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Constraining the in-situ stresses in a tectonically active offshore basin in Eastern Mediterranean

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ABSTRACT

The objective of this study is to estimate numerically the in-situ stress field in a tectonically active marine sedimentary basin. The Levantine basin in Eastern Mediterranean which is currently explored for gas and oil reservoirs is used as a case study. The study was based on elasticity, and poroelastoplasticity constitutive equations which were calibrated with material parameters derived from seismic data and correlation functions. The geometry of the Mechanical Earth Model is also constructed from seismic data. The equilibrium and constitutive equations are solved with the finite element method. The model simulates a basin area initially at rest and then loaded by horizontal motion to simulate the active tectonic movement of the plates over the geological time. The effect of boundary conditions and initial conditions are studied along with other important parameters that influence the problem such as the interface strength of fault surfaces and the plate movement. Information based on mud-density in drilled nearby wells are used to calibrate the horizontal motion and constrain the insitu stresses at the well locations and hence within a good approximation elsewhere. We found that in the active tectonic regime of East Mediterranean the horizontal stress increases in such extent that it can be compared with the vertical stress. The adhesive behavior between the walls of a fault can cause interlocking resulting to even larger horizontal stress values. Smaller stresses are generated in sliding conditions between the fault surfaces due to the dissipated energy in the sliding process. Finally, the stress distributions become highly complex with stress rotation and arching close to the fault area.

1. Introduction

In this paper we present modeling of the in-situ stress state in abnormal stress environment characterized by tectonic movement. As a case study we used data from the Levantine sedimentary basin in East Mediterranean which is characterized by tectonic movement and the presence of a deformation front in fault areas. Characterizing the regional stress in tectonically active settings is more complicated than in relaxed basin settings mainly because one cannot assume the stress field is regionally homogeneous (Plumb et al., 1998). Moreover in an early exploration phase one does not have the luxury of having or obtaining cores, logs and stress measurements at the locations where they are most needed. Information, such as insitu stresses and rock strength, is needed for the design of wellbore stability during drilling, to predict sanding and to avoid damages in the casing and formation during production and reservoir depletion (Plumb et al., 2000; Bell, 2003; Papanastasiou, 2004). Drilling parameters, such as mud weight or the optimal orientation of the wellbore, require knowledge of the in-situ stresses and the mechanical behavior of the rock. The lack of these kind of data in exploratory areas with insufficient constraints for the geological model, increases the risk of wellbore failure and hence the cost. Hence the ability of predicting the geomechanical behavior of the column rock that is going to be drilled is a desire scenario for the oil industry. Furthermore, knowledge of the ambient stress field is important in elucidating tectonic processes.

There are different methods for estimating the three components of the insitu stresses. The vertical stress is determined from the load of the overburden by integrating the density measurements with depth. The most reliable method for estimating the minimum insitu stress, which normally is one of the horizontal stresses, is with a mini hydraulic fracturing technique (Haimson and Fairhurst, 1967). There is no direct measurement for estimating the intermediate stress which is normally one of the horizontal stresses. Instead, it can be constrained using wellbore information derived from log measurements and images such as the presence of stress induced tensile fractures, wellbore breakouts or just the location of wellbore breakouts in inclined wells (Aadnøy, 1990, Djurhuus and Aadnoy, 2003, Zoback et al., 2003, Haimson et al., 2010, Chen et al., 2003, Kidambi and Kumar, 2016).

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These information are used with mechanical models which calculate the near wellbore stresses under anisotropic stresses (Detournay and Cheng, 1988; Tao and Ghassemi, 2010) and the formation of breakouts (Papanastasiou and Vardoulakis, 1992; Papanastasiou and Zervos, 2004; Papamichos, 2010) to derive bounds for the unknown stress if the other two stresses, the rock strength and drilling-mud density are known. An account on the different methods for stress determination can be found in the books by Fjaer et al. (2008) and Zoback (2010). All these methods predict the stresses in the neighborhood of a well which can be further extrapolated to the field scale in normal stress conditions. In abnormal conditions such as active tectonic areas or near the hill-foot an additional tool is needed for extending the wellbore information at the field scale (Plumb et al., 1998). Such as tool is provided by the powerful method of finite element analysis combined with appropriate constitutive modeling, geometry information, material data and local wellbore information.

The present models use concepts from elasticity and poroelastoplasticity theory in numerical models to compute the stationary stresses response of the formation that is submitted to effective compressive vertical stresses generated by the sea water weight and the gravity loading of the lithology of the sedimentary basin. Computational modeling is a step further necessary to understand the behavior of the stress field in a tectonically active area with complex boundary and loading conditions. The geometry of the area is constructed using seismic data. The rock deformation is based on elasticity and poroelastoplasticity constitutive equations which were calibrated with material parameters derived from seismic data and correlation functions. The equilibrium and constitutive equations are solved with the finite element method performed by Plaxis (2010). This study presents a novel approach for estimating all the components of the in-situ stresses and to construct the Mechanical Earth Model in a tectonically active basin which are very different from those obtained based on the usual assumption of gravity loading of a basin at rest.

In the next section we present the model describing the basic equations of poroelastoplasticity, the geometry, the rock properties and the discretized domain. Section 3 presents the results for an elastic, poroelastic and poroplastic analyses of the basin at rest and in active tectonic conditions for different fault sliding conditions. The results are interpreted and discussed in Section 4 and the main findings and conclusions are summarized in Section 5.

