Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 151 (2018) 15–28
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Screening wells by multi-scale grids for multi-stage Markov Chain Monte Carlo simulation☆

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Received 25 February 2017; received in revised form 18 February 2018; accepted 26 March 2018
Available online 9 April 2018

Abstract

For improved prediction of subsurface flows and representation of the uncertainties of geostatistical properties, we use the framework of Bayesian statistical interface in combination with the Markov Chain Monte Carlo (MCMC) method which needs many fine-scale simulations. Hence it is essential to apply cheap screening stages, such as coarse-scale simulation to remove irrelevant proposals of the generated Markov chain, reduce fine-scale computational cost and increase the acceptance rate of MCMC. We propose a screening step, that is examination of subsurface characteristics around injection/production wells, aiming at accurate breakthrough capturing as well as above mentioned efficiency goals. However this short time simulation needs fine-scale structure of the geological model around wells and running a fine-scale model is not as cheap as necessary for screening steps. On the other hand applying it on a coarse-scale model declines important data around wells and causes inaccurate results, particularly accurate breakthrough capturing which is important for prediction applications. Therefore we propose a multi-scale grid which preserves the fine-scale model around wells (as well as high permeable regions and fractures) and coarsens rest of the field and keeps efficiency and accuracy for the screening well stage and coarse-scale simulation, as well. A discrete wavelet transform is used as a powerful tool to generate the desired unstructured multi-scale grid efficiently. Finally an accepted proposal on coarse-scale models (screening well stage and coarse-scale simulation) will be assessed by fine-scale simulation. Accepted proposals are saved for prediction. Numerical results admit increment in acceptance rate, improvement in breakthrough capturing and significant reduction in computational cost by avoiding many forward simulations.

Keywords: Uncertainty quantification; Multi-scale grid; Multi-stage MCMC simulation; Screening wells; Discrete wavelets transform

☆ This research project is financially supported by The Danish Advanced Technology Foundation in the OPTION Project (J.nr 63–2013–3).
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https://doi.org/10.1016/j.matcom.2018.03.014

1. Introduction

Reliable characterization of subsurface is an important part of accurately predicting reservoir behavior and flow patterns which are of high interest in oil and gas recovery or CO_2 sequestration. Uncertainties of porosity and permeability for a large number of grid cells, become a critical challenge in subsurface characterization, since very little data (such as phase fractional flow or transient pressure (dynamic data) and porosity and permeability at injection/production wells (static data)) is available for subsurface characterization. Reducing and quantifying these uncertainties can be achieved by comparison between available dynamic data with response of the physical model of the reservoir to a chain of proposed geological models (realizations) including static data. Hence we face an inverse problem aiming at reconstructing the spatial distribution of the permeability field as the main parameter of the geological model.

However nonlinear properties of flow and transport in porous media flows obstruct direct calculation of the probability distribution for permeability field conditioned to dynamic data. Instead we can estimate the probability distribution which are the outcomes of a large number of realizations. Moreover such estimation can be valid if the permeability realizations correctly reflect the uncertainty of subsurface characteristics. Hence it is essential to consider a reasonable prior covariance of permeability field and it is then possible to specify full prior distribution. In brief assuming known prior distribution, we generate large number of realizations and calculate the response or outcome of each realization (forward simulation) to estimate probability distribution of the permeability field. Such a probability distribution can be used in evaluation of screening criteria for well performances.

Markov Chain Monte Carlo (MCMC) method is a common choice to generate a reliable chain of proposals that needs forward simulation for each proposal and then decides to accept or reject that proposal. However, MCMC is very expensive in computational cost and accepts only a small portion of proposals since it runs many forward simulations also for the irrelevant proposals that should be rejected immediately. Hence it is essential to reject an irrelevant proposal by cheap screening steps (before forward simulation) to reduce computational cost and increase the acceptance rate.

Several developments for efficient MCMC have been proposed; for example employing a perturbation technique to identify irrelevant proposals [11], conditioning to the pressure data [18], blocking MCMC [12] and running MCMC on different scales [15]. A two-stage MCMC is proposed in [9,10] that employs coarse scale model based on single-phase coarsening of the permeability field. At first screening step a proposal is assessed with coarse-scale simulation and if it passed the screening test then a forward simulation will be run to accept or reject it. In [14] a multi-stage MCMC including a tracer test as a screening step before coarse-scale simulation has been developed.

We propose a new screening step which evaluates the response of a proposal (phase fractional curve) around wells. The practical issues and engineering aspects of this approach are addressed in [1,16]. Within short time of a wetting phase injection (for example super critical CO_2 or water in two-phase models) in both injection and production wells, we can obtain phase fractional curves to assess a proposal. More precisely we follow these steps:

1. For a short time interval, inject in injection wells and produce in production wells. The updated state of the reservoir would be the initial state of the reservoir for next step.
2. Having a initial state of the reservoir, inject in production wells and produce in injection wells then gives phase fractional curves corresponding to the injection wells. The updated state of the reservoir would be the initial state of the reservoir for next step.
3. From the latest state of the reservoir, again inject in injection wells and produce in production wells which gives phase fractional curves corresponding to the production wells.
4. Use the estimated phase fractional curves to assess the proposal.

Since in the screening wells stage we evaluate features of the permeability field around wells, it is essential to preserve fine-scale structure of the permeability field around wells, otherwise applying this approach on coarse-scale model declines important data around wells that causes inaccurate evaluation, in particular long delay in breakthrough regarding to dissipative flow behavior of coarsened blocks. If we run a simulation on fine-scale, even for a short time in comparison with full simulation time, this approach might be computationally intractable. Hence we need a multi-scale grid which preserves fine-scale features around wells as well as high permeable regions and fractures, and coarsens the rest of the field. This intelligent grid keeps efficiency and accuracy for screening well step and coarse-scale simulation. In [19,20] a discrete wavelet transform is employed to generate such a coarse-scale grid for two