Hydrologic, Geomechanical, and Geophysical Measurements on Laboratory-Formed Hydrate-Bearing Samples

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Contributors

• Timothy J. Kneafsey, P.E., Ph.D. (hydrologic tests, imaging, process, test development)
• Seiji Nakagawa, Ph.D. (geomechanical and geophysical measurements and interpretation)
• Teamrat Ghezzehei, Ph.D. (hydrologic measurements, modeling/inverse modeling)
• Yongkoo Seol, Ph.D. (now at NETL - hydrologic tests, modeling/inverse modeling, test development)
• Liviu Tomutsa, Ph.D. (imaging, micro CT, test development)
• George Moridis, Ph.D. (modeling)
  • Arvind Gupta, Ph.D. (Colorado School of Mines - now at Shell - hydrologic measurements)
  • Matt Walsh (Colorado School of Mines - hydrologic measurements)
Hydrate Research Areas

• Hydrologic Properties *(necessary for accurate hydrologic modeling)*
  – Relative Permeability
  – Capillary Pressure

• Geomechanical and Geophysical Properties *(necessary for understanding well/seafloor/slope stability)*

• Other
  – Mt. Elbert, NGHP core scanning
  – Gas Production from Natural Samples
  – Effects of Brief Depressurization
  – Properties of HBS
  – Water Flow Through Heterogeneous Hydrate
  – …
Expenditures

- FY 2006 ~$254K
- FY 2007 ~$375K
- FY 2008 (June) $331K
Hydrologic Properties
Relative Permeability
Relative Permeability

- Permeability \((k)\) - measure of the ability for a fluid to move through a medium.
- Relative permeability \((k_r)\) - measure of how the presence of interfering phases (hydrate, water, gas) affect the fluid movement.
- Gas hydrate in the porespace will strongly affect flow behavior
- \(k_r\) is also affected by hydrate location (e.g. grain contacts, pore bodies) and saturation in the porespace.
Relative Permeability $[k_r(S_h, S_w)]$

Measurements

Challenges:
- Maintaining stable conditions while introducing water and/or methane and applying a pressure gradient
- Simultaneously knowing phase saturations

Approach: Sample characterization including x-ray CT, and waterflood technique with inverse modeling (iTOUGH2) to reduce measurement duration and number of fluids introduced.
Method

- Moisten sand and pack column
- Apply a series of conditions - moist, frozen, hydrate-bearing, (*), water saturated, dry
- Measure permeability and CT scan each condition
- * Perform waterflood on the hydrate-bearing sand
- Compute/extend $k_{rg}$ and $k_{rw}$ by inverse modeling of waterflood data using ITOUGH2
Media Investigated

![Cumulative Percent Passing vs. Particle Size (microns)]

- 12% Silt 88% F110
- F110 Silica Sand
- Ksand

![Images of F110 and Ksand particles](1000 microns)
<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity (from CT)</th>
<th>Initial Water Sat</th>
<th>Hydrate Sat</th>
<th>Gas Sat with Hydrate Present</th>
<th>Conversion of Water to Hydrate</th>
<th>Sample Diam. (cm)</th>
<th>Sample Volume (cm³)</th>
<th>Sample Length (cm)</th>
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<tbody>
<tr>
<td>Fsand28</td>
<td>0.31</td>
<td>0.28</td>
<td>0.24</td>
<td>0.65</td>
<td>1.00</td>
<td>5.25</td>
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<td>0.42</td>
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<td>0.60</td>
<td>0.58</td>
<td>0.28</td>
<td>0.76</td>
<td>5.48</td>
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<td>Ksand20</td>
<td>0.38</td>
<td>0.20</td>
<td>0.21</td>
<td>0.75</td>
<td>0.82</td>
<td>5.89</td>
<td>969</td>
<td>35.6</td>
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<td>Ksand28</td>
<td>0.38</td>
<td>0.28</td>
<td>0.31</td>
<td>0.63</td>
<td>0.82</td>
<td>5.78</td>
<td>945</td>
<td>36.0</td>
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<td>0.56</td>
<td>0.49</td>
<td>0.42</td>
<td>0.72</td>
<td>5.41</td>
<td>313</td>
<td>13.6</td>
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</tbody>
</table>
Hydrate Saturation Distributions

F110 Sand

Ksand

F110 Sand/Silt
Gas Permeabilities
Gas Relative Permeabilities

- X - Dry or Intrinsic
- Circles - Moist
- Triangles - Frozen
- Squares - Hydrate-bearing
- Diamonds - Water perm resid gas
Comparison with Models
Waterflood

