Journal of Petroleum Science and Engineering 120 (2014) 194–201

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Prediction of permeability in dual fracture media by multivariate regression analysis

Mahsa J. Habibi *, Ahmad Reza Mokhtari, Alireza Baghbanan, Sajad Namdari

Department of Mining Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

ARTICLE INFO

Article history:
Received 7 November 2013
Accepted 18 June 2014
Available online 24 June 2014

Keywords:
multivariable regression analysis
permeability
dual porosity
Voronoi

ABSTRACT

One of the most important characteristics of naturally fractured rocks for simulating the flow in the hydrocarbon reservoir is permeability. There are two major approaches in modeling fluid flow in fractured rocks: the discrete fracture network (DFN) model which is a special case of DFM models where fractures and matrix of rock mass are treated explicitly. DFN models consider the flow only in fracture pattern and neglect the rock matrix conductivity, and the dual porosity (DP)/dual fracture (DF) model. In the latter method two overlaid media are considered: rock matrix and fractures. In this study the permeability of 2D fractured and permeable rock matrix is calculated using a distinct element method when the rock matrix is modeled by Voronoi tessellations. Totally 860 models of the synthetic fracture networks were generated based on different fracture features with different fracture densities and aperture patterns and different sizes of Voronoi tessellations that exemplify different grain sizes in rock matrix and micro-apertures. According to the literature, this is the first case which such sensitivity analysis about the effect of geometrical parameters of fractures and grain patterns is considered which is the main objective of this research work. The results show a significant difference between calculated permeability of dual fracture models and discrete fracture network (DFN) models. Using all calculated models permeability, a practical equation is proposed that consists of different statistical and fractal characteristics of fracture patterns using multivariate regression analysis (MRA). High correlation coefficient value was emerged between different input parameters. Thus the principal component regression (PCR) was used to eliminate this problem.

1. Introduction

Understanding the accurate value of permebaility in different rock engineering projects is so important. Numerical simulation of flow processes in fractured rock masses is a formidable task due to the often complex geological and hydrological characteristics of such formations. The specific geometry and other characteristics of the fracture system are generally not known; therefore it is not possible to model individual fractures or matrix blocks explicitly. To circumvent this difficulty, double porosity models are often used (Zimmermann et al., 1993). When the rock matrix is permeable, other parts of the fracture system not lying on the backbone structure can also contribute significantly to flow, although their influence is normally secondary to that of the connected fracture structure (Odling and Roden, 1997). Barenblatt and Zheltov (1960) and Barenblatt et al. (1960) studied such systems as a double-porosity medium. Zimmermann et al. (1993) and Bai et al. (1994) proposed semi-analytical and analytical methods for fluid flow simulation in dual porosity media, respectively. Odling (1992) introduced a 2D model matrix while Massonnat and Manisse (1994) used a 3D fracture flow model which they take the matrix permeability into account. Zhang et al. (2002) and Samardzioska et al. (2005) studied the dual-porosity model for a naturally fractured reservoir numerically. Namdari (2010) has employed distinct element method to investigate the effect of the fracture network geometry, fractures density over the total permeability and the effect of matrix permeability and the relation between aperture and fracture length on the representative volume size and the simultaneous influence of these parameters on permeability. Voronoi tesselations with permeable boundary were used as a permeable rock matrix. The discernible differences are observed between DFN and dual porous model. Despite these research works, numerical modeling of dual fracture reservoirs is still a complicated and costly process. Therefore there is a tendency to use the methods which are more simple and inexpensive and need less calculation and time consuming compared to numerical modeling, although these methods include more parameters. Multivariate analysis is one of the methods which prevent tedious calculations especially during the initial stages of investigation and planning the project. Some research works have

* Corresponding author. Tel.: +98 9125707411; fax: +98 3113912776.
E-mail address: m.jhabibi@mi.iut.ac.ir (M.J. Habibi).

http://dx.doi.org/10.1016/j.petrol.2014.06.016
0920-4105/

attempted to predict permeability of fractured rocks employing the multivariate analysis especially in oil fields based on the core data or porosity of the media as a single input for the regression analysis. Jafari and Babadagli (2010) developed an equation for predicting the permeability of synthetic and natural fractured rock model based on their fractal and geometrical properties. However they did not consider the matrix permeability and matrix characteristics. Hence, this is the first time that such sensitivity analysis about the effect of geometrical parameters of fractures and grain patterns and the way of modeling of rock matrix is conducted. A prediction equation should consider all effective parameters including the matrix charactereitics which may not be measured in some limited mapping results from some specific field works. This study is based on the results of a sensitivity analysis about the effect of micro/macro-geometrical properties of intact/fractures of rock mass on permeability of the dual fracture model which was done and reported in Namdari et al. (2012) and the result explained briefly in Section 2 of this paper. A number of dual porous (dual fracture) models are firstly generated. These models are generated by adding the Disceret Fracture Network (DFN) to the granular part (rock matrix) which are modeled by using the tesselation elements called Voronoi tesselations. Then permeability of these models are calculated using numerical modeling to enter as input data for multivariate analysis. Finally, a linear regression equation is developed based on the processed input data. Since other research works in this field of study were either considered a simple DFN model or just a linear regression analysis without considering the inter-correlation effect between input parameters the current work has not been repeated previously.

