Rock Mechanics & Experiment
암석역학 및 실험
- Introduction to Rock Mechanics/Geomechanics
암석역학/지오메카닉스 소개

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Seoul National University

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Outline

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- Introduction to Rock Mechanics/Geomechanics
  - Terminology
  - Area of Applications
  - Nature of Rock Mechanics/Geomechanics
- Applications of Rock Mechanics/Geomechanics
- Methodology to solve Rock Mechanics/Geomechanics problems

Terminology
Rock Mechanics/Geomechanics

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- Rock mechanics: discipline concerned with the stressing, deformation and failure of rock
- Geomechanics: Rock mechanics + Soil Mechanics← becoming more popular in energy industry
- Rock Engineering: Rock mechanics + application to engineering
- Geotechnical Engineering: (Rock mechanics + soil Mechanics) + application to engineering ← used more by civil engineering industry
- Specialized Rock Mechanics/Geomechanics:
  Mining ---, Petroleum ---, Reservoir ---, Borehole ---,

Area of Applications

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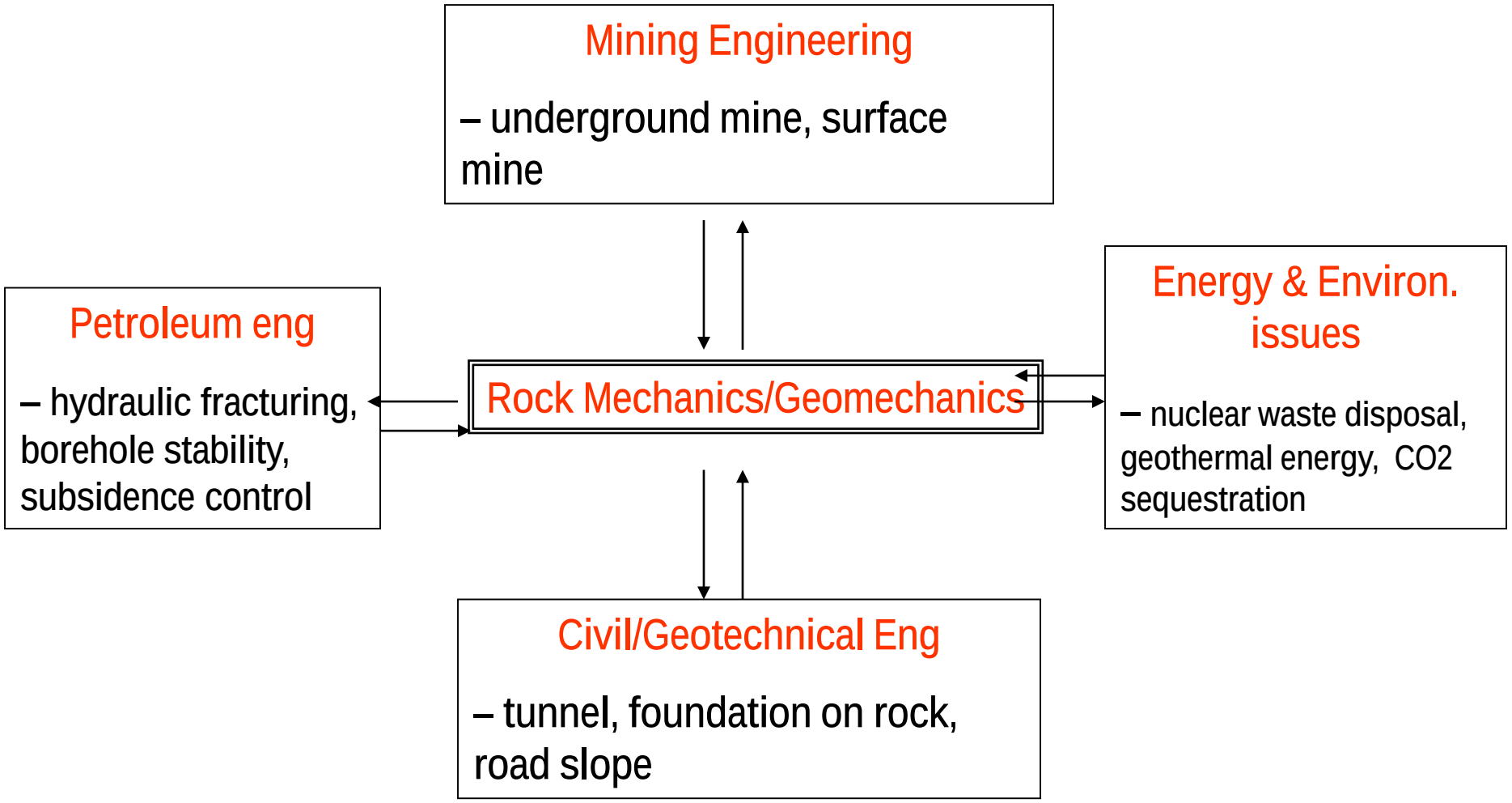

Nature of problem
Data limited problem

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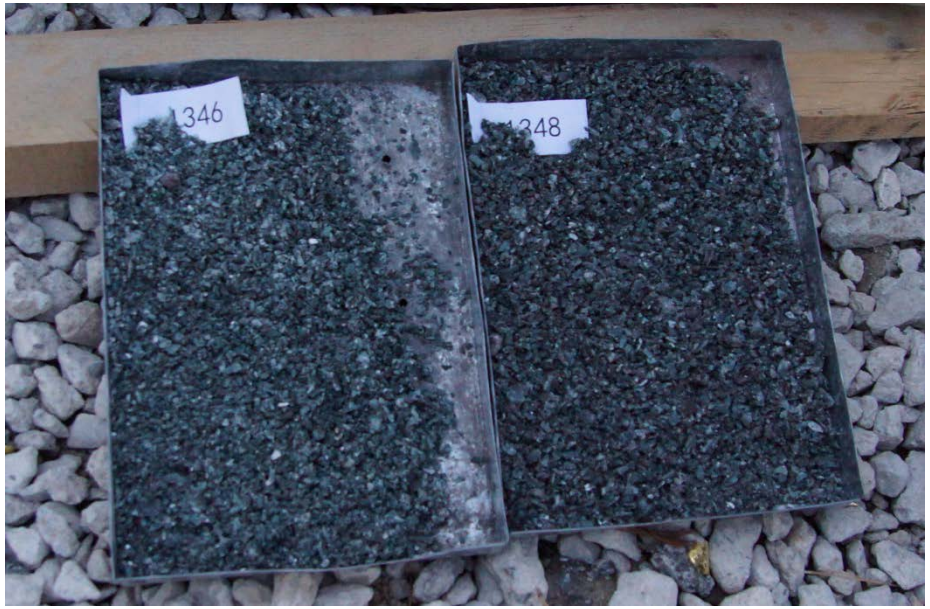

Rock cutting from Pohang EGS site. ~few mm

↑

REALITY

DREAM

↓

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

Nature of problem
Data limited problem

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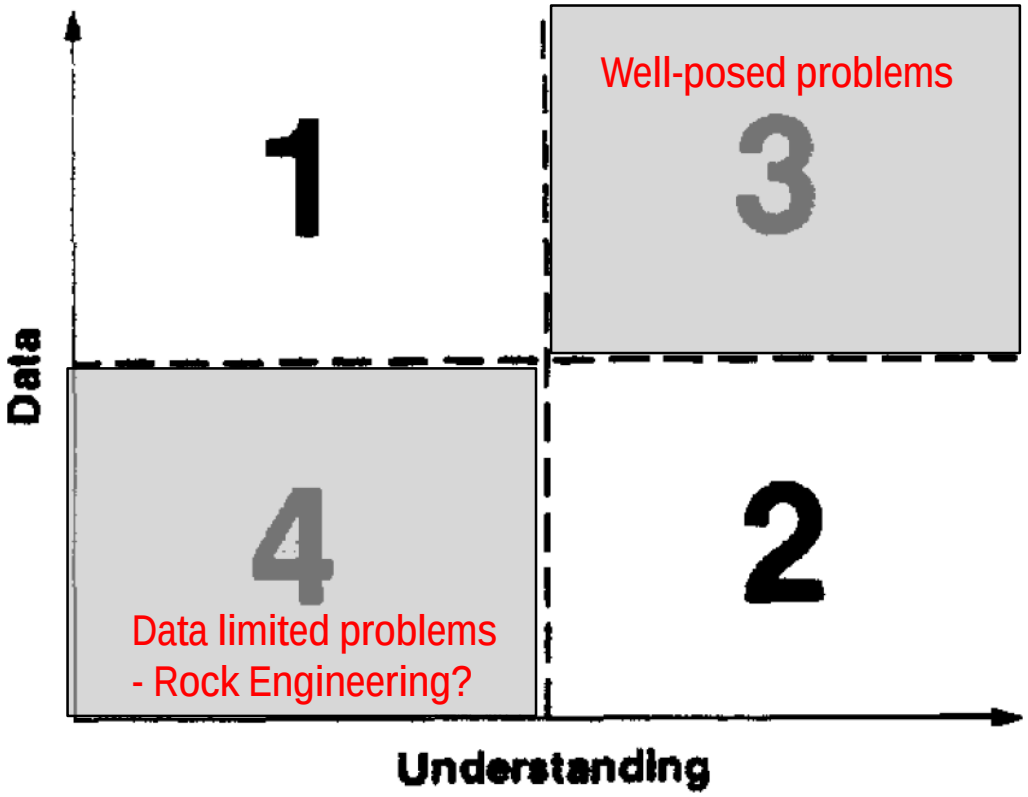

