AADE-23-NTCE-020

A Systematic Approach for Wellbore Instability Using Core Samples for Limestone: A Case Study from the Ratawi Field, Iraq

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Abstract

Many unwanted consequences are associated with drilling through the Yamama formation such as tight holes, differential stuck pipes, and kick issues. Rock samples were obtained from the Yamama formation to implement various rock mechanics testing such as single and multistage triaxial tests. After investigating the impact of introducing different rock failure criteria to determine the most appropriate rock failure criteria, Mogi–Coulomb failure criterion was selected to estimate the possibility of rock failure in the wells for the Yammam formation. The shear failure was examined by detecting the impact of the mud weight, inclination, and azimuth of vertical and directional wells to optimize the wellbore trajectory. Then, a summarized table is introduced to provide the safe and stable mud weights along with the well inclination for vertical, deviated, and horizontal wells. For instance, the optimal mud density for the vertical wells (i.e., the inclination of 0 degrees) is 1.475 g/cc (12.31 ppg); while the optimal mud density for deviated wells (e.g., inclination up to 60 degrees) is within a range of 1.463-1.475 g/cc (12.23 to 12.31 ppg). Furthermore, the optimal mud density for horizontal wells (i.e., inclination over 80 degrees) is within a range from 1.479 to 1.490 g/cc (12.34 to 12.43 ppg) with the most stable direction to drill being the direction of the minimum horizontal stress (135-144 degrees). Furthermore, the created geomechanical model was validated with field case studies from 20 wells. This work aims to use an integrated approach of core samples to design stable and safe mud weight, as well as an optimal well trajectory to safely drill the Yamama formation and avoid any risk related to penetrating this productive zone.

Background

Despite all new development and the leveraging of advanced technology in the petroleum industry, wellbore stability issues remain one of the most expensive aspects in determining the overall cost of drilling and completing a well. Each year there is about eight billion dollars are spent on remediating wellbore instability issues (Peng, 2007), which incurs a 10% additional cost to the drilling allocated budget (Aadnoy, 2003). Therefore, wellbore stability has been extensively studied and regarded as one of the major stages of well planning. (Abbas et al., 2018; Zhang et al., 2009; Gentzis et al., 2009; Zhang et al., 2003; Ding, 2011; Bradley, 1979; Bell, 2003).

The instability of a wellbore can be attributed to many controlling factors such as rock strength variables and elastic properties, pore pressure, and in-situ stresses. The formations underground are normally residing an equilibrium state of stress prior to drilling a well. Once the drilling starts, the stress across the newly drilled borehole will be subjected to stress load as a result of the drilled column of rocks. Thus, there will be a stress concentration due to the disturbance in the in-situ stresses near the borehole wall. That concentration in stress leads to a failure in the wellbore. The important issue is to understand the mechanical loading and the rock reaction to such stresses. To counterbalance stress concentration effects and to avoid the failure of the borehole, sufficient internal wellbore pressure should be subjected by means of hydrostatic pressure resulting from mud density. Additionally, the orientation of the wellbore with reference to the in-situ stress directions must be also considered to mitigate the failure of the wellbore. During drilling operations, the density of drilling mud is the controlling factor to mitigate the wellbore failure if it was designed and maintained to be within the lower bound of collapse pressure and the upper bound of fracture gradient (Bourgoyne et al., 1986).

One of the basic applications of drilling fluids is to provide sufficient hydrostatic pressure to mitigate the formation fluids from flowing and entering the wellbore despite the effects of rock strength and field stress. For practicality, the mud density should be kept at least 100-200 psi (0.3-0.5 ppg) greater than the pore pressure of the formation to suppress formation fluids flow while drilling (Awal et al., 2001; French and McLean, 1992), In general, the hydrostatic pressure of mud required to sustain the wellbore stability is greater than the pore pressure due to in-situ stresses. Therefore, an accurate estimation of drilling fluid density is essential. Better approaches in that estimation are depending on the accuracy in measuring and estimating mechanical rock properties, stress around the borehole, and wellbore trajectory, all these factors assist in designing and executing safe, stable, and effective drilling operations (Basra Oil Company, 2012).

Drilling into the Yamama Formation in the Ratawi field in southern Iraq has been faced with several instability issues such as pipe sticking, tight holes, and flow issues. Those problems have significantly increased non-productive time (NPT) by spending extra time in remedying, circulating, and reaming through the penetrating processes. Some of the cases were very severe that resulted in impeding the drilling processes or complete loss of the wellbore (Basra Oil Company, 2011).

The Yamama formation is a well-known formation being a significant oil reservoir in the Ratawi field in southern Iraq. It is composed of interbedded limestone, which is generally 274 to 279 m thick. The Yamama formation has a significant heterogeneity, and due to the high number of associated issues through the drilling operations, it is necessary to have an accurate geomechanical model for achieving stable and safe mud weight to be invested to penetrate the Yamama formation without unwanted consequences (Basra Oil Company, 2010). Therefore, rock samples have been obtained from this formation to be employed in laboratory tests. Single stage triaxial (SST) and multistage triaxial (MST) tests were executed to obtain mechanical rock properties to be utilized as valuable inputs in constructing the geomechanical model for the Yamama formation. To sum it up, the objectives of this work are to understand the drilling-related problems and investigate their root cause, and to design a safe and stable mud density window as well as optimal wellbore trajectory to mitigate or eliminate the wellbore instability problems, differential stuck pipes, and kick issues by building a verified geomechanical model to ultimately reduce drilling risks, non-productive time, and overall drilling cost.

Methodology

Due to drilling more wells in a very deep depth and hostile environment, challenges not often encountered in normal drilling situations will be presented in these types of wells. Hence, this work suggests an optimal range of stable and safe mud weight alongside the inclination angle and azimuth to ameliorate wellbore stability and unsafe drilling processes while penetrating the Yamama formation. The following systematic workflow presented in **Figure A.1** (Appendix A) shows the process of creating the 1D geomechanical model for the Yamama formation in the Ratawi field to minimize the undesired issues associated with the drilling operations. The following sub-sections will be employed to elucidate in detail the resources and the entire procedures for obtaining the required input data for constructing the 1D geomechanical model.

