

Biaxial Stress condition:

By superposition

Borehole stability problem
Elastic Stress distribution

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



Borehole stability problem
Generalized Kirsch's solution

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

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

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

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

Borehole stability problem
Generalized Kirsch's solution

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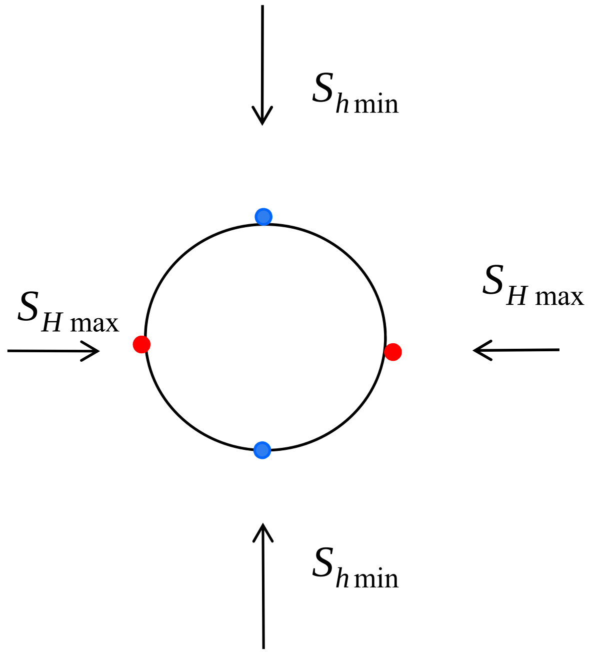
- At the borehole wall (r = R), maximum and minimum hoop stresses are;

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

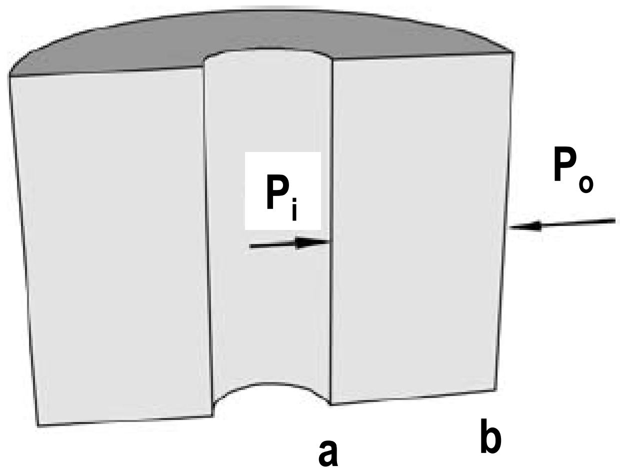
  - $$\sigma_{\theta,\max} = 3S_{h\max} - S_{h\min} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

- Without considering temperature change,

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



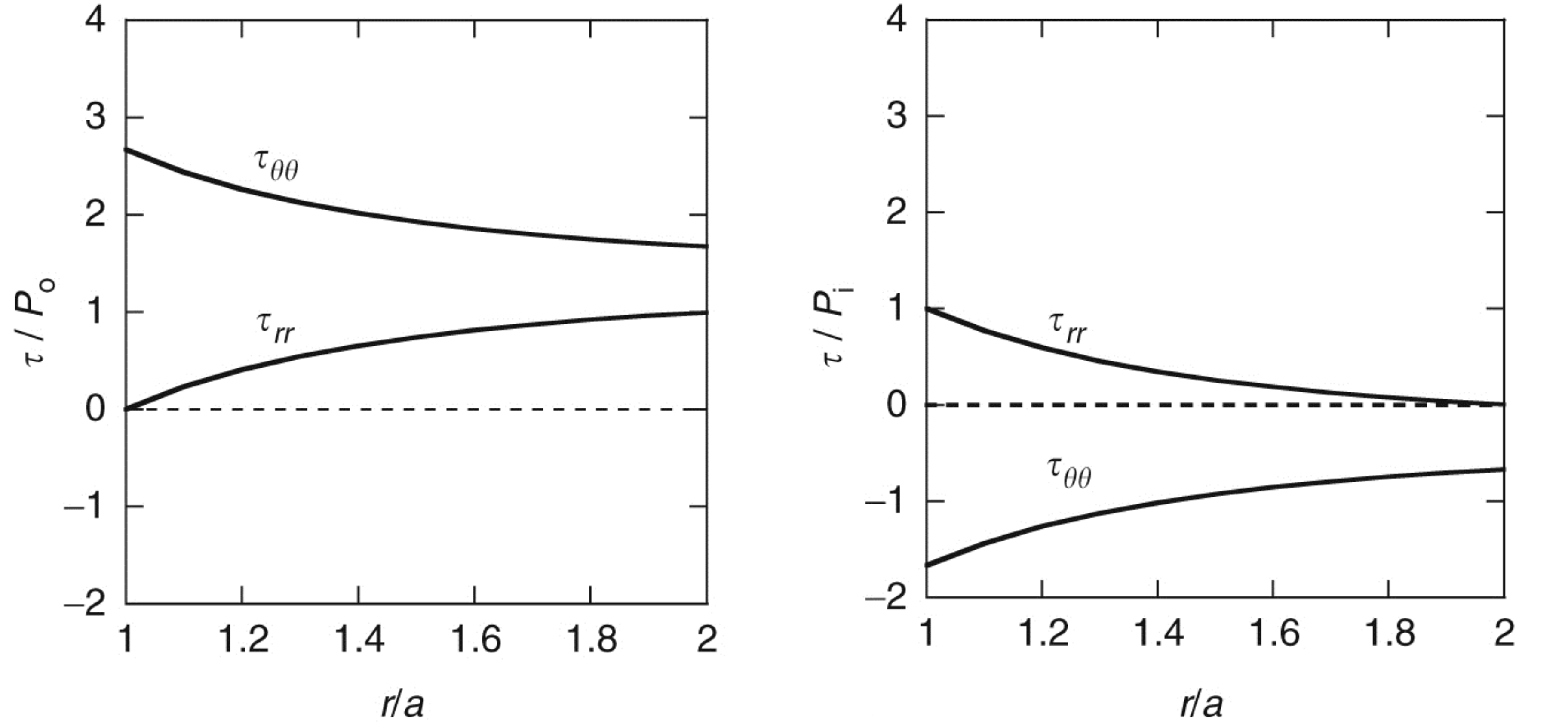
Borehole stability problem
Solution in hollow cylinder



$$\sigma_r = \frac{(b^2 P_o - a^2 P_i)}{(b^2 - a^2)} + \frac{a^2 b^2 (P_i - P_o)}{(b^2 - a^2) r^2}$$

$$\sigma_\theta = \frac{(b^2 P_o - a^2 P_i)}{(b^2 - a^2)} - \frac{a^2 b^2 (P_i - P_o)}{(b^2 - a^2) r^2}$$

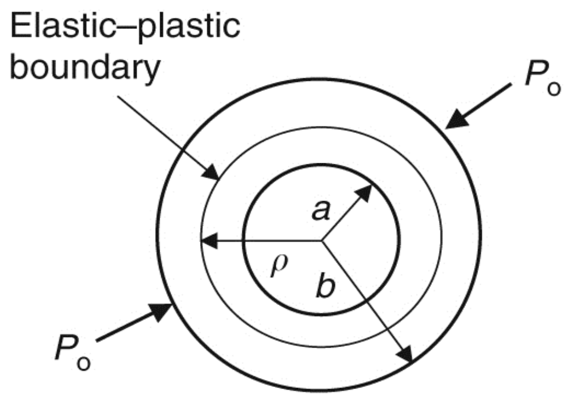
Borehole stability problem
Solution in hollow cylinder

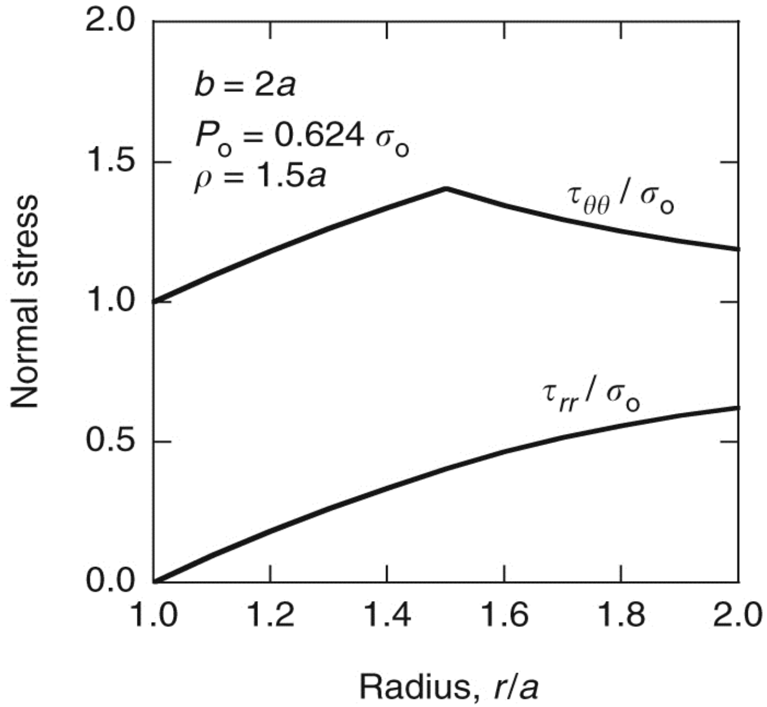


Stress distribution in a hollow cylinder with b = 2a (J,C & Z, 2007)

