Coupled Hydro-Mechanical Simulation of Multi-Phase Fluid Flow in Fractured Shale Reservoirs using Distinct Element Method

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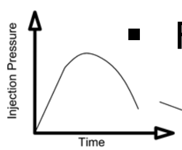
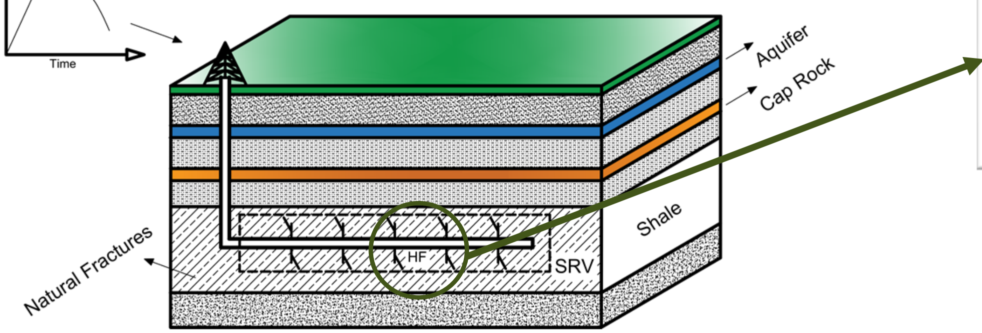
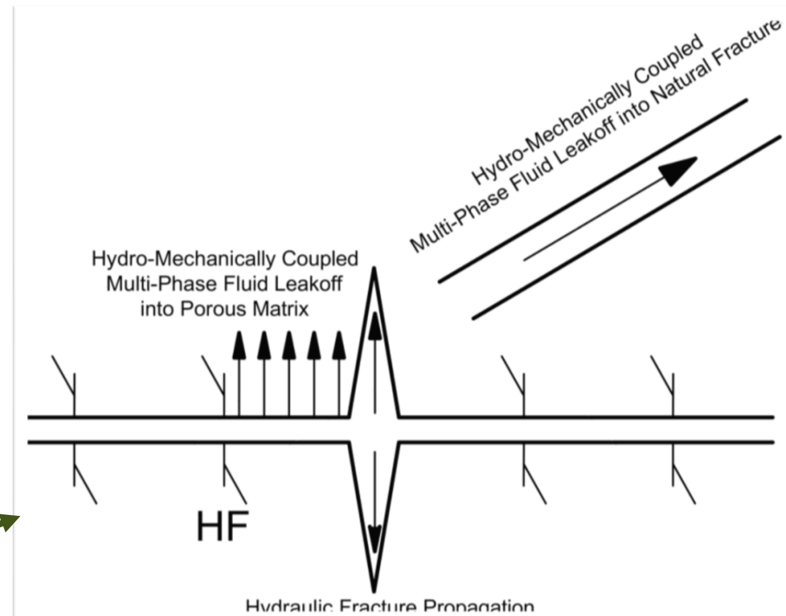
Problem Statement

- ❑ **Multiphase fluid flow through porous matrix and complex deformable fracture system**
  - Matrix-matrix, matrix-fracture and fracture-fracture multi-phase fluid transfer
  - Complex fracture network
  - Pressure gradient
  - Viscous frictional force
  - Gravity
  - Interfacial tension
  - Hydro-mechanical coupling
  - Fluid compressibility and Gas solubility



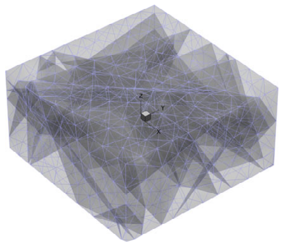




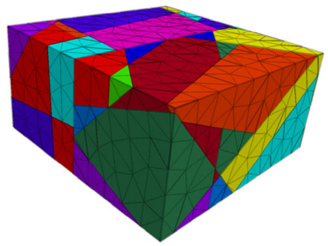
Objective

- **Developing a comprehensive coupled hydro-mechanical multi-phase fluid flow simulation approach**
  - Simulating fluid flow through both porous matrix and complex deformable fractures systems in a unified grid system
  - Simulating compressible multi-phase fluid comprising of aqueous and non-aqueous liquids as well as dissolved and free gas
  - Simulating the effects of pressure gradient, viscous frictional force, gravity and interfacial tension
  - Developing an approach to hydro-mechanically couple 3-dimensional distinct element solid mechanical simulation method (3DEC) with the developed fluid flow simulation approach
  - Implementing the approach into an object-oriented C++ computational code which is flexible to be upgraded and incorporated into other codes
  - Verify the developed code and demonstrate its capabilities in evaluating the effectiveness of stimulation of fractured reservoirs by water injection

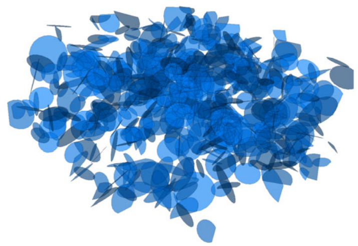
Finite Volume Discrete Fracture-Matrix Model of Multi-Phase Fluid Flow



