Advanced Simulation and Experiments of Strongly Coupled Geomechanics and Flow for Gas Hydrate Deposits: Validation and Field Application

DE-FE0028973

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:

Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Outline

- Project Objectives
- Measures of Success
- Proposed tasks & Technical Status/achievement
- Achievement to date
- Synergy Opportunities
- Summary
- Appendix

Experiment & Simulation

Verification
(Analytic sol.)

Reliable/robust
(Flow+Mech.)

$T+M^{AM}$

Validation

Experiments

Application

Advanced modules
- Parallel sim.
- Large deform.
- Hysteresis
- Failure

Field-wide simulation & prediction

Measures of Success

- Development of T+M^{AM} (TOUGH+ROCMECH with Advanced Modules)
- Validation of T+M^{AM} with experiments
- Field-wide simulation

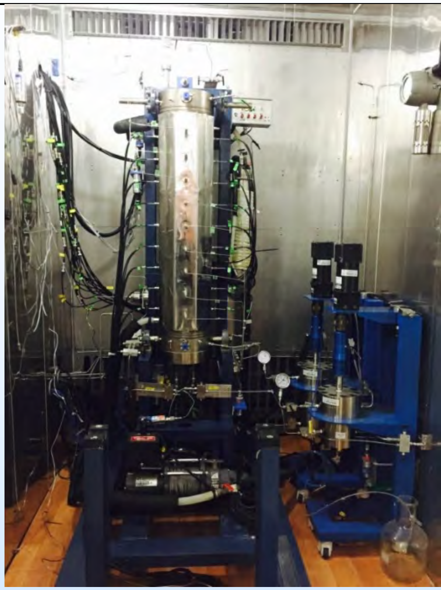
Proposed Tasks

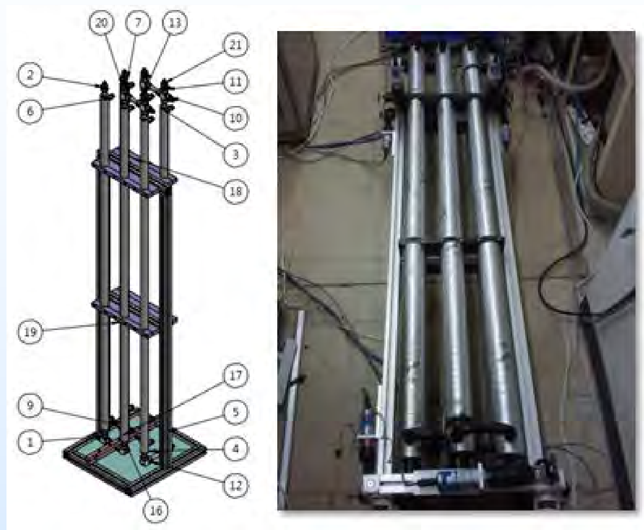
- Task 1: Project Management and Planning (TAMU)
- Task 2: Review and evaluation of experimental data of gas hydrate at various scales for gas production of Ulleung Basin (KIGAM)
- Task3: Laboratory Experiments for Numerical Model Validation (LBNL + TAMU)

Proposed Tasks

- Task 4: Incorporation of Laboratory Data into Numerical Simulation Model (TAMU)
- Task 5: Modeling of coupled flow and geomechanics in gas hydrate deposits (TAMU)
- Task 6 Simulation-Based Analysis of System Behavior at the Ignik-Sikumi and Ulleung Hydrate Deposits (LBNL + TAMU)

Task 2

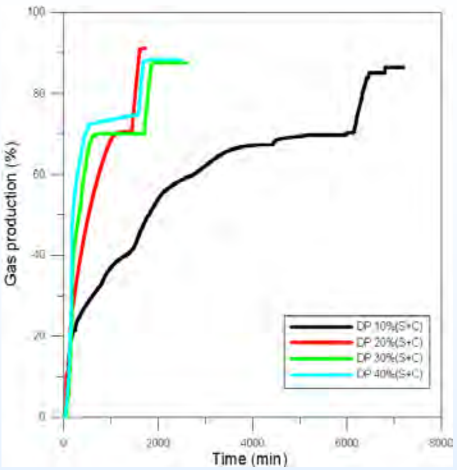




1-m scale 1D | 10-m scale 1D | 1.5-m scale 3D

Reviewed the experimental data to be used for simulation
Provided a summary report on the nature and findings

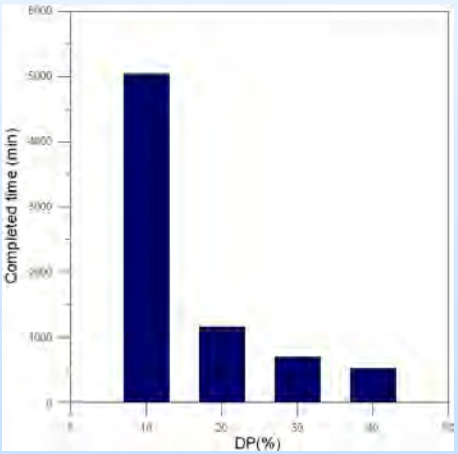
◆Results of depressurization experiment



Gas production

- ✓ Faster gas production with higher level of DP
- ✓ Insignificant effect of DP level on final production

- DP %: level of depressurization
- production: normalized to initial methane content



Completed time

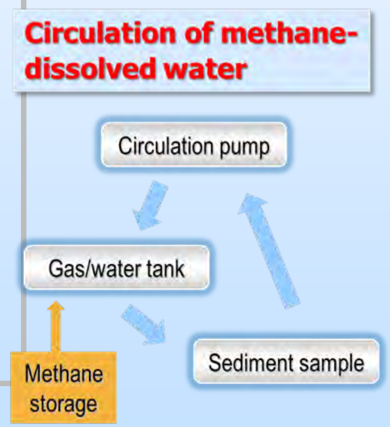
- ✓ Exponential decrease pattern with increasing DP level

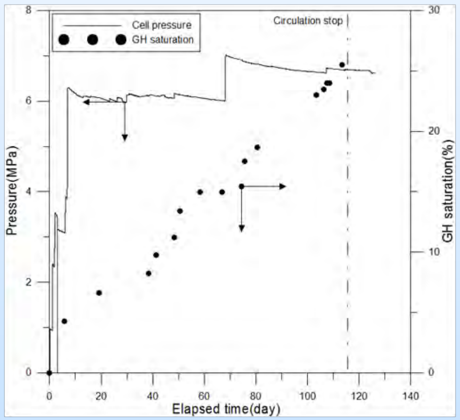
- Completed time: elapsed time to reach 70% gas recover

Obtained the experimental data in 1D and 3D

◆ Gas hydrate formation

➢ **Dissolved-phase hydrate formation process**





Calculation of hydrate saturation by measuring salinity during hydrate formation process

- ✓ Hydrate saturation ≈ 25%
- ✓ System pressure ≈ 6.2~6.9 MPa
- ✓ System temperature ≈ 2°C

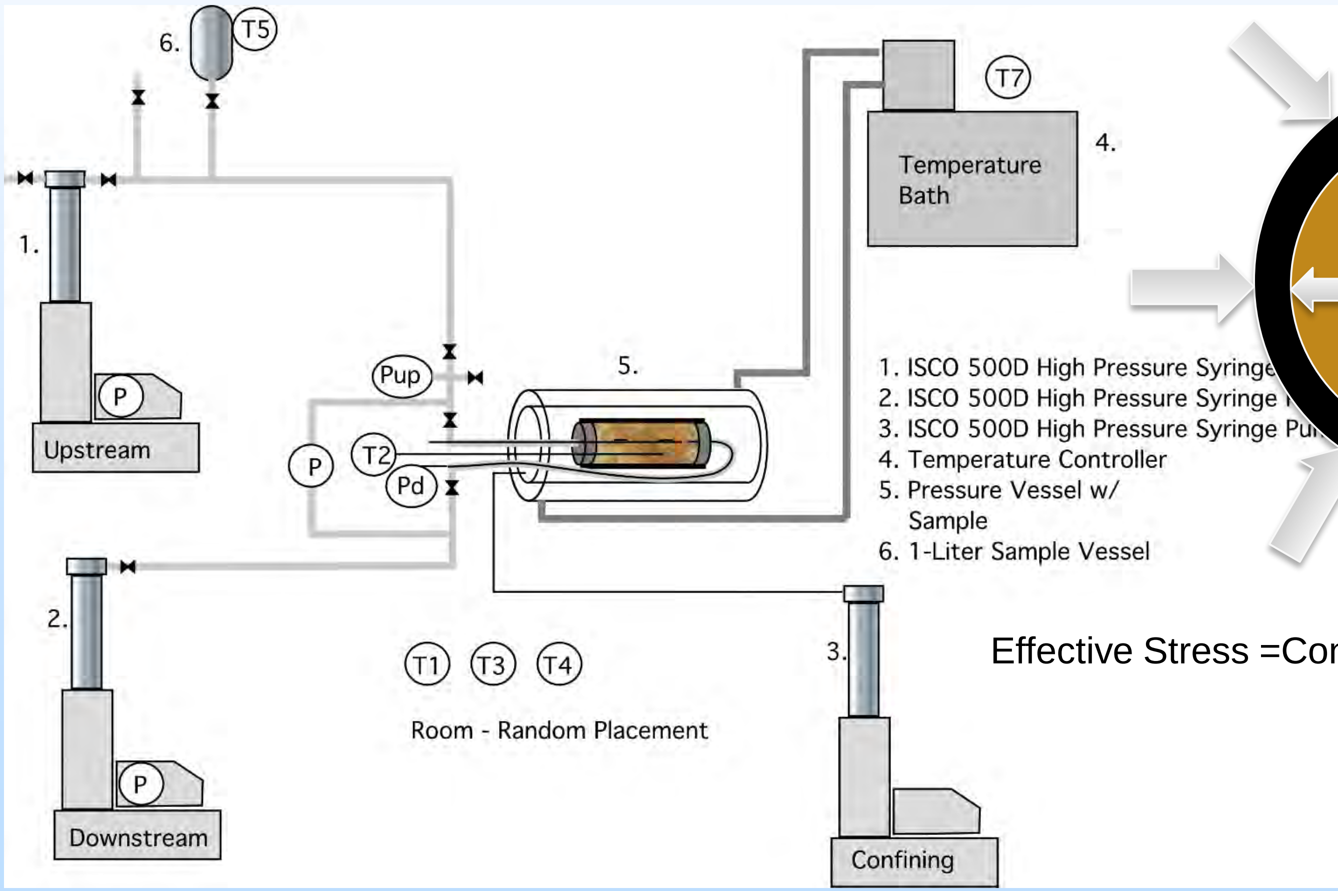
Task 3

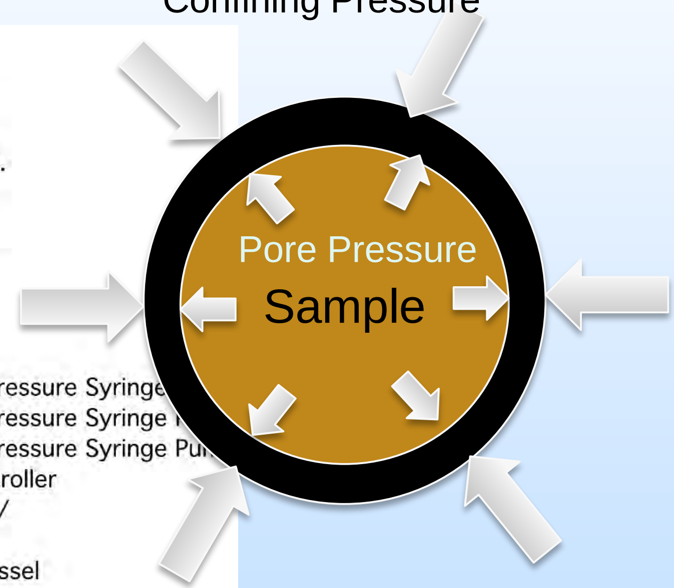
- Subtask 3.1: Effective stress changes during dissociation
- Subtask 3.2: Sand production
- Subtask 3.3: Secondary hydrate and capillary pressure changes
- Subtask 3.4: Construction of the Relative Permeability Data in Presence of Hydrate
- Subtask 3.5: Identification of Hysteresis in Hydrate Stability
- Goal:
  - Provide additional experimental data for numerical model validation
  - Perform advanced simulation of coupled flow & geomechanics