Borehole stability problem
Solution in hollow cylinder

Borehole stability problem
Solution in hollow cylinder - elastoplastic





Failure criterion: $\sigma_\theta - \sigma_r = \sigma_0$

$$\left[1 + 2\ln(\rho/a) - (\rho/b)^2\right] = \frac{2P_0}{\sigma_0}$$

$a < r < \rho$

$$\sigma_r = \sigma_0 \ln(r/a)$$

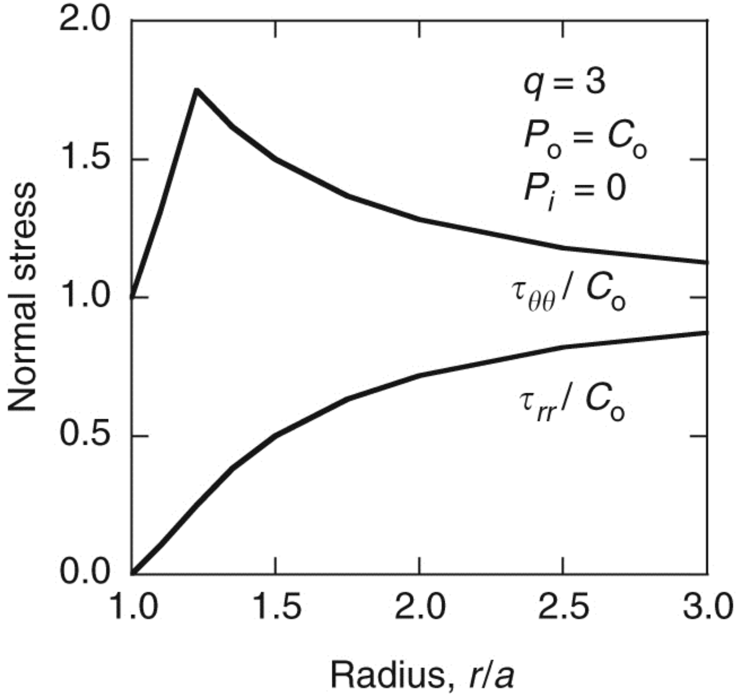
$$\sigma_\theta = \sigma_0\left[\ln(r/a) + 1\right]$$

$\rho < r < b$

$$\sigma_r = \frac{\sigma_0}{2}\left[1 + 2\ln(\rho/a) - (\rho/r)^2\right]$$

$$\sigma_\theta = \frac{\sigma_0}{2}\left[1 + 2\ln(\rho/a) + (\rho/r)^2\right]$$

Borehole stability problem
Solution in hollow cylinder - elastoplastic



Failure criterion: $\sigma_1 = C_0 + q\sigma_3 = 2S_0 \tan\beta + \sigma_3 \dfrac{(1+\sin\phi)}{(1-\sin\phi)}$

$a < r < \rho$

$$\sigma_r = \left[P_i + (C_0/2)\right](r/a)^2 - (C_0/2)$$

$$\sigma_\theta = 3\left[P_i + (C_0/2)\right](r/a)^2 - (C_0/2)$$

$\rho < r < b$

$$\sigma_r = P_0 - \frac{1}{2}\left[P_0 + (C_0/2)\right](r/a)^2$$

$$\sigma_\theta = P_0 + \frac{1}{2}\left[P_0 + (C_0/2)\right](r/a)^2$$

Stress around a circular hole
Anisotropy

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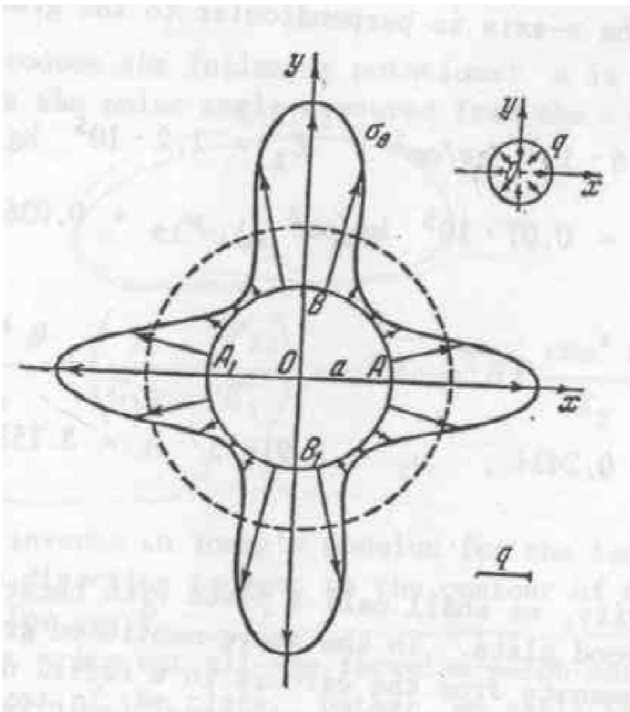
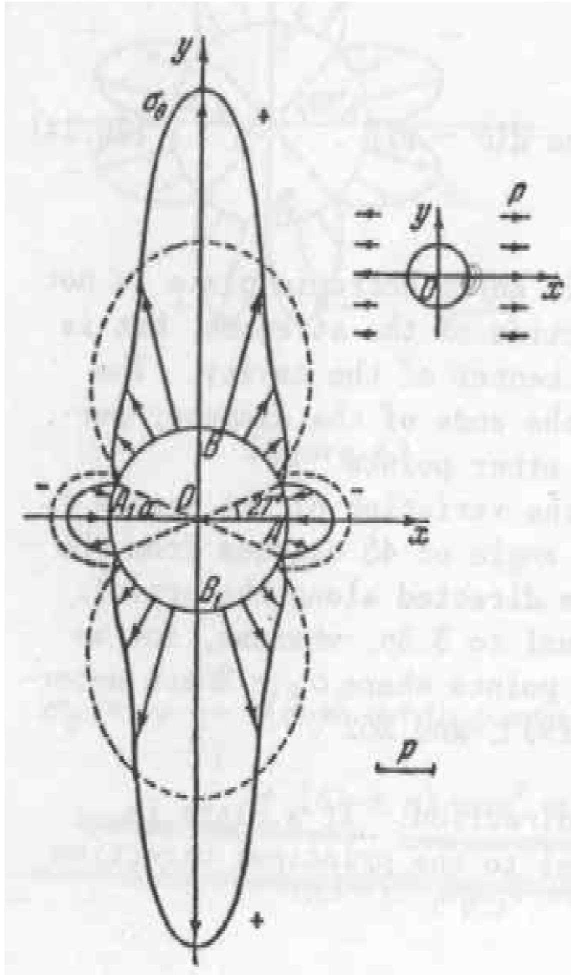
- Some formulae considering anisotropy (internal pressure, uniaxial stress)





Lekhnitskii, 1963

Stress around a circular hole
Anisotropy

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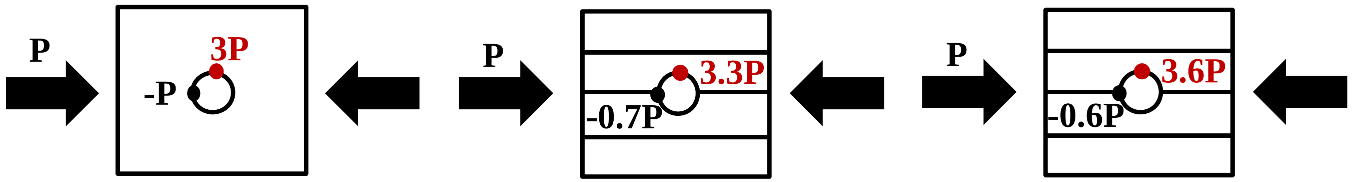
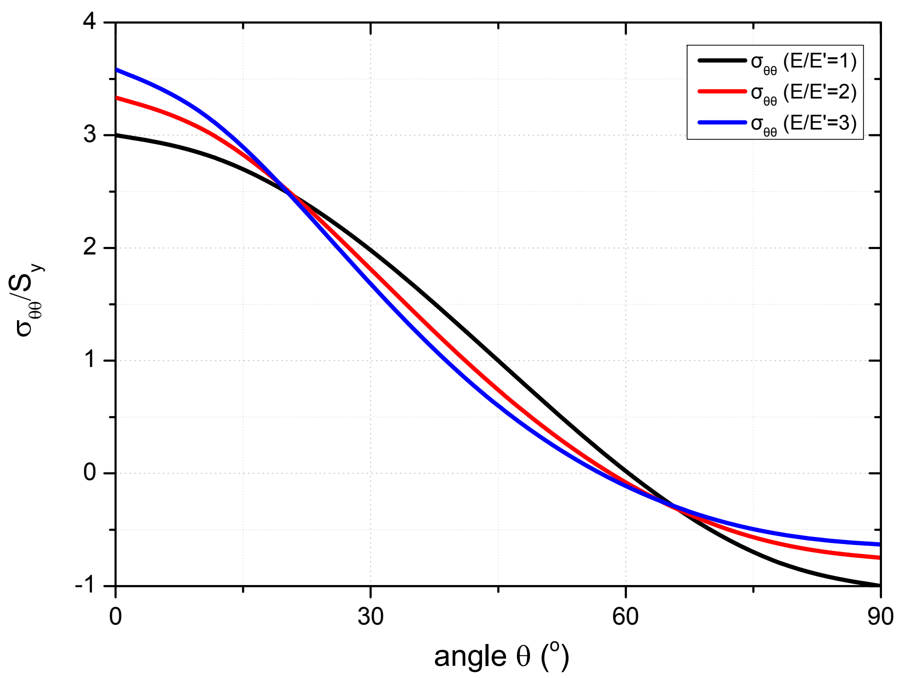


Isotropic rock (E/E′= 1)

Transversely isotropic rock (E/E′ = 2)

Transversely isotropic rock (E/E′ = 3)



- 탄성계수의 이방성에 따라 응력집중의 정도가 달라짐.

