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Development of a new semi-analytical model for cross-borehole flow experiments in fractured media

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ABSTRACT

Analysis of borehole flow logs is a valuable technique for identifying the presence of fractures in the subsurface and estimating properties such as fracture connectivity, transmissivity and storativity. However, such estimation requires the development of analytical and/or numerical modeling tools that are well adapted to the complexity of the problem. In this paper, we present a new semi-analytical formulation for cross-borehole flow in fractured media that links transient vertical-flow velocities measured in one or a series of observation wells during hydraulic forcing to the transmissivity and storativity of the fractures intersected by these wells. In comparison with existing models, our approach presents major improvements in terms of computational expense and potential adaptation to a variety of fracture and experimental configurations. After derivation of the formulation, we demonstrate its application in the context of sensitivity analysis for a relatively simple two-fracture synthetic problem, as well as for field-data analysis to investigate fracture connectivity and estimate fracture hydraulic properties. These applications provide important insights regarding (i) the strong sensitivity of fracture property estimates to the overall connectivity of the system; and (ii) the non-uniqueness of the corresponding inverse problem for realistic fracture configurations.

1. Introduction

The study of fractured rocks is highly important in a wide variety of research fields and applications including hydrogeology, geothermal energy, hydrocarbon extraction, and the long-term storage of toxic waste [3,10,11,16,25]. As fractures represent either rapid access to some resource of interest or potential pathways for the migration of contaminants in the subsurface, identifying their presence and determining their properties are critical, albeit highly challenging, tasks. In order to tackle these challenges, numerous fracture characterization methods have been developed; borehole geophysical logging (e.g., [12,13]), dilution tests (e.g., [21]), single and cross-borehole flow experiments (e.g., [9,18,23]), as well as temperature measurements (e.g., [14,19,24]) have all been used in an effort to gain both qualitative and quantitative information regarding the properties of individual fractures and fracture networks. Amongst these methods, cross-borehole flow analysis aims to evaluate fracture connections and hydraulic properties from vertical-flow-velocity measurements conducted in one or more observation boreholes under forced hydraulic conditions. Previous studies have demonstrated that analysis of these data, especially when acquired in a transient manner, can provide important information on fracture connectivity, transmissivity, and storativity, with significantly less effort and expense than conventional packer tests [18,22,23,26]. As such, cross-borehole flow data can yield, at the very least, key preliminary information on highly conductive fractures and/or fracture zones that may be subsequently targeted for more detailed and costly investigations.

Because of the strong non-linearity and non-uniqueness of the problem, relating vertical-flow velocities measured in a borehole to fracture hydraulic characteristics is by no means straightforward and generally requires the use of adapted mathematical models. To this end, analytically-based [9,22] and numerical [15] forward modeling approaches have been utilized for the interpretation of single and cross-borehole flow data. The strong advantage of analytically-based formulations is their low computational cost, which means that they can be effectively used within stochastic inverse approaches, as well as for parameter and predictive uncertainty quantification and detailed sensitivity analysis. Indeed, numerical solutions such as those involving finite elements, albeit highly flexible, are not generally suitable in the context of the hundreds to thousands of forward solutions necessary to address the latter goals.

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Existing analytically-based solutions for flow experiments in fractured media are either limited to single-borehole tests [9] or based on a semi-quantitative approach involving a relative description of the hydraulic properties that assumes the same storativity for all the fractures [18,23,26]. Although the latter approach, which is designed for cross-borehole studies, allows for individual fractures to intersect either the observation borehole, the pumped borehole, or both, its flexibility is limited in terms of the number of boreholes considered and the interactions between the fractures. In particular, the formulation as presented is limited to a single observation borehole, and its extension to more complex experimental configurations, if feasible, does not seem straightforward.

With the aim of addressing the above limitations, we present in this paper a new semi-analytical model for cross-borehole flow experiments in fractured media. Treating each fracture as a locally-leaky confined aquifer, borehole vertical-flow velocities are calculated by coupling the continuity equations for flow in the aquifers with a set of equations governing flow in the boreholes. Our model is presented in a general manner, with all assumptions fully noted, and it offers the flexibility of modeling a variety of fracture and experimental conditions, for example the presence of multiple observation boreholes and multiple connection configurations. We begin below with a full derivation and description of the developed semi-analytical modeling approach. Next, the approach is demonstrated in the context of sensitivity analysis for a simple two-fracture synthetic problem involving two boreholes and two different connection configurations. Finally, we present the results of estimating fracture connectivity, transmissivity, and storativity from field data collected and previously analyzed by Paillet et al. [23] using their developed semi-quantitative approach.