Distinct Element Model of Solid Phase in Fractured Reservoir

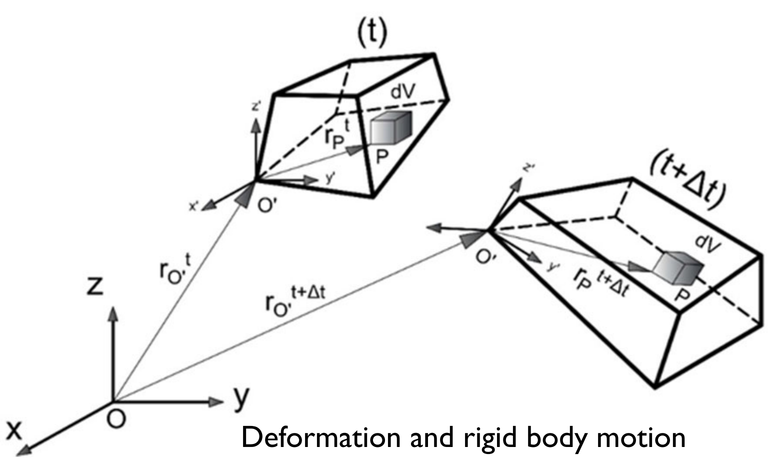


Complex Deformable Discrete Fracture Network

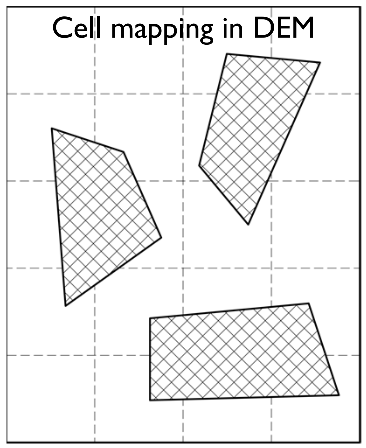


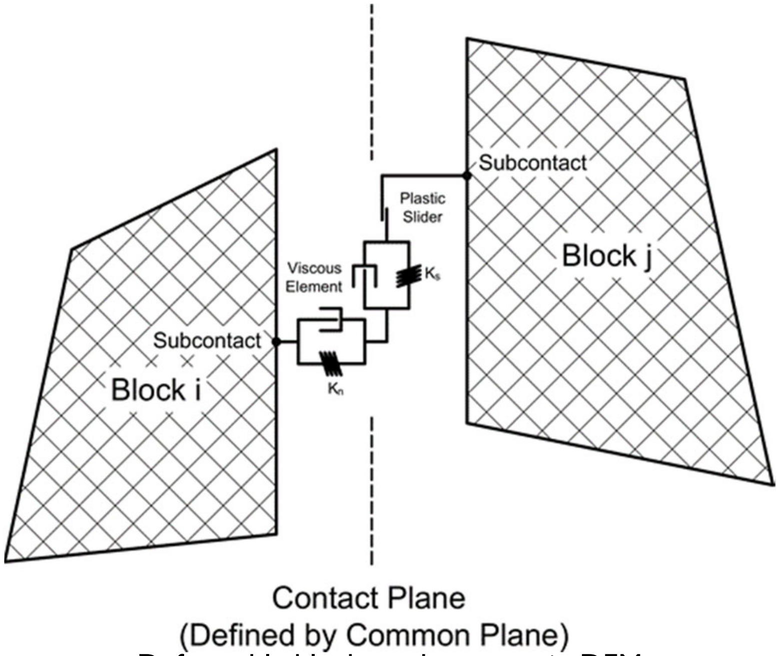
Lagrangian Solid Phase Formulation

Distinct Element Method



Deformation and rigid body motion





Deformable blocks and contacts in DEM

Differential form of coupled hydro-mechanical momentum conservation equation in solid phase:

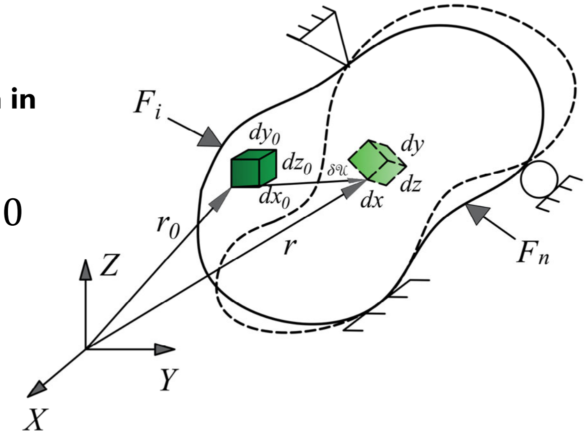
$$\frac{\partial \sigma_{ji}}{\partial x_j} + \rho b_i - \rho \ddot{r}_i - \mathbb{I}^{\mathcal{F}} = 0 \qquad \mathbb{I}^{\mathcal{F}} = -\rho^{\mathcal{F}} \left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_j} u_j \right) \qquad \sigma_{ij} = \sigma_{ij}' + \alpha P \delta_{ij}$$

