Journal of Petroleum Science and Engineering 162 (2018) 102–113

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Production versus injection induced poroelasticity surrounding wells

K. Atefi-Monfared [a,*], J. Rybicki [b]

[a] Dept. of Civil, Structural and Environmental Engineering, 212 Ketter Hall, University at Buffalo, Buffalo, NY, 14260, USA
[b] Dept. of Civil, Structural and Environmental Engineering University at Buffalo, Buffalo, NY 14260, USA

ARTICLE INFO

Keywords:
Poroelastic
Flow-induced geomechanics
Injection
Production
Reservoir
Winkler model

ABSTRACT

This article presents a novel assessment of flow-induced geomechanics in a poroelastic layer, incorporating confining effects of sealing rocks. For the first time, production-induced temporal principal plane variations, and potential failure mechanism/s are analytically evaluated in various stress regimes, and under a wide range of vertical confinement settings replicated via the Winkler model. Results are assessed versus those from injection flow to obtain a novel holistic insight on flow-induced geomechanics. Overall, an intricate near wellbore response is revealed, suggesting reorientation of the minimum principal plane from horizontal to vertical due to: production flow in deep reservoirs where the confining stiffness parameter exceeds that of the target layer; injection flow where the stiffness of the target zone exceeds the confining stiffness (typical in shallow reservoirs, or reservoirs subjected to prolonged injection cycles). Dominant failure mechanisms due to injection and production are shear and pore collapse, respectively. Results suggest generation of shear failure under production flow, where the confining stiffness differs from the stiffness of the reservoir formation. This hypothesis is more prone to occur in geologic formations with lower friction angle.

1. Introduction

Water and energy are key global challenges. There is a critical need for development of sustainable and environmentally safer production and storage techniques for water and energy. Such technologies involve cyclic extraction and/or injection of large volumes of fluids from or into geological reservoirs: aquifer storage and recovery (ASR), enhancement of oil recovery (EOR), geothermal enhancement, and disposal of wastewater. Geo-environmental consequences of such operations remain a topic of dispute. Injection and production operations enforce drastic changes in the in situ water content, specifically within the wellbore vicinity, thus generating pore pressure variations and deformations within the target zone and the surrounding medium. The induced deformations and subsequent stress alterations potentially damage the confining sealing rocks, resulting in leakage and contamination of the surrounding soils and water resources. Furthermore, stress alterations within a reservoir formation can increase the potential for reactivation of existing faults (Soltanzadeh and Hawkes, 2008). Ground surface deformation is yet another inevitable consequence of injection and production operations, and can cause substantial damage in structures and lifelines.

To ensure a safe and sustainable operation, it is critical to assess the very source of the abovementioned effects from flow-induced stress variations specifically in the vicinity of production and injection wells. The involved processes – specifically in weakly-consolidated rocks – are of a coupled nature, i.e., there is coupling between reservoir's mechanical reaction – quantified by stress-strain alterations – and the quantity of the interstitial fluid flow. Furthermore, overall geomechanical response of a reservoir to induced flow can be substantially governed by the vertical confinement of the target zone, directly correlated with the stiffness of sealing rocks (Atefi Monfared and Rothenburg, 2017). Consequently, a realistic formulation of reservoir's intricate geomechanical response to induced flow remains a key challenge, and the formulation remains analytically intractable.

The simplest theory commonly adopted to describe coupled fluid-soil interactions is Terzaghi's theory of poroelasticity (1923), extended to three dimensions by Biot (1941). Geertsma (1957) was the first who discussed the relevance of poroelasticity to rock mechanics, and applied this theory to address coupled geomechanical processes during petroleum production operations. Numerous studies have since been conducted to describe the fundamental coupled mechanisms, specifically related to borehole excavation and energy/water production operations. Most previous studies were developed assuming plane strain conditions perpendicular to the flow current, and/or a steady state (Paslay and Cheatham, 1963; Rice and Cleary, 1976; Carter and Booker, 1982; Risnes

* Corresponding author. Tel.: 17166453455.
E-mail addresses: kameliam@buffalo.edu (K. Atefi-Monfared), jakubryb@buffalo.edu (J. Rybicki).

https://doi.org/10.1016/j.petrol.2017.12.025
Received 17 October 2017; Received in revised form 3 December 2017; Accepted 10 December 2017
Available online 12 December 2017

et al., 1982; Detournay and Cheng, 1988; Segall, 1992; Rudnicki, 1999; Chin et al., 2000; Egberts and Fokker, 2001; Han and Dusseault, 2003; Yin et al., 2006). The former presumption assumes nontrivial strains generated merely in the horizontal plane under radial flow. This assumption stands where the seal rocks surrounding a geological reservoir exhibit substantial stiffness. However, seal rocks are commonly composed of shale, which deform under flow-induced forces. The constitutive behavior of seal rocks thus influences the overall geomechanical response of a reservoir to flow-induced pressures. Evaluation of the vertical reaction stress is thus essential for assessing the integrity of seal rocks during production/injection operations. A steady state assumption will prevent from obtaining a realistic insight into flow-induced geomechanics, as the reservoir stress regime – which plays a key role on the assessment of seal rock integrity – can be of a temporal nature. Uniaxial deformation of the reservoir rock is another common assumption adopted to predict deformations (subsurface and/or ground surface) generated as a result of production or injection-induced stress changes. A uniaxial based compaction or expansion model incorporates for the total horizontal stress changes within the reservoir, whereas the total vertical stresses are assumed to remain constant (Engelder and Fischer, 1994; Zoback and Zinke, 2002; Goulty, 2003; Streit and Hillis, 2004; Hawkes et al., 2005; Soltanzadeh and Hawkes, 2008; Atefi Monfared and Rothenburg, 2011). This hypothesis does not hold for all geometries, shallow or thick reservoirs, or in cases where the mechanical properties of the reservoir formation differ significantly from those of the confining rocks (e.g. the North Sea Reservoirs) (Morita et al., 1989).

