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Near-wellbore permeability alteration in depleted, anisotropic reservoirs

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ABSTRACT

Pore pressure depletion from hydrocarbon production causes an increase in effective stress in the reservoir and can result in significant compaction. The change in stress state with depletion induces a change in permeability both in the far-field and the near wellbore region. Modeling the depletion induced permeability alteration is crucial in forecasting hydrocarbon production and designing a drilling strategy. Porosity-based permeability models are typically used in which the permeability changes are assumed to be isotropic. However, most rocks are anisotropic, and the stress changes due to depletion and drilling a well are also anisotropic. As an example, we compared isotropic and anisotropic permeability predictions around a hypothetical well drilled in the Tor formation in Valhall field in the North Sea. The results show that isotropic permeability models tend to underestimate the degree of permeability reduction in the near-wellbore region, but even when anisotropy is considered, the permeability in the radial direction still only decreases by about 10%. These results may still need to be considered when designing a development strategy in depleted reservoirs.

1. Introduction

An increasing number of hydrocarbon reservoirs in the world are maturing. More than 70% of the oil and gas produced today comes from secondary or tertiary production (Meng and Fuh, 2010). Hydrocarbon production from these fields has resulted in significant pore pressure depletion, causing the effective stress in the reservoirs to increase. This phenomenon can result in consolidation or failure of the rock, surface subsidence, lost circulation, pressure management issues during drilling, fluid production issues and casing failure (e.g., Sulak and Danielsen, 1988; Aadnoy, 1991; Ali et al., 1994a; Dusseault et al., 1998; Streit and Hillis, 2002; van Oort et al., 2003). A particular concern for drilling and production is the associated depletion-induced permeability alteration in the reservoir, as this will influence the production rates of existing wells and drilling fluid invasion in the subsequent wells that are drilled throughout the development program. To properly plan the development of the reservoir and accurately forecast production, models that couple the stress, deformation and permeability must be incorporated in the drilling planning programs and reservoir simulators.

The permeability changes of a porous medium subject to deformation are usually determined through a state variable that accounts for the volumetric change, such as porosity, void ratio or volumetric strain. Such state variables are scalar and hence yield an isotropic change in permeability, i.e. assume the change in permeability is equal in all directions, even though the deformations are different in each direction. Strain can result in both volume change and grain rearrangement, which affects both cross-sectional area available to flow and tortuosity (Rasromani, 2016). Daigle and Dugan (2011) developed a model for changes in permeability both as a function of grain orientation and porosity. Their model allows determination of the permeability tensor from the principal strains rather than relating a bulk permeability to volumetric strain. This therefore allows for anisotropic changes in permeability and hence produces a more realistic representation of deformation-induced permeability alteration.

As an example, we evaluated the changes in near-wellbore and far-field permeability of a vertical producing well in the Tor formation of the Valhall field in the North Sea during pore pressure depletion. In comparing the predicted permeability changes through isotropic and anisotropic permeability alteration models, we assess the potential error associated with assuming an isotropic permeability change and highlight the importance of considering permeability anisotropy in depleted reservoirs. We show that overbalanced drilling in depleted formations can mitigate near-wellbore permeability reduction, and that the degree of permeability reduction, particularly in the anisotropic case, increases as the wellbore pressure decreases, but the permeability in the radial direction still remains around 90% of the original value. These effects may still need to be considered when designing a drilling fluid scheme for wells in depleted formations.

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2. Stresses and permeabilities in depleted reservoirs

2.1. Stresses

A hydrocarbon reservoir experiences large stresses due to overlying rock, surrounding rock, nearby faults and tectonic forces. A portion of the external load of the total stress is supported by the pore pressure of the fluid in the reservoir. As pore pressure decreases due to hydrocarbon production, the load carried by the rock itself increases. Such load is termed the effective stress. Terzaghi (1924) and later Biot (1962) defined the effective stress of a fully saturated rock as

$$\sigma_{ij}^{'} = \sigma_{ij} - \alpha\delta_{ij}P_p, \quad (1)$$

where σ_{ij}' is the effective stress, σ_{ij} is the total stress, δ_{ij} is the Kronecker delta ($\delta_{ij} = 1$ if i = j, $\delta_{ij} = 0$ otherwise), P_p is the pore pressure, and α is the Biot coefficient. Deformations in a rock are evaluated through a constitutive relation that relates the effective stress to the strains. For a linear elastic material the strain tensor $\boldsymbol{\varepsilon}$ related to the change in the effective stress tensor $\boldsymbol{\Delta\sigma}'$ through a fourth-order invariant compliance tensor $\mathbf{D}$:

$$\boldsymbol{\varepsilon} = \mathbf{D}\cdot\boldsymbol{\Delta\sigma}'. \quad (2)$$

Note that bold variables here refer to tensors. It is often useful to express Eq. (2) in matrix notation, also called Voigt notation. Voigt notation takes advantage of the symmetry of the stress and strain tensor and expresses the stress and strain tensor as a six-dimensional vector. Eq. (2) in Voigt notation for isotropic materials is expressed as

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1+\nu}{E} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1+\nu}{E} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1+\nu}{E} \end{bmatrix} \begin{bmatrix} \Delta\sigma_{11}' \\ \Delta\sigma_{22}' \\ \Delta\sigma_{33}' \\ \Delta\sigma_{23}' \\ \Delta\sigma_{12}' \\ \Delta\sigma_{13}' \end{bmatrix}, \quad (3)$$

where ν and E are Poisson's ratio and Young's modulus. Note that linear elasticity assumes infinitesimal strains or small deformations. If strains observed in the reservoir are large and finite, the nonlinear theory of elasticity must be used. In this study, positive stresses are assumed to be compressive, so positive strains correspond to volume loss.

