International Journal of Petroleum and Geoscience Engineering (IJPGE) 1 (4): 306-325, 2013
ISSN 2289-4713

Research Article

Geomechanical Application in Petroleum Engineering

Mahmood Bataee[a,]*, Sonny Irawan[a]

[a] Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia

* Corresponding author.
E-mail address:mahmood_bataee@hotmail.com

A b s t r a c t

Keywords:

Geomechanics.
Petroleum,
Wellbore,
Stability,
failure criteria.

This paper has reviewed the geomechanical studies and their applications in petroleum engineering. Geomechanical studies are applied in the wellbore and reservoir to establish the stability, which is a major problem in oil and gas industry. Most of studies are concerned with the drilling operations, however production operations and enhanced oil recovery (EOR) methods also alter the wellbore and reservoir stresses. It may cause problems such as collapse, sand production and fracture in the wells. Many researchers have tried to model the stress in the borehole in more than fifty years. They have governed various equations to investigate the flow, thermal and chemical effect in stress distribution. They have done their studied for many different conditions in different flow phases. In order to define the stability conditions, different failure criteria have been introduced. Many stability studies have been implemented using these criteria. The stress analysis should be coupled with reservoir simulation. During the lifetime of the reservoir, the change in stress could lead to the failure, so its effect should be studied on the field stability. However, there are lots of reservoir studies that did not consider geomechanics.

Accepted:01December 2013

1. Introduction

Geomechanics is the study of the rock elastic or plastic behavior and has direct impact on well integrity. Over the past two decades the geomechanical analysis has made major changes in the petroleum industry by maximizing production and increasing the life of the well. Wellbore stability is dominated by the in-situ stress system. When a well is drilled, the rock surrounding the hole must take the load that was previously taken by the removed rock. As a result, the stresses are modified in the borehole. This is presented by an increase in stress around the wall of the hole, that is, a stress concentration.

Rocks are generally composed of different materials, and of course not homogeneous. But, the rocks have elastic response, and fail in stresses etc., depend on their pore contents. In this section the void space would take into account, which not only is essential for oil to be produced from a reservoir, but also play an important role in rock mechanical behavior. The theory of thermo-poroelasticity (or porothermoelasticity) is developed by combining the influence of thermal stress and the difference between solid and fluid expansion to rock stresses and fluid diffusion. Poroelastic theory was initially applied in petroleum engineering to understand subsidence, estimate the stress evolution, and predict production. With the development of computer techniques, coupled study of geomechanics and reservoir flow effects have become very popular. Thermal effect in the drilled well will cause additional stress and pressure changes and it will definitely affect the stability.

Enhanced oil recovery (EOR) refers to a variety of processes to increase the amount of oil extracted from a reservoir after primary and secondary recoveries, typically by injecting water or gas. The injected fluids might push the oil in the reservoir or rather interact with the reservoir rock/oil system to create favorable conditions for oil recovery. The thermo-poroelasticity can describe the effect of temperature and fluid flow change on the stress in the borehole and reservoir. The injection of water leads to the changes in temperature, pore pressure and stress in the reservoirs and also effects on the reservoir permeability and porosity. Nowadays most reservoir simulators coupled with the stress changes and rock deformations within the production process, either one or two ways; this is because the physical impact of the geomechanical aspects of the behavior of reservoir is considerable.

The geomechanics research could be categorized into three different parts, although they are not separated and are closely related. These parts are the rock stress and its equations, rock failure criteria and the reservoir geomechanics.

As time pasts, the researchers try to find a new concept in geomechanics science or to modify the past contributed theories. The improvement in each category could be divided into some distinct time steps.

2. Stress Equations and its Application in the Borehole Stability

In order to analyze the stability of the well, the stress distribution in the borehole should be known. The stress state of the region is determined using stress equation solution. In this part, the different rock stress equations, as plastic, elastic poro-elastic and etc. will be investigated respectively. Furthermore, the efforts which made to express the stress distribution around the borehole and their application in the drilling engineering will be presented. The history of research in rock stress could be classified into three time periods; the period between 1940 and 1987 which the plastic and elastic theory had introduced and the researches were focused on the borehole stress and critical drilling mud weight is obtained; 1987-1998 which the research was mainly about the stress of deviated and horizontal wells and the best deviation angel and direction for drilling is obtained; and between 1998 until now which some new stress concepts are presented (as linear poro-elasticity and thermo-elastic) for better understanding of the effect of thermal and chemical stress on stability.

2.1. Theory of plasticity and elasticity and borehole stress distribution

The first notions in the presenting of the rock stress in the well were introduced by Westergaard and Biot. Westergaard [1] applied the stress equation of the solid into the well for the first time. He implemented a mathematical analysis of stress distributions in the borehole. He used the equations of equilibrium with stress functions and plasticity and elasticity factors. Meanwhile, Biot [2] tried to apply the mechanism of consolidation in the elastic porous medium. He extended his work on previous theory of elasticity and consolidation for the isotropic materials in 1955 for a better understanding of the state of stress in the porous media [3,4]. After a year [5] he developed the elasticity equation for the porous materials which have the elastic behave and contains fluid. He also presented a treatment of the deformation mechanics and acoustic propagation within the porous rocks in 1962.

Hodge [6] developed the theory of plasticity. He stated that most general piecewise linear theory depends upon five material constants. These include the initial yield stress, the rate of hardening, and three constants which describe the effect of hardening upon the condition for further yielding. Bishop et al. had extended the effective stress principle in 1959 [7]. They used partially saturated cylindrical samples. Paslay [8] tried to reach an analytical solution for the flow rates and rock stress which is induced by the pressure gradient. He took different considerations to solve the problem. Figure 1 shows his stress results as the function of wellbore radius. In the same year, Shoemaker explained the linear plasticity for the area of strain. And then, better solutions had introduced. Hiramatsu and Oka [9] worked on the problem regarding to the stress in the rock unaffected by borehole made in them. As the items of measurement, they had mentioned the variations in borehole diameter, strain on the bottom surface of the borehole. Nur and Byerlee [10] developed the relation for the effective stress σ_{ij} and, pressure with the assumption that only Hook's law is valid, $(\sigma_{ij}) = \sigma_{ij} - \alpha p \delta_{ij}$ and $(P) = P_c - \alpha p\ p$.

