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A laboratory study of stress arching around an inclusion due to pore pressure changes

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ABSTRACT

When the pore pressure in a porous rock changes, stress arching will occur within the rock and the surrounding region. Stress arching ratio is defined as the total stress changes in the porous rock to the pore pressure change in the region. The region may have the same or different elastic moduli with the surrounding rock, which is usually referred to as inclusion or inhomogeneity. Stress arching is responsible for many geomechanical problems encountered during production or injection; in addition, it is a crucial parameter in stress estimation during field development. This paper aims to present laboratory measurements of vertical stress arching ratio in a material surrounding the inclusion (inhomogeneity). To the authors' knowledge, few laboratory experiments have been reported on direct measurement of stress arching. The inclusion is a cylindrical sandstone (44 mm in diameter and 50 mm in height) embedded in a larger cylindrical sandstone (150 mm in diameter and 154 mm in height), both of which are made synthetically. These two parts are separated and sealed by a internal polyurethane sleeve. Vertical stress changes are recorded by a mini hydraulic sensor embedded in surrounding rock. Laboratory results are compared to those obtained by numerical models. These models are checked with analytical formulations. The results of numerical models show a good agreement with laboratory data. The numerical results also indicate that the sensor response is affected by elastic properties of the internal sleeve. According to the sensitivity analysis performed, in the absence of the internal sleeve, properties of the inclusion have significant effects on the surrounding stress arching induced.

1. Introduction

Pore pressure changes in a porous medium promote changes in stresses due to effective stress law and stress arching. The effective stress law introduced by Terzaghi (1925) and Biot (1941) indicate that stress in rock skeleton is determined by subtracting a percentage of pore pressure from total stress, while the total stress remains unchanged. Stress arching causes change in the total stress within and around a reservoir. Repeated stress measurements in a number of oil fields have revealed that there is a reduction in the total minimum horizontal stress during reservoir depletion, as shown in Fig. 1 schematically. According to Fig. 1, depletion of reservoir causes decrease in reservoir's total horizontal stress in addition to reservoir pressure. The total stress change that accompanies the reservoir pressure change is known as the "stress arching". When the stress arching is generated due to reservoir depletion, partial amount of total stress is supported by the surrounding formations. The total stress changes induced by fluid production or injection (stress arching) can have negative consequences such as cap rock failure, fault reactivation, and wellbore and casing damage (Hillis, 2003; Sayers, 2006; Soltanzadeh et al., 2007; Wang et al., 2015).

Ignoring stress arching can cause considerable errors in engineering design, as shown in Fig. 2. In Mohr circle representation of stresses, when the pore pressure changes with constant total stress (no stress arching), a shift in Mohr circle location is induced without diameter change (Fig. 2a). When the stress arching is considered, the diameter of Mohr circle changes due to pore pressure changes. In other words, the stress arching of total stresses causes development of deviatoric stresses and change of Mohr circle diameter (Fig. 2b). This fact is the reason for unexpected rock behavior in depletion or injection scenarios (Segura et al., 2011; Lynch et al., 2013).

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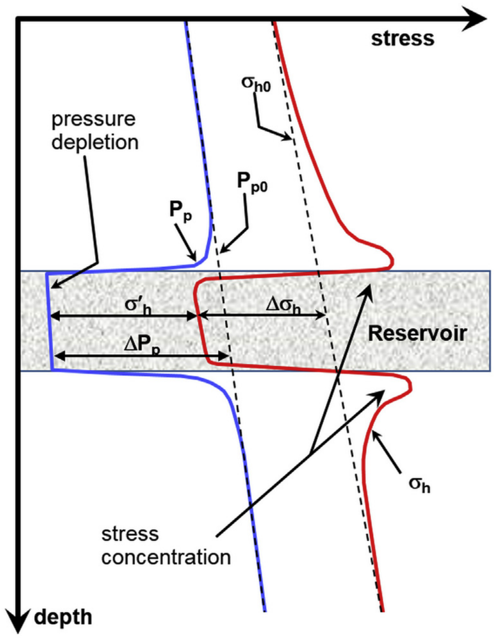

Fig. 1. Horizontal stress arching within and around a reservoir. Dashed lines are the initial stress and reservoir pressure profiles before depletion. Solid lines denote the horizontal stress and reservoir pressure profiles after depletion.

Generally, stress arching in porous media occurs within and around a region that has different conditions from surrounding materials (such as differences in pore pressure, temperature and mechanical properties). In this paper, the effects of pore pressure change in the region and the mechanical properties of materials within and around the region are discussed. According to Eshelby's theories of inclusion and inhomogeneity, when the elastic moduli of materials within and around the region are the same, it is called "inclusion", otherwise, it is referred to as "inhomogeneity" (Eshelby, 1957, 1959; Rudnicki, 1999, 2011; Soltanzadeh and Hawkes, 2007; Mura, 2013). The same definitions are used in this paper. However, the "inclusion" is used as a general term unless "inhomogeneity" is specifically discussed.

