Geothermal Energy (Week 10, 2 Nov)
- Reservoir compaction + Environmental Impact

민기복

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Term Paper
Progressive Report

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- Thank you and I am happy!
- Keep up the good work!
- Will be checked technically and in terms of English.
- A few words:
  - Your presentation must be equally shared
  - Be polite when you approach people outside (KIGAM, …),,,if you were in his/her shoes

Reservoir Geomechanics
outline

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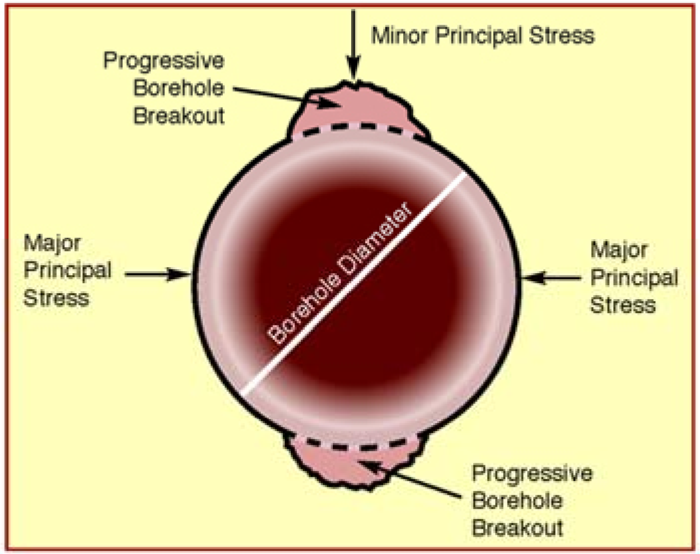
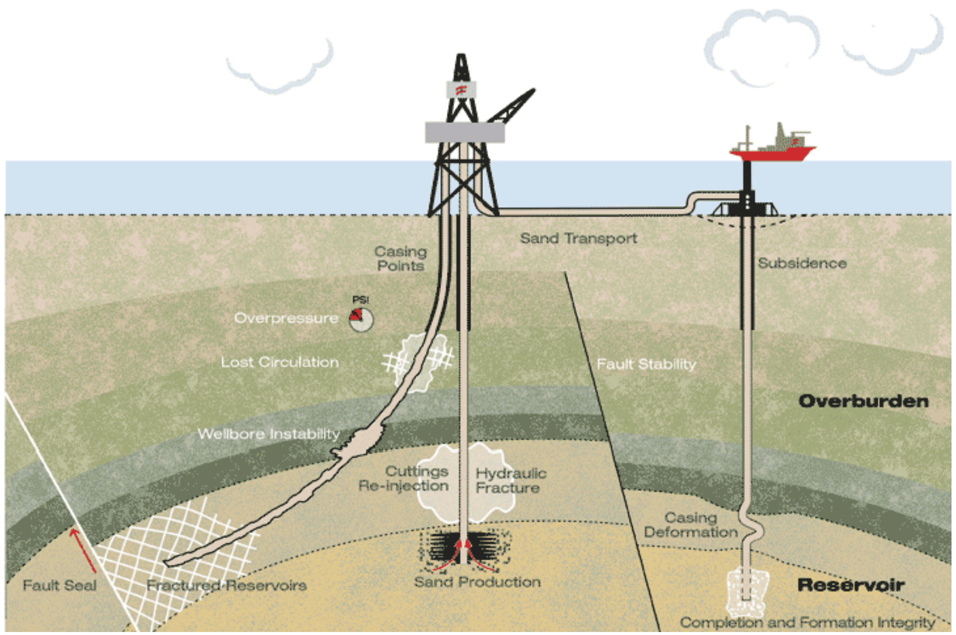
- Fundamentals of rock mechanics
- Borehole stability – stability of geothermal wellbore
- Mechanics of Hydraulic fracturing
- Reservoir Geomechanics