Task 3

Subtask 3.1: Geomechanical changes from effective stress changes during dissociation – no sand or fines production

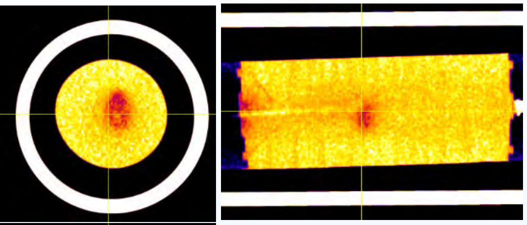
Dissociate by depressurization, results in effective stress increase



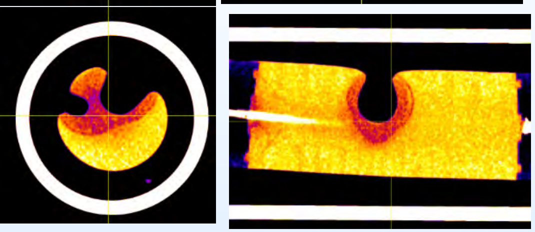


Effective Stress =Confining Pressure - Pore pres

Subtask 3.1 effective stress changes during dissociation



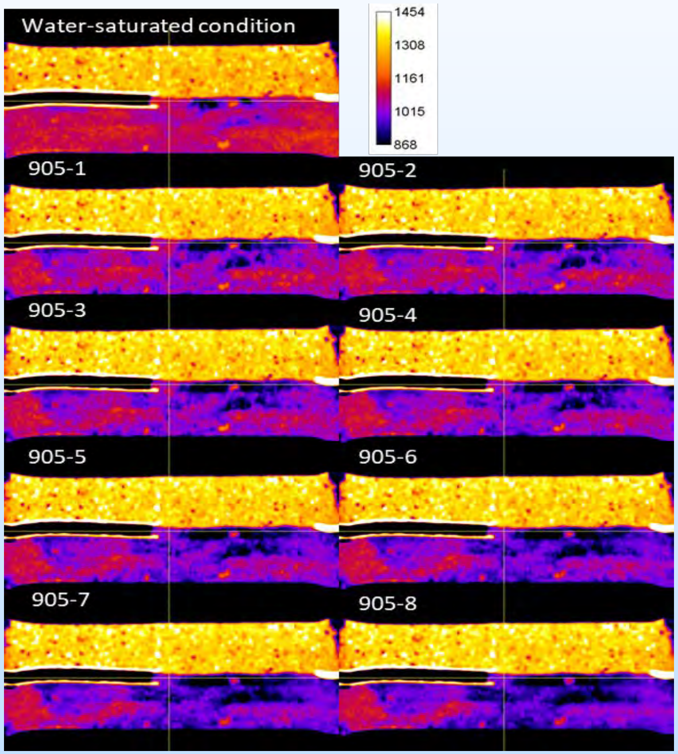
Sand movement, effective stress change from 100 psi to 300 psi (no hydrate)

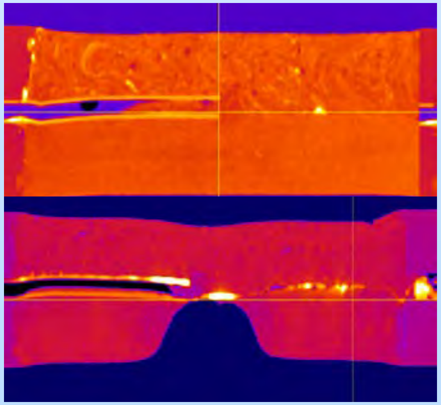


Sand movement, 2 mL/min flow (no hydrate)

Similar deformation in layered systems was also observed

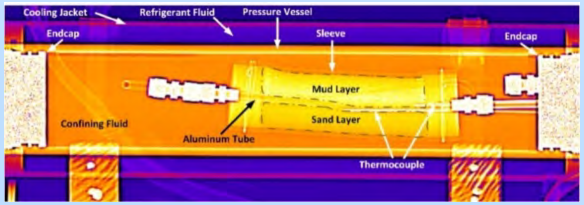
No significant geomechanical changes were observed during dissociation.





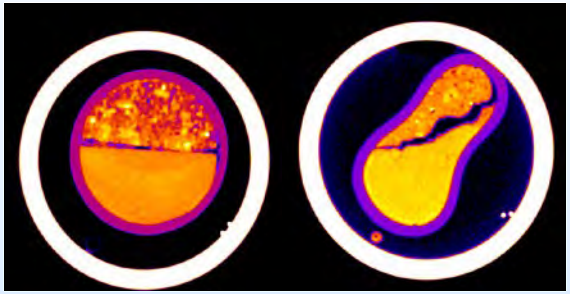
No change, outlet plugged by mud

Lower sand layer movement, no upper layer clay movement after applying vacuum (120 psi effective stress)



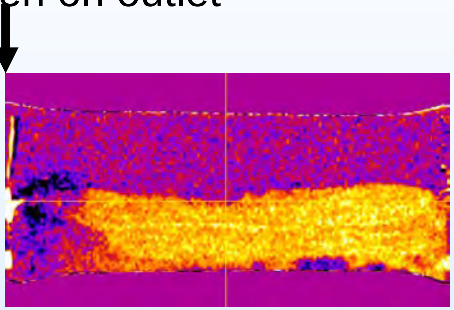
Subtask 3.2 Geomechanical changes from effective stress changes during dissociation – sand production

A subsequent test was run with the outlet tube positioned at the end of the sample

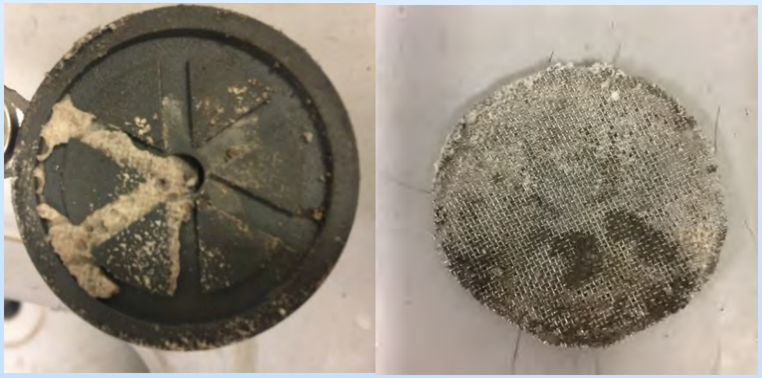


CT scan cross section mid sample showing failure during setup – no outlet plug installed.

Al screen on outlet



Layered mud/sand sample after hydrate dissociation. Effective stress increased from 100 psi to 300 psi during dissociation.

