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Staggered In Time Coupling of Reservoir Flow Simulation and Geomechanical Deformation: Step 1 — One-Way Coupling

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Abstract

An isothermal, implicit, mixed finite element black oil reservoir simulator from the University of Texas is coupled to an explicit, quasistatic, nonlinear finite element solid mechanics code from Sandia National Laboratories. Both codes are 3d and parallel. The former models (in a locally conservative manner) the flow of oil, gas, and water fluid phases in the reservoir while the latter has been specialized to solve large-scale geomechanics problems involving significant inelastic deformations. In this paper we illustrate a uni-directional coupling of the two codes in which flow simulation output (pore pressures) from a 10-year test case based on the Belridge Field in California drives the geomechanics simulation for the same time period. The high-porosity, low-permeability Belridge diatomite undergoes significant compaction including 6 feet of vertical displacement at the top of the reservoir.

Introduction

There is widespread interest in the oil industry in modeling production in highly compactible weak formations. These simulations require an accurate representation of both fluid flow and geomechanical deformation to handle primary and enhanced oil recovery scenarios in a realistic manner. Writing a fully coupled simulator entails a great manpower investment. A more flexible and cost-effective alternative is to couple two separate simulators that have been optimized for specific classes of applications through a common high-level interface (see the paper by Settari and Mourits [1]). In the current work we combine contributions from two projects of the USDOE's Advanced Computational Technology Initiative (ACTI) program. The ultimate goal of this study is to enable "2-way" staggered-in-time linking of these two massively-parallel, three-dimensional simulators. This technique will use periodic pore pressure output from the flow simulator to drive the geomechanical deformation code over that time interval. Resulting stresses are converted to porosity updates and fed back to the flow simulator for the next time step. As a first step towards 2-way coupling, we demonstrate a simpler algorithm ("1-way coupling") in which the flow simulator runs for the full time interval with fixed porosity, outputting pore pressures at specified times during the run. Simulation of geomechanical deformation will cover the same total time interval but will use the pore pressures as periodic inputs to determine displacement and stress updates. The numerical example we describe in this paper is based on stratigraphic data and material properties from the Belridge Field in California which has been demonstrated to undergo considerable subsidence due to the extremely high-porosity diatomite reservoir rock.

Reservoir Simulation

We used an isothermal black oil reservoir simulator developed at the University of Texas to model the flow of three fluid phases: oil, gas, and water. The black oil model code solves Darcy's relation and the mass balance equations for the fluid phase concentrations, pressures, and velocities. This fully implicit, 3D, parallel model is one of several physical models currently implemented within the IPARS framework [2]. The flow domain is parceled to different processors using domain decomposition, and the flow equations are discretized using an extended mixed finite element method which maintains local conservation of mass. The poorly conditioned nonlinear system is solved via a preconditioned, parallel, GMRES iterative method.

Geomechanical Deformation

The geomechanics code (JAS3D) solves for nonlinear material deformations via explicit finite element technology developed over the last twenty years at Sandia National Laboratories. This technology does not require the formation or factorization of global stiffness matrices but relies on iterative, nonlinear conjugate gradient and self-adaptive, dynamic relaxation methods to reduce nodal residuals and achieve global equilibrium. The lack of a global stiffness matrix allows for problems with a large number of elements to be solved efficiently even on a workstation.

Numerical Example

In the flow simulation described here, we modeled a production scenario similar to the first of four production scenarios that have been implemented in the Belridge Field over the past 20 years — a rectangular patch ($\sim$ 2.5 acres) with four production wells in the corners of the domain. In the field, this production scenario ran for eight years and led to substantial subsidence and well-failure [3].

The two simulations covered the same areal extent but very different depths: 688–2264 ft for flow versus 0–3800 ft for geomechanics. The grid spacing (in all three directions) also varied substantially between the two simulations. To capture fine-scale displacement and stress changes, we used 9700 elements for the flow simulation and nearly 10 times that many elements for the geomechanics simulation in the reservoir interval alone. Both simulations were run for 10 years.

Initial water pressure ranged from 331 psi at the top of the reservoir to 900 psi at the bottom. Permeabilities from .002–.2 mD are reasonable for this field as are porosities (constant in each vertical layer) ranging from 40–57%. Eight different sets of relative permeability and capillary pressure curves were used to describe the layered flow simulation setup. The four vertical wells were completed to about 2/3's of the total reservoir depth. Pore pressures were output every 90 days for input to the geomechanics code.

The geomechanical model included three layers of overburden, eight layers of diatomite and a layer of porcelanite, and another thick porcelanite layer constituting the underburden, for a total of 13 stratigraphic layers. The three materials of the overburden and the porcelanite layers were modeled using a Drucker-Prager plasticity model. The diatomite layers were modeled using an extended Sandler-Rubin cap/plasticity model. The loads on the structure were the changes in pore pressure with time, as determined from the reservoir simulation, and gravity. An initial stress field was also specified such that the total vertical stress at any point in the configuration was computed from the weight of the overlying material. The two principal horizontal components of stress were taken to be 0.65 and 1.2 times the vertical values [3]. No displacement was permitted normal to the vertical faces of the configuration, and all displacements at the bottom of the domain were fixed.

Due to the extremely low permeability in the reservoir, the total production volume of hydrocarbons was low. Pressure decreases migrate from the wells into the reservoir domain during the simulation. Moreover, surface subsidence and vertical displacement of the diatomite layers increase with time as shown in Figure 1. Nearly a third of the total vertical displacement occurs through compaction in diatomite layer J. This layer, which is undergoing large pore pressure change, is the weakest of the eight diatomite layers. Ten years of primary production flow simulation results in vertical displacements as large as 6 ft.

Conclusions

In this initial example, we demonstrate the capabilities of the two simulators for handling complex, three-dimensional data on the field scale for both flow simulation and geomechanical deformation. The two simulation grids differed both in extent and spacing (an advantage of loosely coupled simulators). The next step includes addressing mass balance and convergence issues that arise in 2-way coupling where geomechanical porosity updates influence the flow simulation.

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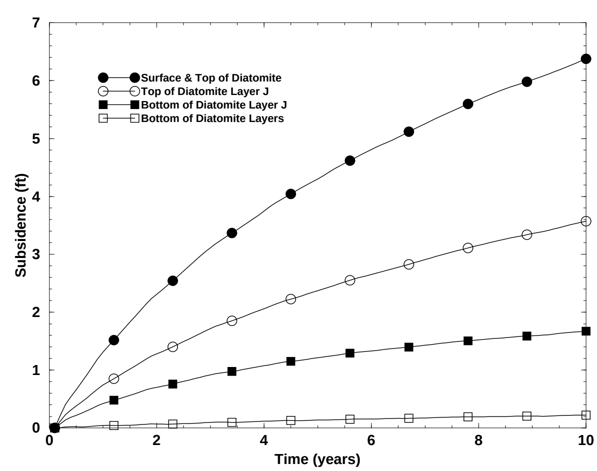

Figure 1: Subsidence history for a fixed (x, y) location and layer depths of 0, 1185, 1327, and 1792 ft.