



Sandia Academic Alliance Spring 2021 Georgia Tech LDRD Virtual Poster Session

Introduction / Motivation

Motivation

Prediction of flow, transport, and deformation in fractured porous media is critical to improving our scientific understanding of coupled thermal-hydrological-mechanical-chemical (THMC) processes across subsurface energy activities. Poroelasticity theory describes the coupled deformation and pore fluid flow within porous media.

Objectives

- Numerical investigation of poromechanics coupling via a fixed stress scheme into an existing Sandia Sierra multiphysics software
 - Verification of the fixed stress scheme for poroelasticity using three benchmark problems (one dimensional (1D) Terzaghi, 2D Mandel, and 3D Cryer sphere)
 - Comparison of the fully coupled and fixed stress solutions against analytical solutions
- Evaluation of the convergence, accuracy, and computational efficiency over a range of permeability and elastic properties

Approach

Approach

Poromechanics Coupling Schemes

Both fully-coupled and fixed-stress schemes are investigated. In the fully coupled scheme, both pressure and displacements are solved for simultaneously. Within the fixed-stress scheme, the flow problem (i.e., pore pressure) is solved first while setting the time derivative of total mean stress to zero. Then, the mechanics problem (i.e., displacement) is solved, as shown in Figure 1.

Sandia Sierra Multiphysics Software

The fixed-stress scheme is newly implemented in the Sandia Sierra multiphysics toolkit, composed of a suite of finite element analysis modules including a thermal/fluid mechanics module (Aria) and a solid mechanics module (SM), which are solved iteratively using Arpeggio.

- Fully-coupled approach: Sierra/Aria for poroelasticity
- Fixed-stress split scheme
 - Implementation in Sierra/Aria
 - Expansion into Arpeggio - coupling Sierra/Aria with Sierra/SM

$$\alpha \frac{\partial \epsilon_{kk}}{\partial t} + S_e \frac{\partial p}{\partial t} = \nabla \cdot \left(\frac{k}{\gamma_w} \nabla p \right) \quad \text{: storage equation}$$

$$\left(K + \frac{1}{3} G \right) \frac{\partial \epsilon}{\partial x_i} + G \nabla^2 u_i = \alpha \frac{\partial p}{\partial x_i} - b_i \quad \text{: equilibrium equation}$$