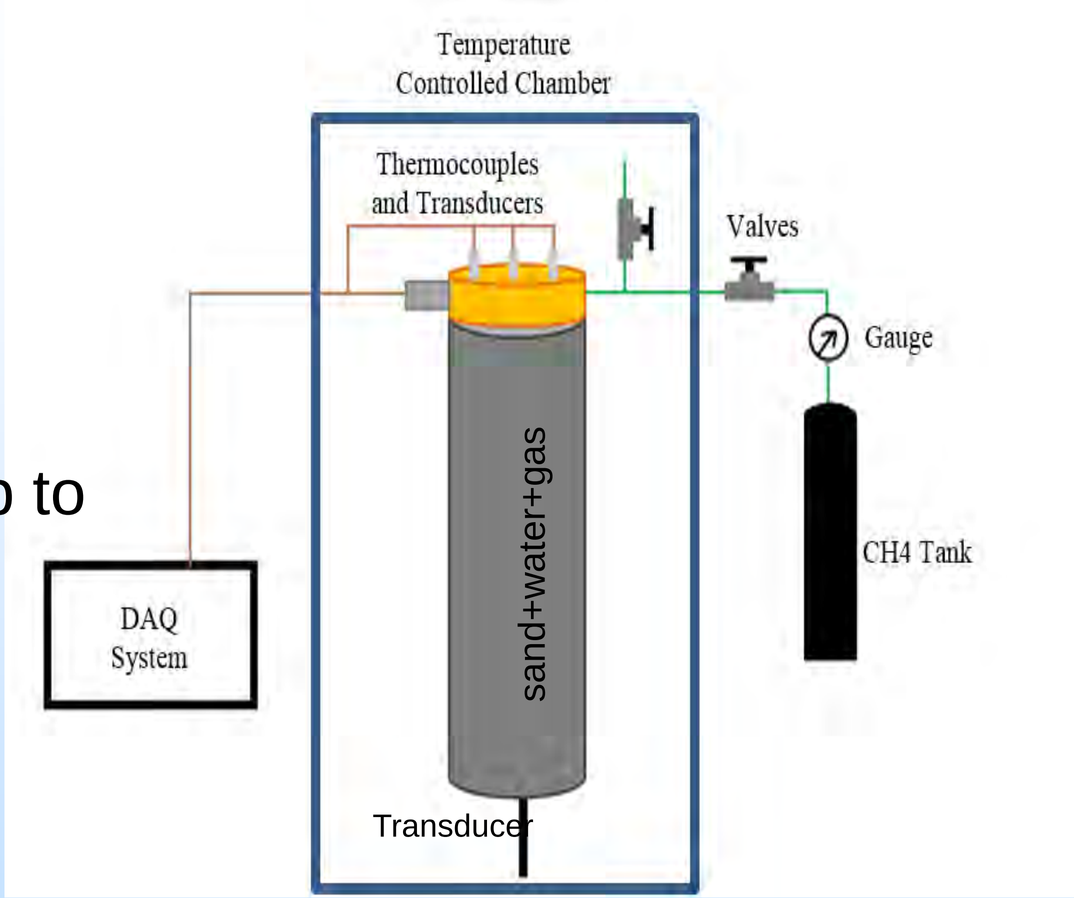


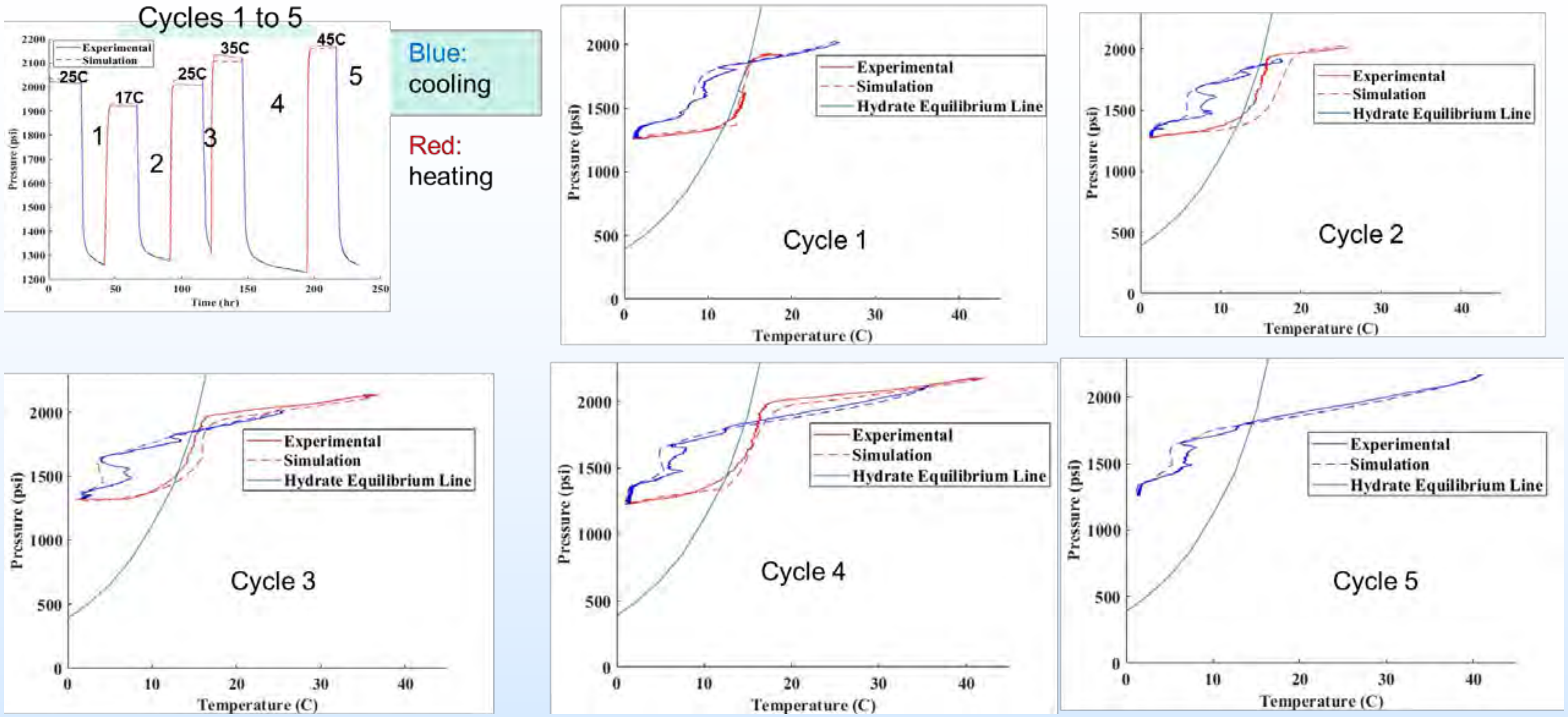
Outlet endcap and screen after disassembly showing some sand migration through the screen.

Subtask 3.5 Hysteresis in Hydrate Stability

Experimental Procedure:

1. Vacuum air out of cell
2. Compact sand
3. Add water to sand
4. Add methane to sand up to 2000 psi
5. Reduce temperature
6. Form hydrate
7. Heat up to a target temperature
8. Melt hydrate
9. Repeat 5-7





$$R \propto -ae^{b}\left(f_{eq} - f_{v}\right)$$

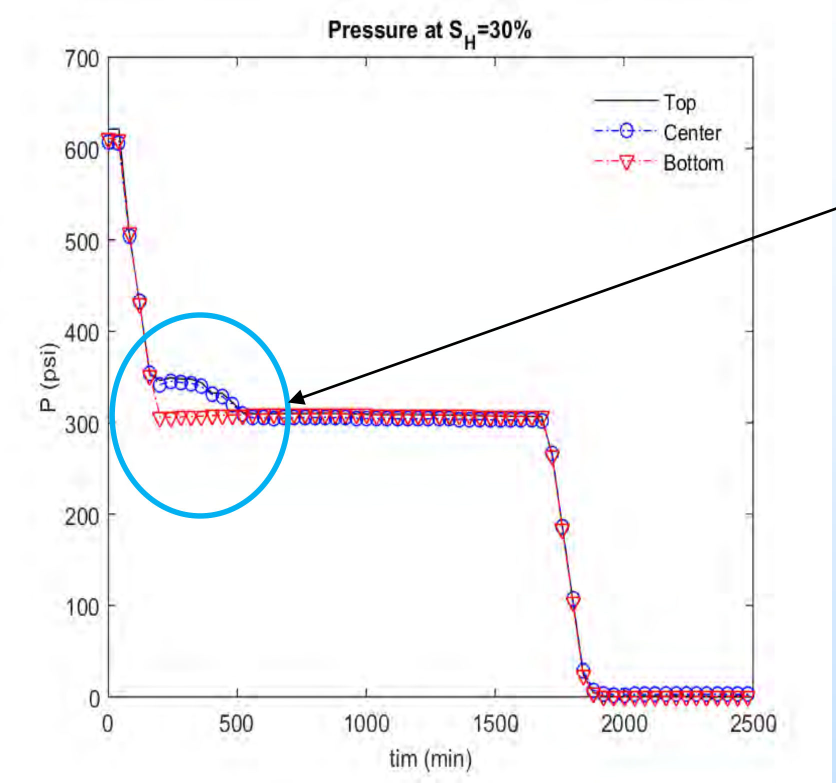
- *a* is a quantity related to crystallization constant x surface area of the crystallization
- *b* is a quantity related to the activation energy
- *a*, *b* include temperature-dependences but temperature is a variable computed by the simulator.

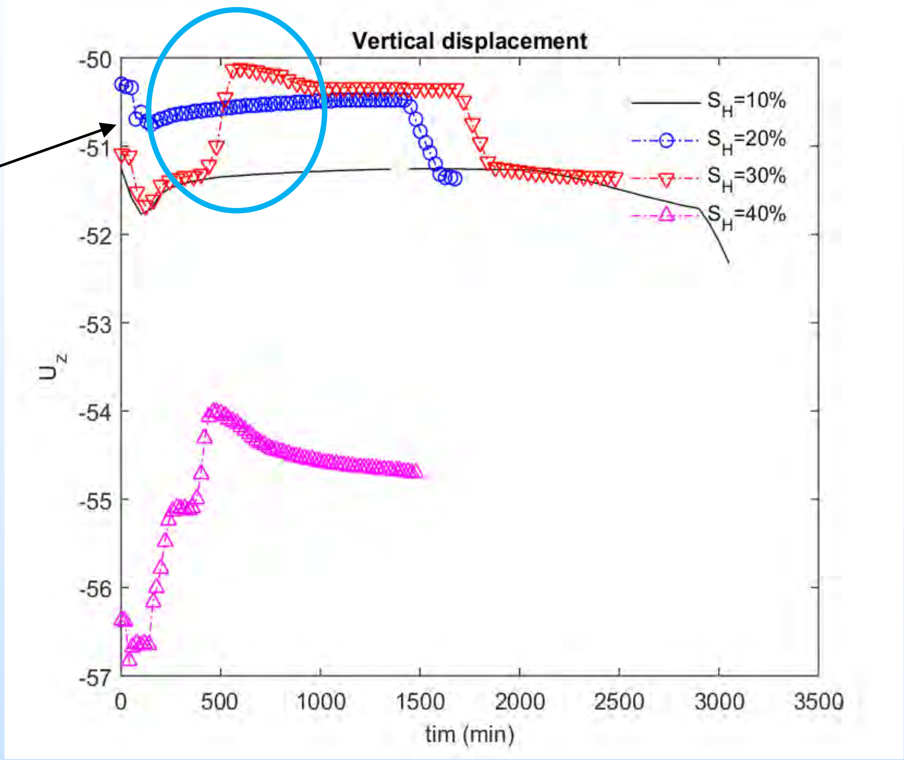
Task 4

- Subtask 4.1: Inputs and Preliminary Scoping Calculations
- Subtask 4.2: Determination of New Constitutive Relationships
- Subtask 4.3: Development of Geological Model

- Goal:
  - Construct appropriate constitutive models
  - Identify major parameters that control/characterize geomechanics responses induced by depressurizaation

Subtask 4.1





Extracting the data of Subtask 2.1 (1D 1-m scale) for validation study

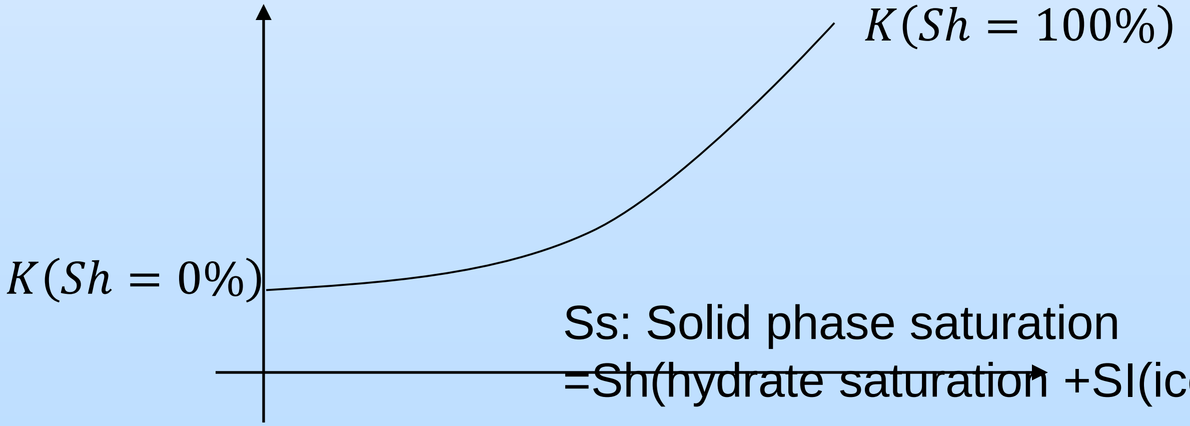
(Pressure vs displacement)

Subtask 4.2

Enhanced the constitutive relations of hydrate-saturation dependent geomechanics moduli

