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Calculating the drilling mud weight window and geomechanical properties of Darian limestone formation in Reshadat oil field

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Abstract

In the oil province of southern Iran like other hydrocarbon zones, thorough understanding and risk management resulting from the rock mass deformation, can be of great help in executing operational processes such as the stabilization of the borehole wall, controlling the sand production in the borehole and hydraulic fracture. In oil well excavation operations, determining maximum and minimum horizontal stresses helps in designing the excavation route in the minimum stress direction so that collapsing of the borehole wall and drilling tube blockage against the rocks is avoided. The aim of this study was removing the main excavation problems especially of the diversion wells through exact geomechanical calculations in the Darian lime formation depth range in the understudy field. In order to develop the geomechanical model, first the bulk, the shear and the Young's modules, the Poisson coefficient and Vp/Vs ratio were calculated using the visual log data integrated with the geomechanical parameters, and the strength parameters like uniaxial compressive strength, internal friction coefficient and tensile strengths and static modulus of elasticity were determined and then the determination of direction and min/max horizontal stresses alongside the formation thickness were studied. In the end by the assessment of the geomechanical model and calculating the mud weight during drilling of the understudy well, and using the STAB View software output, the mud weight window of 80-120 PCF and the drilling Azimuth range of 30°- 45° was recommended for the prevention of borehole wall collapse for Darian formation.

Keywords: **Darian formation, drilling azimuth. Reshadat oil field**

1. Introduction

This study aims at explaining Darian reservoir with adequate accuracy through 1-determining the quantitative and qualitative geomechanical status of the reservoir and the borehole wall stability using the well data including the well drilling final report, the petrophysical and geophysical information and other accessible data and, 2-determining the geomechanical parameters like the rock volumetric and shear modules, the Poisson's ratio, the Young's modulus, internal friction angle of the formation and the like. Also using the stress system of the area and geophysical information, the stress status in depth has been studied with suitable accuracy. The geomechanical studies are used for better explanation of the rock's mechanical behavior (Kilik et al. 2008 and Chang et al. 2006). In general, in order to build a geomechanical model for an oil field or reservoir, the elastic parameters, the rock mechanical properties and the stress field model are needed. Considering that in the understudy field as well as in the relevant well log data, the loss of drilling mud is observed during operation in Darian lime formation range, attempt has been made in this study to achieve a suitable mud weight window for preventing from the borehole wall collapse or mud loss through determining the elastic properties of the rock and stress value.

2. Material and method

2.1. Field description

The understudy area in this paper consists of part of Reshadat oilfield, previously known as Rostam filed. Reshadat filed is located southeastern of Persian Gulf close to the boundary line of Qatar country and within about 100 Km southwest of Lavan Island and 130 Km southwest of Kish Island. The oil produced in this field is mainly supplied from the upper Soruk, Darian and Sormeh reservoirs (Aganabati, 2010 and Aryan et al. 2009). The structural dependency of Reshadat filed lies in different reservoir horizons such as Soruk, Darian and Sormeh reservoirs' vertexes and Dalan formation vertex. (Ghazban, 2007 and Motiei, 2008) The general status of Persian Gulf oilfields features the dominant direction of northwestern- southeastern (Mobarak, Salman, Reshadat and Resalat fields) and northeastern- southwestern (Siri, Vala, Saleh and Hengam).

2.2. Elastic constants calculation methods

One of the main issues of studying geology engineering, oil engineering and mine engineering is the elastic properties of the rocks; geomechanical modeling of hydrocarbon reservoirs and various operations in oil upstream industries need the elastic parameters of rocks because such parameters are dependent on the practical properties of the rock(Zoback, 2003 and

Figure 1. Location of Reshadat oil field in Persian Gulf.

2011). This is while such information is not accessible most of the time. In fact all the oil and gas wells lack a standard log registration as the first source of information and most logs often tackle the approximation of the rock physical properties and largely the calculation of elastic properties of the rock. Geomechanical parameters are divided into two static and dynamic information groups. The most traditional and prevalent methods for calculation of such properties is through the static tests. The dynamic methods also have assigned a special position to themselves in calculating the rocks elastic properties and the geo mechanical model components (Rahman, 2000).