Water saturation during waterflood through “uniform” sandpack having “uniform” hydrate saturation
Flow - Heterogeneous $S_h$
Numerical Inversion

• Numerical inversion of waterflood data using iTOUGH2 is ongoing.
• Initial analyses indicate that relative permeability estimations will be nonunique without measured capillary pressure-saturation data.
• Measurements of capillary pressure-saturation are ongoing.
• We are developing a technique to obtain both relative permeability and capillary pressure from a single test.
Hydrologic Properties

Capillary Pressure and Relative Permeability Functions
Capillary Pressure

- Pressure difference between two phases (e.g. water and gas)
- Caused by interfacial tension, surface wettability, and pore geometry
- $P_c \propto \sigma / r_K$
- Function of saturations of all phases

<table>
<thead>
<tr>
<th>$r_K$</th>
<th>$P_c$</th>
<th>$Sat_w$</th>
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<tbody>
<tr>
<td>small</td>
<td>large</td>
<td>low</td>
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<th>$\text{Sat}_w$</th>
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<td>med</td>
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<td>small</td>
<td>high</td>
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<tbody>
<tr>
<td>small</td>
<td>large</td>
<td>med</td>
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Experimental Setup
## Summary of Tests Conducted

<table>
<thead>
<tr>
<th>Test #</th>
<th>Material</th>
<th>Hydrate Sat</th>
<th>Start</th>
<th>End</th>
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<tbody>
<tr>
<td>1</td>
<td>KSand</td>
<td>35%</td>
<td>10-05-2007</td>
<td>10-29-2007</td>
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<tr>
<td>2</td>
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<td>35%</td>
<td>10-30-2007</td>
<td>11-21-2007</td>
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<tr>
<td>4</td>
<td>KSand</td>
<td>20%</td>
<td>01-07-2008</td>
<td>01-14-2008</td>
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<tr>
<td>5</td>
<td>KSand</td>
<td>20%</td>
<td>01-14-2008</td>
<td>02-04-2008</td>
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<tr>
<td>6</td>
<td>KSand</td>
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<td>12-28-2007</td>
<td>02-08-2008</td>
</tr>
<tr>
<td>7</td>
<td>KSand</td>
<td>45%</td>
<td>02-11-2008</td>
<td>03-05-2008</td>
</tr>
<tr>
<td>8</td>
<td>F110</td>
<td>20%</td>
<td>03-11-2008</td>
<td>04-13-2008</td>
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<tr>
<td>10</td>
<td>F110</td>
<td>35%</td>
<td>04-29-2008</td>
<td>05-03-2008</td>
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<tr>
<td>11</td>
<td>F110</td>
<td>35%</td>
<td>05-03-2008</td>
<td>06-19-2008</td>
</tr>
<tr>
<td>12</td>
<td>F110</td>
<td>45%</td>
<td>06-20-2008</td>
<td>07-30-2008</td>
</tr>
</tbody>
</table>

### Successful test
K-Sand, 45% Saturation, Part 1
K-Sand, 45% Saturation, Part 2
van Genuchten (vG) model of capillary pressure (where \( m = 1 - 1/n \)), with \( P_O \) and \( n \) as fitting parameters:

vG model allows to estimate relative permeability function from capillary pressure function (\( k_S = \) absolute permeability)

\[
S(P_C) = \left(1 + \left(\frac{P_C}{P_O}\right)^n\right)^{-m}
\]

\[
k(S) = k_S \sqrt{S (1 - (1 - S^{1/m})^m)}^2
\]
K-Sand, 45% Saturation

Hysteretic Capillary Pressure Data

van Genuchten Model Fits
K-Sand: All Saturations

Water Potential (cm H2O)

0%

20%

35%

45%

Water Potential (cm H2O)

Primary Drinage

Drainage Model

Primary Drinage

Primary Imbibition

Secondary Drainage

Drainage Model

Imbibition Model

Water Content (cc/cc)
F110 Sand: All Saturations

Water Potential (cm H2O)

Water Content (cm³/cm³)

Primary Drinage
Drainage Model

0%

20%

35%

45%
Capillary Pressure Parameters

K-Sand

F110

Drainage
Imbibition

Hydrate Saturation

vG PO (cm H₂O)

