On the equivalent permeability of fractured porous media

Ismael R. Vasconcelos Neto[1,2], Cristian Mejia[1], Deane M. Roehl[1,2]

[1]*Tecgraf Institute, Pontifical Catholic University of Rio de Janeiro – PUC-Rio*
Rua Marquês de São Vicente 225, 22451-900, Gávea, Rio de Janeiro/RJ, Brazil
ismaelribeiro@tecgraf.puc-rio.br, crisms@tecgraf.puc-rio.br, deane@tecgraf.puc-rio.br
[2]*Dept. of Civil and Environmental Engineering, Pontifical Catholic University of Rio de Janeiro – PUC-Rio*

Abstract. Fractured porous media are present in different geological formations, such as rock masses and oil reservoirs. The proper modeling of these fractured systems is of high relevance to the permeability assessment and production management of the reservoirs. The fracture networks present in these media have a significant contribution to fluid flow, once they create preferential paths for fluid transport. This work discusses the influence of the fracture geometry on the equivalent permeability of fractured porous media. A generalized dual porosity/dual permeability (DPDP) model is adopted to incorporate the fracture sets implicitly into the porous matrix. This formulation was implemented into an in-house multiphysics framework called GeMA. Due to the ease to simulate fractured porous media using DPDP, the influence of several parameters such as fluid viscosity, matrix permeability, and fracture opening, spacing and orientation, are simulated generating a large number of models. For each model, the horizontal and vertical equivalent permeabilities were estimated by applying a horizontal and vertical pressure gradient, respectively. The numerical results showed that the fracture geometric characteristics have a significant influence on the equivalent permeability and the dual porosity/dual permeability model is a powerful approach to represent the behavior of fractured porous media.

Keywords: equivalent permeability, dual porosity/dual permeability, fractured porous media.

1 Introduction

Fractured porous media are present in different geological formations, and they are of interest in several applications: reservoir exploitation for water supply, petroleum reservoir exploitation, geothermal reservoir exploitation and heat storage, mineralization processes, and geotechnical applications [1]. The fractures present in these media can create preferential paths for the fluid flow process, which are strongly induced by them. Thus, the investigation of the fracture systems is important to understand the physical process and properties involved and hence develop improved strategies of exploitation and production on these formations. However, the detailed characterization of fractured media is still challenging, mainly due to the lack of data and information. For this reason, numerical models became essential tools to represent the behavior of fractured porous media and to simulate fluid flow through them [2], [3].

There are many approaches available to simulate the fluid flow process that incorporate the effect of fractures in different ways in these formations. Two major methods have been proposed to represent fractured systems using implicit and explicit representations of fractures: dual-porosity/dual-permeability (DPDP) and discrete fracture models (DFM). The dual continuum concept was first introduced by Barenblatt et al. [4], and assumes fluid flow through two porous medium. Warren and Root [5] applied this concept to characterize naturally fractured reservoirs. In this approach, fluid migration through fractured porous media consists of the fluid flow in the matrix and in the fracture domain, and the fluid exchanges between them are represented by transfer functions. This model is suitable for a fractured porous medium with a large number of highly connected small-scale fractures. On the other hand, the DFMs consider the effect of individual fractures within the domain explicitly, providing more realistic representations of the fracture geometry and accurate results. However, the DFM is computationally expensive and needs mesh refinement to conform with the fracture geometry. This is a time consuming and cumbersome task [6], [7].

Several studies have demonstrated that the permeability, that allows the fluid to flow through the pores, is strongly influenced by fracture characteristics and geometry [8], [9]. Hence, it is important to investigate accurate solutions to model fluid flow problems in fractured porous media. In this context, Bogdanov et al. [10] provided a numerical solution of flow in such media, presenting the determination of the permeability. Matthai and Belayneh [11] examined flow perturbations caused by fractures and the effect of their geometric arrangement on the effective permeability. Based on a 2D model to measure the effective permeability, Paluszny and Matthai [2] reported the impact of fracture patterns on fluid flow as a function of fracture density. Later on, instead of considering only a single fracture set, Kubeyev [3] investigated the influence of multi-sets on the effective permeability of fractured media. More specifically, [3] studied the impact of specific fracture characteristics, such as density, spacing, connectivity, and matrix permeability.