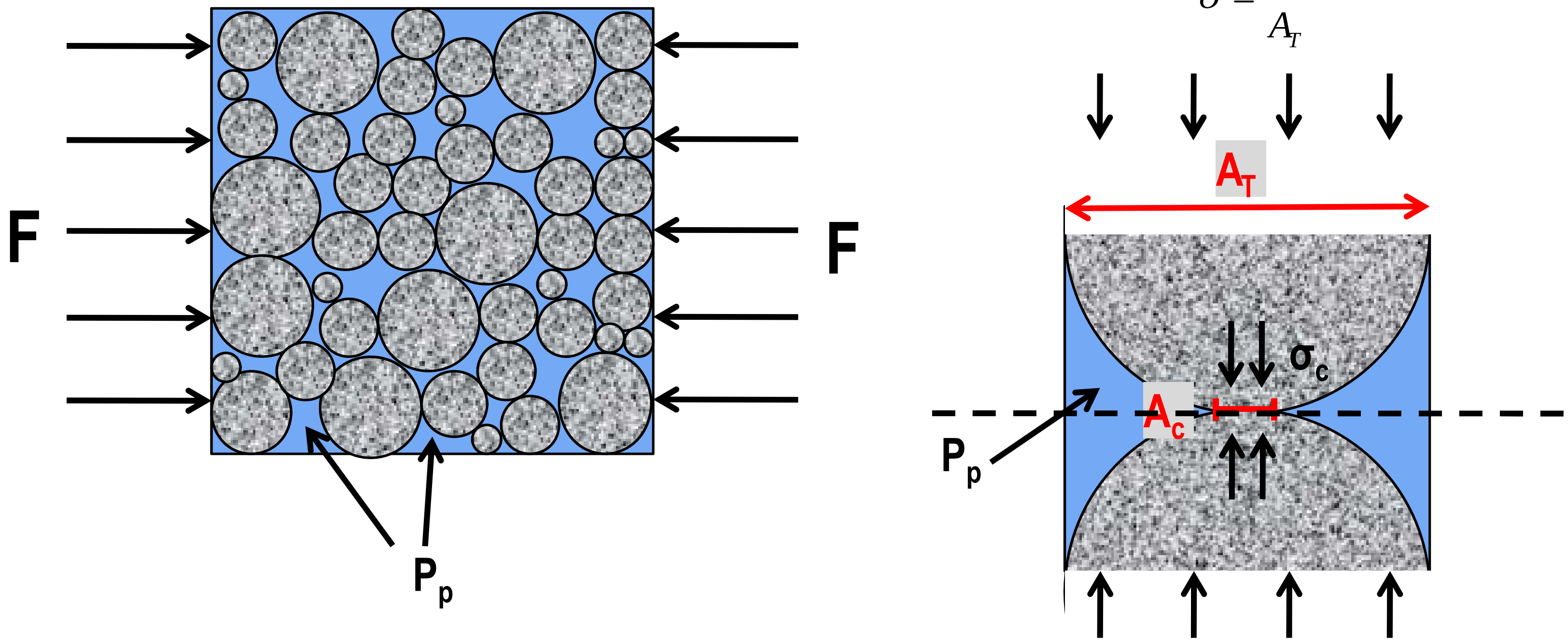


http://www.swri.edu/3PUBS/BROCHURE/D20/geotech/geotech.HTM

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

Effective Stress

$$\sigma = \frac{F_T}{A_T}$$



$$\sigma = \frac{F_T}{A_T}$$

- Ac: contact area of grain
- AT: diameter (area) of grain
- σ_c: normal stress acting on the grain contact
- σ_g: normal stress acting on the grain contact = σ'
- p_p: pore pressure

Effective Stress

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$$\sigma' = \sigma - p$$

- Exact effective stress law (more general)

$$\sigma' = \sigma - \alpha p$$

$$\alpha = 1 - \frac{K}{K_s}$$

- α: Biot coefficient (0< α <1)
- K: bulk modulus of rock
- Ks: bulk modulus of individual grain
- For nearly solid rock with no interconnected pores (such as quartzite): α= 0
- For highly porous rock (such as uncemented sands): α= 1

Effective Stress

- Physically, this means that the solid framework carries the part σ' of the total external stress σ while the remaining part αp is carried by the fluid.
- Two important mechanism explained by the concept of effective stress
  - Deformation due to the change of pore pressure – subsidence and heaving of rock
  - Rock or fracture failure due to the increased pore pressure

Effective stress
failure induced by pore pressure increase

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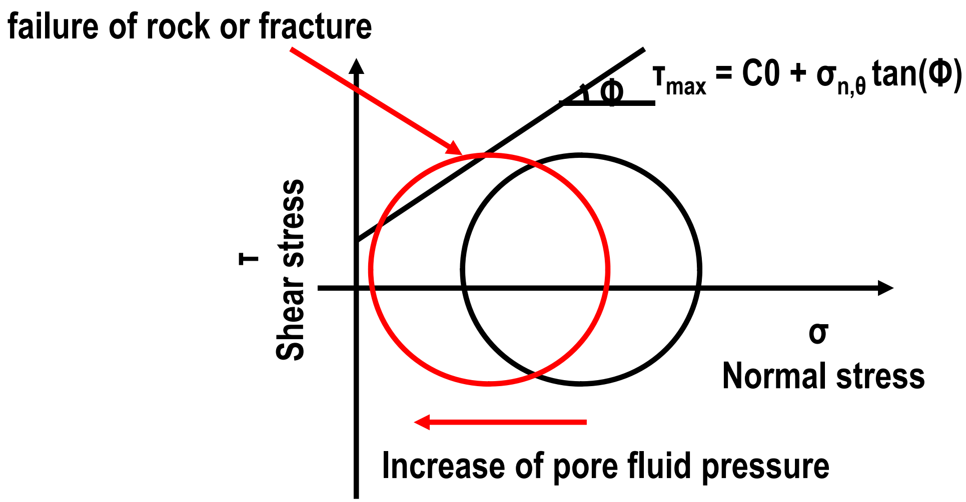

- Increase of pore pressure induce failure of intact rock

Reservoir Compaction and Subsidence

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- Reservoir compaction and associated surface subsidence – best-known example of geomechanical effect in reservoir scale

