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Numerical Calculation of Equivalent Permeability Tensor for Fractured Vuggy Porous Media Based on Homogenization Theory

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Abstract. A numerical procedure for the evaluation of equivalent permeability tensor for fractured vuggy porous media is presented. At first we proposed a new conceptual model, i.e., discrete fracture-vug network model, to model the realistic fluid flow in fractured vuggy porous medium on fine scale. This new model consists of three systems: rock matrix system, fractures system, and vugs system. The fractures and vugs are embedded in porous rock, and the isolated vugs could be connected via discrete fracture network. The flow in porous rock and fractures follows Darcy's law, and the vugs system is free fluid region. Based on two-scale homogenization theory, we obtained an equivalent macroscopic Darcy's law on coarse scale from fine-scale discrete fracture-vug network model. A finite element numerical formulation for homogenization equations is developed. The method is verified through application to a periodic model problem and then is applied to the calculation of equivalent permeability tensor of porous media with complex fracture-vug networks. The applicability and validity of the method for these more general fractured vuggy systems are assessed through a simple test of the coarse-scale model.

AMS subject classifications: 35B27, 35Q30, 76S05

Key words: Fractured vuggy porous media, equivalent permeability tensor, homogenization, upscaling.

1 Introduction

Evaluation of the equivalent permeability of fractured vuggy porous media has a great interest in petroleum and geotechnical engineering. Such porous media, which are very

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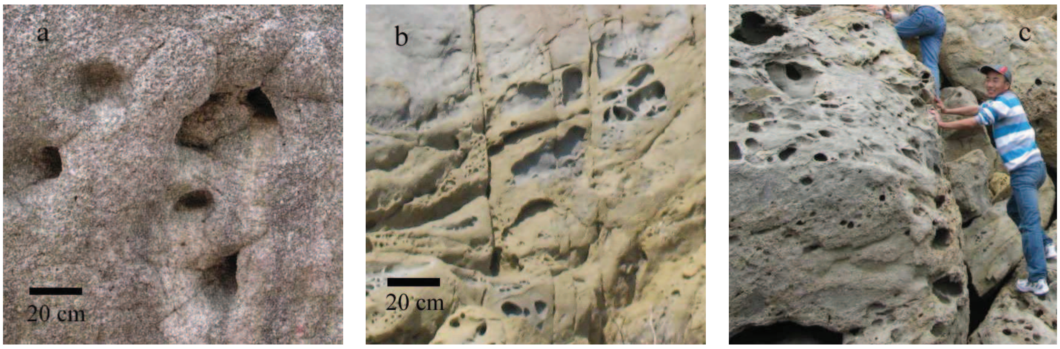

Figure 1: Typical outcrop of fractured vuggy porous media: (a) limestone; (b) dolostone; (c) carbonate rock.

common in the earth's crust especially in carbonate rocks (cf. Fig. 1), contain not only matrix and fractures but also the vugs that are irregular in shape and vary in size from centimeters to meters in diameter [1,2]. The presence of vugs which are connected via discrete fracture networks can significantly increase both the porosity and the permeability of the porous media [3,4]. Although there are reliable methods to estimate porosity and fluid saturation, reliable permeability estimation is difficult for fractured vuggy porous media due to the presence of fractures and vugs at multiple scales. These types of multiscale rock fabric are difficult to study mainly because they are on a scale that is too large to quantify using thin sections, and frequently on a scale that is too large to quantify adequately using core samples which are only a few centimeters in diameter [5]. Therefore, it is not realistic to predict the effective permeability of these rock fabrics on the field scale using experimental methods.

As an alternative method, numerical upscaling calculation based on accurate geologic models has received much attention recently. While using numerical upscaling calculation methods to evaluate the permeability of porous materials, two important steps should be mentioned. Modeling the fluid flow through fractured vuggy porous media on fine scale is the first step on which the main difficulty is the co-existence of porous flow and free-flow regions. And then, how to incorporate this fine scale data into coarse scale flow properties is the key step. Neal et al. [6] are the pioneers of the related research; they studied the impact of spherical vugs on the permeability in homogeneous isotropic porous media. In their study, creeping Navier-Stokes equation was employed in the spherical cavity, and the Darcy equation was used to describe the flow in porous medium. Applying the formula for the pressure field near a single spherical cavity, they developed an analytical formula for permeability of a vuggy porous medium.

Recently, Arbogast et al. [3,7,8] modeled the vuggy porous medium on the fine scale using Stokes equations in the vugs, Darcy's law in the porous rock, and the Beavers-Joseph-Saffman boundary condition on the interface between the two regions. By using the tools from homogenization theory, they obtained a macroscopic Darcy's law governing the medium on coarse scale. In order to evaluate the effective coarse scale permeabil-