Understanding the mechanisms of fluid flow and fracturing in poorly consolidated porous media

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What are poorly consolidated sands?

• Sandstone rock with little or no cohesion between the grains
• Poorly consolidated weakly cemented sandstones
Problem Statement

Why do we care really?

The injection of a fluid into a porous medium is required for many applications in the fields of groundwater hydrology, hydraulics and hydrogeology, and geo-environmental engineering and in the oil and gas industry.

01 SHALLOW GROUND
Managed aquifer recharge (MAR), aquifer storage and recovery (ASR), hydraulic barriers, transportation of various fluids in the subsurface, artificial ground freezing, groundwater decontamination

02 GREATER DEPTH
Hydraulic fracturing
Water flooding
Flowing tests to determine horizontal stresses

03 UNCONVENTIONAL APPLICATIONS
CO₂ sequestration
Hydrogen injection in depleted reservoirs
Synthetic rock specimens can provide virtually limitless quantities and customisable characteristics, allowing relevant structural parameters to be varied independently.

Assess the effect of material properties (strength, permeability, porosity).

1. Observation of fracture
2. Create most relevant environmental conditions (e.g. true triaxial stresses)

Tests under various stress states, material properties and fluid flow conditions.

Use of critical concepts, which have been neglected in numerical studies, to interpret the results.
Synthetic rock specimens can provide virtually limitless quantities and customisable characteristics, allowing relevant structural parameters to be varied independently. Assess the effect of material properties (strength, permeability, porosity).

**ULTIMATE GOAL**

- **Preparation of artificial specimens**
- **Characterise artificial specimens**
- **Testing of weakly cemented sandstones**
- **Design of experimental apparatus**
- **Interpretation of experiments**
Artificially cemented sandstones

Step 1: Prepare sand column

Step 2: Inject bacteria

Step 3: Inject cementation solution

\[ CO(NH_2)_2 + 2H_2O \rightarrow H_2CO_3 + 2NH_3 \]

\[ CaCl_2 \rightarrow Ca^{2+} + 2Cl^- \]
Artificially cemented sandstones

- Microbially induced carbonate precipitation (MICP) to induce cementation within the granular medium
- Technique is environmentally friendly and non-destructive

- Challenges of an effective MICP formulation
- Parametric study for development of artificial specimens


**Most cited articles in JRGE since 2021** http://www.jrmge.cn/newscontent-4-145.html/
Aim

- Push the boundaries of the ‘compatibility region’ on both sides
- The ability of the MICP recipe selected to cement very fine and very coarse soils
Silt properties

- Chemical efficiency: 30-40%
- Cementation level: about 3-4 %.
- Key to cementing silt:
  - higher hydraulic gradient
  - larger supernatant flow
Gravel Properties

- Chemical efficiency: 60-70%
- Cementation level: about 8-10%
- Key to cementing gravel:
  - High flow rates (percolation)
  - Higher bacterial optical density
Material properties (1)

- Unconfined compressive strength (UCS)
- Point load index
- Tensile strength
- Fracture toughness
- Porosity
- Permeability
- Calcite crystals network (with SEM)
- MicroCT imaging
Material properties (2)

- UCS
- Porosity
- Permeability
Material properties (3)
Material properties (4)

Table 1: The mechanical properties of bio-cemented sandstones.

<table>
<thead>
<tr>
<th>Property</th>
<th>Equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>cementation level C (%)</td>
<td>4-10 %</td>
<td>(Cui et al., 2017)</td>
</tr>
<tr>
<td>c (kPa)</td>
<td>$0.79C + 35.73$</td>
<td>(Cui et al., 2017)</td>
</tr>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>$93.3e^{0.15C-1}$</td>
<td>(Konstantinou and Biscontin, 2021)</td>
</tr>
<tr>
<td>Unconfined compressible strength (kPa)</td>
<td>$56.11e^{0.4018C}$</td>
<td>(Konstantinou et al., 2021a)</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$\frac{\phi}{1+\log(UCS)} \times \log\left(\frac{UCS}{\sigma_3+0.1}\right)$</td>
<td>(Zhao and Cai, 2010)</td>
</tr>
<tr>
<td>Tensile Strength (kPa)</td>
<td>$81.24C - 211.21$</td>
<td>(Konstantinou et al., 2021b)</td>
</tr>
<tr>
<td>Fracture Toughness (Mpa $\sqrt{mm}$)</td>
<td>$0.1449e^{0.2496C}$</td>
<td>(Konstantinou, 2020)</td>
</tr>
<tr>
<td>Permeability (m/sec)</td>
<td>$0.0007e^{-0.66C}$</td>
<td>(Konstantinou, 2020)</td>
</tr>
</tbody>
</table>