Lagrangian Solid Phase Formulation

Distinct Element Method

Integral form of coupled hydro-mechanical momentum conservation equation in solid phase:

$$\delta W = \oint_A t_i \delta \mathcal{U}_i dA - \int_V \sigma_{ji}\, \delta \varepsilon_{ij}\, dV + \int_V \left(\rho b_i - \rho \ddot{r}_i - \mathbb{I}^{\mathcal{F}}\right) \delta \mathcal{U}_i dV = 0$$



Virtual work principle using virtual deformation

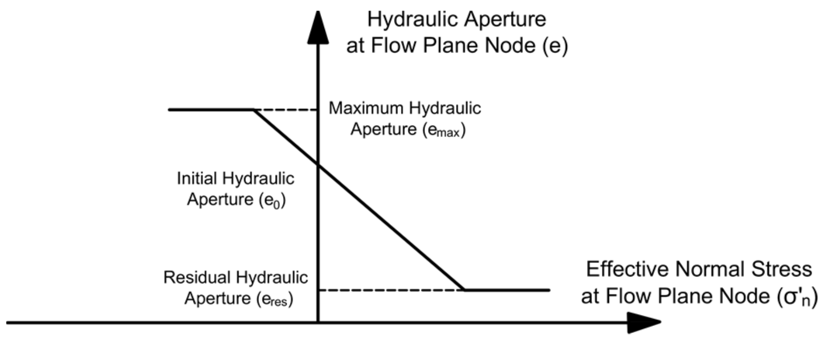
Fracture aperture change in distinct element approach:

$$dF_t = \begin{cases} K_t du_t & if: F_t < c + F_n tan\phi \ (without\ slide) \\ c + dF_n tan\varphi & if:\ F_t \geq c + F_n tan\phi \ (with\ slide) \end{cases}$$

$$dF_n = K_n du_n$$

$$du_n = du_t tan\psi$$

$$e = e_0 + \delta u_n$$



Constitutive behavior of hydraulic aperture in DEM

Eulerian Fluid Phase Formulation

Black Oil Model

Equations of motion of multi-phase fluid in porous media:

$$u_i^{p} = -\frac{K k_r^{p}}{\mu^{p}} \nabla (P^{p} + \rho^{p} g z)$$

Darcy's Law

$$\frac{\partial}{\partial t}\left(\frac{S^{w}\phi}{B^{w}}\right) + \nabla.\left(\frac{u^{w}}{B^{w}}\right) + \frac{q^{w}}{\rho_{SC}^{w}} = 0$$

Water Mass Conservation

$$\frac{\partial}{\partial t}\left(\frac{S^{o}\phi}{B^{o}}\right) + \nabla.\left(\frac{u^{o}}{B^{o}}\right) + \frac{q^{o}}{\rho_{SC}^{o}} = 0$$

Oil Mass Conservation

$$\frac{\partial}{\partial t}\left[\left(\frac{S^{g}}{B^{g}} + \frac{R_s^{w} S^{w}}{B^{w}} + \frac{R_s^{o} S^{o}}{B^{o}}\right)\phi\right] + \nabla.\left(\frac{u^{g}}{B^{g}} + \frac{R_s^{w} u^{w}}{B^{w}} + \frac{R_s^{o} u^{o}}{B^{o}}\right) + \frac{q^{g}}{\rho_{SC}^{g}} = 0$$

Gas Mass Conservation

Implicit pressure-explicit saturation method

$$(B^{w} - R_s^{w} B^{g})\left[\nabla.K\frac{k_r^{w}}{B^{w}\mu^{w}}\nabla P^{o} + CG^{w} - \frac{q^{w}}{\rho_{SC}^{w}}\right] + (B^{o} - R_s^{o} B^{g})\left[\nabla.K\frac{k_r^{o}}{B^{o}\mu^{o}}\nabla P^{o} + CG^{o} - \frac{q^{o}}{\rho_{SC}^{o}}\right] + B^{g}\left[\nabla.K\left(\frac{k_r^{g}}{B^{g}\mu^{g}} + \frac{R_s^{w} k_r^{w}}{B^{w}\mu^{w}} + \frac{R_s^{o} k_r^{o}}{B^{o}\mu^{o}}\right)\nabla P^{o} + CG^{g} - \frac{q^{g}}{\rho_{SC}^{g}}\right] = \frac{\partial C_t P^{o}}{\partial t}$$

Pressure Equation

$$\nabla.K\frac{k_r^{w}}{B^{w}\mu^{w}}\nabla P^{o} + CG^{w} - \frac{q^{w}}{\rho_{SC}^{w}} = \frac{\partial}{\partial t}\left(\frac{S^{w}\phi}{B^{w}}\right)$$

Water Saturation Equation

$$\nabla.K\frac{k_r^{o}}{B^{o}\mu^{o}}\nabla P^{o} + CG^{o} - \frac{q^{o}}{\rho_{SC}^{o}} = \frac{\partial}{\partial t}\left(\frac{S^{o}\phi}{B^{o}}\right)$$

