Investigation of Wellbore Stability in Saadi Tight Reservoir/Halfaya Oil Field

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Abstract

Wellbore stability analysis has proven to be a useful tool for reducing drilling risks and expenditures associated with unwanted drilling events such as stopped pipe, loss circulation, hole collapse, kick, and so on. Wellbore stability issues typically arise when drilling in reservoirs of hydrocarbons such as shale, fractured carbonate formations, and high-pressure, high-temperature formations with a narrow safety mud weight. These issues can have a substantial impact on drilling time, expenses, and the overall drilling operation. The aim of this study is to predict wellbore stability in Halfaya oil field (Saadi reservoir) using 1D mechanical earth model built with well logs. The workflow includes the calculating the pore pressure, vertical stress, rock strength, rock elastic parameters,and horizontal stresses Mogi-Coulomb failure criteria determined the deformation of the well. 1DMEM can also be conduct a comprehensive geomechanical wellbore stability analysis for the Saadi formation.The results showed that the failure occurred in the well is mud loss and kick on the left boundary and the breakout and breakdown type were not observed. Also, the magnitude of the utilized mud weight (10.25 ppg) is the most safe to avoid a lot of problem of WBS. Mud loss and kick did not significantly affect the stability of the well. Mud loss and kick are the wellbore instability issues appeared in this study along all formations, but mud loss is increased in the top of Hartha, Tanuma and KhasibA and Khasib B. and the formation of Saadi B has a little of mud loss effect the borehole stable that means the drilling operation will continue without problems. Finally, we concluded that the well HF-55 is rather stable. The Modified Lade failure criteria doesn't neglect the intermediate principal stress effect on the predicted failure. The regime of stress in all formations are normal fault regime due to (SV> SH>Sh).

Keywords: *Geomechanics properties, pore pressure, Eaton's method, wellbore, min and max horizontal stress, Mud Weight Window.*

1. Introduction

2. rock mechanics is a branch of geomechanics where the main focus is on rock deformation and possible failure of rock due to the applied manmade or natural forces. Knowledge of rock strength is a necessary element in analysis and modeling of earth stress, borehole stability during drilling, sand production and hydraulic fracturing. Rock strength is defined as the peak of stress reached when rock begins deforming throughout a compress test. Geomechanical characterization of hydrocarbon reservoir rock gives the description of mechanical parameters based on the physical and chemical composition (Dusseault, 2011) of rock

mass of the geologic formation. Reservoir formations are affected by the collective load of the overlying strata which causes vertical compressive stress, together with lateral (horizontal) stresses thereby creating imbalance upon the extraction of hydrocarbon(Rasouli, Pallikathekathil and Mawuli, 2011). The directions and magnitudes of these formation stresses are used to characterize reservoir conditions for various geomechanical applications (Sinha et al., 2008). For instant, the bearing and size of these stresses are requisite for forecasting geomechanical issues such as borehole stability, hydraulic fracturing for enhanced production and for discerning intervals of perforation for sand management(Sinha *et al.*, 2008). Hence, they play important roles in petroleum prospecting for oil and gas and reservoir development (Sinha *et al.*, 2008). The term brittle rock described the property of fracturing or rupturing with slight or no plastics flow occurrence within the earth upper crust (Hucka and Das, 1974). The best representative of the actual rock strength behavior is the mechanical tests, but, acquiring this data is expensive and time consuming because these approaches involve extracting formation core samples, and merely symbolize the properties of rock at that precise position (Almalikee and Almalikee, 2019).

3. Wellbore instability is one of the key challenges influencing the drilling and production operations. Problems associated with it are both time-consuming and expensive. Therefore, an accurate prediction of wellbore state is of paramount importance(Abdollahipour *et al.*, 2019).
4. Wellbore instability is one of the major causes for wellbore failure and leads to several issues for drilling and completion operations. These issues like stuck pipe, collapse, wellbore washout, blowouts, breakouts, kicks, and mud losses may take place due to a reduction of accurate wellbore stability analysis and the change in the subsurface stress level, particularly at the wellbore, is the cause of these problems.