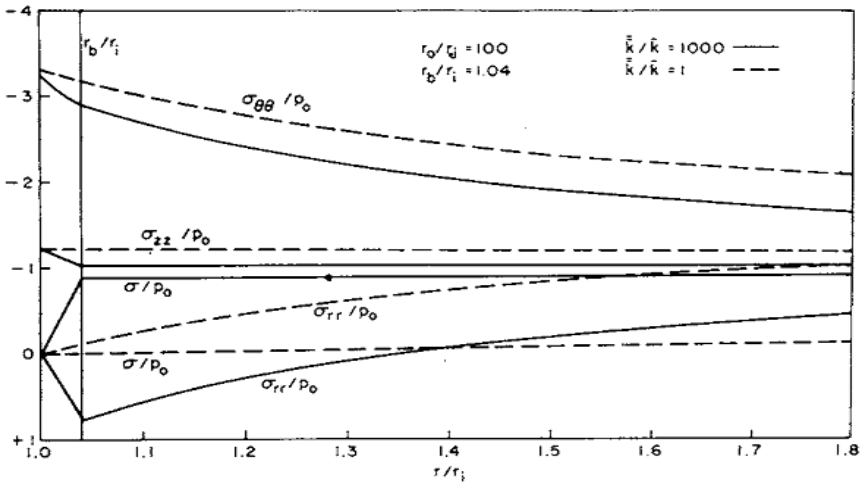

Fig.1: stresses as functions of radius [8].

As it is obvious, researchers tried to demonstrate different stress theories to better expression of the state what really happened in the well, step by step. These experiments and studies had simulated the wellbore and although it was primeval, it showed reasonable results.

By the time, the laboratory studies become very popular. Although it is almost impossible to reach the real well condition, studies show the effect of different parameters encountering the stress values. Lade [11] determined an elasto-plastic stress-strain theory of cohesionless soil with curved yield surfaces is developed on the basis of soil behavior observed in laboratory tests. Hoek and Brown [12] proposed an empirical criterion for rock strength. The criterion includes the uniaxial compressive strength of the rock and it uses some dimensionless parameters.

Bratli and Risnes [13] stated that by the production from unconsolidated sand boreholes, sand arches might form behind the perforation. After one year they had studied the stress in the poorly consolidated sand in the wellbore theoretically by some assumptions. One year later they leads to the result that, when a critical flow rate is reached, the arch will collapse. Figure 2 shows their stress solutions in the specific flow rate.

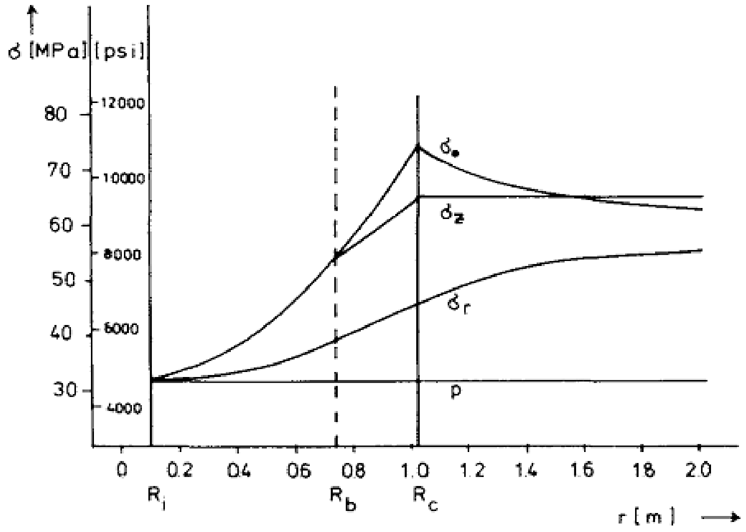

Fig.2: stress solutions with specified fluid flow rate, Po and So [13].

Santarelli and Brown [14] obtained some important results. They mentioned that the porous or clastic rocks often have elastic moduli which are not constant and increase with increasing minor principal stress. The use of classical constant modulus linear elasticity in these cases can lead to untrue predictions of the deformations and of the initiation and extent of failure around underground excavations. Brown et al. also [15] explained their solution for displacements and stresses induced around the wellbore. They had expressed that the elasticity is related to the minimum principal stress.

Mitchel et al. [16] presented the elastic-plastic model to determine the effect of yield around the borehole. In the same year [17] Aadnoy developed a linear elastic model. The model includes horizontal, axial and fluid movement stress in the borehole.

Fjær and Ruistuen [26] studied the effect of the intermediate principal stress on the rock strength; and they had created a numerical model to reach the result.

These studies lead to defining the effect of fluid pressure on stress in porous rocks and allow predicting the mud weight window for the safe drilling. Regarding this weight instructor prohibits the mud lost and on the other hand protects the well from being collapsed.

2.2. Wellbore deviation

Then researchers begin to investigate the stress in the horizontal and deviated wells. Aadnoy and Chenevert [18] studied the stability of inclined boreholes. Figure 3 shows the result of their study on collapse pressure versus borehole inclination. Two years later [19] Aadnoy investigated the stability in horizontal boreholes. Peska and Zoback [20] investigated the compressive and tensile failure for different well inclination degree and different stress conditions. In Figure 4 they had shown the magnitude of the maximum horizontal stress SH_{max} and azimuth of the minimum horizontal stress

Sh_{min} resulted in a case study. Detoumay and Cheng [21] modeled the poroelastic response in the wellbore in a non-hydrostatic stress condition. The paper was important and brings a new notion to the field stress consideration. Veeken [22] studied an elasto-plastic model which could estimate the wellbore stability. He had used finite element approach and his methodology became very popular and many researchers tried to make his approach afterwards.

These studies applied to find the best well direction and angle to reach the maximum well stability, especially in the presence of the fault.

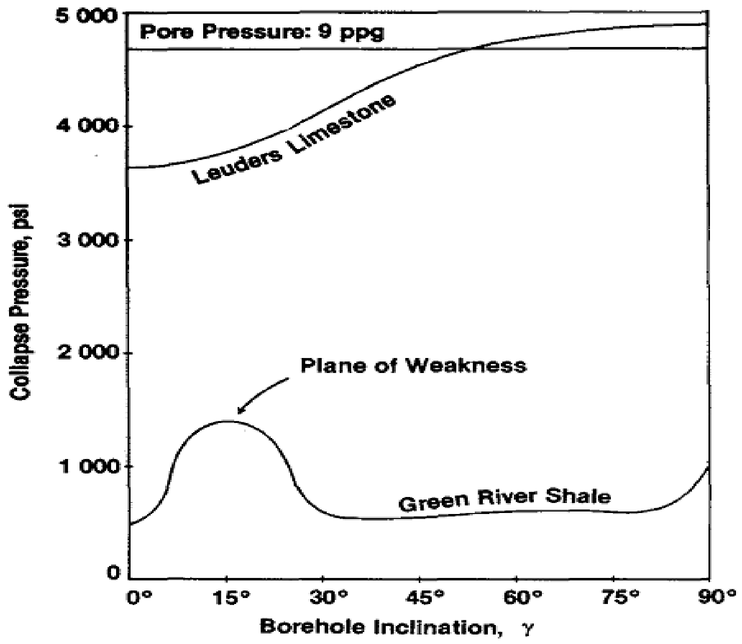

Fig. 3: collapse pressure versus borehole inclination [18].

