Parson's Model Modification to Describe the Aperture/Closure Behavior of Naturally Fractured Systems*

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Abstract

An extension to the geomechanical behavior of Parson's model is proposed, using a combination of both Parson' and Pedrosa's models. The new Parsons model is expressed in terms of normal effective stress acting on the natural fracture system. Results show a decreasing of aperture of fracture system, when it is compared with classical Parson's model. There are models for studying the opening/closing of a fracture system; they take into account characteristics of the system like fracture indices and the inclination angle respect to the horizontal plane, among others, but they do not consider the state of stress acting on the system and the azimuth angle; so, from geomechanical viewpoint, they describe partially the behavior of fracture system reactivation. The proposed model is an extension of Parson's model, which is expressed in terms of normal effective stress acting on the system of natural fractures. The resultant expression describes the opening/closing of a natural fracture system as a function of the parameters mentioned. The model has been applied to wells in the Colombian Foothills field, which have presence of natural fracture systems and show sensitivity to stresses. The results show opening/closing behavior of the natural fracture system as a function of pore pressure. Some applications are: i) in a stimulation process is possible to identify the viability of packaging of fracture system; ii) in the production process, optimal production pressure for stabilizing the shutdown of natural fractures and maximizing well production can be determined. In addition, results are compared to those obtained with Parson's model, finding that for same pressure change, opening/closing of new model is minor than Parson's model. The outstanding difference of the modified Parson's model is the consideration of geomechanical aspects such as the stress state and the stress alignments respect to orientation of the natural fracture system.

Introduction

The characteristics of naturally fractured reservoirs can be determined appropriately by indirect analysis of logging and production tests. In the case of UBI log interpretation, it allows to identify the properties of naturally fractured system properties such as fracture index, inclination and azimuth angles, among others. In the literature, it is possible to find different studies related with the description of naturally fractured systems' behavior. One important study was conducted by Barton et al. (1983), who investigated the deformation characteristics of rock joints under normal and shear loading, identifying an exponential behavior of fracture apertures with respect to normal stress (Bandis et al., 1983). In addition, it is possible to find laboratory studies, like in triaxial cells (Cook and Kemeny, 1987) and measurements of fracture surface topography (Yuting et al., 2000). Furthermore, several studies have utilized theories involving energy criteria (Cook and Kemeny, 1987) and elasto-plasticity (Yuting et al., 2000), among others. In addition, certain types of rocks have been tested: granite (Cook and Kemeny, 1987), limestone, dolomite and tight sandstone (Duan et al., 2000).

On the other hand, there are theoretical studies that describe the behavior of naturally fractured systems. Parson (1966) proposed a model to calculate the naturally fractured systems' aperture, in terms of geometrical and petrophysical parameters of a system (Parsons, 1966). Heffer et al. (1999) proposed a model based on the geostatistical approximation of the strain tensor considering the elastic energy as the unique factor that causes deformation of the fracture system (Heffer et al., 1999). In 2002, Hossain et al. presented a model based in fractal theory; the expression allows calculating the aperture behavior as a function of fractal dimension and normal and shear stresses acting on the fracture (Hossain et al., 2002). Moos and Barton (2008) presented a model to identify the behavior of a fracture, focusing on the process uncertainty. This model was utilized to estimate optimal well trajectories and stimulation pressures to enhance productivity of naturally fractured systems (Moos and Barton, 2008). In 2013, Alonso et al., (2013) introduced a coupled thermo-hydro-mechanical model, to describe aperture behavior in unsaturated media (Alonso et al., 2013). In this same year, Barton proposed a series of problems and solutions related to angle friction, normal and shear stresses acting on the fracture plane, etc (Barton, 2013).

In this study we present a model that takes into account the interaction between stress state and fluid flow, using three main concepts: i) Parson's aperture/closure model, ii) Pedrosa's permeability model and ii) Biot's and Terzaghi's theories. This paper is divided in three sections: first, the theoretical aspects are given; second, results are presented; and finally, conclusions are given.

Theoretical Aspects

The theoretical model is made up of three main elements: Parson's model based on fluid flow through both a channel and a matrix media; Pedrosa's model that describes the behavior of permeability media in terms of stress state, and the effective stress concept, grounded on Biot's and Terzaghi theories (Jaeger et al., 2007). With this in mind, the physical model is considered first, and afterwards the mathematical model is developed.

Initially, we consider that the physical model is made up of a natural fractures system located inside a reservoir, which is sensitive to stress. The stress state is assumed anisotropic, with one principal stress having a vertical orientation and the other stresses lying on a horizontal plane. Now, for the natural fractures system that is being considered, two angles characterize it: azimuth and inclination. Azimuth is measured from the maximum horizontal stress direction and inclination is calculated with respect to the vertical orientation. Figure 1 shows schematically the physical model.

Also, fluid flow in a single fracture is assumed equal to laminar flow between two infinite parallel smooth plates. This is expressed as (Huitt, 1956):

$$v = \frac{w^2}{12\mu B}\frac{dp}{dL} \tag{1}$$

$$q = \frac{hw^3}{12\mu B}\frac{dp}{dL} \tag{2}$$

Where v is the fluid velocity, w is the fracture width, μ is the fluid viscosity, p is the pressure, L is the length, q is the flow rate, h is the height and B is the volume factor of the fluid. Turbulent flow in fractured reservoirs is neglected. Reynolds number is defined to characterize the flow regime. The transition zone from laminar to turbulent flow goes from 1800 to 4000. Surface roughness on the fracture faces lowers this number.