2.2.1. Static method

The most traditional and prevalent method of calculating the rocks elastic properties and geomechanical parameters is performing the static tests. The static information is obtained through performing direct physic-mechanical tests on the reservoir's rock sample in the laboratory or through residual method (Mengiiao et al. 2003). Normally the rock's elastic parameters and the reservoir's rock geomechanical properties are obtained via laboratory tests performed on the rock core (uniaxial compressive strength test). It should be noted that calculating the elastic modules and uniaxial compressive strength by elastic method has a number of limitations such as inaccessibility of cores, location based results, excessive costs of coring and the rock mechanical tests (Gandehari, 2012). For most of the conventional accessible models, the rock's critical strength has been presented in terms of tensile and sheer strength of the formation. The shear strength is usually defined through Mohr-Coulomb failure index and is explained using the failure enveloping of two cohesion and internal friction angle. The static parameters can be obtained through a chain of triaxial compression tests (Jose et al. 2000). The elastic properties of the rock is calculated according to the following equations: (Faroughoseini, 2008).

$$K = \frac{E}{3(1-2\upsilon)} \qquad (1)$$

$$E = \frac{\sigma_x}{\varepsilon_{ax}} \qquad (2)$$

$$G = \frac{E}{2(1+\upsilon)} \qquad (3)$$

Where E is the Young's modulus, Kis the bulk modulus, Gis the shear modulus, ε_{ax} is the strain in X direction, σ_x is the axial stress in X direction and υ is the Poisson coefficient.

2.2.2. Dynamic method

Application of dynamic methods has expanded increasingly during the recent years due to their unharmed nature dealing with the samples (Kilik, 2003). In this method, by transmitting shear and compressive waves from the reservoir's rock sample and determining the transmission time, the elastic properties of the rock is calculated without harming the sample. The most important information sources for dynamic approximation of the reservoir's rock elastic parameters and the geomechanical parameters along the well are the bipolar shear sonic well loggers and the petrophysical graphs (density, gamma radiation, etc.). From the advantages of using the dynamic method the affordable cost and continuity of the results during the understudy well and from the disadvantages the indirect measurement could be mentioned, (Faroughoseini, 2008).

$$Ed = \left[\frac{9K_p.V_p^{\,2}}{3k + p.V_p^{\,2}}\right] \qquad (4)$$

$$E = \frac{\sigma_x}{\varepsilon_{ax}} \qquad (5)$$

$$G_d = P.V_p^{\,2} \qquad (6)$$

$$\upsilon_d = {}^{1}\!/_{2}\left(\left[\frac{V_s^{\,2}}{V_p^{\,2}}\right] - {}^{2}\!/\left[\frac{V_s^{\,2}}{V_p^{\,2}}\right] - 1\right) \qquad (7)$$

Where E_d, K_d, G_d, υd are the dynamic Young's modulus, dynamic bulk modulus, dynamic shear modulus and dynamic Poisson coefficient respectively. Also $V_s V_p$ and ρ are the shear wave velocity, the compressive wave velocity and the formation density respectively.

The rock's elastic parameters resulting from the static method are normally different from that of the dynamic method. Most of the dynamic modules are greater than their corresponding static modules and such a difference is more observable in weaker rocks. The reason is that the pores and discontinuities existing in the rock produces more impacts in the elastic properties of the rock obtained in the static method (e.g. static Young's modulus) than the dynamic method.

2.3. The rock failure properties

2.3.1. The Rock Strength

The rock strength is the ability and endurance of the formation rock against the stress environment around the well. The axial compressive strength (UCS) is one of the most prevalent parameters often estimated for the rock's strength (Chang, et al. 2006) In the present study, the USC has been calculated based on the empirical relationships specific to the shale and carbonates. Modulus of elasticity and the friction angle (USC) are rock failure properties that include the internal uniaxial compressive strength.

