PROCEEDINGS
JOINT CONVENTION YOGYAKARTA 2019, HAGI – IAGI – IAFMI- IATMI (JCY 2019)
Tentrem Hotel, Yogyakarta, November 25th – 28th, 2019

Caprock Integrity Assessment in Fluid Injection for Enhanced Oil Recovery (EOR) Based On Geomechanics and Rock Physics Modeling: Case Study Related to The Impact of Chemical Alteration, Temperature, Water Content, Pore Pressure

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Abstract

Enhanced oil recovery (EOR) also called tertiary recovery, is the process of increasing the amount of recovered oil from an oil reservoir, usually by injecting a substance into an existing oil well to increase pressure and reduce the viscosity of the oil. EOR can extract 30% to 60% or more of a reservoir's oil compared to 20% to 40% using primary and secondary recovery. Some methods of EOR use fluid injection, i.e., Gas injection, Steam injection, Chemical injection, and CO2 injection.

The strength of caprock rocks plays an important role when the fluid injection is carried out for EOR. Knowledge of the caprock strength's limits greatly determines the success of fluid injection EOR which based on both factors of increasing hydrocarbon production and also safety factors. The fluid injection will result in subsurface stress changes caused by increasing subsurface temperature pressure and may decrease the strength of the rock. In this paper, we show the physical and geomechanical modeling based on rock physics for modeling the caprock rock strength when the injection of fluid for EOR is done in the reservoir. The geomechanical data of rock strength many parameters such as stress state, Mohr-Coulomb criteria, static friction coefficient, permeability, and also rock mechanics data various temperature. The rock mechanics data, geomechanical data in various pressures, fluid saturations and temperatures are essential in caprock integrity for steam injection EOR.

The output of the integrity assessment is essential for designing the safe fluid injection of EOR parameters, especially for avoiding the risk of fluid leaking upwards to the surface which very risky for the environment.

Keyword: EOR, caprock integrity, fluid injection, steam injection, rock physics, geomechanics.

Introduction

EOR can extract 30% to 60% or more of a reservoir's oil compared to 20% to 40% using primary and secondary recovery. Some methods of EOR are Gas injection, Steam injection, Chemical injection, and CO2 injection.

Caprock integrity is critical parameter in many fluid injection project, such as: CO2 sequestration, Steam flood injection, CO2 injection for EOR and water flood injection, and etc. Geomechanics plays an important role in the selection of operation procedure, design of the injection scenario, and the mitigation of the risk of the injection process such as fault stability, including maintaining safety and minimizing environmental impact. Rock physics plays as a bridge between seismic wave and rock's parameter including geomechanics parameter. Therefore, we can produce 3D geomechanics parameter model, such as elastic parameter (Young Modulus, Bulk Modulus, Shear Modulus, etc.), failure criteria, alteration parameter etc.

In this paper, we present an integrated geomechanics and rock physics workflow to evaluate caprock integrity for EOR. The development of geomechanics model integrates whole field measurements and laboratories measurements using statistical rock physics and neural network. The field measurements include seismic wave data, well log data, well testing data and interpreted or processed of well data, such as: petrophysics data. The well testing data comprise leak-off test, extended leak off test, minifract, borehole image scanner data, pressure test, etc. The laboratory data cover seismic rock physics core measurement, Triaxial, UCS, core flood leak-off test, porosity, permeability test data.

Our geomechanics modeling includes subsurface stress tensor, elastic parameter, failure criteria and the altered parameter, such as: altered elastic parameter, altered failure criteria, chemical alteration induced rock strength, temperature and also water content induced rock strength. These parameters may produce non linearity in the elastic parameter to the failure criteria.

The finite element computation was done for reservoir geomechanics modeling, and these are coupled by fluid flow modeling simultaneously. The iterative coupled computations between these two simulation modules continue until an equilibrium state between pore pressure and stress is achieved within a given tolerance. The efficiency of this approach is demonstrated through a case study of a proposed injection rate in some scenarios.

Method

The applicability of fluid injection needs good knowledge of caprock and reservoir. Parameter of integrity covers: and Geomechanic aspects. In addition, injecting steam into a very shallow unconsolidated reservoir has potential risk of having loss of containment issue

Caprock integrity as well as reservoir integrity assessments have become a key element in the design and operation of steam injection projects and a critical element in the selection of a maximum steam injection operating pressure. By necessity, these caprock integrity assessments involve geomechanical engineering principles and have generally lead to more use of reservoir-geomechanical simulations (one way coupled or sequentially coupled) in the establishment of what is termed "safe" maximum steam injection pressures.

