Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0086

Vol. **28**, No. 1, pp. 401-423
July 2020

Time-Lapse 3-D Seismic Wave Simulation via the Generalized Multiscale Finite Element Method

Yongchae Cho[1,*], Richard L. Gibson, Jr.[2], Hyunmin Kim[3], Mikhail Artemyev[4] and Yalchin Efendiev[5,6]

[1] *Shell International Exploration & Production Inc., 150 N Dairy Ashford Road, Houston, TX 77079, USA.*
[2] *Department of Geology & Geophysics, Texas A&M University, College Station, Texas 77843-3115, USA.*
[3] *Shell Exploration & Production Company, 701 Poydras Street, New Orleans, LA 70139, USA.*
[4] *Arista Networks, Dublin, Ireland.*
[5] *Department of Mathematics, Texas A&M University, College Station, Texas 77843-3368, USA.*
[6] *Multiscale Model Reduction Laboratory, North-Eastern Federal University, Yakutsk, Republic of Sakha 677980, Russia .*

Received 1 April 2018; Accepted (in revised version) 28 October 2018

Abstract. Numerical solution of time-lapse seismic monitoring problems can be challenging due to the presence of finely layered reservoirs. Repetitive wave modeling using fine layered meshes also adds more computational cost. Conventional approaches such as finite difference and finite element methods may be prohibitively expensive if the whole domain is discretized with the cells corresponding to the grid in the reservoir subdomain. A common approach in this case is to use homogenization techniques to upscale properties of subsurface media and assign the background properties to coarser grid; however, inappropriate application of upscaling might result in a distortion of the model, which hinders accurate monitoring of the fluid change in subsurface. In this work, we instead investigate capabilities of a multiscale method that can deal with fine scale heterogeneities of the reservoir layer and more coarsely meshed rock properties in the surrounding domains in the same fashion. To address the 3-D wave problems, we also demonstrate how the multiscale wave modeling technique can detect the changes caused by fluid movement while the hydrocarbon production activity proceeds.

AMS subject classifications: 86A15

Key words: Fluid simulation, time lapse, Generalized multiscale finite element, elastic wave.

*Corresponding author. *Email addresses:* `ycho.geo@gmail.com` (Y. Cho), `gibson@tamu.edu` (R. L. Gibson, Jr.), `hmkim1030@tamu.edu` (H. Kim), `artemiev.mikhail@gmail.com` (M. Artemyev), `yalchinrefendiev@gmail.com` (Y. Efendiev)

1 Introduction

Time-lapse seismic monitoring problem requires a large amount of computational resources since it needs repetitive seismic imaging and waveform inversion. A classical approach of 4D seismic data processing is often done by migrating baseline and monitoring data on the same smooth tomographic model. In the 4D seismic images, we can observe that the images are misaligned due to the change of the fluid composition in the reservoir by calculating time-shifts or applying post-stack alignment by the computation of image difference products. We can apply ray theory based approach such as Kirchhoff migration for the reservoir with relatively simple structures. However, when the reservoir includes a complicated structure (i.e., salt diapir or karsts), we often take a wave-equation based method to resolve the seismic images with complex geology. In this case, an accurate simulation of seismic wave propagation is important, and the computational burden becomes more critical when we perform the wave modeling in 3D models.

In addition, characterization of the physical properties of a reservoir for flow simulations is typically performed on a coarser scale than a general seismic resolution, and that creates significant challenges for classical methods for seismic wave simulation such as finite difference or continuous-Galerkin finite element methods, because in many cases the domain is discretized according to the smallest elements. When the size of the grid cell used in flow simulations is greater than the scale of earth model (or seismic), we often need to apply an upscaling or averaging technique. This might incur a distortion of the earth properties, and too large size of the grid cell hinders a stable simulation of seismic waves with high frequency. In spite of expensive computational cost, to capture the details of the change in reservoir we need accurate simulation of seismic waves and this calculation should be repeated at time intervals corresponding to monitoring surveys. Therefore, many studies have been done to develop full wavefield modeling methods and have demonstrated a method to optimize them for time-lapse calculations. For example, Malcolm and Willemsen [1] proposed an optimization technique where a local solver is used around the time-lapse region to prevent recomputation of the wavefield in the unchanged overburden.

A popular approach for solving the wave equation numerically is to apply the finite difference method (FDM) [2–7]. FDM is widely used due to its easiness for discretization; however, it also has inherent drawbacks such as the problem of free surface topography and less flexibility to deal with an unstructured mesh. The finite element method (FEM), in contrast, provides the solutions for more flexible mesh structuring, which can model the complex topography or fracture networks. Various FEM approach have been proposed, and one classical method is continuous-Galerkin (CG) FEM [8–10]. However, compared to the other FEM methods, CG FEM might be computationally expensive since the global matrix is not diagonal or block diagonal, which requires non-trivial sparse-matrix operations for multiplication of mass and stiffness matrices with the wave solutions at each time step. As a solution of this issue, spectral element method (SEM) is proposed by Komatitsch et al. [11–13]. Nevertheless, CG FEM still has limita-