2.3.2. Uniaxial compressive strength

The rock's uniaxial compressive strength is one of the popular criteria of the intact rock's strength evaluation. Studies based on the mechanical tests on the rock core are considered as the main and most prevalent methods of approximation of the uniaxial compressive strength (Lashkaripour, 2002). In most of the drilled wells and in many borehole spans where such data are needed, no core exists. Accordingly in the past several decades numerous empirical relationships for calculation of the uniaxial compressive strength have been introduced based on physical parameters of the rock, specially the compressive wave velocity, density and the porosity in different lithology (John et al. 2000). Considering that the reservoir rock in the understudy field is of the carbonated type, and because the rock's tensile strengths (TSTR) is usually 1.12 to 1.8 of axial compressive strength (USC), in case of lack of information on the shale and carbonated rocks, the tensile strengths has been considered as equal to 1.10 of the axial compressive strength.

2.3.3. Internal friction angle

The internal friction angle is one of the important parameters of the rock's mechanics which calculates the rock's strength. In general, by the increase in the shale proportion in the formation, the internal friction angle is increased. It must be noted that the internal friction angle can be useful in predicting the sand produced from the reservoir. For this purpose several empirical relationships have been presented for estimating the internal friction angle based on the physical parameters of the rock, especially the compressive wave velocity, porosity and the amount of shale.

2.3.4. Pore Pressure

The pore pressure is one of the most important parameters involved in designing a geomechanical model and excavation design; it is also one of the influential parameters in calculation of the residual stresses and well stability analysis. The pore pressure changes with the hydrostatic pressure and in the overpressure areas it is about 48 to 98 percent of the Overburden Pressure. The pore pressure being higher or lower than the hydrostatic pressure (normal pore pressure), it is called over-pressure or under-pressure respectively ý (Zhang, 2011). the pore pressure can be obtained by direct measurement or using the geophysical logs and the seismic data. (Reynolds et al. 2006).

2.3.5. Minimum and maximum stresses

In the suitable depths of oil and gas exploration, the direction of residual stresses is determined by examining several phenomena. Such phenomena include the active faults in the borehole wall, foliation of the cores, induction fissures due to drilling operation, central fracture in the core and natural or induction earthquakes. This type of wall collapsing is a sign of determining the inhomogeneous compaction around the borehole wall. When there is a major difference between, σ_h in the rocks around the well, a collapse is sure to happen. In addition to the above mentioned cases, enough time for distribution and merger of this fissure and ultimately the collapse of rock is needed, and possibly the vibration of the drilling thread will make its decisive contribution in development of the collapse. Determining the direction of the stresses is vital, for it is the direction with highest possibility of distribution and diffusion of the induction fissures. Also knowing the direction of stresses would help in determining the direction of natural joints (Mengiiao et al. 2003). The σ_H is parallel to the tensile fractures and perpendicular to the collapse direction (Garbutt and Donna, 2004). Various methods are used for determining the horizontal stresses. The σ_h value can be determined through performing hydraulic leakage and failure tests. Finally the σ_H value is obtained using the existing relationships. In case the above test data are inaccessible, the min/max horizontal stresses value can be calculated using the relevant formulae. The most common model for calculating these values in relationship with the depth is surface strain model (Pro-elastic model) (jose, 2000 and Reynolds et al. 2006). In this model, using the overburden pressure values, the Yung modulus, the Poisson coefficient and the horizontal strains, the horizontal stresses values can be calculated for which the following relationships are introduced:

$$\sigma_h = \frac{v}{1-v}(\sigma_v - ap_w) + ap_w + \frac{E\varepsilon_y}{1-v^2} + \frac{vE\varepsilon_\chi}{1-v^2} \quad (8)$$

$$\sigma_h = \frac{v}{1-v}(\sigma_v - ap_w) + ap_w + \frac{E\varepsilon_y}{1-v^2} + \frac{vE\varepsilon_\chi}{1-v^2} \quad (9)$$

where σ_H and σ_h are the maximum and minimum horizontal stresses respectively, u is the Poisson coefficient, is the Biota coefficient, Pw is the excavation fluid pressure, E is the Young's modulus (as per GPa) and x and y are the strain in x ε and y direction respectively.