The reservoir is under the assumption that it is a homogeneous permeable rock with a number of natural fractures, oriented in the same direction and with the same spacing. There is no restriction to flow of fluid between the fracture and the permeable matrix blocks. To obtain the reservoir permeability, Parson (1966) considered three cases:

a. *Homogeneous permeable medium*: the flow rate per unit area perpendicular to the pressure gradient for this case is given by Darcy's equation

$$\frac{q_r}{h} = \frac{k_r dp}{\mu B dL} \tag{3}$$

Where q_r is the flow rate and k_r is the permeability of rock. This case is observed in Figure 2a.

b. *Impermeable medium with a regular fracture set*. Here, a naturally fractured system is considered, with both same orientation and width. There is a fracture index, *IF*, that represents the number of fractures per foot (see Figure 2b). The average flow rate per unit area perpendicular to the pressure gradient comes from the equation for the flow rate between two parallel plates

$$\frac{q_f}{h} = \frac{w^3 IF cos^2\alpha dp}{12\mu B dL} \tag{4}$$

Where $cos^2\alpha$ comes from the component of dp/dL along the fracture direction and from the number of fractures per unit area of the face.

c. *Composite of homogeneous and regularly fractured medium cases*. It is assumed that fracture widths, w, are small in comparison with fracture indices. This is shown in the Figure 2c. Assuming that the pressure fields in the two systems are identical, and applying the superposition principle, it is possible to write

$$k_{fr} = \frac{(q_r + q_f)B\mu}{h\, {dp}/{dL}} \quad (5)$$

Substituting equations (3) and (4) into (5), gives:

$$k_{fr} = k_r + {w^3 IF cos^2\alpha}/{12} \quad (6)$$

Now, consider that the medium is composed of a matrix and one naturally fractured system. Assuming that the permeability of a naturally fractured system can be written as $k_f = k_{fr} - k_r$ .i.e. that the media behaves as two overlapping parallel systems, then from equation (6), we can obtain

$$k_f = {w^3 IF cos^2\alpha}/{12} \quad (7)$$

At this point, we take Pedrosa's model given by (Pedrosa, 1986)

$$k_f = k_i e^{-\gamma(p_i - p)} \quad (8)$$

Where k_i is the permeability at the reference pressure p_i, and γ is the permeability modulus, which is defined as the derivative of permeability with respect to pressure, divided by the average permeability. The idea is to express the exponential function argument as a function of effective normal stress, to which the naturally fractured system is subject. Figure 3 shows both normal and shear effective stresses acting on the fracture planes. Thus, the effective normal stress acting on these fracture planes could be expressed as $\sigma_N' = \sigma_N - \alpha p$. Therefore, $p = (\sigma_N - \sigma_N') / \alpha$ and the exponential function argument is given by

$$-\gamma(p_i - p) = -\frac{\gamma}{\alpha}\left[(\sigma_N - \sigma_N')_i - (\sigma_N - \sigma_N')\right] \quad (9)$$

Assuming that regional stress is maintained constant, then $\sigma_{Ni} = \sigma_N$ and

$$-\gamma(p_i - p) = \frac{\gamma}{\alpha}\left[\sigma_{N_i}' - \sigma_N'\right] \quad (10)$$

Now, the normal effective stress can be written in terms of the three principal stresses and both inclination and azimuth angles. Figure 3 shows an arbitrary configuration of a fracture plane subject to a general stress state. The azimuth and inclination angles are measured with respect to the effective maximum horizontal stress σ_H' and effective minimum horizontal stress σ_h', respectively. Therefore, applying basic trigonometric relations, and taking into account the main stresses, it is possible to obtain a function for the normal stress that acts on the fracture plane (Jaeger et al., 2007):

$$\sigma_N{}' = \sigma_H{}' n_H^2 + \sigma_h{}' n_h^2 + \sigma_v{}' n_v^2 \qquad (11)$$

Where $\boldsymbol{n}$ is the director cosine and the subscripts *H*, *h* and *v* are the maximum horizontal, minimum horizontal and vertical directions, respectively. The direction cosines are defined in terms of the inclination α and azimuth δ of the naturally fractured system with respect to the maximum horizontal stress orientation. Thus

$$n_H^2 = \cos^2\alpha \sin^2\delta$$

$$n_h^2 = \cos^2\alpha \cos^2\delta$$

$$n_v^2 = \sin^2\alpha \qquad (12)$$

This can also be written as

$$\left([\![(\sigma]\!]_H{}' \cos^2\alpha \sin^2\delta @ + (\sigma_h{}' \cos^2\alpha \cos^2\delta @ + (\sigma_v{}' \sin^2\alpha \right)] \qquad (13)$$

Defining $[\![[\![(\sigma]\!]_l]\!]^{\prime} = [\![\sigma_{li}]\!]^{\prime} - [\![\sigma_l]\!]^{\prime}$ with l = {H, h, v} and replacing equation (13) in equation (10) and the resulting into (7), fracture aperture as a function of the effective stress state acting over the naturally fractured system is obtained.

$$w = \{ [\![12k]\!]_i / ([\![IF\cos]\!]^2\alpha) \exp[\gamma/\alpha (\blacksquare([\![[\![(\sigma]\!]_H]\!]^{\prime} [\![\cos]\!]^2\alpha [\![\sin]\!]^2\delta @ + "(" [\![\sigma_h]\!]^{\prime} [\![\cos]\!]^2\alpha [\![\cos]\!]^2\delta @ + [\!["(" \sigma_v]\!]^{\prime} [\![\sin]\!]^2\alpha))]\}^{(1/3)}$$
(14)

The model allows studying the aperture/closure behavior of a naturally fractured system that is subject to an arbitrary stress state. This expression is also a function of both geometrical and petrophysical properties such as inclination angle, azimuth angle, spacing and the average permeability of the naturally fractured system.

It is important to observe the problem in a small scale. Figure 4 shows the representation of a natural fracture that belongs to the system, which is controlled by both normal and shear stresses. Notice that, inside the fracture, an angle φ appears which is called internal friction angle. It depends on the properties of fractures like roughness, contact point, etc. Barton and Choubey (1977) presented basic friction angles for different rocks (Zhang, 2005). Here, it is necessary to understand that the naturally fractured system could be reactivated if the shear sliding condition is reached due to the shear stress. Consequently, it is noticed that the aperture/closure of the fracture, ***w***, is related to both the angle φ and the normal stress acting in the naturally fractured system. In addition, shear stress depends on φ. This dependence is given by $\boldsymbol{\sigma_N \tan \varphi}$, which is the Coulomb failure criterion with cohesion zero.

The assumption is that the shear sliding displacement does not occur, while the angle of internal friction is under the critical angle, i.e., when one of the failure criteria is fulfilled. Therefore, there is a limit in the aperture of a naturally fractured system, which happens when the system surpasses a critical pore pressure, e.g. during an injection process. This condition can be described by some failure criteria. We consider the Mohr - Coulomb criterion

$$\tau = \sigma'_N tan\varphi_c \tag{15}$$

Where, φ_c is the critical internal friction angle and the reactivation of the fracture occurs when the shear stress over the natural fracture is equal to the shear stress obtained by Mohr-Coulomb criteria, i.e.

$$\beta = \pm 45 \mp \frac{\varphi_c}{2} \tag{16}$$

Where β is the angle that gives the state stress in the Mohr's circle and φ_c shall take values in the interval (25°, 35°). Therefore, a new model has been developed, where (14) and (15) are the main equations. In the next section, the results are presented.