This work studies the influence of fractures on the equivalent effective permeability of a porous medium using the DPDP formulation presented by Rueda et al. [12]. This approach incorporates the effect of multiple fracture sets implicitly. Due to the facility to simulate fractured porous media, the influence of fracture parameters on the effective permeability is investigated simulating a large number of models varying the fracture opening, spacing and orientation, matrix permeability, and fluid viscosity.

This paper is organized as follows. Section two summarizes the governing equations for fluid flow using dual-porosity/dual-permeability formulation. Section three presents the numerical model adopted to study the fracture influence on the equivalent permeability of fractured porous media. Section four discusses the numerical results obtained. Finally, section 5 presents the concluding remarks.

2 Dual-porosity/Dual-permeability formulation

A hydraulic model based on dual porosity approach was proposed to compute the effective permeability and to evaluate the effect of fracture characteristics on the fluid flow of a fractured porous medium.

2.1 Governing equations of fluid flow

The dual-porosity/dual-permeability model represents the single-phase fluid flow in a fractured porous medium using two porous media. The governing equations of both media, matrix and fractures, are expressed by the following equations:

$$\nabla \cdot \left(\frac{k_m}{\mu} \nabla p_m\right) + \beta_m \frac{\partial p_m}{\partial t} + \omega\left(p_m - p_{fr}\right) + q_m = 0\,, \tag{1}$$

$$\nabla \cdot \left(\frac{k_{fr}}{\mu} \nabla p_{fr}\right) + \beta_{fr} \frac{\partial p_{fr}}{\partial t} - \omega\left(p_m - p_{fr}\right) + q_{fr} = 0\,. \tag{2}$$

The subscripts m and fr denote the parameters of matrix and fractures, respectively. Here, k is the permeability, μ the fluid viscosity, β the relative compressibility, q is the applied fluid flow, and p the fluid pressure. As mentioned before, the fluid exchange between the two systems is expressed through the transfer function that is represented by the shape factor ω.

2.2 Fracture permeability

The model adopted represents the fractured media through fracture sets. Considering incompressible and Newtonian fluid, the cubic law of smooth parallel plates describes the fluid flow through the fracture system[12], [13]. The fracture permeability of a single fracture set is defined as follows:

$$k_{fr} = \frac{b^3}{12\, s}\,, \tag{3}$$

where b is the fracture opening and s represents the fracture spacing.

2.3 Equivalent permeability of fractured porous media

Based on the flow-based approach, the effective permeability of a fractured porous medium can be approximated using Darcy's law. A pressure gradient ΔP is prescribed to induce a fluid flow rate Q through the model and evaluating the effective permeability as follows

$$K_{eq} = \frac{Q\ \mu_f\ L}{A\ \Delta P}\ , \tag{4}$$

where L is the length of the model in the flow direction, A is the cross-sectional area perpendicular to the flow, and μ_f is the dynamic fluid viscosity.

3 Experimental setup

The numerical simulations were performed using the DPDP approach implemented into the multiphysics framework GeMA (Geo Modeling Analysis) [14]. The simulator is capable of simulating fractured porous media considering multiple fracture sets with different orientations. The fracture systems are defined in the model by the fracture opening, spacing, and angle between fracture sets. They are distributed uniformly in the model domain.

The model consists of a block of porous media (50 m x 50 m) with fracture sets. Two scenarios are investigated. The former considers a single fracture set while the second scenario adopts two fracture sets. Figure 1 illustrates the boundary conditions and schematic representation of the fractured porous medium. Horizontal and vertical fluid flow through the fractured porous medium is induced by prescribing horizontal and vertical fluid pressure gradient, respectively. The fluid flow rate Q_{in} and Q_{out} in the steady-state flow condition is obtained from the numerical model. .