2. Numerical model

2.1. Basics of poroelasticity theory in a matrix formulation

The basic theory of poroelasticity was initially introduced by the pioneer work of Biot (1941). Since then many researchers have contributed to further developments. A comprehensive review of the theory of poroelasticity can be found in Detournay and Cheng (1993). The theory is commonly applied to soil mechanics problems especially for consolidation problems. The elastic response of the porous medium is given by the elastic strain rate and the elastic fluid mass content. These two parameters are related to the rates of total stress and pore pressure through isotropic constitutive equations.

The analysis in this study was formulated and carried out for plane strain conditions. The coupling between the solid and fluid phases was carried out through a pressure-displacement (u–p) formulation. The governing equation of motion of coupled solid–fluid problem can be written in matrix form as follows:

$$\boldsymbol{L}^T\boldsymbol{\sigma}-\rho\boldsymbol{b}^T=0 \tag{1}$$

$$\boldsymbol{m}^T\dot{\boldsymbol{\varepsilon}}=div\hat{\boldsymbol{v}}+\left(\frac{n}{K_w}\right)\dot{p} \tag{2}$$

where n is the porosity and K_w is the bulk modulus of the pore fluid. The total stresses $\boldsymbol{\sigma}$, and the body loads **b**, are time dependent given as

$$\boldsymbol{\sigma}=[\sigma_{xx},\ \sigma_{yy},\ \sigma_{xy}] \tag{3}$$

$$\boldsymbol{b}=[b_x,\ b_y] \tag{4}$$

with the differential operator L

$$\boldsymbol{L}^T=\begin{bmatrix}\partial/\partial x & 0 & \partial/\partial y\\ 0 & \partial/\partial y & \partial/\partial x\end{bmatrix} \tag{5}$$

and

$$\boldsymbol{\varepsilon}=[\varepsilon_{xx}\ ,\ \varepsilon_{yy}\ ,\ \varepsilon_{xy}] \tag{6}$$

with

$$\boldsymbol{m}=\{1\ \ 1\ \ 0\}^T \tag{7}$$

By definition the total stresses are related to the effective stresses through:

$$\boldsymbol{\sigma}=\boldsymbol{\sigma}'+\boldsymbol{m}\alpha p \tag{8}$$

where, $\boldsymbol{\sigma}'$ is the effective stress, which is assumed to govern the deformation and failure of the rock and α is the poroelastic Biot constant which is independent of the fluid properties and is defined as:

$$\alpha=\frac{3(\nu_u-\nu)}{B(1-2\nu)(1+\nu_u)}=1-\frac{K}{K_s} \tag{9}$$

that involves four material coefficients, namely: (a) the drained Young modulus E (b) the drained Poisson ratio ν, (c) the undrained Poisson ratio ν_u and (d) the Skempton coefficient, B. K is the bulk modulus of the matrix and K_s is the bulk modulus of the solid grains. An important distinction when applying the formulation to rock is that the compressibility of the constitutive materials must be considered. For soils B and α are equal to unity but in rocks are significantly less than one. Nevertheless for plastic deformation B and α approach the value of one.

The fluid velocities are determined from the Darcy's equation

$$\hat{v}\ =-\mathbf{k}\,(grad\ p-\boldsymbol{b}/\boldsymbol{g}) \tag{10}$$

where the relevant parameters are the coefficient of permeability $\boldsymbol{k}$, the density of water ρ_w, and the gravitational acceleration **g**.

In elastoplastic analysis the strain increment d“ij is decomposed into an elastic d“and a plastic part

$$\boldsymbol{\varepsilon}=\boldsymbol{\varepsilon}^e+\boldsymbol{\varepsilon}^p \tag{11}$$

For the linear elastic case the constitutive relation may be expressed as a linear relation in incremental form between strain and effective stresses:

$$\dot{\boldsymbol{\varepsilon}}=D_e^{-1}\dot{\boldsymbol{\sigma}}' \tag{12}$$

where, D_e is the elastic stiffness matrix which is expressed in terms of Young modulus, E_s and Poisson ratio, ν.

Proroelasticity theory is extended to poroelastoplasticity through the effective stress principle and standard plasticity concepts. Plastic strains are generated when the yield surface, F=0 is reached. Among the different yield criteria, the Mohr–Coulomb model adequately describes the pressure-sensitive behavior of rocks which exhibit dilatancy (increase in porosity) when sheared. The Mohr–Coulomb model is usually employed in cases of compressive shear yielding or failure. The Mohr–Coulomb criterion can be written as

$$F=\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_1{}'-\sigma_3{}'-2c\frac{\cos\varphi}{1-\sin\varphi}=0 \tag{13}$$

where, c is the material cohesion, φ is the angle of internal friction and σ_1 and σ_3 are the maximum and minimum principal stresses

The plastic strain increments are generated according to a flow rule

$$\dot{\boldsymbol{\varepsilon}}^p=\dot{\lambda}\frac{\partial Q}{\partial\boldsymbol{\sigma}'} \tag{14}$$

where, Q is the plastic potential and λ is the scalar function, called plastic multiplier, which is a function of the elastic matrix, derivatives