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Multiscale Modeling and Simulations of Flows in Naturally Fractured Karst Reservoirs[†]

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Abstract. Modeling and numerical simulations of fractured, vuggy, porus media is a challenging problem which occurs frequently in reservoir engineering. The problem is especially relevant in flow simulations of karst reservoirs where vugs and caves are embedded in a porous rock and are connected via fracture networks at multiple scales. In this paper we propose a unified approach to this problem by using the Stokes-Brinkman equations at the fine scale. These equations are capable of representing porous media such as rock as well as free flow regions (fractures, vugs, caves) in a single system of equations. We then consider upscaling these equations to a coarser scale. The cell problems, needed to compute coarse-scale permeability of Representative Element of Volume (REV) are discussed. A mixed finite element method is then used to solve the Stokes-Brinkman equation at the fine scale for a number of flow problems, representative for different types of vuggy reservoirs. Upscaling is also performed by numerical solutions of Stokes-Brinkman cell problems in selected REVs. Both isolated vugs in porous matrix as well as vugs connected by fracture networks are analyzed by comparing fine-scale and coarse-scale flow fields. Several different types of fracture networks, representative of short- and long-range fractures are studied numerically. It is also shown that the Stokes-Brinkman equations can naturally be used to model additional physical effects pertaining to vugular media such as partial fracture with fill-in by some material and/or fluids with suspended solid particles.

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1 Introduction

Naturally fractured karst reservoirs presents multiple challenges for numerical simulations of various fluid flow problems. Such reservoirs are characterized by the presence

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of fractures, vugs and caves at multiple scales, as shown in Fig. 1. The media can be described, at each individual scale, as an ensemble of porous media with well defined properties (porosity and permeability), and a free flow region where the fluid (oil, water, gas) meets no resistance form the surrounding rock [13].

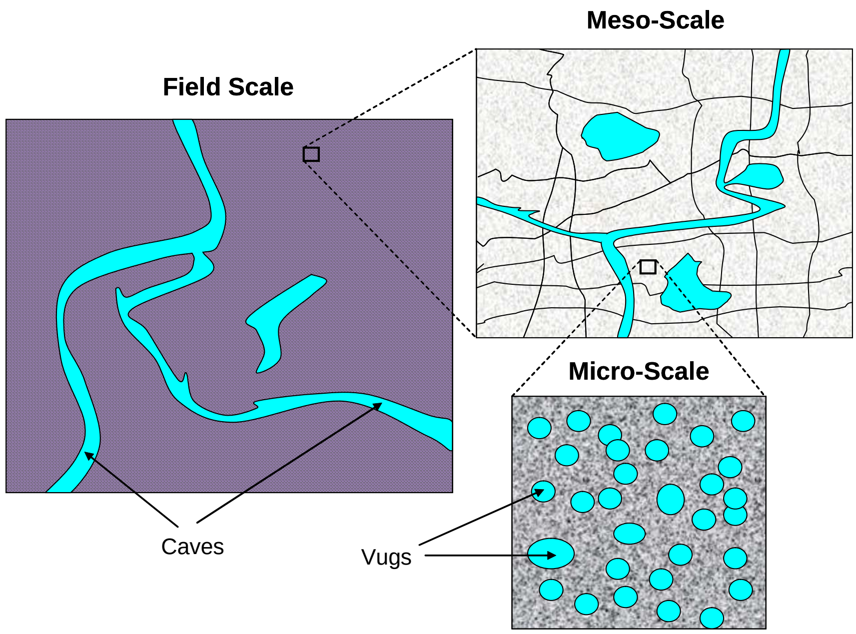

Figure 1: Conceptual model of a vuggy, fractured reservoir at multiple scales.

The main difficulty in numerical simulations in such reservoirs is the co-existence of porous and free flow regions, typically at several scales. The presence of individual voids such as vugs and caves in a surrounding porous media can significantly alter the effective permeability of the media. Furthermore, fractures and long range caves can form various types of connected networks which change the effective permeability of the media by orders of magnitudes. An additional factor which complicates the numerical modeling of such systems is the lack of precise knowledge on the exact position of the interface between the porous media (rock) and the and vugs/caves. Finally, the effects of cave/fracture fill in by loose material (sand, mud, gravel, etc), the presence of damage at the interface between porous media and vugs/caves and the roughness of fractures can play very important role in the overall response of the reservoir.

The modeling of fractured, vuggy media is traditionally done by two different approaches. The first approach, which has usually been used for vuggy media, is to use the coupled Stokes-Darcy equations [2,4,13–17,20,26,28,29]. The porous regions is modeled by the Darcy equation [8,29], while the Stokes equation (c.f., e.g., [22]) is used in the free flow region. At the interface between the two, various types of interface conditions are postulated [4,20,26,29]. All of these interface conditions require continuity of mass and