Recited from Starfield and Cundall (1988)

Nature of problem
Effect of fractures & Scale

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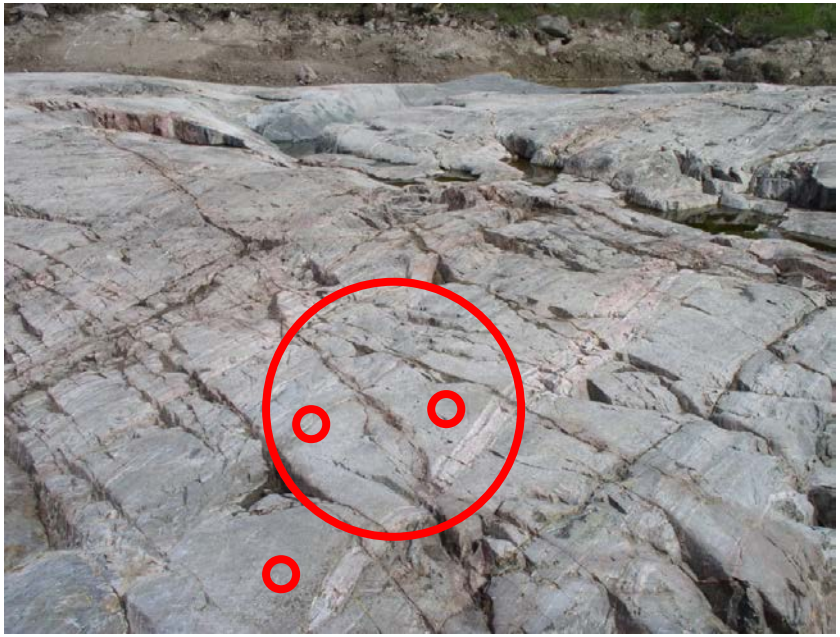


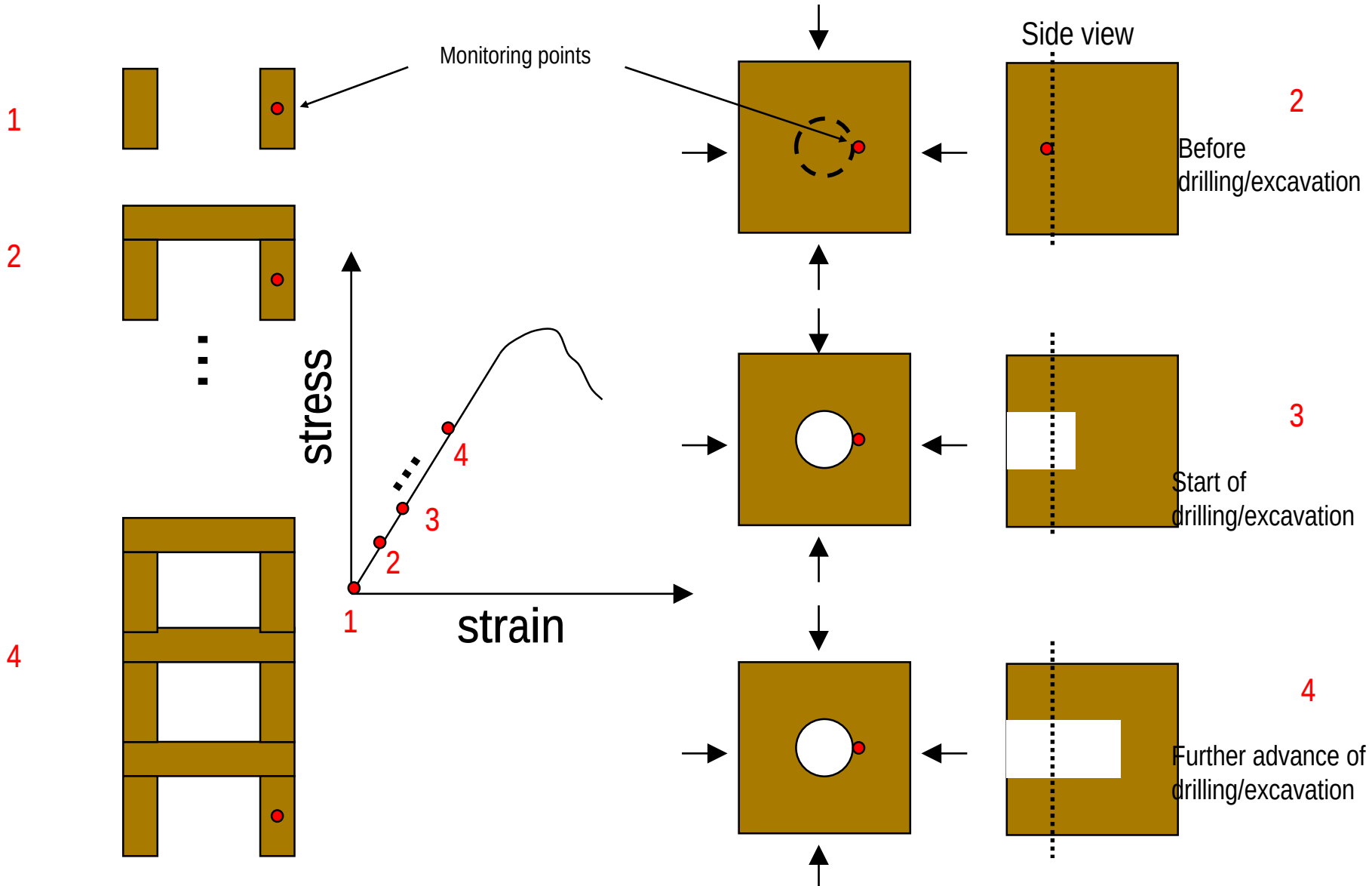
Forsmark, Sweden, 2004

Forsmark, Sweden, www.skb.se

Nature of Underground Geomechanics

Civil structural problems:
Mechanics of "Addition"

Underground Geomechanics problems:
Mechanics of "Removal"



Nature of problem
Structural problem/Rock Mechanics

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	건축/토목 구조문제 Civil Structural Problem	암석역학 Geomechanics
재료 및 물성 Material & nature of its properties	철강 혹은 콘크리트 Steel, Concrete - 인공물질 (Man-made material) - 균질(Homogeneous) - 연속체(Continuum)	암석 및 토질 (Rock & Soil) - 자연물질 (Natural material) - 불균질 (Heterogeneous) - 불연속체 (Discontinuum) (절리를 함유, contain joints)
경계조건 Boundary condition (loading condition)	자중 + 서비스 하중 (Weight + service load) - 불확실성 적음 (low uncertainty)	현지응력 (In situ stress) - 불확실성 큼 (great uncertainty)
하중재하의 경로 Stress Concentration source	재료의 추가 (상재) (Addition of material)	재료를 없앰 (굴착, removal of material: excavation or drilling)
지하수의 영향 Groundwater	-	매우 중요함 very important
크기 효과 Size effect	-	매우 중요함 Very important

Applications
Mining Engineering (1) – Surface Mine

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Prominent Hill, Australia, 2008