Oil Saturation Equation

Eulerian Fluid Phase Formulation

Finite Volume Discrete Fracture-Matrix Approach

Finite Volume Discrete Fracture Matrix Discretization

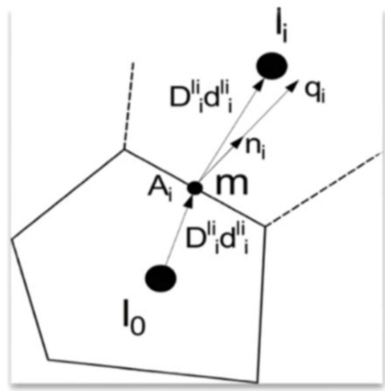
$$\sum_{i=1}^{n_{fc}} \overline{\Lambda}_{i\,l_0}^{\mathfrak{N}} T_{l_0 l_i}^{\mathfrak{N}} \left(\overline{P^{\sigma}}_{l_i}^{\mathfrak{N}+1} - \overline{P^{\sigma}}_{l_0}^{\mathfrak{N}+1}\right) + C_{CG}{}_{l_0}^{\mathfrak{N}} + C_q{}_{l_0}^{\mathfrak{N}} = C_t{}_{l_0}^{\mathfrak{N}} V_{l_0}^{\mathfrak{N}} \frac{\overline{P^{\sigma}}_{l_0}^{\mathfrak{N}+1} - \overline{P^{\sigma}}_{l_0}^{\mathfrak{N}}}{\Delta t}$$

Two Types of Transmissibility

$$\alpha^{l_i} = \frac{K_{l_i} A_i}{D_i^{l_i}} \left(d_i^{l_i} . n_i\right)$$

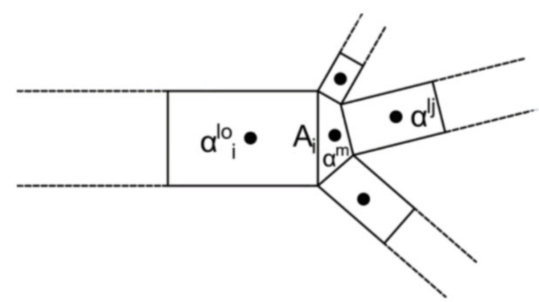
Matrix – Matrix

Matrix - Fracture



$$T_{l_0 l_i} = \frac{\alpha_i^{l_0} \alpha^{l_i}}{\alpha_i^{l_0} + \alpha^{l_i}}$$