Hydrate Saturation

vG n

Hydrate Saturation

vG n

Hydrate Saturation
Inverse Modeling of Transient

- **Objective**: To infer relative permeability from transient pressure data.
- Assume decoupled capillary pressure and relative permeability curves.
- Optimize $m$ & $k_s$ in vG model
- Consider only half volume: 6,680 grid blocks, 18,700 connections.
- Isothermal flow, with passive gas and hydrate phases.
Modeling Result: F110, 20%

Moisture distributions during drainage
Fits at Multiple Drainage Stages: F110, 20%

Drainage #5

Drainage #6

Drainage #7

Drainage #8
Fitted Relative Permeability Function:
F110, 20%

Inverted van Genuchten
Challenges

• Minor temperature differences cause large apparent capillary pressures
• Uncertainty in packing density within a sample and between samples
• At low saturation and/or permeability, imposed flow rate can be higher than permeability. This may lead to strong capillary-pressure gradients and/or hydraulic discontinuity
Hydrologic Properties
Path Forward

- Complete $k_r$ repeat measurements
- Complete capillary pressure measurements
- Complete waterflood $k_r$ modeling (with NETL)
- Complete capillary pressure/$k_r$ inversions to estimate $k_r$ and $P_c(S)$ functions
- Compare and understand $k_r$ values estimated by each method
- Understand hydrate formation distribution in samples (would like to work with a graduate student on this)
- Continue investigating hydrate porespace occupation importance relevance [with USGS, and others (Ebinuba?)]
Geomechanical and Geophysical Properties

Mechanical strength and seismic property measurements of hydrate-bearing sediments (HBS) during hydrate formation and loading tests
Delays in CH4-HBS Test Approval

**DOE mandates strict Environment, Health, and Safety practices at national labs**

**New mechanical safety approver**
- Enforcing *very* strict safety requirement for “high-hazard” pressure vessels
- Full-scale 3-D finite element stress analysis
- Formerly acceptable Mech.Eng.Handbook/ASME code-based analysis and actual pressure testing (completed in Jan.’08) not sufficient

**Vessel modifications to satisfy safety requirements**
- Many modifications have been made through interactions among scientists (user), engineers (FEM modelers, machinists), and the safety approver
- LBNL/Eng. Spent $>75K from the lab’s internal safety budget
- Modified test vessel currently in production
Gas hydrate→ Understanding the geomechanical and geophysical properties is important for
(1) Assessing stability of oil and gas wells and seafloor, and
(2) Resource development (methane gas) and production monitoring

Laboratory data for geomechanical and geophysical properties of hydrate-bearing sediments (esp. for methane hydrate) is still scarce

(from Snyder et al., AAPG, 2004)
Introduction

- Gas hydrate within sediments can exist in a variety of forms.
- Both geomechanical properties (e.g., strength) and geophysical properties (e.g., seismic velocities) are a strong function of hydrate distribution within sediment pore space.

Kleinberg and Dai, OTC17205 (2005)

Yun et al., GRL (2005)
Introduction

• Both laboratory and field samples are often heterogeneous, which could lead us to wrong conclusions on their properties → Needs for visualization

We conduct concurrent measurements of hydrate’s mechanical and geophysical (seismic) properties, with real-time x-ray CT imaging
Strength and seismic property measurements on HBS

Experimental Setup

**Experimental Setup**

- Rubber membrane
- Aluminum shell

**Diagram:**

- X-ray-transparent triaxial testing cell
- Sediment/rock core
- LVDT

**Measurements:**

- 11.4 cm
- 3.8 cm
Strength and seismic property measurements on HBS

Experimental Setup

- Temperature sensor
- Cooling tube
- Cooling jacket
- Thermal insulation
- CT scanner (Somatom Hi-Q)
- Load/disp. and seismic data acquisition system
Experimental Setup

Strength and seismic property measurements on HBS

Seismic Source

Hybrid compression/torsion piezoceramic (PZT) source

Seismic Sensor

Miniature piezoelectric accelerometers (PCB Piezoetronics)
Strength and seismic property measurements on HBS

Samples

- Silica sand pack (US Silica, F-110, nominal grain size ~100 µm
- Tetrahydrofuran (THF) + H₂O mix → THF hydrate forms under ambient pressure
- Three samples:

