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

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Outline

• 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

- **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

- **Mining Engineering**
  - underground mine, surface mine

- **Rock Mechanics/Geomechanics**

- **Petroleum eng**
  - hydraulic fracturing, borehole stability, subsidence control

- **Civil/Geotechnical Eng**
  - tunnel, foundation on rock, road slope

- **Energy & Environ. issues**
  - nuclear waste disposal, geothermal energy, CO2 sequestration
Nature of problem
Data limited problem

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

Recited from Starfield and Cundall (1988)
Nature of problem
Effect of fractures & Scale

Forsmark, Sweden, 2004

Forsmark, Sweden, www.skb.se
Nature of Underground Geomechanics

Civil structural problems:
Mechanics of “Addition”

Underground Geomechanics problems:
Mechanics of “Removal”

Before drilling/excavation

Start of drilling/excavation

Further advance of drilling/excavation

Monitoring points

stress

strain
<table>
<thead>
<tr>
<th>Nature of problem</th>
<th>Structural problem/Rock Mechanics</th>
</tr>
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<tbody>
<tr>
<td>재료 및 물성</td>
<td>建筑及材料性能，Civil Structural Problem</td>
</tr>
<tr>
<td>Material &amp; nature of its properties</td>
<td>钢和混凝土，Steel, Concrete</td>
</tr>
<tr>
<td>철강 혹은 콘크리트</td>
<td>人工材料，Man-made material</td>
</tr>
<tr>
<td>- 인공물질 (Man-made material)</td>
<td>- 均质材料 (Homogeneous)</td>
</tr>
<tr>
<td>- 균질 (Homogeneous)</td>
<td>- 连续体 (Continuum)</td>
</tr>
<tr>
<td>경계조건</td>
<td>状态条件，Boundary condition (loading condition)</td>
</tr>
<tr>
<td>Boundary condition (loading condition)</td>
<td>自重 + 服务荷载 (Weight + service load)</td>
</tr>
<tr>
<td>- 저장실성 적음 (low uncertainty)</td>
<td>- 储压室性 小 (low uncertainty)</td>
</tr>
<tr>
<td>하중재하의 경로</td>
<td>应力集中源，Stress Concentration source</td>
</tr>
<tr>
<td>Stress Concentration source</td>
<td>재료의 추가 (상재) (Addition of material)</td>
</tr>
<tr>
<td>지하수의 영향</td>
<td>地下水影响，Groundwater</td>
</tr>
<tr>
<td>Groundwater</td>
<td>-</td>
</tr>
<tr>
<td>크기 효과</td>
<td>Size effect</td>
</tr>
<tr>
<td>Size effect</td>
<td>-</td>
</tr>
<tr>
<td>암석역학</td>
<td>Geomechanics</td>
</tr>
<tr>
<td>암석 및 토질 (Rock &amp; Soil)</td>
<td>岩石及土壤 (Rock &amp; Soil)</td>
</tr>
<tr>
<td>- 자연물질 (Natural material)</td>
<td>- 均质材料 (Homogeneous)</td>
</tr>
<tr>
<td>- 불평질 (Heterogeneous)</td>
<td>- 储压室性 小 (low uncertainty)</td>
</tr>
<tr>
<td>- 불연속체 (Discontinuum)</td>
<td>- 地下水影响 very important</td>
</tr>
<tr>
<td>(절리를 함유, contain joints)</td>
<td>(含裂隙，contain joints)</td>
</tr>
<tr>
<td>재료를 없앰 (굴착, removal of material: excavation or drilling)</td>
<td>非材料 remove (掘采，excavation or drilling)</td>
</tr>
<tr>
<td>매우 중요함</td>
<td>Very important</td>
</tr>
</tbody>
</table>
Applications

Mining Engineering (1) – Surface Mine

Prominent Hill, Australia, 2008

Pasir Mine, Indonesia, 2010
Applications
Mining Engineering (2) – Underground Mine

- Hendersen Mine, Colorado, USA – 1976 operation start (10 years prior to $500 million investment)
- World's largest molybdenum mine – 1000-meter-deep ore body, maximum depth 1,600 meters

Hustrulid & Bullock, 2001
Applications
Mining Engineering (2) – Underground Mine

• Drawpoints

Defected steel rib 휘어진 강지보
Applications

Mining Engineering (2) – Underground Mine

Relatively large ore size and intact concrete lining

Slabbing at the side of opening (production level)
Applications

Mining Engineering (3) – Quarry

- Dalhalla Concert hall in Sweden – abandoned limestone quarry

http://www.dalhalla.se
Applications
Petroleum Engineering (1)

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

Applications
Petroleum Engineering (2) – Shale Gas production

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

Hydraulic Fracturing

In situ stress

Borehole stability

Chesapeake Energy, 2011, Hydraulic Fracturing Fact Sheet, April
** O'Sullivan, 2012, GHGT-2012, Kyoto, Japan
Applications
Petroleum Engineering (3) – wellbore stability