2. Calculating permeability of dual fracture models

2.1. Model development

The fractured permeable rocks modeling in numeric analysis could be divided into two major and separate steps: generation of discrete fracture network (DFN) and simulating the rock matrix. Firstly, in order to simulate the granular texture of rock matrix and correspond porosity of it, the Voronoi tessellation is used. Using universal distinct element code (UDEC) randomly sized polygonal blocks are used to generate the rock matrix. These tessellations previously used to simulate the propagation of cracks between blocks, but here the appropriate size of them considering the limitation of software are used to shape the matrix. The size distribution of Voronoi blocks can be more uniform by increasing the iteration number (UDEC User's guide, 2004); however the grain textures are not quite uniform, hence in this study the default number of iteration ($n=5$) is used to approach the real texture of rock. The initial model was generated with 3 mm grain size and 85 nm corresponding aperture which are approximated using back analysis technique through the back calculation and calibration with field/laboratory experimental test results. Then for expanding the range of data the different realization of 2, 3 and 5 mm Voronoi are generated within square domain (20×20 cm^2) which geometric shape and size of all the samples remain constant to study the other parameter effect on the total permeability. In addition, the boundary of these elements could be defined permeable and have changeable distance with each other for representing the porosity of matrix which is called here, micro-aperture. Hence, three different values: 40, 85 and 160 nm assigned to these micro-apertures. The discernible difference in Voronoi pattern is depicted in Fig. 1. In addition, permeability in DFN can be controlled by the density of fractures and it depends on individual fracture characteristics such as aperture, orientation and trace length of fractures. In generation of DFN, all these factors should be taken into account. The fracture networks were generated by a developed code FracIUT^{2D} (Baghbanan and Joolaei, 2010) based on the probabilistic density function of fracture trace length, orientation of fractures and location of fractures using the Monte Carlo method which is a computational algorithm that rely on repeated random http://en.wikipedia.org/wiki/Random sampling to obtain numerical results (Baghbanan, 2008).

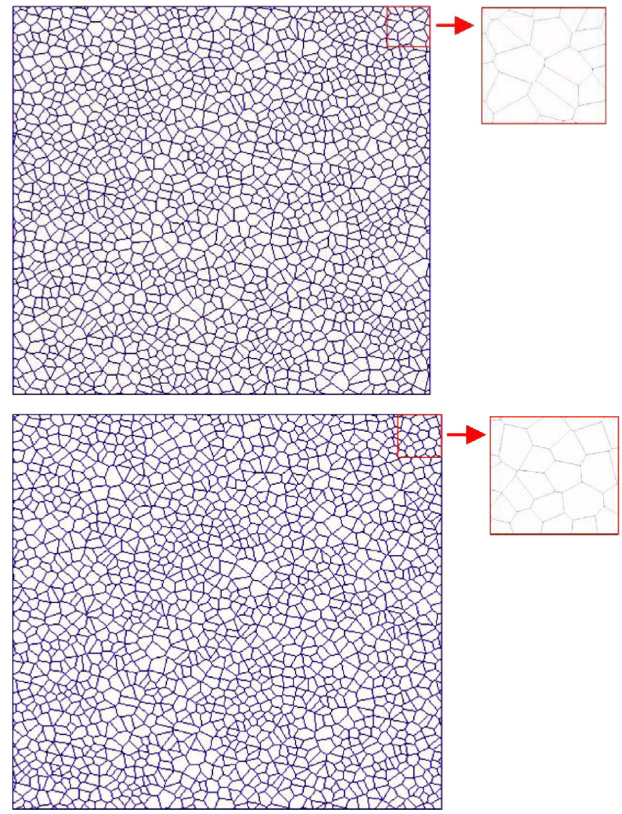

Fig. 1. Difference between 5 mm Voronoi tessellation pattern in different realization of models.

Table 1
The statistical parameters measured in Sellafield.

Joint set	Dip angle/direction	Fissures coefficient (K)	Density (m^{-2})
1	8.145	5.9	4.6
2	88.148	9.0	4.6
3	76.21	10.0	4.6
4	69.87	10.0	4.6

To generate the synthetic models and fracture networks required parameters were collected and classified from Sellafield site, United Kingdom. Table 1 shows the statistical parameters measured in Sellafield site. In this study it was assumed that fracture trace lengths follow power law distribution and calculate using the following equation:

$$l=(l_{min}^{-D}+F(l_{max}^{-D}-l_{min}^{-D}))^{-1/D} \quad (1)$$

where l_{min} and l_{max} are the minimum and maximum trace lengths, D is the fractal dimension, and F is random number uniformly distributed in the range $0\le F\le1$. The location of fractures follow a Poisson distribution which the coordinate of the middle point of