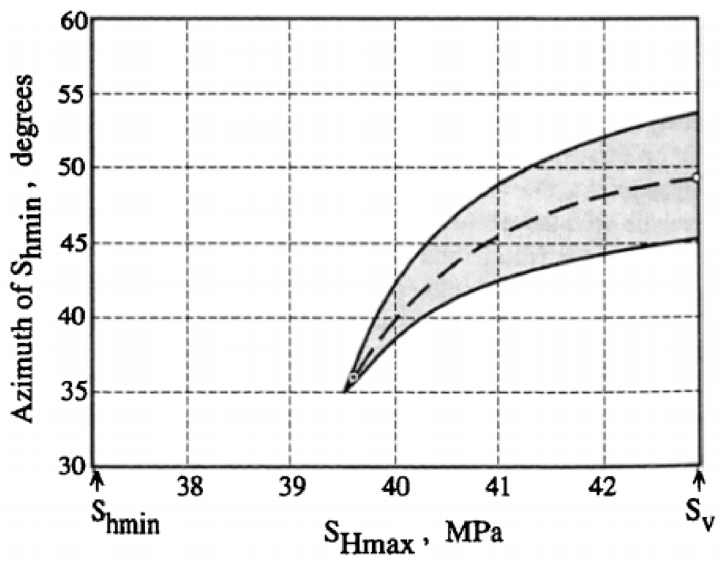

Fig.4: Magnitude of the maximum horizontal stress SH_{max} and azimuth of the minimum horizontal stress Shmin in a case study [20].

2.3. Some new concepts, and stress distribution studies

The borehole stress studies are very important in the drilling operations, especially in the shale stability. The chemical effect in the stress should be considered for the shale, which shows the most recorded formation encountered the stuck pipe. Bjørlykke and Høeg [23] expressed that the effects of chemical compaction, diagnostic processes and cementation must be considered in addition to the mechanical processes governed by effective stresses.

The effect of temperature is also considered in the studies afterward. Chen et al. [24] researched on the poroelastic chemical and thermal effects on wellbore stability in shale. They had completed their research two years later [25].

Cheng et al. [27] tried to solve the equation of dynamic poroelasticity. He had worked seven years until he reaches the fundamental solutions of poroelasticity [28]. In fact his work was the basis of the many papers. Zimmerman [29] worked on coupling in poroelasticity and thermoelasticity. He solved a simplified equation of linearised poro-elasticity and thermo-elasticity. Recently, solving these equations became popular. Yin and Rothenburg [30] worked on the poroelastic modeling in the reservoir, which the reservoir is prone to the multiphase flow. Three years later [31] they had extended their works on thermal reservoirs. Ghassemi et al. [32] had studied the effect of coupled chemo-poro-thermoelasticity on both the stress and flow rate in the borehole for the shale. Zhai et al. [33] did another study on coupled thermo-poro-mechanical effects on borehole stability. Figure 5 shows their result on tangential stress at a specific time step. Lee and Ghassemi [92] solved a three-dimensional thermo-poro-mechanical finite element problem in the wellbore. Figure 6 shows the mesh grid that they used in their simulation study. Sayed and Zhai [34] investigated the effect of thermal-poro-elasticity on the change in stress for production and injection wells.

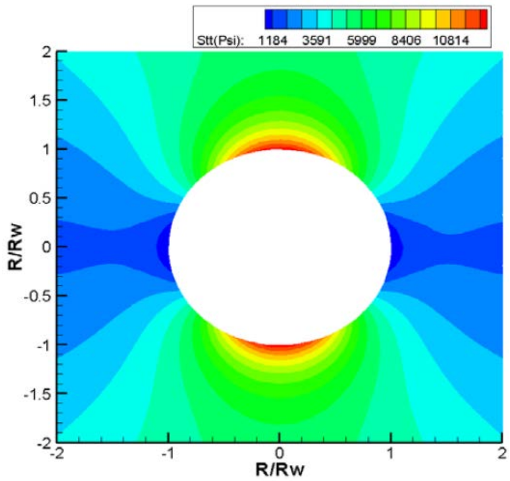

Fig.5: Effective tangential stress at specified time [33].

Solving the thermal and chemical poroelasticity is used widely in defining the stress values for the borehole. Researchers use these solutions to maintain the shale stability during drilling or designing the EOR thermal and chemical processes in injection wells.

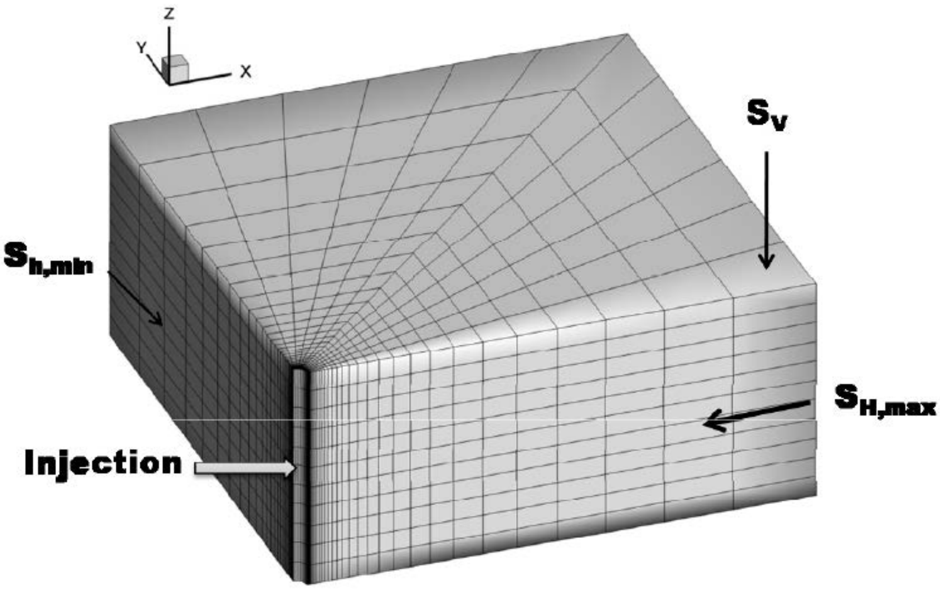

Fig. 6: Mesh used in the simulation study [92].

3. Borehole Failure

The second part illustrates the idea of the failure criteria and its development. Since 1960 several failure criteria developed and modified to establish a mechanical stability state. Many researchers have tried to use these criteria to avoid stability problems, as fracturing and sand production.