Linear model → Nonlinear model

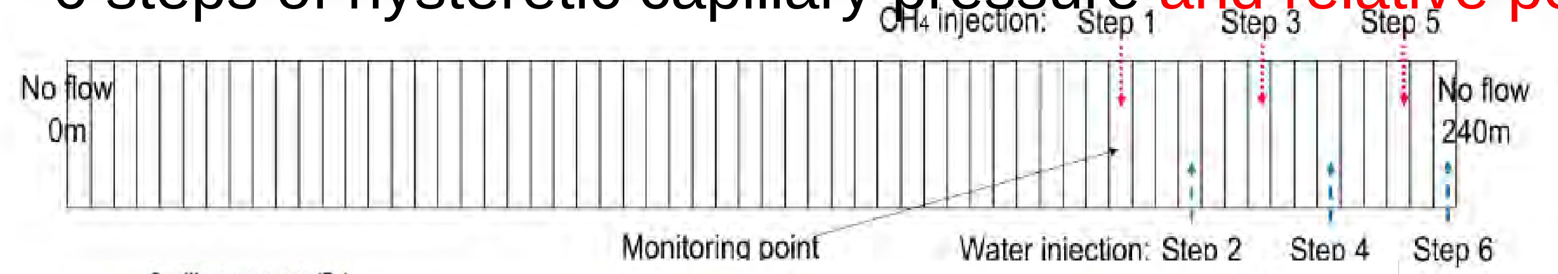
$$K(Ss) = K(Ss = 0\%) + (K(Ss = 100\%) \text{-} K(Ss = 0\%)) \times Ss^n$$

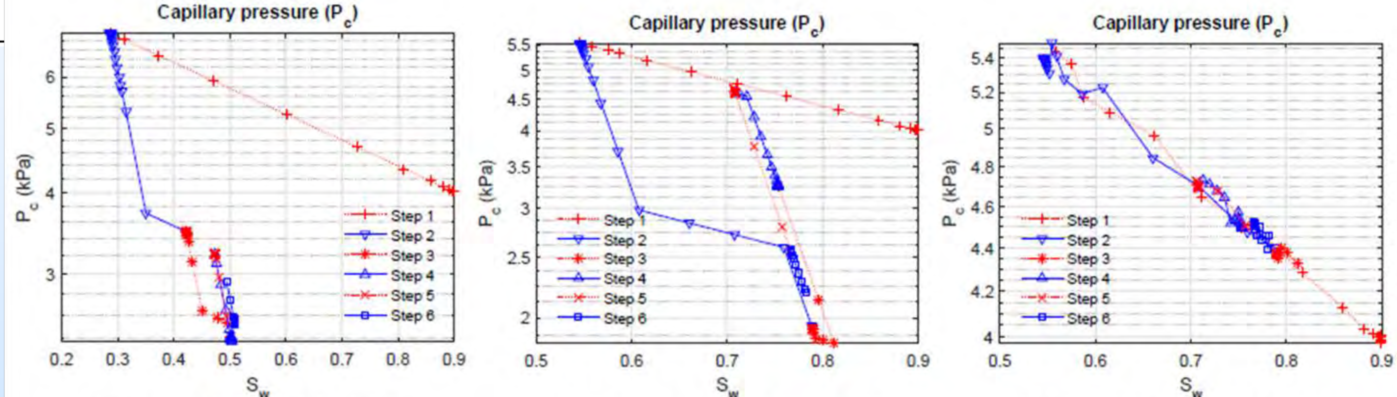


Ss: Solid phase saturation
=Sh(hydrate saturation +SI(ice saturation)

Subtask 4.2

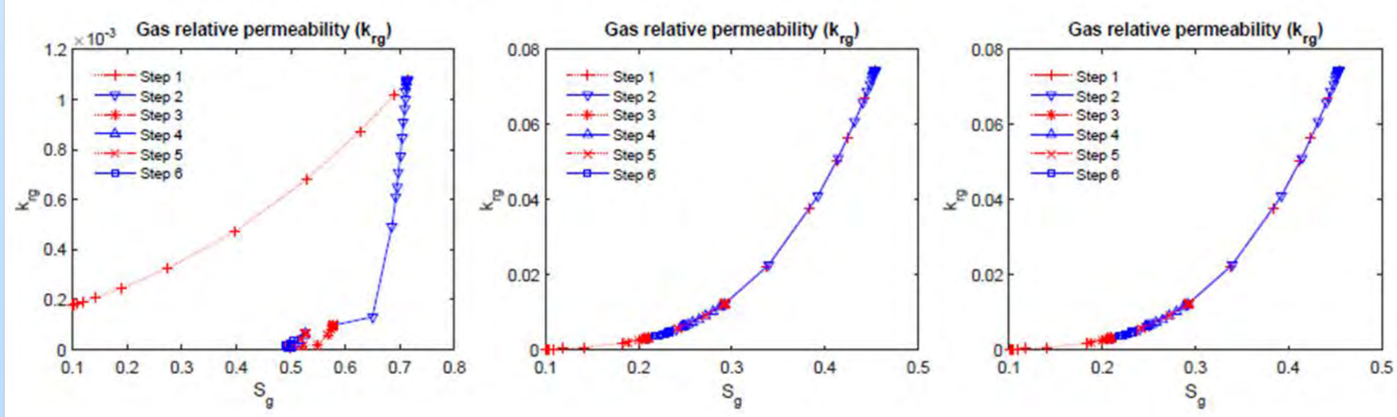
6 steps of hysteretic capillary pressure and relative permeability





(Pc, Kr)=(O,O) (Pc, Kr)=(O,X) (Pc, Kr)=(X,X)

Evolution of capillary pressure for the reference case (left), Case 2 (center), and Case 3 (right).

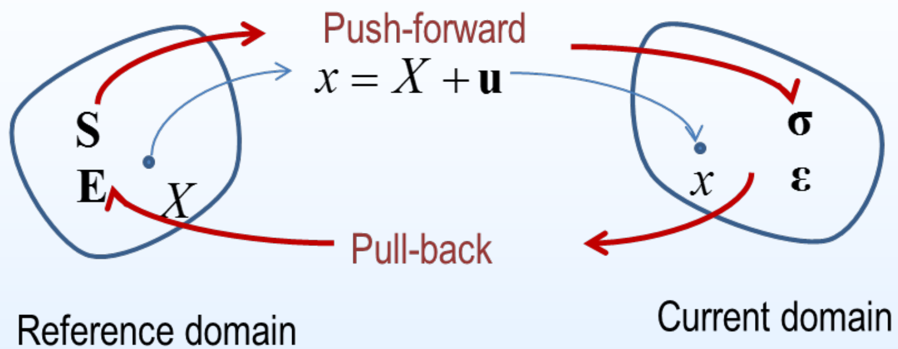


Task 5

- 5.1: Development of a coupled flow and geomechanics simulator for large deformation
- 5.2: Validation with experimental tests of depressurization
- 5.3: Modeling of sand production and plastic behavior
- 5.4: Induced changes by formation of secondary hydrates: Frost-heave, strong capillarity, and induced fracturing
- 5.5: Field-scale simulation of PBU L106
- 5.6: Field-wide simulation of Ulleung Basin (UBGH2-6)

Subtask 5.1: Large deformation

$$\mathbf{K}^0 = J\mathbf{F}^{-1}\mathbf{k}^t\mathbf{F}^{-T}$$

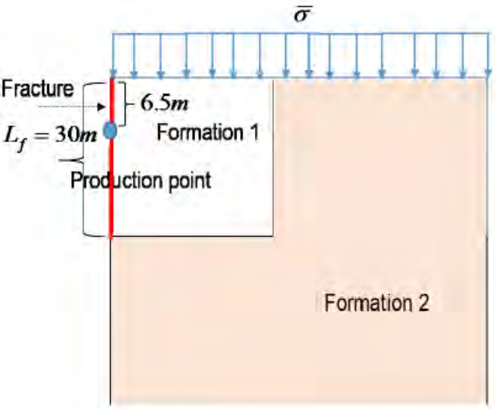


$$\int \mathbf{S} : \delta\mathbf{E}(\mathbf{u})\, d\Omega^0 = \int \rho_b^0 \mathbf{g} \cdot \delta\mathbf{u}\, d\Omega^0 + \int \bar{\mathbf{t}}^0 \cdot \delta\mathbf{u}\, d\Gamma^0$$

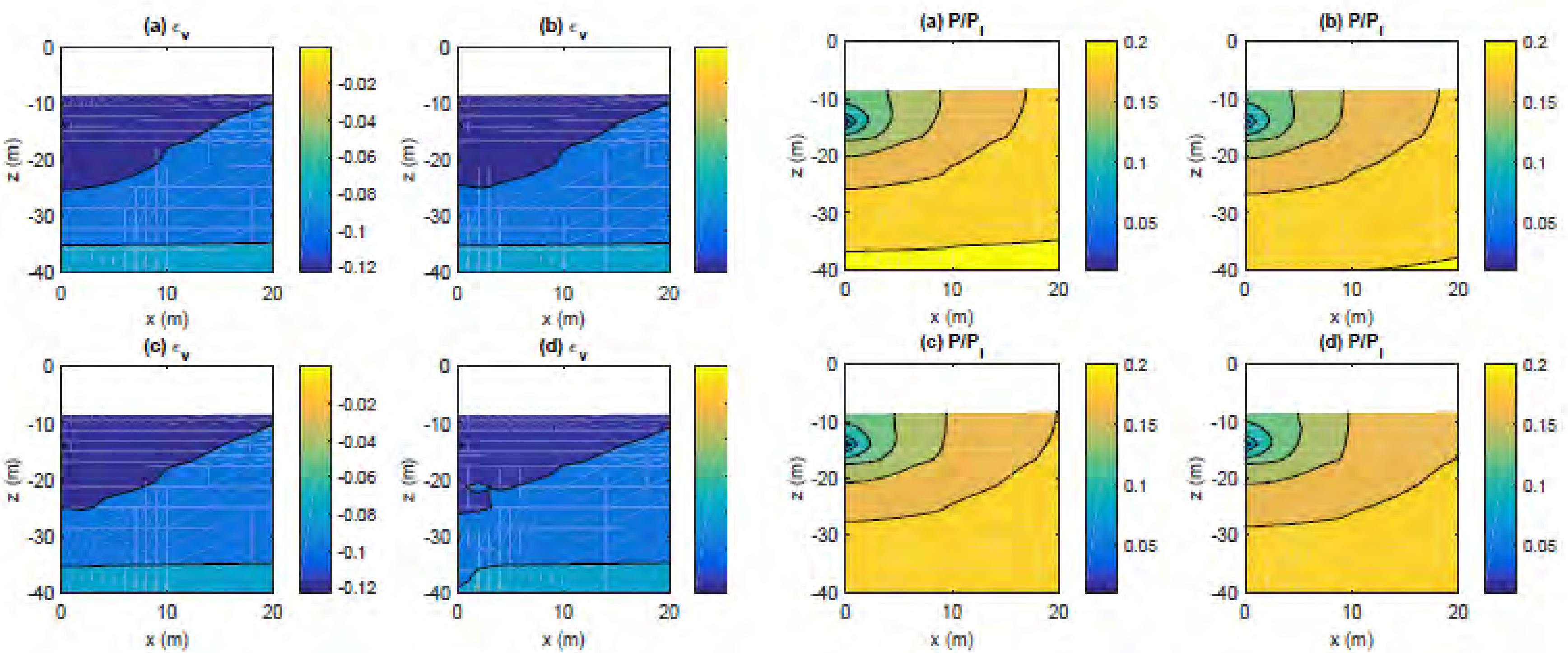
$$\frac{d}{dt}\int M^k d\Omega^0 + \int \mathbf{DIV} \cdot \mathbf{W}^k d\Omega^0 + \int Q^k d\Omega^0 = 0$$