2. Model development

2.1. Overall approach

We consider in this paper a general cross-borehole flow experiment whereby hydraulic forcing (i.e., pumping or injection) is conducted in one borehole and transient vertical-flow-velocity measurements are acquired at different depths in one or more observation boreholes, the latter of which are usually different from the pumped borehole. Measurements of the flow velocity are considered to be available between each fracture intersecting the observation borehole(s), as well as between the most shallow fracture(s) and the surface. Depending on the connectivity of the system, the fractures in the observation borehole(s) may or may not intersect the pumped/injection borehole. As an example, Fig. 1(a) shows a schematic representation of a fractured environment where the fracture located at position $z = 26$ m in the observation borehole intersects only this borehole. The fracture located at position $z = 52$ m, on the other hand, intersects both the observation and pumped boreholes.

To model the general configuration described above, we represent the fractures as a series of equivalent confined aquifers that are hydraulically connected through the boreholes (e.g., [22,23,26]). Fig. 1(b) shows the equivalent representation of the system in Fig. 1(a) involving five confined aquifers and two boreholes. The vertical-flow velocities occurring in each borehole under forced hydraulic conditions are denoted by q_I^i, where i is the borehole number and I is the aquifer number above which the vertical flow occurs. The hydraulic properties of aquifer I are its transmissivity T_I and storativity S_I. Note that lower- and upper-case indices are used below to indicate borehole and aquifer numbering, respectively.

Development of our model for cross-borehole flow involves coupling of the continuity equations for flow in the confined aquifers with equations governing the vertical flows between the aquifers through the boreholes. The latter flows are taken into account as localized source/sink terms and their average velocities are related to hydraulic head differences in the boreholes through the Hagen–Poiseuille law. It should be noted that similar coupling methods have been used for the evaluation of fluid leakage through abandoned wells in multilayered-aquifer systems [1,6,20]. In these studies, the final solution is expressed in terms of the hydraulic head and formulated in either the time or Laplace domains, and

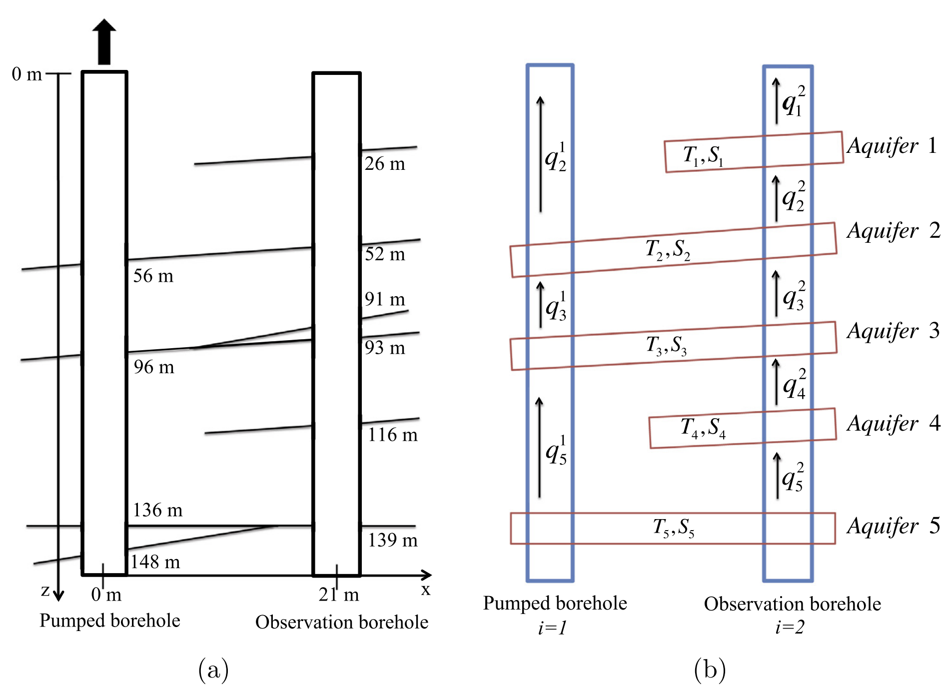

Fig. 1. (a) Schematic illustration of the fractured geological formation considered in Paillet et al. [23]; (b) Equivalent representation as a series of confined aquifers connected through the boreholes. Vertical-flow velocities measured above aquifer I in borehole i are denoted by q_I^i, whereas aquifer transmissivities and storativities are denoted by T_I and S_I, respectively.