Kim H, 2012, MS thesis SNU

Stress around a circular hole
Anisotropy

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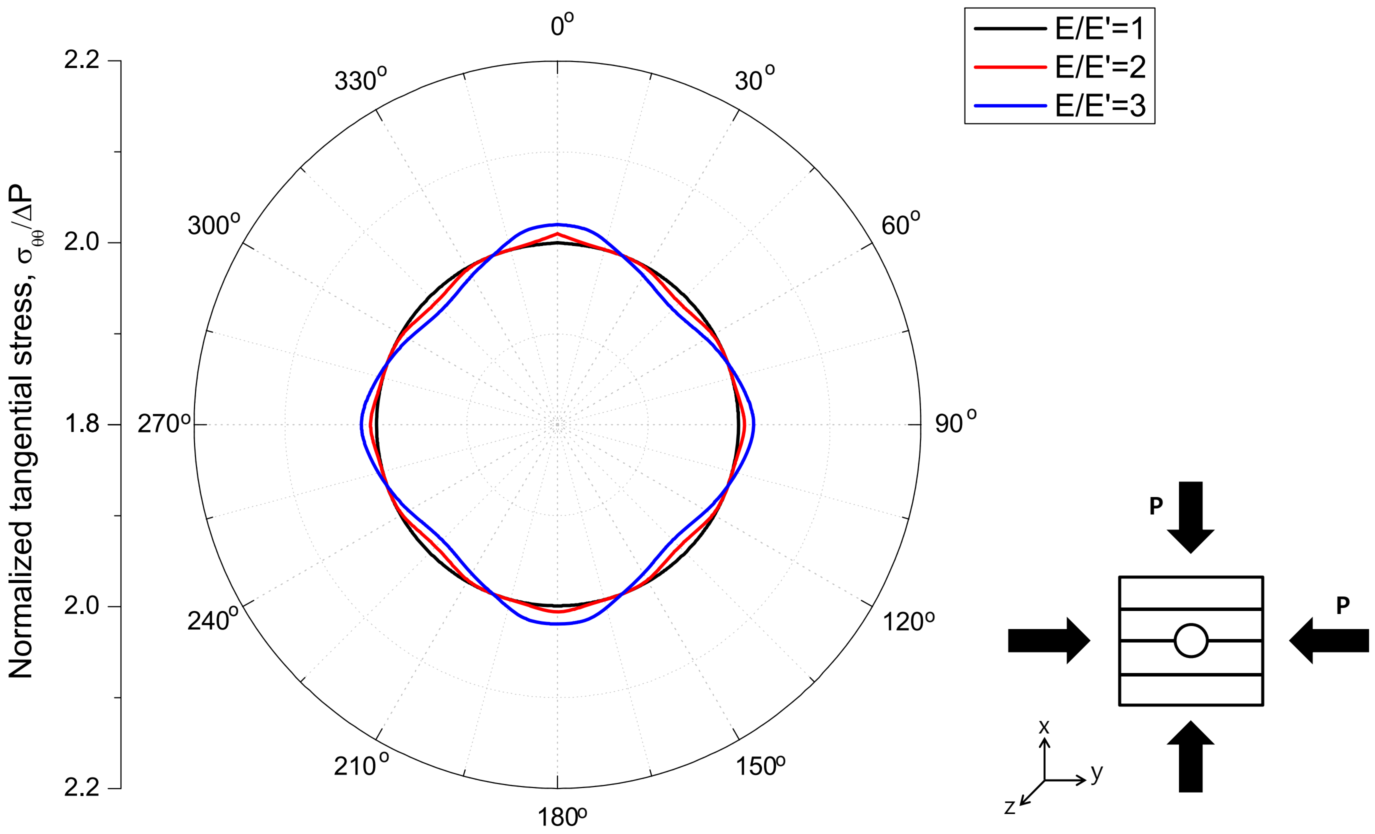

Kim H, 2012, MS thesis SNU

Stress around a circular hole
Anisotropy

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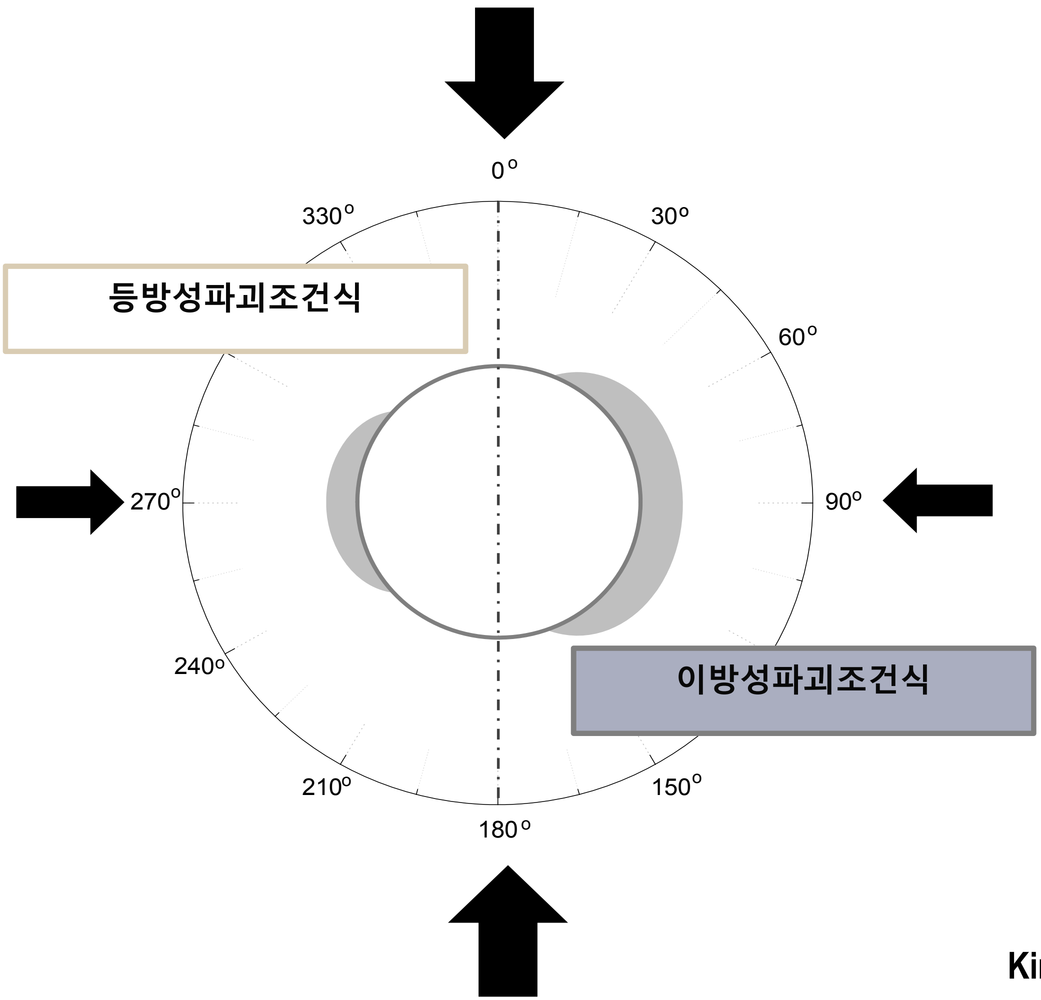
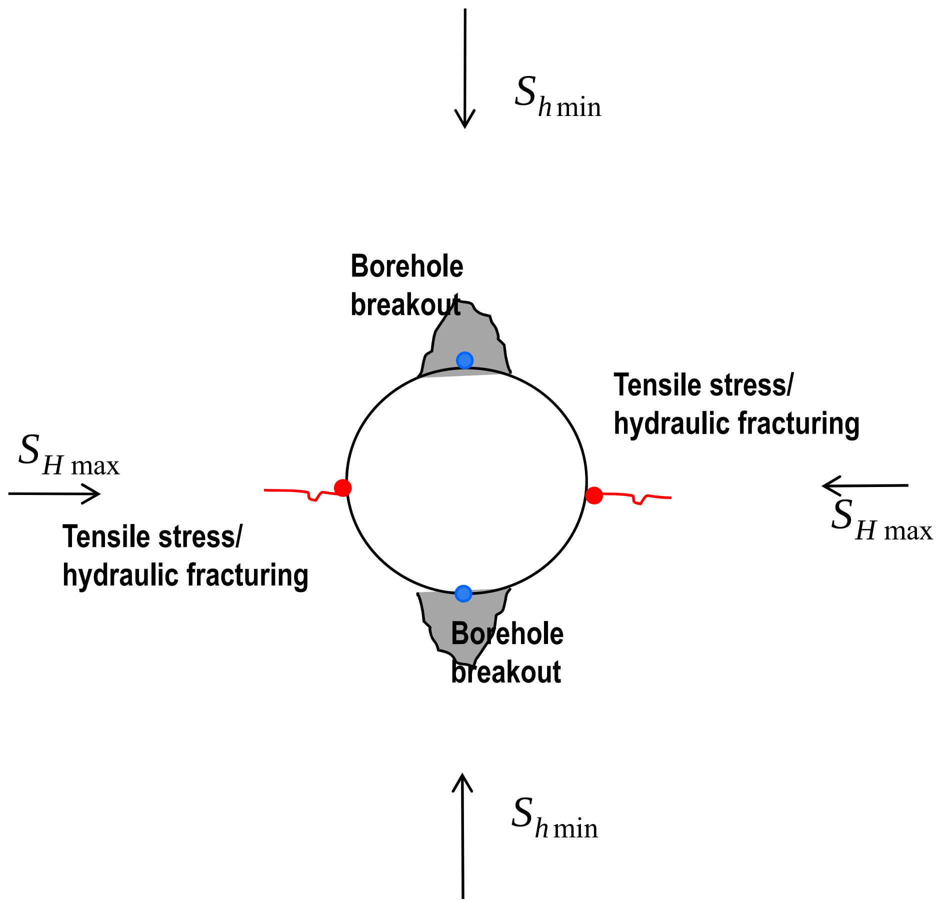
- 어떤 파괴조건식을 적용하느냐에 따라 파괴범위가 다르게 나타남