Geomechanics and flow are solved at the reference domain (Total Lagrangian approach)

Subtask 5.1



Simulation is stable even for large deformation

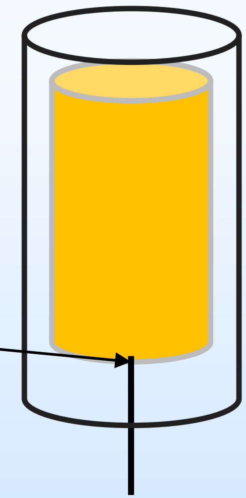


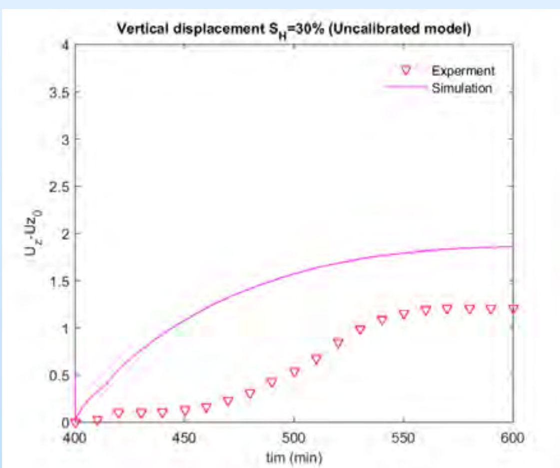
Subtask 5.2: Validation of T+M

Ongoing validation with data of Subtask 2.1 (1m-scale experiment)

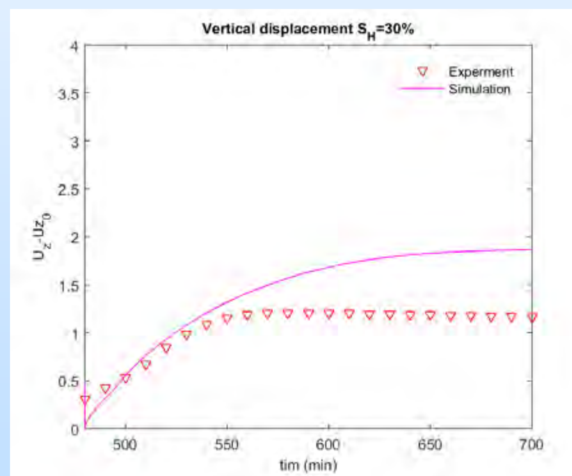
Discretized with 20 grid blocks (1by20)

Production





Uncalibrated

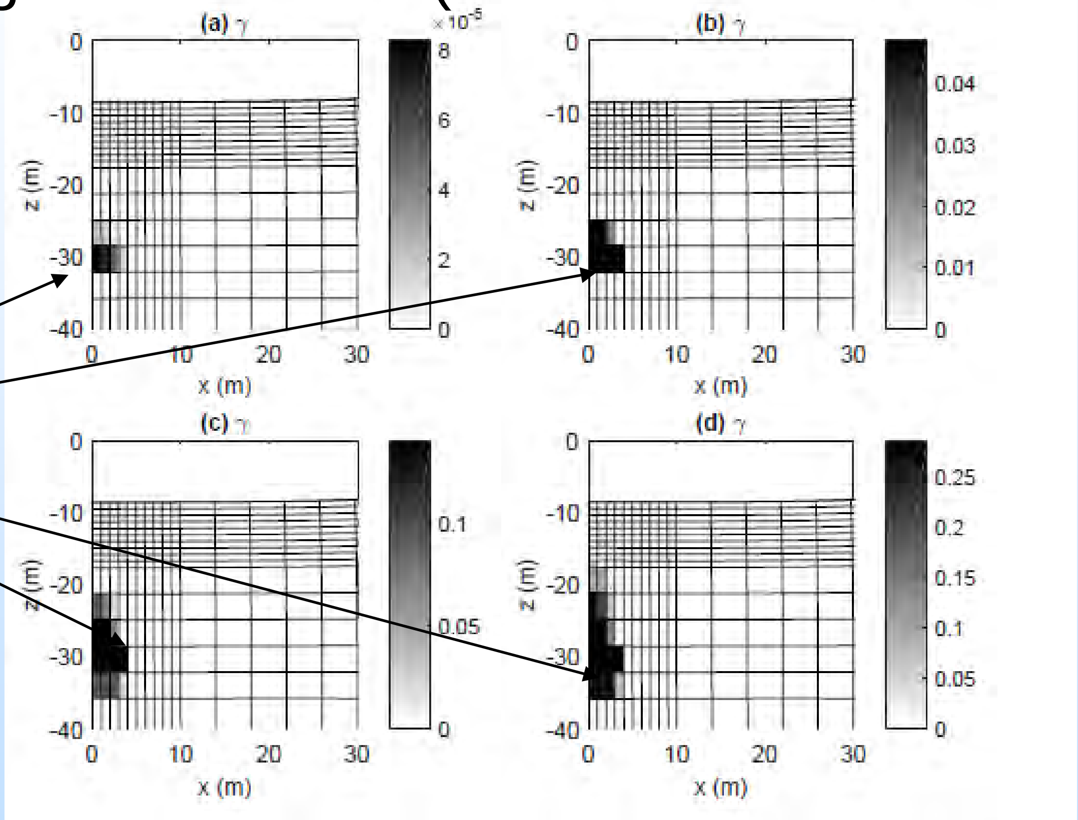


Being calibrated

…

Subtask 5.3 (TAMU)

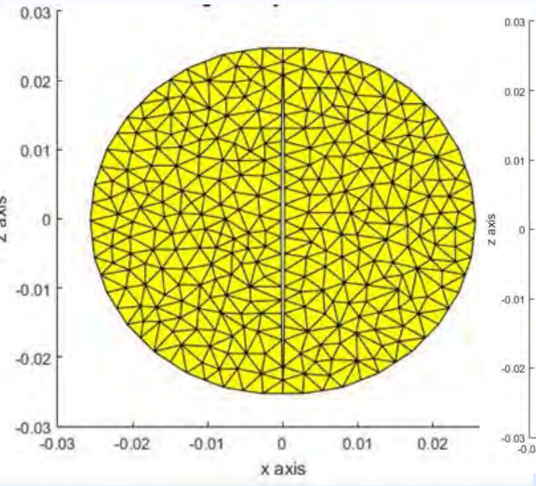
Plasticity in large deformation (substantial subsidence)

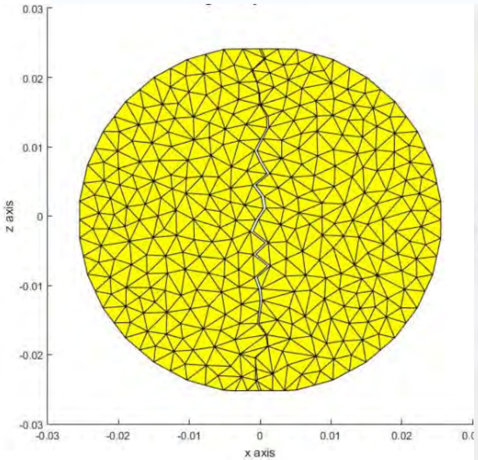


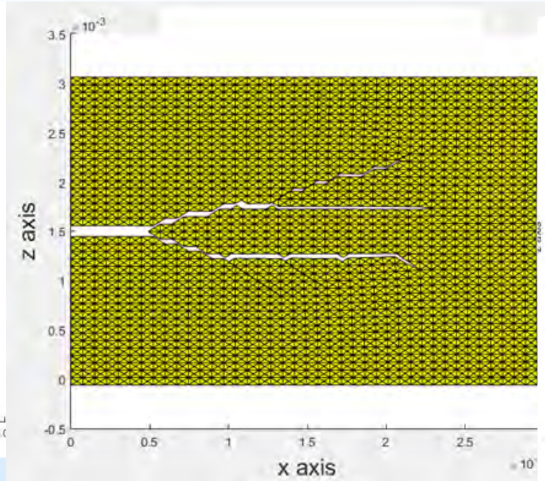
Shear failure
(Drucker-Prager)

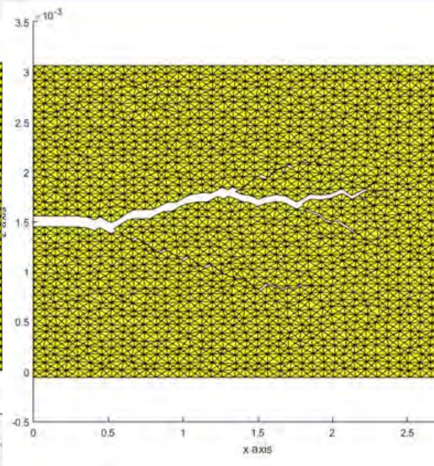
The failed regions are related to well-bore collapse or sand production.

Subtasks 5.4









Mesh-dependent fracture propagation has been investigated. The propagations are still similar.

The draft of the manual for the fracturing geomechanics code has been made.

Coupling between flow and geomechanics is ongoing.

Subtasks 5.4

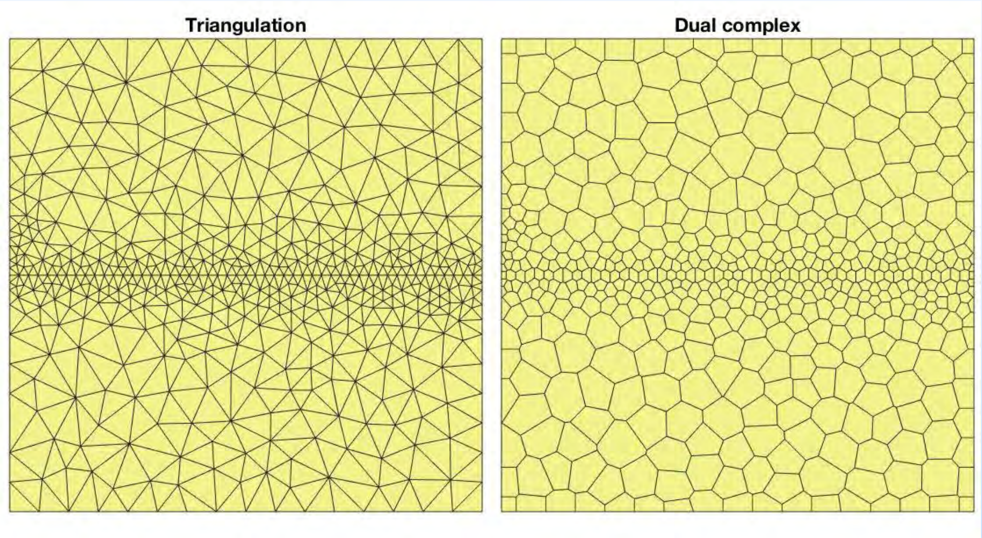
Coupling: Fixed-stress sequential method