2.3.6. The failure criteria

The application of failure criterion is predicting or approximating the rock failure. Modeling of the failure process and its procedure is based on a suitable failure criterion, consistent with the initial conditions of the formation. in fact during the commence and distribution of micro- fractures as well as during the junction of such micro-fractures and complete failure of the rock, the failure mechanism cannot accurately be explained; in both cases the process is highly complicated and cannot be explained using the simplified models. The most primitive conditions for stability of wall of a borehole during excavation are the existence of equilibrium and balance between the stress concentration in vicinity of the borehole wall and the rock strength. The instability of the well occurs due to the rock failure around the borehole wall when the effective stress value in the borehole wall is greater than the rock strength (Coduto, 2008). If the rock strength is greater than the induction stress value, the well will remain stable, otherwise the rock will yield and the borehole wall is likely to be unstable. There are different failure criteria. Each criterion through creating relationship between several factors tries to explain the failure conditions. For example the Mohr-Coulomb criterion explains the relationship between the normal and shear stresses in the failure situation. The Griphith criterion explains the uniaxial tensile strength based on the required strain energy for distribution and development of the micro-fractures and the uniaxial compressive strength in terms of the tensile strength. In the oil industry, particularly in order to study the stability of the oil wells, certain criteria like Mohr-Coulomb, Drucker-Pragerþ and Von Misesþ are widely used and acceptable results have been achieved from them. (Grandi et al. 2002).

2.3.7. Mohr-Coulomb failure criterion

In this study to investigate and analysis of stability of the borehole wall, the Mohr-Coulomb failure criterion has been used which is briefly discussed below: According to Mohr-Coulomb theory, none of the perpendicular or maximum shear stresses alone could cause failure but a critical combination of both might result in the failure. The theory suggests that the failure in the rock will occur when the following relationship exists between the shear and perpendicular stresses planes.

$$\sigma_c = \frac{2C.\cos\phi}{1-\sin\phi} \qquad (10)$$

$$\acute{o}_t = \frac{2C.\cos\phi}{1+\sin\phi} \qquad (11)$$

$$\tau = C + \sigma n \tan \qquad (12)$$

In these relationships, τ is the shear strength, C is the cohesion strength, σ_n is the pressure perpendicular to the shear plane, Φ is the friction angle, σ_c and σ_t are the uniaxial and tensile strengths of the rock respectively.

Using the initial main stresses, the normal and shear stresses imposed on every surface with any angle can be obtained using conversion equations relevant to the Mohr circle. Using the cohesion coefficient and internal friction angle concepts, the Mohr linear diagram is obtained which determines the failure threshold (Coduto, 2008). In other words, in using this diagram any point depicted based on (τ , σ) will pose three states:

a- If the point is below the failure curve, there will be no failure.

b- If the point falls on the failure curve, the rock is in critical condition.

c- And if the point lies above the failure point, the rock will be sure of failure. Albeit, it must be mentioned that such a state will never occur because the rock will experience the failure before the formation of such state (Grandi et al. 2002).

3. Result and discussion

Primarily by loading of the input data in Mechanical Properties section of Geolog software using the petrophysical data (Fig. 2), we will have the dynamic elastic properties' output the mean value of which are shown table 1. It's noteworthy that Darian formation is equivalent to Shuiba Arabic formation (Ameen, 2009). In the next stage, as was mentioned in the study cocepts section, the static elastic properties were obtained via the dynamic properties and the compressive wave velocity Vp (Yasar et al. 2004). The internal friction angle, the uniaxial compressive strength and the tensile strengths values were calculated in segregation for each formation using the bulk modulus (Table 2) and the output wave modulus P (the compressive velocity module) was plotted in the Geolog software.

Table 1. Mean value of Darian formation dynamic elastic properties for the understudy well.