5. Geomechanical properties

The determination of mechanical rock properties plays a significant role in any geomechanical analysis. The basic mechanical rock properties include elastic properties (Poison's ratio (v), and Young's modulus (E)), and rock strength properties, unconfined compressive strength (UCS), and tensile strength. The first stage in building the model of Geomechanic for Saadi reservoir in Halfaya oil field requires set of important data including well logs such as (bulk density, compressional and shear slowness, resistivity, gamma ray and caliper and mini- frac tests to verficate the result of stress. The model can be constructed through depending on basic well logs data. Then, estimating the hydrostatic pressure, pore pressure, rock strength, elastic properties, horizontal stresses is the second stage in construction the 1D MEM. Also. We need the calibration data such as core test data to insure the calibration of mechanical earth model, mini frac test to veficate the results of horizontal stresses. To construct this model, set of logs were used such as bulk density, Gamma ray, compressional ansd shear wave velocity (DT_c, DT_s) and caliper.

5.1 Rock Mechanical properties

These properties play a vital role in building 1D mechanical earth model. It's including Poisson'sratio and Young modulus as elastic properties, while tensile strength, friction angle, compressive stress are the characteristics of rock strength. These parameters are necessary in determining the optimal mud weight to maintain the wellbore stable.

2.1.1 Dynamic elastic parameters

Young's modulus, Poisson's ratio, shear modulus, and bulk modulus were estimated based on the concept of elastic modulus equations defined by Clark (1966)from the shear acoustic wave velocity, compressional acoustic wave velocity with bulk density logs for the carbonate formation (Fjar *et al.*, 2004) Fig2.

Young’s modulus can be referred to as the amount of pressure needed to deform the rock. Young’s modulus measures a rock’s hardness, and the higher the young’s modulus, the stiffer the rock(Economides and Martin, 2007). It can be calculated using Eq1.

$$Ed = \frac{\rho b\, VS2\,(3VP2-4VS)\,2}{(VP2-VS2)} \quad (1)$$

where Ed is dynamic Young’s modulus, ρb is density (g/cm3), Vs is Shear-wave velocity (m/s), Vp is compressional-wave velocity (m/s) and υ is Poisson’s ratio.

Poisson's ratio (v) is important elastic parameter that plays an important role in deformation of the rock. (measure of a rock’s strength)(Fjar *et al.*, 2004). It was estimated by Eq2.

$$\nu_d \quad \frac{V_P^2-2V_S^2}{2*(V_P^2-V_S^2)} \quad (2)$$

Dynamic Shear modulus G_{dyn} and bulk modulus K_{dyn} are calculated from the following equations (3,4):

$$G_{dyn} = 1374.45 * \frac{\rho_b}{(\Delta t_{comp})^2} \quad (3)$$

$$K_{dyn} = 1374.45 * \frac{\rho_b}{(\Delta t_{comp})^2} - \frac{4}{3} G_{dyn} \quad (4)$$

2.1.2 Static properties

Static young's modulus was estimated by the John fuller correlation by using dynamic young's modulus which calculated from isotropic properties as Eq 5. In addition, the static Poisson's ratio was assumed to equal the dynamic Poisson's ratio as shown in Fig3.

$$E_{static} = 0.74\,(E_{dynamic}) - 0.82 \quad (5)$$

2.1.2.2 Unconfined compressive strength (UCS) and Tensile Strength (TSTR)

UCS which is defined as the capacity of rock to failure resistance was estimated using modified empirical equation of Chang (2004) based on porosity because it gives the best correlation in this field using Eq6.

$$UCS = 135.9 exp\,(-4.8\varphi) \quad (6)$$

The tensile strength is calculated directly from UCS for this model

2.2 Determination of in situ stresses magnitudes

2.2.1 Overburden Stress

The vertical stress applied to the top of the elementary cube of rock is equal to the weight of the vertical rock column above it, and is then called the overburden. The overburden weight per unit area is the overburden stress. It is increased when the sedimentation of rocks at the depth increased. The overburden stress is calculated from the bulk density in (Eq 7), and the bulk density can be calculated by extrapolated density method using Eq 8. This equation can give good results for vertical stress.

$$\sigma_v = g \int_0^z \rho_b(z)\, dz \quad (7)$$

σ_V is the vertical stress or overburden stress at depth TVD.

