Journal of Petroleum Science and Engineering 121 (2014) 174–179

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Technobites

Distinguishing fluid injection induced ground deformation caused by fracture pressurization from porous medium pressurization

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A R T I C L E I N F O

Article history:
Received 26 November 2013
Accepted 29 June 2014
Available online 10 July 2014

Keywords:
hydraulic fracture
cohesive finite element method
porous medium
poroelasticity
land deformation

A B S T R A C T

Ground deformation (both deformation patterns and deformation magnitudes) due to porous medium pressurization and fracture pressurization exhibits different characteristics. However, whether these differences can be detected during fluid storage is a complicated issue. Two analytical solutions have been previously developed to correlate ground deformation with underground fluid injection/extraction. One is Geertsma's (1973) solution on ground deformation associated with a disc-shaped reservoir (porous medium), and another is Sun's (1969) solution on ground deformation associated with a circular fracture. In this technique note, we compare these two solutions through a finite element modeling approach based on comparable boundary conditions, i.e., the similar areal extent, burial depth and fluid injection volume. We found that the deformation patterns are similar for these two cases on the ground surface, but very different underneath, especially in the horizontal direction. The radial extent of horizontal deformation is more restricted for the fracture pressurization case and more importantly, much higher magnitudes of ground deformation occur for the fracture pressurization case, which can provide new understanding of how to distinguish a fracture pressurization effect from porous medium pressurization.

1. Introduction

Land surface deformation caused by fluid injection or withdrawal has long been observed above aquifers, oil fields, and geothermal reservoirs (Yerkes and Castle, 1969; Holzer and Bluntzer, 1984; Fielding et al., 1998; Hoffmann et al., 2001; Bell et al., 2002; Hole et al., 2007; Teatini et al., 2011; etc.). In order to investigate such problems by analytical or numerical approaches, the rock medium may either be considered exclusively as a porous medium (Geertsma, 1973; Du and Olson, 2001; Gambolati et al., 2001; Scanlon et al., 2003); as an impervious medium with fractures (Sun, 1969; Davis, 1983; Okada, 1985; Yang and Davis, 1986); or as a porous medium with fractures (Bai and Elsworth, 1994; Segall et al., 1994; Burbey, 2002, 2008; Rutqvist et al., 2010; Zhou and Burbey, 2014a). The latter sometimes can be considered as a dual porosity dual permeability system in the simplest case (Warren and Root, 1963; Pride and Berryman, 2003a, 2003b; etc.).

As CO_2 storage in geological formations is increasingly being considered as an important climate change mitigation option, gaining knowledge about the poromechanical properties of target formations becomes vitally important (Vasco et al., 2000, 2010). However, hydrogeological and geo-mechanical information about these host reservoirs are generally very limited, including their (exact) thickness, areal extent, the transition from permeable regions to less permeable regions, locations of preexisting fractures, etc. With the development of sophisticated surface monitoring techniques such as InSAR and GPS, careful surface monitoring of ground deformation signals during fluid injection can yield critical information about the geometric configuration and characterization of the host reservoir. Such information is expected to be used to monitor the fate and transport of the injected fluid. For example, numerical modeling results from the In Salah project indicated that the best fit of simulated ground deformation values with observed values was obtained when a combination of reservoir and fracture/fault pressurization was implemented together, rather than either one or the other alone (Morris et al., 2011).

Generally, ground deformations (both deformation patterns and magnitudes) due to porous medium pressurization and fracture pressurization exhibit different characteristics. However, whether these differences can be detected during fluid storage is a complicated issue. In case where the fracture is vertical or subvertical, the existence of such a fracture may be relatively easy to detect since the movements of the two walls on the opposite sides of the fracture may present a unique feature at the land surface (Davis,

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http://dx.doi.org/10.1016/j.petrol.2014.06.028
0920-4105/Published by Elsevier B.V.

1983). However, identifying whether a horizontal or sub-horizontal fracture exists from monitoring surface deformations can be much more challenging because its ground deformation behavior is very similar to the situation in which the fluid is stored in a horizontally layered porous formation. During the fluid injection process the extent of the evolving fracture is of special concern because fracture breakout may cause unexpected percolating flow paths associated with environmentally sensitive regions (Evans, 1983; Bonnet and Constantinescu, 2005). Therefore, it is of great importance to differentiate the fracture pressurization from that of porous medium pressurization by detecting ground deformation behaviors. In addition, it is also of great interest to know which storage mechanism dominates during fluid injection, i.e., whether fluid is stored in the rock matrix or fractures, or both.

Two well-known analytical solutions exist in the past to correlate ground deformation with underground fluid injection/extraction. One is Geertsma's (1973) solution on ground deformation associated with a disc-shaped reservoir (porous medium) storage, and another is Sun's (1969) solution on ground deformation associated with a circular fracture storage. In this paper, we make a comparison of these two solutions by applying comparable boundary conditions, i.e., the buried depth and areal extent of the reservoir and the fracture were kept the same, as well as the properties of their hosting formations, and the injected fluid volume. In this investigation, we found that even though the ground deformation patterns are similar for these two cases on the land surface, their magnitudes can be quite different, which provides an indication of how to distinguish a fracture pressurization effect from a porous medium pressurization effect.