Pasir Mine, Indonesia, 2010

Applications
Mining Engineering (2) – Underground Mine

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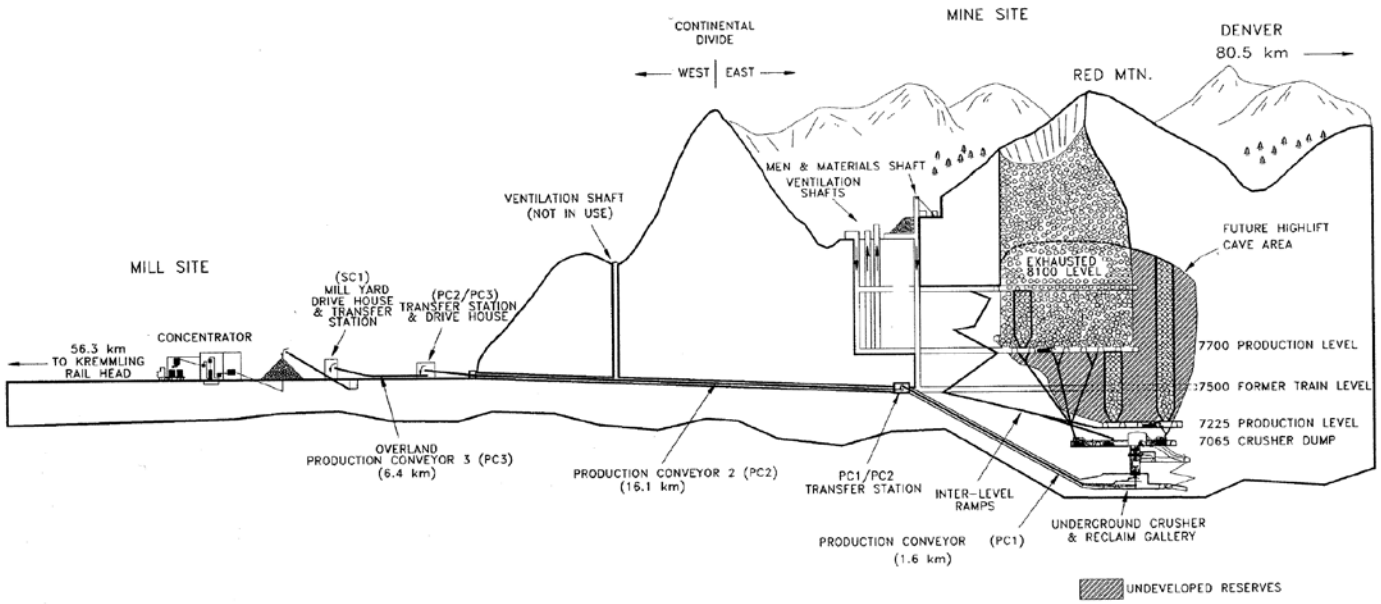
- 헨데센 광산 (Hendersen Mine), 콜로라도, 미국
  - 1976 년 운영시작 (시작전 10년간 약 $500 million 투자)
  - 세계최대의 몰리브덴 광산
  - 1000 미터 하부에 광체, 최대심도 1,600 미터



Hustrulid & Bullock, 2001

Applications
Mining Engineering (2) – Underground Mine

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- Drawpoints

Defected steel rib 휘어진 강지보

Applications
Mining Engineering (2) – Underground Mine

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Relatively large ore size and intact concrete lining

Slabbing at the side of opening (production level)

Applications
Mining Engineering (3) – Quarry

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- Dalhalla Concert hall in Sweden – abandoned limestone quarry

http://www.dalhalla.se

Applications
Petroleum Engineering (1)

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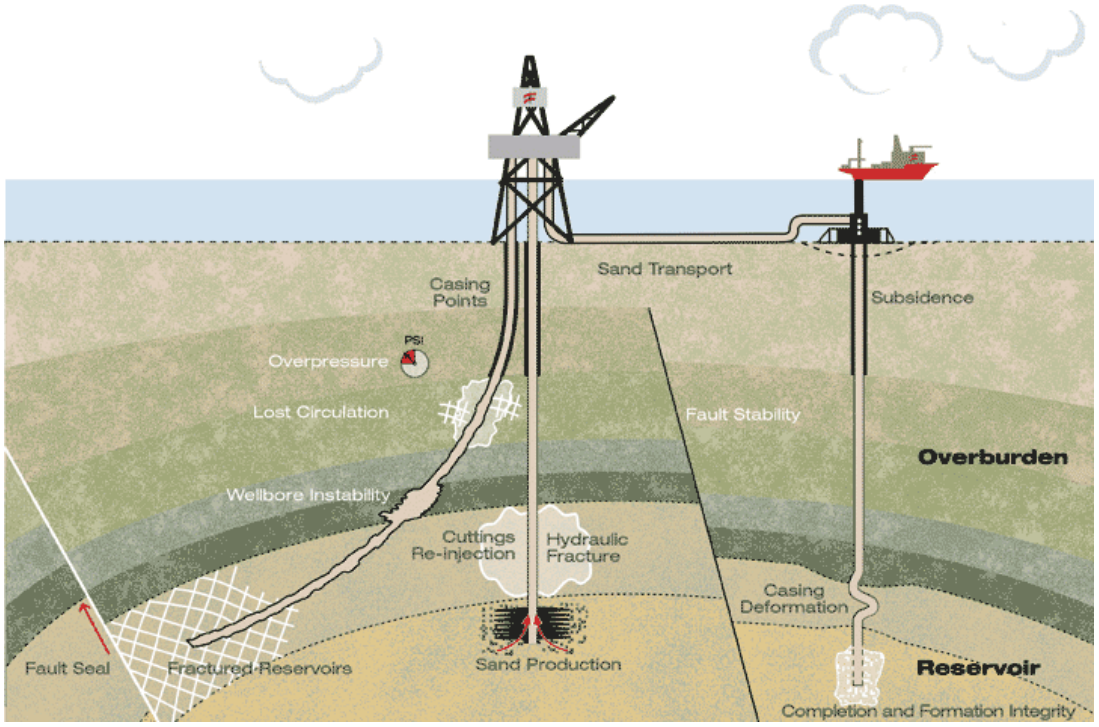
- Areas of Reservoir Geomechanics
  - Hydraulic Fracturing
  - Borehole Stability
  - Fault reactivation
  - Subsidence
  - Sand Production



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

Applications
Petroleum Engineering (2) – Shale Gas production

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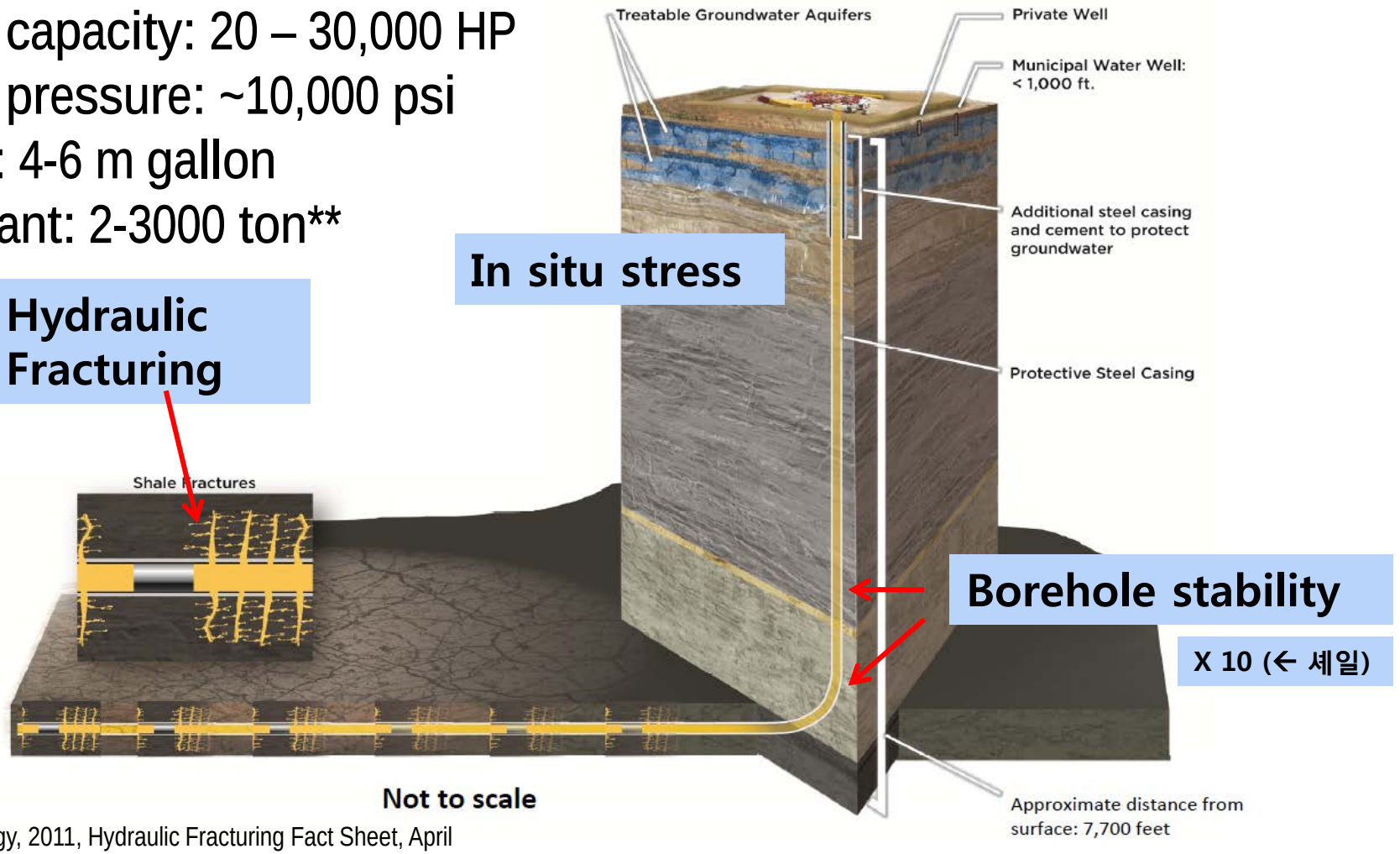
Pump capacity: 20 – 30,000 HP
Pump pressure: ~10,000 psi
Water: 4-6 m gallon
proppant: 2-3000 ton**