ρ_b is the bulk density.

g is the gravitational constant

$\rho_{ex} = \rho_{mudline} + A_o * (TVD - air\ gap - D_w)^a$

where ρ midline is the density at the seafloor or ground level, and A_o and α are the fitting parameters:

2.2.2 Pore Pressure (p_P)

pore pressure is an important parameter in selecting the suitable procedure of drilling and can be estimated using Eaton's method (Eaton's geomechanic stability criteria) due to gives the probability failure of the wellbore based on the rock strength and horizontal stresses as shown in Fig 3 . Eq 9 used to calculate pore pressure based on the wireline measurements (sonic log) (Khan et al., 2022).

$$\mathbf{pp = OBP - (OBP - NP) * (DT_{NCTL}/DT)n}$$

Where

Pp = pore pressure (gradient), OBP= overburden pressure (gradient). NP= normal pressure (hydrostatic). DT= slowness from log ms/ft, $\mathbf{DT_{NCTL}}$ Slowness of **normal** compaction trend line and n= Eaton exponent parameter =3**.**

2.2.2 Horizontal stresses (S_H, S_h)

The min and max horizontal stresses are perpendicular to the vertical stress. They can be estimated using correlation of Poroelastic Horizontal Strain Model depend on set of logging parameters which are pore pressure, young's modulus, possion's ratio and lateral and longtudinal strain through using eq 10 and 11 introduced by Zobac et al 2003(Zoback *et al.*, 2003). The minimum horizontal stress can be estimated by various direct methods such as mini-frac, hydraulic test, or leak - off test.

$$\delta_{min} = \frac{v}{1-v}\sigma v - \frac{v}{1-v}\alpha Pp + \alpha Pp + \frac{E}{1-v2}\varepsilon x + \frac{Ev}{1-v2}\varepsilon y$$

$$Shmax = \frac{v}{1-v}\sigma v - \frac{v}{1-v}\alpha Pp + \alpha Pp + \frac{Ev}{1-v2}\varepsilon x + \frac{E}{1-v2}\varepsilon y$$

εy :Lateral horizontal strain, **εx**: Longtudinal horizontal strain(Al-Ameri, Hamd-Allah and Abass, 2020a)

2.3 Diagnostic Fracture Injection Test (DFIT)

Diagnostic Fracture Injection Test was used for the porpuse of estimating the amount of minimum horizontal stress in a formation. It is done by injecting some amount of slick water at 180F° into the well for short time to create a hydraulic fracture. There are several analyses to calculate closure pressure which are G-Function, Square root of time and Log-Log(McClure Mark *et al.*, 2016). One of the most important analysis is G-Function test that the estimated closure pressure is 6251 psi with closure pressure gradient of 0.695899 psi/ft. This pressure can be used to calibrate the min horizontal stress.

Mini frac job was implemented by injection fluid into the formation. This process can be divided into two stages as shown in **Fig2**:

1- Injection test

2- Step down test

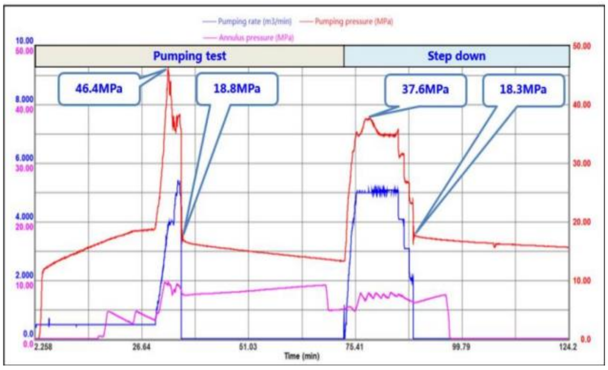


Fig 2. Mini frac test (Syed *et al.*, 2018)

3. Results and Discussion

This secction shows the findings of MEM to determine the optimum mud weight to know how the well is stable.

Fig 3. Shows the essential dynamic mechanical properties such as dynamic Poisson's ratio, young modulus, bulk modulus, and shear modulus. These properties demonstrate the elasticity of rocks.