Various models exist for coupling the stress, strain and permeability. The simplest models relate changes in effective stress relative to some reference value directly to changes in permeability (e.g., Zhai and Sharma, 2005). More complex models invoke the porosity-permeability relationship in accounting for changes in porosity, tortuosity and surface area through evaluation of the volumetric strain. Note that in the linear theory of elasticity, the volumetric strain ε_{vol} is expressed from the normal strains as

$$\varepsilon_{vol} = -\frac{\Delta V}{V} = 1 - (1-\varepsilon_{11})(1-\varepsilon_{22})(1-\varepsilon_{33}). \quad (4)$$

If the solid grains are assumed to be incompressible, the volumetric strain is related to the change in porosity through

$$\varepsilon_{vol} = \frac{\phi_0 - \phi}{1-\phi}, \quad (5)$$

where ϕ and ϕ_0 are the final and initial porosity respectively. Eq. (5) is derived in the Appendix.

The Kirsch equations describe the stress around a circular cavity of a linear isotropic material subject to external loading (Kirsch, 1898). The discontinuity in material properties and stresses at the wall of the cavity causes a local perturbation in the stress field with a stress component acting tangent to the borehole wall, perpendicular to the borehole axis, which may be tensile or compressive depending on the far-field stresses and the pressure within the cavity. Aadnoy and Chenevert (1987) successfully applied the Kirsch equations to calculate the stresses around a deviated wellbore and assessed the fracture pressure and collapse pressure through incorporating various rock failure criteria. The Kirsch equations for a vertical wellbore are

$$\sigma_r = \frac{1}{2}(\sigma_{hmax} + \sigma_{hmin})\left(1 - \frac{R^2}{r^2}\right) + \frac{1}{2}(\sigma_{hmax} - \sigma_{hmin}) \left(1 + 3\frac{R^4}{r^4} - 4\frac{R^2}{r^2}\right)\cos 2\theta + \frac{R^2}{r^2}p_w, \quad (6a)$$

$$\sigma_\theta = \frac{1}{2}(\sigma_{hmax} + \sigma_{hmin})\left(1 + \frac{R^2}{r^2}\right) - \frac{1}{2}(\sigma_{hmax} - \sigma_{hmin})\left(1 + 3\frac{R^4}{r^4}\right)\cos 2\theta - \frac{R^2}{r^2}p_w, \quad (6b)$$

$$\sigma_z = \sigma_v - 2\nu(\sigma_{hmax} - \sigma_{hmin})\frac{R^2}{r^2}\cos 2\theta, \quad (6c)$$

$$\sigma_{r\theta} = \frac{1}{2}(\sigma_{hmax} - \sigma_{hmin})\sin 2\theta\left(1 - 3\frac{R^4}{r^4} + 2\frac{R^2}{r^2}\right), \quad (6d)$$

$$\sigma_{rz} = \sigma_{\theta z} = 0, \quad (6e)$$

where σ_{ij} is the total stress in cylindrical coordinates, R is the radius of the wellbore, σ_{hmax} and σ_{hmin} are the maximum and minimum horizontal stresses respectively, σ_v is the overburden stress, ν is Poisson's ratio, r and θ are the radial and azimuthal coordinates of point of interest, respectively, and p_w is the wellbore pressure. Fig. 1 illustrates the local stress field around the well in relation to the far-field stresses. Pore pressure depletion does not only increase the effective stress in the reservoir, but it also changes the far-field stresses. Although the overburden stress is commonly assumed to be constant, the horizontal stresses change significantly with depletion. The stress path A is defined as the ratio of the change in horizontal stresses to the change in pore pressure and is expressed as

$$A = \frac{\Delta\sigma_h}{\Delta P_p} = \alpha\frac{1-2\nu}{1-\nu}, \quad (7)$$

for linear, isotropic homogenous reservoir of infinite extent (Addis, 1997; Hillis, 2001; Engelder and Fischer, 1994). Note that Eq. (7) assumes that the magnitude of the changes in the minimum and maximum horizontal stresses with depletion are the same. According to Segall and Fitzgerald (1998), Eq. (7) is applicable when the ratio of the reservoir lateral extent to its thickness is 10:1.

2.2. Permeabilities

Predicting how permeability anisotropy changes due to depletion and associated strains requires some sort of physical model. Here, we combine two existing models in the literature to account for permeability anisotropy development due to a combination of vertical consolidation and horizontal strain. Daigle and Dugan (2011) developed a model to explain permeability anisotropy in sedimentary rocks as a function of consolidation and shearing. In this model, direction variations in permeability are assumed to be due only to directional variations in