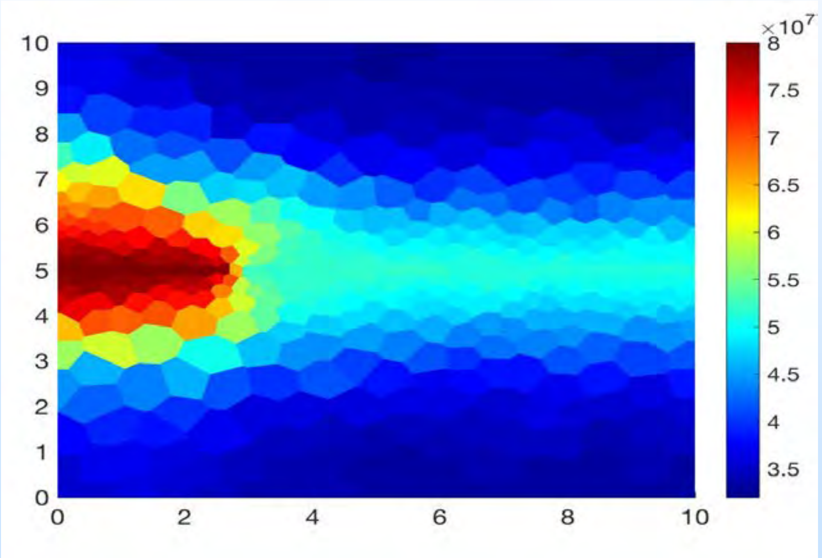
Voronoi element for flow, Triangles for geomelchanic

Geomechanics

Flow

Pressure distribution



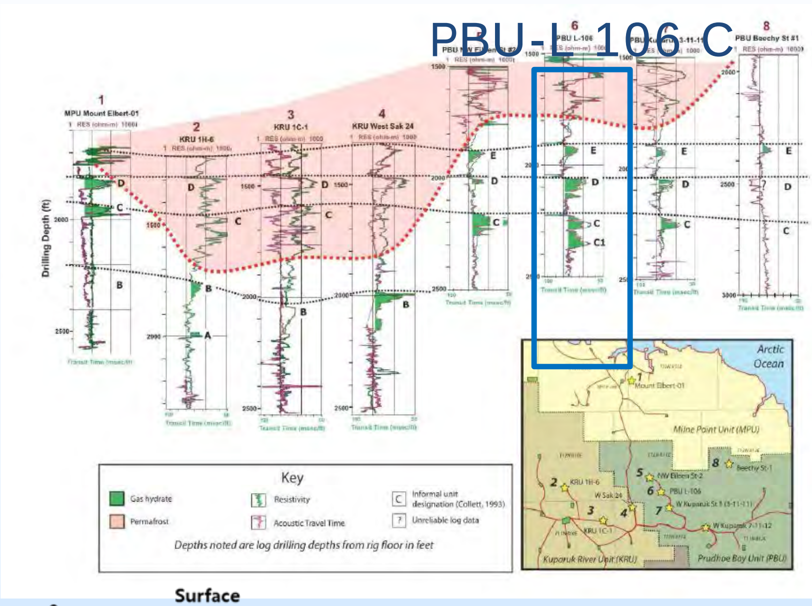


Preliminary study with single phase flow

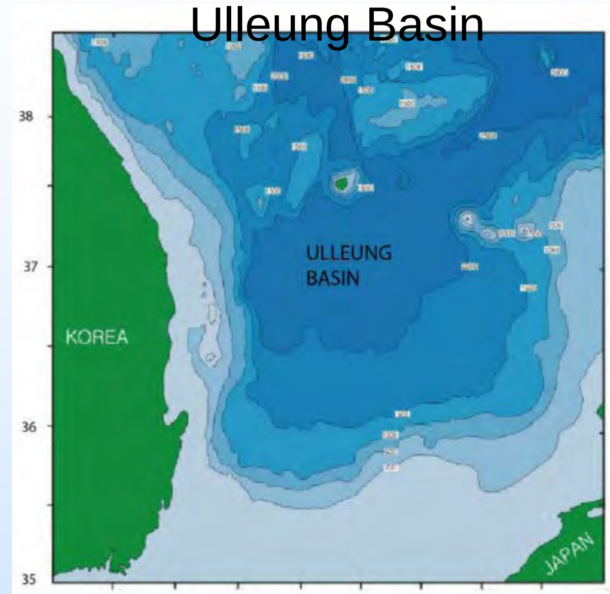
Working on simulation of fracturing induced by hydrate formation (frost-heaving)

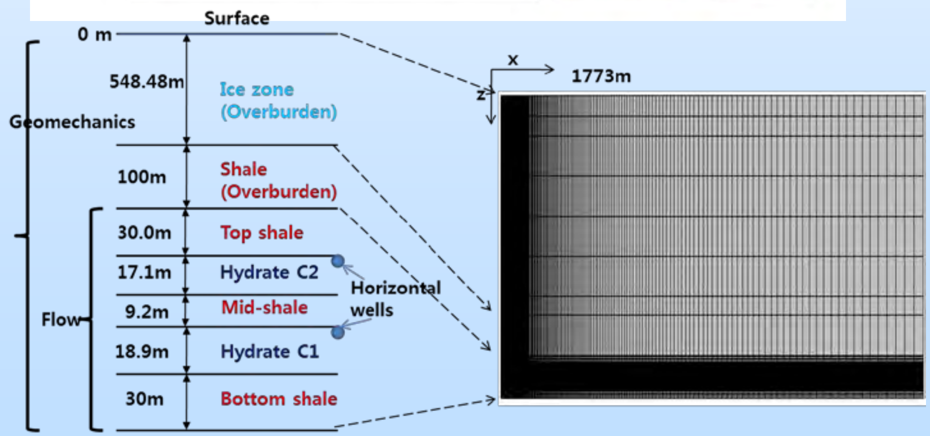
Subtasks 5.5-5.6 & Task 6

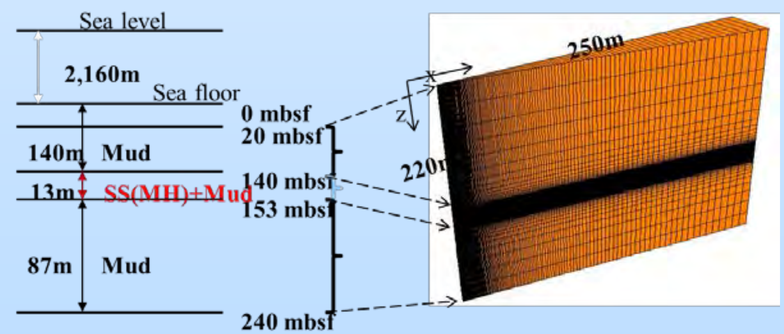
PBU-L 106 C



Ulleung Basin

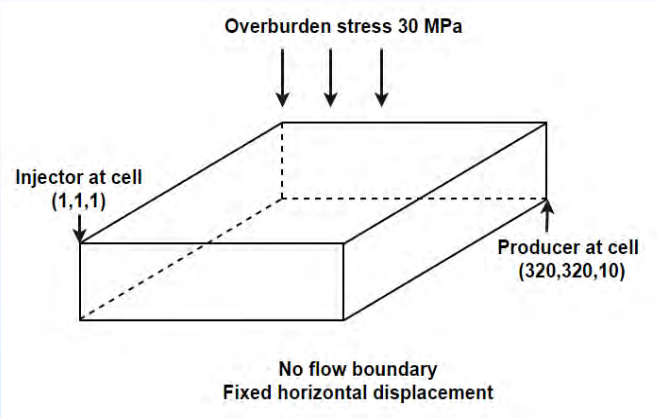


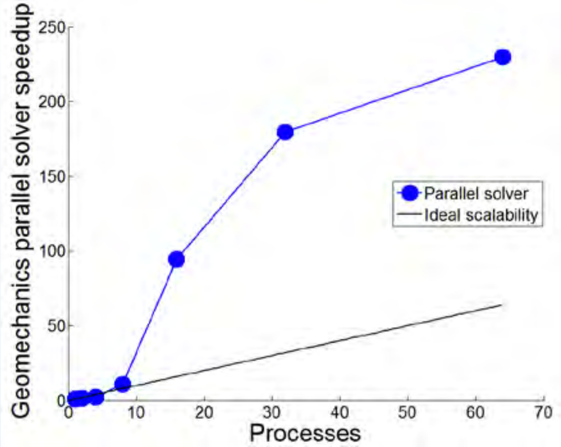


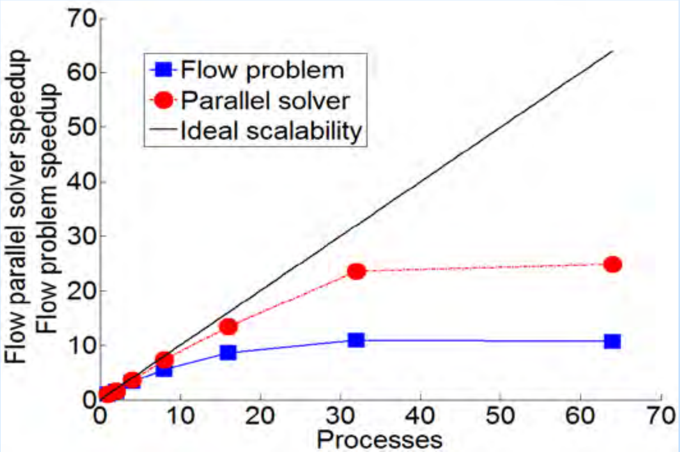


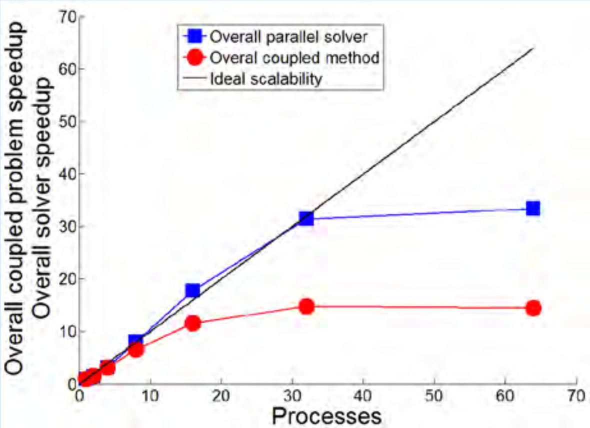
High performance computing (parallel computation) is required.

Subtasks 5.5-5.6 & Task 6





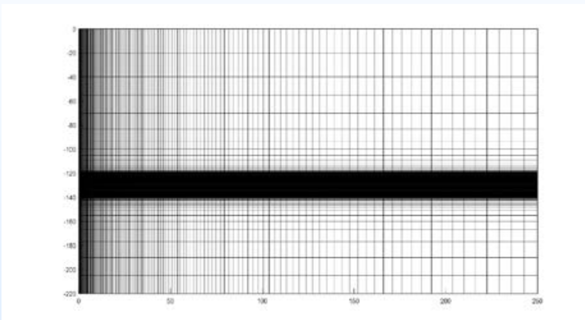


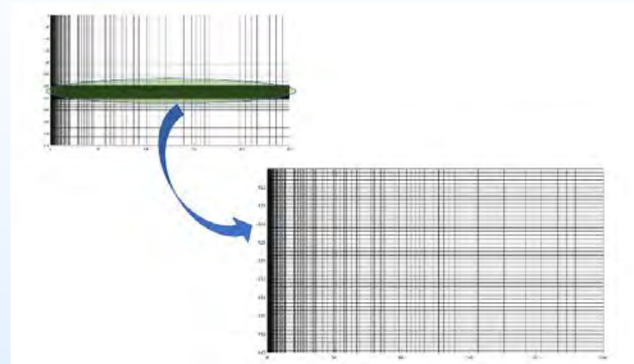


Up 32 CPUs, the scalability is good in elasticity.