<table>
<thead>
<tr>
<th></th>
<th>Sample#1</th>
<th>Sample#2</th>
<th>Sample#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>36%</td>
<td>34%</td>
<td>38%</td>
</tr>
<tr>
<td>Sample Volume (from CT)</td>
<td>120.01 cc</td>
<td>122.15 cc</td>
<td>134.98 cc</td>
</tr>
<tr>
<td>THF hydrate Saturation</td>
<td>100%</td>
<td>50%</td>
<td>40%</td>
</tr>
<tr>
<td>THF (liquid) Saturation</td>
<td>0%</td>
<td>50%</td>
<td>~0%</td>
</tr>
<tr>
<td>Cooling temp. (hydrate formation temp.)</td>
<td>+1°C (4.4°C)</td>
<td>-12°C (-10°C)</td>
<td>+1°C (4.4°C)</td>
</tr>
</tbody>
</table>

Cementation model

Pore-filling model
Triaxial Loading Test

- Confining stress = 0.69 MPa (100 psi)
- Loading rate =
  - Disp. controlled (solid lines): 0.077 %/min (1.28 x 10^{-5} /s)

Strength and seismic property measurements on HBS

- "Quasi-elastic" region
- Global (specimen) collapse
- "Large deformation" region
- Hydrate-sand grain debonding, Hydrate breakage (grain-scale local failure)
Triaxial Loading Test

- Confining stress = 0.69 MPa (100 psi)
- Loading rate =
  - Stress controlled (broken lines): 0.33 MPa/min
  - Disp. controlled (solid lines): 0.077 %/min (1.28 \times 10^{-5} /s)

Strength and seismic property measurements on HBS

Global failure

Grain-scale failure

Unsaturated 40% THFH

Saturated 50% THFH

Saturated 100% THFH
Strength and seismic property measurements on HBS

Fully THF hydrate-saturated sand

Before hydrate formation

CT density (g/cc)

2.16
2.08
1.99
1.91
1.82
Strength and seismic property measurements on HBS

50% THF+50% THF-Hydrate

Before hydrate formation  After hydrate formation  After failure

CT density (g/cc)

- 2.16
- 2.08
- 1.99
- 1.91
- 1.82
- 1.74
40% THF-Hydrate (partially saturated sand)

Before hydrate formation

CT density (g/cc)
- 2.08
- 1.99
- 1.91
- 1.82
- 1.74
- 1.65

Shear localization?
40% THF-Hydrate Saturated
Seismic Measurement (Sample#1)

- Small wave amplitudes → Intense noise reduction is required

Strength and seismic property measurements on HBS
Strength and seismic property measurements on HBS

Velocities vs. Strain

- Brittle sample (100% THFH) fails immediately after the peak velocities
- More ductile samples (50% and 40% THFH) appear to show velocity peaks before the sample failure strain

![Graph showing Velocities vs. Strain for Compression Waves and Torsion (Shear) Waves](image)
Geomechanical and Geophysical Properties Path Forward

- Complete vessel rebuild
- Perform triaxial and geophysical measurements on methane hydrate-bearing samples
- Compare results with existing measurements on THF hydrate-bearing samples from others
- If applicable, perform needed tests with THF hydrate to bridge to the existing THF hydrate data set
Other Tests

• NGHP and Mt. Elbert Core Scanning and Evaluation
• Natural Gas Production from Natural Samples
• Five Minute Sample Depressurization
• Hydrate Crystal Observation
• Properties of HBS
• ...
Core Scanning

Mt Elbert

NGHP

- CT scanned many cores to aid in deciding tests to be performed.
- Performed initial analyses on CT data prior to sending samples to recipients

![Core Scanning Images](image-url)
Gas Production Test

- Weak clayey material
- Produced mud
- No gas in spite of dissociation
Effect of Sample Handling - Five Minute Depressurization

Density Change (g/cm³)

-0.10  -0.05  0  0.05  0.10
Other Tests
Paths Forward

- Continue to provide CT scanning of samples for others when requested
- Perform production test on Mt. Elbert sample by depressurization
- Look into hydrate crystal formation and morphology changes near equilibrium surrounded by 1) gas and 2) water.
- Measure p- and s-wave velocities and CT scan unsaturated and water saturated samples held near equilibrium over time.
Presentations


Publications


Gupta, A., G.J. Moridis, T.J. Kneafsey, and E. D. Sloan, Jr., Modeling Pure Methane Hydrate Dissociation Using a Numerical Simulator from a Novel Combination of X-ray Computed Tomography and Macroscopic Data, in preparation for submittal to Chemical Engineering Science