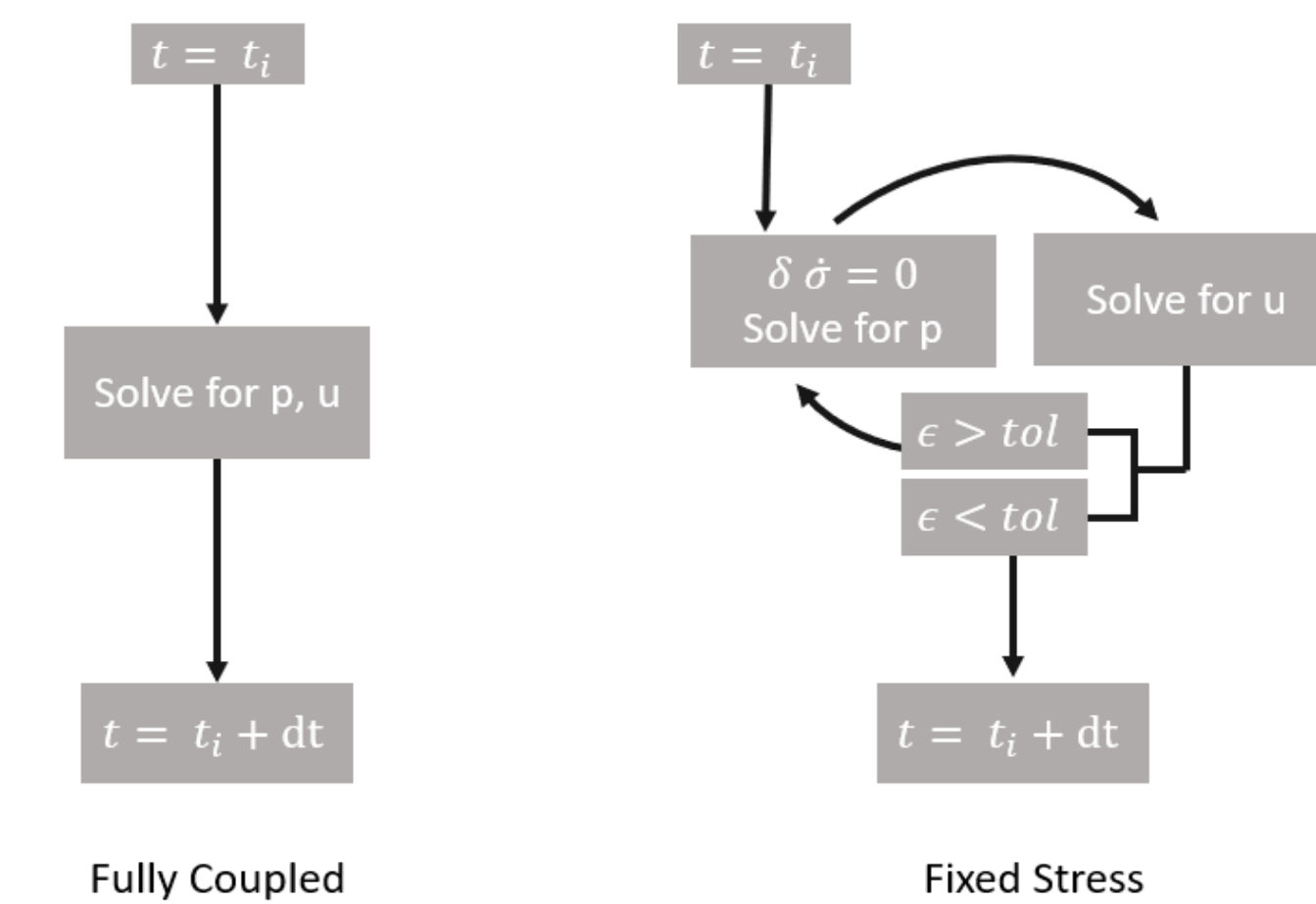


Figure 1: Schematic of Coupling Schemes

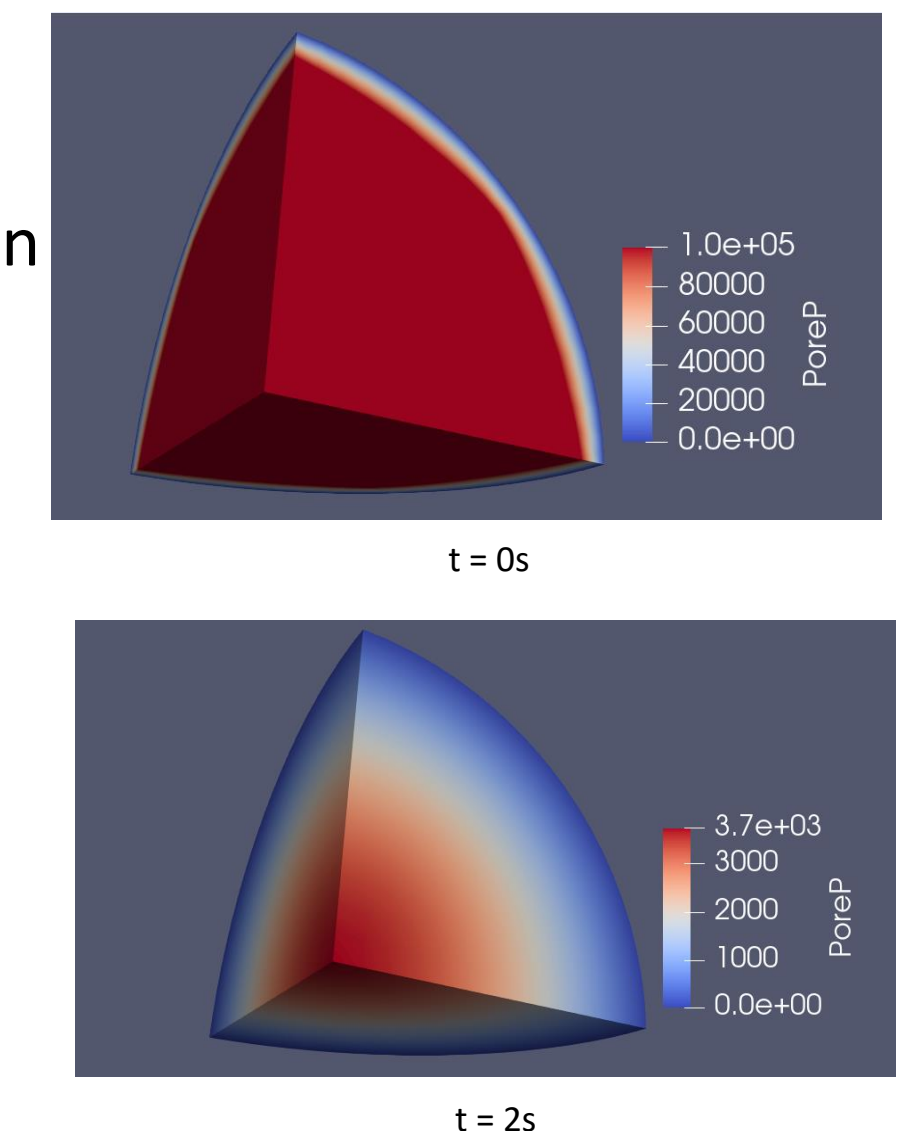


Figure 2: Pore pressure dissipation visualization in Cryer Sphere benchmark problem

Current Status/ Results

Benchmark Problem Implementation

Material Properties:
Saline Aquifer