In situ stress

Hydraulic Fracturing



Borehole stability

X 10 (← 셰일)

Chesapeake Energy, 2011, Hydraulic Fracturing Fact Sheet, April
** O'Sullivan, 2012, GHGT-2012, Kyoto, Japan

Applications
Petroleum Engineering (3) – wellbore stability

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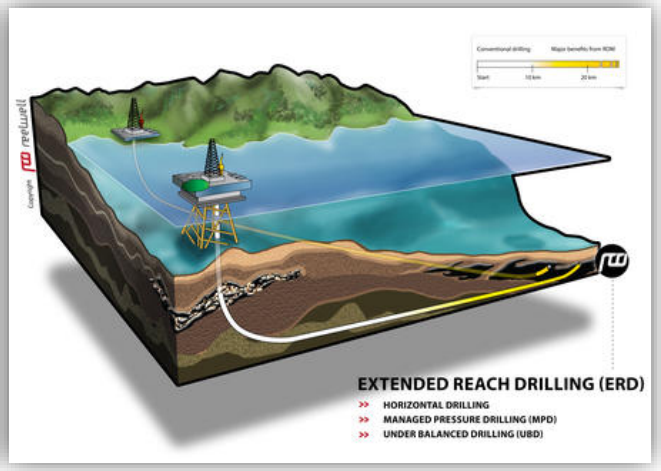
Oseberg in North Sea (Norway)

- 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

Applications
Petroleum Engineering (3) – wellbore stability

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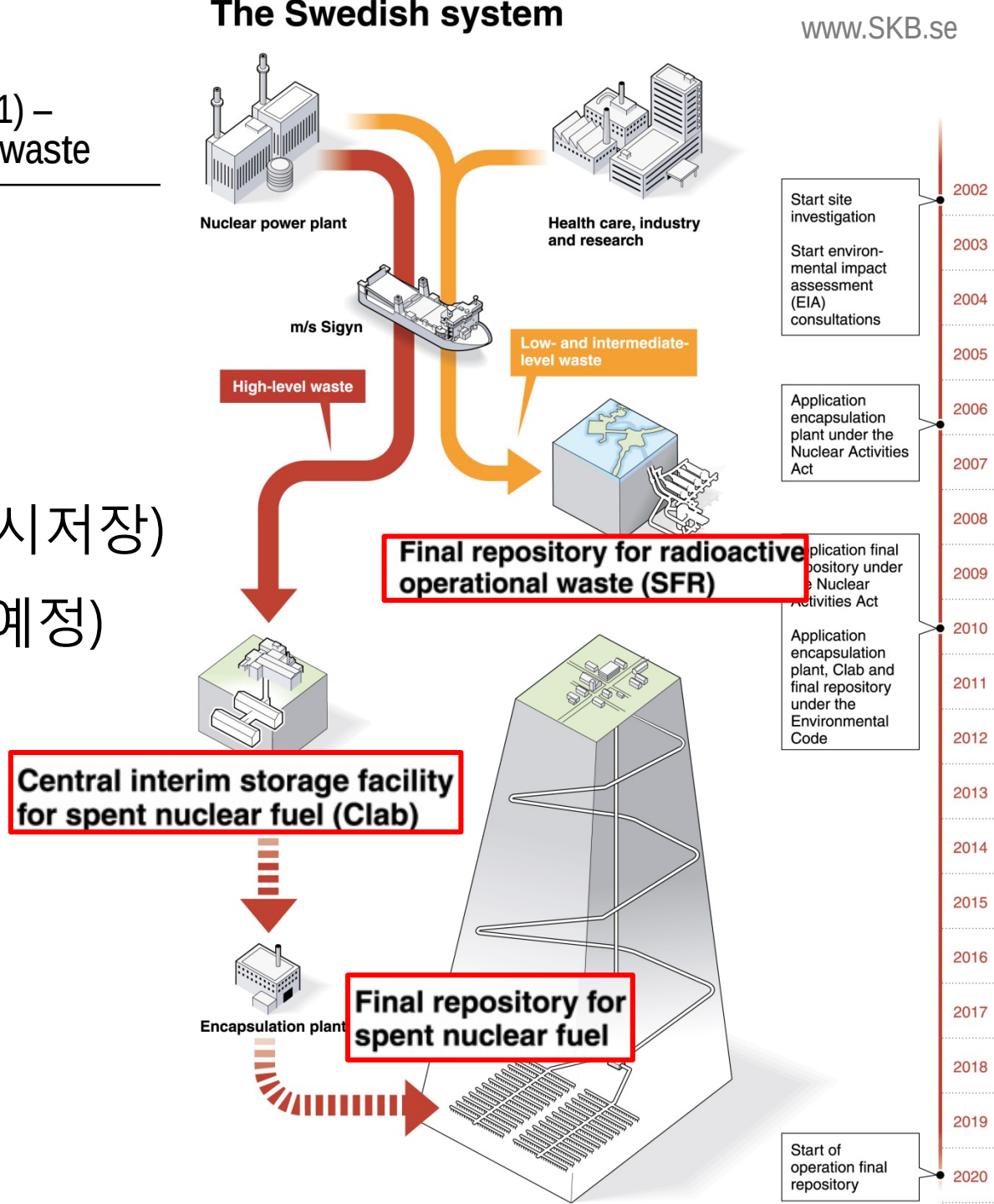
Slide not publishable

Applications

Geo-Environmental Engineering (1) –
Geological repository for nuclear waste

- 지하처분시설:
  - SFR (중저준위)
  - CLAB (고준위 임시저장)
  - 고준위 처분장 (예정)
- 지하연구시설
  - Stripa Mine (1980-1992)
  - Äspö HRL (1995 -)