Fig4. Shows the static Poisson's ratio in track 3 and static young modulus in track 4. These parameters are very important in application of hydraulic fracturing, sand production and wellbore stability analysis. As can be seen from the outcomings that there is an acceptable agreement between the computed and actual (log) Static Young's Modulus and Static Poisson's ratio in Saadi formation as shown in the **table 1**. Also, the study found significant differences in the mechanical characteristics of rocks based on their deposition depth.

The calculated static passion's ratio was 0.26 in Saadi formation and static young modulus 5.4 Gpa. So, the instability issues are hardly existed which meant the used mud weight is the best.

Table 1. Difference between calculated and actual

Mechanical properties	Depth	Calculated value	Measured value
Friction angle	2701	33º	35º
	2735	32º	36º
	2794	31º	33º

Poisson's and Young modulus

Geomechanical properties	Calculated value	Measured value
Static Poisson's ratio	0.242- 0.277	0.26
Static Young modulus (Gpa)	5-12.9	5.4
Compressional slowness	274	72.53
Shear slowness	270	143

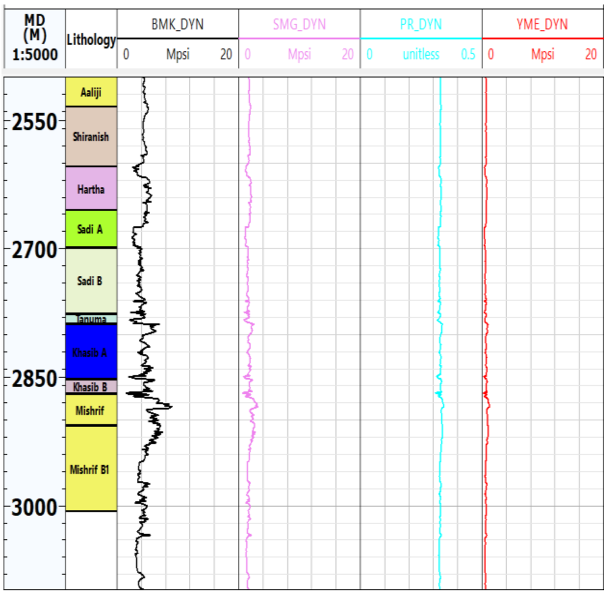


Fig. 3. Dynamic Elastic Properties

The model of 1D of overburden stress obviously confirms that this stress rises with depth as shown in **Fig4.**The range of vertical stress falls between 7440- 8140 psi for the Saadi formation. The tensile stress and unconfined compressive strength display the same distribution. The lowest value of TSRT at the Saadi formation as appeared in the same figure. Also, the estimation of friction angle, can be calibrated with core tests for rock mechanical properties. As we notice that there is a great matching in the behavior with the calculated results in the Saadi formation as shown in **table 2**.

Table 2. Calculated and measured values of Friction angle.

Fig4. demonstrates the minimum and maximum horizontal stresses in track 7. Their magnitudes were estimated based on poro elastic equations (Eqs 14 and 15). The min horizontal stress can be calibrated depend on Mini frac test through DFIT (diagnostic fracture injection test) using G-function analysis as shown in Fig 5 (Hasan and Hamd-Allah, 2023)

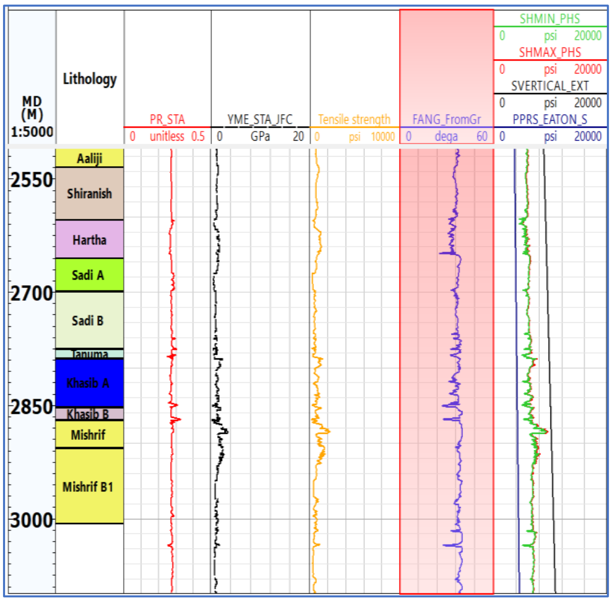


Fig. 4. Static elastic properties, Tensile strength, Friction angle, pore pressure, vertical stress, min and max horizonatal stress