Preparation of artificial specimens

Characterise artificial specimens

Testing of weakly cemented sandstones

Design of experimental apparatus

Interpretation of experiments

1. Observation of fracture
2. Create most relevant environmental conditions (e.g. true triaxial stresses)
Features of the experimental apparatus

• Injection, flow and transport of a fluid into a porous medium
• **Aim:** develop a fundamental understanding of hydro-mechanical interactions
• Examine the problem at its core and then concentrate on one application at a time

Hele-Shaw Cell, a device used in fluid dynamics experiments

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A modified Hele-Shaw cell was used to provide a 3D representation of the porous medium.

- Differential confining conditions
- True triaxial stresses
- Real-time visualisation of the initiation and progression of the fracture.
- Allow drainage

Injection, flow and transport of a fluid into a porous medium.
Experimental Setup

Stresses applied via bladders
Window at the bottom

RESULTS & ANALYSIS

Experimental Setup

Preparation of artificial specimens

Design of experimental apparatus

Characterise artificial specimens

Testing of weakly cemented sandstones

Tests under various stress states, material properties and fluid flow conditions

Interpretation of experiments

ULTIMATE GOAL
An example experiment (1)

Material characteristics: 8% cementation.

Fluid composition: calcium carbonate (with mean particle size 8 \( \mu m \)) 59 gr/L, xanthan gum 1.2 g/L, magnesium oxide 0.35g/L, water 327.4 g/L.

Flow rate: 100 mL/min.

Stress state: \( \sigma_v = 800 \) kPa, \( \sigma_H = 650 \) kPa, and \( \sigma_h = 500 \) kPa.
An example experiment (2)

Results & Analysis

Stress state 2 ($\sigma_v=800 \text{ kPa} / \sigma_H=650 \text{ kPa} / \sigma_h=500 \text{ kPa}$)
Preparation of artificial specimens -> Characterise artificial specimens -> Testing of weakly cemented sandstones -> Interpretation of experiments

Design of experimental apparatus
Experimental cycles 1 & 2

- No confinement
- Various grain sizes and various porous networks

- Various flow rates
- Fixed viscosity at 178 mPa x sec with clean fluids injection
- Fixed flow rate
- Fluids containing solids of various grain sizes and solids amount

Groundwater decontamination application

RESULTS & ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tbody>
<tr>
<td>No solids</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
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<tr>
<td>Sol2-F8</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
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<tr>
<td>Sol5-F8</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
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<tr>
<td>Sol2-F22</td>
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<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
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<tr>
<td>Sol5-F22</td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
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<tr>
<td>Sol2-F50</td>
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<td><img src="image22" alt="Image" /></td>
<td><img src="image23" alt="Image" /></td>
<td><img src="image24" alt="Image" /></td>
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**Interpretation of results (1)**

- **Regime I:** Strength of the material
- **Regime II:** Transition zone
- **Regime III:** Darcy flow

![Graph showing the relationship between Peak Pressure (kPa) and Predicted Pressure (kPa) for different regimes.](image)
Experimental cycles 3 & 4

- Various confining levels
- Fixed flow rate at 100 mL/min
- Fixed flow composition

- Various cementation levels
- Various porous media properties
- Various stress states
- Various stress ratios

## Results & Interpretation (1)

### Britteness Index

Britteness Index derived from the Lade-Duncan failure criterion:

\[
t_4 = \frac{I_1^3}{k_1 I_3}
\]