Young's modulus(Gpa)	16.86
Poisson ratio	o.3272
Wave modulus P (Gpa)	24.8638
Internal friction angle	24.8638
Compressive strength (PSI)	2078.2715
Tensile strength (PSI)	207.8271

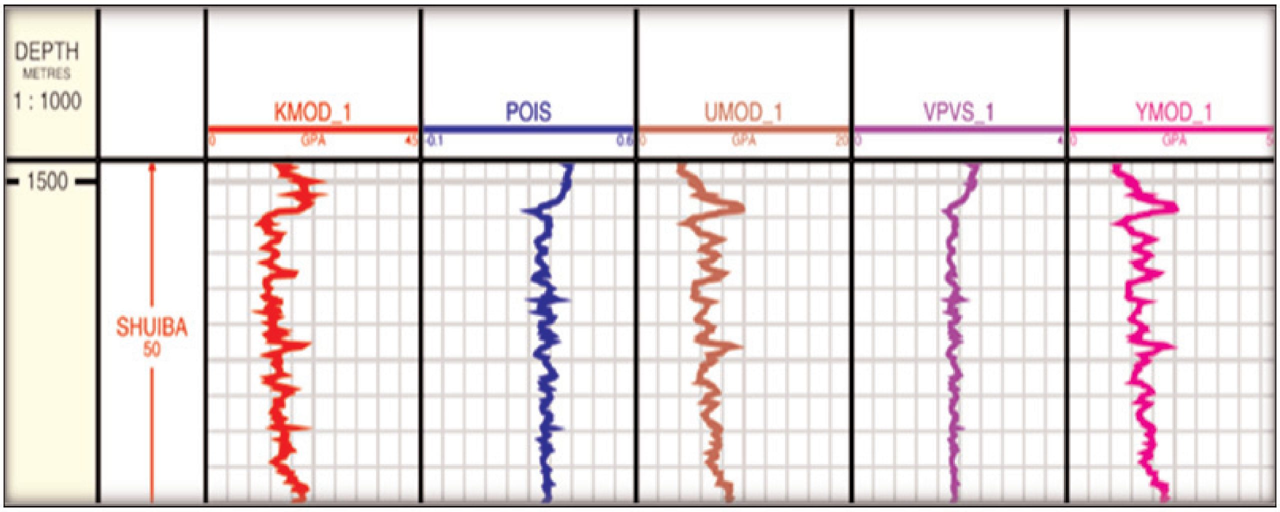

Figure 2. Elastic dynamic properties' log in the Darian formation range; where KMOD is the Young's modulus, POIS is the Poisson's ratio, UMOD is the shear modulus, VPVS is the Vp/Vs ratio and YMOD is the Young's modulus.

As was described in the initial concepts section of the study, by direct survey from the petrophysical logs of the under study well and the existing seismic data, (Alishvandi et al. 2010) the pore pressure output log output of Geolog software is like the following illustration (Fig.4) and the mean values of each pore pressure item have been calculated for Darian formation (Table 3).

The next stage of developing the geo mechanical model of the formation is determining the direction and calculating the stresses' values within the formation range; accordingly, the hydraulic fractures occur generally along the maximum main stress around the well. In a vertical well, the maximum main stress direction belongs to the maximum horizontal stress, so the hydraulic fracture direction in vertical wells shows the maximum horizontal stress. The hydraulic fractures' direction can be found out from the visual logs (Zeng et al. 2004) The visual logs are employed for interpretation of the horizontal stress direction. The most common visual logs used in this section are called Full bore Formation Micro Imager (FMI). Using FMI log data in examining the understudy well's natural fractures and the layer slope of the understudy formations, the minimum and maximum horizontal stress are along NW-SE and SW-NE directions respectively, (Najari, 2014).

To determine the minimum and maximum horizontal stresses values the stress log is used (Fig. 6), the mean values of which along Darian limestone formation have been determined (Najari, 2014). The min/max horizontal stresses values are Sh max (Psi):4131.79 Sh min (Psi): 364.88.

3.1. The main factors involved investigating the drilling mud window

Pore pressure (Pp): If the pressure of mud weight were less than the pore pressure inside the well, the instability of the well wall would be possible.

The minimum mud weight (Mw): Below of this mud weigh value, we will witness the rock failure and consequently the failure of the borehole wall. Mud weight lower will cause intense tensile failure (Breakout) of the well.

-The minimum residual stress (Pfrac): In case a natural failure or any other crevasse exists around the well or the well lies in a very penetrable area, the increase in the excavation mud weight to a value higher than the minimum residual stress value will cause fractures around the well and the loss of excavation mud will occur.

