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STUDY CASE IN A NATURALLY FRACTURED RESERVOIR DURING DEPLETION USING FINITE ELEMENT METHOD

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RESUMEN

Este caso de campo busca cuantificar la magnitud de las anomalías de presión y entender el Los yacimientos naturalmente fracturados son sistemas complejos de caracterizar y predecir, por esto es importante establecer algunos criterios básicos para identificar cuando las fracturas son un elemento importante en el desarrollo del yacimiento y también reconocer la naturaleza y características de este tipo de yacimientos. Estas fracturas están presentes en la mayoría de los yacimientos de hidrocarburos, pero su verdadera importancia es dada cuando existe una red interconectada de estas fracturas ya que afecta el flujo en el sistema.

El modelo presentado en este trabajo es simulado en un código numérico que adopta la aproximación de discontinuidades fuertes embebidas en una malla de elementos finitos que permite el análisis de flujo en un yacimiento deformable. El comportamiento mecánico de la roca es representado por el mecanismo de daño continuo que esta basado en el proceso termodinámico irreversible y es formulado para describir el mecanismo antes de la creación de la macro fractura. El modelo asume que la degradación del material es el resultado del crecimiento y la interconexión de las microfracturas existentes. El acoplamiento hidromecánico es determinado por la ley que relaciona la permeabilidad como una función del desplazamiento del problema mecánico.

INTRODUCTION

Naturally fractured rock formations form important subsurface flow systems with a high degree of local heterogeneity. A basic differentiating characteristic of such formations is that a small volume of the medium (i.e fractures) transmits a large portion of the flow through it. The displacement of oil and gas from fractured reservoirs, estimated to contain a substantial amount of reserves is of importance to the oil and gas industry. In order to accurately predict production from such reservoirs, it is essential to understand fluid flow behavior in such systems. This in turn requires an in-depth understanding of fully-coupled rock deformation and fluid flow. In the case of fractured rock formations, the presence of fractures increases the overall compliance of the rock-fluid system a factor which may cause tensile effective stresses near the borehole, thereby affecting its stability during the initial drilling phase (Nair, 2003).

This kind of reservoirs can be approached using the mathematical development of the continuous approximation of strong discontinuities, which introduces the effect of a strain band within existing finite elements that has been accepted as an efficient technique for the simulation of fractures in quase-fragile materials, such as concrete. It becomes unnecessary to use interface elements or mesh reconstruction over and over again, as discrete fracture methods require the technique is consistent with the principles of continuum mechanics, in addition to reducing computational costs and simplifying the discretization of the fractured medium (Beserra, 2015).

In this paper is presented the simulation results of the problem of closing natural fractures by reservoir depletion. The scenario analyzed is representative of a field located in Colombia. This study was developedby LMCG (Laboratorio de MétodosComputacionaisemGeomecânica) and with the help of Equion Energy.

Model Formulation

A strong discontinuity approach to embed discontinuities into finite elements was also considered to represent the behavior of fractures in rock formation. The mathematical development of the continuous approximation of strong discontinuities introduces the effect of a strain band within existing finite elements. This approach, as proposed by Manzoli&Shing (2006), was implemented in CODE_BRIGHT (Guimarães *et al.*, 2007; Olivella *et al.*, 1994), a finite element procedure that performs numerical analysis of fluid flow in a deformable porous media in a fully coupled scheme.

To properly derive embedded discontinuity finite element formulations, fundamental aspects regarding to the kinematics and statics of the discontinuity must be considered. The kinematic enrichment must correctly reflect the position of the interface in the element as well as the relative displacement (opening and sliding) between the two opposite faces of the interface. Furthermore, the traction continuity condition must be correctly imposed to ensure a correct relationship between the tractions in the internal interface and the stresses in the surrounding continuum portion (Beserra, 2015).

The implementation of this technique in CODE_BRIGHT has been quite convenient and can bedone in a non-intrusive way in the code. Since the jump in the field of displacements can be approximated as equivalent inelastic deformations, which can be calculated in the constitutive module of the program in finite elements, within the procedure of integration of stresses in the elements.

The standard MEF equations (without discontinuity) are used to represent the continuous part. The behavior of the discontinuity interface can be described by a constitutive equation that directly relates tensions and displacements (discrete model) or by a constitutive model of the continuous type, which relates tensions and deformations, according to the continuous approximation of strong discontinuities (Manzoli, 2008).

Consider the triangular element with three nodes from domain, with a band of strain localization Se, width h, which divides the element into two parts, isolating the node 1 from nodes 2 and 3, as shown in Figure. 1(a).