<table>
<thead>
<tr>
<th>Cementation Level</th>
<th>Stress State 1 ((\sigma_v=500) kPa / (\sigma_H=400) kPa / (\sigma_h=300) kPa)</th>
<th>Stress State 2 ((\sigma_v=800) kPa / (\sigma_H=650) kPa / (\sigma_h=500) kPa)</th>
<th>Stress State 3 ((\sigma_v=1000) kPa / (\sigma_H=850) kPa / (\sigma_h=625) kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 %</td>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
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<tr>
<td>5 %</td>
<td><img src="image4.png" alt="Image 4" /></td>
<td><img src="image5.png" alt="Image 5" /></td>
<td><img src="image6.png" alt="Image 6" /></td>
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<tr>
<td>6 %</td>
<td><img src="image7.png" alt="Image 7" /></td>
<td><img src="image8.png" alt="Image 8" /></td>
<td><img src="image9.png" alt="Image 9" /></td>
</tr>
<tr>
<td>8 %</td>
<td><img src="image10.png" alt="Image 10" /></td>
<td><img src="image11.png" alt="Image 11" /></td>
<td><img src="image12.png" alt="Image 12" /></td>
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<tr>
<td>9 %</td>
<td><img src="image13.png" alt="Image 13" /></td>
<td><img src="image14.png" alt="Image 14" /></td>
<td><img src="image15.png" alt="Image 15" /></td>
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</tbody>
</table>
For weakly cemented highly porous materials the stress state is more important than other parameters such as the fluid properties and strength of material.
Results & Interpretation (3)

Cavity Expansion

- The observed fracturing behaviour reminds of cavities with multiple fractures (off-shots) giving a mixed response.
- Linear elastic hydraulic fracturing models fail to predict such high breakdown pressures as the ones predicted in this series of experiments --> other dominant mechanisms take place.
- The BI models also show that there is a transition between ductile and brittle behaviour which depends on the stress state and the strength of the material tested.
- The theory of cavity expansion in cohesive soils is used and the pressure limit is calculated for each experiment.

The limit pressure for cohesive frictional materials is given by the following equation:

\[
\frac{2G}{p_o + Q} = \frac{N - 1}{N + 1} \left\{ T \left( \frac{p_L + Q}{\sigma_R + Q} \right)^Y - 2 \frac{p_L + Q}{\sigma_R + Q} \right\}
\]

where \( G \) is the shear modulus, \( p_o \) the insitu stress, \( p_L \) the limiting internal pressure and \( Q \) is defined as:

\[
Q = \frac{c}{\tan \varphi}
\]
Conclusions

• The observed fracturing behaviour reminds of cavities with multiple fractures (off-shots) giving a mixed response.
• Design parameters should include permeability and porosity of such weak materials
• Fracture response is heavily controlled by the stress state and stress ratios
• Pressure limit from cavity expansion theory seems to better fit the peak pressures
• Fractability coefficient explains the fracture ‘readiness’ of weakly cemented porous media
**Numerical Modelling**

**01**

**SHALLOW GROUND**

**Hydraulic barriers**

**Aim:** Design parameters for managed aquifer recharge without dislocating the particles based on porous media properties

**Design Parameters:**
1. Distance from the coastal line (well location)
2. Pumping rate

**02**

**GREATER DEPTH**

**Hydraulic fracturing problem**

**Aim:** Understand the various hydro-mechanical interactions and identify the design parameters

1. Discrete Element Modelling
2. Finite Element Modelling
Behind every milestone, there's a team that never settles for less.

Dr. Ramesh Kannan
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IIT, Madras, India
Experiments

Dr. Giovanna Biscontin
University of Cambridge
US National Science Foundation
Experiments and modelling

Dr. Paula Gago
Post-doctoral researcher
Imperial College London
DEM modelling

Prof. Panos Papanastasiou
Professor
University of Cyprus
Numerical and analytical modelling

Dr. Yuze Wang
Assistant Professor
Southern University of Science and Technology, China
MICP for ocean engineering

Dr Charalampos Konstantinou
Research Associate
University of Cyprus

Matheos Giakoumi
Research Assistant
University of Cyprus
Modelling – multiphase flows

Antonis Tsagkarides
Research Assistant
University of Cyprus
Modeling - hydraulic barriers design parameters

Research theme 01
Microbially induced carbonate precipitation
Application of MICP for various applications in geo-engineering

Research theme 02
Fluid flow in porous media
Experimental, numerical and analytical modelling
Acknowledgement

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