**ORIGINAL ARTICLE**
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# Two-grid coupled multiphase flow and geomechanics: A computational framework to monitor surface deformation along with fault slip due to pore pressure perturbations

**Saumik Dana[1*] | Xiaoxi Zhao[1*] | Birendra Jha[1*]**

[1]University of Southern California, Los Angeles, CA 90007

**Correspondence**
University of Southern California, Los Angeles, CA 90007
Email: sdana@usc.edu

**Present address**
[*]Mork Family Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, CA 90007

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We develop a computational framework that leverages the features of sophisticated software tools and numerics to tackle some of the pressing issues in the realm of earth sciences. The algorithms to handle the physics of multiphase flow, concomitant geomechanics and the complex geometries of field cases with surfaces of discontinuity are stacked on top of each other in a modular fashion which allows for easy use to the end user. The current focus of the framework is to provide the user with tools for assessing seismic risks associated with energy technologies and for estimating properties in the subsurface as they evolve real-time.

**KEYWORDS**
Induced seismicity, Inversion analysis, Energy technologies, Coupled multiphase flow and geomechanics, Finite element method, Finite volume method, Computational geometry

## 1 | INTRODUCTION

The development of a computationally inexpensive framework with the capability to model deformation of the earth's surface and fault slip due to deep subsurface pressure perturbations associated with multiphase flow is critical from two different standpoints

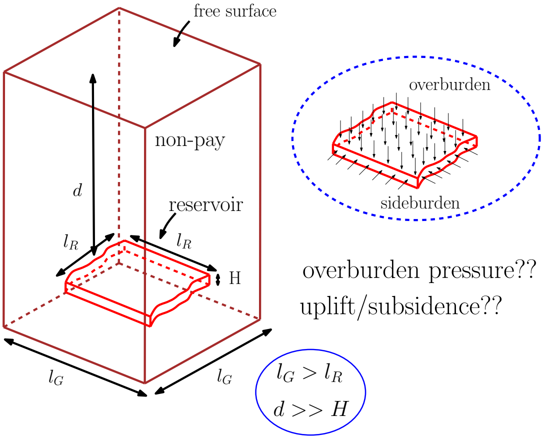


**FIGURE 1** Direct imposition of heuristic overburden pressures on the flow domain completely disregards the mechanical behavior of the surrounding rock and obviates a study of fault slip away from the reservoir as well as deformation of earth's surface

- Assessing the seismic risks associated with carbon sequestration, enhanced geothermal systems, waste water disposal, enhanced oil recovery thereby offering guiding protocols for the design of these operations [1, 2, 3, 4, 5, 6, 7, 8]
- Estimating subsurface properties using inversion analysis of ground deformation data obtained from Global Positioning System (GPS) and interferometric synthetic aperture radar (InSAR). This typically requires multiple forward simulations with the geomechanical domain extending all the way to the earth's surface [9, 10, 11, 12, 13, 14, 15, 16, 17, 18]

The major bugbear to developing such a framework is the computationally intractable size of the geomechanical grid no matter which numerical method is used to resolve the coupled system of equations. The typical approaches to avoid such issues are to impose an overburden pressure directly on the reservoir thus treating it as a coupled problem domain (see Fig. 1) or to model flow on huge domain with zero permeability cells mimicking the no flow boundary condition between the flow and non-flow region. The former approach precludes a study of surface deformation, does not mimic the true effect of the overburden on the stress sensitive reservoir, and is incapable of capturing induced seismicity inside faults away from reservoir whereas the latter approach is computationally intractable for large field scale problems due to memory requirements. In order to address this, we develop a two-grid coupled multiphase flow and geomechanics framework which allows for spatial decoupling of the flow and geomechanics domains with the geomechanics subproblem being resolved on a separate grid with a larger spatial extent going all the way to the free surface (see Fig. 2). This computational framework is built on top of a staggered solution algorithm that solves the flow and mechanics subproblems sequentially and iteratively.

Typically, in such problems, the geomechanics mesh is expected to be coarser than the flow mesh everywhere the two meshes exist, but we generalize the method to the cases where the geomechanics elements can be smaller than the flow elements in small localized region where capturing the mechanics is more pertinent. Furthermore, we would like to generalize the notion of the two-grid from structured hexahedral meshes (as was done in [19]) to unstructured tetrahedral meshes. A depiction of the intersection of two tetrahedral elements in given in Fig. 3. We first demonstrate the convergence of the two-grid method for unstructured tetrahedral grids using the classical

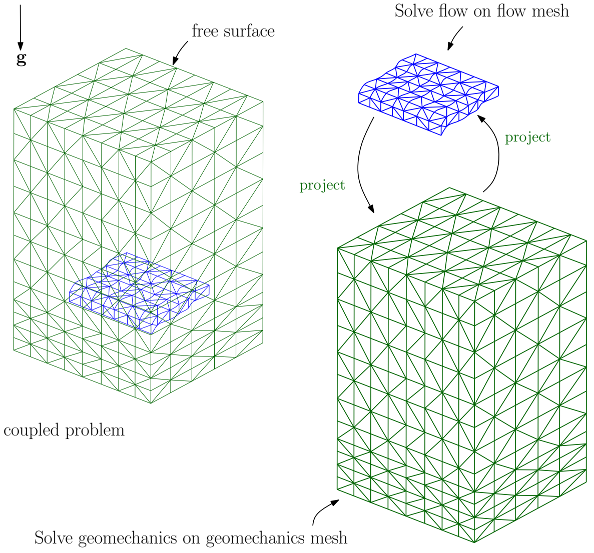


**FIGURE 2** The two-grid method enables the study of induced seismicity in faults away from reservoir, takes into account the mechanical behavior of surrounding rock and allows for determination of surface deformation due to subsurface pressure perturbation

Mandel's problem [20, 21] analytical solution. The field problem is a $CO_2$ storage-enhanced oil recovery site where we monitor the movement of $CO_2$ , hydrocarbons and water, and the associated evolution in mechanical stability of faults along with the surface deformation. This paper is structured as follows: the governing equations are provided in section 2, the solution strategy is explained in section 3, the numerical simulations for a benchmark problem and a field scale problem are provided in section 4, and the conclusions and outlook are provided in section 5.

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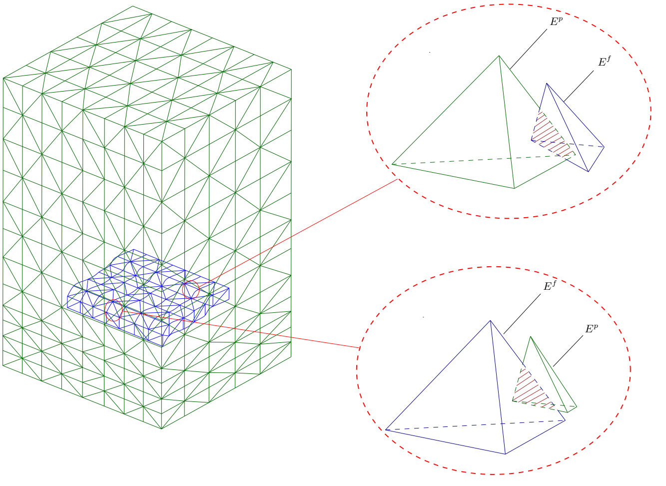


**FIGURE 3** Depiction of couple of intersecting flow-geomechanics element pairs. We refer to the flow element as $E^f$ and geomechanics element as $E^p$. Depiction is to reiterate the point that there is no restriction of whether the flow or geomechanics element needs to be smaller than the other


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