Kim H, 2012, MS thesis SNU

Some Important Phenemona that are encountered around boreholes

Borehole stability problem
borehole breakout vs. hydraulic fracturing



Assumption: Impermeable reservoir & impermeable borehole wall

– 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 (if pw=0)

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

Borehole stability problem
borehole breakout

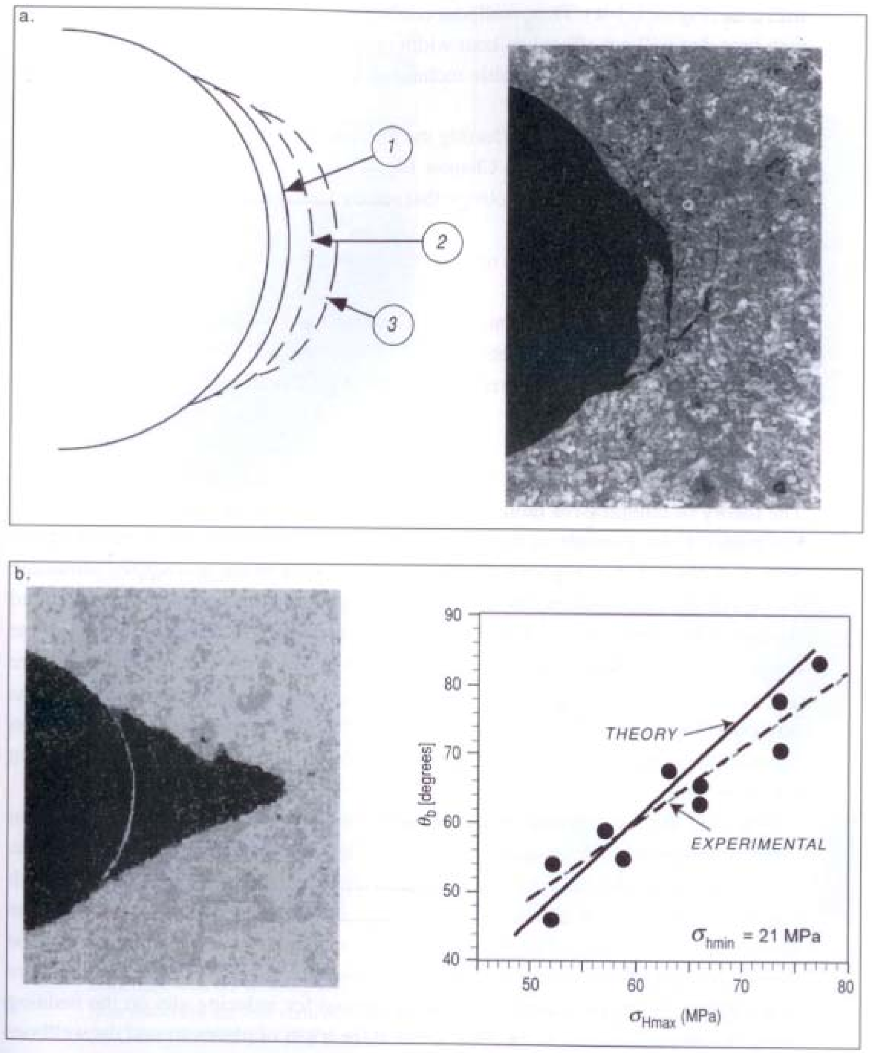
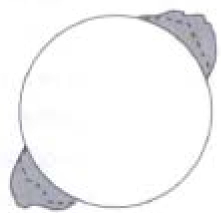


Figure 6.15. After the formation of wellbore breakouts, they are expected to increase in depth, but not width. This is as shown theoretically in (a) after Zoback, Moos *et al.* (1985) and confirmed by laboratory studies (Haimson and Herrick 1989). It can be seen photographically that breakouts in laboratory 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 (shear) failure
- Occur in the direction of minimum horizontal stress



Zoback, 2007

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Borehole stability problem
borehole breakout (Pohang EGS site)

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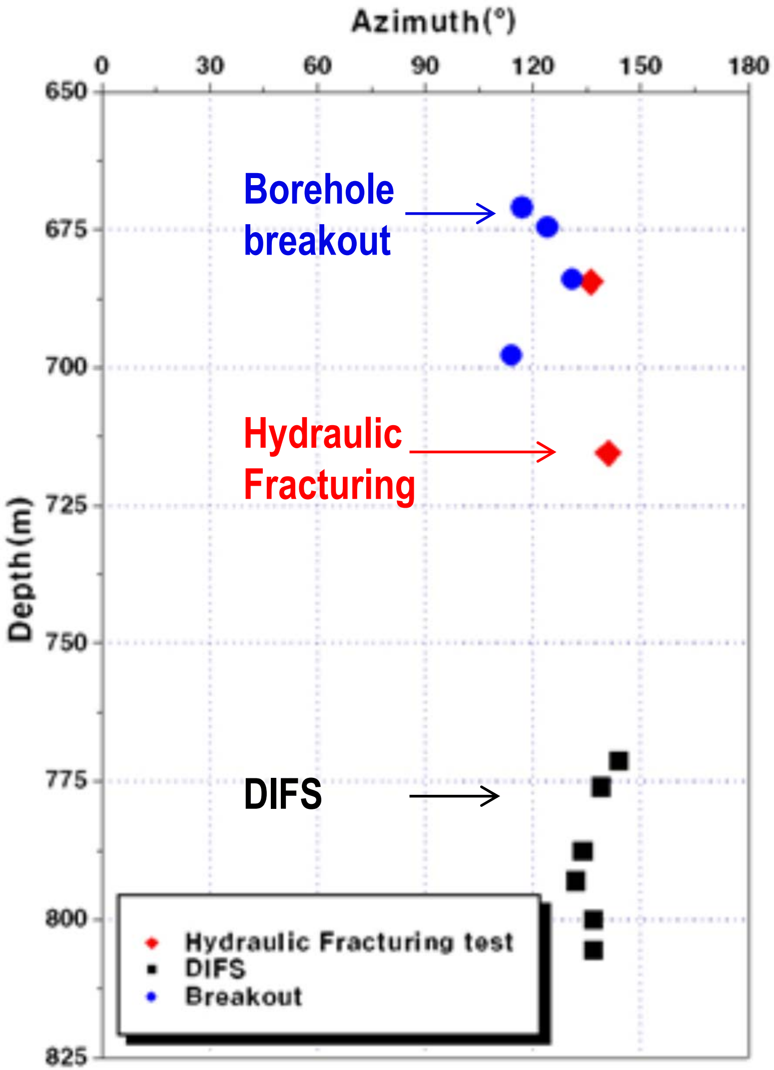
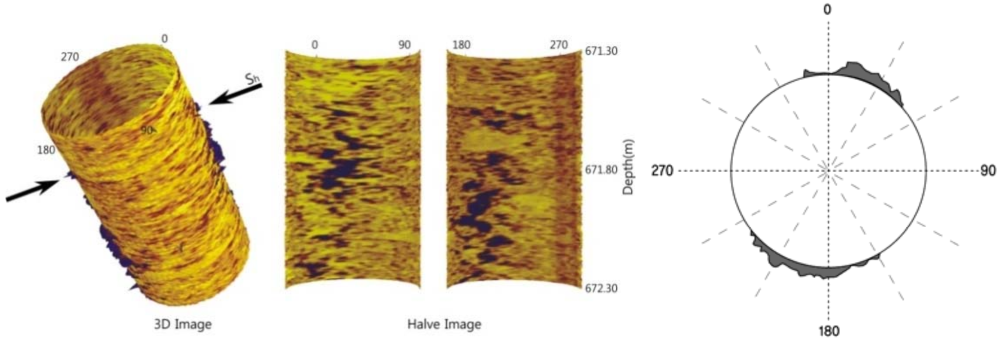
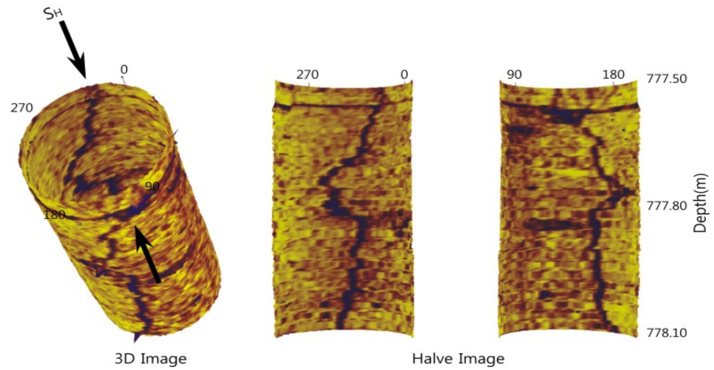