The study of failure criteria and well geomechanical stability could be figured as two main time periods; the studies between 1960 and 1995 which the failure criteria were introduced and modified to relate the borehole stress to stability; 1997 until now which the research was mainly about the sand production and shale stability in drilling operations.

3.1. Failure criteria and its application to the borehole stability

Basically the first notion of the failure came from the solid materials [35]. In 1960 Brace tried to apply this theory of solid rupture in the rock to model the failure in the well [36]. He mentioned the friction coefficient and explained that for the friction between 0.8 to 1.0 the failure condition is nearly the same as the Coulomb failure law observed in rocks. It could be concluded that for the low confining pressures, the Griffith mechanism of crack growth has an important effect in the fracturing. Figure 7 shows the modified Griffith graph as a Mohr envelope.

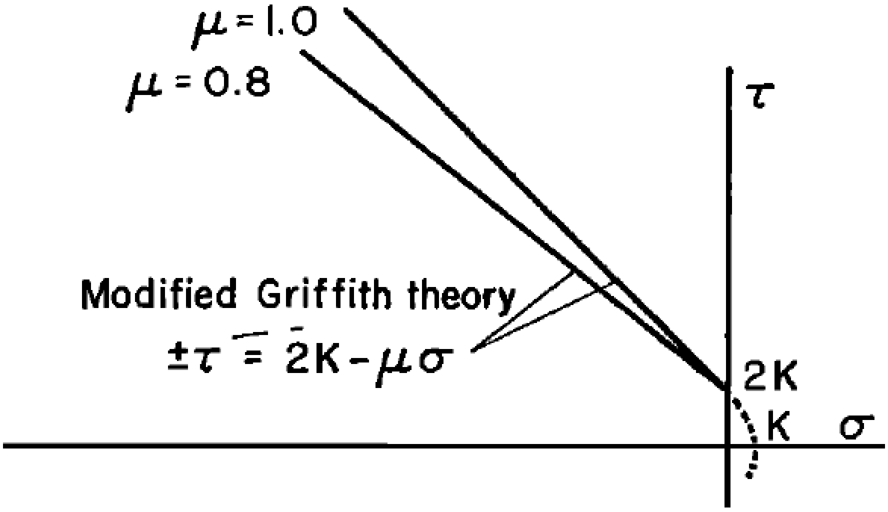

Fig.7: .Modified Griffith as a Mohr envelope [36].

Mogi [37] studied the role of intermediate principal stress in the failure of the rock. He applied experimental studies on some different rock type to obtain their stability.

Haimson (1967) studied the hydraulic fractures in rocks to demonstrate a criterion for analyzing the initiation of vertical hydraulic fracturing in the borehole. One year later he extends his works to determine the stresses at greater depth and for porous and non-porous rocks. Wiebols (1968) expressed an energy criterion for the rock strength in compression. It is generally accepted that the strength of the rock is determined by the presence of flaws, usually known as Griffith cracks. His theory was based on the additional energy around cracks due to the sliding of crack surfaces over each other. Murrell [38] studied the brittle fracturing in the triaxial stress condition.

Anthenuis [39] worked on the failure in the sandstone perforated boreholes. In order to analyze the collapse in perforation, he had loaded a number of rock cylinders to failure.

Bradley [40] tried to determine the borehole failure in drilling operations, using a mathematical concept. As the result he developed a borehole failure model which determines the conditions for hydraulic fracturing and collapse. The study concludes with an illustration on selecting the proper drilling mud weights for different pressures and depth to prevent the failure. And then, Risnes et al. [41] has studied the stress in unconsolidated sand in the wellbore.

Vardoulakis [42] analyzed the instability of the surface layer under uniaxial compression. Material behavior is described by a deformation plastic theory, for incompressible material with the Mohr-Coulomb condition. Zoback et al. [43] studied the shape of stress regarding to the wellbore breakout by using the ultrasonic televiewer data. Roegiers and Detoumay [44] investigated the failure for deviated boreholes, with respect to the principal stress directions.

Bardet [45] analyzed the rock-burst as a buckling by the finite element method. Some other research had been done in the same year. Takahashi and Koide [46] worked on the sedimentary rocks to investigate the effect of the intermediate principal stress on deformation. In order to clarify the effect of the intermediate principal stress on the rock deformation, some rocks were deformed under triaxial stress state. In this study, the intermediate principal stress is not equal to the maximum, neither to the minimum principal stresses. Maloney and Kaiser [47] conducted a series of experiments to simulate the borehole of sedimentary rocks as the investigation into the borehole breakouts mechanisms. In the same year Marsden investigated the sedimentary rocks for the peak strength behavior in the wellbore. He had implemented some triaxial experimental tests, which included stress studies for drained sedimentary rocks, and wellbore stability. Cheatham [48] proposed a hypothesis to determine the borehole breakout stability. He stated that the borehole breakouts are elliptical-like holes caused by unequal in-situ stresses during the drilling of oil and gas wells. This study can show us the shape of break out in the well as lots of experimental studies proven this afterward.

3.2. Borehole failure studies

Some research had been done, trying to modify the existed failure criteria. Hoek and Brown [49] modified their failure criteria. They had changed the correction because the criterion is used for different rocks with different degree of consolidation. Ewy [50] investigated the stability of wellbore using modified Lade criterion. He explained that neither Mohr–Coulomb, nor Drucker–Prager criteria (which are the two most commonly used criteria) are compatible with three dimensional measurements of the rock strength. Figure 8 shows the result of his work as required mud weight versus hole angle. Al-Ajmi and Zimmerman [51] studied the relationship between the parameters of the Mogi and Coulomb failure criterion to develop this failure criterion, and showed that it is reasonably accurate in modelling polyaxial failure data from a variety of rocks. And one year later, they had implemented the borehole stability study by using the modified Mogi–Coulomb criterion [52].