$$k = 3e - 14 \text{ sq. m.}$$

$$\nu = 0.2$$

$$E = 20 \text{ GPa}$$

$$\phi_0 = 0.15$$

Initial pore pressure:
 $p_0 = 100 \text{ kPa}$

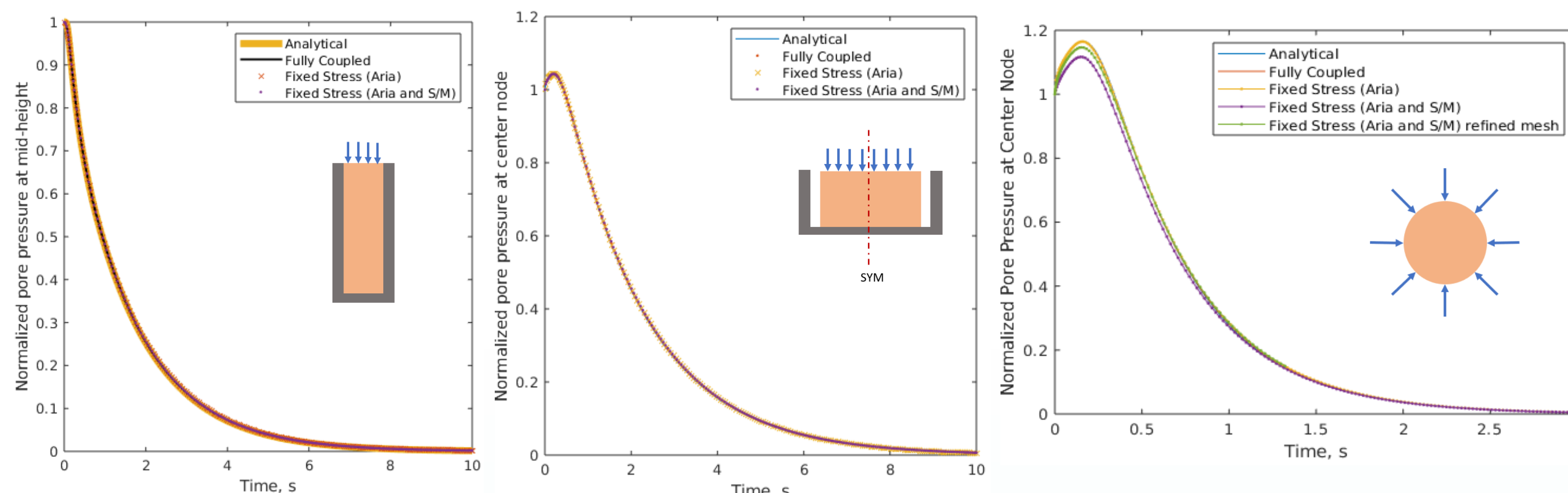


Figure 3: Terzaghi Problem, Pore Pressure Figure 4: Mandel Problem, Pore Pressure Figure 5: Cryer Problem, Pore Pressure