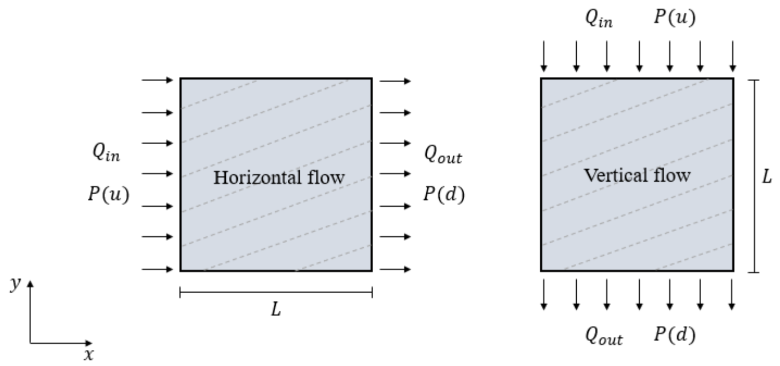

Figure 1. Schematic representation of fractured porous medium and boundary condition

The numerical results present the influence of the following parameters: fluid viscosity, matrix permeability, and fracture opening, spacing, and fracture orientation. Table. 1 summarizes the range of each parameter. These values were combined to generate a large number of different configurations of the fluid flow in fractured porous media.

Table 1. Input parameters adopted for scenario 1

Parameter	Unit	Range of values
Fluid viscosity, μ_f	cp	[1, 10, 50, 100, 250, 500, 750]
Matrix permeability, K_m	mD	[1, 10, 50, 100, 250, 500, 750, 1000]
Fracture opening, b	mm	[0.05, 0.1, 0.25, 0.5, 0.75, 1]
Spacing, S	m	[1, 5, 10, 15, 20, 25]
Orientation, θ	º	[0, 10, 20, 30, 40, 50, 60, 70, 80, 90]

Furthermore, the fracture influence for scenario 2 with two fracture sets was also investigated. The same parameters adopted in scenario 1 were varied for each fracture set including the relative angle between both fracture sets. Table 2 presents the input parameters adopted in scenario 2.

Table 2. Input parameters adopted for scenario 2

Parameter	Unit	Range of values
Dynamic fluid viscosity, μ_f	cp	[1, 100]
Matrix permeability, K_m	mD	[1, 100]
Fracture opening for both sets, b_1, b_2	mm	[0.05, 0.1, 0.25, 0.5, 0.75, 1]
Spacing for both sets, S_1, S_2	m	[1, 5, 20]
The orientation of 1st set, θ_1	º	[0, 10, 20, 30, 40, 50, 60, 70, 80, 90]
Relative angle between both sets, θ_e	º	[10, 20, 30, 40, 50, 60, 70, 80, 90]

4 Results

This section discusses the numerical results obtained after the parametric analysis. For each scenario, several parameter combinations are investigated to evaluate the horizontal and vertical equivalent permeability. Thus, a data set was built considering all numerical simulations. Thereby, the effect of some fracture parameters on the horizontal equivalent permeability is presented below.

4.1 The effect of matrix permeability and fluid viscosity

The effect of matrix permeability is studied varying the fracture spacing, orientation, and adopting constant values of fluid viscosity and fracture aperture. Figure 2 shows the influence of matrix permeability on the equivalent horizontal permeability. Figure 2a presents the effect of matrix permeability considering fluid viscosity of 1.0 cp and fracture opening of 0.05 mm while Fig. 2b shows the permeability effect considering a fluid viscosity of 1.0 cp and fracture opening of 1.0 mm.