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

Slide not publishable
Applications
Geo-Environmental Engineering (1) – Geological repository for nuclear waste

- 지하처분시설:
  - SFR (중저준위)
  - CLAB (고준위 임시저장)
  - 고준위 처분장 (예정)

- 지하연구시설
  - Äspö HRL (1995 - )
Applications

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

- Cladding tube
- Fuel pellet of uranium dioxide
- Spent nuclear fuel
- Copper canister with cast iron insert
- Bentonite clay
- Crystalline bedrock

www.skb.se
Applications
Geo-Environmental Engineering (1) – Geological repository for nuclear waste

• 스웨덴 SFR
  - 심도: 60 m
  - 운영시작: 1988년
  - 저장용량: 63,000m³
  - 30 m x 70 m

SFR Expansion plan

대부분의 폐기물은 사일로에 보관하며 주요 폐기물은 원자로의 방사능 물질을 흡수하는 필터가 교체된 것임. 사일로내서는 자동화되어 원격 조종됨.

수평동굴
중저준위 폐기물을 위한 수평동굴로 칸막이로 나뉘어져 있음. 칸이 채워지면 콘크리트 두껑으로 밀폐.

Facts SFR
Start of operation: 1988
Disposal capacity: 63,000 m³
Receiving capacity: 1,000–2,000 m³/year
Personnel: 20
Cost of construction: SEK 740 million
Cost of operation: approx. SEK 40 million/year

www.skb.se의 Mats Jerndahl에서 한글 번역 추가

SFR Expansion plan

스웨덴 SFR
- 심도: 60 m
- 운영시작: 1988년
- 저장용량: 63,000m³
- 30 m x 70 m
Applications

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

• 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

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

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

T-centralen, Stockholm subway (Per Olof Ultvedt 1975)
Applications
Civil/Infrastructure (1) – Tunnels

- 24.5 km long, 10m wide
- Three 30 m wide mountain hall
- Over 1 km overburden
Applications
Civil/Infrastructure (1) – Tunnels

✓ Tunnel Boring Machine (TBM)
스위스
Gottard Base Tunnel 에 사용
Applications
Civil/Infrastructure (2) – Slopes

Slopes to be scaled

Youngyang, Korea (1999)

Goksong, Korea (1999)
Applications

Civil/Infrastructure (2) – Slopes

Reinforcement: Rock Anchor

Chunchon, Korea (1999)

Artificial tunnel

Inje, Korea (1998)
Applications
Civil/Infrastructure (3) – Dams

Three Gorges Dam (Christoph Filnkößl)

Ship locks for river traffic
## Applications

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

<table>
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<tr>
<th>발주처</th>
<th>SK 가스 주식회사</th>
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<tbody>
<tr>
<td>위치</td>
<td>한국, 울산시</td>
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<tr>
<td>사업 기간</td>
<td>1985. 11 ~ 1988. 11</td>
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<tr>
<td>사업 개요</td>
<td></td>
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<tr>
<td>- 저장 유종 : Propane, Butane</td>
<td></td>
</tr>
<tr>
<td>- 저장 용량</td>
<td></td>
</tr>
</tbody>
</table>
|   - Propane : 275,000 m³  
   Butane : 225,000 m³    |
| - Propane 저장동굴 : 4 개   |
|   - 저장동굴단면 : 307.24 m² |
|   - 저장동굴연장 : 835 m     |
| - Butane 저장동굴 : 3 개   |
|   - 저장동굴단면 : 341.45 m² |
|   - 저장동굴연장 : 616 m     |
| 사업 범위   |
| - 전체 사업관리 |
| - 지하 및 지상저장시설 시공 (현재 운영중) |
Applications
Civil/Infrastructure (5) – Foundations

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

FEM modeling

(Goodman, 1989)

(Park and Min, 2015)

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

• EGS (Enhanced Geothermal System, 인공저류층 지열시스템): 투수율이나 공극률이 낮은 암반 이 경제적인 지열 생산을 가능하 도록 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

• 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
• 해석적 방법 (Analytical method)
  - 알려져 있는 수학적 해를 이용하여 응력과 변위를 계산
  - 커쉬해 (Kirsch solution) 등이 원형공동주위의 응력상태를 알려주는 대표적인 수학적 해임.
• 경험이적 방법 (Empirical method)
  - 축적된 경험이 이용하여 여러 범주에 점수를 부여하여 해석
  - 일반분류법이 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)
Mining Engineering
Depth: ~ 2.5 km

Enhanced Geothermal System

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

THINK BIG!
GO DEEP!!

Underground repository for nuclear waste
depth: 0.5 ~ 5.0 km

CO₂ sequestration
depth: ~ 2.5 km