Borehole breakout (670 – 900 m)

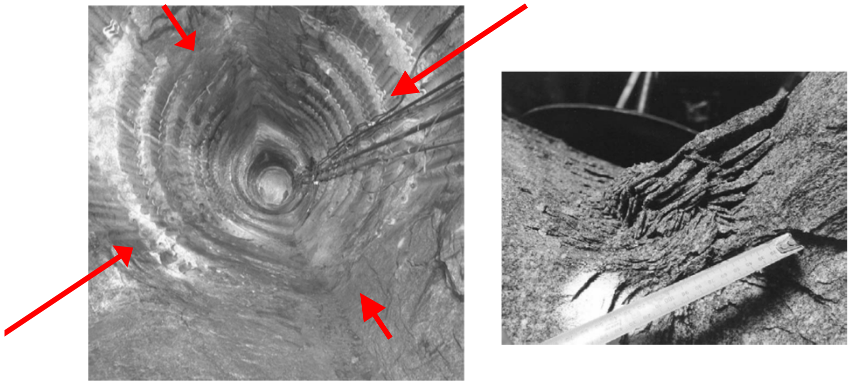
by borehole acoustic scanner



Drilling induced fractures (DIFS) (770 – 810 m)

Borehole stability problem
borehole breakout – rock spalling

- Similar observation can be found in underground construction



V notched failure due to high in situ stress
(400 m, Winnipeg, Canada, Chandler, 2004)

Winnipeg, Canada (Min, 2002)

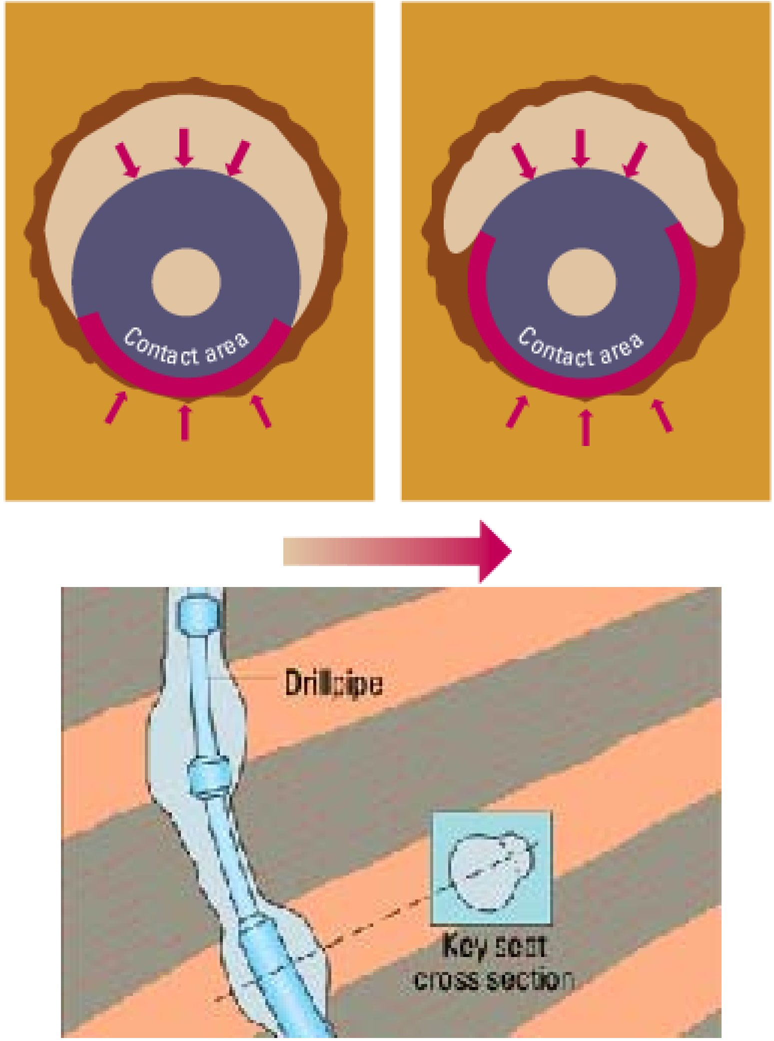
Borehole Stability Problems
Tight hole/stuck pipe

- Tight hole/stuck pipe
  - Hole collapse
    - Increased borehole size due to brittle failure and caving of the wellbore. Stuck because of accumulated cavings ("sloughing shale")
    - Reduced borehole size by plastic deformation – gumbo shale. Require reaming and result in a lost drillpipe
  - Inappropriate hole cleaning
    - When drilling cuttings (could be also from formation failure) were not fully removed

www.wellideas.com

Borehole Stability Problems
Tight hole/stuck pipe

- Differential sticking
  - Conditin in which Drilling string cannot be moved along the axis of the borehole
  - Caused by overpressure in the hole
  - Usually in the permeable formation
- Deviation from ideal trajectory
  - Dogleg and keyseat problem

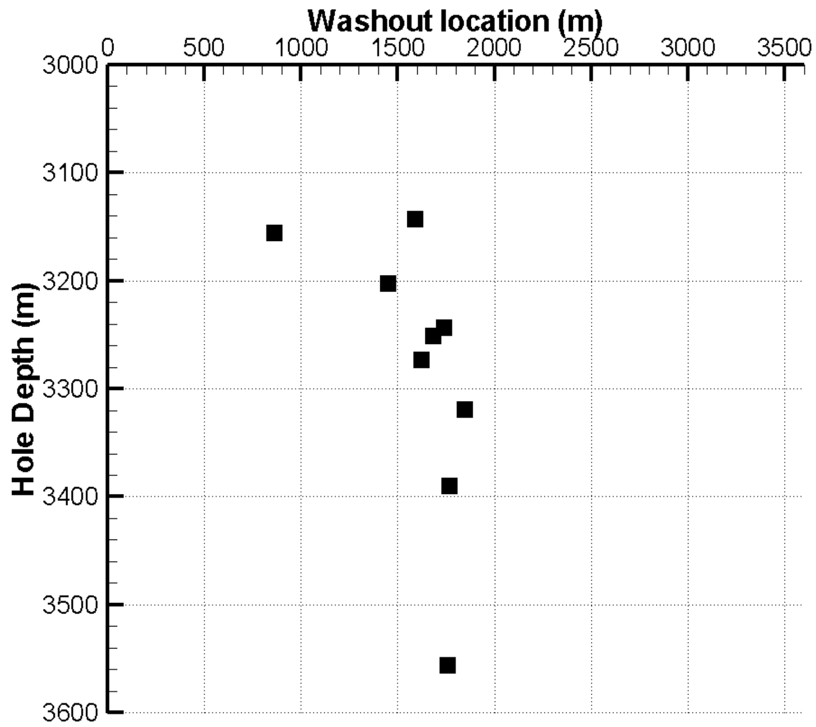


Differential sticking and key seat (Schlumberger oilfield glossary)

Dogleg: a particularly crooked place in a wellbore where the trajectory of the wellbore in three-dimensional space changes rapidly (schlumberger)