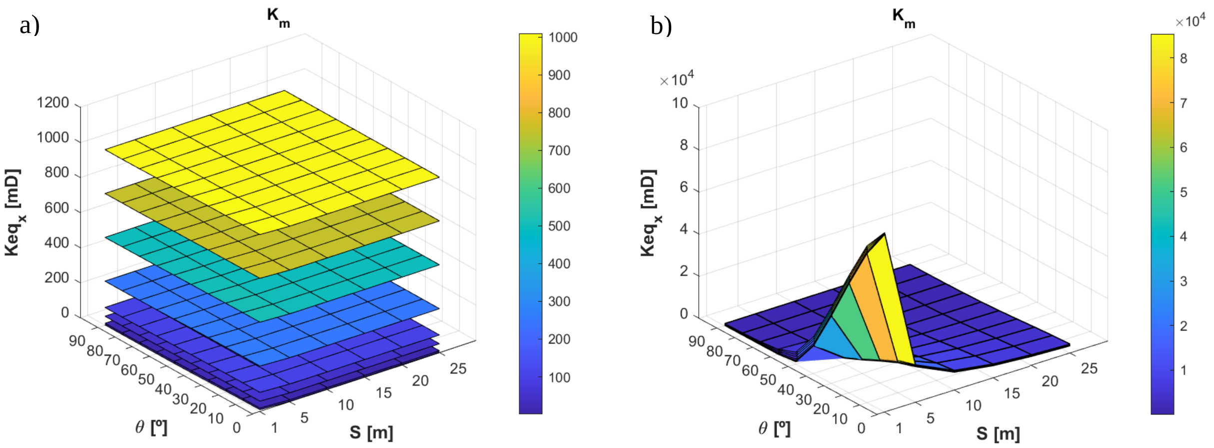

Figure 2. The effect of matrix permeability considering fracture opening of (a) 0.05 mm and (b) 1.0 mm

In both cases, high fracture density (small fracture spacing) and low fracture orientation show larger influence on the equivalent permeability. Although the high fracture density, small fracture opening has a small contribution to the equivalent permeability. It means that the equivalent permeability is very close to the matrix permeability. On the other hand, Fig. 2b presents a significant influence of the large fracture aperture (1mm) on the equivalent permeability. Then, high fracture density with a high fracture aperture has the greatest contribution to fluid flow through the fractured porous medium.

The fluid viscosity effect was studied considering a constant matrix permeability of 1 mD and two combinations of fracture opening. Figure 3a shows the influence of fluid viscosity on the equivalent permeability considering fracture opening of 0.05 mm, while Fig. 3b presents the effect of viscosity on the equivalent permeability for fracture aperture of 1.0 mm. The orientation and the fracture spacing were varied.

For both cases, the surfaces obtained for different fluid viscosity are the same and overlap each other, indicating that this parameter does not influence the equivalent permeability for the analyzed situations.

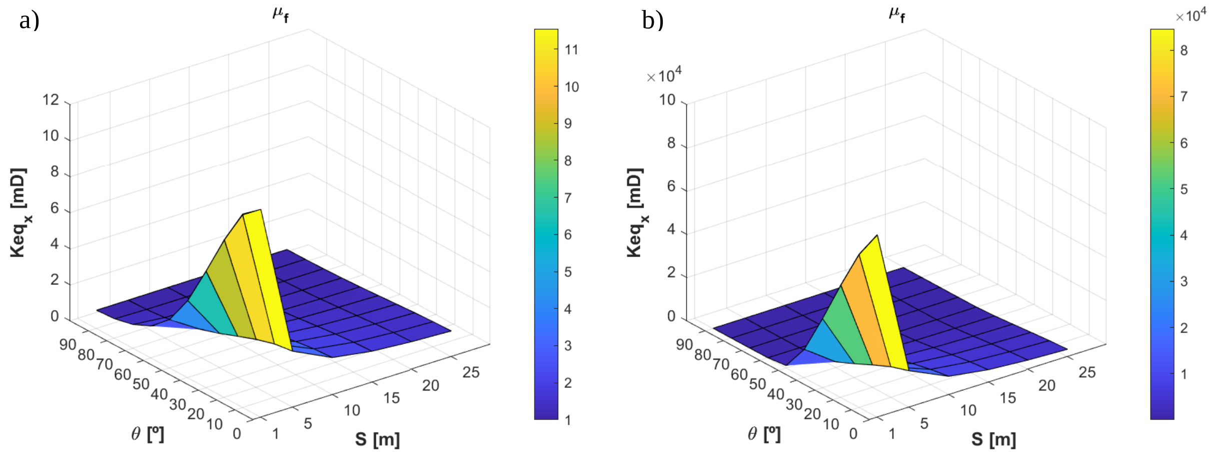

Figure 3. The effect of fluid viscosity considering fracture opening (a) 0.05 mm and (b) 1.0 mm

4.2 The effect of fracture opening, spacing, and orientation

The effect of fracture characteristics on the equivalent permeability was investigated by assuming a constant fluid viscosity of 1 cp and matrix permeability of 1 mD. Figure 4 depicts the equivalent permeability for different fracture characteristics. Each surface is obtained for different orientations and varying fracture opening and spacing. The results demonstrate that the fracture set with a high fracture aperture and small spacing has the most significant contribution to the equivalent permeability. Considering horizontal fluid flow, the fracture set with a low angle with the fluid flow direction (near 0°) increases its contribution in the equivalent permeability. In comparison, a high angle (near 90°) reduces its contribution.