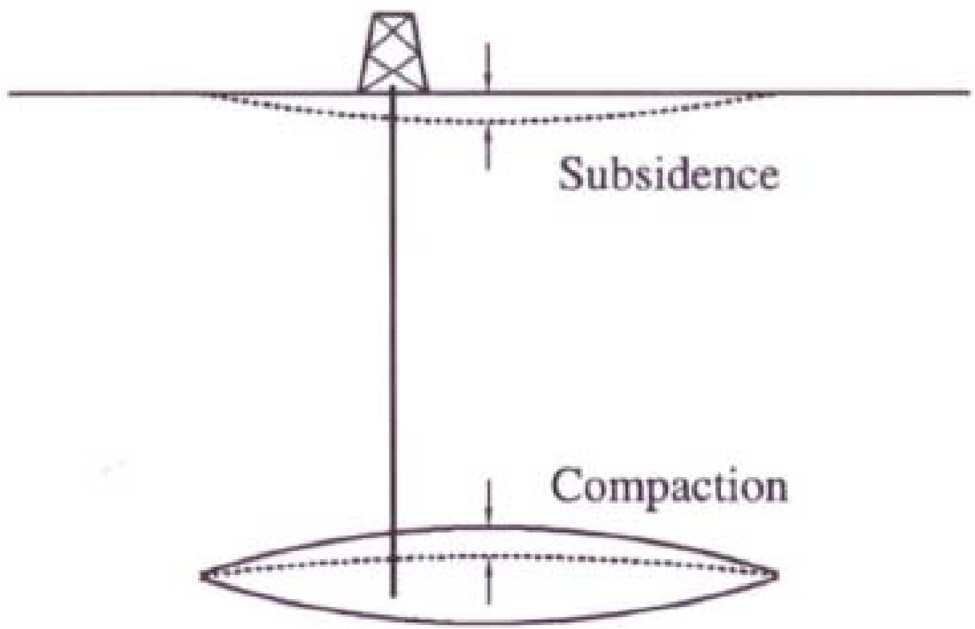

Fig. 12.1. Compaction and subsidence.

Fjaer et al., 2008

Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

- In homogeneous and isotropic rock,

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

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– Lateral extent of a reservoir is much larger than its thickness
  → lateral strain is neglible

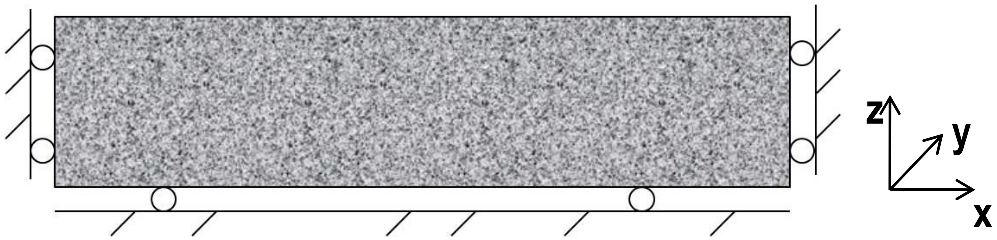
$$\varepsilon_x = \varepsilon_y = 0$$

$$\varepsilon_z = \frac{1}{E}\left\{\sigma_z - \nu\sigma_x - \nu\sigma_y\right\} = 0$$

$$\varepsilon_x = \frac{1}{E}\left\{\sigma_x - \nu\sigma_y - \nu\sigma_z\right\} = 0 \rightarrow \sigma_x = \nu\sigma_y + \nu\sigma_z$$

$$\varepsilon_y = \frac{1}{E}\left\{\sigma_y - \nu\sigma_x - \nu\sigma_z\right\} = 0 \rightarrow \sigma_y = \nu\sigma_x + \nu\sigma_z$$

$$\sigma_x = \nu^2\sigma_x + \nu(1+\nu)\sigma_z \rightarrow \sigma_x = \sigma_y = \frac{\nu}{1-\nu}\sigma_z$$



Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

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- When we assume that the total vertical stress acting on the reservoir remains constant during depletion,
- By considering the change of stress,

$$\Delta\sigma' = \Delta\sigma - \alpha\Delta p = -\alpha\Delta p$$

$$\varepsilon_z = \frac{1}{E}\left\{\Delta\sigma_z - \nu\Delta\sigma_x - \nu\Delta\sigma_y\right\} = 0$$

Expressed in terms of effective stress →

$$\varepsilon_z = \frac{1}{E}\left\{\Delta\sigma'_z - \nu\Delta\sigma'_x - \nu\Delta\sigma'_y\right\} = 0$$

$$\varepsilon_z = \frac{1}{E}\left\{\Delta\sigma'_z - \nu\frac{\nu}{1-\nu}\Delta\sigma'_z - \nu\frac{\nu}{1-\nu}\Delta\sigma'_z\right\} = 0 \longrightarrow \varepsilon_z = \frac{1}{E}\left\{1 - \frac{2\nu^2}{1-\nu}\right\}\Delta\sigma'_z = -\frac{1}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu}\Delta p$$

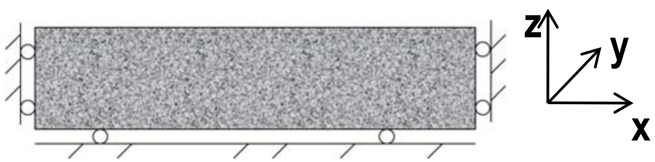
Considering only hydraulic pressure change

$$\varepsilon_z = -\frac{\Delta h}{h}$$

Compression (+)
Tension (-)

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

There was a mistake in sign in last lecture.



Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

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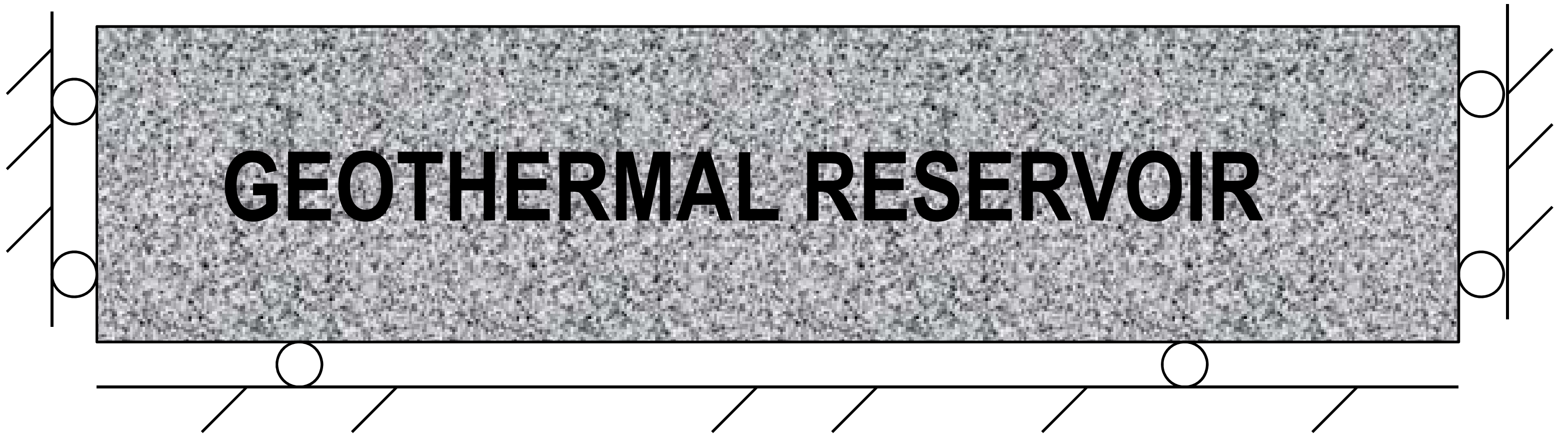
- Compaction coefficient or unaxial compressibility, Cm;

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



Reservoir Compaction and Subsidence
Uniaxial reservoir compaction/realistic case

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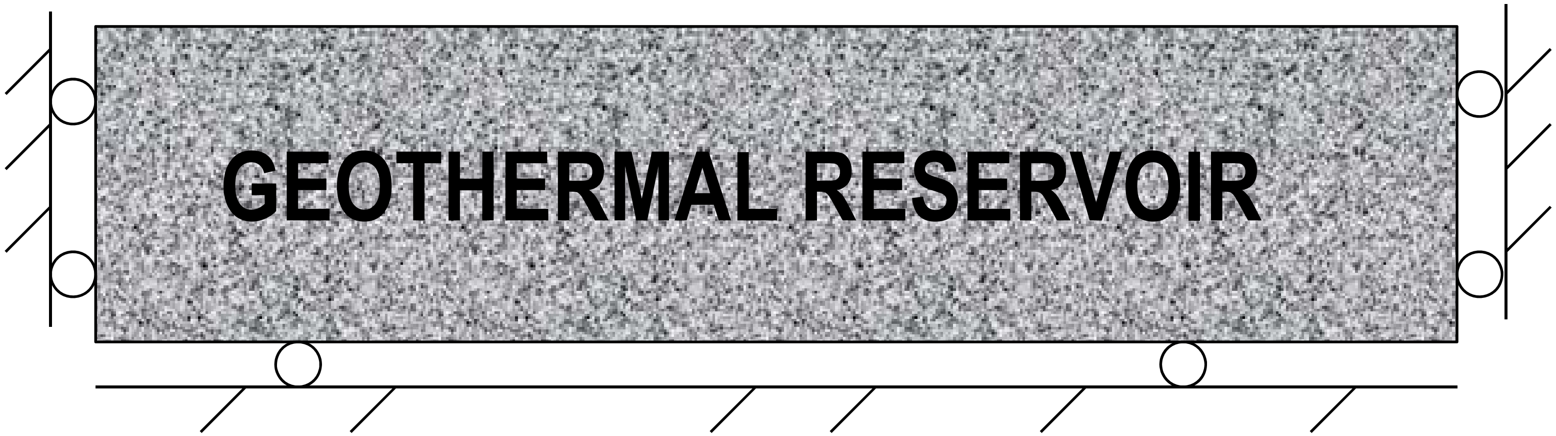
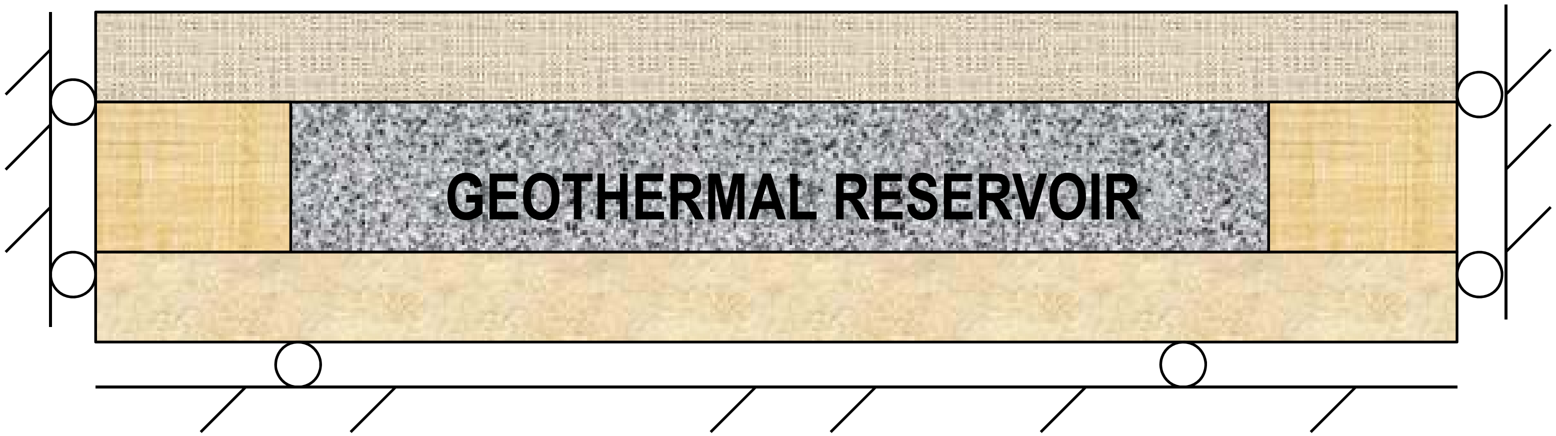
- Simplification