Results

The modified Parson's model was applied in a well located in Colombian foothill fields. During its production stage, the well showed high depletion rates by the presence of an active natural fractures system, whose existence has been corroborated by UBI log measurements that were ran in this well. Figure 5 shows the fracture index of high quality (*IF*) distribution with depth, data used to obtain the average value of this variable for the well. Here it is noticed that there are several intervals which present different values of IF, however the interpretation of data is performed considering the depth interest depth, (12400'-14300' approximately).

Also, the UBI log data was interpreted and the information related to inclination and azimuth angles were obtained by using descriptive statistics. In Table 1, the average, standard deviation, minimum and maximum values, as well as confidence level and the number of data used to obtain these results are shown. It is noticed that the confidence level is of 95%, which allows to state that there are a probability of 0.95 that variables studied are in the confidence interval, e.g. the 95% of IF data belonging to the interval (1.2 1/ft, 2.0 1/ft).

The data to describe the behavior of the aperture / closure of a naturally fractured system are given in Table 2. Here, the permeability, which is given with respect to reservoir pressure, is obtained from a well test interpretation. The permeability modulus was obtained by a well test interpretation method proposed by Argoty and Naranjo (2009). Finally, the state stress was calculated using a geomechanical model for the well. Figure 6 presents both the aperture / closure behavior of the naturally fractured system calculated using Parson's model and Parson's modified model.

In Figure 6, it is observed that Parson's modified model estimates values of aperture /closure smaller than Parson's model. In fact, this was expected, because the new model considers the state stress effect, which is affected by pore pressure changes. In other words, the pressure in Parson's model only acts on the wall of fractures of the fractured systems, but in the new model the pressure must affect the stress field and the aperture / closure of the naturally fractured system. Therefore, in this system, the energy is used to counteract the two previous effects.

On the other hand, the reactivation shear stress of reactivation was estimated applying the equations (11) and (15) and considering a friction inner angle of 25°, a value of 3292 psi was obtained. This implies that natural fractures system in the well of study does not present reactivation when this criterion is used, because the shear stress at which is subjected the fractured systems is 909 psi, i.e. it is less than reactivation shear stress.

In contrast, when tension criterion is used result shows that pressure coincide with the reservoir pressure. One possible explanation for this is that Parson's model does not consider the roughness of the fracture; then, if the system is subject to an injection process, it is probable that the reactivation occurred instantaneously.

On the other hand, a parametric study using the ends of confidence interval was performed. The idea was to identify a band or surface that allows define an interval of fracture aperture to one state stress condition. The variables used were fracture index, inclination and azimuth angles. Results are showed in the Figure 7 and Figure 8.

Figure 7 presents parametric study of fracture index of the well chosen, the ends confidence interval values are 1.2 1/ft and 2.0 1/ft., the results show that the opening of the fracture system is less, as the index of fractures increases. This is because one fracture is opening for the pore pressure and if the number of fractures of system arise, considering that the same pore pressure is affecting the system, then this pressure (or density of energy) must be distributed to open each of the fracture that belong to the system. Therefore, at the initial conditions the aperture of fractures of the system could be taking values in the interval (123 μm, 174 μm).

In contrast, Figure 8 shows the parametric results of azimuth angle, which varies in the range (59.0°, 69.6°). Clearly, it is observed that the variation of approximately ten degree does not cause changes in the aperture of the naturally fractured system. Likewise, similar results were obtained by making the inclination angle parametric study, where the interval of variation of this is (64.9°, 68.7°).

Conclusions

We have proposed a new model using three main aspects: Parson's model based on the fluid flow through both a channel and a matrix media; Pedrosa's model, which describes the behavior of the medium permeability in terms of the stress state and the effective stress, grounded on Biot's and Terzaghi theories. The new model shows that the stress state acting on a naturally fractured system, limits the aperture / closure of these systems, being the aperture/closure in the new model smaller than in the Parson's model, which can be explained by the fact that the pressure has to counteract the effects of both the stresses and the fracture walls. Although the new model has proven to be effective, further works need to be undertaken to incorporate the effect of the fracture's roughness, plastic behavior and others failure criteria, that considers intermediate stresses.

Nomenclature

B	Formation volume factor
h	Thickness
IF	Fracture index
k	Permeability
L	Length
n	Director cosine
p	Pressure
q	Flow rate
v	Fluid velocity
w	Fracture width
α	Inclination angle between fractured system and σ_H
α'	Biot's coefficient
δ	Azimuth angle between fractured system and σ_H
σ	Normal stress
σ'	Effective stress
γ	Permeability modulus
φ_c	Critical internal friction angle
τ	Shear stress
μ	Viscosity

Subscript

f	Fractured system
fr	Fractured system and rock
h	Minimum horizontal stress direction
H	Maximum horizontal stress direction
i	Reservoir or reference
N	Normal to fracture plane
r	Rock or matrix
v	Vertical direction

Conversion Factors SI

cp x 1.0*	E -03 = Pa.s
ft x 3.048*	E -01 = m

Darcy x 9.869233 E -13 = m^2
psi x 6.894757 E+03 = kPa
*Exact conversion factor.