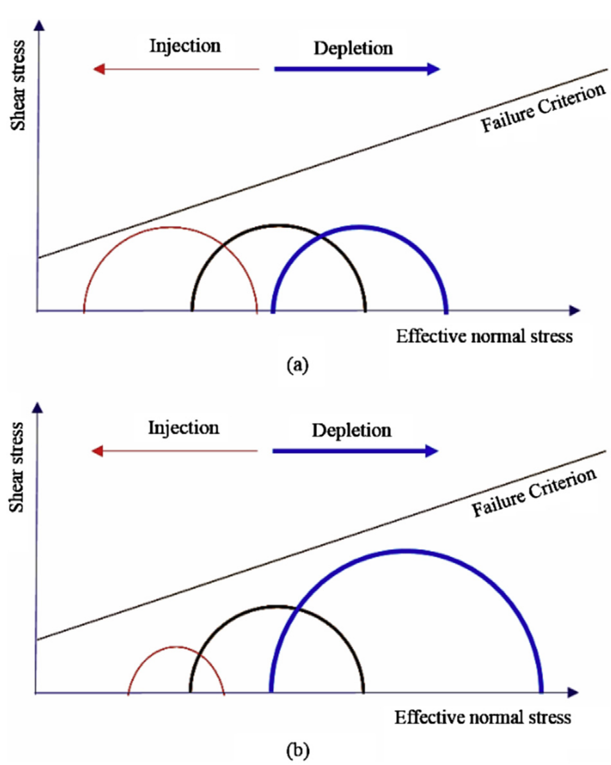

Fig. 2. Significance of stress arching in porous rock behavior. Blue circles represent the initial stress conditions. (a) In the case of ignoring stress arching, the diameters of Mohr circles are constant in reservoir injection or depletion; and (b) In the case of considering stress arching, the diameters of Mohr circles change due to injection or depletion.

Stress arching, also referred to as reservoir stress path (Goulty, 2003; Segura et al., 2011; Lynch et al., 2013), pore pressure-stress coupling (Hillis, 2003; Tingay et al., 2003; Altmann et al., 2014), or depletion/injection induced stress changes (Segall, 1992; Holt et al., 2004), is the ratio of total stress changes to the pore pressure change. According to Hettema et al. (2000), stress arching ratios are defined as follows:

$$\gamma_H = \frac{\Delta\sigma_H}{\Delta p_p}, \gamma_h = \frac{\Delta\sigma_h}{\Delta p_p}, \gamma_v = \frac{\Delta\sigma_v}{\Delta p_p} \tag{1}$$

where γ_H and γ_h are the horizontal stress arching ratios (in two perpendicular directions); γ_v is the vertical stress arching ratio; $\Delta\sigma_H$, $\Delta\sigma_h$, and $\Delta\sigma_v$ are the corresponding horizontal and vertical stress changes, respectively; and ΔP_p is the reservoir or inclusion pore pressure change. In the literature, deviatoric stress path (K) is defined as the ratio of horizontal effective stress change to the vertical effective stress change during pore pressure drawdown (Teufel et al., 1991; Khan and Teufel, 2000; Segura et al., 2011):

$$K = \frac{\Delta\sigma'_h}{\Delta\sigma'_v} \tag{2}$$

where K is a representative parameter for stress anisotropy. The relationship between Eqs. (1) and (2) is presented as (Segura et al., 2011):

$$K = \frac{1-\gamma_h/\alpha}{1-\gamma_v/\alpha} = \frac{\alpha-\gamma_h}{\alpha-\gamma_v} \tag{3}$$

where α is the Biot coefficient. According to the theory of poroelastisity, with assumptions of uniaxial strain boundary condition and no vertical stress arching, the horizontal stress arching is defined as follows (Segura et al., 2011):

$$\gamma_h = \frac{1-2\nu}{1-\nu} \tag{4}$$

where ν is the Poisson's ratio of rock. Eq. (4) is valid in ideal condition such as deep laterally extended reservoirs without natural complexity. In these reservoirs, the uniaxial strain boundary condition can be assumed with minimum error (Settari, 2002). In addition, overburden weight is fully transferred to the reservoirs without vertical stress arching because of their great width and small thickness (Goulty, 2003). It is clear that this assumption is not valid for many natural reservoirs because they do not have such ideal conditions. This has been confirmed by field measurements, and analytical and numerical analyses (Addis, 1997; Segall and Fitzgerald, 1998; Gambolati et al., 1999; Ruistuen et al., 1999; Hettema et al., 2000, 2009; Zoback and Zinke, 2002; Alassi et al., 2006; Sayers and Schutjens, 2007; Schutjens and Kuvshinov, 2010).

Analytical solutions show that, for particular geometries in an infinite medium such as sphere, cylinder and infinite layer, the following relationship holds among poroelastic stress arching ratios (Fjar et al., 2008):

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