4. The formation failure pressure (FBP)

In case the mud weight pressure is higher than the compressive strength of the formation, again the break out of the formation rock and hydraulic fractures of the borehole wall are bound to occur. Also in case such mud pressure is higher than the minimum residual stress, it might turn the formation into thoroughly broken state (Gandehari, 2012).

In general, determining the stable mud window for stabilization of the borehole wall is dependent to the excavation angle and the well deviation and is defined in output interpretations of Stab View software as the point between Formation Breakdown Pressure Gradient (the maximum mud weight for the formation failure prevention) and Breakout Pressure Gradientþ (the minimum mud weight required for the borehole wall prevention).

Considering the above parameters and the input data including the static elastic parameters the dynamic modulus of elasticity as well as the values and direction of minimum and maximum stresses obtained from Stab View software, the output for Darian formation along its thickness is illustrated in figure of 8. As was explained in previous discussions, in cases where the drilling mud weight is less than the minimum strength of the formation failure, the tensile failure or Breakout occurs and if the mud weight pressure is greater than the maximum strength of the formation failure, the shear failure or Breakdown will happen and the safety zone should lie in between the two mentioned range, in line with the minimum horizontal stress in any of the understudy formations, (Schlumberger Co, 2011).

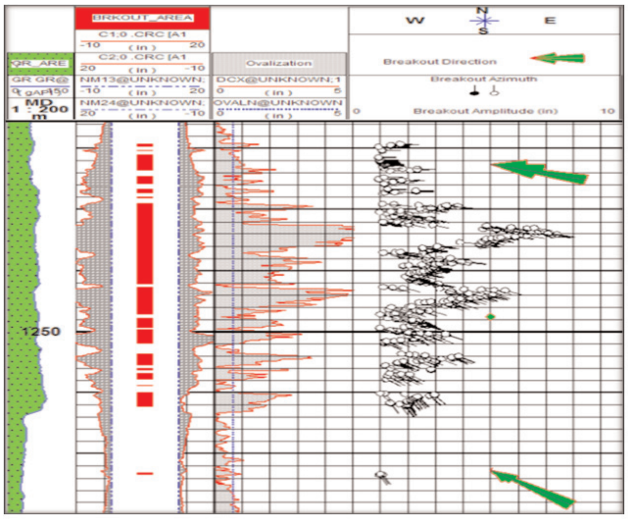

Figure 5. Log of the obtained results in determining the minimum horizontal stress direction along the NW-SE direction.

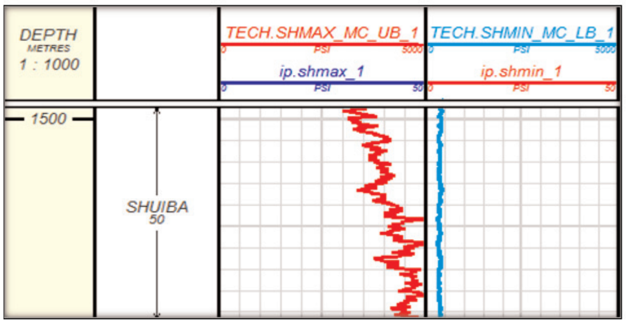

Figure 6. The min and max stress value in Darian formation range

In figure of 8 the software output for Darian formation illustrates that the right section which is indicative of the breakdown zone lies in azimuth N0° to N60°, consistent with the general direction of the fractures and almost in conformance with the mean maximum horizontal stress axis.

The drilling mud weight status for failure prevention must indicate the lowest value, hence according to the figure, in the azimuth range of 0°-60° shows the lowest mud weight of about 90 to 130 PCF. On the contrary, in the azimuth range of N60° to N180° the excavation mud weight is increased and the highest value will be in line with the minimum horizontal stress, that is, N120° or N60°W(N300) azimuth so that the mud weight of 90 to 145 PCF is observed. In figure of 9 the left section which is indicative of the breakout state, if the well deviation angle advances toward the angle of 90°, there would be more possibility for Loss and Kick, and with the smaller deviation angles between 0-30°, the excavation mud weight status with 75 to 105 PCF will pose the smaller value for Breakout and Loss prevention. With the angles 30-45° the mud weight of 80 to 105 PCF can be observed in the well. Comparing the two Breakout and Breakdown states and non-occurrence of Loss and Kick in Darian formation, the drilling mud weight is estimated within the range 80 to 120 PCF with 30° to 45° drilling azimuth.