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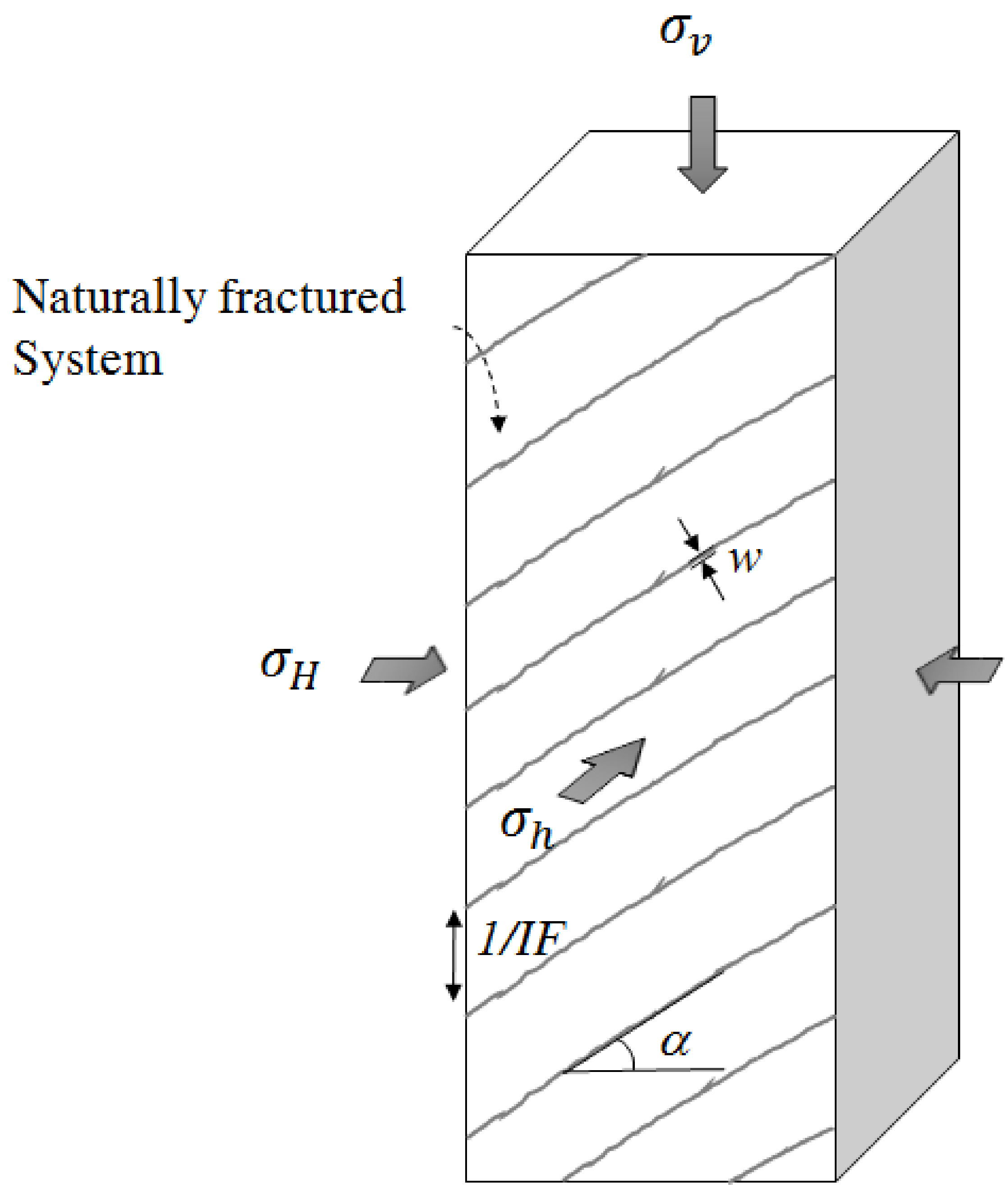

Figure 1. Schematic representation of a naturally fractured system with fracture index *IF*, inclination α and azimuth zero.

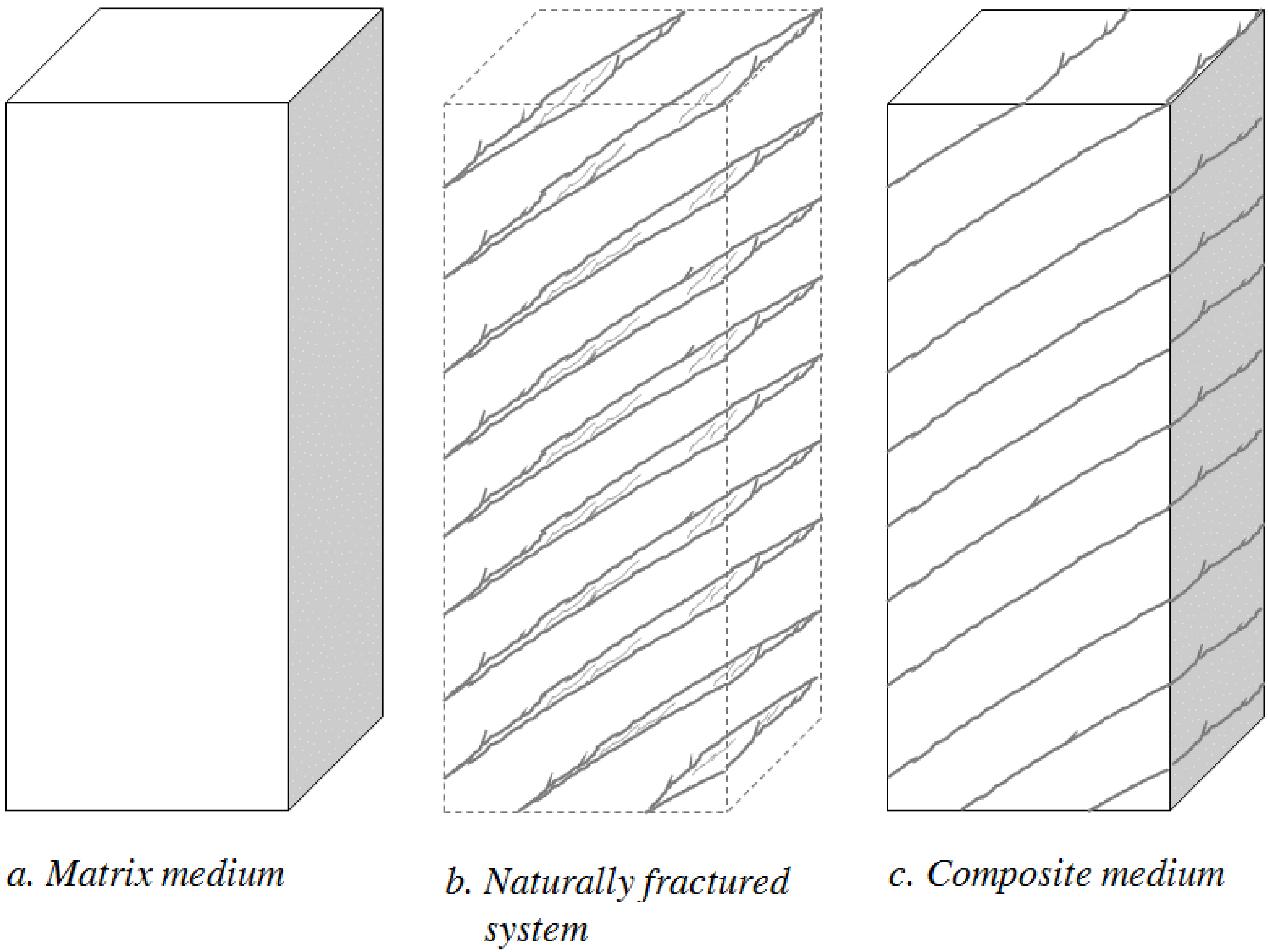

Figure 2. Schematic of different reservoir structures. a. Matrix medium without natural fractures; b. Naturally fractured system and c. Matrix and naturally fractured systems.