Abaqus (Hibbitt, Karlsson & Sorensen, Inc., 1998) was selected as the numerical tool as it is a sophisticated finite-element software package capable of handling the hydro-mechanical coupling problem and hydraulically induced fracture problem.

2. Ground deformation associated with fluid injection in a disc-shaped reservoir

This scenario involves injecting fluid in a diffusive manner into the reservoir (porous medium) that contains no obvious fracturing, thus fluid diffusion is the dominant process. Pore pressures increase more greatly in the permeable reservoir than they do in the surrounding low permeability units during fluid injection, leading to a large strain mismatch. The elastic fields due to inclusions in infinitely extended media were investigated by Eshelby (1957), who showed that the resulting strain in the inclusion (i.e., the reservoir) can be expressed by

$$\varepsilon_{ij}^{inclusion} = -\varepsilon_{ij}^{T} + S_{ijkl}\varepsilon_{kl}^{T} \qquad (1)$$

where ε_{ij}^{T} is called the "transformation" strain, S_{ijkl} represents the rank four tensors known as the "Eshelby shape factors" (Mura, 1982; Segall and Fitzgerald, 1998). The "Eshelby shape factors" depend not only on the shape of the inclusion and elastic properties of the matrix but also on the position and the distance of the inclusion from the free surface (Seo and Mura, 1979). The term $S_{ijkl}\varepsilon_{kl}^{T}$ represents the constraint of the elastic surroundings applied to the reservoir.

Table 1
Input parameters for the 3D model.

Model dimension (m)	200 × 200 × 144
Host formation property	
Density	2500 (kg/m^3)
Young's modulus	35 GPa
Poisson's ratio	0.28
Reservoir property	
Young's modulus	35 GPa
Poisson's ratio	0.28
Bulk modulus	26.5 GPa
Grain bulk modulus	65 GPa
Pore fluid modulus	2.2 GPa
Void ratio	0.10

This problem can also be analyzed most conveniently with the help of the so-called nucleus-of-strain concept in the half-space, as introduced by Mindlin and Cheng (1950). For the isotropic solid of infinite extent, the fundamental solution is that of Kelvin for a single force applied at a point. The displacement vector u is given in terms of the Galerkin vector F by

$$2Gu = 2(1-\nu)\nabla^2 F - \nabla\nabla\cdot F \qquad (2)$$

where G is the shear modulus, ν is Poisson's ratio and ∇, $\nabla\cdot$ and ∇^2 are the gradient, divergence and Laplacian operators, respectively.

From this concept, the displacement field for a disc-shaped reservoir at the free surface due to a nucleus of strain of small but finite volume under the influence of a pore-pressure change has been derived by Geertsma (1973). The detailed analytical solution as derived by Geertsma (1973) is provided in Appendix A. The input parameters for our numerical model are summarized in Table 1. The mini-reservoir has a radius of 20 m and a thickness of 4 m and is buried at 40 m depth. The injection point is at the center of the reservoir, which is at 42 m depth; and the total injected volume is 6.3×10^{-4} m^3 and the injection time is 450 s.

Good agreement exists between the land-surface deformations determined from the analytical solution and the numerical simulation results (Fig. 1).

3. Ground deformation due to fluid injection in a circular fracture

Underground void space can be grouped into two categories: the pore spaces in well-cemented rock formations that can be treated based on poroelasticity (Wang, 2000), and the spaces offered by fracture openings that fall out of the continuum elastic mechanical theory. We conduct a numerical test to investigate the scenario that involves injecting fluid into a circular fracture contained within an impervious medium. If the injected fluid is stored in a circular fracture instead of a disc-shaped reservoir, the fluid storage mechanism changes from a porous medium pressurization to fracture pressurization. Ground deformation due to fracture pressurization has been investigated by many researchers in the past (Sun, 1969; Pollard and Holzhausen, 1979; Davis, 1983,

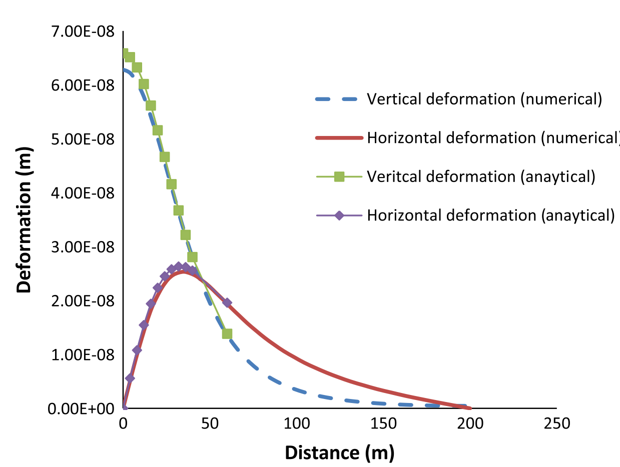

Fig. 1. Comparison between simulation results and Geertsma's analytical solutions.