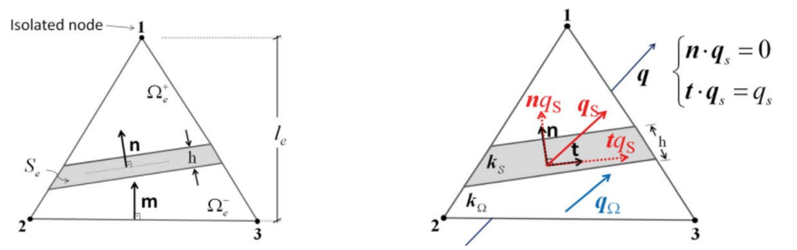

Figure 1. (a) Finite Element crossed by a discontinuity band; (b) the normal and tangential component of fluid flow in fracture.

A displacement field jump, [[u]], on S lead to a rigid-body relative motion, the strain field of the continuum portion and discontinuity can be written as:

$$\varepsilon_\Omega = \boldsymbol{\varepsilon} - \frac{1}{l_e}\boldsymbol{M}[[\boldsymbol{u}]] \qquad (1)$$

$$\varepsilon_S = \boldsymbol{\varepsilon} - \frac{1}{l_e}\boldsymbol{M}[[\boldsymbol{u}]] + \frac{1}{h}\boldsymbol{N}[[\boldsymbol{u}]] \qquad (2)$$

The corresponding stress field is given by:

$$\begin{aligned} \boldsymbol{\sigma}_\Omega &= \Sigma(\varepsilon_\Omega) = \Sigma(\boldsymbol{\varepsilon} - \frac{1}{l_e}\boldsymbol{M}[[\boldsymbol{u}]]) \\ \boldsymbol{\sigma}_S &= \Sigma(\varepsilon_S) = \Sigma(\boldsymbol{\varepsilon} - \frac{1}{l_e}\boldsymbol{M}[[\boldsymbol{u}]] + \frac{1}{h}\boldsymbol{N}_n[[\boldsymbol{u}]]) \end{aligned} \qquad (3)$$

Where h denotes the bandwidth of strain localization, Σ is the constitutive matrix of the material; $\boldsymbol{M}$ and $\boldsymbol{N}$ are the matrices obtained from the components of vectors m and n respectively and [[u]] is the jump in displacement field. Traction continuity is assured as follows:

$$\boldsymbol{n} \cdot (\boldsymbol{\sigma}_\Omega - \boldsymbol{\sigma}_S) = 0 \qquad (4)$$

1. Closure constitutive model

To model the mechanical behavior of material, it was adopted a hyperbolic model of fracture closure proposed by Barton *et al.* (1985) this model treats the closure of preexisting fractures when submitted to normal compressive stresses.

The normal stress to the fracture is obtained as follows:

$$\sigma_n = \boldsymbol{n} \cdot \boldsymbol{\sigma}_S \cdot \boldsymbol{n} \qquad (5)$$

The normal closure, j, is obtained from Barton's model, that treats the closure of preexisting fractures when subjected to normal compressive stresses. It is a non-linear elastic model with an initial rigidity of Barton-Bandis κ_{ni} and asymptotically converges for maximum fracture closure V_m.

$$j = \frac{\sigma_n V_m}{\sigma_n - \kappa_{ni} V_m} \qquad (6)$$

The displacement jump vector , [[u]],is written as:

$$[[\boldsymbol{u}]] = j_n \boldsymbol{n} \qquad (7)$$

Finally, the strain field in discontinuity is given by:

$$\boldsymbol{\varepsilon}_S = \boldsymbol{\varepsilon} - \frac{1}{l_e}\boldsymbol{M}[[\boldsymbol{u}]] + \frac{1}{h}\boldsymbol{N}[[\boldsymbol{u}]] + \boldsymbol{\varepsilon}_S^0 \qquad (8)$$

Where $\boldsymbol{\varepsilon}_S^0$ is the strain field corresponding to in situ stress field.

2. Flow Problem

The Darcy's flow into the discontinuity can be decomposed in a normal and tangential component, the formulation adopted in this paper considers that the fluid flow in a fracture occurs on its direction, therefore only the tangential component is taken into account. Darcy's law can be written, for continuum and fracture, as follows:

$$\boldsymbol{q}_\Omega = -\boldsymbol{K}_\Omega \nabla p$$
$$\boldsymbol{q}_S = -\frac{h}{l_e} K_s \boldsymbol{t} \otimes \boldsymbol{t} \nabla p \qquad (9)$$

As a result, an effective permeability tensor for the element is given by:

$$\boldsymbol{q} = -\boldsymbol{K}_{ef} \nabla p$$
$$\boldsymbol{K}_{ef} = \left(\boldsymbol{K}_\Omega + \frac{h}{l_e} K_s \boldsymbol{t} \otimes \boldsymbol{t} \right) \qquad (10)$$

Two different permeability variation laws, one for continuum portion and other for fracture, are adopted as shown in Figure 2.