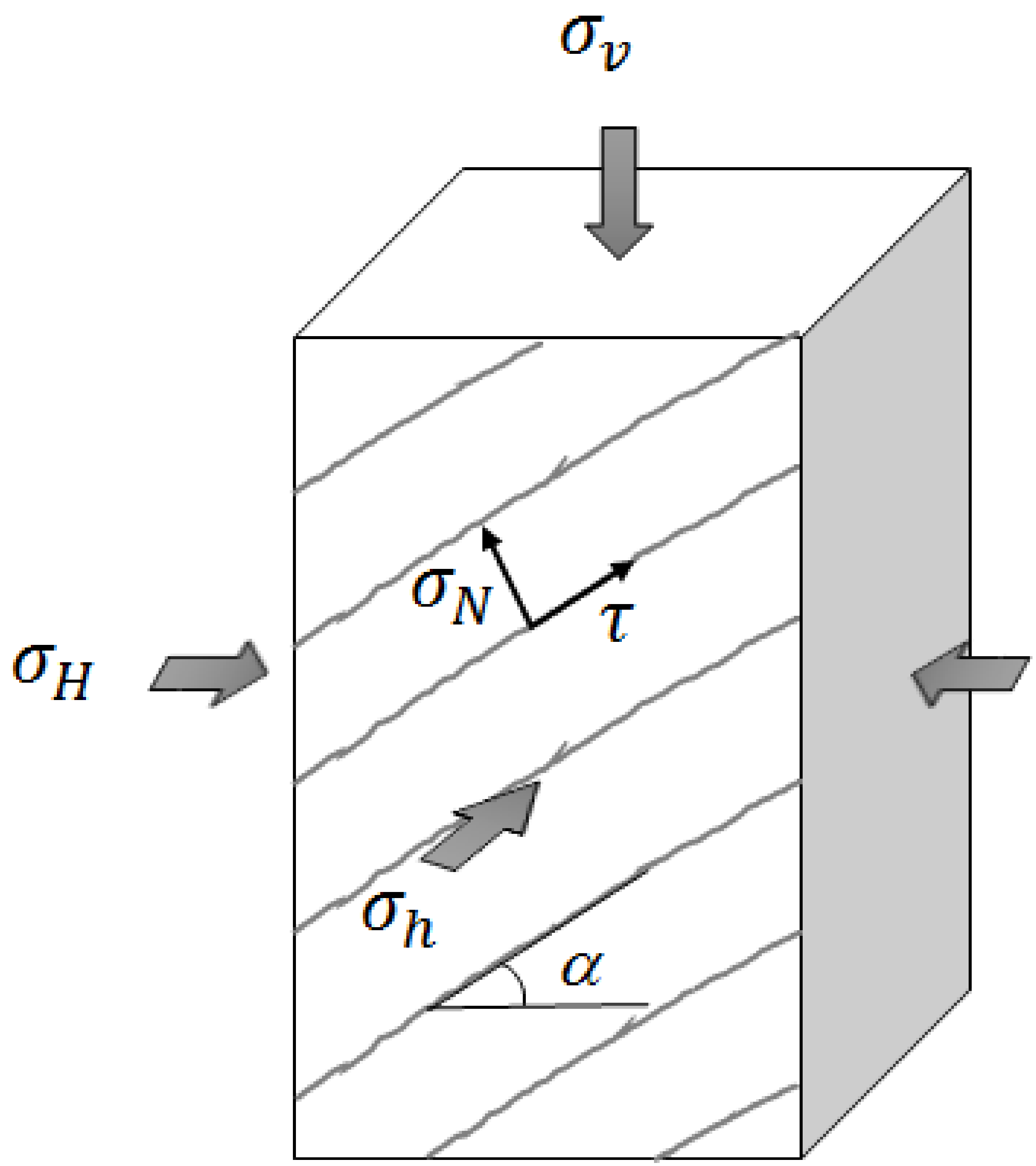

Figure 3. Schematic representation of a naturally fractured system with both normal and shear effective stresses.