Core Samples

One of the biggest and most famous oil fields in southern Iraq is Ratawi. However, to reach out to the target formation (i.e., the Yamama formation), many obstacles will be encountered that are related to wellbore instability (e.g., tight holes) and unsafe drilling (e.g., kick and differential stuck pipe). The Yamama formation is considered the main pay zone in the Ratawi oil field, and it composes mainly of limestone. 3589 to 3600 m is the range of the formation top, while 3863 to 3879 m is the range of the formation bottom with a thickness of 274 to 279 m. The Yamama is underlain by the Sulaiy zone (limestone with some shale streaks at its base) and is overlain by the Ratawi formation, and it has porosity ranges between 5-20% (Basra Oil Company, 2010; Jassim & Goff, 2006). To build the 1D geomechanical model and sustain a safe and stable mud weight, real core plugs from the Yamama formation were acquired to execute various geomechanical tests. The rock samples have standard dimensions (one inch in diameter and two inches in length) to meet the standard criteria of the experimental study for rock testing. **Figure A.2** (Appendix A) shows the rock samples for implementing a single stage triaxial test (SST) and a multistage triaxial test (MST) for the Yamama formation.

Single Stage Triaxial Test (SST)

To precisely estimate the mechanical rock properties, SST is generally utilized, particularly for obtaining elastic moduli (e.g., static Young modulus (E_s), static bulk modulus (K_s), and Poisson's ratio (v_s)) by utilizing one rock plug. However, to estimate the parameters of the rock strength (i.e., internal friction angle (ϕ), cohesion (S_o), and unconfined compressive strength (UCS)), three core plugs will at least be needed to conduct SST on them separately, and that may be an issue in case there are limitations related to the number of the available rock samples and time (Fjær et al., 2008; Zoback, 2007; Ameen et al., 2009; Abbas et al., 2018). Therefore, for this study, SST was executed on a rock plug from the Yamama formation to obtain only elastic moduli. To simulate the horizontal stresses, confining pressure was set initially as a constant value through the entire SST test, and its value was equal to 5309 psi (±1 psi). It is important to mention that the set value of the confining pressure was not selected randomly, where it was chosen according to the real field data of the horizontal stresses in the Yamama formation. Also, the axial stress was maximized through the SST until the rock sample reached the maximum compressive strength (MCS) (i.e., till the sample's failure occurred). Moreover, a computerized digital data acquisition system was employed to keep an eye on and record axial and radial deformation, axial load, and confining pressure.

Multistage Triaxial Test (MST)

To avoid the limitations that are usually associated with the availability of the rock samples and the issue of the time-consuming, MST is normally invested to be executed on one core plug to obtain the rock strength parameters (UCS, S_o, and ϕ) with decent accuracy (Kovari et al., 1983; Fjær et al., 2008; Zoback, 2007; Abbas et al., 2018). On the contrary, MST is not preferred to be utilized to estimate the elastic moduli because the elastic mechanical characteristics (i.e., the elastic moduli) are considerably impacted by impairment resulting from the preceding load procedures (Holt and Fjær, 1991). Hence, a rock sample was obtained from the Yamama formation to be subjected to MST approach and obtain the rock strength parameters with an acceptable range of accuracy due to the limitations of the number of available core plugs for the Yamama formation. The rock sample was put in a triaxial cell, and it was loaded axially by axial load and radially by confining pressure. For MST approach, confining pressure will be set for each stage of MST, and those values will be selected according to the real field data of the horizontal stresses in the Yamama formation. Four stages were conducted on the rock sample; where the confining pressures were equal to 250 psi, 500 psi, 850 psi, and 1200 psi for the first, second, third, and last stages, respectively. In the same context, for the first stage of MST, the axial load is raised till accomplishing the yield point (i.e., the point of positive dilatancy (PPD)), and similar procedures were repeated for other stages by raising confining pressure for every stage till the confining pressure reached 1200 psi in the last stage (the fourth stage). It is crucial to mention that the maximum compressive strength (MCS) was obtained in the last stage by increasing the axial load until the sample's failure occurred. Finally, data acquisition systems were used to monitor and report all the data of the MST (e.g., axial and radial deformation, axial load, and confining pressure).

Elastic Modulus

Both static Young modulus (E_s) and Poisson's ratio (v_s) were utilized as inputs for the 1D geomechanical model to represent the elastic mechanical properties of the Yamama formation. Thus, to sustain a high level of accuracy for both E_s and v_s and build a robust model, the SST approach was conducted on the rock sample. For estimating E_s from the lab data, the plot of axial stress versus axial strain was utilized. However, various techniques are normally available to be utilized to achieve the purpose of estimating E_s. The first method uses the initial slope of the curve and it is called the initial modulus, and the second method uses a fixed percentage of the peak stress where E_s is measured up to and it is called secant modulus; while the third method uses a given specific percentage of the peak stress and it is called tangent modulus. Nevertheless, the fourth method uses the average of the linear portion of the curve within a specific maximum and minimum stress level and it is called the average modulus. The most common method is to utilize the slope from 1/3 to 2/3 MCS (peak stress) of the axial stress-strain graph, and it has been used in this study to estimate E_s (Fjær et al., 2008). Equation 1 was used to obtain E_s. For v_s, it was calculated based on the lab data measurements by plotting radial strain versus axial strain, it represents the slope of the radial strain divided by the axial strain (radial strain/axial strain) as shown in Equation 2.

$$E_s = \frac{\triangle \sigma_a}{\triangle \varepsilon_a} \tag{1}$$

$$\upsilon_s = \frac{\varepsilon_r}{\varepsilon_a} \tag{2}$$

Rock Strength Parameters

The parameters of the rock strength are the most essential inputs for constructing a robust 1D geomechanical model and estimating the stable and safe mud weight. As mentioned earlier, due to the limitations of the number of available core plugs for the Yamama formation, MST was invested to obtain the rock strength parameters as a feasible approach for providing decent and acceptable accuracy of UCS, S_o, and ϕ findings. Two graphical methods have been utilized to obtain the rock strength parameters for the Yamama formation. The first graphical method was the p/q plot and it was used to estimate S_o, while the second graphical method (σ_1 vs. σ_3 plot) was invested to estimate UCS. However, ϕ was almost the same for the two plots, which is why it can be obtained from any graphical method.