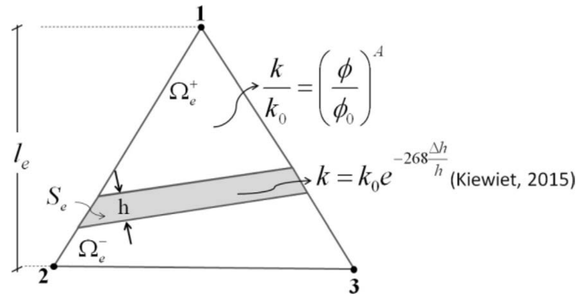

Figure 2. Permeability variation laws for continuum media and fractures.

It is important to highlight that the finite element program CODE_BRIGHT coupled the problem of fluid flow in oil reservoirs sensitive to the stress state. The equations of the flux problem are solved together with the equilibrium equation of the mechanical problem in a fully coupled scheme, where, for each Newton-Rapshon interaction, a single system of equations is solved for the entire mesh, where unknown is pressure (hydraulic problem) and displacement (mechanical problem).

A fracture in a porous medium becomes a preferred path for the flow towards the discontinuity, which can be interpreted as an anisotropy induced, in the direction of the fracture, throughout the medium.

3. Variation Law of Permeability

The hydro-mechanical coupling has been determined by a law thet relates the variation of permeability as a function of the displacement jump from the mechanical problem, as follow:

$$k_s = \frac{[\![u]\!]_n{}^2}{12} \qquad (11)$$

where $[\![u]\!]_n$ is the normal jump aperture.

The numerical code, CODE_BRIGHT, uses the convergence criterion of Newton-Raphson. Also, it works with an IMPLEX algorithm (Beserra, 2015).

Study Case

A naturally fracture reservoir is simulated, in Figure 3 is shown the fracture network obtained according to the geological attributes provided and incorporated into the finite element mesh. The simulated reservoir is cut by two families of fractures and is subjected to a state of high confining stresses. The formation is located in a region in Colombia of high tectonic stresses, where the vertical tension is the intermediate between the major and minor horizontal stress.

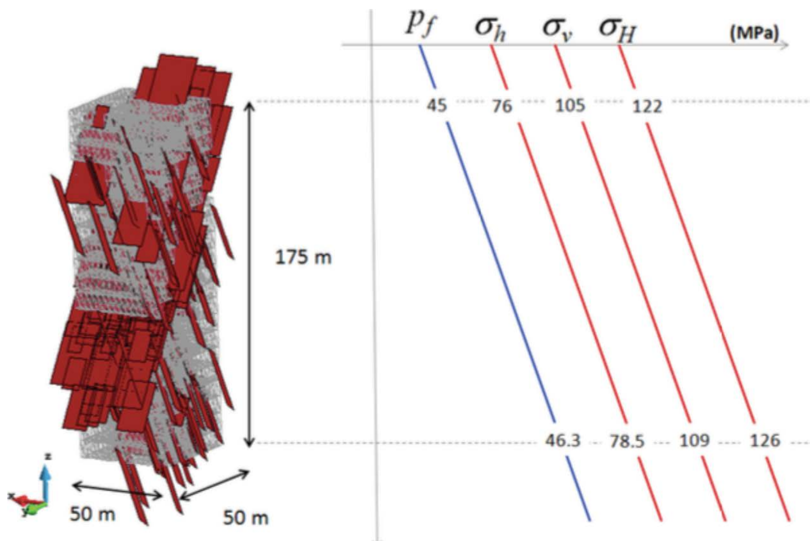

Figure 3. Reservoir Stress State (Beserra, 2015).

In the Figure 4 is shown a scheme of the numerical model. Shift constraints are imposed on all faces of the geometry, and the initial stress state is also imposed. In one node at a center of reservoir it is applied a fluid pressure of 10 MPa less than to a static press of the reservoir.