- Reality



Reservoir Compaction and Subsidence

Uniaxial reservoir compaction/realistic case

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- Normally we don't have uniform distribution of;
  - Pressure/mechanical properties
  - And the reservoir geometry is complex
- We would need more sophisticated model, which usually is numerical simulation.

The Geysers Geothermal Field

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From J Rutqvist

- **The largest geothermal electricity generating operation in the world (850 MW)**
- **Also one of the most seismically active regions in northern California**

SURFACE DEFORMATIONS FROM SATELLITE (1992-1999)

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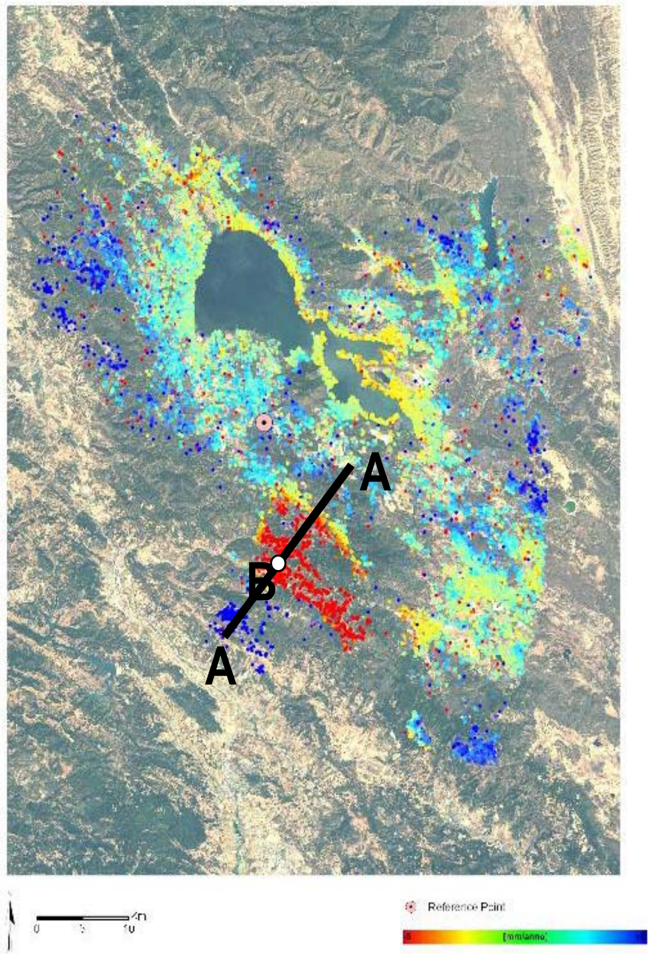
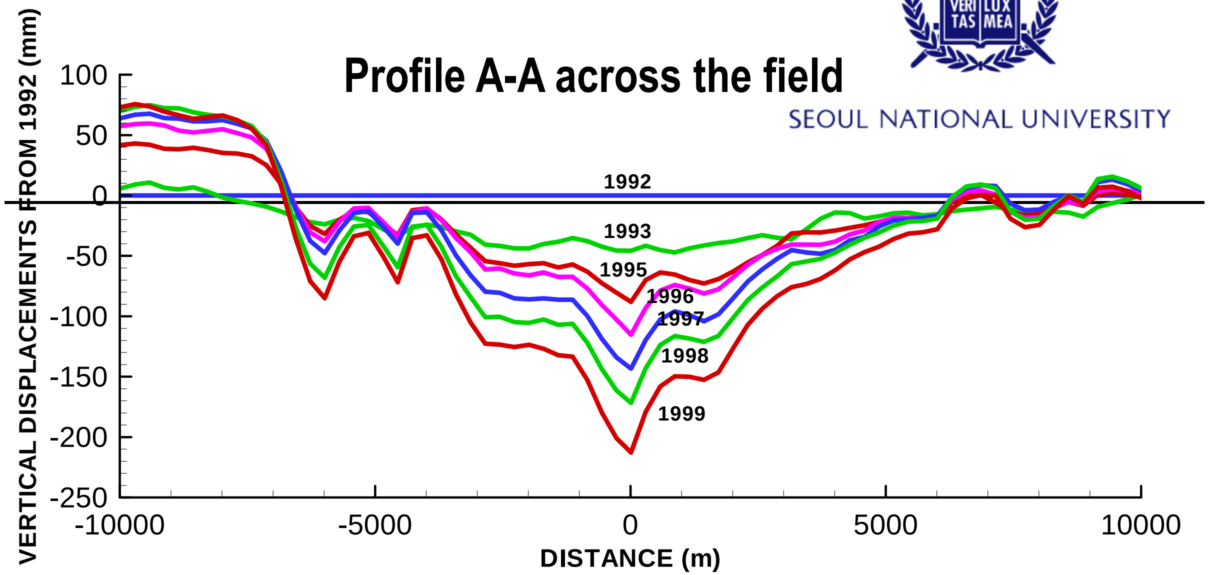
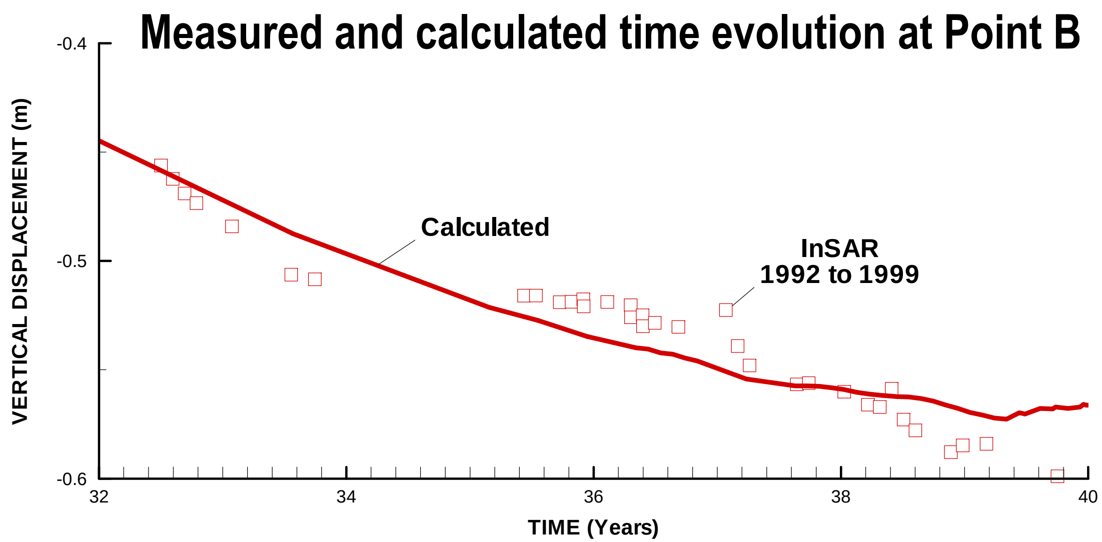