The Magnitude and Orientation of Principal Stresses

According to the assumption of an Andersonian in-situ stress state, the state of the stresses in the sub-surface at any depth and formation of the interest consists of three principal stresses. It is important to mention that this assumption is safe, adequate, and commonly used in the oil and gas industry by assuming the geology is not complex along with little activity of the tectonic. Thus, based on this assumption, all shear stresses will have vanished, and the state of stress is defined by the 3 normal stresses — the principal stresses. The three principal stresses are perpendicular to each other, but not necessarily equal in magnitude. One of the principal stress is in the vertical direction represents the overburden stress or vertical stress (σ_v) while the other two principal stresses are horizontal; minimum and maximum horizontal stresses (σ_h and σ_H), which are perpendicular to the vertical stress (Anderson et al. 1973; Fjær et al., 2008; Zoback, 2007).

The vertical direction is related to the overlying formations and the overburden weight of the formations. Based on the assumption of an Andersonian in-situ stress state, σ_v is considered principal stress. The vertical stress is one of the most crucial inputs in the 1D geomechanical model to precisely estimate the safe and stable drilling density. Therefore, to guarantee the accuracy of calculating the vertical stress for the Yamama formation, the bulk density was obtained based on the lab measurements for the rock sample along with the vertical depth and by utilizing Equation 3 (Anderson et al. 1973; Fjær et al., 2008; Zoback, 2007).

$$\sigma_v = \int_0^D \rho(D) g dD \tag{3}$$

Where g is the acceleration due to gravity (m/s^2), D is the true vertical depth (m), and ρ is the bulk density (g/cm^3).

To construct the 1D geomechanical model, both σ_h and σ_H have to be estimated accurately since they both considered substantial inputs for obtaining a safe and stable mud weight, as well as the optimal trajectory. For homogenous, isotropic rock, and without the complexity of the geological structures (e.g. salt dome, faults, and anticlines), it can be assumed that the magnitude of σ_h is equivalent to the magnitude of the σ_H; while they both cannot be assumed to be equal in the complication of the geological structures such as effective exists of the tectonics and central faults. As a result, the magnitude estimation of both

σ_h and σ_H is not a straightforward approach, and it represents the most complicated techniques as compared to the estimation approach of σ_v. Therefore, many approaches (laboratory and field techniques) have been established to be employed to obtain σ_h and σ_H to know the stress tensor along with σ_v. Examples of the estimating methods for σ_h and σ_H are the mini-frac test, leak-off test, extended leak-off test, formation integrity test, jacking, and strain recovery as well as analytical methods and empirical equations (Najibi et al. 2017; Fjær et al., 2008; Zoback, 2007). For this study, Equations 4 and 5, which represent the approach to the poroelastic horizontal strain, were utilized to estimate both σ_h and σ_H for the Yamama formation due to the good level of accuracy and commonness (Gholami et al., 2017; Cao et al., 2018; Thiercelin et al., 1994; Dokhani et al. 2015).

$$\sigma_h = \frac{\upsilon}{1-\upsilon}\sigma_v + \frac{1-2\upsilon}{1-\upsilon}\alpha P_p + \frac{E}{1-\upsilon^2}\varepsilon_x + \frac{\upsilon E}{1-\upsilon^2}\varepsilon_y \quad (4)$$

$$\sigma_H = \frac{\upsilon}{1-\upsilon}\sigma_v + \frac{1-2\upsilon}{1-\upsilon}\alpha P_p + \frac{E}{1-\upsilon^2}\varepsilon_y + \frac{\upsilon E}{1-\upsilon^2}\varepsilon_x \quad (5)$$

Where ε_x and ε_y are the strains in the directions of the σ_h and σ_H, respectively, and can be obtained from Equations 6 and 7; while α represents the Biot's coefficient and it was assumed to be 1.

$$\varepsilon_x = \frac{\sigma_v \upsilon}{E}\left(\frac{1}{1-\upsilon} - 1\right) \quad (6)$$

$$\varepsilon_y = \frac{\sigma_v \upsilon}{E}\left(1 - \frac{\upsilon^2}{1-\upsilon}\right) \quad (7)$$

The knowledge of the orientation of both the minimum and maximum horizontal stresses is a crucial key for designing safe and stable mud weight as well as achieving optimal wellbore trajectory. Wellbore failure such as tensile and shear failures (i.e., drilling-induced tensile failure and borehole breakouts) is normally utilized to obtain the orientation of the horizontal stresses (Kingdon et al., 2016). To identify the wellbore failures, image logs or caliper logs are usually employed individually or together, breakouts will appear as two dark patches 180º apart on image logs while drilling-induced tensile failure will appear as two vertical lines (black) 180º apart on image logs. However, wellbore instability can be distinguished from the caliper logs according to the change in the hole diameter (e.g. borehole enlargement or reduction) (Fjær et al., 2008; Zoback, 2007; Zoback et al., 1985). The tensile failure takes place in conjunction with the direction of the σ_H. However, the orientation of σ_h can be identified along with the occurrence of shear failure (Wiprut and Zoback, 2000).