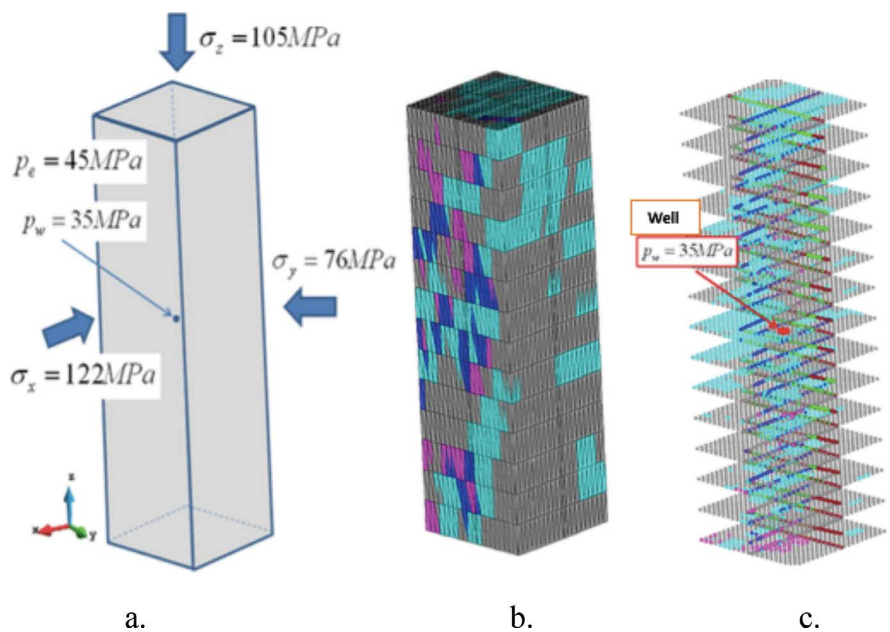

Figure 4 a. Stress State. b. Finite Element Mesh. c. well in mesh (Beserra, 2015).

In the Table 1 is presented the properties used in the simulation.

Table 1. Fluid and Mechanical Properties.

Properties	Values
Fluid Viscosity	$1x10^{-9}$MPa/s
Intrinsic Permeability	$4x10^{-22}m^2$
Fracture Initial Aperture	1.0 mm
Porosity	0.05
Biot Coefficient	1.00
Young`s Modulus	10 GPa
Poisson Ratio	0.30
Barton-Bandis Initial Stiffness	200 MPa

The reservoir permeability was considered practically null, therefore, the flow occurs mainly through the network of natural fractures. The depressurizing of the well can cause the fractures to close and drastically reduce the overall permeability of the formation.