To analyze caprock integrity due to the injection process of steam, an integrated geomechanics analysis is needed to evaluate caprock integrity in thermal operations. Geomechanical parameter (Young Modulus, Shear Modulus, Poisson including failure criteria i.e. Mohr-Coulomb) and rock's reservoir properties (porosity, permeability, water saturation etc.) are required as input data. All of data will be integrated with coupled reservoir properties and geomechanics modeling to calculate changes of rock strength due to steam injection.

Assumptions which are implemented on the model follow presumption on Darcy law. In three dimensional space gravity must be accounted for, as the flow is not affected by the vertical pressure drop caused by gravity when assuming hydrostatic conditions. Therefore, the model uses the equation of Darcy law with elevation term

$$\vec{u} = -\frac{\kappa}{\mu}\left(\vec{\nabla}\rho + \rho g \vec{\nabla} D\right)$$

Equation 1

Where: p, ρ, g, μ, κ, D are pressure, fluid density, gravitation, viscosity, permeability, and elevation, respectively. The velocity $\vec{\boldsymbol{u}}$ subjugates to continuity equation below,

$$\frac{\partial}{\partial t}\left(\rho \in_p\right) + \vec{\nabla}.(\rho\vec{u}) = Q_m$$

Equation 2

The fluid flow obeys this equation with ϵ_p and Q_m are porosity of porous media and debit. Equation (**Equation 1**) and (**Equation 2**) are solved simultaneously to obtain pressure and velocity. These equations implement Initial and boundary condition on the model. Initial value of pressure is inserted into well while symmetrical boundary condition is applied at the edges of the model. The velocity at the edges cannot pierce due to symmetrical boundary condition.

The model combines the heat transfer in porous medium with equation (**Equation 1**) and (**Equation 2**) trough velocity.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u}\vec{\nabla}T = \vec{\nabla}.\left(k\vec{\nabla}T\right) + Q$$

Equation 3

With C_p, k and Q are heat capacity in constant pressure, heat conductivity, and heat source.

Equation 3 gives TT (temperature) as solution. The temperature is needed to calculate the new viscosity of fluid. Equation below gives a relation between viscosity and temperature.

$$\mu(T) = 2.83x10^{11}\exp\left(-0.078T\right)$$

Equation 4

The velocity is used not only in heat transfer but also in solid mechanics. **Equation 5** depicts utilizing velocity.

$$\rho\frac{\partial^2\vec{u}}{\partial t^2} - \vec{\nabla}\sigma = \vec{F}V$$

Equation 5

Where σ, $\vec{F}$and V are stress, force and Poisson ratio subsequently. This equation accords strain as the solution. Every time step repeats the calculation process and stops at the required time.

And the chemical alteration of coupled reservoir properties and geomechanics modelling shows in equation below:

$$\frac{\partial(\boldsymbol{bc})}{\partial\boldsymbol{t}} + \boldsymbol{\nabla}.(\boldsymbol{qc}) - \boldsymbol{\nabla}.(\boldsymbol{bD\nabla c}) = \boldsymbol{R}(\boldsymbol{c})$$

Equation 6

$$\boldsymbol{R}(\boldsymbol{c}) = \boldsymbol{k_{eff}}(\boldsymbol{c} - \boldsymbol{c_0})$$

Equation 7

$$\frac{\partial^2\boldsymbol{c}}{\partial\boldsymbol{r}^2} + \frac{\boldsymbol{1}}{\boldsymbol{r}}\frac{\partial\boldsymbol{c}}{\partial\boldsymbol{r}} + \frac{\boldsymbol{k_{eff}}}{\boldsymbol{D_m b_0}}(\boldsymbol{c} - \boldsymbol{c_0}) = \boldsymbol{0}$$

Equation 8

Where b is the local aperture, q is fluid flux, D is the local dispersion, c is dissolve concentration, $R(c)$ is the local mass transfer rate, r is radius and k_{eff} is effective reaction-rate coefficient.

These caprock assessments includes geological framework studies of caprock, in situ stress determination, constitutive property characterization, failure criteria from numerous situations and numerical simulations to ensure the steam injection scenario is always in proper condition.

Cap-rock Integrity Analysis in Non-Faulted Area (Fault generation in cap-rock)

By analyzing the stress that works on cap-rock as shown in Figure 1, cap-rock integrity is calculated through Equation 9. This equation shows disequilibrium of stress where shear stress on left side exceeds Mohr-Coulomb (M-C) on right side, and then cap-rock will be failure and fault generation will occur. Failure based on cap-rock integrity is assuming no pressure change in shale cap-rock. Therefore, no Shmax and Shmin change when calculating failure based on cap-rock integrity.