Pore Pressure

It is also called formation pressure and it is the pressure exerted by naturally occurring fluids trapped in the pore spaces of the formation. Formation fluids can be saltwater, oil, or gas. The formation pressure can be affected by the weight of the overburden which is the layers of the rocks all the way to the surface. The overburden exerts pressure on the grain structure of the rocks as well as the pore fluids. When the pore fluids are free to move due to the permeability, the grains lose some of the fluid resistance and move closer to each other which causes the formations to get compacted (Rabia, 2005). The pore pressure is also one of the most important inputs for constructing the 1D geomechanical model because it has a pivotal influence on the stability of the wellbore and the deformation around the drilled formations. Therefore, inaccurate estimation of pore pressure can lead to many unwanted consequences such as kicks, blowouts, differential stuck pipes, and wellbore instability (Detournay and Cheng, 1988). Many direct and indirect techniques have been developed to estimate the formation pressure (Standifird et al., 2004). However, the most accurate and direct way to obtain pore pressure is the repeat formation test (RFT), which is normally used for the permeable zones. Hence, the pore pressure of the Yamama formation was obtained from RFT to ensure the accuracy of this crucial input, which in turn will contribute to building a robust 1D geomechanical model.

Rock Failure Criteria

Selecting the failure criteria is a crucial factor in sustaining wellbore stability during drilling operations. Various failure criteria are available in the literature. Hence, the most common ones have been explored in this analysis to select the most suitable and efficient ones for accomplishing safe drilling and avoiding non-productive time through drilling the Yamama formation. In general, each failure criterion takes into consideration the condition of the stresses around the well to estimate the magnitudes of the stresses at which wellbore failures may occur (Abbas et al. 2019; Fjær et al., 2008; Zoback, 2007). After exploring the failure criteria, the decision was made to go with Mogi–Coulomb and Mohr-Coulomb to be utilized in this work to predict the safe and stable drilling density alongside the optimal wellbore trajectory.

This failure criterion (Mohr-Coulomb) is considered one of the most common failure criteria in rock mechanics and it is commonly utilized in the petroleum industry. The main advantage of this criterion is having a simple linear form along with a decent level of accuracy in estimating rock failure. However, the Mohr-Coulomb criterion normally provides overestimation for the safe and stable drilling destiny due to eliminating the intermediate stress from the calculations and wellbore stability analysis. This criterion deduced that the failure of the rock will take place side by side with a plane because of acting shear stress on that plane. The frictional force is going to withstand the plane failure, and this force is a function of the rock's internal friction and the rock's internal cohesion as well as the components of the normal stress. Based on the theory of the Mohr-Coulomb criterion, as the confining pressure increase, the requirement of the compressive stress for achieving the rock failure will linearly be maximized (Rahimi and Nygaard, 2015).

Laboratory tests (true-triaxial experiments) were implemented on various types of core plugs along with their interpretations by Mogi (1971), and according to the findings of the experimental work, Mogi (1971) deduced that the strength of the rock (for different lithologies) were affected by intermediate principal stress (σ_2), besides that, the fracture occurs along a plane in the orientation of σ_2. Based on his insights and conclusions from lab data work, σ_2 has a pivotal effect on rock failure, and it has to be considered in the analysis of rock mechanics to provide realistic analysis, particularly in estimating the safe and stable mud weight. However, the Mogi–Coulomb criterion (failure function) was criticized since it is difficult to relate its parameters to the Coulomb strength parameters (e.g., UCS and ϕ) (Colmenares and Zoback, 2002). To overcome this shortcoming, a linear relation was presented by Al-Ajmi and Zimmerman (2006) to fit the outcomes of the polyaxial test in a similar and same format to the criterion of the Mohr-Coulomb.

Results and Discussion

Summary of 1D Geomechanical Model Inputs

In this subsection, a summary of the inputs used to create the 1D geomechanical model will be presented. Starting with the vertical stress (σ_v), it was calculated using the measured bulk density of the core samples in the lab (ρ = 2.2 (gm/cc))) at a depth of 3685.95 m to be 79.6 MPa (Equation 3). Maximum horizontal stress (σ_H) and minimum horizontal stress (σ_h) were calculated using Equations 4 and 5 to be 77.22 MPa and 67.81 MPa, respectively. Thus, the results suggest a normal faulting regime in southern Iraq, which is in agreement with the literature (Abbas et al., 2019; Alkamil et al., 2018). The orientation of σ_H was acquired from the literature to be 45-54 degrees based on nearby fields (Abbas et al., 2019; Alkamil et al., 2018; Azim et al., 2011). Furthermore, pore pressure (P_p) was estimated from the repeat formation test (RFT) executed for the Yamama formation to be 51.27 MPa. As discussed earlier, SST and MST tests were executed for cores acquired from the Yammam formation. Elastic properties; Young's modulus (E_s) and Poisson's ratio (ν_s) were estimated using SST while rock strength parameters; unconfined compressive strength (UCS) and friction angle (ϕ) were estimated from MST. E_s and ν_s were estimated to be 17.46 GPa and 0.217, respectively. Two plots were used to estimate UCS and ϕ; σ_1 vs. σ_3 and p/q plot. **Figure A.3** (Appendix A) shows σ_1 vs. σ_3 plot where the y-intercept represents UCS. Using **Figure A.3** (Appendix A), UCS was estimated to be 23.03 MPa. On the other hand, **Figure A.4** (Appendix A) shows the p/q plot where the slope was used to estimate ϕ. Utilizing **Figure A.4** (Appendix A), ϕ was estimated to be 43.78 degrees.

Safe and Stable Mud Weight

To drill wells with the least problems and save time and money, a sufficient mud weight that is safe (no kick/blowouts) and stable (no collapse and mud losses issues) is required. Designing safe and stable mud weight is vital for the success of the drilling operation to limit stuck pipes, collapse issues, tight holes, kick/blowouts, tensile fractures, etc. In this subsection, the inputs of the 1D geomechanical model were used to estimate minimum mud weight to avoid collapse. Two commonly used failure criteria were utilized to estimate the minimum mud weight to avoid collapse; Mohr-Coulomb and Mogi–Coulomb. **Figures A.5** and **A.6** (Appendix A) show stereographic contour plots for the minimum mud weight predicted using Mohr-Coulomb and Mogi–Coulomb failure criteria, respectively with all possible azimuths and inclinations created using MATLAB (Åstrand, 2015). The dashed-black circles represent the inclination of the wells. Both failure criteria have predicted the most stable drilling azimuth to be perpendicular to the direction of maximum horizontal stress (the direction of minimum horizontal stress, 135-144 degrees) since it requires the lowest minimum mud weight to avoid collapse. Thus, avoiding drilling in the direction of the maximum horizontal stress will contribute to the stability of the deviated and horizontal wells drilled in the Yammam formation.

