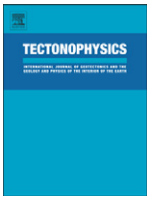
Tectonophysics 690 (2016) 63–75

Contents lists available at ScienceDirect

Tectonophysics

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



The impact of in-situ stress and outcrop-based fracture geometry on hydraulic aperture and upscaled permeability in fractured reservoirs

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ARTICLE INFO

Article history:
Received 24 October 2015
Received in revised form 25 March 2016
Accepted 3 April 2016
Available online 8 April 2016

Keywords:
Aperture
Naturally fractured reservoirs
Equivalent permeability
Fracture geometry
Discrete fracture networks

ABSTRACT

Aperture has a controlling impact on porosity and permeability and is a source of uncertainty in modeling of naturally fractured reservoirs. This uncertainty results from difficulties in accurately quantifying aperture in the subsurface and from a limited fundamental understanding of the mechanical and diagenetic processes that control aperture. In the absence of cement bridges and high pore pressure, fractures in the subsurface are generally considered to be closed. However, experimental work, outcrop analyses and subsurface data show that some fractures remain open, and that aperture varies even along a single fracture. However, most fracture flow models consider constant apertures for fractures. We create a stress-dependent heterogeneous aperture by combining Finite Element modeling of discrete fracture networks with an empirical aperture model. Using a modeling approach that considers fractures explicitly, we quantify equivalent permeability, i.e. combined matrix and stress-dependent fracture flow. Fracture networks extracted from a large outcropping pavement form the basis of these models. The results show that the angle between fracture strike and σ_1 has a controlling impact on aperture and permeability, where hydraulic opening is maximum for an angle of 15°. At this angle, the fracture experiences a minor amount of shear displacement that allows the fracture to remain open even when fluid pressure is lower than the local normal stress. Averaging the heterogeneous aperture to scale up permeability probably results in an underestimation of flow, indicating the need to incorporate full aperture distributions rather than simplified aperture models in reservoir-scale flow models.

1. Introduction

Naturally fractured reservoirs are thought to have a large potential for increased hydrocarbon recovery (Nelson, 2001). This potential is, however, largely untouched partly because of the difficulty of predicting flow along complex fracture networks such as those occurring in nature (Berkowitz, 2002). The difficulty mainly lies in the heterogeneous subseismic-scale characteristics of fractures, which can only be partially sampled by core data or image logs (National Research Council, 1996; Wu and Pollard, 2002; Laubach, 2003). Therefore, outcrops are often used to better characterize the fracture spatial distribution, including length, height, orientation, spacing and aperture (Bonnet et al., 2001; Chesnaux et al., 2009; Agosta et al., 2010; Guerriero et al., 2010; Wilson et al., 2011; Hooker et al., 2013, 2014).

Out of these parameters, the fracture aperture distribution is one of the main factors controlling flow, as aperture defines fracture porosity and permeability (National Research Council, 1996; Guerriero et al., 2013). A wide range of studies, mostly based on outcrops where the aperture distribution can be studied in full, have shown that aperture size varies within fracture orientation sets and along the length or height of individual fractures (Laubach and Ward, 2006; Hooker et al., 2012, 2013, 2014; Iñigo et al., 2012). The most common observation in these studies is that the aperture-size distribution is best described by power-law scaling (Hooker et al., 2014). These outcrop observations have also been observed in subsurface datasets (Laubach, 2003; Hooker et al., 2009; Becker et al., 2010).

Stress, in the form of relatively high fluid pressures, can drive generation and propagation of cracks in the subsurface (Atkinson, 1987), but the propagation of fractures in the absence of high fluid pressures is most likely driven by a coupled process of stress and cement precipitation (Laubach et al., 2004a; Alzayer et al., 2015). Moreover, partial cementation, and particularly the occurrence of cement bridges, is crucial in ensuring that fractures remain hydraulically open, even if fluid pressure is low (Laubach et al., 2004b). By modeling cement precipitation, the rate of fracture growth or propagation can be quantified, to better understand how fracture networks grow (Philip et al., 2005; Lander and Laubach, 2015).

Although models and outcrop descriptions of heterogeneous apertures along single fractures exist, they are only rarely included in Discrete Fracture Network (DFN) models, which typically consider a

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http://dx.doi.org/10.1016/j.tecto.2016.04.006
0040-1951/

constant aperture per fracture or even per orientation set, with some notable exceptions (Philip et al., 2005; Olson et al., 2009; Nick et al., 2011; de Dreuzy et al., 2012; Lei et al., 2014). Using a heterogeneous aperture distribution derived from the local stress acting on a fracture surface, we aim to illustrate the impact of a heterogeneous versus homogeneous aperture distribution on permeability. The relation between stress and aperture is quantified using the Barton–Bandis method, which has been shown to produce highly heterogeneous aperture distributions (Lei et al., 2014).

The Barton–Bandis model is an empirical approach that quantifies the aperture that remains when irregular mismatching fracture walls are partially closed under compression (Barton, 1982; Bandis et al., 1983). Whereas the critical stress model used for faults and fractures requires high pore pressures, such that the stress within the fracture is close to the least principle horizontal stress (Barton et al., 1995; Rogers, 2003; Zoback, 2007), the Barton–Bandis model predicts that fractures can be hydraulically open in the absence of high fluid pressures (Olsson and Barton, 2001). Barton–Bandis furthermore takes into account horizontal stress anisotropy during production and the subsequent heterogeneous flow behavior along fracture walls, where local stress conditions may prevent flow along some fractures (Olsson and Barton, 2001; Matsuki et al., 2008). This model does not consider the impact of diagenesis, and hence it may not be representative for chemically reactive rocks such as carbonates, but it has been successfully applied to model permeability in shales (Barton, 2014).