Applications

Geo-Environmental Engineering (1) – Geological repository for nuclear waste

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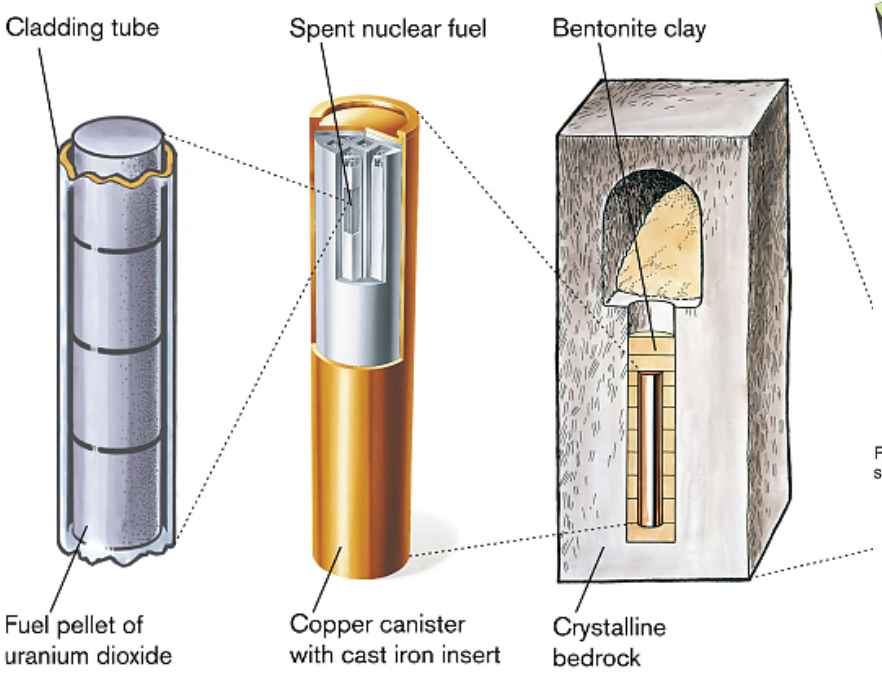
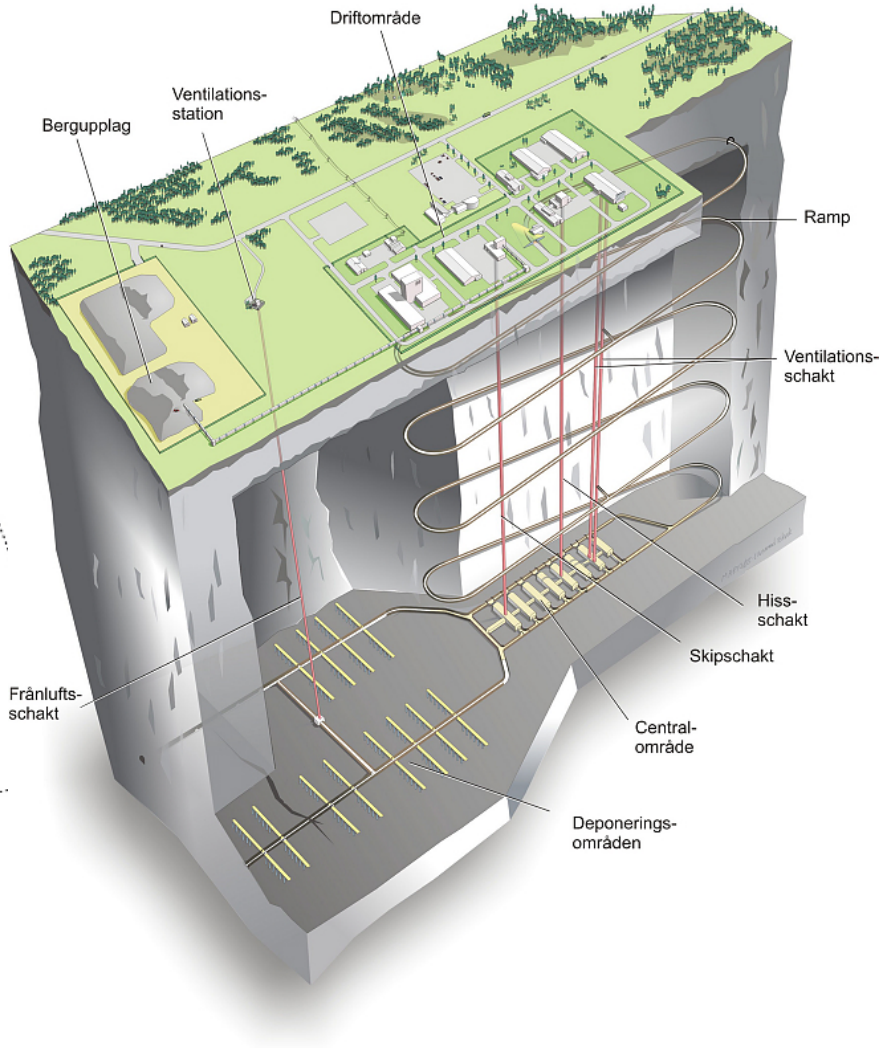


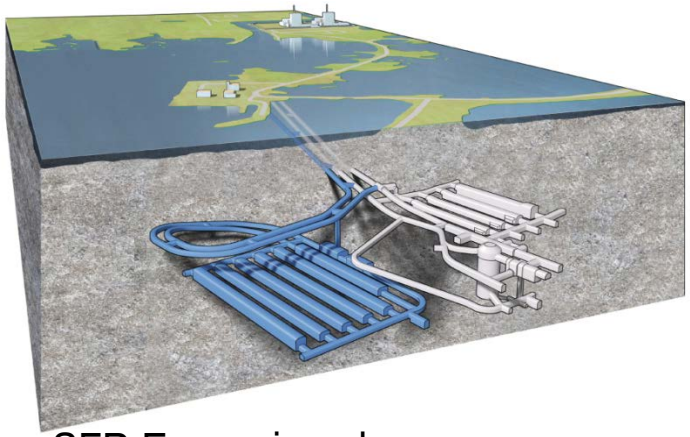


www.skb.se

Applications

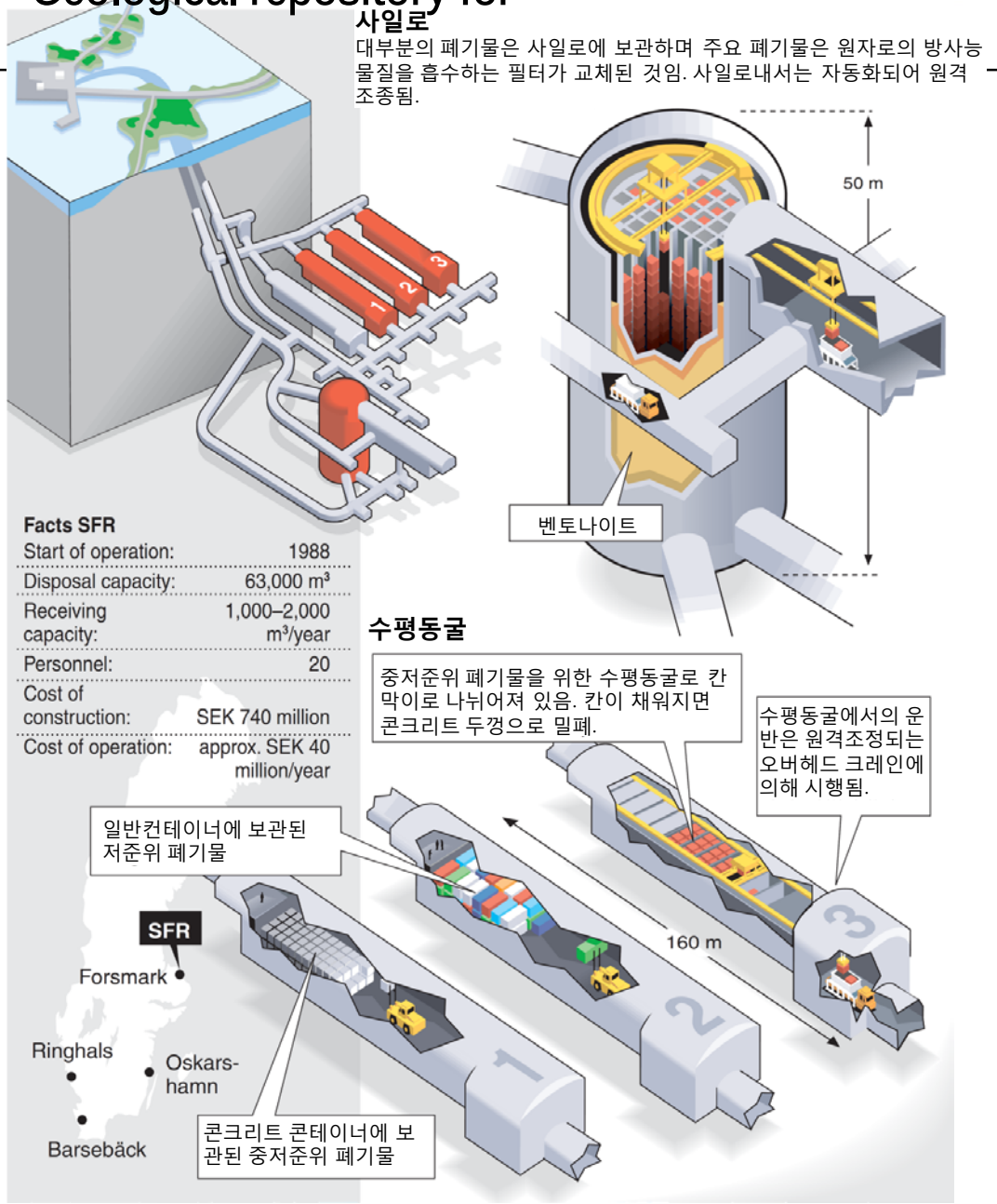
Geo-Environmental Engineering (1) – Geological repository for nuclear waste