For vertical wells, the Mohr-Coulomb criterion predicted a minimum mud weight of 1.581 gm/cc while the Mogi–Coulomb criterion predicted a minimum mud weight of 1.475 gm/cc. For deviated and horizontal wells drilled in the direction of the minimum horizontal stress; the Mohr-Coulomb criterion predicted minimum mud weights of 1.576, 1.559, and 1.569 gm/cc for 30, 60, and 90 degrees, respectively. On the other hand, the Mogi–Coulomb criterion predicted minimum mud weights of 1.472, 1.463, and 1.49 gm/cc for 30, 60, and 90 degrees, respectively. There is a large discrepancy between the results of the Mohr-Coulomb and the Mogi–Coulomb failure criteria. The mohr-Coulomb criterion is overly conservative at estimating the minimum safe and stable mud weight yielding a higher value when compared to the Mogi–Coulomb criterion. This is because the Mohr-Coulomb criterion underestimates rock strength and it ignores the intermediate principal stress while Mogi–Coulomb considers the intermediate principal stress when predicting the minimum mud weight to avoid collapse (Rahimi and Nygaard, 2015). Based on the Mogi–Coulomb criterion, inclinations of 20-70 degrees are among the most stable inclinations when drilling in the direction of the minimum horizontal stress while anything above 80 degrees will require a higher minimum mud weight to avoid collapse which can trigger the risk of differential stuck pipes and other issues. **Table A.1** (Appendix A) shows a summary of the predicted minimum mud weights to avoid collapse using the Mohr-Coulomb and the Mogi–Coulomb failure criteria for all inclinations (assuming drilling in the direction of the minimum horizontal stress).

Model Validation with Field Case Studies

Model validation is a very important step of the analysis. By validating the created 1D geomechanical model, reliable results can be produced and used in the field. To validate the created 1D geomechanical, a sample of twenty vertical wells drilled in the Ratawi field, southern Iraq was used. These wells are diverse in terms of their problems while drilling the Yamama formation. These problems are kicks, differential stuck pipes, and collapse (tight hole). Some wells were also safe and stable wells as shown in **Table A.2** (Appendix A). The mud weights used to drill the Yamama section in each well are also presented in **Table A.2** (Appendix A). **Figure A.7** (Appendix A) shows the breakdown of problems while penetrating the Yamama formation in the aforementioned wells. Out of the 20 wells, 15% had kicks, 20% had differential stuck pipes, 15% had collapse issues, and 50% were safe and stable wells. Starting with the differential stuck pipe problem (wells 7-10), the mud weight used to drill wells 7-10 was 1.51-1.54 gm/cc. Differential stuck pipes occur when the hydrostatic pressure exerted by the drilling mud exceeds the formation pressure, the differential pressure will force the drill string to the borehole wall. When drilling a permeable formation with overbalanced case (hydrostatic pressure is higher than formation pressure), a thick filter cake may be built around the borehole wall which also increases the contact between the outside diameter of the drill string and the borehole wall, leading to a worse differential stuck pipe. This is especially common along the drill collar because there is less clearance between the borehole wall and the outside of the drill collar (drill collars have a larger diameter than drill pipes). Mitigating differential stuck pipes can be achieved by utilizing minimum mud weights (Helmick and Longley, 1957; Rehm et al., 2013). The Yamama formation is a limestone formation with high permeability and productive zone which makes it vulnerable to differential stuck pipes when using inappropriate mud weight while drilling. It is important to mention that not only mud wight but all drilling fluid properties are intercorrelated, meaning the fluid properties must be maintained during the drilling operation and failure to maintain appropriate fluid properties may hinder wellbore stability. However, for the purpose of this study (finding the minimum mud weight to avoid collapse), only mud weight will be discussed. The Mohr-Coulomb criterion predicted a minimum mud weight of 1.581 gm/cc for vertical wells while the Mogi–Coulomb criterion predicted 1.475 gm/cc. Wells 7-10 used mud weight of 1.51-1.54 gm/cc and resulted in differential stuck pipes. The Mohr-Coulomb criterion being conservative of the risk of collapse, in this case, will result in differential stuck pipes. Thus, this confirms that the failure criterion that is recommended for the Yamama formation is the Mogi–Coulomb criterion. Furthermore, even if using a higher than recommended minimum mud weight does not result in differential stuck pipes, it will add additional cost to the drilling mud. These costs are related to adding more base fluid and materials such as barite, CMC, etc. to weigh the mud to higher mud weight. Thus, the optimal design for the minimum mud weight always should be one that minimizes the cost and maximizes efficiency if applicable. If the designed minimum mud weight can mitigate collapse issues, it should be used and not a higher mud weight to avoid differential stuck pipes and save time and money.

Wells 1-3 had kick problems while wells 4-6 had collapse issues. Both problems are related to the fact that the mud weight used is not enough. In the kick case, the mud weight did not provide enough hydrostatic pressure to mitigate the pore pressure. As a result, the formation fluid will enter the wellbore. While it is a major safety issue, having a kick can lead to a major setback in the drilling program since safety always come first and the operation must be shut down to control the kick. This will add an additional non-productive time (NPT) and cost. To avoid kicks, the hydrostatic pressure must be slightly higher than pore pressure (overbalanced phase), and this is done by using higher mud weight to ensure sufficient hydrostatic pressure to prevent the formation fluid from entering the wellbore and achieve stable and safe drilling. On the other hand, wells 4-6 had collapse issues related to not using enough mud weight to support the wellbore and avoid collapse. When having collapse issues, the collapsed rock will be falling and due to inefficient hole cleaning, tight holes and mechanical stuck pipes will result. This also leads to a major delay in the drilling operation and also causes an additional NPT and cost. Wells 1-3 (kick wells) and wells 4-6 (collapse wells) had a range of mud weight of 1.44-1.46 gm/cc which is less than the recommended mud weight by both the Mohr-Coulomb (1.581gm/cc) and the Mogi–Coulomb (1.475 gm/cc) criteria.