The aperture distribution and subsequent fluid flow through fractures predicted by the Barton–Bandis method has been studied before, but mainly in synthetic fracture networks with simplified geometries or outcrop-based models with small dimensions (Nemoto et al., 2009; Tao et al., 2009; Lei et al., 2014). We apply this aperture method to models of fractured rocks under in-situ stress conditions in 2-D horizontal cross-sections of natural fracture networks affecting bodies of up to 360 m across. These fracture networks are digitized from outcropping fracture pavements in central Tunisia which display well resolved fracture geometries.

The impact of hydraulic aperture on fluid flow is modeled using a hybrid Finite-Element Finite-Volume (FEFV) approach that models single-phase incompressible flow through explicit fractures, as well as the flow exchange between fractures and matrix (Matthäi and Belayneh, 2004; Matthäi et al., 2007; Paluszny et al., 2007). Using this integrated workflow, we quantify the impact on aperture and permeability of: i) different fracture geometrical parameters, ii) variations in the magnitude and direction of horizontal principle stresses and iii) rock properties.

The last section of this paper focuses on upscaling. The Barton–Bandis method produces heterogeneous aperture distributions even along single fractures, while reservoir-scale fracture-flow models generally assume a constant aperture per fracture or sometimes even per fracture set. Models with single apertures per fracture found that a single equivalent aperture can be defined, that yields the same result as a heterogeneous aperture distribution (Nick et al., 2011). We analyze whether such an aperture can still be derived for an aperture distribution that varies even along a single fracture. Secondly, we study whether permeability calculated for small-scale (i.e. single reservoir grid cells) models accurately predicts the permeability of a larger-scale model with heterogeneous apertures.

2. Stress-induced Barton–Bandis aperture modeling

The Barton–Bandis method defines aperture based on fracture mechanical properties and the local shear and normal stresses (Barton and Choubey, 1977; Barton and Bandis, 1980; Bandis et al., 1983; Barton et al., 1985). The full set of equations used to translate stress into aperture is discussed in Bisdom et al. (in press). Here, we provide a brief recap of the main functions defining aperture, followed by describing how the aperture model is implemented into the Finite Element (FE) modeling workflow.

2.1. Barton–Bandis aperture model

The Barton–Bandis method is based on an initial aperture, which is a function of fracture roughness (JRC) and strength (JCS) (Barton and Bandis, 1980). An overview of all variables and their meaning is presented in Table 1. The initial aperture is defined by $E_0 = JRC/50$.

By applying in-situ compression, the initial aperture decreases, whereby part of the fracture may remain open by poorly interlocking irregular fracture walls (Fig. 1). The resulting physical or mechanical aperture is a function of *normal*, i.e. perpendicular to two sub-parallel fracture walls, and shear-related opening. In this study, we focus on *normal aperture* E_n and the shear-related *hydraulic aperture* e, which is the opening that effectively contributes to fluid flow under given in-situ stress conditions, controlled by the amount of shear-induced dilation. Normal and hydraulic apertures are defined by (Bisdom et al., in press):

$$E_n = E_0 - \left(\frac{1}{v_m} + \frac{K_{ni}}{\sigma_n}\right)^{-1} \tag{1}$$

$$e = \begin{cases} \dfrac{E_n{}^2}{JRC^{2.5}} for \dfrac{u_s}{u_{peak}} \leq 0.75 \\ \sqrt{E_n} JRC_{mob} for \dfrac{u_s}{u_{peak}} \geq 1 \end{cases} \tag{2}$$

The u_s/u_{peak} term quantifies the shear displacement as a function of a peak shear displacement, which depends mainly on the block size of a fracture. The block size L is the spacing between fractures that intersect the fracture of interest (Barton, 1982). The domain in between $0.75 \leq u_s/u_{peak} \leq 1.0$ is interpolated linearly (Olsson and Barton, 2001). The normal stress σ_n and shear displacement u required for calculating aperture in the above equations are quantified using FE models.

Table 1
Overview of parameters.

Symbol	Definition	Units	Constant
JRC	Joint Roughness Coefficient	–	15.0
JCS	Joint Compressive Strength	MPa	120
E_0	Initial 'unstressed' aperture	mm	0.3
E_n	Normal aperture	mm	
u_s	Shear displacement	mm	
u_{peak}	Peak shear displacement	mm	
L	Block size	m	
e and $\bar{e}$	Hydraulic aperture (and averaged hydraulic aperture)	mm	
v_m	Maximum closure	mm	
K_{ni}	Initial stiffness	MPa/mm	
E	Young's Modulus	GPa	
ν	Poisson's ratio	–	
σ_n, σ_1 and σ_3	Normal, maximum and minimum horizontal stress	MPa	
δ_{ij}	Kronecker delta	–	
ε	Strain	–	
β	Angle between fracture strike and σ_1	°	
τ	Shear stress	MPa	
c	Cohesion	MPa	
ϕ	Internal friction angle	°	
q	Darcy flow	m/s	
k, k_{eq}, k_m, k_f	Permeability (equivalent, matrix, fracture)	m^2 or mD	
s	2D fracture spacing	m	
A	Fractured rock area	m^2	
T	Total length of fractures	m	
d_0	Dimension parallel to main fracture trend	–	
l_e	Element length	m	