3.1 Verfication of min horizontal stress by DFIT (Closure pressure)

The estimated closure pressure from the mini-frac test is 6251psi at the depth of the test (Mini-frac test) is 2738 m which is aproximately equal to min horizontal stress result (which is the lower pressure (stress) at which the fracture is closed) that found from geomechanics (min and max horizontal stress) in Techlog software leading to a good match between calculated min horizontal stress from the Techlog and from the mini-frac as shown in **table 3.** SHmax has been validated and applied in several conventional and unconventional fields by using available Minifrac/DFIT measurements. It has been verfied through utilizing the following equation modified from Nolte and smith 1981 based on net pressure, Poisson's ratio, min and max horizontal stress(Nolte and Smith, 1981) using the equation below.

$$\Delta pnet = \frac{SHmax - SHmin}{1 - 2\nu} \qquad (9)$$

$\Delta pnet$: Process zone stress (net pressure), psi

ν : possion's ratio, unitless

SHmax: Max horizontal stress, psi

SHmin: Min horizontal stress, psi

The value of ($\Delta pnet$ is 199. 43 psi) achieved on from the G-function analysis of Mini frac test(Hasan and Hamd-Allah, 2023).

It looks there is a good agreement between calculated max horizontal stress from Techlog and from the above equation as in **table 3.**

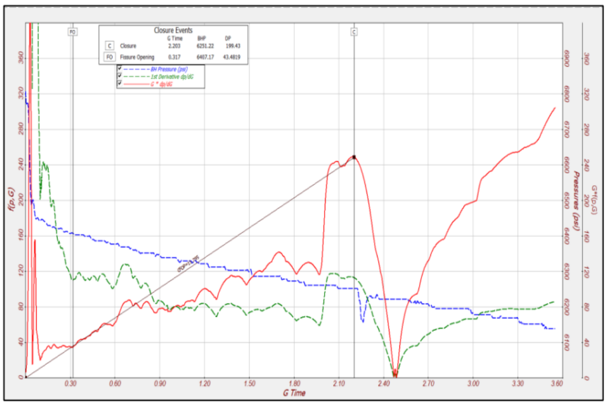


Fig. 5 G-Function Analysis

Depth of test (m)	Min Epsllone	Max Epsllone	SHmax (from equation)(psi)	SHmax (from Techlog software)(psi)	SHmin (Mini frac test) (psi)	SH min (from Techlog software) (psi)
2738	0.001	0.0011	6404.1	6420	6251	6266