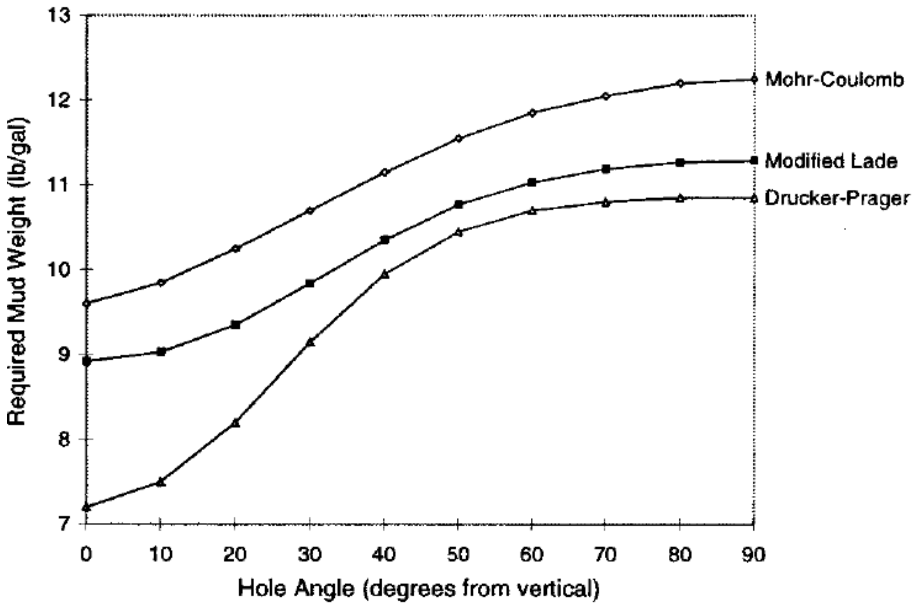

Fig.8: Required mud weight versus hole angle (Ewy 1999).

Some research tried to model the sand production. Bianco and Halleck [53] analyzed the sandstone rocks to determine the arch sand stability and production in two phase condition. Wan and Wang [54] started to model the sand production phenomenon. He also studied the effect of sand production on porosity as in figure 9 which shows the porosity distribution regarding to the sand production. They continued their works on sand production and four years later they modelled the erosion and stress deformation [55]. Papamichos modelled the rock erosion by the experimental data from tests on hollow cylinders [56]. Four years later he analyzed the effect of pore pressure on the wellbore failure [57].

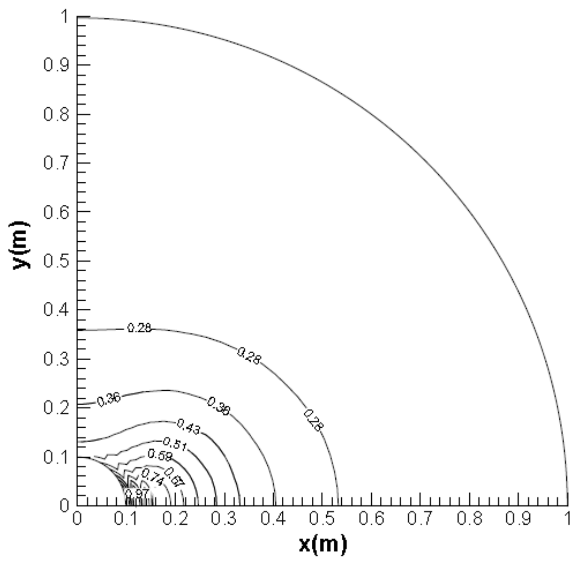

Fig.9: Porosity distribution due to the sand production [54].

Some researchers had investigated the effect of breakthrough on sand production. Skjaerstein [58] tried to explain the relation between sand production and water breakthrough by experimental studies. Wu et al. [59] implemented another experimental study to find the relation between sand production and the percentage of water production. Papamichos [60] developed the effect of multiphase flow on the sand production phenomenon.

4. Reservoir Stress Redistribution

The last part is the application of geomechanics in the field scale. The stress situation of the reservoir will practically change after production. This stress redistribution changes the state of reservoir properties as permeability and porosity; as the consequence, the reservoir simulators started to act coupled with geomechanics. There are some studies tried to explain the stress redistribution in the field after some EOR processes (which is mostly focused on the SAGD process). The idea of geomechanical application in the field was first ignited in 1973, after observing the field subsidence after some years of production. Researchers tried to find the relation of the change in pressure and the change in rock properties until 1998. In order to improve the reservoir simulation, the geomechanical features has been applied to estimate the better situation for the reservoir and different geomechanical programs had coupled with the reservoir simulators. As the result different cases of production and EOR processes have been simulated with the more accurate results.

4.1. Field subsidence

The first attempt to determine the field subsidence was the research of Geertsma [61]. A simple procedure was outlined to single out the subsidence after production in the reservoir.

Zoback and Byerlee [62] studied the effect of changing in stress on the permeability. He measured the permeability of the Berea sandstone as a function of both confining pressure and pore pressure. Ten years later [63], Anderson et al. studied the relation of the permeability value to the depth.
Zheng et al. [64] determined the pore compressibility for the rock at some reservoir drawdown conditions. They had simulated such conditions in the laboratory by subjecting a reservoir rock sample to virgin in-situ conditions and their implication for models of hydromechanical coupling. Pereira and De Freitas [65] used shear tests for understanding the shear failure mechanisms in fractures. In the same year [66], Chenevert and Sharma studied the swelling pressure and permeability in the shale formations, using the experimental data of permeability and pressure data to determine the swelling pressure. Brignoli et al. [67] studied the capillary and saturation effects in the uniaxial stress, which is important in the water-flooding.

These studies were important as they show the effect of stress on the reservoir characterization and flow properties.

4.2. Reservoir simulation coupled with geomechanics

There are some programs such as visage and CMG who start using co-worker programs. Some better reservoir description works using coupled programs, and many geomechanical studies had been done, but there is lots of reservoir simulation and EOR studies which the geomechanics is ignored in them.

Hettema et al. [68] investigated the effect of sand compaction on the production to describe the influence of stress in the field. They completed his study two years later [69].

Settari et al. brought a new idea of reservoir geomechanical coupling to reservoir engineering analysis [70]. As they had explained, reservoir simulators ignore the geomechanical aspect of porous rocks. They completed his study two years later [71]. Their attempts were the basis of the many works afterwards. Wang et al. [72] analyzed the stability of sand by using a coupled reservoir and geomechanical model. Benavides et al. [73] also studied the fluid flow coupled stress in the reservoir simulation. Borja and Aydin worked on the deformation modelling in granular media. They published two separate papers, first [74] in mathematical solution and the second [75] in the numerical solution.

Lots of reservoir geomechanical study using reservoir simulators to better understanding of fluid flow affection on the stress distribution. The coupling between reservoir simulation and geomechanics is necessary because the flow will alter the stress and the porosity-permeability. As a result this will change the flow pattern. Some geomechanical programs, (such as ABAQUS and FLAC) provide a one-way analysis for the reservoir simulators. Some reservoir simulators have a geomechanic module, so the two-way co-operation provides more accurate results.

Bostorm and Skomedal [76] studied the coupled hydro-mechanical behaviour of a HPHT gas-condensate field by ABAQUS. Tran et al. [77] developed an iterative method for coupling between the geomechanic model and reservoir simulation. One year later [78], they improved his study to get more accurate results. Freeman et al. [79] studied the geomechanics of bitumen formations.

