Fast Upscaling of the Hydraulic Conductivity of 3D Fractured Porous Rock for Geothermal Reservoir Modeling

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A fast upscaling procedure for determining the equivalent hydraulic conductivity of a three dimensional (3D) fractured rock is presented in this paper. A modified semi-analytical superposition method is used to account for both the hydraulic conductivity of the porous matrix (Km) and of the set of fractures (Kf). The connectivity of the conductive fracture network is also taken into account. We validate our upscaling approach by comparison with the hydraulic conductivity of synthetic samples calculated and upscaled with numerical procedures. The modified superposition approach is in good agreement with numerical results for infinite size fractures. For finite size fractures, we propose an improved model to take into account the connectivity of the fracture network, by introducing semi-empirical multiplicative connectivity indices. The improved model shows good agreement with the numerical results for different configurations of fracture networks.

Key words: Fractured porous medium; 3D upscaling; Equivalent conductivity; Numerical simulations; Darcy, Random fracture sets; Connectivity.

Extended Abstract

This work is being conducted as a part of a French R&D project (www.geotref.com), funded by the French national agency Ademe, for developing & modeling the recovery of geothermal energy from deep, high temperature fractured reservoirs. One of our contributions to the project is to provide upscaling procedures for determining the equivalent continuum (macroscale) hydro-thermal properties of the heterogeneous fractured rock. At this stage, we are interested in upscaling the hydraulic conductivity (K).

This study is an extension of the superposition approach for upscaling initiated by Snow (1968), continued by Oda (1986), and later adapted to account for matrix as well as fracture flow (Canamon 2005; Ababou et al. 2010).

In the updated superposition approach (present work), the 3D fractured porous domain is partitioned into a set of “single-fracture” blocks, or “unit” blocks. Each block contains a single fracture surrounded by a portion of the permeable matrix (determined from statistical densities). An analytical solution is obtained by setting appropriate boundary conditions (piecewise linear pressure), averaging the pressure gradient and flux, and finally obtaining the “exact” equivalent local hydraulic conductivity of each “unit” block. Then, the contributions of all unit blocks to the total flux are superposed, taking into account fracture orientations, diameters, and apertures, to deduce finally a tensorial equivalent conductivity (Kij) for the upscaling domain.

The resulting tensor takes into account the geometric anisotropy of the fracture set, and at the same time, it incorporates the permeability of the porous matrix. This is important, because the matrix may contain finer fractures that are not seen explicitly, and hence, its permeability must not be neglected.

To validate the superposition method and to test for improvements, we have developed computational flow experiments to determine numerically (rather than theoretically) the equivalent hydraulic conductivity of synthetic samples of fractured porous rocks in 2D & 3D. We use for these the commercial software Comsol Multiphysics (Finite Elements), and the free software BigFlow 3D (Finite Volumes). As expected, for fully connected fracture networks (e.g. infinite size fractures), the upscaled permeability tensors obtained by superposition and numerically are in good agreement. For non-connected or weakly connected networks, the superposition method over-estimates the equivalent hydraulic conductivity.

We use these comparative results to design a modified upscaling approach that accounts for fracture connectivity as well as matrix permeability. Empirical connectivity indices are proposed, and the superposition method is reformulated. Comparisons between the new superposition (as reformulated here) and numerical results, indicate a significant improvement on predicting the equivalent hydraulic conductivity of fractured porous media with different degrees of connectivity (Figure 1).

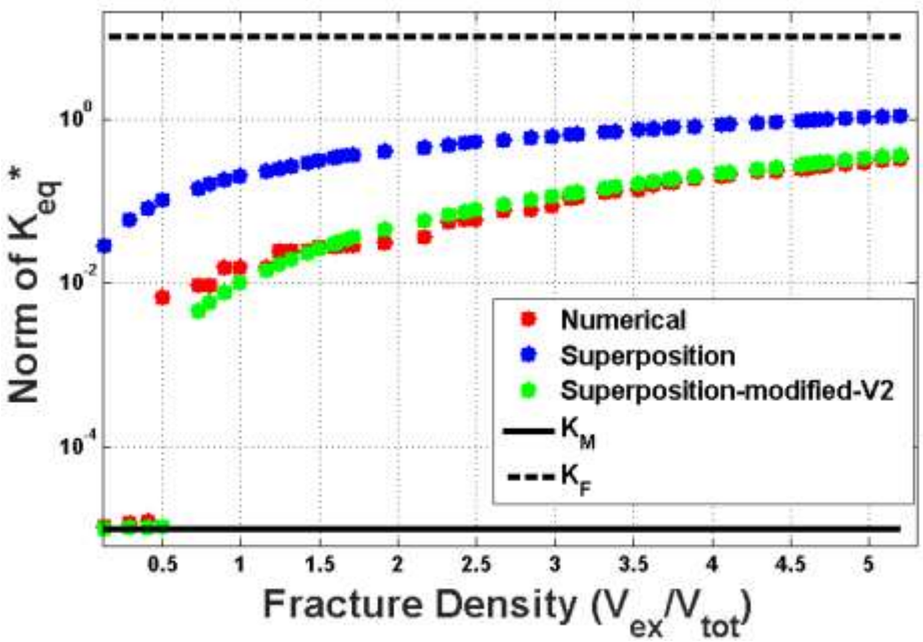

Figure 1: Semi-log representation of the norm of the equivalent hydraulic conductivity tensor, as a function of the dimensionless fracture density: numerical (red symbols), initial superposition method (blue symbols) and modified superposition method (green symbols). For comparison, the matrix and fracture conductivities are also shown: the solid curve represents Km (matrix conductivity) and the dashed curve represents Kf (fracture conductivity).

Outlook. We are currently extending this work towards application to a fractured geothermal reservoir. The equivalent tensorial Kij(x,y,z) is spatially distributed (projected) over an unstructured Finite Volume grid (Open Foam), in order to implement reservoir scale simulations with injection and production wells.

References

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