Table 1: Comparison of Error for Fully Coupled and Fixed Stress Schemes

k (sq. m.)	Error Norm								
	Terzaghi Problem			Mandel Problem			Cryer Problem		
	FC	Aria FS tol=1e-6	Aria FS tol=1e-8	FC	Aria FS tol=1e-6	Aria FS tol=1e-8	FC	Aria FS tol=1e-6	Aria FS tol=1e-8
1e-10	.0293	0.0553	0.0356	.0346	0.0444	0.0444	.0271	0.0435	0.0433
1e-12	.0293	0.4095	0.0553	.0346	0.0457	0.0444	.0271	0.0548	0.0435
1e-14	.0293	0.4227	0.4095	.0346	0.0740	0.0457	.0271	0.2840	0.0548

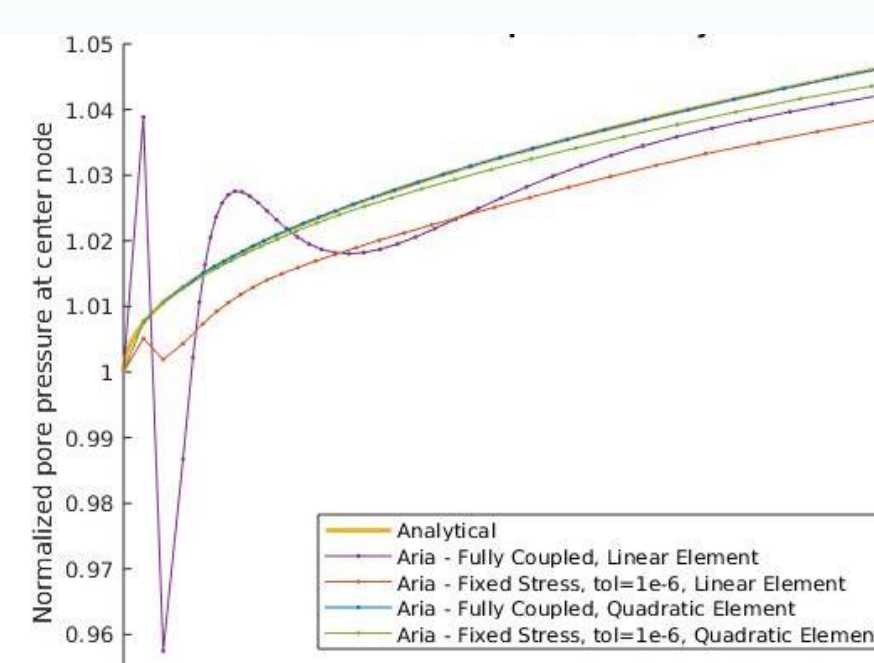


Figure 6: Instabilities at early times

- Implementation of fixed stress scheme in Aria and SM requires finer mesh and smaller timestep
- At early times ($dt \approx \frac{t_{ss}}{1000}$), LBB stability issues for fully coupled scheme
- Solved with Q2 elements, but computationally demanding
- Significantly improved with fixed stress scheme

Low-Permeability - Aria Fixed Stress

- Identified relationship between permeability of porous media and required tolerance for fixed stress scheme in Aria
- Currently implementing into multi-material problems

Challenges

Fully Coupled Scheme with Low Permeable Media

- Iterative solver for small permeabilities ($k \leq 10^{-17} \text{ m}^2$) is inaccurate due to
 - Large condition number of matrix
 - But, fixed-stress works accurately