Yearly average deformation - 5 (red) to +5 (blue) mm/year





InSAR: Interferometric Synthetic Aperture Radar

Seismicity induced by fluid injection

shear slip induced by hydraulic pressure increase

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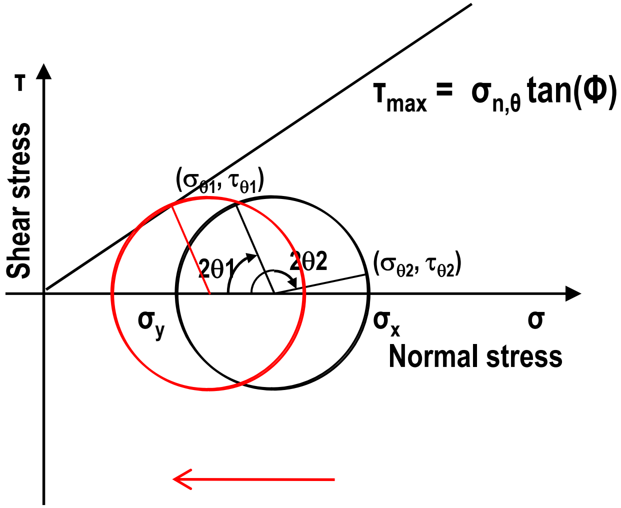
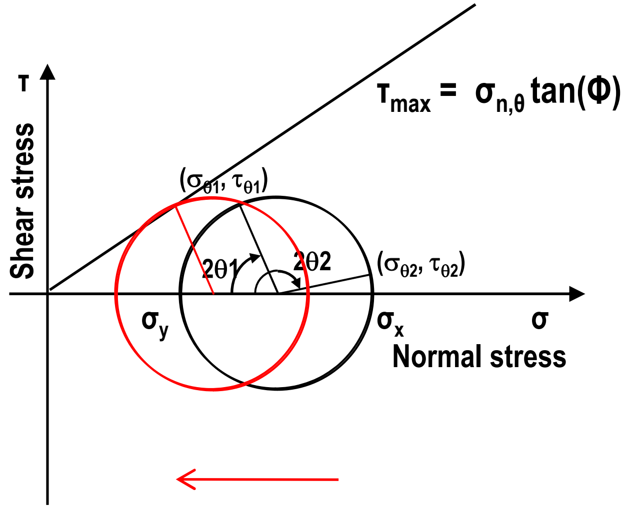
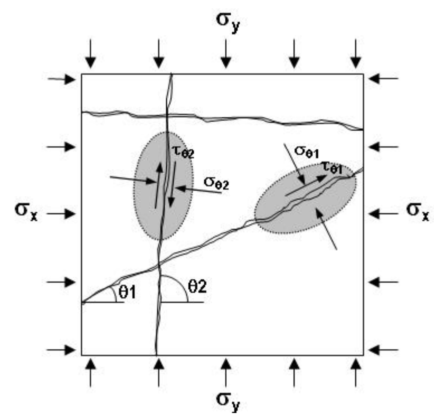


