Maximum Horizontal Stress Validation Based on Wellbore Breakout Model

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Abstract. Maximum horizontal stress is one of the most critical parameters that affect the stability of the wellbore during drilling operations. Currently, no direct measurement of the maximum horizontal stress is available to validate its magnitude obtained from existing solutions. It is usually estimated from an extended leak-off test or from equations that depend on other parameters such as the minimum horizontal stress, rock properties and the overburden stress. Borehole breakout is a function of in-situ stresses, pore pressure, elastic and plastic properties. These parameters are calculated from sonic logs and calibrated by triaxial tests and mini-frac jobs for wellbore stability design. In this study, four-arm caliper data is used to determine the breakout length in the wellbore. The breakout data is compared with simulation results using 2D numerical model to validate the maximum horizontal stress magnitude. The material law is based on elastoplastic model to capture the rock deformation process in the region based on an iterative process until the same extent of the breakout from the caliper log is attained. The results showed that the estimated magnitude of the maximum horizontal stress by the wellbore breakout model is 5% higher than corresponding values obtained from the existing solutions. This study determines how accurate can the existing equations estimate the maximum horizontal stress compared to numerical breakout model. The numerical model incorporates more physics and simulate realistic process of progressive breakout failure while drilling. The accuracy of maximum horizontal stress magnitude influences the overall wellbore stability design to estimate safe mud weight window for an oil and gas well.
1. Introduction

In-situ stresses have been extensively studied in the past to maintain a stable and gauged borehole while drilling. During drilling, the in-situ stress is redistributed around the wellbore. When rock compressive strength exceeds the rock’s compressive failure, a possible rock failure or breakout could occur. Maintaining a stable borehole requires taking into consideration that there are controllable and uncontrollable factors. For example, the in-situ stresses, rock strength, and pore pressure are uncontrollable factors that highly affect the stability of the well. The controllable factors include the fluid pressure and mud chemical composition. It is important to understand that in order to correctly calculate the fluid pressure used for drilling the uncontrollable factors must be properly determined and validated (Cheatham, J.B., Li, L., Aubertin., and R. Simon). Maximum horizontal stress is one of the important uncontrollable parameters that affects the stability of the wellbore during the drilling operations. Unfortunately, unlike the minimum horizontal and overburden stress, there is no direct measurement that validates the value of the maximum horizontal stress. The value of the maximum horizontal stress is still a challenge in the oil and gas industry as it is usually estimated using theoretical and empirical relationships; such as the extended leak-off test or calculated using the existing solutions (Blanton, T.L., Olson J.E., Najm, Ehab, and John Quirein.) that depend on other geomechanical and petrophysical properties such as the minimum horizontal stress and the overburden stress.

Incorrect calculation of the parameters in the mechanical earth model (MEM) results in borehole instability that results in breakouts, which can affect the hydraulic fracture process and the completion of the well. The value of the maximum horizontal stress obtained using the existing solutions is used to build the 1D (MEM) and determine the safe mud weight window. The safe mud weight window is defined by two main points which are the critical collapse pressure and the critical fracture pressure, between these two points is what is known as the safe mud weight window, it is the region with the lowest risk of creating a fracture or causing the well to collapse during drilling (Aslannezhad, M., Khaksar Manshad, A. & Jalalifar, H). This makes the value of the maximum horizontal stress very critical when it comes to keeping the borehole stable and gauged while drilling as it has a direct effect on determining the optimum mud weight to be used in drilling the well. Although borehole instability and major breakouts could be minimized by using a higher mud weight value, it could also cause many issues such as low rate of penetration, fluid loss, stuck pipe, or even formation damage. This is why it is important to optimize the mud weight while drilling instead of just keeping the mud weight high. The mud weight window is calculated as a function of the formation properties that are calculated and verified from the MEM. The validation of the MEM data will result in having an optimum mud weight that will prevent borehole instability and formation damages.

Since the value of the maximum horizontal stress could not be verified with any of the available tests, this paper will use a 2D numerical model to simulate the wellbore breakout length and compare the depths with the observed breakouts length from the caliper log to validate the value of the maximum horizontal stress (Addis, M.A., Last N.C., Yassir N.A.). Assuming all other parameters in the MEM are verified and correct, the magnitude of the maximum horizontal stress will be changed in an iteration process to match the breakouts observed from the caliper log and optimize the mud weight during the drilling process. The purpose of this study is to demonstrate the effect of the maximum horizontal stress value on the mud weight window calculation of the wellbore.
2. Methodology

In this study, the first step was to retrieve the caliper log from the logging while drilling (LWD) data, plot the caliper with the baseline of the wellbore, and observe the breakouts by comparing the logging data to the baseline of the borehole. Looking at the data, three depths were selected for this study to observe the effect of the maximum horizontal stress magnitude on the breakout length observed from the caliper log using a 2D numerical model. The three points were selected based on the breakout lengths observed from the caliper log where it showed the most significant breakouts noticed compared to other depths in the well. Table 1 below shows caliper log data of a certain well.