5. Conclusions

After developing the geomechanical model and analyzing the excavation mud weight window in Darian formation, the results included determining the excavation mud weight window for minimizing the risk and management of instability of borehole wall and preventing the drilling tube from sticking and loss of mud and in sum, decreasing the drilling costs. Elastic constants (Young modulus, bulk modulus, shear modulus) were evaluated in dynamic state using petrophysical and visual logs via employing ultrasonic waves, and the elastic constants were plotted for the understudy formation thickness. The results obtained for the dynamic Young's modulus, bulk modulus and shear modulus in Darian formation were 17.7 , 15.8 and 6.78 GPa respectively. The Young's modulus in this study in static state was calculated as equal to 16.86 GPa along Darian formation thickness. Using statistical analysis, the data resulting from the uniaxial compressive strength tests were studied on the cores obtained from the understudy reservoir. The empirical relationships between the uniaxial compressive strength (USC) and dynamic Young modulus (Ed) and their relationships with the compression wave velocity is indicative of a uniaxial compressive strength mean value of 2078.28 PSI in Darian formation. The minimum and maximum stresses along Darian formation thickness were equal to 364.88 PSI and 4131.8 PSI respectively.

Considering the requirement for choosing the best direction for excavation along the minimum horizontal stress in order to overcoming the borehole wall