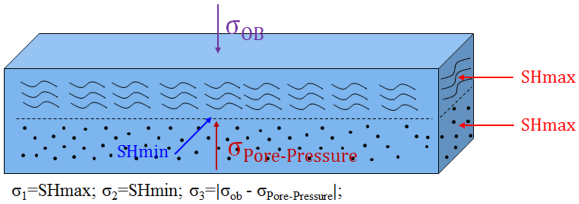

Figure 1 **Illustration of Cap-rock Integrity Analysis**

The fault generation depends on the condition of $\boldsymbol{\sigma_1}, \boldsymbol{\sigma_2}, \boldsymbol{\sigma_3}$ where $\boldsymbol{\sigma_1}$ indicates highest principle stress, $\boldsymbol{\sigma_2}$ indicates medium principle stress and $\boldsymbol{\sigma_3}$ indicates lowest principle stress. These stress is applied to Equation 6 as following.

$$\tau > c + tan\theta\ \sigma_n$$

$$sin2\beta\left(\frac{\sigma_1 - \sigma_3}{2}\right) > c + tan\theta\left(\left(\frac{\sigma_1 + \sigma_3}{2}\right) + \left(\frac{\sigma_1 - \sigma_3}{2}\right)cos2\beta - PP\right)$$

$$\cos\theta\left(\frac{\sigma_1 - \sigma_3}{2}\right) > c + tan\theta\left(\left(\frac{\sigma_1 + \sigma_3}{2}\right) - \left(\frac{\sigma_1 - \sigma_3}{2}\right)\sin\theta - PP\right)$$

Equation 6

Where:
τ = Shear stress
σ_1 = SHmax (unaffected by pore pressure since cap-rock is shale)
σ_3 =$\left|\sigma_{ob} - \sigma_{porepresure}\right|$
θ = friction angle of Mohr-Coulomb
β = Fault plane

The possibility of fault generation types which induced by injection program are listed as following:

(a) Strike Slip
Strike-slip fault will occur when S_{Hmax} value is greater than overburden pressure, and $S_{overburden}$ itself is greater than S_{Hmin} value ($S_{HMAX}>S_{OVERBURDEN}>S_{HMIN}$) as shown in Figure 2.

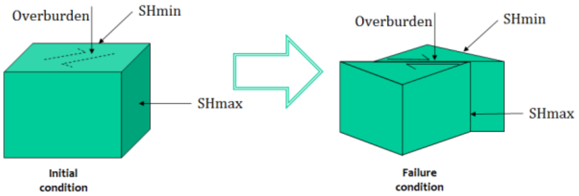

Figure 2. **Illustration of Strike-Slip Fault**

(b) Thrust-Fault
Thrust fault occurred when S_{Hmax} is greater than S_{Hmin}, and S_{Hmin} value is greater than Overburden pressure ($S_{HMAX}>S_{HMIN}>S_{OVERBURDEN}$) as shown in Figure 3.

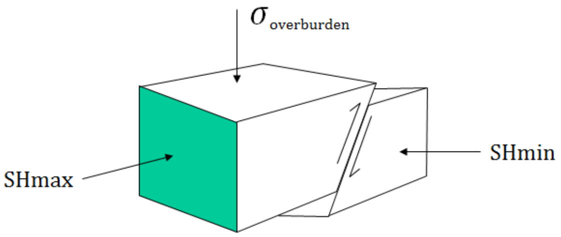

Figure 3. **Illustration of Thrust fault**

(c) Normal Fault
Normal fault will occur when $S_{Overburden}$ pressure value is higher than S_{Hmax}, and S_{Hmax} has higher value than S_{Hmin} ($S_{OVERBURDEN}>S_{HMAX}>S_{HMIN}$). The ilustration is shown in Figure 4.

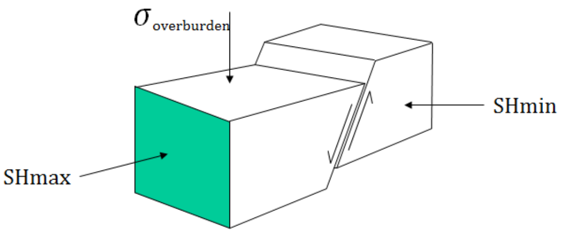

Figure 4. **Illustration of Normal fault**

The illustration on Figure 5 shows how pore pressure shifting $\boldsymbol{\sigma_3}$ on the Mohr-Coulomb circle to the left which can be increasing the risk to M-C (Mohr-Coulomb) failure criteria during steam injection.