- 스웨덴 SFR
  - 심도: 60 m
  - 운영시작: 1988년
  - 저장용량: 63,000m^3
  - 30 m x 70 m



SFR Expansion plan

www.skb.se의 Mats Jerndahl 에서 한글 번역 추가



Applications

Geo-Environmental Engineering (1) – Geological repository for nuclear waste

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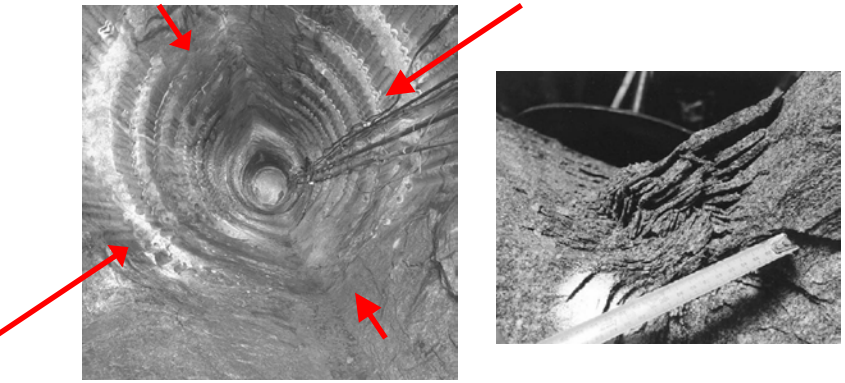
- Underground Research Laboratory in Winnipeg, Canada - Similar observation can be found in underground construction/mining



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

Winnipeg, Canada (Min, 2002)

Applications

Geo-Environmental Engineering (2) – CO2 Geosequestration

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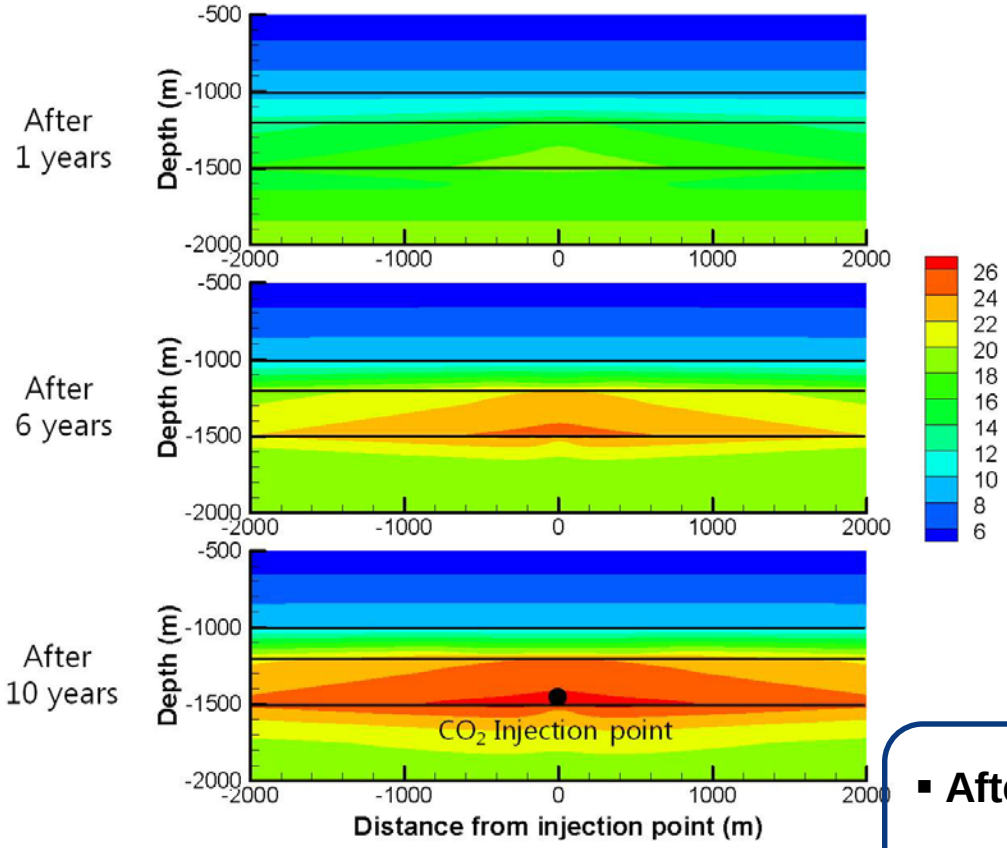
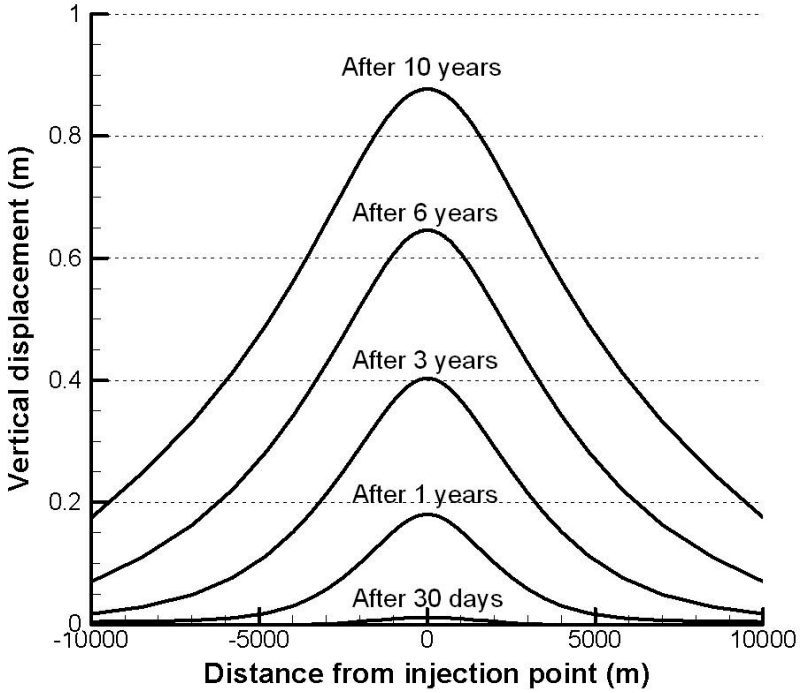


Pressure change with time near the injection point (Units: MPa)



Vertical displacement profile

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

Lee, Min, Rutqvist (2012), RMRE

Applications
Civil/Infrastructure (1) – Tunnels

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- Civil/Infrastructure
  - Tunnel
  - Slope
  - Dam
  - Oil/Gas Storage Cavern
  - Foundation

T-centralen, Stockholm subway (Per Olof Ultvedt 1975)

Applications
Civil/Infrastructure (1) – Tunnels

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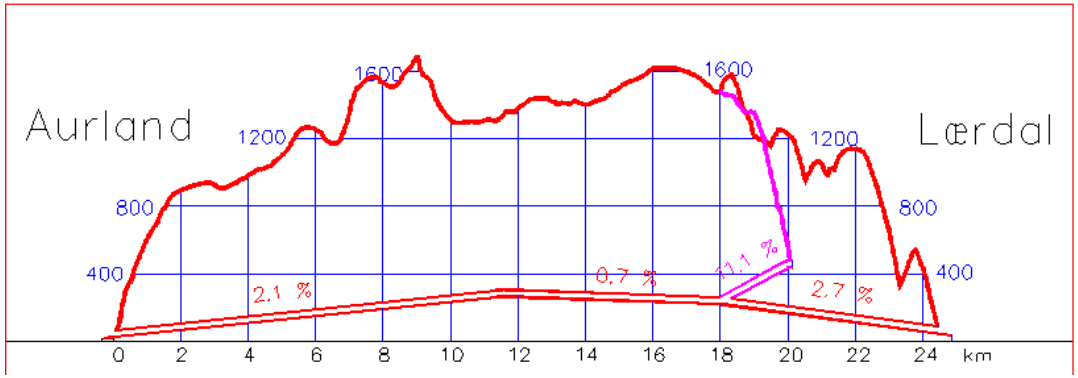
- 24.5 km long, 10m wide
- Three 30 m wide mountain hall
- Over 1 km overburden



Applications
Civil/Infrastructure (1) – Tunnels

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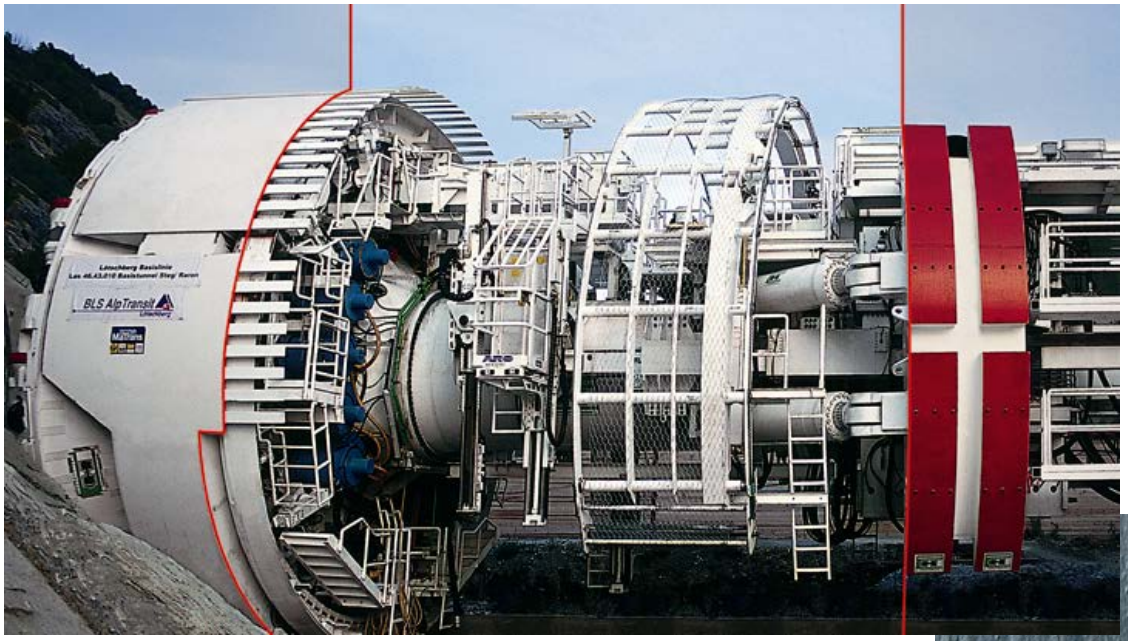