Furthermore, wells 11-20 had safe and stable drilling while penetrating the Yamama formation. the range of mud weight used to drill these wells was 1.47-1.5 gm/cc. This range is in agreement with the minimum mud weight predicted by the Mogi–Coulomb criterion which is 1.475 gm/cc. Thus, this is another confirmation that the Mogi–Coulomb criterion is the one that should be used to predict the minimum mud weight to avoid collapse in the Yamama formation. To sum it up, the best mud weight that is recommended to be used to drill vertical wells in the Yamama formation is 1.475 gm/cc predicted by the Mogi–Coulomb failure criterion. This mud weight will avoid kicks, collapse issues, differential stuck pipes, and provide safe and stable drilling while penetrating the Yamama formation. To drill deviated and horizontal wells, the minimum mud weight predicted by the Mogi–Coulomb failure criterion is recommended to be used as summarized in **Table A.1** (Appendix A).

Conclusions

The Ratawi field is one of the biggest oilfields in Iraq, and wells penetrated in this field are quite prone to wellbore instability and unsafe drilling when penetrating the Yamama formation. The Yamama is a productive zone and, it is formed of interbedded limestone, which is generally 274 to 279 m thick. Hence, to select the stable and safe mud weight as well as the optimal wellbore trajectory for the Yamama formation to avoid drilling risks and non-productive time when drilling vertically, directionally, and horizontally, a comprehensive geomechanical model was built as a base to generate a stable wellbore trajectory and mud weight window.

This study introduces 1D geomechanical modeling to attain a precise approach in terms of achieving good design limits of the stable and safe mud weight window. Experimental tests (e.g., single and multistage triaxial tests) have been implemented on real core plugs from the Yamama formation in the Ratawi field, Iraq. Also, the findings of the lab have been incorporated with field data (e.g., pore pressure). Then, different criteria of rock failure have been examined to select the most suitable one in terms of attaining the stability and safety of the wellbore. The investigations of the various rock failure criteria revealed that Mogi–Coulomb failure criterion is the most appropriate one to be employed for selecting the optimum drilling density, angle, and well direction for the Yammam formation. The Mogi–Coulomb criterion predicted the minimum mud weight for the vertical wells to be 1.475 g/cc (12.31 ppg); while the optimal mud density for deviated wells (e.g., inclination up to 60 degrees) is within a range of 1.463-1.475 g/cc (12.23 to 12.31 ppg). Moreover, the optimal mud density for horizontal wells (i.e., inclination over 80 degrees) is within a range from 1.479 to 1.490 g/cc (12.34 to 12.43 ppg) with the most stable direction to drill being the direction of the minimum horizontal stress (135-144 degrees). Furthermore, a summary of mud weights and inclination angles was tabulated to be invested as practical guidelines for drilling vertical, deviated, and horizontal wells through the Yamama formation. This work gives another evidence that planning and designing the well prior to drilling can significantly contribute to reducing expenses and non-productive time. One of the most important planning elements is providing the limits of the mud weight to avoid or at least mitigate the issues related to the wellbore instability and unsafe drilling through the exploration and development processes.

Acknowledgment

The authors would like to thank Basra Oil Company from Iraq for providing the core samples and for the permission to publish this work. The authors would also like to thank MetaRock Laboratories for their unequivocal help and support in conducting the laboratory experiments.

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Appendix A

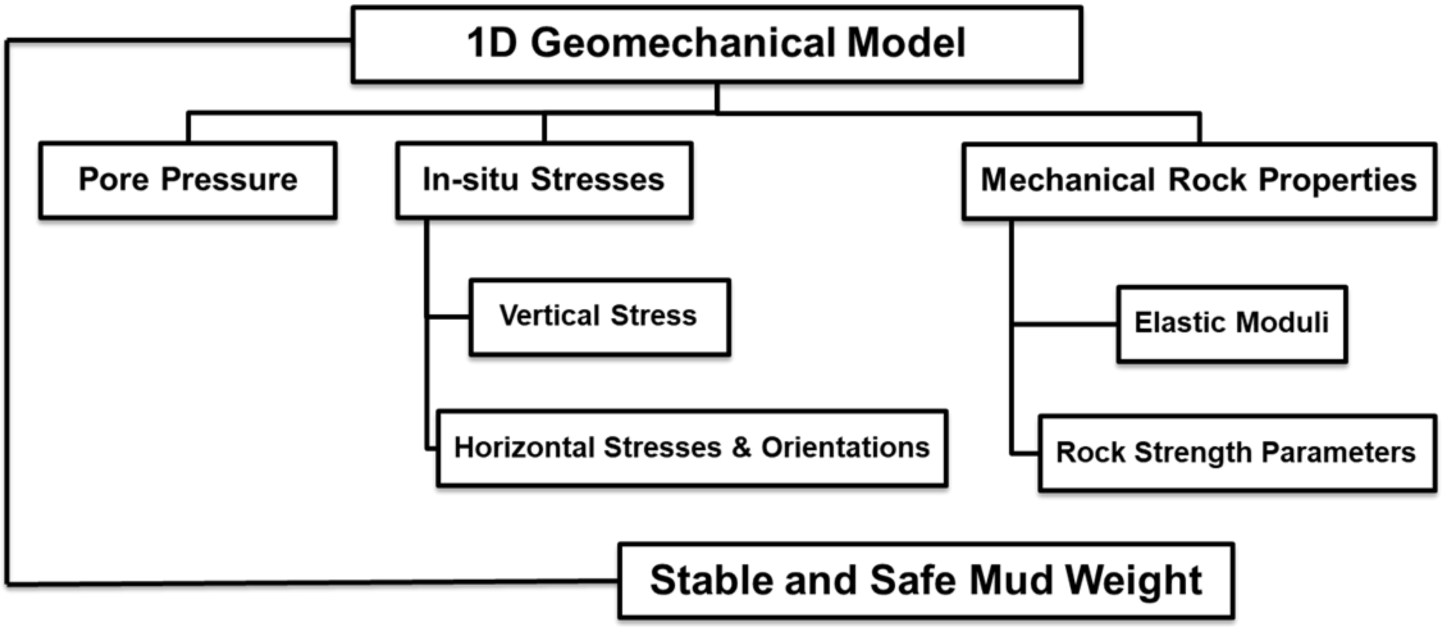

Figure A. 1- The Workflow of the 1D Geomechanical Model.