Capasso and Mantica [80] numerically simulated the subsidence and compaction using a geomechanical simulator. Birkholzer et al. [81] studied the effect of CO_2 storage on the stress of the induced formation. Some other geomechanical studies on CO_2 storage and injection have been done. Chiaramonte, [82] published a book on the subject of geomechanical and simulation for a CO_2 sequestration. He and Zoback did another CO2-EOR simulation project in a fractured reservoir [83]. Rutqvist et al. also published some papers in coupled reservoir-geomechanical analyses of CO_2 injection and storage using TOUGH-FLAC. Figure 10 shows the result of one of his studies as the stress changes due to the change in pressure and the temperature [84-88].

Also some of EOR methods had been simulated coupled with geomechanical analysis. Gong et al. and Patrick and Collins published a very popular paper on the subject of coupled geomechanical and reservoir simulations for the SAGD [89]. Nowadays, EOR coupled geomechanical studies are very popular. Qobi et al. studied the EOR geomechanical screening in order to identification of risks to the pressure [90]. Safari and Ghassemi analyzed the geomechanical aspect of huff and puff process [91].

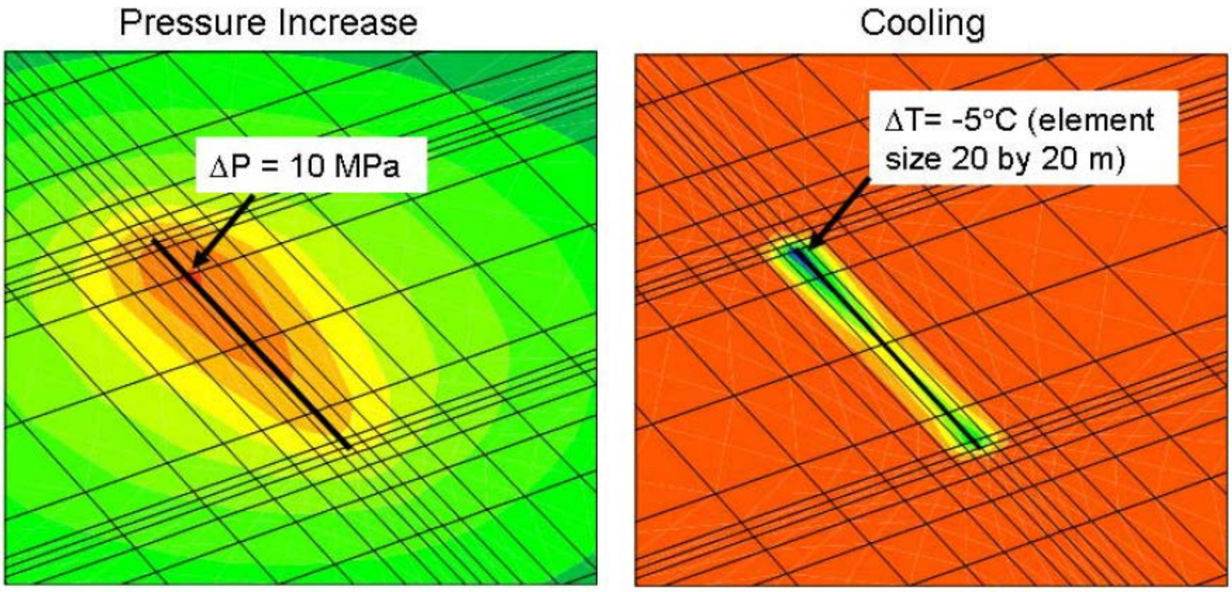

Fig.10: Resulted stress distribution due to the change in pressure and temperature [88].

5. Conclusions

The geomechanics has major contribution in the petroleum engineering, as they need a geomechanical study in lots of design such as borehole stability, mud window, directional drilling (drilling), sand production, perforation stability (production planning), reservoir characterization and simulation (reservoir engineering).

The stress distribution has been improved as lots of studies have been done over the last 60 years. Many researchers had studied the concept of stress by different geomechanical experiments, modeling and analysis in the petroleum engineering field. Also they deal with the fluid rock interactions, thermal, chemical and other equations to reach a complete approach to reservoir characterization and development.

The state of reservoir stress has different applications in petroleum engineering such as optimum drilling program and trajectory, stimulation, borehole instability, injection and production rate, and fluid loss. Not regarding to the stress state could lead to the failure.

Lots of failure criteria as Mohr-Columb Mogi and etc. has been introduced and improved to reach the more accurate results of the stability both in the wellbore and in the field. The most common failure in the well is the shale instability and formation fracturing during drilling operation, sand production in production wells.

The relation between stress, strain, fluid flow, and heat is complicated but solving it is the key to knowing the field stress state and its subsidence/inflammation over the years. The flow will alter the stress and the porosity-permeability; as the result, the coupling in reservoir simulator and geomechanics is necessary an also very popular nowadays. Although lots of field stress studied had been done, the stress change in different reservoir conditions and characters should be investigated.

Although lots of field stress studied had been done, the stress change in different reservoir conditions and characters should be investigated.

References

[1] Westergaard. H.M., Plastic state of stress around a deep well, 1940.

[2] Biot. M.A., General theory of three-dimensional consolidation, *Journal of applied physics*, 1941, 12(2):155-164.

[3] Biot. M., Theory of elasticity and consolidation for a porous anisotropic solid, *Journal of applied physics*, 1955, 26(2): 182-185.

[4] Biot. M., General solutions of the equations of elasticity and consolidation for a porous material, *J. appl. Mech*, 1956, 23(1): 91-96.

[5] Biot. M., Generalized theory of acoustic propagation in porous dissipative media, *The Journal of the Acoustical Society of America*, 1962, 34(9A): 1254-1264.

[6] Hodge. P.G., A general theory of piecewise linear plasticity based on maximum shear, *Journal of the Mechanics and Physics of Solids*, 1957, 5(4): 242-260.

[7] Bishop. A.W., et al., Factors controlling the strength of partly saturated cohesive soils, 1960.

[8] Paslay. P., Rock stresses induced by flow of fluids into boreholes, *Old SPE Journal*, 1963, 3(1): 85-94.

[9] Hiramatsu. Y., Oka. Y., Determination of the stress in rock unaffected by boreholes or drifts, from measured strains or deformations., 1968, Elsevier.

[10] Nur. A. Byerlee. J., An exact effective stress law for elastic deformation of rock with fluids,. *Journal of Geophysical Research*, 1971, 76(26): 6414-6419.

[11] Lade. P.V., Elasto-plastic stress-strain theory for cohesionless soil with curved yield surfaces, *International Journal of Solids and Structures*, 1977, 13(11): 1019-1035.