Borehole Stability Problems
Tight hole/stuck pipe

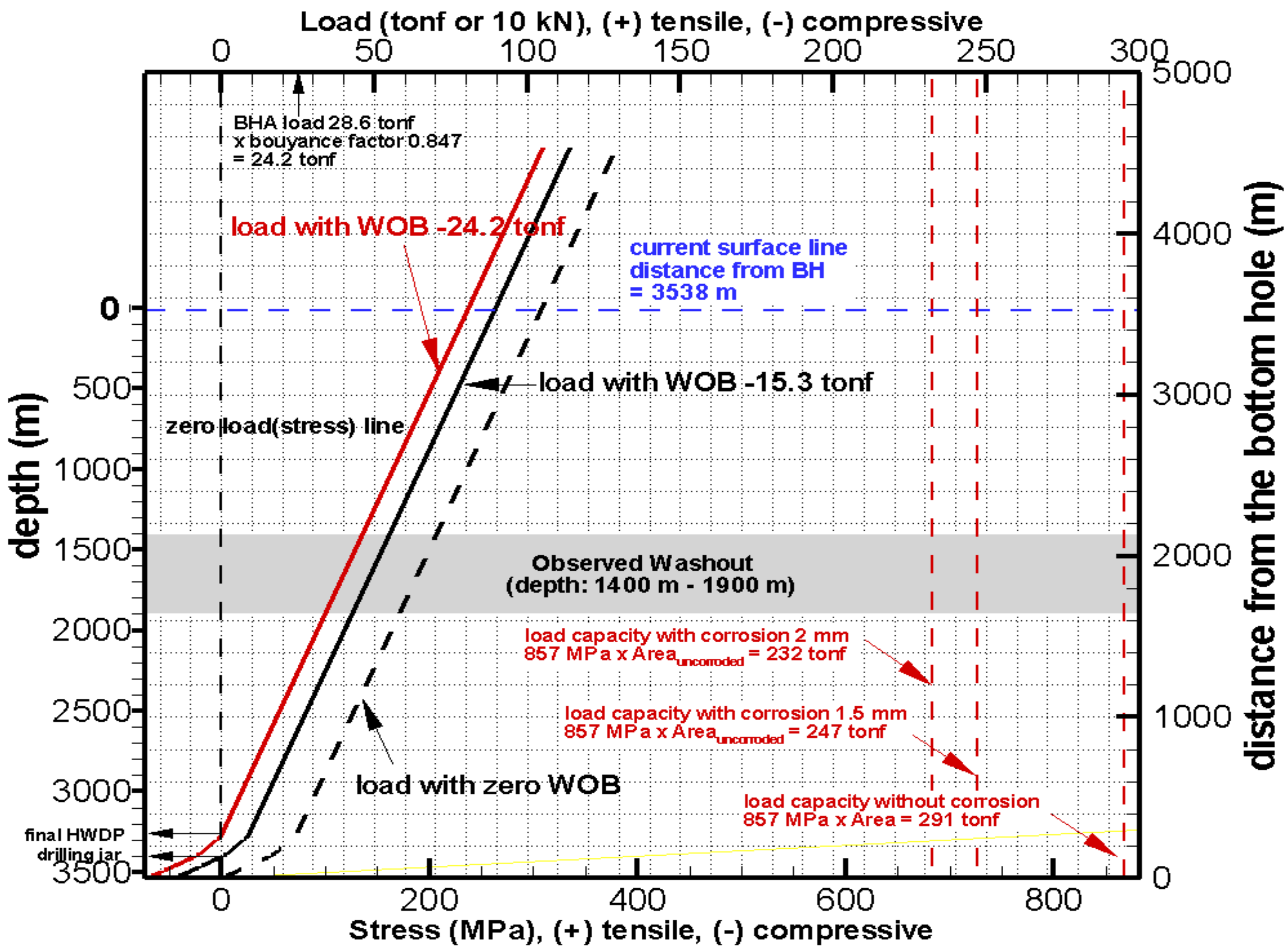
- Drill pipe wash out (Pohang EGS site, 2013)



PMC (2013)

Min (2013)

Borehole Stability Problems
Tight hole/stuck pipe



Min (2013)

Borehole Stability Problems
Tight hole/stuck pipe

- Consequencese of tight hole/stuck pipe
  - Loss of time (← reaming or sidetracking needed)
  - Difficulty in wireline logging
- Good well design necessary
  - Mudweight and composition
  - Casing setting depth
  - Well trajectory
  - Diagnostic analysis needed

Borehole Stability Problems
Lost circulation/mud loss

- Lost circulation/mud loss
  - Significant drilling fluid is lost into the formation – e.g., through (new or existing) fractures.
  - Can cause temperary pressure drop → flow into the well from permeable layers higher up → + gas lead to kick, and blow-out
  - Problem: mud is expensive, mud is limited at the site, safety issue.
  - Solution: keep the mud weight sufficiently low, use prevention additive (Lost Circulation Material, LCM)

Borehole Stability Problems
Mud Weight Window (Fjaer et al., 2008)

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- Static mud pressure

$$p_w = \rho_w g D \tag{9.1}$$

  – Mud pressure in the well is usually higher than the static pressure above in the order of 5-10%.

- Equivalent Circulating Density (ECD): static + pressure diffence effect

Borehole Stability Problems
Mud Weight Window (Fjaer et al., 2008)

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- Minimum mud weight
  - Shear failure

$$p_{\mathrm{w,min}}^{(a)} = \frac{3\sigma_{\mathrm{H}}' - \sigma_{\mathrm{h}}' - C_0}{\tan^2\beta + 1} + p_{\mathrm{fo}} \quad (9.3)$$

$$p_{\mathrm{w,min}}^{(b)} = \frac{\sigma_{\mathrm{v}}' + 2|\nu_{\mathrm{fr}}|(\sigma_{\mathrm{H}}' - \sigma_{\mathrm{h}}') - C_0}{\tan^2\beta} + p_{\mathrm{fo}} \quad (9.4)$$

  - Radial tensile failure

$$\sigma_r' = -T_0 \Longrightarrow p_{\mathrm{w,min}}^{\mathrm{rad.tension}} = p_{\mathrm{f}} - T_0 \quad (9.5)$$

  - Pore pressure (when underbalanced drilling is prohibited)

- Maximum mud weight
  - Minimum horizontal stress (with preexisting natural fractures)
  - Fracturing of borehole wall

$$p_{\mathrm{w,max}}^{\mathrm{frac}} = 3\sigma_{\mathrm{h}} - \sigma_{\mathrm{H}} - p_{\mathrm{fo}} + T_0 \quad (9.6)$$

Borehole stability problem
Mud Weight Window (Fjaer et al., 2008)

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Condition for shear failure in vertical boreholes (Fjaer et al., 2008)

Case	$\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$	Borehole failure occurs if
a	$\sigma_\theta \geqslant \sigma_z \geqslant \sigma_r$	$p_w \leqslant p_f + \dfrac{2(\sigma_h - p_f) - C_0}{1 + \tan^2\beta}$
b	$\sigma_z \geqslant \sigma_\theta \geqslant \sigma_r$	$p_w \leqslant p_f + \dfrac{\sigma_v - p_f - C_0}{\tan^2\beta}$
c	$\sigma_z \geqslant \sigma_r \geqslant \sigma_\theta$	$p_w \geqslant p_f + 2(\sigma_h - p_f) - \dfrac{\sigma_v - p_f - C_0}{\tan^2\beta}$
d	$\sigma_r \geqslant \sigma_z \geqslant \sigma_\theta$	$p_w \geqslant p_f + \dfrac{2(\sigma_h - p_f)\tan^2\beta + C_0}{1 + \tan^2\beta}$
e	$\sigma_r \geqslant \sigma_\theta \geqslant \sigma_z$	$p_w \geqslant p_f + (\sigma_v - p_f)\tan^2\beta + C_0$
f	$\sigma_\theta \geqslant \sigma_r \geqslant \sigma_z$	$p_w \leqslant p_f + 2(\sigma_h - p_f) - (\sigma_v - p_f)\tan^2\beta - C_0$

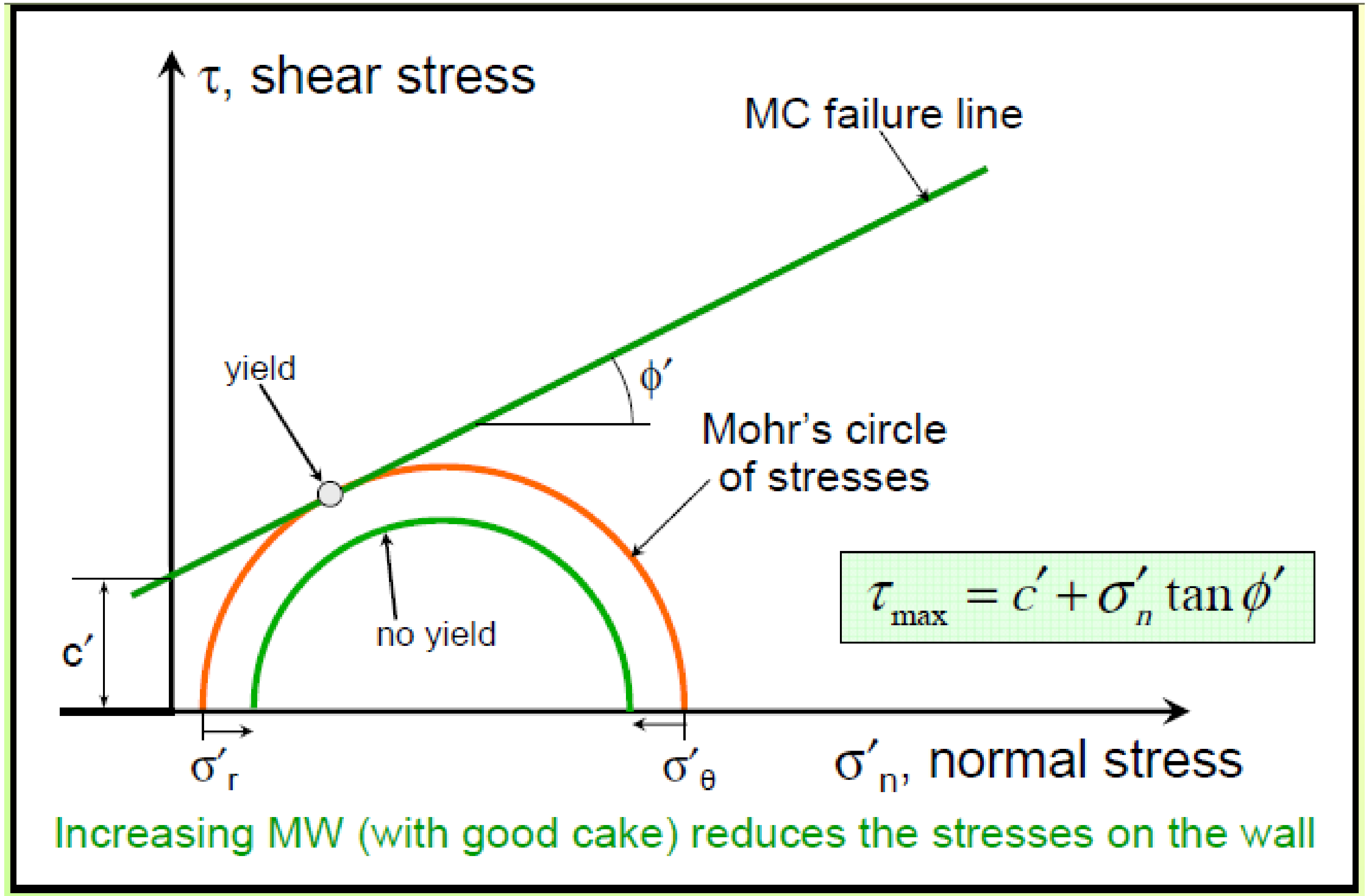
Condition for tensile failure (Fjaer et al., 2008)

$$p_{w,max}^{frac} = 2\sigma_h - p_f + T_0$$

Assumption: Permeable reservoir & impermeable borehole wall

Borehole Stability Problems
Mud Weight Window

- Effect of Increased of mud weight



Dusseault, 2012

Borehole Stability Problems
Mud Weight Window (Fjaer et al., 2008)