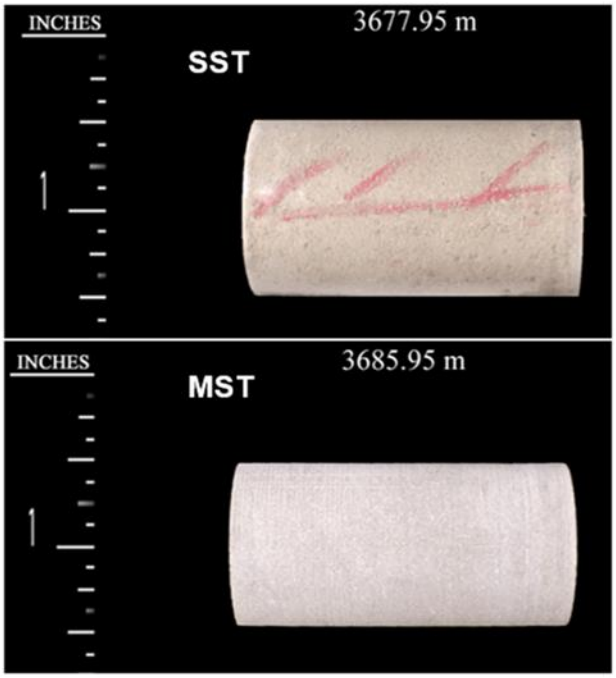

Figure A. 2- The Yamama Rock Samples.

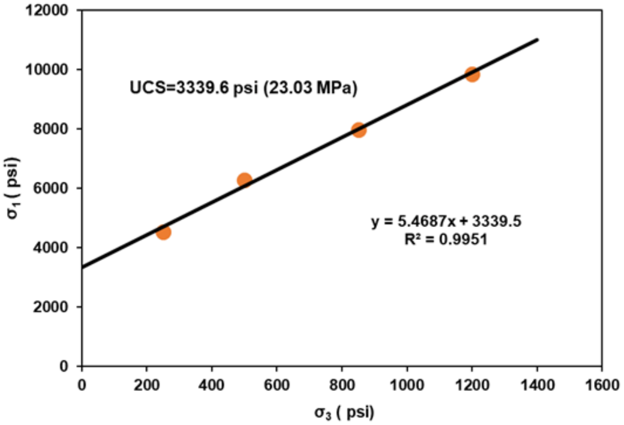

Figure A. 3- σ_1 vs. σ_3 Plot Using MST Data.

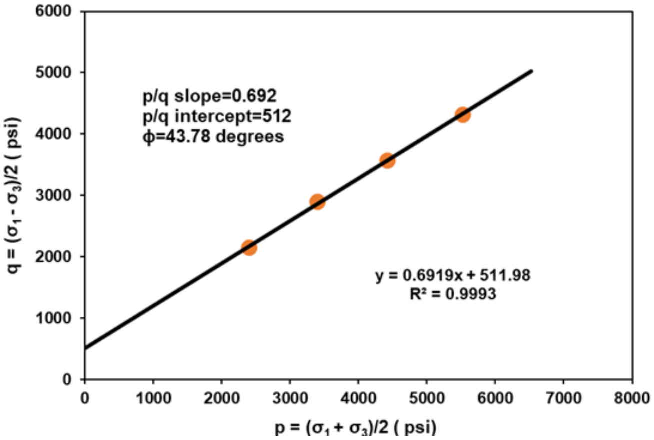

Figure A. 4- p/q Plot Using MST Data.

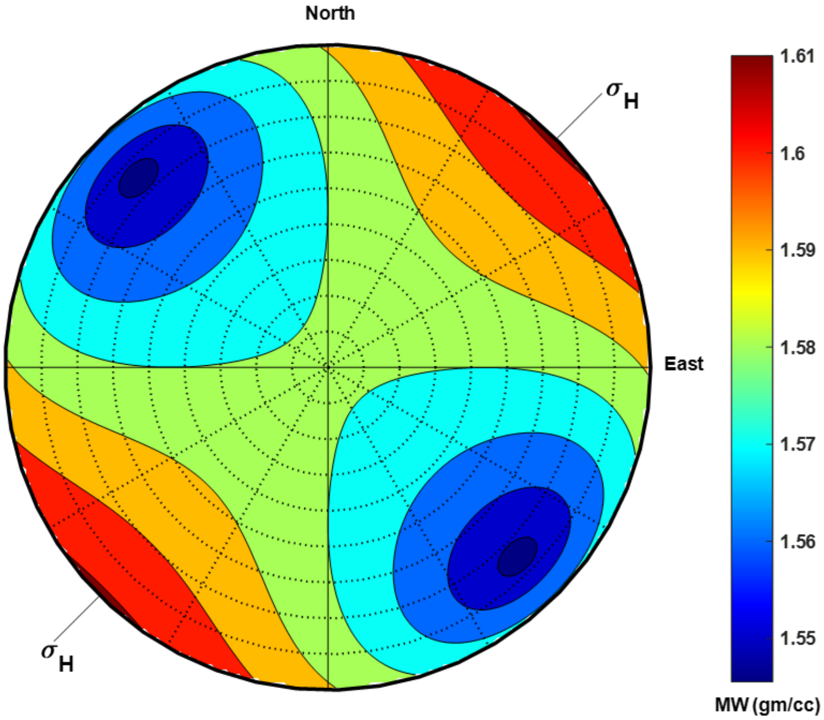

Figure A. 5- Minimum Mud Weight to Avoid Collapse with all Inclinations and Azimuths Based on Mohr-Coulomb Criterion.