Atefi Monfared and Rothenburg (2017) proposed closed-form poroelastic analytical solutions for axisymmetric stress and strain components as well as the vertical reaction stress in a geological reservoir subjected to injection flow. Vertical confinement effects were incorporated for the first time using the Winkler model. Therefore, while simplifying the response of sealing rocks in the direction perpendicular to the reservoir plane, the proposed solutions represent a generalization of previous formulations obtained for plane strain conditions. An assessment was conducted to evaluate principal plane variations under injection in a confined porous layer in various stress regimes (Atefi Monfared and Rothenburg, 2016). Results revealed the manner in which vertical confinement will affect the geomechanical response of a porous layer under injection flow. Rafieepour et al. (2017) conducted a series of triaxial experiments on Caslegate sandstone specimens to assess effects of confinement on stress responses under depletion and injection tests. Results confirmed boundary conditions to be a controlling parameter, affecting reservoir's flow-induced response.

Qualitative and quantitative effects of vertical confinement – governed by the stiffness of the sealing medium – on reservoir's coupled response to production flow are not yet well understood. A comprehensive assessment of production versus injection-induced geomechanics is critical for operational control and monitoring purposes, as it is typical for production wells to be converted into injection wells in the field. Furthermore, a realistic assessment and formulation of post failure response of a confined formation to induced flow involves the knowledge of principal planes at failure initiation. The current article is aimed at providing a novel insight into reservoir's geomechanical response to production flow via incorporating the confining effects of the sealing rocks. More specifically, such effects on principal plane variations and failure initiation at the wellbore are of interest. The adopted methodology is a synthesis of that of Atefi Monfared and Rothenburg (2016) which was proposed for injection. To obtain a novel holistic insight into flow-induced geomechanics, reservoir response under both production-induced and injection-induced flow is assessed. The collation of figures include results from both case scenarios, based on which a comprehensive qualitative analyses is presented comparing production versus injection induced stress variations at the wellbore. Such assessment provides a unique insight into flow-dependent temporal principal planes, critical for identifying potential failure planes to ensure long-term preservation of reservoir's leakage integrity, both during production and injection. This study is of significant value for the design of operations and monitoring strategies, and providing a more accurate insight into in situ stress state at failure initiation.

First, a geomechanical explanation of the problem of interest is presented, proceeded by fully coupled equations for flow-induced (injection and production) pore pressure, stress, and strain variations in a porous layer confined with flexible sealing rocks. Next, for both production-induced flow and injection-induced flow, stress variations as well as principal planes prior to yield state are examined in isotropic and anisotropic stress fields. Analyses are carried out for an entire range of vertical confinement setting, thus incorporating effects of seal rock behavior on the coupled response of the medium to induced flow. This qualitative assessment of reservoir response at wellbore vicinity to flow is key to a successful-sustainable operation. Results will help facilitate optimization of production and injection processes based on the in situ stress regime and the confining stiffness characteristics relative to the target zone.

2. Problem description

A schematic of the problem of interest is illustrated in Fig. 1. First step in a quantitative assessment of flow-induced geomechanics, based on which effective monitoring strategies are designed, is to obtain a realistic understanding of the reservoir response to both injection and production flow. The critical parameter for achieving the aforementioned is the spatiotemporal stress regime, which is a function of both the initial in situ stress regime (σ_{oij}) as well as flow-induced stresses ($\Delta\sigma_{ij}$). A correct representation of in situ stresses is therefore of great significance. The

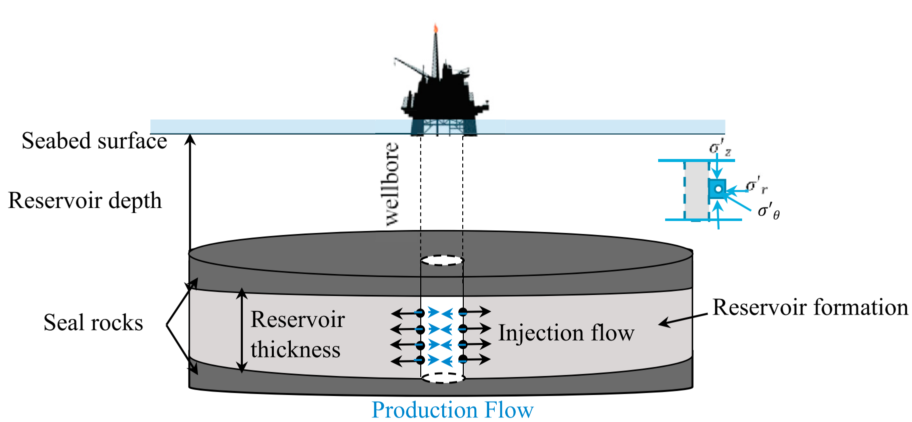

Fig. 1. A schematic of injection/production in a confined geological layer (not to scale).