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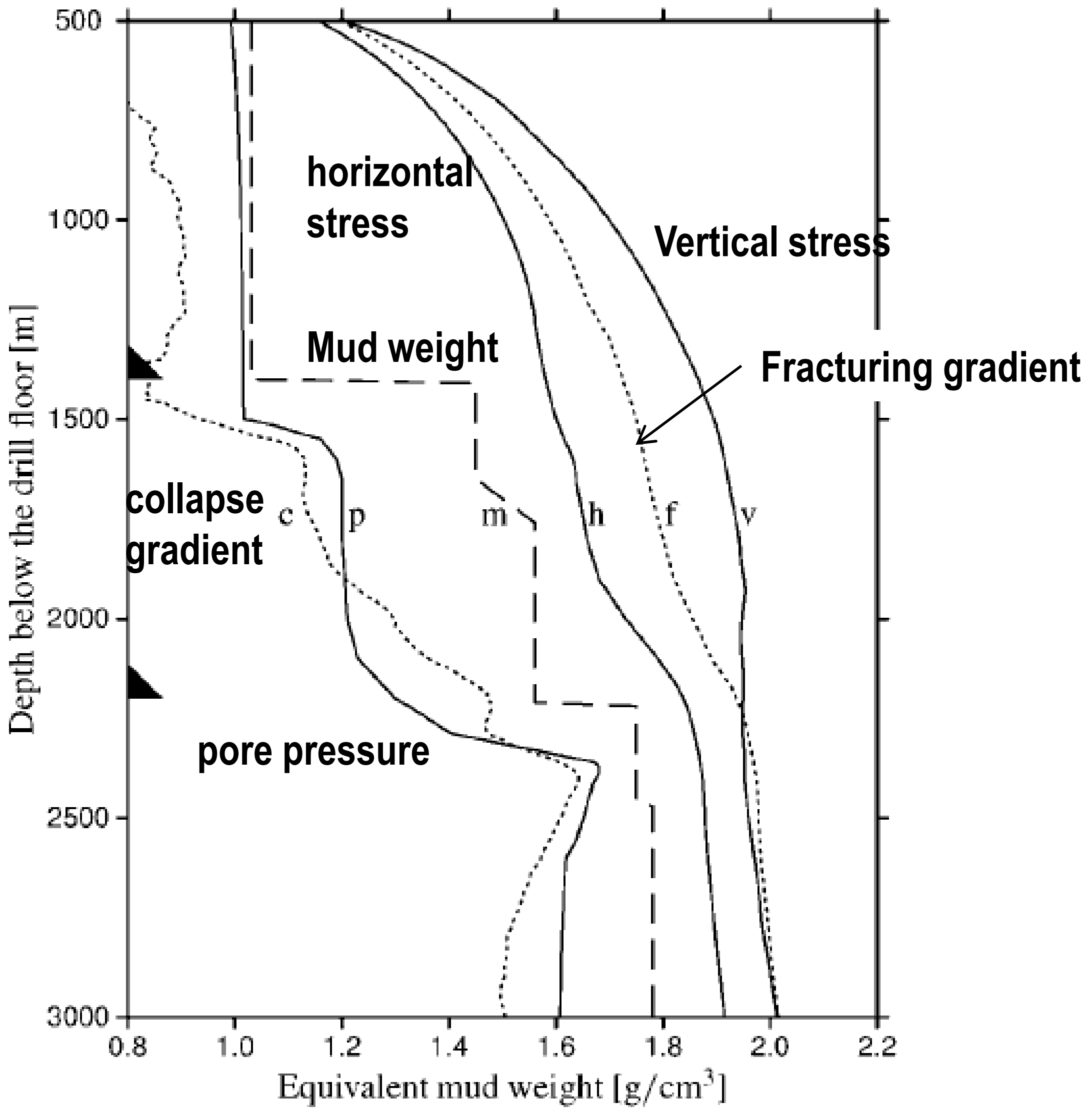

Fracturing gradient: stress required to induced fractures with the increase of depth, usually psi/ft, Schulumberger dictionary

Borehole Stability Problems
Mud Weight Window (Fjaer et al., 2008)

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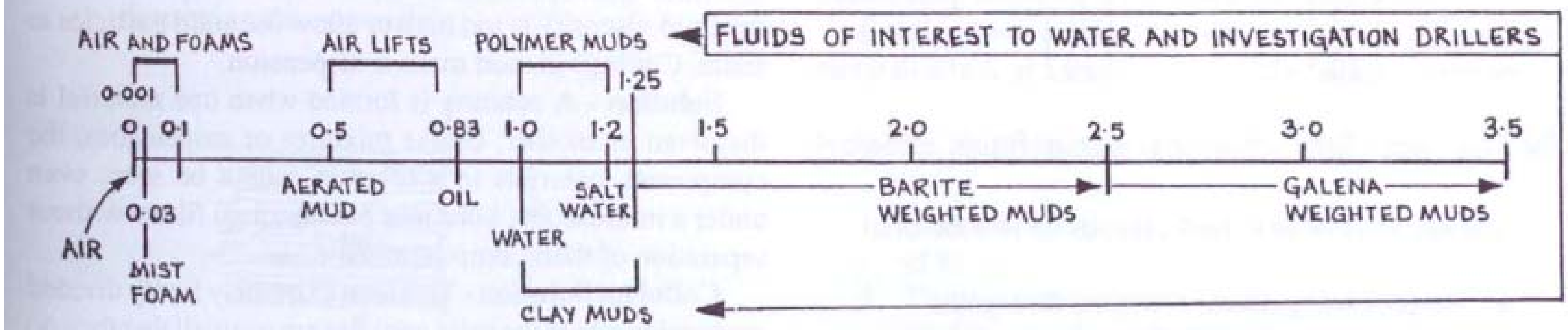
- ppg: usually used for unit of mud density. Abbreviation for density, pounds-per-gallon. Ex) density of water is ~8.33 ppg.



The available drilling fluids cover a wide range of specific gravities.

Australian Drilliing Industry Training Committee Limited, 1997, Drilling – The manual of methods, applications, and management, CRC Press

Borehole Stability Problems
Time-delayed failure (Fjaer et al., 2008)