[12] Hoek. E., Brown. E.T., Empirical strength criterion for rock masses, *Journal of Geotechnical and Geoenvironmental Engineering*, 1980, 106(ASCE 15715).

[13] Bratli. R., Risnes. R., Stability and failure of sand arches, *Old SPE Journal*, 1981, 21(2): 236-248.

[14] Santarelli. F., Brown. E., Performance of Deep Well Bores In Rock With a Confining Pressure-dependent Elastic Modulus, 1987.

[15] Brown. E., Bray. J., Santarelli. F., Influence of stress-dependent elastic moduli on stresses and strains around axisymmetric boreholes, *Rock Mechanics and rock engineering*, 1989, 22(3): 189-203.

[16] Mitchell. R., Goodman. M., Wood. E., Borehole stresses: plasticity and the drilled hole effect, 1987.

[17] Aadnøy. B.S., A complete elastic model for fluid-induced and in-situ generated stresses with the presence of a borehole, *Energy Sources*, 1987, 9(4): 239-259.

[18] Aadnoy. B., Chenevert. M., Stability of Highly Inclined Boreholes (includes associated papers 18596 and 18736), *SPE Drilling Engineering*, 1987, 2(4): 364-374.

[19] Aadnoy. B.S., Stresses around horizontal boreholes drilled in sedimentary rocks, *Journal of Petroleum Science and Engineering*, 1989, 2(4): 349-360.

[20] Peska. P., Zoback. M.D., Compressive and tensile failure of inclined well bores and determination of in situ stress and rock strength, *Journal of Geophysical Research*, 1995, 100(B7): 12791-12,811.

[21] Detournay. E., Cheng. A.H.D., Poroelastic response of a borehole in a non-hydrostatic stress field, 1988, Elsevier.

[22] Veeken. C., et al., Use of plasticity models for predicting borehole stability, 1989.

[23] Bjørlykke. K., Høeg. K., Effects of burial diagenesis on stresses, compaction and fluid flow in sedimentary basins, *Marine and Petroleum Geology*, 1997, 14(3): 267-276.

[24] Yu. M., et al., Chemical and thermal effects on wellbore stability of shale formations, 2001.

[25] Chen. G., et al., A study of wellbore stability in shales including poroelastic, chemical, and thermal effects, *Journal of Petroleum Science and Engineering*, 2003, 38(3): 167-176.

[26] Fjær. E., Ruistuen. H., Impact of the intermediate principal stress on the strength of heterogeneous rock, *Journal of Geophysical Research*, 2002, 107(B2): 2032.

[27] Cheng. A.H.D., Badmus. T., Beskos. D.E., Integral equation for dynamic poroelasticity in frequency domain with BEM solution, *Journal of engineering mechanics*, 1991, 117(5): 1136-1157.

[28] Cheng. A.H.D., Detournay. E., On singular integral equations and fundamental solutions of poroelasticity, *International Journal of Solids and Structures*, 1998, 35(34): 4521-4555.

[29] Zimmerman. R., Coupling in poroelasticity and thermoelasticity, *International Journal of Rock Mechanics and Mining Sciences*, 2000, 37(1): 79-87.

[30] Yin. S., Dusseault. M.B., Rothenburg. L., Multiphase poroelastic modeling in semi-space for deformable reservoirs, *Journal of Petroleum Science and Engineering*, 2009, 64(1-4): 45-54.

[31] Yin. S., Dusseault. M.B., Rothenburg. L., Thermal reservoir modeling in petroleum geomechanics, *International journal for numerical and analytical methods in geomechanics*, 2009, 33(4): 449-485.

[32] Ghassemi. A., Tao. Q., Diek. A., Influence of coupled chemo-poro-thermoelastic processes on pore pressure and stress distributions around a wellbore in swelling shale, *Journal of Petroleum Science and Engineering*, 2009, 67(1): 57-64.

[33] Zhai. Z., et al., Coupled Thermoporomechanical Effects on Borehole Stability, 2009.

[34] Abou-Sayed. A., Zhai. Z., Thermal-poro elastic stress effect on stress reorientation in production and injection wells, 2011.

[35] Griffith. A.A., The phenomena of rupture and flow in solids. Philosophical transactions of the royal society of london, *Series A, containing papers of a mathematical or physical character*, 1921. 221: 163-198.

[36] Brace. W., An extension of the Griffith theory of fracture to rocks, *Journal of Geophysical Research*, 1960. 65(10): 3477-3480.

[37] Mogi. K., Effect of the intermediate principal stress on rock failure, *Journal of Geophysical Research*, 1967, 72(20): 5117-5131.

[38] Murrell. S., Digby. P., The theory of brittle fracture initiation under triaxial stress conditions—I, *Geophysical Journal of the Royal Astronomical Society*, 1970, 19(4): 309-334.

[39] Antheunis. D., et al., Perforation collapse: Failure of perforated friable sandstones, 1976.

[40] Bradley. W., Mathematical concept-Stress Cloud-can predict borehole failure, *Oil Gas J*, (United States), 1979, 77(8).

[41] Risnes. R., Bratli. R., Horsrud. P., Sand stresses around a wellbore, *Old SPE Journal*, 1982, 22(6): 883-898.

[42] Vardoulakis. I., Rock bursting as a surface instability phenomenon, 1984, Elsevier.

[43] Zoback. M.D., et al., Well bore breakouts and in situ stress, 1985.

[44] Roegiers. J., Detoumay. E., Considerations on failure initiation in inclined boreholes, 1988.

[45] Bardet. J., Finite element analysis of rockburst as surface instability, *Computers and Geotechnics*, 1989, 8(3): 177-193.

[46] Takahashi. M., Koide. H., Effect of the intermediate principal stress on strength and deformation behavior of sedimentary rocks at the depth shallower than 2000 m, 1989.

[47] Maloney. S., Kaiser. P., Results of borehole breakout simulation tests, 1989.

[48] Cheatham. J., A new hypothesis to explain stability of borehole breakouts, 1993, Elsevier.

[49] Hoek. E., Brown. E., Practical estimates of rock mass strength, *International Journal of Rock Mechanics and Mining Sciences*, 1997, 34(8): 1165-1186.

[50] Ewy. R., Wellbore-stability predictions by use of a modified Lade criterion, *SPE drilling & completion*, 1999, 14(2): 85-91.

[51] Al-Ajmi. A.M., Zimmerman. R.W., Relation between the Mogi and the Coulomb failure criteria, *International Journal of Rock Mechanics and Mining Sciences*, 2005, 42(3): 431-439.

[52] Al-Ajmi. A.M., Zimmerman. R.W., Stability analysis of vertical boreholes using the Mogi–Coulomb failure criterion, *International Journal of Rock Mechanics and Mining Sciences*, 2006, 43(8): 1200-1211.