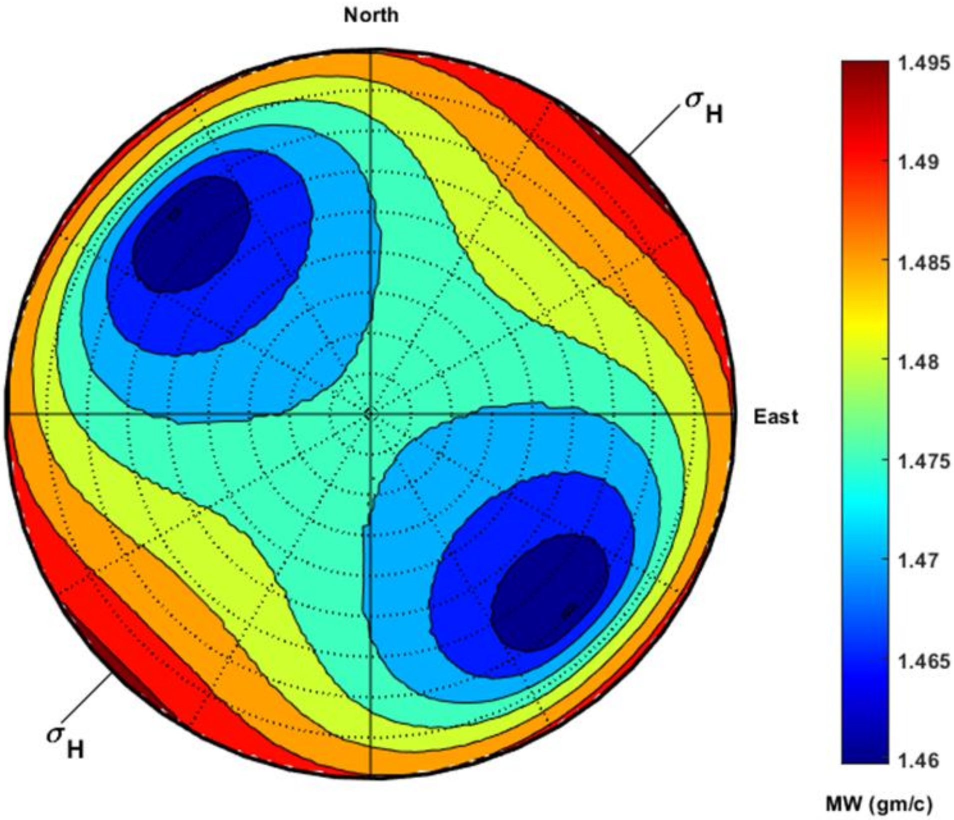

Figure A. 6- Minimum Mud Weight to Avoid Collapse with all Inclinations and Azimuths Based on Mogi–Coulomb Criterion.

Table A. 1- Summary of the Minimum Mud Weights to Avoid Collapse Using Mohr-Coulomb and Mogi–Coulomb Failure

Inclination Angle (degrees)	Minimum MW (gm/cc) (Mohr–Coulomb)	Minimum MW (gm/cc) (Mogi–Coulomb)
0	1.581	1.475
10	1.58	1.475
20	1.579	1.47
30	1.576	1.472
40	1.572	1.469
50	1.566	1.466
60	1.559	1.463
70	1.552	1.46
80	1.55	1.479
90	1.569	1.49

Table A. 2- Examples of Real Mud Weights Used to Drill the Yamama Formation

Well Number	Used Mud Weight (gm/cc)	Problems
Well 1	1.44	Oil and Gas Kick
Well 2	1.44	Oil and Gas Kick
Well 3	1.45	Oil and Gas Kick
Well 4	1.45	Collapse (Tight Hole)
Well 5	1.45	Collapse (Tight Hole)
Well 6	1.46	Collapse (Tight Hole)
Well 7	1.52	Differential Stuck Pipe
Well 8	1.53	Differential Stuck Pipe
Well 9	1.51	Differential Stuck Pipe
Well 10	1.54	Differential Stuck Pipe
Well 11	1.47	Safe and Stable Drilling
Well 12	1.49	Safe and Stable Drilling
Well 13	1.48	Safe and Stable Drilling
Well 14	1.47	Safe and Stable Drilling
Well 15	1.47	Safe and Stable Drilling
Well 16	1.48	Safe and Stable Drilling
Well 17	1.5	Safe and Stable Drilling
Well 18	1.47	Safe and Stable Drilling
Well 19	1.48	Safe and Stable Drilling
Well 20	1.5	Safe and Stable Drilling

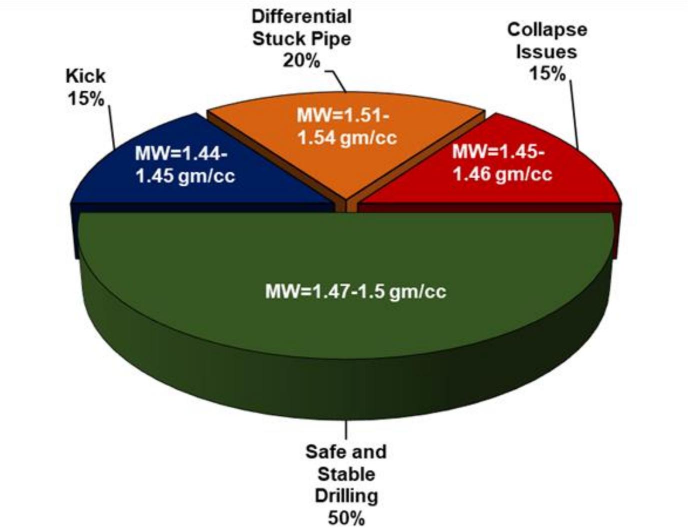

Figure A. 7- Problems during Drilling the Yamama Formation.