- Poroelastic time dependent effect

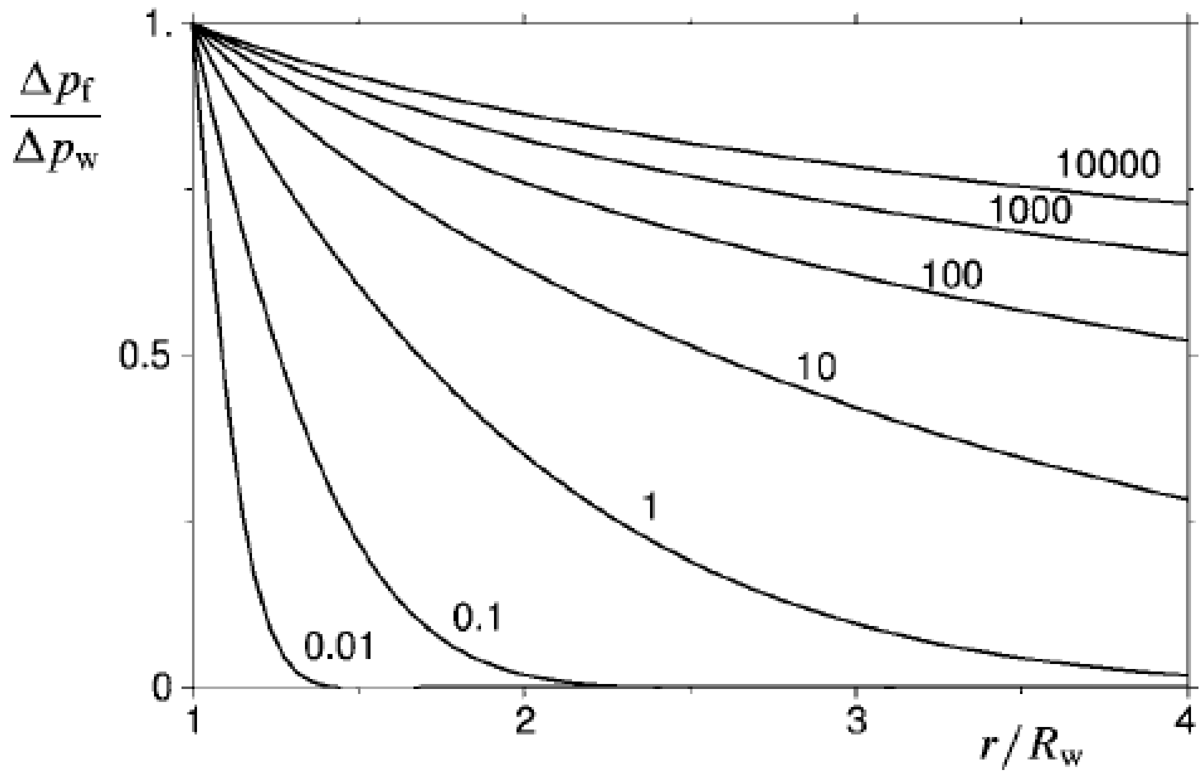
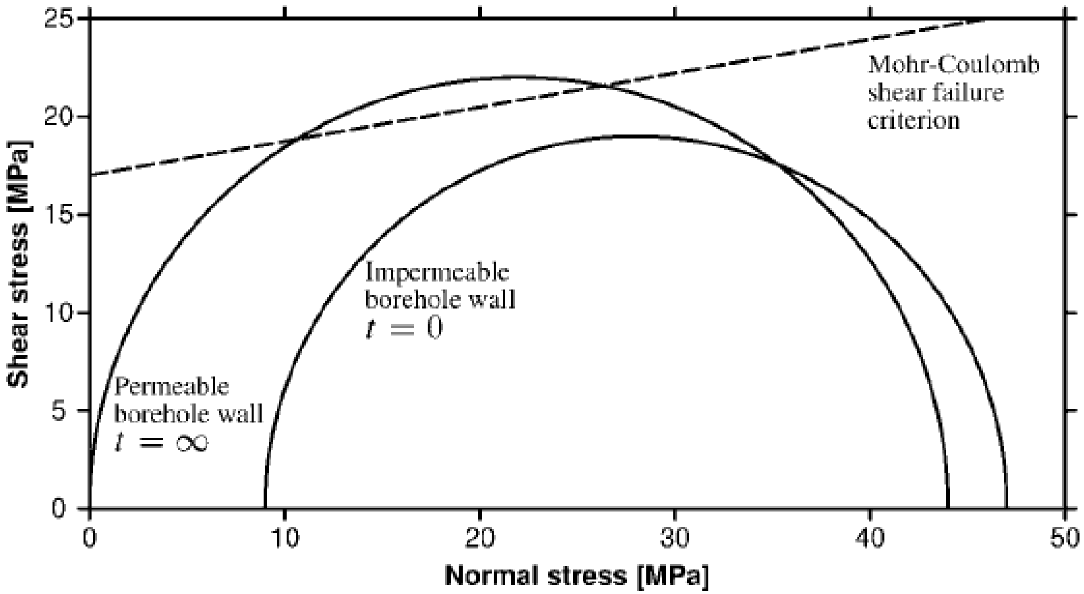


Fig. 4.9. Well pressure penetration. The curves are labelled by the dimensionless time t' (see Eq. (4.107)). After Detournay and Cheng (1988), with permission from Elsevier Science Publishers.

Borehole Stability Problems
Time-delayed failure (Fjaer et al., 2008)

- Pore pressure near the wellbore will increase resulting in reduced hole stability with time. Time to reach pore pressure equilibrium (l_D: ~10 cm, k 1 nD, ~5-10 days)

$$\tau_D \approx \frac{l_D^2}{C_D} \tag{9.12}$$



Borehole Stability Problems
Time-delayed failure

- Creep can be also important

Borehole stability problem
Thermal stress

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- Thermal stress can be significant

$$\sigma_{\theta,T} = \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

$$\sigma_{z,T} = \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

- Cold borehole fluid → strengthen the borehole & higher possibility of tensile failure
- Cooling reduces pore pressure too
  - Why?
  - Thermal expansion coef. Fluid > rock
- Cooling → mud weight increase

Borehole stability problem
Thermal stress

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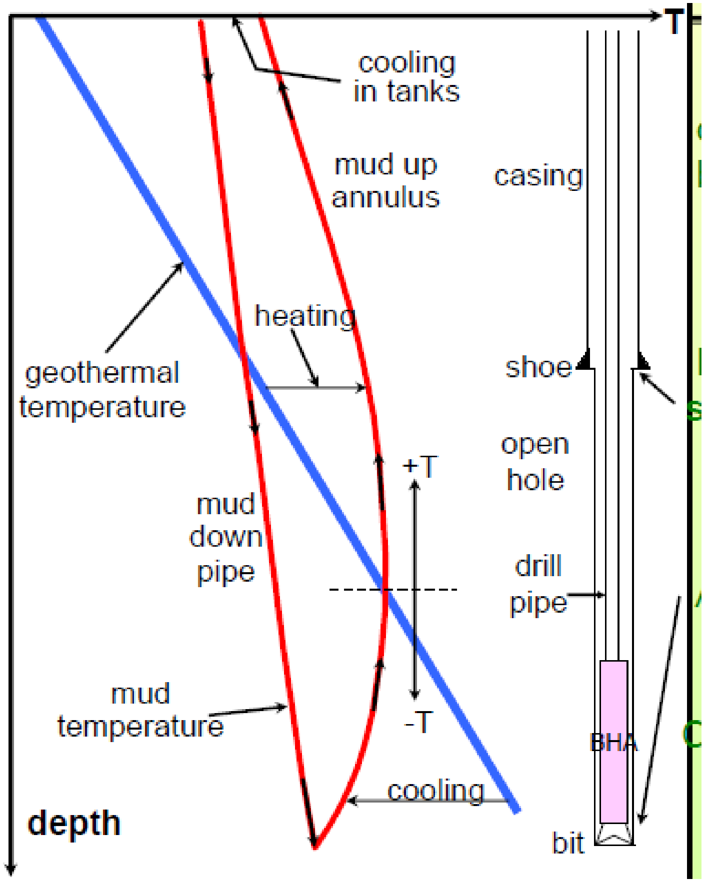
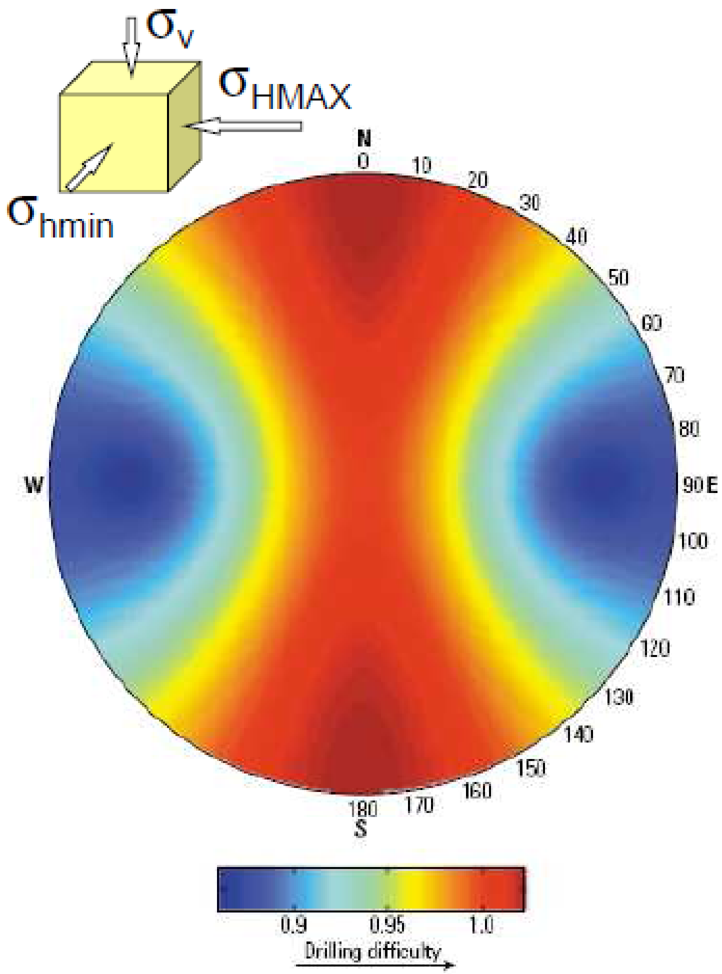
- Downhole : Cooling → stabilize
- Uphole: Heating → can induce failure



Dusseault, 2012

Borehole stability problem
Borehole Trajectory

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



Dusseault, 2012

Presentation

- Thermal effect
- Pore pressure effect
- Chemical effect
- Borehole breakout (width, depth, issues?)
- Borehole stability and stress estimation
- Deviated borehole
- Core discing

References

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- Main references:
  - Fundamentals of Rock Mechanics (Jaeger, Cook & Zimmerman, 2007), ch.8, ch.9.1 – 9.4
  - Petroleum related Rock Mechanics (Fjaer et al., 2008), Ch.4, ch.9
- Secondary references:
  - Reservoir Geomechanics (Zoback, 2007), ch.6, ch.8, ch.10
  - Geomechanics for Geophysicists, short course materials by SINTEF & NTNU (2012)
  - Unconventional Geomechanics, short course by Itasca Consulting Group (2011)
  - Vincent M, Stress and borehole stability, Revue Européenne de Génie Civil 2006 10(6-7): 763-801