Increase of hydrauilc fluid pressure
← due to injection



Cooling of rock → shrinkage → decrease of stress

- Sources of seismicity – Microseismicity
  - change of hydraulic pressure
  - cooling of rock



Seismicity induced by fluid injection

shear slip induced by hydraulic pressure increase

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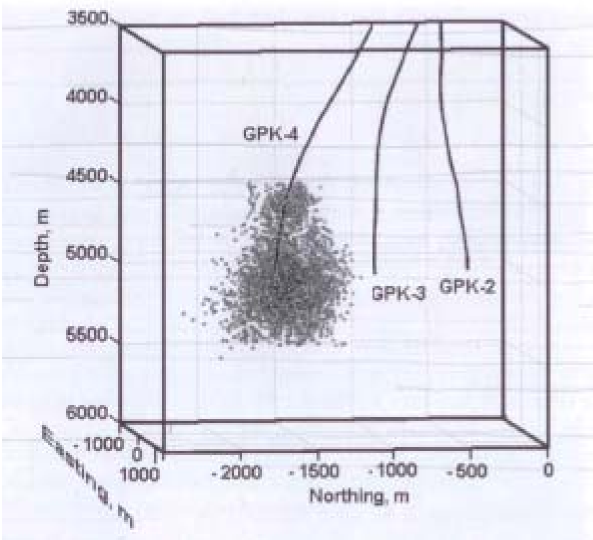

3D swarm of acoustic noise in Soultz site (DiPippo, 2008)

Environmental Impact
Working environment

- Most countries have laws that regulate the construction and operation of power plants;
  - To preserve the natural environment
  - To safeguard the health and well-being of people
- We should use Geothermal Energy while we minimize the adverse environmental impact
- Summary of chapter 19 by DiPippo (2008)

Environmental Impact
General Impact of electricity generation

- Gaseous emissions to the atmosphere
- Water Pollution
- Solid emissions to the atmosphere
- Noise pollution
- Land usage
- Land subsidence
- Induced seismicity
- Induced landslides
- Water usage
- Disturbance of wildlife habitat and vegetation

Environmental Advantage
Gaseous emissions

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- Geothermal power plants have very low gaseous emissions.

From DiPippo (2008)

Plant type	CO2 Kg/MWh	SO2* Kg/MWh	Nox** Kg/MWh	Particulates Kg/MWh
Coal-fired steam plant	994	4.71	1.955	1.012
Oil-fired steam plant	758	5.44	1.814	N/A
Gas turbine	550	0.0998	1.343	0.0635
Hydrothermal –Flash steam	27.2	0.1588	0	0
Hydrothermal –Dry-steam***	40.3	0.000098	0.000458	Negligible
Hydrothermal – Closed loop binary	0	0	0	Negligible

*SO_2: sulfur dioxide
**NO_x: Nitrogen oxides

***: The Geysers in the US

Environmental Advantage
Land usage

- Area required for geothermal power plant
  - Well field
  - Auxiliary buildings
  - Substation (변전소)
  - Access roads
- Well field for a 20-50 MW power plant can cover ~10km2 or more

Environmental Advantage
Land usage

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- Geothermal power generation does not require much land

From DiPippo (2008)

Power plant technology	Land usage, m2/MW
110 MW geothermal flash plant (including wells)	1,260
20 MW geothermal binary plant (excluding wells)	1,415
2258 MW coal plant (including strip mining)	40,000
670 MW nuclear plant (plant site only)	10,000
95 MW hydroelectric plant (reservoir only)	1,2000,000
47 MW solar thermal plant (Mojave Desert, CA)	28,000
25 MW wind farm (10 x 2.5 MW)	16,000

Environmental Advantage
Water usage

- The needs for geothermal projects are relatively easy to satisfy. Two main areas of water usage;
  - Drilling of wells → is recirculated.
  - Discharge of waste heat if a water cooling tower is used.