[53] Bianco. L., Halleck. P., Mechanisms of arch instability and sand production in two-phase saturated poorly consolidated sandstones, 2001.

[54] Wan. R., Wang. J., Modelling sand production within a continuum mechanics framework, 2000.

[55] Wan. R., Wang. J., Analysis of sand production in unconsolidated oil sand using a coupled erosional-stress-deformation model, *Journal of Canadian Petroleum Technology*, 2004, 43(2).

[56] Papamichos. E., Sand production, *Revue européenne de génie civil*, 2006, 10(6-7): 803-816.

[57] Papamichos. E., Erosion and multiphase flow in porous media, *European Journal of Environmental and Civil Engineering*, 2010, 14(8-9): 1129-1154.

[58] Skjaerstein. A., et al., Effect of water breakthrough on sand production: Experimental and field evidence, 1997.

[59] Wu. B., Tan. C., Lu. N., Effect of Water-Cut on Sand Production-An Experimental Study, *SPE Production & Operations*, 2006, 21(3): 349-356.

[60] Papamichos. E., et al., Sand Production Rate under Multiphase Flow and Water Breakthrough, 2010.

[61] Geertsma. J., Land subsidence above compacting oil and gas reservoirs, *Journal of Petroleum Technology*, 1973, 25(6): 734-744.

[62] Zoback. M.D., Byerlee. J., Permeability and Effective Stress: GEOLOGIC NOTES, AAPG Bulletin, 1975, 59(1): 154-158.

[63] Anderson. R.N., et al., Permeability Versus Depth in the Upper Oceanic Crust'In Situ Measurements in DSDP Hole 504B, Eastern Equatorial Pacific, 1985.

[64] Zheng. Z., John M., Arfon. J., Pore volume compressibilities under different stress-conditions, 1990.

[65] Pereira. J., De Freitas. M., Mechanisms of shear failure in artificial fractures of sandstone and their implication for models of hydromechanical coupling, *Rock Mechanics and rock engineering*, 1993, 26(3): 195-214.

[66] Chenevert. M., Sharma. A., Permeability and effective pore pressure of shales, *SPE drilling & completion*, 1993, 8(1): 28-34.

[67] Brignoli. M., Papamichos. E., Santarelli. F., Capillary effects in sedimentary rocks: application to reservoir water-flooding, 1995.

[68] Hettema. M., et al., Production-induced compaction of sandstone reservoirs: the strong influence of field stress, 1998.

[69] Hettema. M., et al., Production-induced compaction of a sandstone reservoir: the strong influence of stress path, *SPE Reservoir Evaluation & Engineering*, 2000, 3(4): 342-347.

[70] Settari. A., Walters. D., Behie. G., Reservoir Geomechanics: New Approach to Reservoir Engineering Analysis, 1999.

[71] Settari. A., Walters. D., Behie. G., Use of coupled reservoir and geomechanical modelling for integrated reservoir analysis and management, *Journal of Canadian Petroleum Technology*, 2001, 40(12).

[72] Wang. J., et al., Sand production and instability analysis in a wellbore using a fully coupled reservoir-geomechanics model, paper ARMA/NARMS, 2004.

[73] Benavides Bello. Y., Maya. G., Osorio. J., Compositional Simulation of Fluid-Flow Coupled Stress-Sensitive Reservoirs, 2005.

[74] Borja. R.I., Aydin. A., Computational modeling of deformation bands in granular media. I. Geological and mathematical framework, *Computer methods in applied mechanics and engineering*, 2004, 193(27): 2667-2698.

[75] Borja. R.I., Computational modeling of deformation bands in granular media. II. Numerical simulations, *Computer methods in applied mechanics and engineering*, 2004, 193(27): 2699-2718.

[76] Bostrøm. B., Skomedal. E., Reservoir Geomechanics with ABAQUS, 2004.

[77] Tran. D., Settari. A., Nghiem. L., New iterative coupling between a reservoir simulator and a geomechanics module, *SPE Journal*, 2004, 9(3): 362-369.

[78] Tran. D., Nghiem. L., Buchanan. L., Improved iterative coupling of geomechanics with reservoir simulation, 2005.

[79] Freeman. T., Chalaturnyk. R., Bogdanov. I., Geomechanics of heterogeneous bitumen carbonates, 2009.

[80] Capasso. G., Mantica. S., Numerical Simulation of Compaction and Subsidence using Abaqus, 2006.

[81] Birkholzer. J.T., Zhou. Q., Tsang. C.F., Large-scale impact of CO2 storage in deep saline aquifers: A sensitivity study on pressure response in stratified systems, *International Journal of Greenhouse Gas Control*, 2009, 3(2): 181-194.

[82] Chiaramonte. L., Geomechanical Characterization and Reservoir Simulation of a Carbon Dioxide Sequestration Project in a Mature Oil Field, Teapot Dome, WY, 2009, ProQuest.

[83] Chiaramonte. L., et al., 3D Stochastic Reservoir Model and Fluid Flow Simulation of a CO2-EOR Pilot in a Fractured Reservoir, 2012.

[84] Rutqvist. J., Birkholzer. J., Tsang. C.F., Coupled reservoir–geomechanical analysis of the potential for tensile and shear failure associated with CO2 injection in multilayered reservoir–caprock systems, *International Journal of Rock Mechanics and Mining Sciences*, 2008, 45(2): 132-143.

[85] Rutqvist. J., Vasco. D.W., Myer. L., Coupled reservoir-geomechanical analysis of CO2 injection at In Salah, Algeria, *Energy Procedia*, 2009, 1(1): 1847-1854.

[86] Rutqvist. J., Vasco. D.W., Myer. L., Coupled reservoir-geomechanical analysis of CO2 injection and ground deformations at In Salah, Algeria, *International Journal of Greenhouse Gas Control,* 2010, 4(2): 225-230.

[87] Rutqvist. J., Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid flow and crustal deformations, *Computers & Geosciences*, 2011, 37(6): 739-750.

[88] Rutqvist. J., The Geomechanics of CO 2 Storage in Deep Sedimentary Formations, Geotechnical and Geological Engineering, 2012, 1-27.

[89] Gong. J., Polikar. M., Chalaturnyk. R., Fast SAGD and Geomechanical Mechanisms™, 2002.

[90] Qobi. L., et al., EOR Geomechanical Screening; Identification of Risks to Mitigate and opportunities to pursure, 2010.

[91] Safari. M., Ghassemi. A., 3D Analysis of Huff and Puff and Injection Tests in Geothermal Reservoirs, 2011.

[92] Lee. S., Ghassemi. A., A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore On Damage Evolution, 2010.