| Dataset | Depth Point (ft) | Formation type | Observed Breakout Length (m) | Percent Difference with Respect to Drill Bit (%) |
|---------|-----------------|----------------|-----------------------------|---------------------------------------------|
| #1      | 13284           | Carbonate      | 0.1563                      | 5                                          |
| #2      | 13250           | Carbonate      | 0.1651                      | 11                                         |
| #3      | 13263           | Carbonate      | 0.1535                      | 3                                          |

The second step included using a 2D numerical model (IRAZU – GEOMECHANICA software) to simulate the borehole and observe breakouts by using the rock properties shown in Table 2. The model consists of 83060 elements and 41844 nodes, the mesh around the wellbore was refined within average area of 4.2x10^{-7} mm². Coarsen mesh was also applied in the model away from the wellbore to optimize simulation run time. The model was initialized by applying the far field stresses at the external boundary until the model reached equilibrium. A surface pressure boundary condition was applied at the inner circle (borehole) and the breakout simulation was conducted using the surface pressure until the model reached equilibrium state. (Voegeli, S., Nopola, J., Moos, D., and T. Doe.)

Data such as in-situ stresses, pore pressure, elastic and plastic properties of the rock were used to build a 1D MEM. These parameters were calculated from sonic logs and calibrated using triaxial and mini-frac tests. As there was no direct measurement of the maximum horizontal stress it could not be verified using any of the available tests, as a result the effect of the magnitude of the maximum horizontal stress was still a question when it came to calculating the mud weight window for a safe mud for the drilling process. For this paper, the magnitude of the maximum horizontal stress is changed using an iterative process in the 2D numerical model until the same extent of the breakout is observed from the caliper log and the model (Barton C.A., Zoback M.D., Burns, K.L.) (Al-Tahini, Ashraf M., Ashraf , M., Abousleiman, Younane N., and N. Younane.). The process shows that the maximum horizontal stress is in direct relationship with the breakout observed in the caliper log, the greater the maximum horizontal stress the greater the breakout. Thus, the criterion that describes the agreement between the numerical model and the caliper log is the calibrated maximum horizontal stress value found from having the caliper log breakout depth and numerical model breakout depth in close agreement. (Papamichos, E., P. Lionios and P.J. van den Hoek)
Values obtained from the MEM were converted to the correct units and used in the 2D numerical model (Table 2). The maximum horizontal stress value was changed by first increasing the magnitude by 1%, then the largest breakout length observed from the model were compared to the breakout length from the caliper log. If the breakout length from the numerical model was smaller than the breakout length found in the caliper log, the magnitude of the maximum horizontal stress is increased another 1%. When the breakout length observed from the numerical model is larger than the breakout observed from the caliper log, the magnitude of the maximum horizontal stress is decreased by 1%. The process was repeated until breakout length is in close agreement between the numerical model and the caliper log.

| Dataset | #1 | #2 | #3 |
|---------|----|----|----|
| Depth (ft) | 13284 | 13250 | 13263 |
| Density (kg/m³) | 2.65x10³ | 2.65x10³ | 2.88x10³ |
| Young Modulus (Pa) | 5.48x10¹⁰ | 6.50x10¹⁰ | 6.96x10¹⁰ |
| Poisson’s Ratio (-) | 0.23 | 0.25 | 0.27 |
| Friction Angle (Rad) | 0.75 | 0.75 | 0.87 |
| Cohesion (Pa) | 1.61x10⁷ | 1.62x10⁷ | 1.74x10⁷ |
| UCS (psi) | 1.07x10⁴ | 1.09x10⁴ | 1.38x10⁴ |
| Tensile Strength (Pa) | 3.70x10⁶ | 3.74x10⁶ | 4.75x10⁶ |
| Mud Pressure (Pa) | 5.72x10⁷ | 5.71x10⁷ | 5.71x10⁷ |
| Minimum Horizontal Stress (Pa) | 5.72x10⁷ | 8.59x10⁷ | 8.60x10⁷ |
| Maximum Horizontal Stress (Pa) | 1.25x10⁸ | 1.25x10⁸ | 1.24x10⁸ |

Table 2. Summary of Formation Properties Used in Numerical Simulation.
3. Results and Discussion

Three points were chosen based on the breakout length observed from the retrieved caliper log. The first chosen point was at a depth of 13,284 ft where the caliper log had a reading of 0.1563 m. Given that the diameter of the wellbore was equal to 0.1490 m, the breakout observed at that length was equal to the difference between the caliper and the wellbore diameter, which was 0.2775 ft. Using Equation 1, the magnitude of the maximum horizontal stress ($\sigma_H$) was calculated to be 26.11 ppg at the depth of 13,284 ft. (Blanton, T.L., Olson J.E.) (Zoback, M.D. 2012)

$$\sigma_H = \frac{\nu}{1 - \nu} (\sigma_v - \alpha PP) + \alpha PP + \frac{E}{1 - \nu} \epsilon_h + \frac{\nu E}{1 - \nu} \epsilon_H$$  \hspace{1cm} (1)