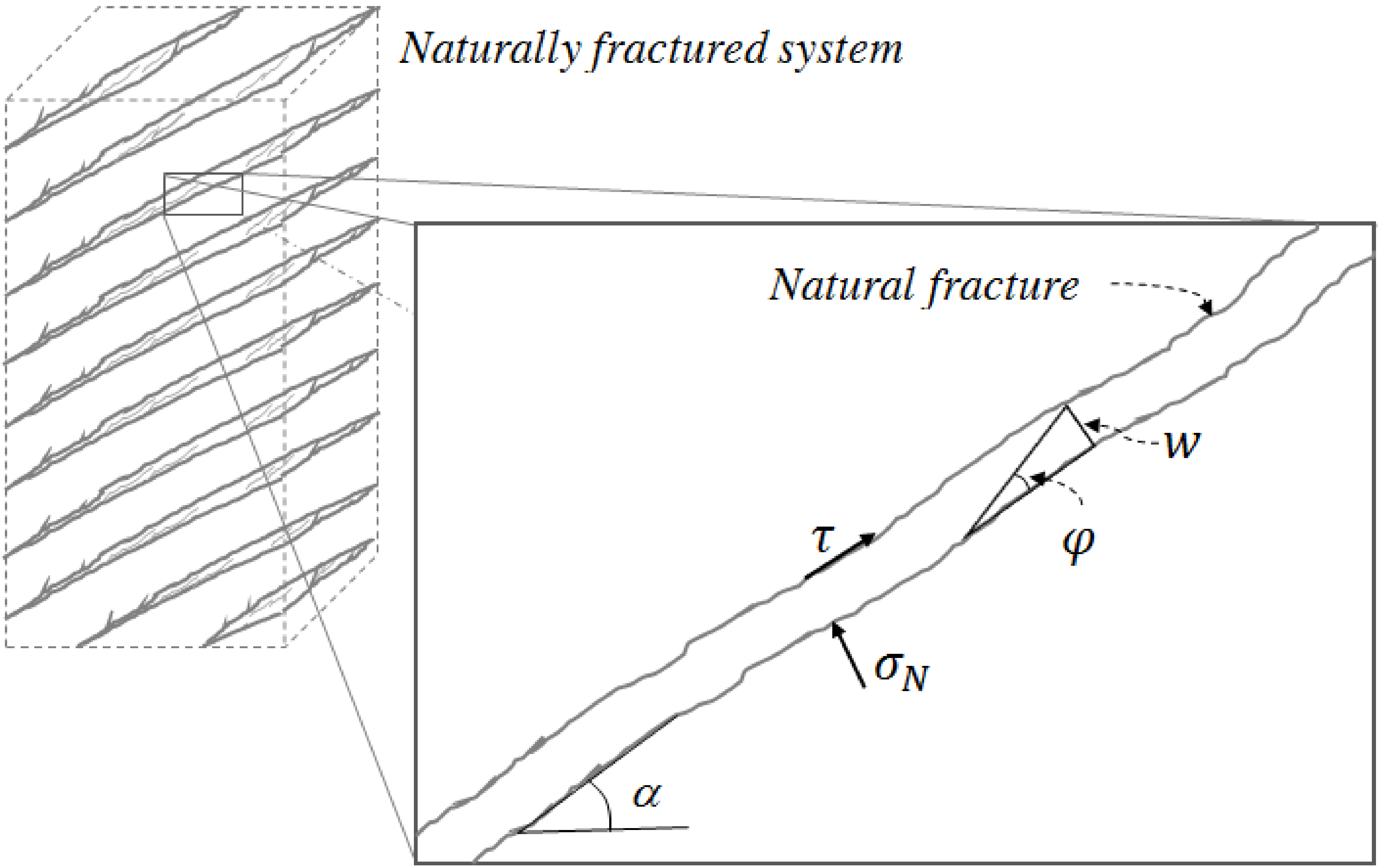

Figure 4. Natural fracture subject to normal and shear stresses.

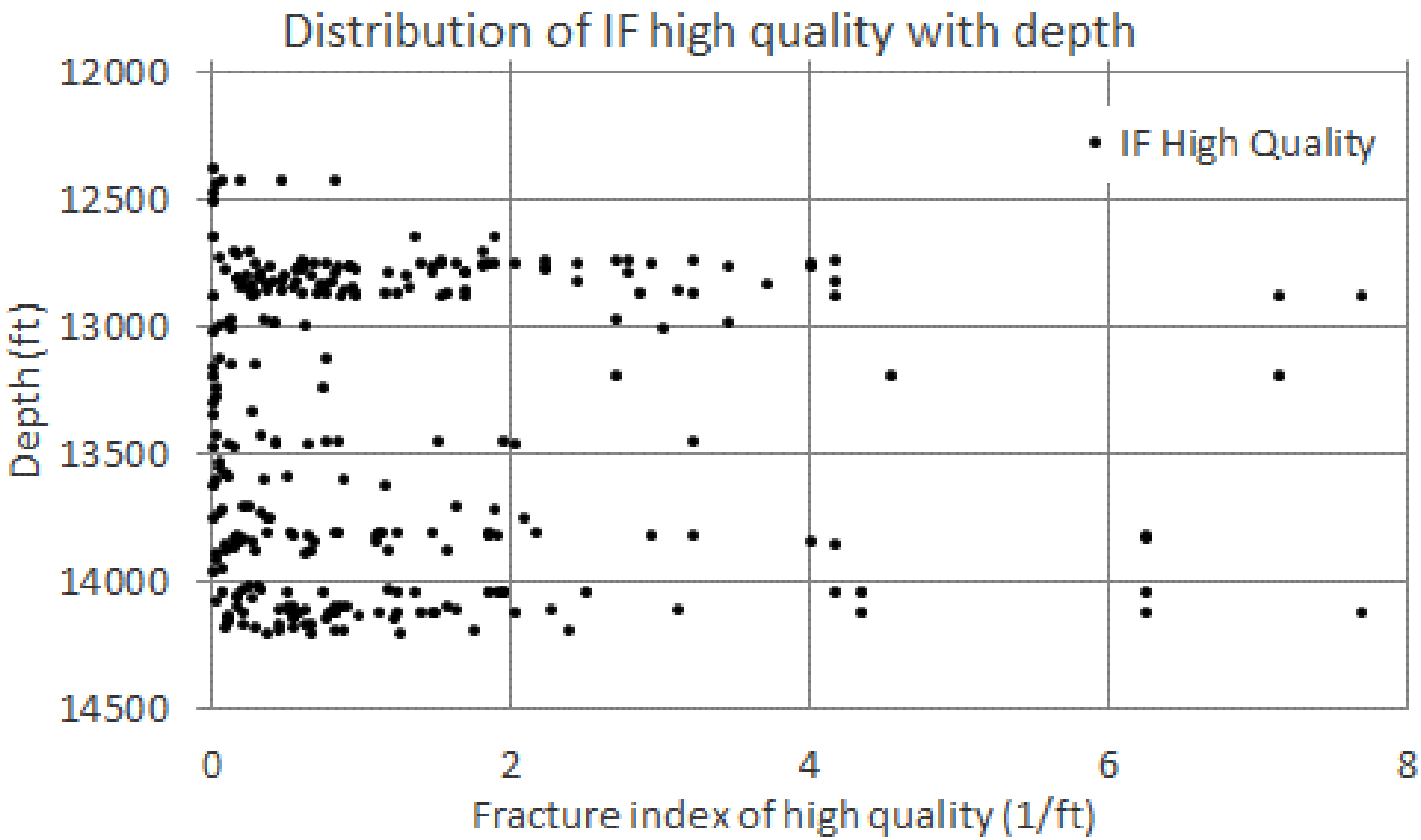

Figure 5. Behavior of the fracture index of high quality (*IF*) with depth for the studied well.