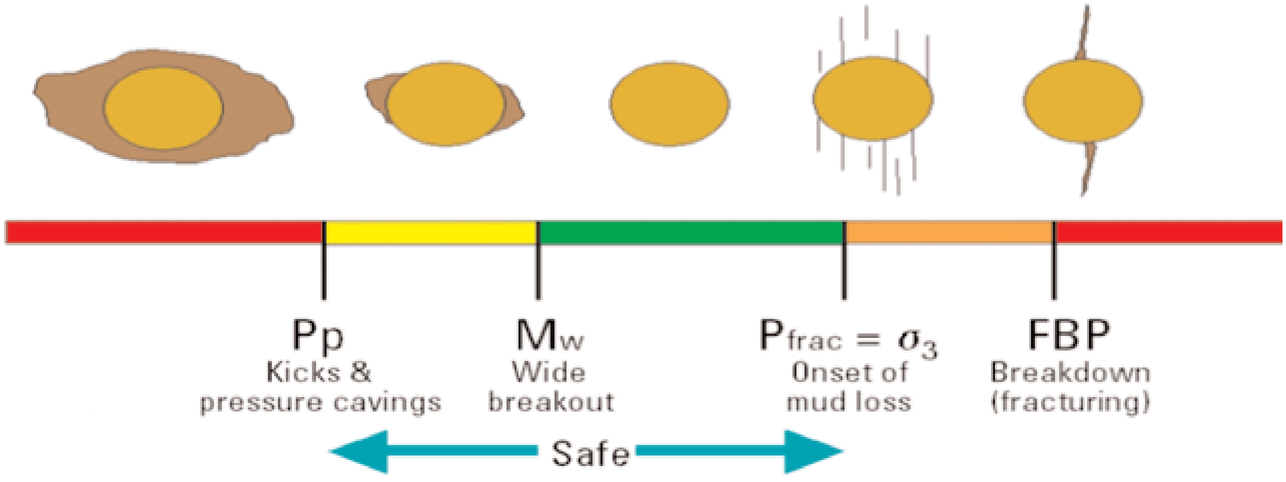

Figure 7. Factors effective in different fractures due to the mud weight

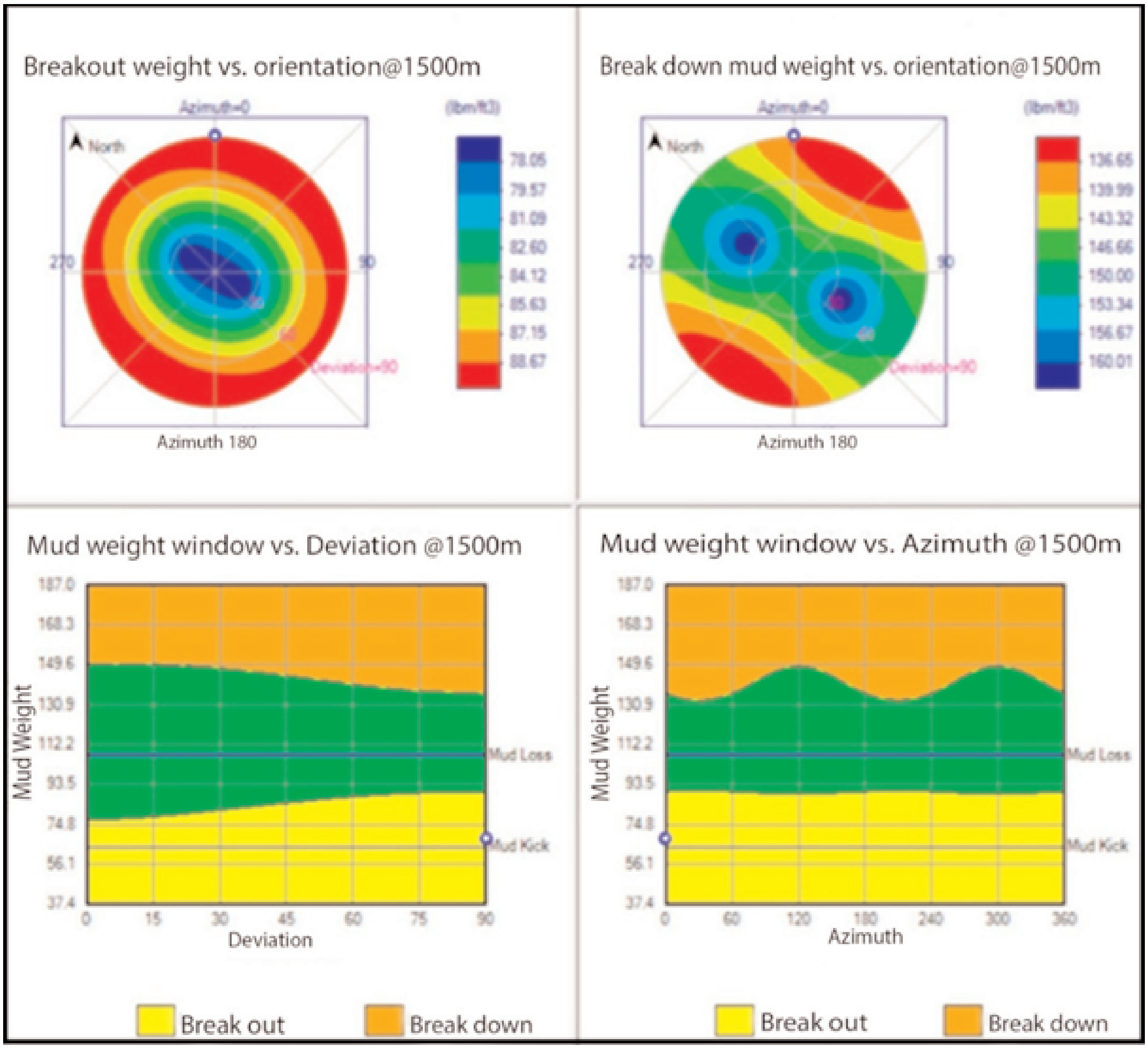

Figure 8. The STAB View software output for determining the mud weight window and azimuth in Darian formation

instability in Darian reservoir formation, the mud weight of 80 to 120 PCF with 30° to 45° azimuth along northwestern - southeastern direction is recommended. The obtained geomechanical model has applications in many designing procedures of oil recovery methods including optimizing the reservoirs' recycling capacity such as hydraulic fracture improvement, finding suitable type and amount of fluid with adequate physical properties for performing hydraulic fracture operations and finding the most appropriate production zones for maximum recovery as well as vapor injection in secondary exploitations. This geomechanical model may be used in reservoir engineering including determining the optimum well completion methods, determining the permeability of the fractured reservoirs, predicting the reservoir performance changes during production and finding the reservoir's sand production capacity.

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