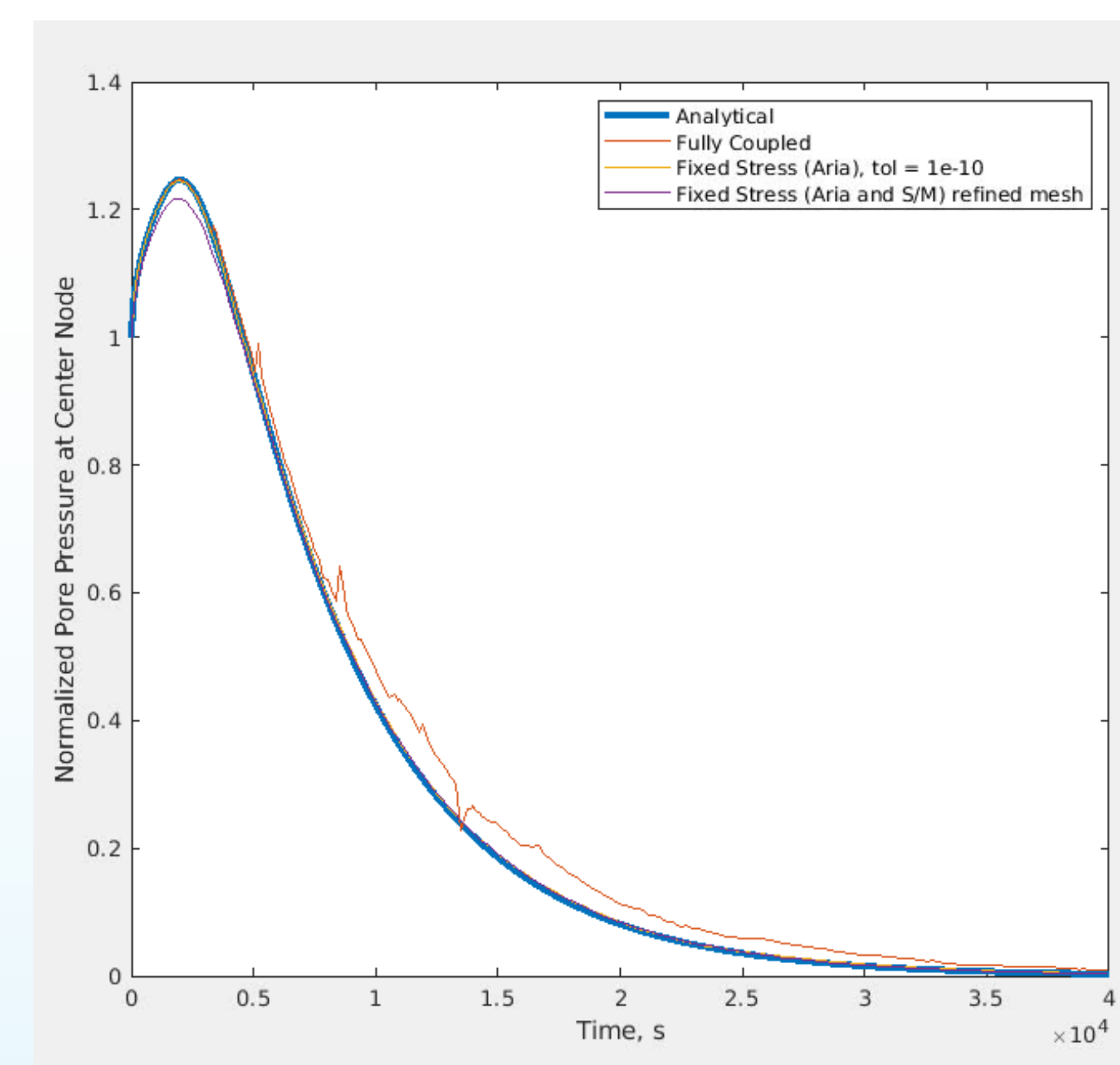


Figure 7: Cryer Problem, Pore Pressure for low permeability porous medium

Next Steps/ Future Work

Conclusions

- The fixed-stress scheme lowered computational times while maintaining error commensurate to fully-coupled methods
- Along with decreasing the computational demand, the fixed stress scheme maintained the stability over a range of properties
- For low permeable media, we have observed
 - Loss of stability in the fully coupled scheme with an iterative solver
 - Loss of accuracy in the Aria fixed stress schemes
- Fixed stress scheme using Aria and S/M is less sensitive to small permeabilities, but requires improved accuracy for 3D problems

Ongoing Work

- Multi-layer Terzaghi problem with varying permeabilities
- Multi-phase flow with CO₂ and water