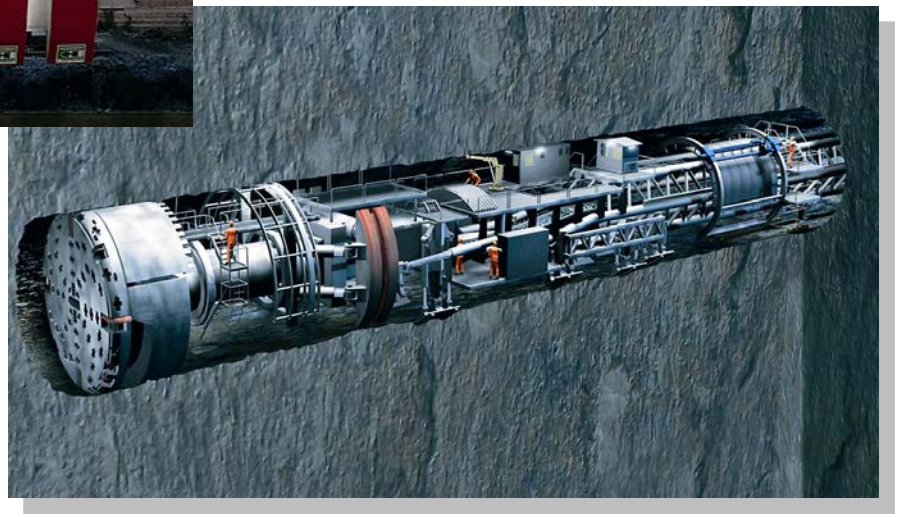

✓ **Tunnel Boring Machine (TBM)**

스위스
Gottard Base Tunnel 에 사용

Applications
Civil/Infrastructure (2) – Slopes

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Slopes to be scaled

Youngyang, Korea (1999)

Goksong, Korea (1999)

Applications
Civil/Infrastructure (2) – Slopes

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Reinforcement: Rock Anchor

Chunchon, Korea (1999)

Artificial tunnel

Inje, Korea (1998)

Applications
Civil/Infrastructure (3) – Dams

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Three Gorges Dam (Christoph Filnkößl)

Ship locks for river traffic

Applications
Civil/Infrastructure (4) – Oil/Gas Storage Cavern

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발 주 처

SK 가스 주식회사

위 치

한국, 울산시

사업 기간

1985. 11 ~ 1988. 11

사업 개요

- 저장 유종 : Propane, Butane
- 저장 용량
  - Propane : 275,000 m^3 Butane : 225,000 m^3
- Propane 저장동굴 : 4 개
  - 저장동굴단면 : 307.24 m^2
  - 저장동굴연장 : 835 m
- Butane 저장동굴 : 3 개
  - 저장동굴단면 : 341.45 m^2
  - 저장동굴연장 : 616 m

사업 범위

- 전체 사업관리
- 지하 및 지상저장시설 시공
  (현재 운영중)

Applications
Civil/Infrastructure (5) – Foundations

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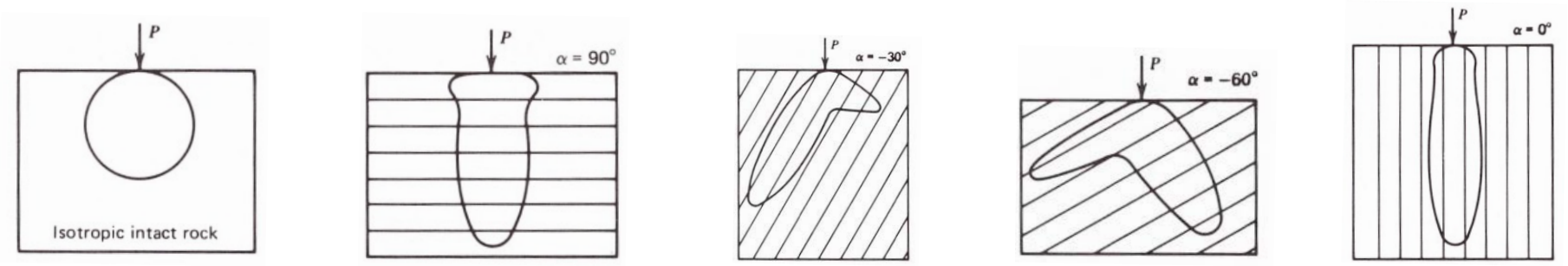
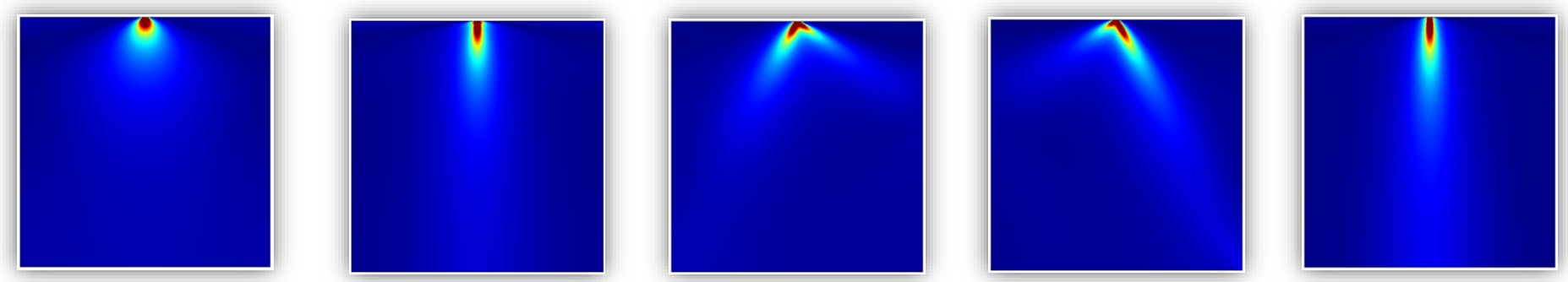
Foundation under line load on transversely isotropic rock (radial stress is shown)



(Goodman, 1989)



FEM modeling

(Park and Min, 2015)

Goodman R, Introduction to rock mechanics, 1989, 2nd ed., Wiley

Park, B. and Min, K.B., Discrete element modeling of transversely isotropic rock applied to foundation and borehole problems, 13rd ISRM Congress, 2015, Vancouver, Canada

Applications
Geothermal Energy

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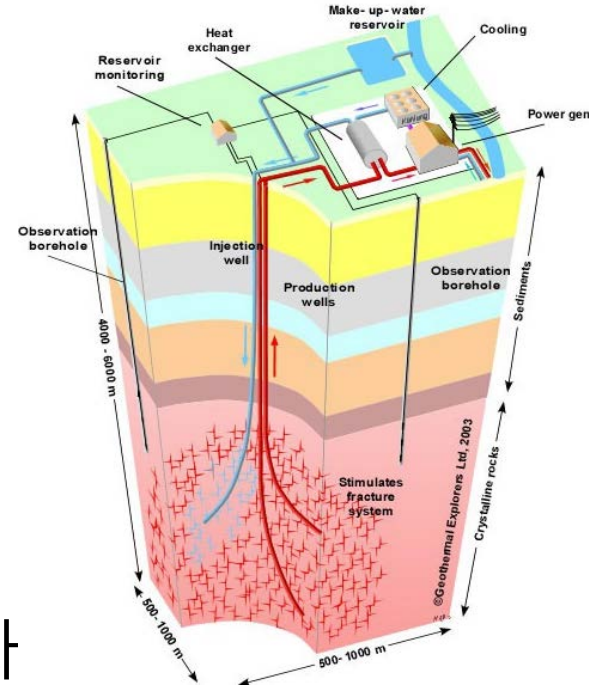
- EGS (Enhanced Geothermal System, 인공저류층 지열시스템): 투수율이나 공극률이 낮은 암반이 경제적인 지열 생산을 가능하도록 투수율을 높힌 인공저류층을 대상으로 한 지열에너지 개발시스템
- EGS 의 핵심기술
  - 심부 시추 (3 ~ 5 km)
  - 인공저류층 형성(수리자극)
  - 저류층 특성화
  - 저류층 모니터링(미소진동 관리)
- 심부지열발전 핵심기술은 석유 가스 등의 자원개발에 필요한 탐사, 개발, 생산 기술과 매우 유사함