Where
\begin{align*}
\nu & \text{ Poisson’s ratio} \\
\sigma_v & \text{ overburden stress} \\
E & \text{ Young’s modulus} \\
\alpha & \text{ Biot’s constant} \\
PP & \text{ Pore pressure} \\
\epsilon_h, \epsilon_H & \text{ Minimum, maximum principal horizontal strain}
\end{align*}

Using the 2D simulation model, the breakout length of 0.2775 ft was observed with a maximum horizontal stress value of 27.54 ppg. The magnitude of the maximum horizontal stress noticed from the simulation model (Figure 1) was greater by almost 5% than the magnitude of the maximum horizontal stress obtained using the known correlation. Figure 1 shows the 2D simulation model for the three different depths respectively
Figure 1. Breakouts observed from numerical model for point 1, 2 and 3, respectively.
A 5% increase in the magnitude of the maximum horizontal stress may not seem very significant at this point. A wellbore stability analysis was performed for this point to analyze the effect of this increase. A wellbore stability software was used to run an elastic analysis using a Mohr-Coulomb failure criterion, the borehole condition was assumed to be impermeable and the same rock characteristics were used in both cases with only changing the maximum horizontal stress value to compare the results. Figure 2 represents the mud weight window analysis with the original data from the MEM with the maximum horizontal stress value calculated using the above equation. Figure 3 illustrates the mud weight window analysis with the same data with only changing the maximum horizontal stress magnitude to the value obtained from the 2D numerical simulation model.

In the first case when drilling with a mud weight of 105 pcf, the safe mud weight window predicts that this is within the safe zone. Using the validated maximum horizontal stress value from the model shows that the safe mud weight window shifted and increased. The effect of the maximum horizontal stress is very critical when it comes to calculating the safe mud weight window. The incorrect determination of the mud weight window may cause the wellbore to collapse or fracture during drilling. The other two points that were chosen are at depth 13250 ft and 13263 ft. These points showed that the maximum horizontal stress calculated using the existing solution exceeded the maximum horizontal stress found from the numerical model by 19% and 20%, respectively. The three depths have an average of 11% less than the calculated values of the maximum horizontal stress used in determining the optimum mud weight. The results are summarized in Table 3.

| Dataset | Depth Point (ft) | Maximum Horizontal Stress Calculated Using Equation 1 (ppg) | Maximum Horizontal Stress from Numerical Model (ppg) | Percent Difference (%) |
|---------|------------------|----------------------------------------------------------|---------------------------------------------------|-----------------------|
| #1      | 13284            | 26.114                                                   | 27.536                                            | 5                     |
| #2      | 13250            | 26.031                                                   | 21.033                                            | -19                   |
| #3      | 13263            | 26.049                                                   | 20.839                                            | -20                   |
| Average |                  |                                                          |                                                   | -11                   |
Figure 2. Mud weight window using the estimated value of Sigma_H from Equation 1

Figure 3. Mud weight window using validated value of Sigma_H from wellbore breakout model.

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Wellbore stability analysis is usually determined assuming a linear elastic model. This is the most common model used in the industry, due to its simplicity when preforming the analysis, when calculating the safe mud weight window. A poroelastic approach is a more complex solution that accounts for more physical parameters when performing the wellbore stability analysis of the wellbore. Using a linear elastic solution to predict the minimum required mud weight value for drilling could result in different value when compared to a poroelastic solution. Figure 5 and 6 illustrate the difference of mud weight window when using a linear elastic solution and a poroelastic solution. Correctly determining the stresses that are affecting the rock will have a great impact when calculating the safe mud weight window (Li, S. & Purdy, C.C.). Using the poroelastic solution in wellbore stability analysis, as the 2D numerical model simulates, calculates a more realistic value of the parameters as it accounts for more physical parameters in the solution making it more complex and more accurate.

![Figure 4. Mud weight window using linear elastic solution.](image-url)
4. Conclusion
Wellbore instabilities cause higher than necessary drilling costs due to the issues occurring during the drilling process. Determining the minimum required value of the mud weight is the first step toward preventing hole instabilities. The calculated mud weight depends on many parameters. The maximum horizontal stress is one of the most critical parameters, especially when it comes to keeping the borehole in a safe and stable condition during drilling operations. Unlike the other parameters that affect the minimum required value of the mud weight, the maximum horizontal stress value cannot be verified or calibrated using any of the available tests. The value of the maximum horizontal stress is fully determined using linear elastic equations that depend on other mechanical properties of the well.

The study in this paper concludes that the value of the maximum horizontal stress calculated from the existing solution varies appreciably from the maximum horizontal stress value obtained from the 2D numerical model. The critical collapse pressure in the safe mud weight window is very sensitive to the magnitude of the maximum horizontal stress. A slight increase in the maximum horizontal stress value causes the critical collapse pressure point to shift, which changes the safe mud weight window that is available for drillers to drill the well with the least risk possible. Using the unvalidated maximum horizontal stress value in the calculation for wellbore stability analysis could cause wellbore stability issues as the mud weight used for drilling can in fact be outside of the safe mud weight window range (McLean, M.R. and Addis, M.A.).

Figure 5. Mud weight window using poroelastic solution.
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