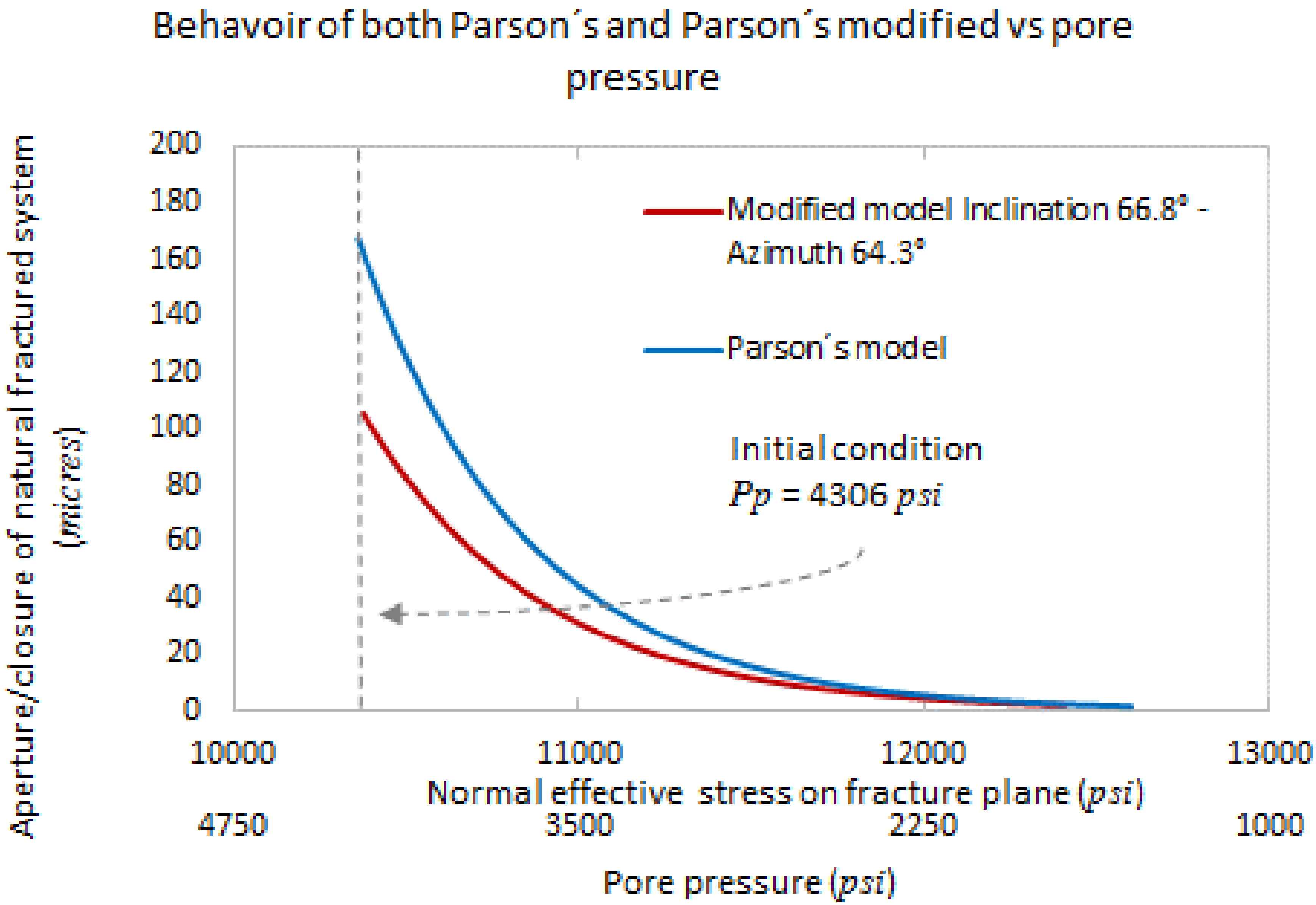

Figure 6. Behavior of both Parson's and Parson's modified models vs. Normal stress and pore pressure.