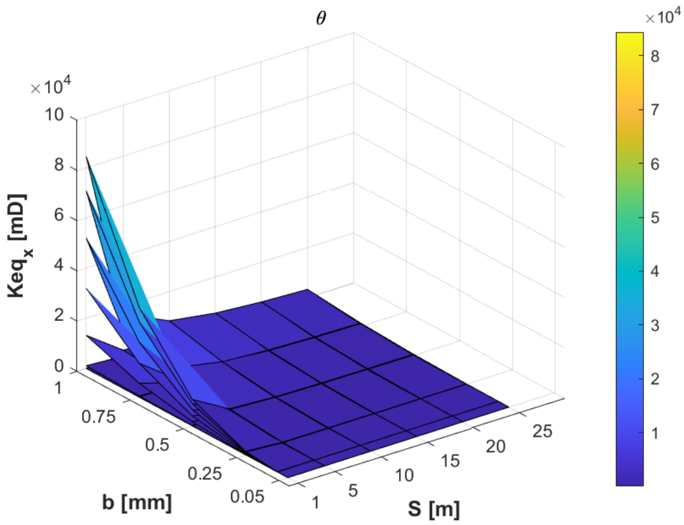

Figure 4. Influence of fracture opening, spacing, and orientation on the equivalent permeability

4.3 The effect of two fracture sets

This section investigates the influence of two fracture sets on the equivalent permeability. For this case, more parameters affect the equivalent permeability as detailed in Tab.2. Therefore, some fracture parameters are adopted constant such as fluid viscosity of 1.0 cp, matrix permeability of 1 mD, fracture spacing for set 1 and 2 of 1.0 m, and fracture orientation of 0º related to the fluid flow direction. The parametric analysis focused on the influence of the aperture of both fracture sets b_1, b_2 and the angle θ_e between them.

Figure 5 shows the influence of two fracture sets on the equivalent permeability for the described configuration. Based on the numerical results, the most significant contribution to the equivalent permeability is observed for high fracture apertures and a low relative angle between fractures.

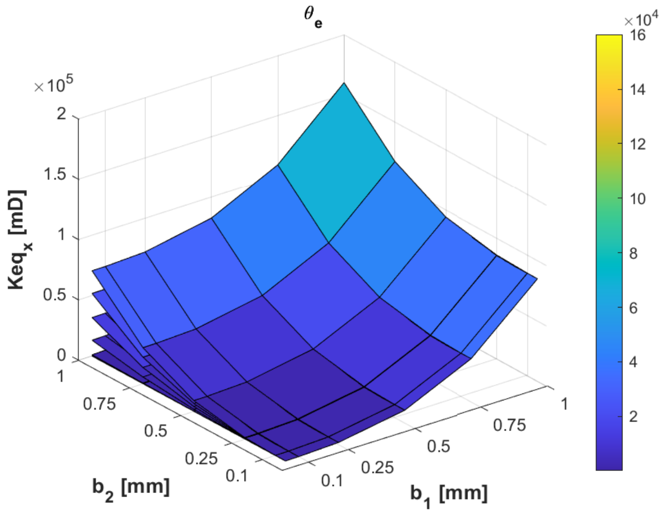

Figure 5. The effect of two fracture sets on the equivalent permeability

5 Concluding remarks

This work adopts a DPDP model to include the fracture contribution implicitly into the fractured porous media. The results show the influence of different fracture parameters in the equivalent horizontal permeability. The parametric study reveals a low contribution of the matrix permeability and fluid viscosity to the equivalent permeability. On the other hand, the fracture characteristics (opening, spacing, and orientation) have a significant influence. Then, the parametric study demonstrates that the equivalent permeability is strongly affected by the fracture opening and spacing. Also, fractures oriented with the pressure gradient have a substantial contribution to fluid flow, while fractures perpendicular to the pressure gradient have an insignificant contribution.

This work provides a better understanding of the influence of fracture geometry on the equivalent permeability of fractured porous media. The DPDP formulation proved to be a powerful approach to represent fracture sets with different scales in the porous media.

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