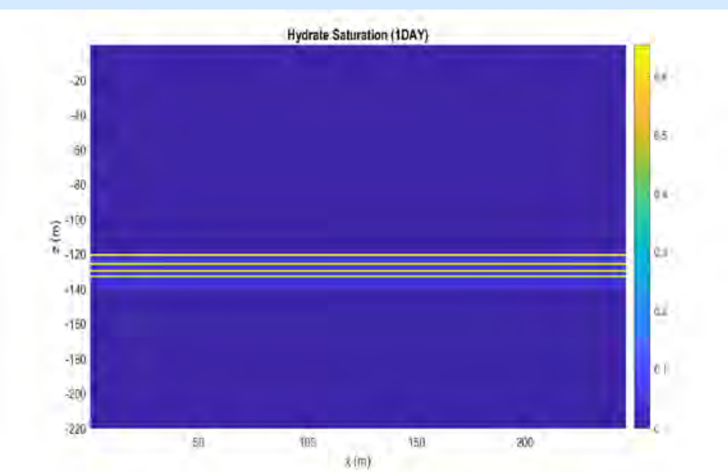
Subtasks 5.5-5.6 & Task 6

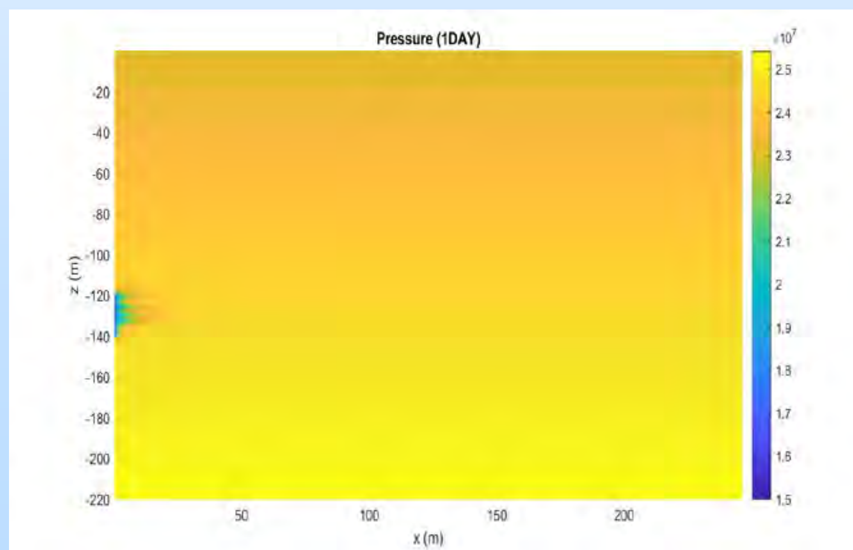
Ulleung Basin simulation





2D axisymmetric discretized domain.
The grid is refined around the vertical well and the hydrate zone





Accomplishments to Date

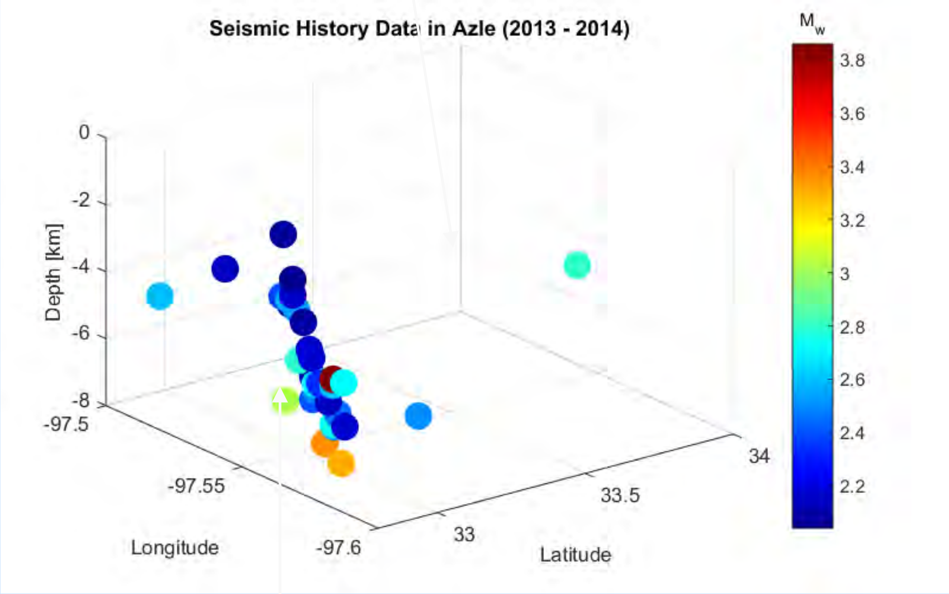
- Achieved Main/Core T+M Development of (TOUGH+ROCMECH with Advanced Modules)
- Reviewed and analyzed the previous experimental results/data
- Delivered and post-processed the data of Task 2 from KIGAM
- Performed new experiments of Task 3
- Validating T+M with the data of Task 2
- Performing large scale field-wide simulation

Synergy Opportunities

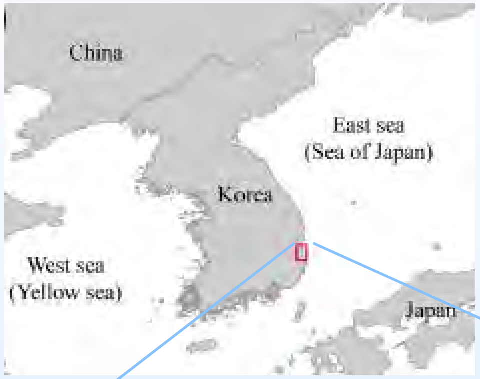
- Coupled flow-geomechanics simulator (T+M) can be used for CO2 storage, gas hydrate deposits, geothermal reservoirs, Shale gas
- Joint analysis/inversion of flow/geomechanics/ geophysics (Induced Seismicity & Electromagentic geophysics)

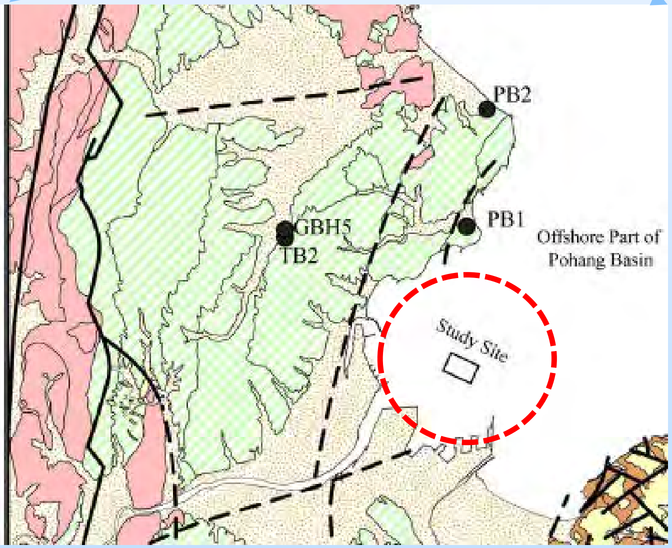
Induced Seismicity in Coupled Flow and Geomechanics

Waste water injection (Azle, Texas)



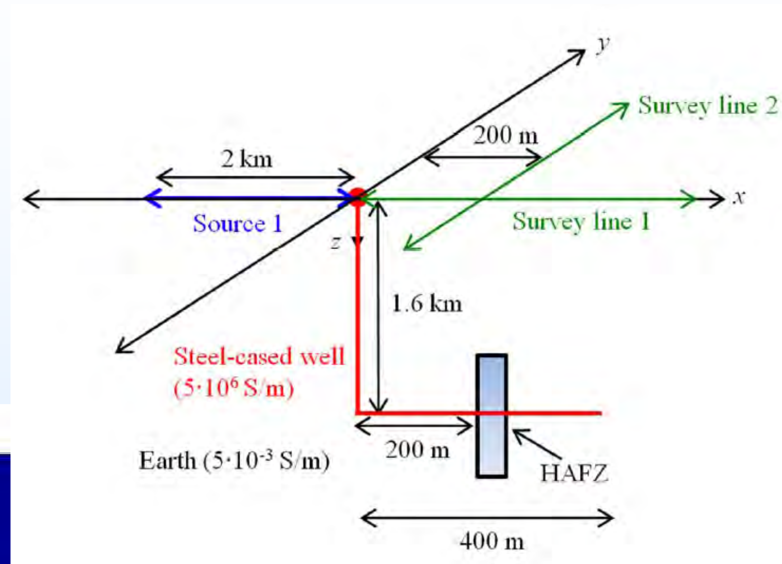
Induced seismicity at the fault (Mw up to 4)

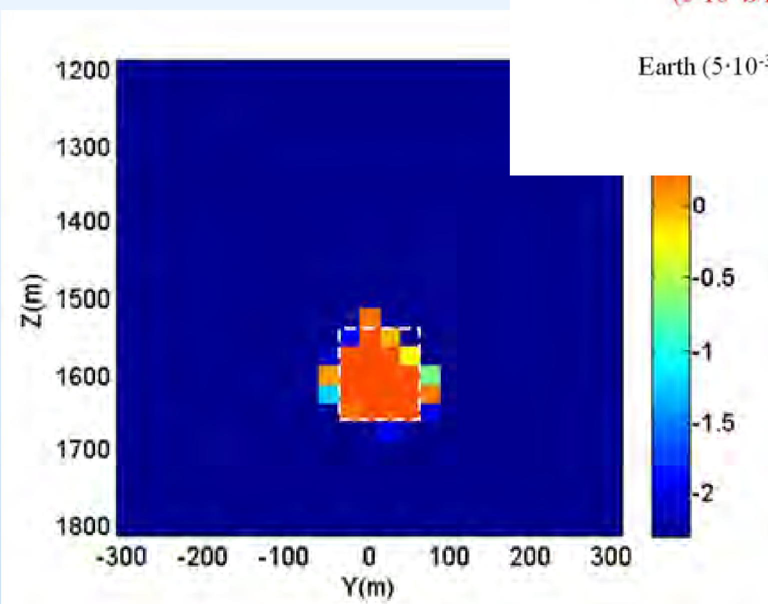


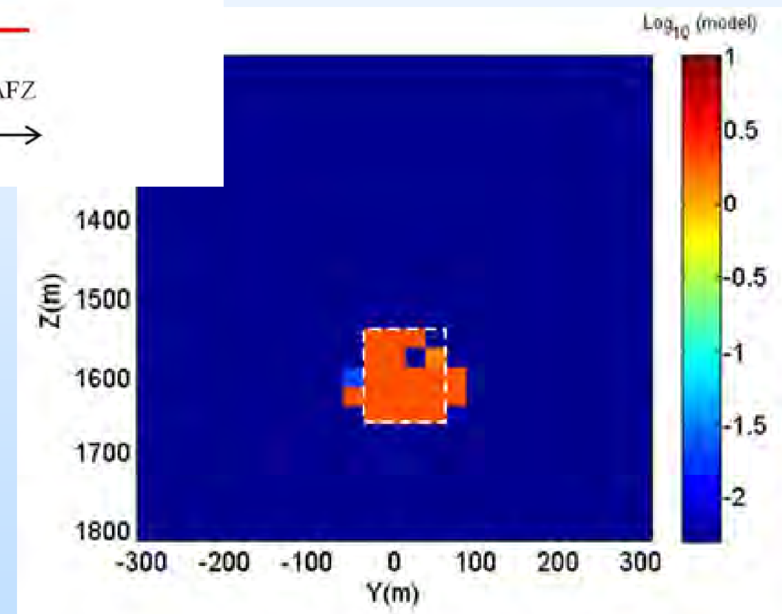


Two Potential CO2 sites in Pohang, South Korea

Coupled EM-Flow and Geomechanics







Not constrained by coupled flow-geomechanics (EM only)

