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ScienceDirect
Computer methods in applied mechanics and engineering
Comput. Methods Appl. Mech. Engrg. 335 (2018) 538–562
www.elsevier.com/locate/cma

A new numerically stable sequential algorithm for coupled finite-strain elastoplastic geomechanics and flow

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Received 6 February 2017; received in revised form 24 October 2017; accepted 24 February 2018

Highlights

- New sequential method for largely deformable poromechanics.
- Mathematical stability analysis of the proposed sequential method.
- Straightforward implementation using existing simulators.
- No need to update the mesh for flow and geomechanics.

Abstract

We propose a new numerically stable sequential implicit method for coupled flow and finite-strain multiplicative elastoplastic geomechanics. We find from stability analysis that the sequential method that solves the flow problem first by fixing the first Piola–Kirchhoff total stress, solving the geomechanics (solid deformation) problem at the next step, is unconditionally stable (contractive and B-stable). In this sense, this method named the fixed first Piola–Kirchhoff stress method is an extension of the fixed stress method in coupled flow and infinitesimal geomechanics. We also study the fixed second Piola–Kirchhoff stress method, comparing it with the fixed first Piola–Kirchhoff stress method, because the constitutive relations are formulated by the second Piola–Kirchhoff total stress, although fixing the second Piola–Kirchhoff total stress field does not provide theoretical unconditional stability. In space discretization, we use the finite element method for the geomechanics problem with the total Lagrangian approach, while employing the finite volume method for the flow problem. Geometrical nonlinearity from the total Lagrangian approach results in full-tensor permeability even if the initial permeability is isotropic. To consider the full-tensor permeability accurately, we employ the multipoint flux approximation in solving the flow problem. In time discretization, the backward Euler method is used. Then, we perform numerical experiments of the two fixed-stress sequential methods with various scenarios, and find superiority of their numerical stability. Specifically, the two fixed-stress sequential methods provide almost identical results for elasticity. For $J2$ plasticity, the two sequential methods yield slightly different numerical results although the trends of the results are similar. For the Drucker–Prager plasticity, we find that the results from the two methods are almost identical. For all the test cases, the two sequential methods are numerically stable.
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Keywords: Large deformation; Sequential scheme; Poromechanics; Multipoint-flux approximation; Multiplicative elastoplasticity

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https://doi.org/10.1016/j.cma.2018.02.024
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1. Introduction

Coupled flow and geomechanic problems in geosciences are typically based on the assumption of small deformation (i.e., infinitesimal transformation) [1–7]. This assumption is usually valid in reservoir engineering problems associated with rock, which induce small deformation. However, this assumption might not be valid in some geological formations that experience substantial compaction or dilation, accompanied by large deformation (e.g., Borja and Alarcón [8], Armero [9], and Benett et al. [10]). Large deformation can occur in unconventional reservoirs such as oceanic gas hydrate deposits or unconsolidated formations in geotechnical engineering, inducing significant changes in the initial configuration as well as huge subsidence. For example, the skeleton of a gas hydrate deposit consists of porous media (rock/soil) and solid phase (hydrate/ice). Thus, when gas hydrates are dissociated, part of the skeleton disappears, which makes the deposit softer [11]. In particular, the gas hydrate deposit in Ulleung Basin is located in the deep sea under high overburden and depressurization for gas production can cause significant large deformation [12], showing geometrical nonlinearity. The laboratory tests have identified large deformation of the samples from the fields (e.g., Kwon et al. [13] and Lee et al. [14]). As a result, the infinitesimal transformation based on small deformation is no longer valid in this case. This geometrical nonlinearity induces full-tensor permeability even when the initial permeability is isotropic. Then, pore-volume and permeability in the flow problem are strongly coupled with the geomechanical problem.

Two schemes can be considered to solve the coupled problem: fully implicit and sequential implicit methods. The fully implicit method solves the coupled problem simultaneously in a time-stepping algorithm, taking the Newton–Raphson method [15–21]. This scheme typically yields unconditional stability when the coupled problem is well-posed. On the other hand, the sequential implicit method partitions the coupled problem and solves the sub-problems sequentially, allowing each sub-problem to take a different implicit time-stepping algorithm [22–24]. In addition, the sequential method can make use of existing robust simulators for the sub-problems, yielding smaller systems of equations. However, the sequential approach does not necessarily guarantee unconditional stability even though the uncoupled sub-problems are unconditionally stable. Armero [9] studied the undrained sequential method for coupled finite-strain geomechanics and fluid flow, where the geomechanical problem is solved with the undrained flow condition at the first step and the flow problem is solved at the next step. Yet, the study of sequential implicit algorithms for largely deformable poromechanics has little been investigated. Thus, in this study, we focus on an unconditionally stable sequential method to solve the coupled finite strain geomechanics-flow problems.

There are two representative approaches in modeling large deformation. One approach is the updated Lagrangian method in which the grid system is updated every time step [25,26]. This approach recalculates geometric information for both flow and geomechanics at every time step. Even though this method seems straightforward to understand, it requires high computational cost, updating the mesh in numerical simulation. The other approach is the total Lagrangian method that keeps the same grid system as a reference (initial) configuration during simulation, unlike the updated Lagrangian method [25,27–29,9]. Instead, geomechanical properties and variables are mapped onto the reference configuration while mass balance for flow and momentum balance for geomechanics are conserved, respectively. Mathematically, both updated and total Lagrangian approaches are equivalent [25]. In this study, we employ the sequential approach based on the total Lagrangian method because it can reduce computational cost (e.g., no update of the grid system) and coding effort.

Precisely, we propose an unconditionally stable sequential implicit algorithm for coupled flow and finite-strain multiplicative elastoplastic geomechanics. The sequential algorithm first solves the flow problem by fixing the first Piola–Kirchhoff total stress field, and then solves the geomechanics problem. As a result, the sequential algorithm can be considered as an extension of the fixed stress sequential method used for coupled flow and infinitesimal geomechanics. We will show by mathematical analysis that the fixed first Piola–Kirchhoff stress sequential algorithm is contractive and B-stable.

In addition, we consider another sequential method that fixes the second Piola–Kirchhoff total stress field at the flow step. This method can be implemented more easily than the fixed first Piola–Kirchhoff stress sequential method because the constitutive relations are formulated with the second Piola–Kirchhoff total stress, although it does not guarantee B-stability.

For numerical simulation, for space discretization we use the finite element method for the geomechanics problem, while employing the finite volume method for the flow problem. In particular, we employ the multipoint flux approximation to solve the flow problem in order to deal with full-tensor permeability [30]. Geometrical nonlinearity

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