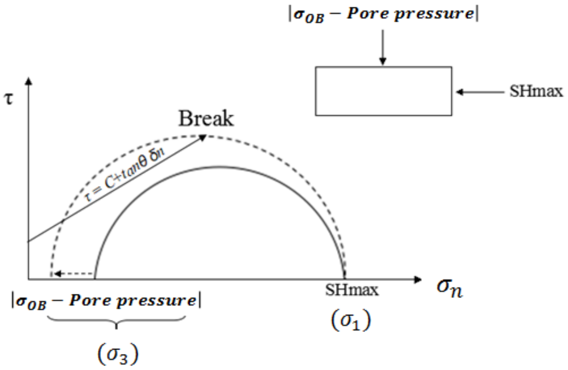

Figure 5. **Failure criteria from Mohr-Coloumb diagram in cap-rock-reservoir interface**

Fault Integrity Based on Fault Reactivation

The fault integrity during the steam injection simulation is also analysed to prevent the risk of fault reactivation. Fault reactivation illustration is shown in Figure 6 below.

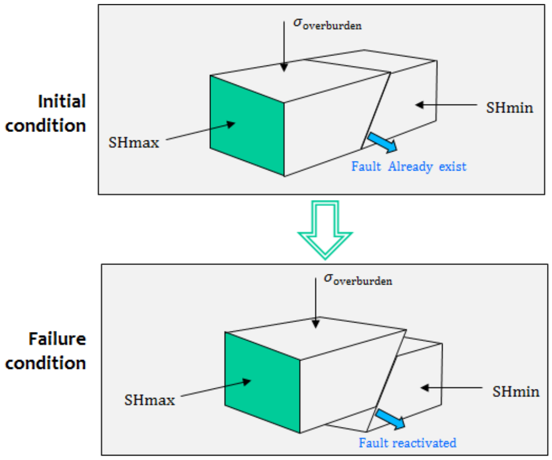

Figure 6. **Fault reactivation illustration**

Fault integrity is calculated through Equation 7. This equation shows disequilibrium of stress where shear stress on left side exceeds Mohr-

Coulomb (M-C) on right side. Therefore, fault integrity will fail and fault reactivation will be occured.

$$\tau > c + tan\theta\ \sigma_n$$

$$|-\sigma_{OB}\sin\theta + \sigma_{SHMax}\cos\theta| > (\sigma_{OB}\cos\theta + \sigma_{SHMax}\sin\theta - P_{pore})\mu_s$$

Equation 7

Where:
θ = dip fault from horizontal
μ_s = static friction coefficient
P_{Pore} = Pore Pressure
τ = Shear stress

The thrust fault reactivation caused by pore pressure injection will occure when these requirements are fullfiled:

$$S_{Hmax} > S_{Hmin} > \sigma_{OB}$$

While Strike slip fault reactivation will be happened when these requirements are fulfilled:

$$S_{Hmax} > \sigma_{OB} > S_{Hmin}$$

To provide deeper knowledge of geomechanical parameters, laboratory measurement can be performed through Core Flood Leak-off Test for fault plane, Internal Friction Coefficient Testing, elasticity as well as failure criteria in various temperatures, and also measuring Biot’s Willis Coefficient.

The the fault integrity during the fluid injection simulation can also analyzed to prevent the risk of fault reactivation as mentioned above.

The concept of factor of safety for both vertical failure and horizontal failure should be reviewed based on geomechanical engineering. The dynamic nature of the “factor of safety” will be highlighted showing that careful attention to how the steam is injected time to time which can impact to the tensile and/or shear failure conditions.

Conclusions

Static fault friction coefficient based on core laboratory measurement which is useful for predicting fault reactivation during fluid injection. Pore pressure influences failure criteria in reservoir, therefore failure criteria (SHmin) will be higher when pore pressure is increased. Laboratory testing of core sample in high temperature condition (by injecting the core sample using hot steam) shows decreasing velocity of P-wave as well as S-wave velocity compared with one in room temperature. In addition, Geomechanical Laboratory testing of core sample in high temperature condition shows decreasing C value (Cohesion Parameter) as well as Friction Angle of Mohr Coulomb curve compared with one in room temperature. Therefore, failure criteria of high temperature become lower. Injection scenario is key point in caprock integrity. To maintain caprock integrity, steam injection is suggested to be injected in safe pressure as well as safe injection rate while huff and puff scenario is performed (steam injection with scenario: injection, soaking and production are performed sequentially).

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