Constrained by coupled flow-geomechanical

Project Summary

- Performed advanced experiments related to geomechanics in gas hydrates
- Enhanced T+M with advanced tools (hysteresis, large deformation, parallel computing, fracture propagation)
- Matching numerical results with the experimental data along with reliable constitutive relations
- Applying T+M to the gas hydrate fields

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Beneficial to accurate understanding of gas hydrate systems related to deep oceanic deposits, such as in the Ulleung Basin, Gulf of Mexico, Nankai Trough, or Krishna-Godavari Basin.
- Can motivate future laboratory tests, from advanced numerical modeling, that can identify stabilized geomechanical behavior as well as reduction of waste water.
- Beneficial to the current users of the TOUGH family codes in LBNL, who are working on other subsurface problems such as geological CO_2 storage, geothermal research, reservoir engineering.

Project Objectives

- Investigate geomechanical responses induced by depressurization experimentally and numerically
- Enhance the current numerical simulation technology in order to simulate complex physically coupled processes by depressurization
- Perform in-depth numerical analyses of two selected potential production test sites (Ulleung basin, Prudhoe Bay)

- Total Cost: $1,465,247=$506,415(TAMU),+ $225,000 (LBNL)+ $733,832 (cost share, KIGAM)

Organization Chart

PI: Jihoon Kim

Task 1: Project Management and Planning
Task Lead: Jihoon Kim
Participants: Jihoon Kim, Joo Yong Lee, Tim Kneafsey, Yucel Akkutlu, George Moridis

Task 2: Experimental study of gas hydrate in various scales for gas production of Ulleung Basin
Task Lead: Joo Yong Lee
Participants: Joo Yong Lee, Tae Woong Ahn, Jihoon Kim, Research Assistant 1 (Kim's Ph.D student)

Task 3: Laboratory Experiments for Numerical Model Verification
Task Lead: I. Yucel Akkutlu
Participants: I. Yucel Akkutlu, Tim Kneafsey, Sharon Borglin, Research Assistant 2 (Akkutlu' Ph.D student)

Tasks 4: Incorporation of Laboratory Data into Numerical Simulation Model
Task Lead: Jihoon Kim
Participants: All team members

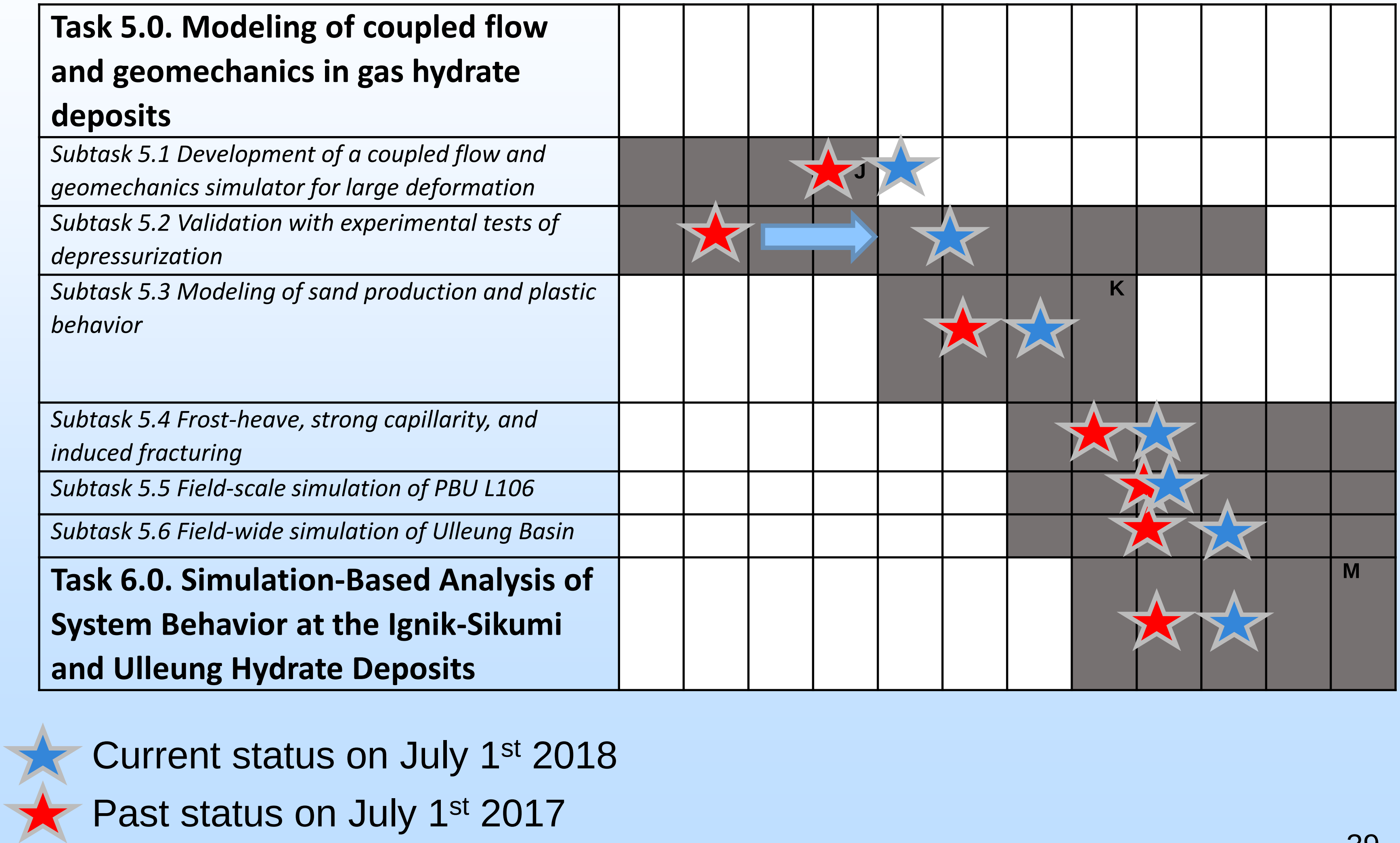
Tasks 5: Modeling of coupled flow and geomechanics in gas hydrate deposits
Task Lead: Jihoon Kim
Participants: Jihoon Kim, Joo Yong Lee, Tae Woong Ahn, Research Assistant 1

Tasks 6: Simulation-Based Analysis of System Behavior at Ignik-Sikumi /Ulleung Hydrate Deposits
Task Lead: George Moridis
Participants: George Moridis, I. Yucel Akkutlu, Research Assistant 2

Project timeline & milestones

	FY17				FY18				FY19			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0. Project Management/Planning	A											
Task 2.0. Review experimental data at various scales for gas production of Ulleung Basin												
Subtask 2.1. Depressurization of 1 m scale in 1D				B								
Subtask 2.2 Depressurization of 10-m scale in 1D							C					
Subtask 2.3. Depressurization of 1.5-m scale in 3D										D		
Subtask 2.4. Revisit to the centimeter-scale system												
Task 3.0. Laboratory Experiments for Numerical Model Verification												
Subtask 3.1. Effective stress changes during dissociation				E								
Subtask 3.2. Sand production								F				
Subtask 3.3. Secondary hydrate and capillary pressure changes												G
Subtask 3.4. Relative Permeability Data												
Subtask 3.5. Hysteresis in Hydrate Stability												
Task 4.0. Incorporation of Laboratory Data into Numerical Simulation Model												
Subtask 4.1. Inputs and Preliminary Scoping Calculations										H		
Subtask 4.2. Determination of New Constitutive Relationships												
Subtask 4.3. Development of Geological Model												

Project timeline & milestones



Product/Publication/Tech-transfer

Papers published (Journal)

- Yoon H.C., Kim J., 2018 Spatial stability for the monolithic and sequential methods with various space discretizations in poroelasticity, *International Journal for Numerical Methods in Engineering*, 114:694-718
- Kim J., 2018, A New Numerically Stable Sequential Algorithm for Coupled Finite-strain Elastoplastic Geomechanics and Flow, *Computer Methods in Applied Mechanics and Engineering*, 335:538-562
- Kim J., 2018, Unconditionally Stable Sequential Schemes for All-way Coupled Thermoporomechanics: Undrained-Adiabatic and Extended Fixed-Stress Splits, *Computer Methods in Applied Mechanics and Engineering*, 341:93-112

Product/Publication/Tech-transfer

Papers/presentations in conferences (Full-length)

- Guo X., Kim J., Killough J.E, 2017, Hybrid MPI-OpenMP Scalable Parallelization for Coupled Non-Isothermal Fluid-Heat Flow and Elastoplastic Geomechanics, 2017 SPE Reservoir Simulation Conference, 20-22 Feb., Montgomery, Texas, SPE-182665-MS
- Yoon H.C., Zhou P., Kim J., 2017, Hysteresis Modeling of Capillary Pressure and Relative Permeability by using the Theory of Plasticity, 2017 SPE Reservoir Simulation Conference, 20-22 Feb., Montgomery, Texas, SPE-182709-MS
- Yoon H.C., Kim J., 2017 The Order of Accuracy of the Fixed-Stress Type Two-Pass and Deferred Correction Methods for Poromechanics, 2017 SPE Reservoir Simulation Conference, 20-22 Feb., Montgomery, Texas, SPE-182664-MS

Presentation in conference (Extended abstract)

- Kim, J., Lee, J.Y., 2017, Rigorous simulation of coupled non-isothermal flow and largely deformable geomechanics for gas hydrate deposits., 9th International Conference on Ga Hydrates, Denver, Colorado, June 25-30
- Ahn, T., Lee, J., Lee, J.Y., Kim, S.J., Seo, Y.J., 2017 Depressurization-induced productio behavior of methane hydrate in a meter-scale alternate layer of sand and mud., 9th International Conference on Gas Hydrates (ICGH), Denver, Colorado, June 25-30