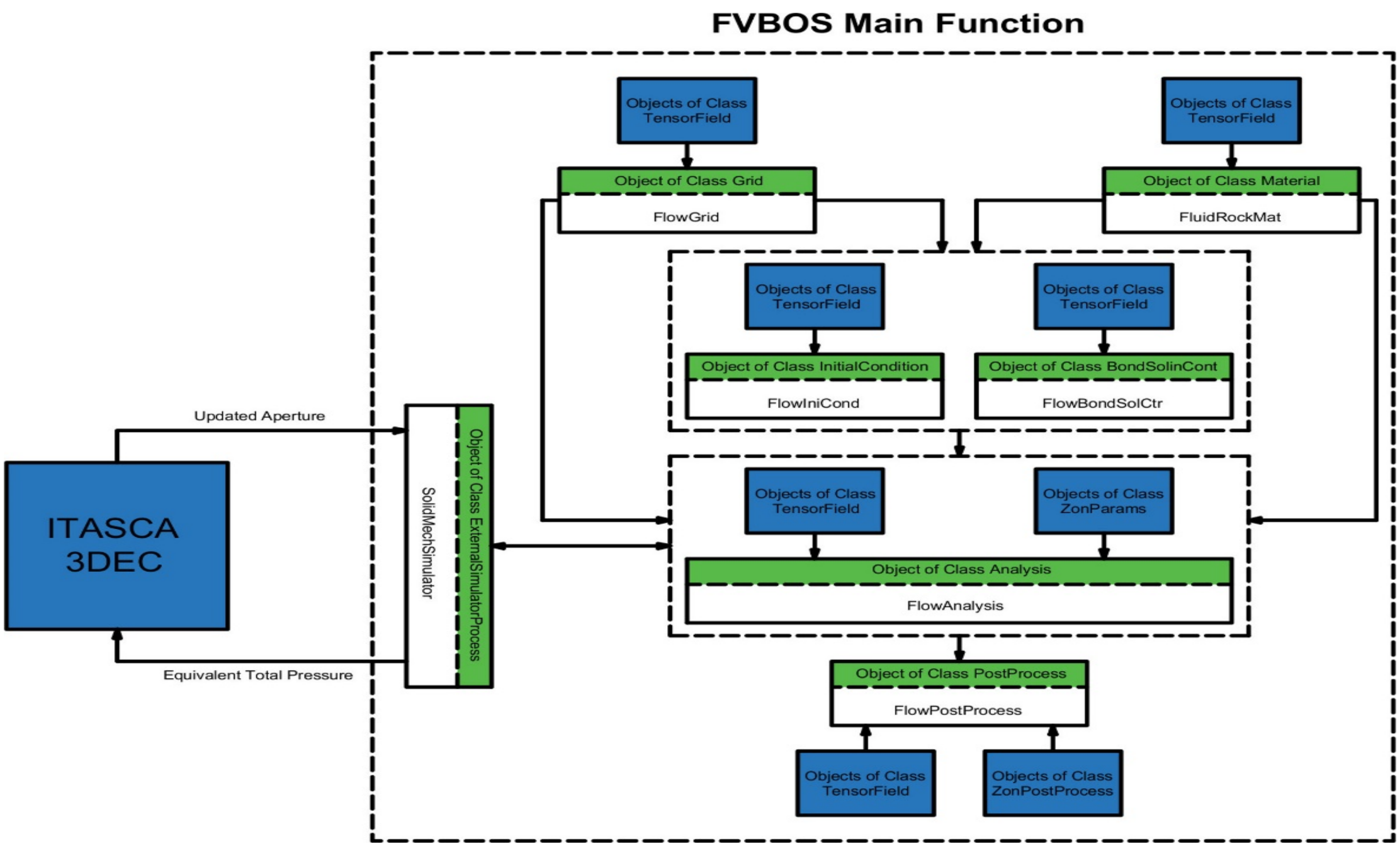
Fracture - Fracture



$$T_{l_0 l_j} = \frac{\alpha_i^{l_0} \alpha^{l_j}}{\sum_{j=1}^{n_{fr}} \alpha^{l_j} + \alpha_i^{l_0}}$$

Finite Volume Black Oil Simulator (FVBOS)

Overall Flowchart



Finite Volume Black Oil Simulator (FVBOS)

C++ Implementation

- Solution 'FVBOS' (1 project)
  - FVBOS
    - References
    - External Dependencies
    - Header Files
      - Analysis.h
      - BondSolinCont.h
      - ExternalSimulator.h
      - Grid.h
      - InitialCondition.h
      - Material.h
      - PostProcess.h
      - TensorField.h
      - ZonParams.h
      - ZonPostProcess.h
    - Source Files
      - Analysis.cpp
      - BondSolinCont.cpp
      - Grid.cpp
      - InitialCondition.cpp
      - Main.cpp
      - Material.cpp
      - PostProcess.cpp
      - ZonParams.cpp
      - ZonPostProcess.cpp

```cpp
#include "TensorField.h"
#include "Grid.h"
#include "Analysis.h"
#include "Material.h"
#include "InitialCondition.h"
#include "BondSolinCont.h"
#include "PostProcess.h"
#include <iomanip>

using namespace std;

int main()
{
    int itstep, mtstep; double anlstime;
    Grid FlowGrid;
    FlowGrid.Gridset(); FlowGrid.ZoneNeighbor(); FlowGrid.GridEcho();
    Material FluidRockMat;
    FluidRockMat.RockMatSet(); FluidRockMat.FluidMatSet();
    FluidRockMat.FluidRockMatSet(); FluidRockMat.MaterialEcho();
    InitialCondition FlowIniCond(FlowGrid);
    FlowIniCond.IniPrsSet(FlowGrid, FluidRockMat);
    FlowIniCond.IniSatSet(); FlowIniCond.IntCondEcho();
    BondSolinCont FlowBondSolCtr;
    FlowBondSolCtr.SolnCtrlParams(); FlowBondSolCtr.InjPrdSet();
    FlowBondSolCtr.InjPrdZons(FlowGrid); FlowBondSolCtr.BndSlnEcho();
    mtstep = FlowBondSolCtr.MaxTimeStepNum();
    ExternalSimulatorProcess SolidMechSimulator;
    Analysis FlowAnalysis(FlowGrid, FlowIniCond, FluidRockMat, FlowBondSolCtr);
    PostProcess FlowPostProcess(FlowGrid, FlowBondSolCtr, mtstep);
    for (itstep = 1; itstep <= mtstep; itstep++)
    {
        FlowAnalysis.CHMMPFSimulation(FlowGrid, FluidRockMat, FlowBondSolCtr, SolidMechSimulator, itstep);
        anlstime = FlowAnalysis.AnsTime();
        FlowPostProcess.CumWelPhaseInjPrd(FlowGrid, FlowAnalysis, FluidRockMat,
            FlowBondSolCtr, anlstime, itstep);
        FlowPostProcess.MatBalErrorOutFile(FlowAnalysis, anlstime, itstep);
        FlowPostProcess.ContVectTPFile(FlowGrid, FlowAnalysis, FluidRockMat,anlstime, itstep);
        FlowPostProcess.GraphOnLine(FlowGrid, FlowAnalysis, anlstime, itstep);
    }
    return 0;
}
```