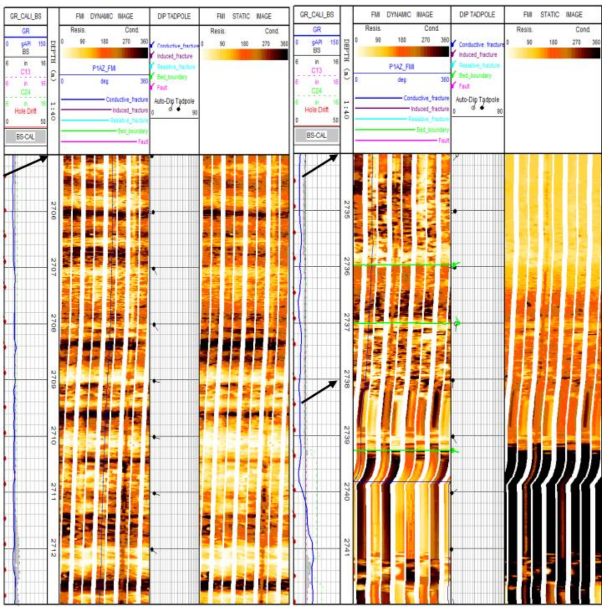
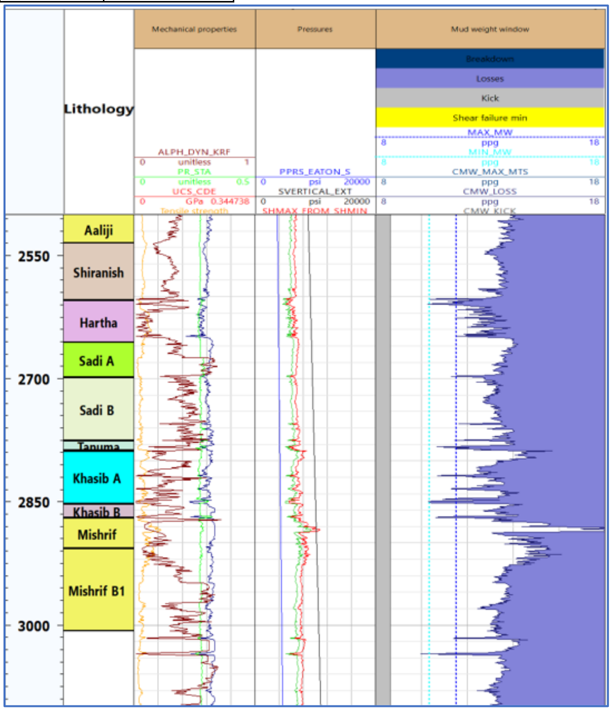


Fig6. FMI image log for Saadi reservoir

As can be seen from **Fig 5.** that there were no breakdowns and breakouts within the normal mud weight limits which range from (8-18 ppg), which meant that the well is stable, however, a clear loss of drilling mud was observed, which varies from formation to another. When the CMW loss approaches from the normal mud weight (10.25ppg), the well get worse and it become unstable, thus increasing NPT. So, more time and cost is needed to tackle this problem.



3.2 Wellbore Instability Analysis

The WBS evaluation is one of the most important studies in reducing drilling risks and costs. The mud weight for drilling the well is 10.25ppg or a wellbore pressure gradient of 0.533 psi/ft. when the estimated pore pressure is greater than the used mud weight, wellbore washout and kick may be happened. Drilling losses happen when the well pressure exceeds the value of minimum horizontal stress. The wellbore failure can be identified depend on the utilized mud weight and the failure criteria. So, Its necessary to use the suitable criteria of failure to determine the concentration of stress leading to maintaine the well from breakout or breakdown. These criteria are Mohr coulomb, Mogi coulomb, and Modified Lade failure criteria were used to pridect the rock failure.

6. Conclusions

The essential findings from this study can be sumrized in the following points:

- Based on the results of mechanical rock analysis, Saadi formation showed an increase in Poisson's ratio with decrease in Young's modulus and rock strength (tensile strength and unconfined compressive stress). This indicates a greater probability of wellbore stability problems.
- The regime of stress in all formations are normal fault regime due to (SV> SH>Sh).
- The wells will be stable in whole directions as the deviation range from (0-40 degrees). While in the higher deviation of (45-90 degrees), the shear failure will take placed in both direction of min and max horizontal stresses.
- The well can be drilled with mud weight 1.24-1.26 sg, if the inclination of it ranges from (0-25 deg). Whereas the well's inclination of (25-40 deg), it can be drilled with mud weight 1.28-1.30 sg.
- Wells with inclination of 0-40 deg are more robust to tensile failure, while inclination greater than 60 degrees are considered to increase the probability of breakdown.
- The results of the failure are mud loss and kick on the left boundary and the breakout and breakdown type are were not observed.
- Mud loss and kick are the wellbore instability issues appeared in this study along all formations, but mud loss is increased in the top of Hartha, Tanuma and KhasibA and Khasib B. and the formation of Saadi B has a little of mud loss effect the borehole stable that means the drilling operation will continue without problems
- Finally, the results demonstrated that the utilized mud weight (10.25 ppg) is the safe and the well HF-55 is kind of stable

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