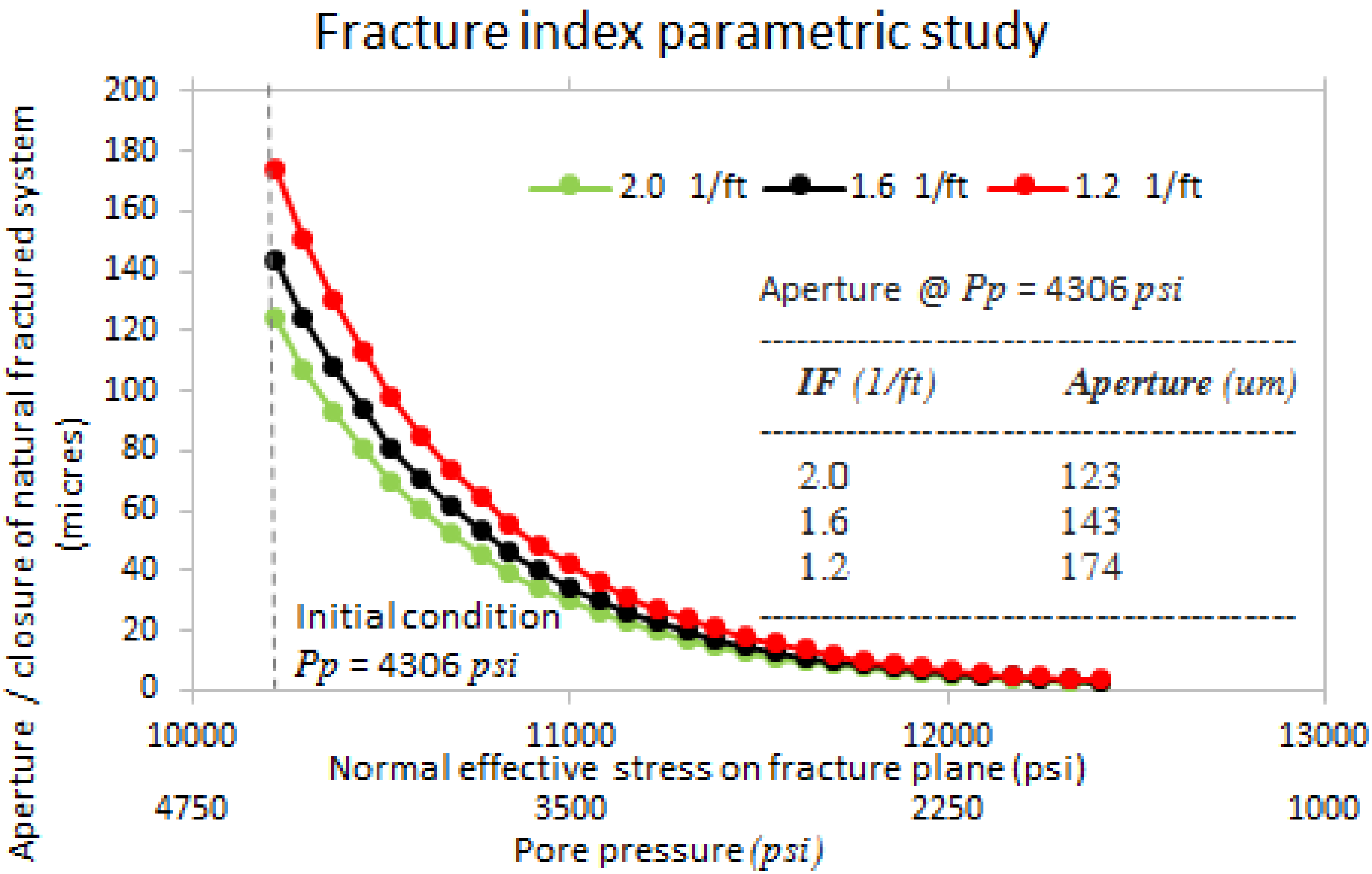

Figure 7. Behavior of Parson’s modified model vs. normal stress and pore pressure when fracture index is varied.

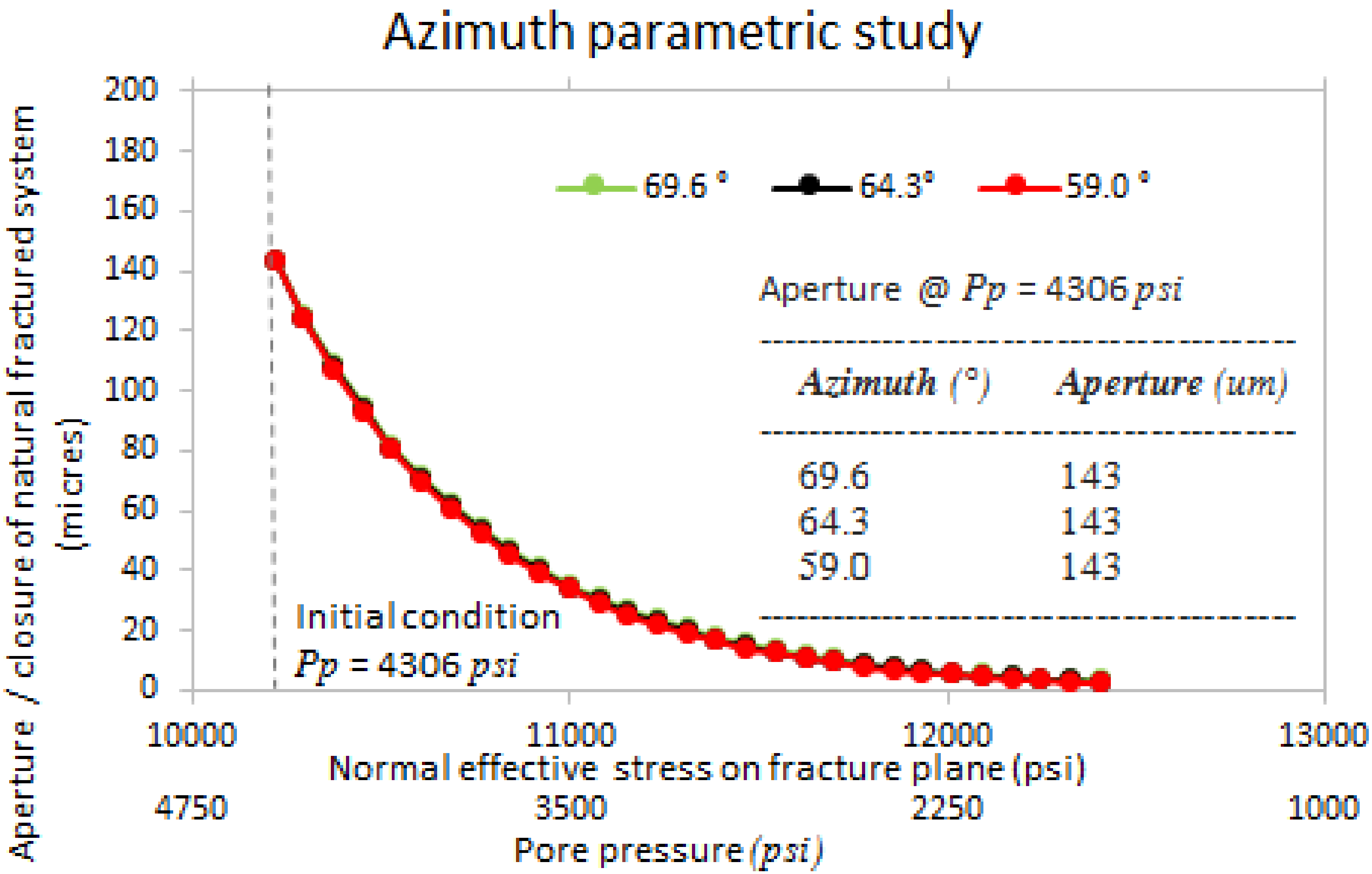

Figure 8. Behavior of Parson's modified model vs. normal stress and pore pressure when fracture index is varied.

Variable	**Fracture Index**	**Inclination**	**Azimuth**
	(1/ft)	*(°)*	*(°)*
Average	1.6	66.8	64.3
Standard deviation	3.7	16.5	45.7
Minimum value	0.0	15.6	0
Maximum value	7.7	89.9	180
Number data	290	291	291
Confidence level (95%)	0.4	1.9	5.3

Table 1. Descriptive statistics of fracture index, inclination and azimuth angles of well of study.

Variable	**Units**	**Value**
Permeability	*(mD)*	27.7
Permeability modulus	(*1/psi*)	4.7E-03
Fracture index	(*1/ft*)	1.6
Inclination	(°)	66.8
Azimuth	(°)	64.3
Reservoir pressure	(*psi*)	4306.4
Vertical stress	(*psi*)	15909
Maximum horizontal stress	(*psi*)	17022
Minimum horizontal stress	(*psi*)	12409
Biot's coefficient		0.85

Table 2. Well data to describe the aperture/closure of a naturally fractured system.