Verification of FVBOS

Buckley-Leverett Problem for Porous Matrix

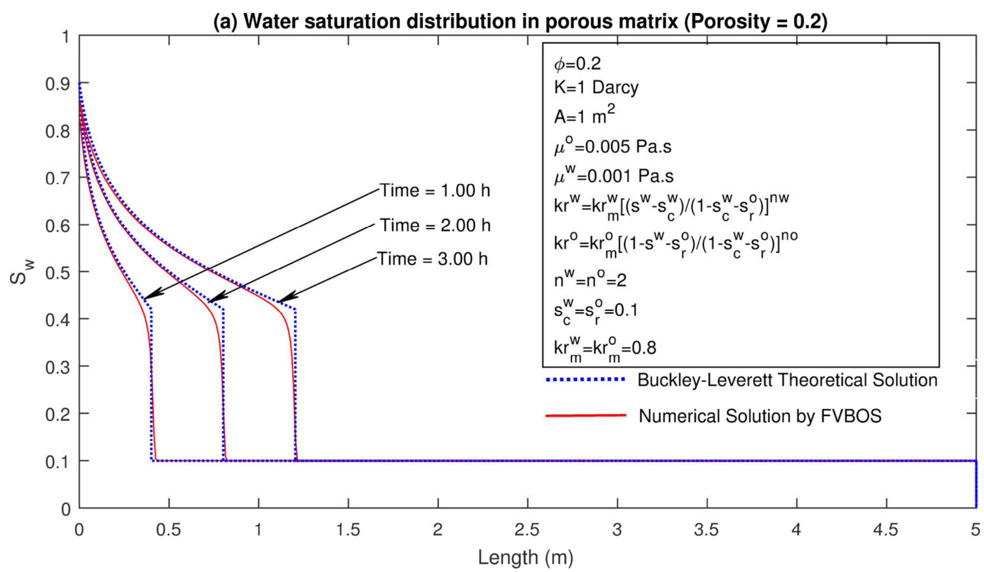
Agents affecting the multi-phase fluid flow:

Pressure gradient, viscous frictional force and interfacial tension between fluid phases and porous matrix

Theoretical Solution:

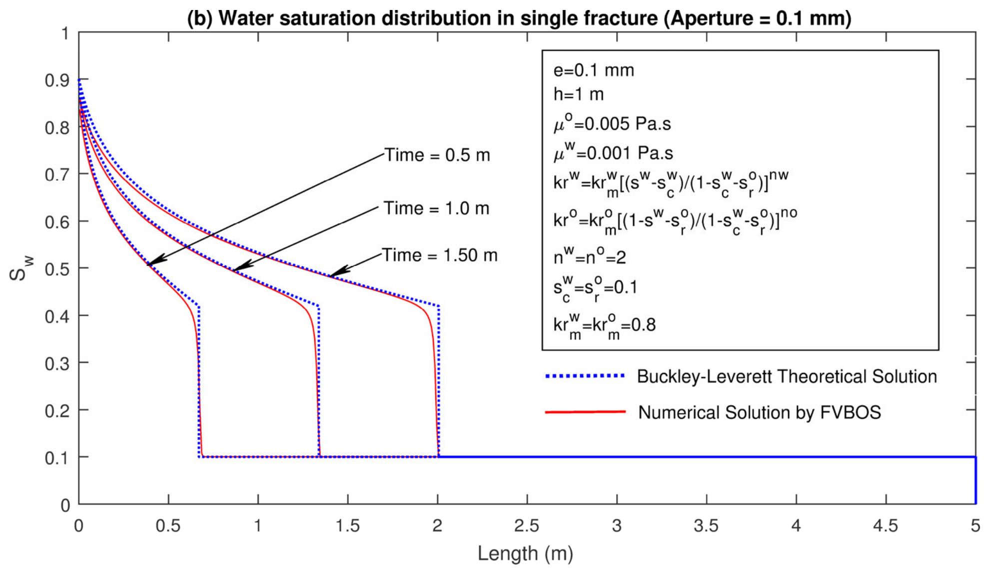
$$\frac{\partial q_w}{\partial x} = -\phi A \frac{\partial S^w}{\partial t}$$

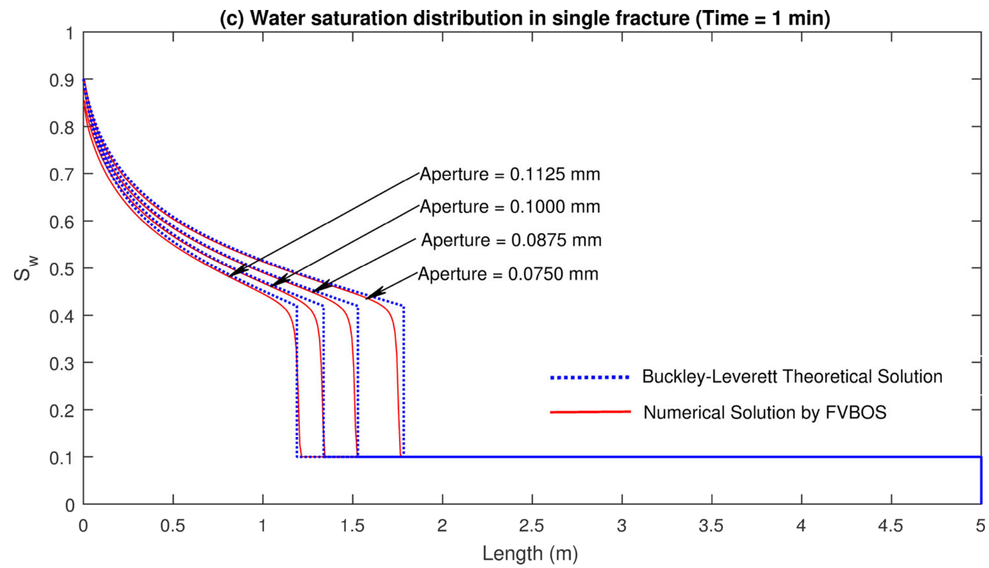
$$[x]_{S^w=cons} = \frac{q_t t}{\phi A}\left[\frac{dF_w}{dS^w}\right]_{S^w=cons}$$