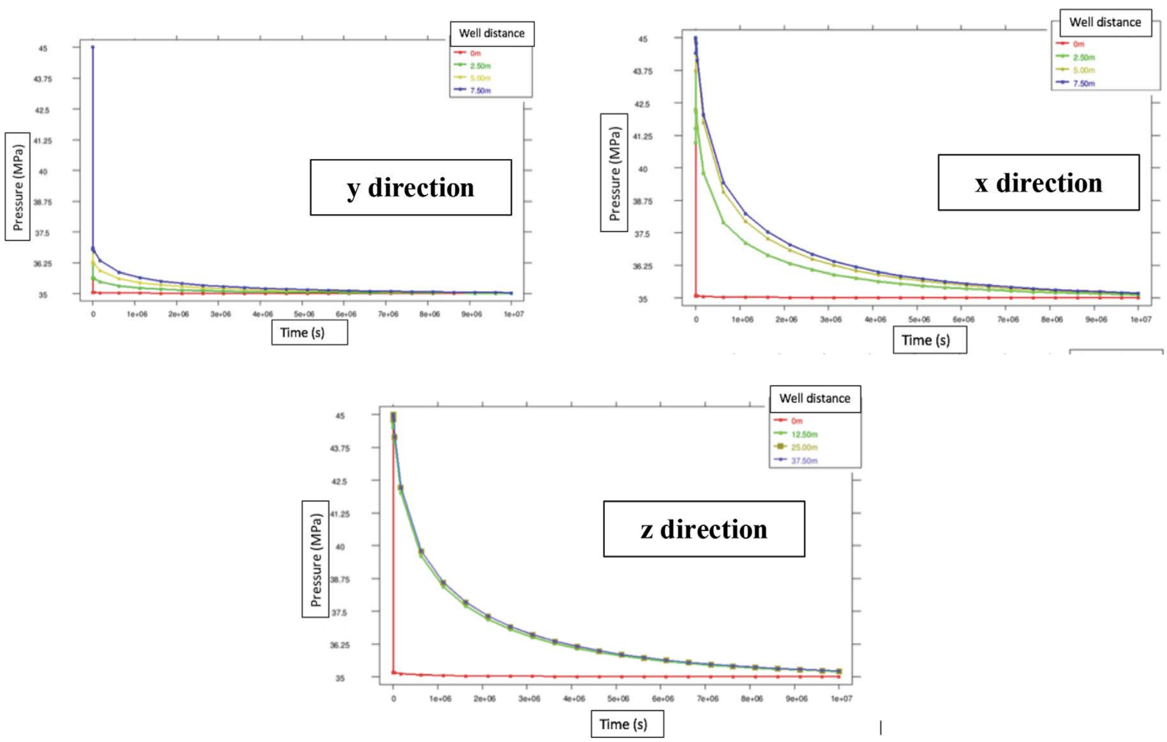

Figure 5. Evolution of fluid pressure for different points of the mesh (Beserra, 2015).

In the Figure 5 is presented the pressure evolution in each direction. For y direction it is observed that the well pressure propagates rapidly to the nodes in its vicinity, indicating that the permeability in this direction has not been decreased, for directions x and z the well pressure does not propagate so rapidly, which may indicate that the fractures in these directions have collapsed and the permeability in the vicinity of the well has been reduced. This effect of anisotropy on the permeability of the formation is exclusively due to the position of the natural fractures with respect to the x, y and z axes.

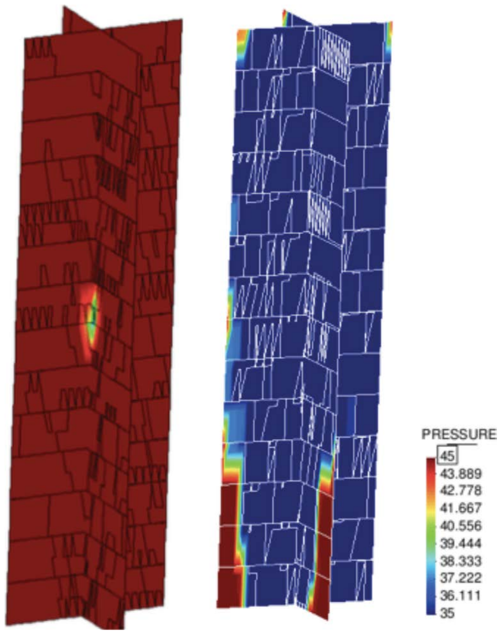

Figure 6. Fluid pressure distribution (Beserra, 2015).

The distribution of the fluid pressure in the reservoir at the initial and final moments of the simulation regions that have not been depressurized because they are not affected by fractures are highlighted.

The decrease in the overall permeability of the formation, due to the closure of the fractures, can be observed in Figure 7, which shows the permeability distribution for the initial and final instants of the simulation.

For the final time of simulation, the permeability of the fractures is completely null due to the displacement vectors converge towards the well and there is a compaction of the reservoir, with subsidence effect on the upper surface of the well.

CONCLUSIONS

The decay of static pressure, during the production of naturally fractured reservoirs, may lead to the closure of these fractures, due to the increase of the effective confining stress. In this sense, the constitutive model of Barton-Bandis was implemented, which is capable of adequately reproducing the behavior of the closure of fractures submitted to a normal compressive stress.

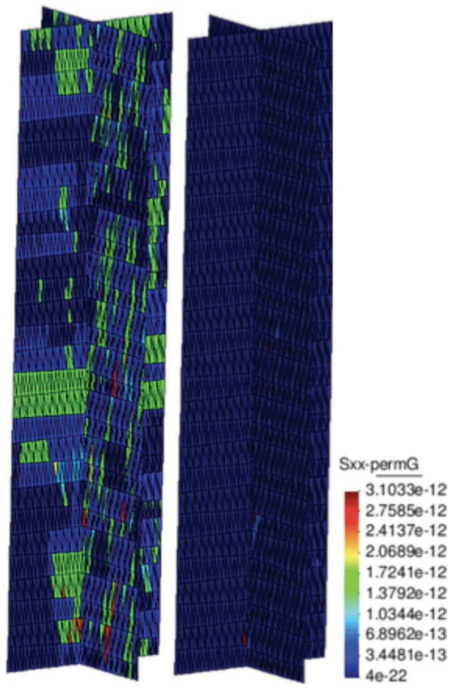

Figure 7. Permeability distribution (Beserra, 2015).

The technique of strong discontinuities allows a good approximation to simulate the behavior of naturally fracture reservoirs.

Understanding the hydraulic characteristics of the fracture network as a function of the effective confining tension is fundamental for the estimation of the reservoir performance, to increase the productivity and also to optimize the exploitation plan of the same.

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