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Non-stationary transport phenomena in networks of fractures: Effective simulations and stochastic analysis

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Highlights

- Optimization approach for unsteady advection–diffusion problems in fracture networks.
- Non-conforming meshes at the interfaces are used.
- Viable method to perform time-dependent simulations in large scale fracture networks.
- Stochastic collocation techniques to measure the effect of a random transmissivity.
- UQ analysis of the dispersion of a pollutant in a network of fractures.

Abstract

Among the major challenges in performing underground flow simulations in fractured media are geometrical complexities in the domain and uncertainty in the problem parameters, including the geometrical configuration. The Discrete Fracture Network (DFN) model is largely applied in order to properly account for the directionality of the flow in fractured media. Generation of DFN configurations is usually based on stochastic data and this contributes to generate very complex geometrical configurations for which a conforming mesh generation is often infeasible. Moreover, uncertainty in the geometrical and hydro-geological properties calls for a deep uncertainty quantification analysis; the corresponding huge computational cost of the simulations requires modern efficient approaches faster and cheaper than the classical Monte Carlo approach. In this paper we numerically investigate both these aspects, proposing a viable solution for dealing with geometrical complexities arising in the computation of the hydraulic head and in the solution of the unsteady transport problem of a passive scalar in the DFN, and for dealing with uncertainties in hydro-geological parameters of the fracture distribution considered.

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1. Introduction

Simulation of transport phenomena in underground fractured media is a key issue in many applications requiring the analysis of the advection–diffusion transport of a passive pollutant immersed in a bulk fluid, such as aquifers monitoring, disposal and geological storage of nuclear wastes, and, more in general, the control of the dispersion in the subsoil of any kind of contaminant deriving from industrial activities.

According to the Discrete Fracture Network (DFN) model [1–7], the underground is described as a rock matrix crossed by a network of intersecting fractures, each one being modelled as a planar polygon; fracture-resembling polygons intersect each other in segments called *traces* (see Fig. 1). DFN models are alternative to continuum-like models [8], for geological sites with a relatively low density of fractures, and are particularly useful for the description of transport phenomena, as they allow for a realistic representation of the directionality of the flow. Dimensions, orientation and hydraulic properties of the fractures in a DFN are extrapolated by probability distribution functions, derived from experimental data and samplings of the ground.

As a consequence of the stochastic generation of the networks, DFNs for practical applications are usually intricate networks, counting a large number of fractures and fracture intersections, with possibly critical features such as, for examples, very narrow angles formed by intersecting traces, non intersecting traces very close to each other and traces with length spanning several orders of magnitude. These geometrical complexities require targeted approaches for the discretization of the governing system of equations , moving from standard finite elements on conforming meshes to more unconventional settings [9–15]. In fact, it is well known that the generation of a mesh conforming to fracture intersections in a DFN often results in an infeasible process, due to the extremely large number of constraints, or would yield poor quality meshes, which in practice could not be used. Due to the above mentioned complexities, the simulation of transient flows and transport phenomena in discrete fracture networks is still a very challenging task. Some recent works on the subject can be found in [16–20].

In the present work, we will focus on the effective simulations of unsteady advection–diffusion processes in DFNs by means of a reformulation of the problem as a PDE-constrained optimization problem. We propose a modification of the optimization-based approach introduced in [13,21,22] and further developed in [23–28]; this new formulation is suitable for the application in the advection–diffusion framework in DFNs. The approach inherits the advantages of the original optimization approach: namely, the meshing process can be performed independently on each fracture; this makes the method a reliable and robust resolution tool, with an intrinsic parallel nature. These characteristics are of paramount importance also to perform uncertainty quantification analyses of transport phenomena.

The starting point of the new approach is the computation of the Darcy velocity in the DFN, which is a function of the gradient of the hydraulic head. The evaluation of the hydraulic head is performed by means of the optimization approach [13,21,22], in which the matching conditions prescribing continuity of the hydraulic head and flux balance at fracture intersections are imposed through the minimization of a proper functional, and the equations for the Darcy law on the fractures act as constraints for the minimization process. Conditions of continuity of the hydraulic head and flux balance at fracture intersection are a common choice in DFN flow simulations [9,29], but alternative choices prescribing more complex matching conditions (see, e.g., [19,30,31]) could be plugged in the optimization framework. The computed velocity field is then post-processed to remove the small components of the computed velocity in the direction normal to the fracture boundaries due to the numerical approximation of the solution where a no-flow boundary condition is prescribed. Then, the unsteady advection–diffusion problem is tackled again with a PDE-constrained optimization approach with modified constraints to account for the transport problem and for the SUPG-stabilization terms for advection-dominated flow regimes [32].

Furthermore, due to the stochastic generation of the network features, an uncertainty quantification analysis of the output of the simulations, as a function of the random parameters affecting the network, is of crucial importance. Here, we will focus on a framework in which the hydro-geological properties of the fractures are stochastically generated, whereas the geometry is assumed to be deterministic. We will use effective, recently developed uncertainty quantification techniques to analyse the effect of a stochastic transmissivity, with a prescribed distribution, on the transport of pollutants in DFNs in a time dependent framework. The use of a stochastic collocation approach on sparse grids allows to perform an uncertainty quantification analysis with a number of simulations which is smaller than the one required by, e.g., Monte Carlo method. Keeping the number of simulations as small as possible is a crucial issue, considering the high computational cost of each time-dependent simulation in large DFNs.

The structure of the paper is as follows. In Section 2 we introduce some useful notation; in Section 3 we describe the problem providing the transport velocity field, whereas in Section 4 we introduce the advection–diffusion formulation

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