Environmental Challenges

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- Land subsidence
- Induced seismicity
- Induced landslide
- Noise pollution
- Disturbance of wildlife habitat and vegetation

Can be serious and careful study is needed (Land subsidence, Induced seismicity)

Environmental Challenges
Land subsidence

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- Geothermal reservoir production at rates much greater than recharge can lead to surface subsidence
- This is a site-specific problem
  - Larderello, Italy: negligible subsidence
  - Wairakei, New Zealand: ~500 mm/year, maximum exceeds 15 m
- Although reinjection does not guarantee the avoidance of subsidence, it can reduce the risk.
- Nowadays, geothermal developers normally incorporate reinjection into reservoir management right from the start to 1) minimize the subsidence and 2) to prolong the life of the reservoir

Environmental Challenges
Induced seismicity

- Induced seismicity: change in fluid pressure within a stress rock formation leads to movement of the fractured rock
- The energy released is transmitted through the rock and may reach the surface with enough intensity to be heard or felt by persons in the area.
  - Dam (when reservoir was filled)
  - Oil extraction
  - Fluid injection for geothermal
- Nearly every geothermal field under exploitation has experienced induced seismicity to some degree

Environmental Challenges
Induced seismicity

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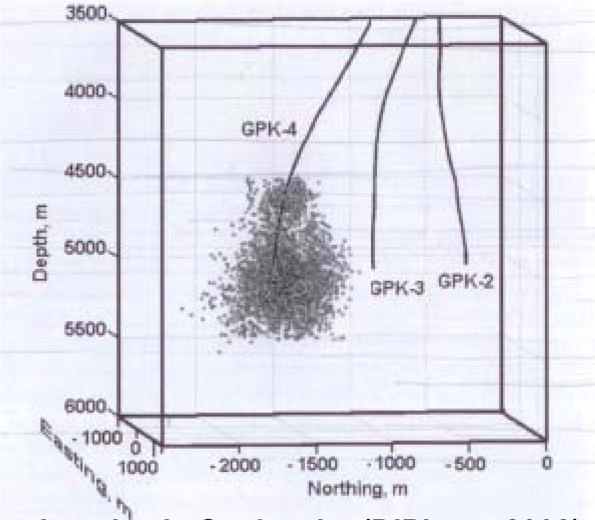
- This is particularly important for Enhanced Geothermal System (EGS).
- A 2007 incident at an EGS site in Basel, Switzerland: magnitude 3.3 earthquake.
- The acoustic noise can be monitored with sensitive, high-precision instruments to provide real-time information.



3D swarm of acoustic noise in Soultz site (DiPippo, 2008)

Environmental Challenges
Induced seismicity

- Thorough scientific study should be carried out before drilling to determine the geologic and tectonic conditions
- Monitor the site for any unexpected natural or induced microseismic events
- Education program should be put in place to inform residents of the possibility of felt seismic events.

Environmental Challenges
Induced landslides

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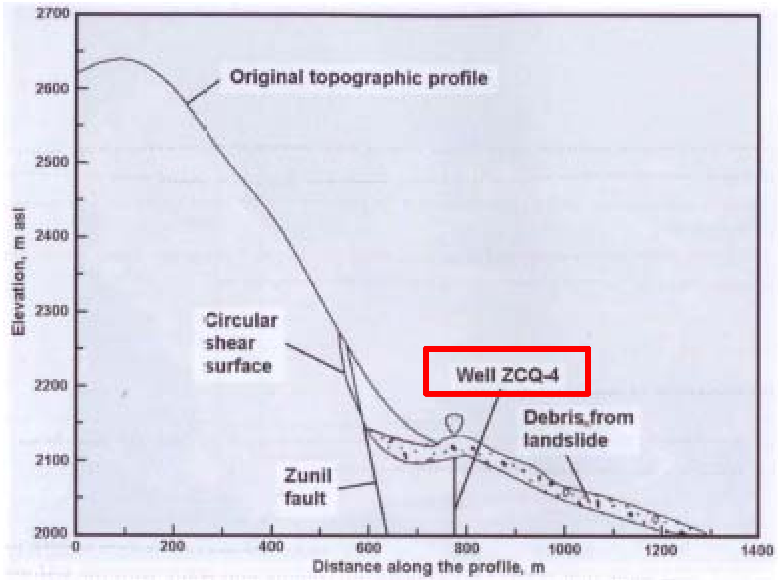
– Landslides can be triggered by earthquake
– An exmple: Landslide at Zunil geothermal field, Guatemala



From DiPippo (2008)

Environmental Challenges
Induced landslides

- Recommendations:
  - Development of a hazard map identifying all potential landslides areas
  - Slope monitoring instrumentation
  - Monitoring of springs for changes in flow rate, temperature, chemistry
  - Installation of drains in slopes
  - Avoidance of obvious unstable areas for wells, road and other construction activity

Environmental Challenges
Noise pollution

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- During road construction, excavation for drilling sites, well drilling and well testing
- May be disturbing to the residents, but they are of limited duration
- Objectionable sounds can be reduced by using mufflers and other sound deadening materials.

Environmental Challenges

Disturbance of wildlife habitat and vegetation

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- Relatively small area needed for geothermal development → impact is minimized
- Compared to wind turbines, solar thermal power towers, fossil-fueled plants, geothermal plants generally have a low profile and are less conspicuous.

Today

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- Reservoir Geomechanics
  - Subsidence of reservoir (simple model)
- Environmental Impact
  - Land subsidence
  - Induced seismicity
  - Induced landslide
  - Noise pollution
  - Disturbance of wildlife habitat and vegetation

References

- Fjaer E et al., 2008, Petroleum-related Rock Mechanics, 2nd Ed., Elsevier
- Rutqvist J, Oldenburg CM, 2008, Analysis of Injection-Induced Micro-Earthquakes in a Geothermal Steam Reservoir, The Geysers Geothermal Field, California
- DiPippo, 2008, Geothermal Power Generation, 2nd ed., Elsevier