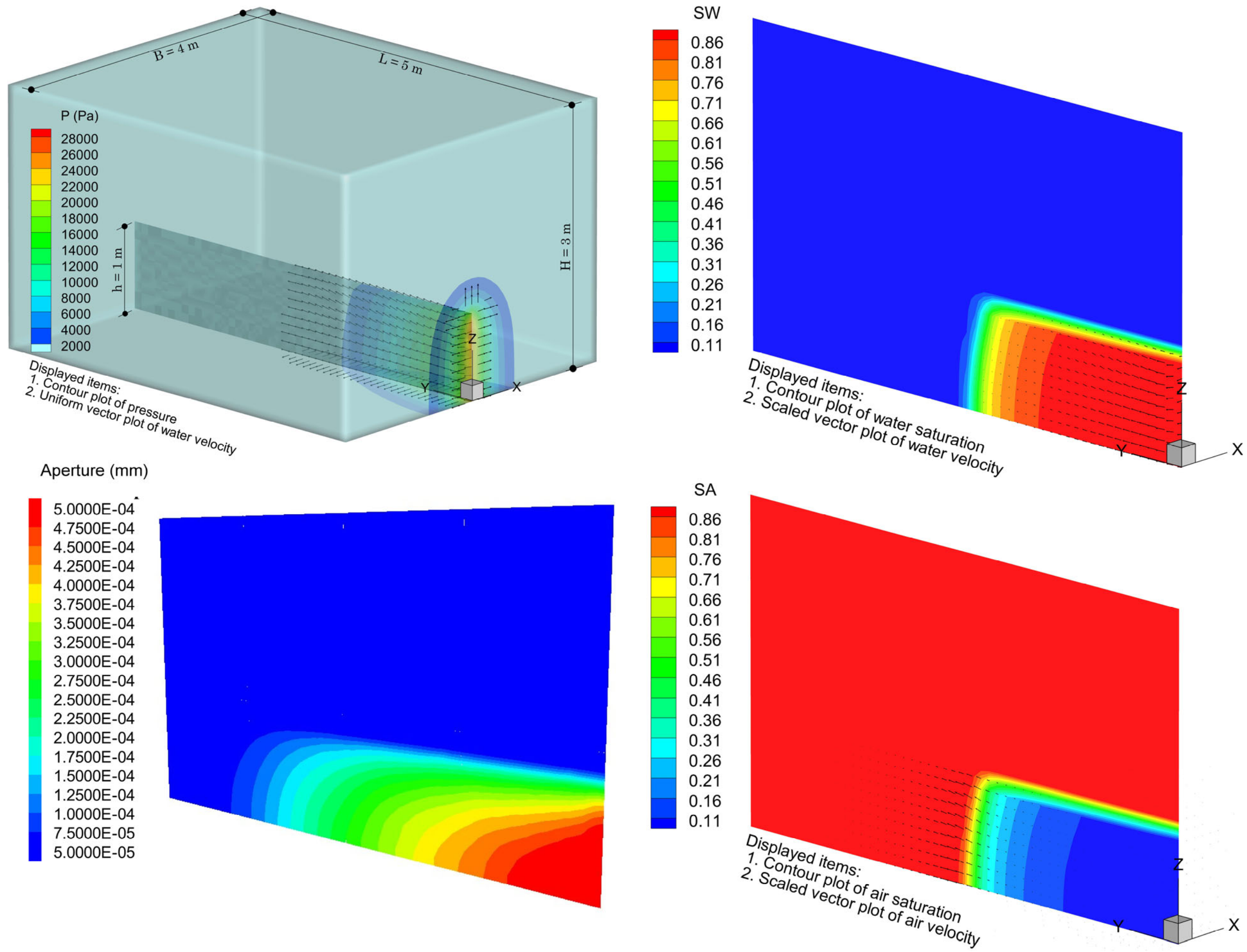
Verification of FVBOS

Buckley-Leverett Problem for Single Fracture

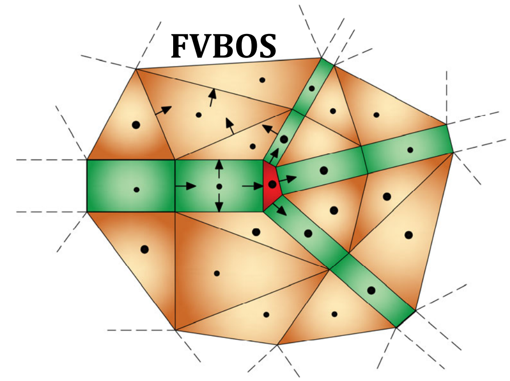




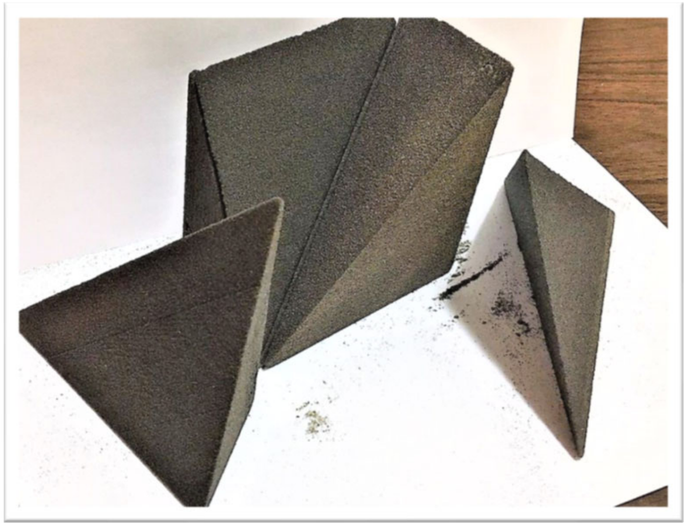
Simulation of Coupled Hydro-Mechanical Multi-Phase Fluid Flow Through Porous Matrix and Single Fracture by FVBOS



Contribution to Current Research Projects in Reservoir Geomechanics Research Group (RG^2)

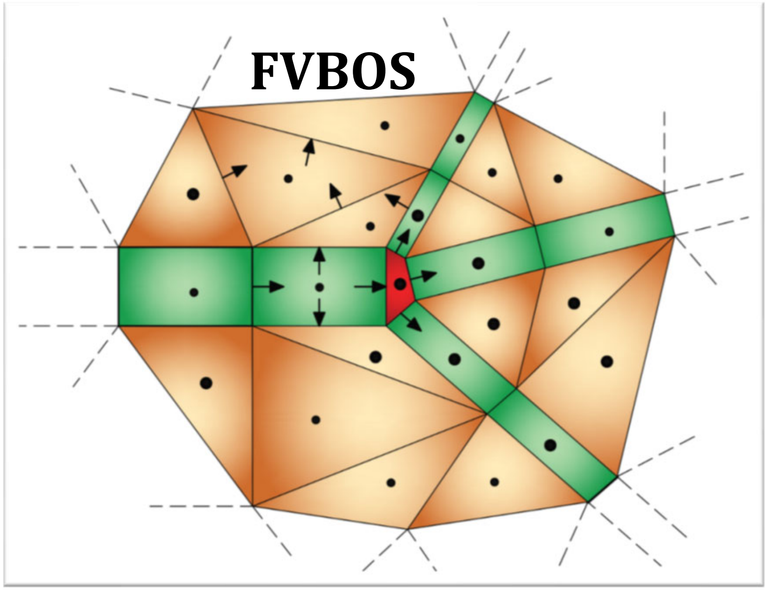


- ❑ **FVBOS Involves highly complicated and uncertain physical processes**
  - ➢ Verification of FVBOS with physical models
  - ➢ Physical models generated by RG^2 centrifuge & 3D printing technology
- ❑ **Application of FVBOS in multi-phase fluid flow modeling**
  - ➢ Micro seismicity
  - ➢ Caprock integrity
  - ➢ Upscaling of hydro-geomechanical properties of fractured reservoir rocks



Contribution to Industry

- ❑ **FVBOS provides**
  - ✓ a better tool for analyzing multiphase fluid flow in fractured reservoirs
- ❑ **FVBOS Provides**
  - ✓ a better understanding of fluid flow through naturally and hydraulically fractured reservoirs
- ❑ **FVBOS offers**
  - ✓ Hydro-mechanical coupling
  - ✓ Complex deformable fracture systems
  - ✓ Multi-Phase discrete fracture-matrix simulation
- ❑ **FVBOS is a more comprehensive alternative for**
  - ✓ Conventional multi-phase flow simulators



Recommendations for Future Research

- ❑ **Calibrate FVBOS based on systematic experimental Research**
  - ✓ Using 3-D printing technology of GeoPrint Facility at RG^2 to produce repeatable precise fractured porous samples
- ❑ **Automate FVBOS simulations by artificial intelligence and machine learning approaches**
  - ✓ Upscaling of hydro-geomechanical properties of fractured reservoir rocks
  - ✓ Train the artificially intelligent computational tool by the experimental data provided by centrifuge facility of GeoRef at RG^2
- ❑ **Upgrade FVBOS by implementing stress singularity and surface energy released by fracture propagation**
  - ✓ Simulation of highly complex hydraulic fracturing processes in unconventional reservoir formations
- ❑ **Upgrade FVBOS by implementing compositional multi-phase fluid models along with a computational heat transfer method**
  - ✓ Coupled thermo-hydro-mechanical simulations in fractured unconventional reservoirs

Questions ?