Geothermal Explorer, 2010

Applications
Geothermal Energy – example

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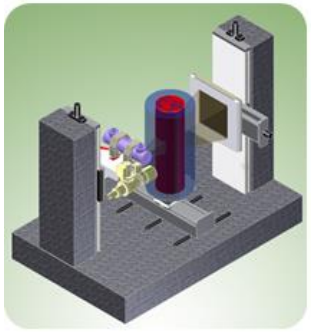
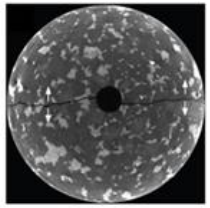
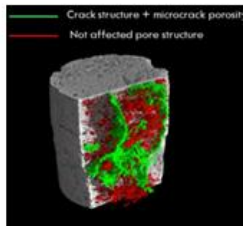
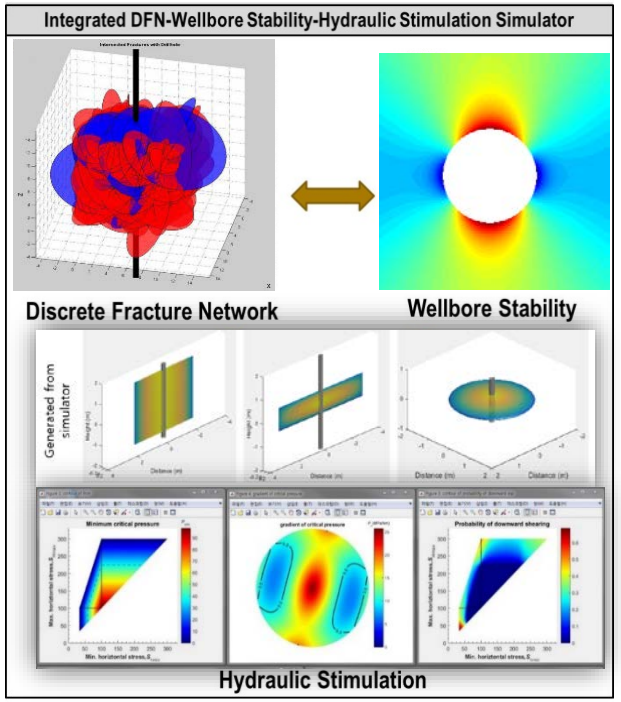
- Laboratory scale experiment
  - Hydraulic fracturing on cylindrical rock sample (~ 5.4 cm diameter) inside CT-chamber
  - Basis for conceptual design of hydraulic stimulation
- Thermal performance
  - Conceptual calculation by analytical solution
- Hydraulic shearing initiation and propagation analysis
  - Condition for upward and downward migration of hydroshearing
- Hydraulic shearing and fracturing simulator
  - DFN-Hydraulic stimulation-borehole stability









Methods for Rock Mechanics/Geomechanics Analysis

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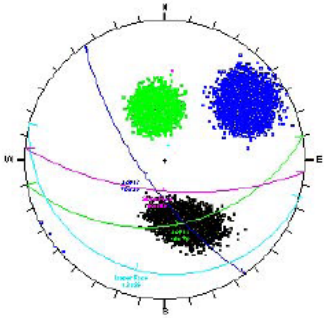
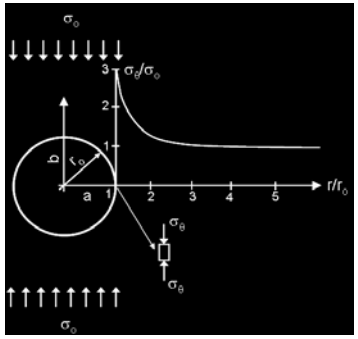
- 해석적 방법 (Analytical method)
  - 알려져 있는 수학적 해를 이용하여 응력과 변위를 계산
  - 커쉬해 (Kirsch solution) 등이 원형공동주위의 응력상태를 알려주는 대표적인 수학적 해임.
- 경험적 방법 (Empirical method)
  - 축적된 경험을 이용하여 여러 범주에 점수를 부여하여 해석
  - 암반분류법이 대표적인 예 (RMR (Rock Mass Rating), Q-system)
- 수치해석적 방법 (Numerical Method)
  - 주어진 경계조건과 형상에서 컴퓨터 시뮬레이션을 이용하여 응력과 변위를 계산 (편미분방정식을 푸는 것임)
  - 복잡한 형상에서 효과적임
  - 유한요소법 (Finite Element Method, FEM), 유한차분법 (Finite Difference Method, FDM), 개별요소법 (Discrete Element Method, DEM)



Example of streographic projection method

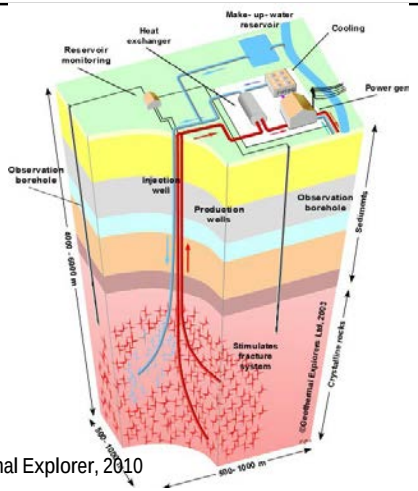


Stress distribution around a circular opening

Aitik Mine, Sweden, Min, 2012

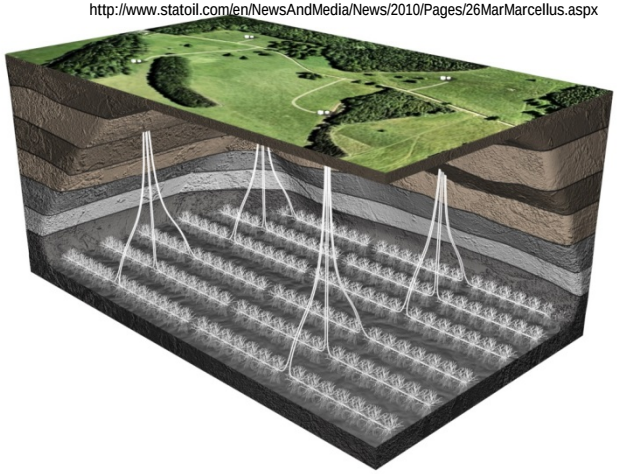
Mining Engineering
Depth : ~ 2.5 km

Enhanced Geothermal System

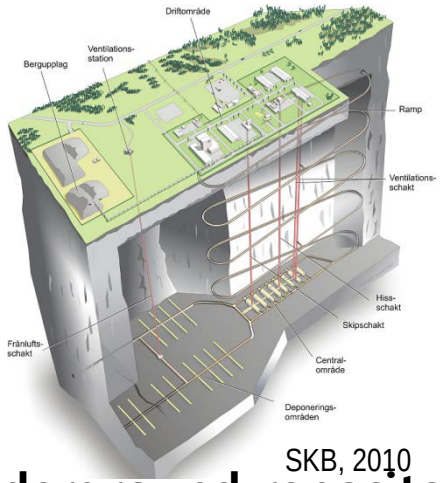


Geothermal Explorer, 2010

http://www.statoil.com/en/NewsAndMedia/News/2010/Pages/26MarMarcellus.aspx



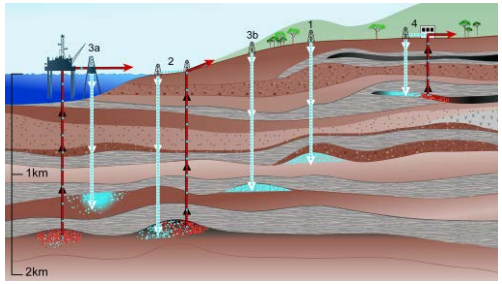
Shale gas production & oil/gas
depth: ~ 3.0 km



SKB, 2010

Underground repository for nuclear waste
depth: 0.5 ~ 5.0 km

THINK BIG!
GO DEEP!!



IPCC, 2005

CO_2 sequestration
depth: ~ 2.5 km